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An exploration on the relationship between airport characteristics and the occurrence of runway incursions

Master Thesis

H.B. Koopmans

7 March 2019

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MASTER OF SCIENCE THESIS

to obtain the degree of Master of Science in Civil Engineering and Management
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H.B. Koopmans

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Preface

This report is the result of the master thesis research, which I conducted as my final assessment of the study programme Civil Engineering and Management, at the University of Twente. In a period of approximately half a year, from the first proposal until the drawing of the final conclusion, I dived into the world of aircraft, airports and runway incursions. It has been a very inspiring project, that completely fitted my interest in the aviation sector. The study was executed on behalf of NACO, Netherlands Airport Consultants, because of the importance to obtain a better understanding on the influence of airport characteristics on the occurrence of runway incursions.

The project was impossible without the guidance of my supervisors who helped me through the research process.

First, my gratitude goes to Peter Vorage and Fer Mooren from NACO for their guidance, support and dedication. I was always able to ask questions and to schedule brainstorm sessions, in order to head for the right direction. The feedback taught me a lot about the airport- and aviation-related themes and challenged me to improve the research. Moreover, I was provided with the freedom to shape the assignment myself.

Furthermore, I would like to thank Tom Thomas and Eric van Berkum from the University of Twente for their supervision and sharing of knowledge. The feedback was always helpful to improve the process and to get back on track at the moments I got stuck. They also taught me to approach the research problem from multiple viewpoints.

I am also thankful to Jelmer van der Meer, for providing me the opportunity to graduate on this topic, and to my other colleagues at NACO, for expressing their interest in the thesis and making me feel welcome. They were always willing to help.

Finally, I am grateful for the support of my family and friends, who continuously motivated me during the project in every possible way.

It is with pleasure that I present my master thesis. Hopefully, you enjoy reading this report and become also enthusiastic and inspired by this interesting sector.

Henk Koopmans

Delft, 7 March 2019

Executive summary

Runway incursions are considered as one of the most critical incident types in aviation, as the consequences can be catastrophic, leading to large damage and deadly injuries. Worldwide, approximately 30% of the aviation accidents of commercial aircraft are runway-related. Within the boundaries of an airport, incursions are one of the top priority safety issues; an investigation by the Dutch Safety Board (DSB) showed that at Schiphol Airport (AMS), the largest share of incidents is represented by runway incursions. Between 2010 and 2017, 282 incursions were recorded here. At the measured airports in the United States (US), 16,785 incursions were observed between 2002 and 2015; on average three incursions occur daily. Figures show that most incursions concern low severity incidents in which a single aircraft or vehicle is involved, without any risk of collision. Only a relatively small number of serious incursions can be related to the safety of the air transport system annually.

A runway incursion is defined as "any occurrence at an aerodrome 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." ICAO defined four severity levels: A, B, C and D, with A being the most severe example and D the least severe incident. The main factor in the severity determination is the Closest Horizontal Proximity between two aircraft during the incident. Furthermore, three types of incursions are known, which indicate the actor that caused the incursion, namely: air traffic controller-induced (operational incidents), flight crew-induced (pilot deviation) and vehicle driver-induced (vehicle/pedestrian deviation). Figure 0.1 summarises the incursion severities and types.

D	C	B	A
An incident that meets the definition of runway incursion with no immediate safety consequences, because of the incorrect presence of a single object on the runway area.	An incident characterised by ample time and/or distance to avoid a collision.	An incident in which separation decreases and there is significant potential for collision, which may result in a time-critical evasive response to avoid a collision.	A serious incident in which a collision is narrowly avoided.

Operational incident An incident caused by the Air Traffic Control
Pilot deviation An incident caused by a pilot
Vehicle/pedestrian deviation An incident caused by a vehicle or pedestrian

Figure 0.1: Runway incursion severities and types

Due to a forecasted growth of the air transport industry and the resulting increase of traffic volumes, more airports are faced with these incidents. Figures show that incursions have been on the rise and that 20% increase in airport traffic means an incursion risk increase of 140%. Incursions can be caused by a wide range of factors, from technical and physical elements, to regulations and operational procedures, human error and a combination of these factors. Since incidents are often the consequence of a series of factors and components cannot be assessed in isolation, the SHELL model is considered. This is a conceptual framework that explains the interaction between factors for aviation incidents. From this can be learned that influencing factors should always be considered in the broader context.

To cope with the rising number of incidents, agencies have targeted runway incursions as one of the main priorities in airport planning, often in established Runway Safety Teams. To support improvements, various directives, guidelines and initiatives have been implemented to propose effective safety management systems. Common examples include the designation of hot spots, additional visual aids, incursion warning systems and Runway Status Lights (RSL). However, the search for additional mitigation measures continues. More specifically, to adapt, improve and design airports in such a way that the risk of incursions is mitigated, it is necessary to understand how infrastructure relates to it. For example, as stated in the European Action Plan for the Prevention of Runway Incursions "new aerodrome infrastructure and changes to existing infrastructure should be designed to prevent runway incursions".

For the development of effective measures, it is necessary to have a thorough understanding of the interaction between infrastructure and incursions. Various qualitative and quantitative studies have been performed over the years to improve this understanding, though, open ends still exist. As the literature review showed, multiple airport characteristics relate to the likelihood of incursions. Causes can be found in a variety of areas, such as communication, signage, operations and geometrics. It is for instance found that the likelihood is influenced by the airport size, the traffic volume and the traffic mix at an airport. Other likelihood-increasing factors were identified as the presence of frequent construction notices, irregular signage and surface markings and non-convenient airport lighting.

Furthermore, a large share of the influencing factors was found in airport infrastructure. Guidelines encourage for example to limit the number of non-right-angled intersections such as Rapid Exit Taxiways. Also, the presence of intersecting runways and a higher number of runway intersections was found to relate to a higher incursion likelihood. The same conclusion was demonstrated for the presence of complex intersections. In contrast to these studies, other researchers argued that runway geometry is not a significant predictor for incursions and that the rate of incursions was hardly associated with airport characteristics. All studies faced complications with the analysis for severities, due to the scarcity of high severity incident observations.

Because of the increasing availability of incident data over the recent years, analysis-induced studies with the aim to model the relationships between variables and to propose prediction tools, became more common. However, detailed analyses on certain airport-related elements lack in current conclusions. Nevertheless, some recent studies analysed geometrics in more detail. Though, the studies indicated the demand for extension of the analysis for the validation of their results, using additional data and more variables.

For NACO, as airport consultancy firm, it is valuable to obtain more insight in these airport-related interactions, in order to design airports in an incursion-preventive manner. From the observed trend in the aviation industry, the inducement from the DSB report and the findings from literature, we arrived at the research problem: "*to expand airports for growth of traffic volumes, and to design green field airports in a way such that the probability of runway incursions is reduced, it is necessary to have an understanding of the relation between the geometric factors and elements of an airport and the probability of runway incursions*." The aim of this study is to obtain knowledge on how airport characteristics influence the likelihood of runway incursions.

Based on the proven potential for statistical analysis in this field and the difficulty to achieve additional relevant findings from a qualitative approach, it was decided to conduct a data analysis and to develop an improved frequency model, extended with a partly qualitative validation. The data analysis was conducted on 420 US airports, since the US provides the largest publicly available collection of incident data for a large variety of airport characteristics. Also, the busiest airports in terms of aircraft movements are in the country and the data is audited and assumed to be representative. The period 2007-2017 is analysed, since the severity classification was implemented in 2007.

The research is phased in four phases, the theoretical framework, the data collection and preparation, the analysis, the modelling and the application. To validate the retrieved characteristics for the analysis from the literature review, a panel of senior experts is created, consisting of airport users that represent each of the incursion type inducers. The aim for this was to justify the relevance of the characteristics and to combine the knowledge from literature and practical experience. As a result, relevant characteristics were selected for the analysis.

After the data is collected, a high-level analysis is conducted to understand the relation between airport characteristics and runway incursions on an aggregated level. For this, the aim is to select appropriate indicators which can be used for the model estimation. Incursion frequencies throughout the study are expressed as the incursion rates R_{rate}, which represents the number of incursions per 100,000 airport movements during operational and good visibility condition hours. The analysis of airport characteristics is based on the exclusion of low visibility incidents, to make fair airport comparisons possible.

Thereafter, the frequency model is estimated. First, it is decided for which type of incursions the most accurate model can be proposed. To achieve this, association tests are conducted, outliers are identified and the regression method is chosen. It appeared that the share of A and B incidents are too small to provide significant analysis results. To deal with the data shortage, A, B and C incidents are aggregated into a high severity category, because of their similar character. D incidents are often represented by a different type of occurrence. It is found that the impact of airport characteristics on the incursion likelihood depends on the way of expressing the incursion rate. The R_{rate} cannot be properly modelled regarding airport characteristics. However, the high severity incursion rate is associated with the majority of the characteristics, including the geometry variables. Also, the likelihood of D incidents is generally not explained by the infrastructure. Likewise, only for OI, most of the characteristics showed an association. For PD and V/PD various outside-the-scope circumstances could play a role.

From the model development, the following equation (0-1) was found to provide the best fit and the most appropriate estimation of the incursion rate. Here $a_1, ..., a_5$ are the Beta-coefficients, T_h represents the number of hourly airport movements, I_n is the number of taxiway intersections per runway-km, C_{req} means the number of required runway crossings to reach the farthest runway, measured from the terminal acreage, and I_r stands for the ratio intersecting runways (i.e. total RWY-RWY intersections/total number of runways). Considering the attributes in isolation, C_{req} has the strongest effect on the incursion rate, followed by I_r and I_n. In the model, the interaction of I_r and I_n has the strongest effect.

$$\widehat{R_{rate}} = b_0 + a_1 {T_h}^{0.5} + a_2 I_n + a_3 {C_{req}}^{2.2} + {I_r}^{1.9}(a_4 + a_5 I_n) \quad (0\text{-}1)$$

The estimation of the frequency model resulted in an accurate predictor for incursion rates, as comparison by means of the existing model of Claros et al. (2007) showed. Therefore, the results presented in this research are assumed to give a more accurate estimation compared to this model, due to a longer measurement period and the application of other attributes and variable definitions. The final model achieves to explain almost 40% of the variability of the response data and is therefore, based on comparable studies in the field, quite accurate. Apparently, airport geometry represents an important share in the occurrence of the incidents. The remaining share is represented by other factors.

From the model residuals, three airport cases were selected. Honolulu (HNL) was chosen since it observed a much higher incursion rate than was predicted by the model. Phoenix (PHX) was chosen because it showed a smaller observed rate than was estimated by the model. Also, Houston (IAH) was selected, as the model performed the best on the R_{rate} estimation for this airport. The deviations were analysed as airport cases, in which all incidents were mapped according to their location of occurrence. The variation can be explained by geometric elements that are not captured in the model due to collinearity, such as closely situated parallel runways and operational procedures.

The topic of runway incursions has shown to be very broad; many circumstances determine the risk of an incursion, i.e. the component of severity and likelihood. Even the estimation of incursion likelihoods requires many variables that are complicated to capture. Although it is complex to predict incursions, as has been shown in literature, it is known that the characteristics of an airport, and especially the geometry, represent an important share of the causes. This study aimed to perform a statistical analysis to obtain insight in the relations between airport characteristics and the likelihood of the incursion types and severities. From the results can be seen that this objective was fulfilled. The analysis refutes the assumption of earlier studies that geometry is not a significant predictor for incursions. Also, it is shown that airport characteristics have an impact on both the rate and severity. Hence, despite strong correlations, the complication of indicating the causality remains complex. Though, based on the statistics, it can be concluded that airport characteristics and runway incursions are clearly linked.

Despite the relatively long measurement period, the share of the highest severity levels A and B was such small that appropriate statistical analysis was impossible. Given that A and B incidents rarely occur, it is not expected that a longer time interval would allow statistical modelling of these incidents. Moreover, the number of these high severity incidents shows a decreasing trend, and therefore, category C maintains the most interesting category for analysis.

Based on the results, a series of recommendations can be done regarding airport geometry planning.

It is recommended:

- to position right-angled intersects near the runway-ends, such that these are mainly used by departing aircraft;
- to position non-right-angled intersections in the mid-range of the RWY for landing aircraft (no-entry from TWY);
- to only add intersections at the mid-range of the runway for the absence of required runway crossings;
- to position aircraft-designated areas on the same side of the runway as the terminal acreage;
- to implement designated runways for dedicated terminals, airport areas or air traffic types, such that required crossings are minimised.

It is discouraged:

- to implement runway crossings;
  - if necessary, it is encouraged for the runway-ends as right-angled intersections;
- to implement intersecting runways;
  - if necessary, it is encouraged to construct these only if their operations are independent;
  - or otherwise it is encouraged to implement RSL;
- to implement complex intersections.

Contents

Acronyms

AAS	Amsterdam Airport Schiphol
ADG	Airplane Design Group
ATC	Air Traffic Control
ATCO	Air Traffic Controller
AMS	Amsterdam Airport Schiphol
ASDE	Area Surface Detection Equipment
CHP	Closest Horizontal Proximity
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration
FAA LID	FAA Location identifier
GA	General Aviation
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
LIFR	Low Instrument Flight Rules
LVNL	Luchtverkeersleiding Nederland
METAR	Meteorological Terminal Air Report
MVFR	Marginal Visual Flight Rules
RET	Rapid Exit Taxiway
REL	Runway Entrance Lights
RIASS	Runway Incursion Alerting System Schiphol
RIL	Runway Intersection Lights
RSA	Runway Safety Area
RST	Runway Safety Team
RSL	Runway Status Lights
RWY	Runway
SSP	Schiphol Safety Platform
THL	Take-off Hold Lights
TWY	Taxiway
VFR	Visual Flight Rules

Glossary

Airport size	Large hub, medium hub, small hub, non-hub, other
Incident	A runway incursion that meets one of the severity classifications (e.g. near-collision) and is thus no accident
Incursion	Reference to runway incursion
Likelihood	Expected number of runway incursions divided by the number of operations
Probability	Numerical value [0,1] indicating the chance that a given event occurs
Required crossings	The maximum number of required runway crossings to reach the farthest runway, measured from the terminal acreage
Risk	The composite of the likelihood of potential effect and the predicted severity of the effect
Study period	Measurement period 1 January 2007 – 31 December 2017

Symbols

a_i	Final model coefficients $i = 1, \ldots, 5$
ADG_i	Airplane Design Group, category E ($i = E$), category F ($i = F$)
B	General parameter coefficient
b_0	Estimated Y intercept
β	Standardised parameter coefficient
C_{req}	Required runway crossings
d	Dummy variable
E_R	Runway incursion type
f	Frequency
G	Interaction term
h	Hour
K	Runway incursion risk
L_{tot}	Total runway length
N, n	Number
N_{dep}	Number of departures
N_{tot}	Number of departures plus arrivals
O_i	Operational hours ($i = h$), hours per week ($i = w$), hours per year ($i = y$)
P, p	Probability
R	Runway incursion number
r	Ratio
R_i	Runway incursion number per year ($i = y$), per week ($i = w$), per hour ($i = h$)
R_{rate}	Runway incursion number per 100,000 movements
S_R	Runway incursion severity classification
T_i	Aircraft movements, heavy traffic ($i = HVY$), general aviation ($i = GA$), commercial traffic ($i = CO$), per hour ($i = h$), hours per year ($i = y$)
t	Time window
I_n	Number of TWY-RWY intersections per runway-km
I_r	Ratio number of RWY-RWY intersections/total number of runways
$\mathcal{L}_K$	Risk matrix likelihood category
w	Week
y	Year
X	Independent variable of Y
Y	Dependent variable of X

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1 Introduction

In 2017, the Dutch Safety Board (DSB) published a report about the air traffic safety situation at Amsterdam Airport Schiphol (AMS), based on the investigation of serious incidents in the last few years. The DSB expressed concerns about the current situation at the airport. It states that the boundaries in which the traffic can be safely handled are coming closer:

"The investigation found no evidence to suggest that safety at Schiphol is inadequate. However, the investigation did reveal a number of safety risks that need to be tackled integrally and systematically in order to guarantee safety both now and in the future,,

Dutch Safety Board (2017b)

The DSB listed several specific safety concerns and recommendations. It describes that the airport is complex, both in terms of infrastructure layout and in the way the air traffic is handled. Due to the ongoing growth, the complexity within both aspects is increasing even further. Frequent runway configuration changes, which are the result of economic and environmental considerations (arrival and departure peaks, noise nuisance, etc.), make the traffic handling process more complex. It leads to high workloads for the air traffic controllers. The numerous taxiways, runway exits and entries and the relative (sometimes converging) runway orientations at AMS give rise to the safety risk, concludes the report. It is advised to reduce the complexity of the airports infrastructure. Meanwhile, there are expansion plans for the airport, increasing the number of flights on the long term[1].

The investigation shows that the largest share of the incidents at AMS concern runway incursions. These incidents are the most critical as their impact can be catastrophic, leading to large damage and deadly injuries. Hence, runway incursions are not only a safety problem for AMS. With a forecasted growth of the air transport industry and associated increasing traffic volumes, many airports are faced with these kind of safety issues. Meanwhile, various airports have the ambition to expand and grow in terms of traffic volumes. This goes hand in hand with a global rise in the number of incursions (ICAO, 2007). Transport Canada (2012) reported that the 20% increase in airport traffic will increase incursion risk by 140%. For future airport planning, measures are required to safely accommodate the growing air traffic volumes.

This report presents the research of my master thesis at NACO, Netherlands Airport Consultants, as part of the study programme Civil Engineering and Management at the University of Twente. Through this introductory chapter, the inducement for the research, the objective and the research questions will become clear.

1.1 Runway incursions in perspective

At AMS, 282 runway incursions were observed between 2010 and 2017 (LVNL). As part of the investigation, the DSB studied 24 severe incidents at AMS between 2006 and 2016, of which 15 were related to a runway incursion. An explanation of the severity classification definition is given in the theoretical framework (Chapter 2).

For instance, in the United States (US), 16,785 runway incursions were observed between 2002 and 2015, including the small general aviation (GA) airports until the large airline hubs (Mathew et al., 2017). Figures show an average annual increase in this type of incidents in the US (FAA, 2018d). Here, an average of three incursions occur daily. Worldwide, approximately 30% of the aviation accidents of commercial aircraft between 1995 and 2008 were runway-related, leading to 973 fatalities (Flight Safety Foundation, 2009)

Agencies have targeted incursions in its strategic planning (e.g. FAA, LVNL), and various directives, guidelines (e.g. ICAO, EUROCONTROL) and initiatives have been implemented to propose effective safety management systems. Nonetheless, the rate in which incursions occur continues to rise (Joslin et al., 2011). Incident mitigation strategies tend to be sometimes biased because of the different responsibilities and interests of the involved stakeholders, resulting in a shortcoming on the interactions and interdependencies between them (Wilke et al., 2014a).

1.2 Inducement

The DSB report was the main inducement for a master thesis about the specific topic within airport planning. In order to adapt, improve and design airports in such a way that the risk of runway incursions is mitigated, it is necessary to

[1] Until 2021, the growth of Schiphol is limited to the ceiling of 500,000 annual aircraft movements, as is agreed at government level in the Alderstafel. This number includes commercial air traffic and does not include general aviation and technical air traffic.

understand how infrastructure interacts with it. This study proposes to address the research topic based on an exploration of historical incidents and a quantitative approach. The reasoning for this is explained in Chapter 2. For NACO, it is valuable to obtain more insight in this interaction, in order to improve airport layouts and to design new airports in an incursion-preventive manner.

Until recently, there was no standard procedure for measuring the complexity of an airport and there was no quantitative data explaining the relationship between aerodrome complexity and human performance (Transport Canada, 2012). Various qualitative and quantitative studies have been conducted on underlying factors contributing to incursions, e.g. regarding human factors (Chang & Wong, 2012; Joslin et al., 2011; Stroeve et al., 2016), technical factors (Stroeve et al., 2013) and environmental factors (Rogerson & Lambert, 2012). However, the impact of the airport and its associated characteristics itself has received little attention.

Nonetheless, a number of geometry aspects have been studied on their effects on runway incursions, e.g. Wilke et al. (2015b) and Johnson et al. (2016). The results provide a basic understanding of the geometry influence. However, further research is suggested to include more geometry aspects, as well as other airport characteristics. Moreover, most previous studies have not paid attention to the effect of the interaction of characteristics. Also, because of insufficient data, considerations of severity and types of incursions are often omitted. Previous research focusses mainly on determining the likelihood of occurrences, although runway incursions are one of the most frequent incident types in aviation (EUROCONTROL, 2014; FAA, 2014a). Therefore, rather than only predicting their likelihood, their causes and their relationship to severity should predominantly be addressed to avoid near-collisions.

This quantitative study will be based on statistical incident analysis, which is a conventional method in the aviation industry. Much can be learned by analysing previous incidents and accidents. Comprehensive analyses of data are essential to distinguish trends and causal factors and develop cost-effective risk reduction strategies (ICAO, 2007).

In Figure 1-1, the inducement and the context for this study are summarised.

1.3 Problem statement

Runway incursions have been on the rise, while it is one of the main priorities for air transport agencies, with much attention being paid to the implementation of preventive measures. To expand airports for growing traffic volumes, and to design green field airports in such a way that the risk of incursions is reduced, it is necessary to understand the relationship between the geometric factors and other aspects of an airport and the likelihood of incursions.

The DSB report states that research is necessary on the exact relationship between the growth of the air traffic at AMS and the increase in the number of incidents. The sector parties within the Schiphol Safety Platform (SSP) have set the goal to reduce the number of incursions between 2006 and 2011 by 50%. By 2014, the target was achieved, however, in the subsequent years the number of incident increased again, more or less in proportion to the increase in air traffic movements.

Although modifying airport layouts is expensive option, on the long term, it is also an effective way to reduce incursions and to improve runway safety, in line with the recommendations from the FAA's Runway Incursion Mitigation program (Wilke et al., 2015b). Furthermore, as stated in the European Action Plan for the Prevention of Runway Incursions "new aerodrome infrastructure and changes to existing infrastructure should be designed to prevent runway incursions".

To develop effective mitigation measures, it is necessary to have a thorough understanding of the infrastructure-related causes of runway incursions. However, there are significant weaknesses in the current methods to model these factors. Therefore, the causal factors for incursions maintain a focus area for research.

1.4 Research questions

This research aim is to obtain knowledge on how airport characteristics influence the likelihood of runway incursions, using historical incident data. Furthermore, the aim is to distinguish incursion severities and types in this respect. To give guidance for the study, the following research question has been defined:

RQ Which airport characteristics influence the likelihood, the severity and the type of runway incursions and which recommendations can be made for incursion-preventive planning?

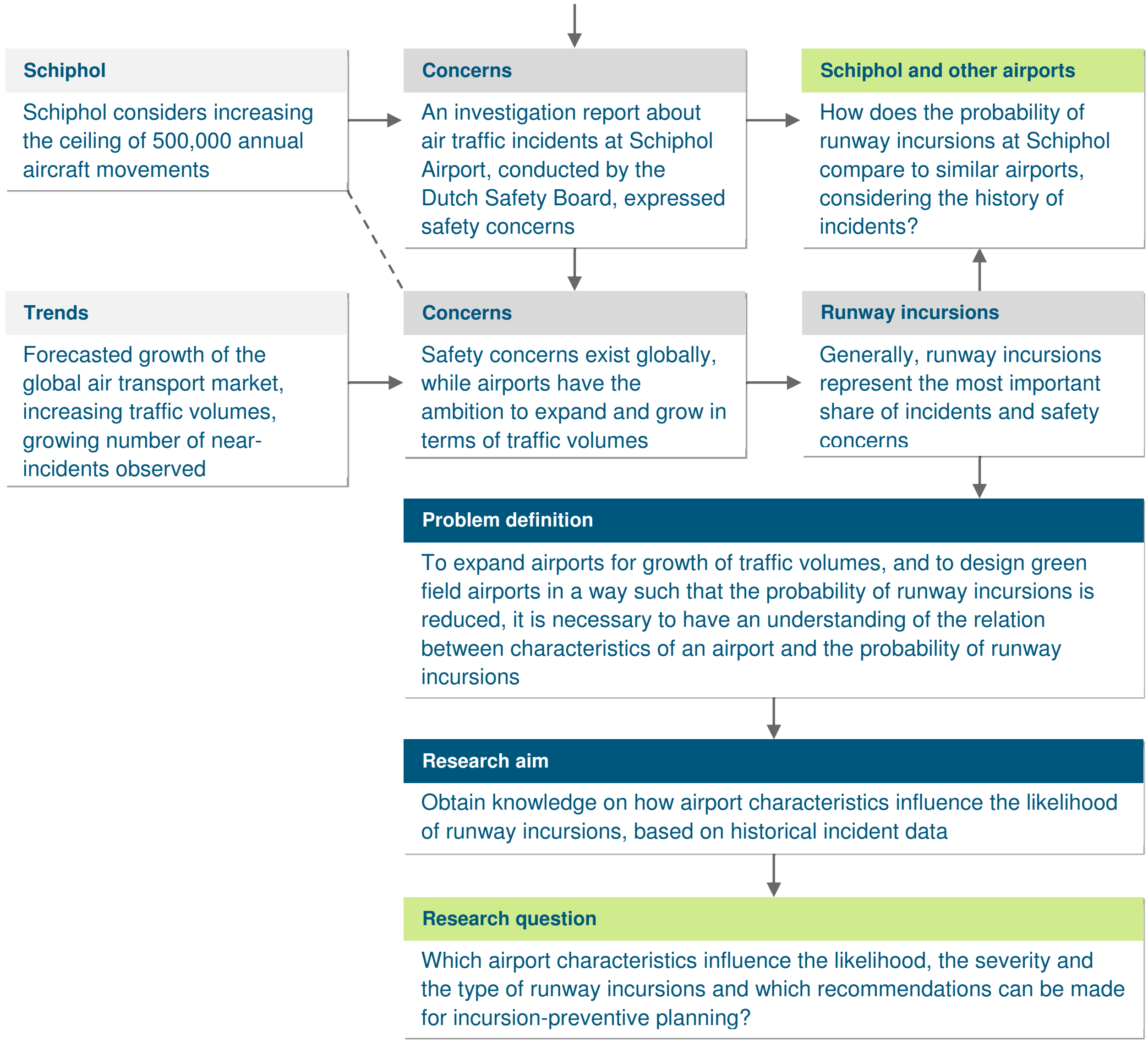


Figure 1-1: Inducement and study context

Throughout the research, in order to answer the main research question, a series of sub questions have been developed:

SQ1 What do global standards direct and advice regarding incursion risk-mitigating airport design?
SQ2 Which airport characteristics are defined as causal factors for incursions in incident investigation reports?
SQ3 Which airport characteristics are relevant for data analyses?
SQ4 What is the influence of the airport characteristics on the rate of runway incursions?
SQ5 How do the results differ depending on the severity and type?
SQ6 Are there significant airport outliers in the regression models? How does Schiphol perform compared to the model?
SQ7 How can these outliers be clarified?

1.5 Scope

The research is conducted for airports that meet the specific characteristics which are necessary to show possible associations with runway incursions and to model the effects. Therefore, the selection of airports is determined in the data collection phase. Nonetheless, airports should meet the following general requirements, to ensure a fair comparison:

- Presence of commercial air traffic
- Only towered airports (presence of ATC)
- No GA-only airports
- No military airfields

In order to select appropriate airport and incident data, it is required to identify airports in countries that follow the ICAO definition. Wilke et al. (2015a) used data from multiple countries (US, Norway, UK and Australia), since these countries have diverse airport characteristics and the data was representative in terms of global air traffic. However, the study advised not to combine the data due to the differences in operational practices between the countries.

The data analysis for this study is conducted on US airports, because the US provides the largest data collection of runway incursions and is publicly available. In addition, US airports show a large variety of airport characteristics and the busiest airports in terms of aircraft movements are located in the country (ACI, 2018).

For reliable and accurate analysis, the sample size of airports per studied characteristic should be at minimum 20 (Subotic, 2007). For example, in order to show the influence of the presence of runway intersections on incursion frequencies (i.e. incursion rates), it is required to create a sample of at least 20 airports equipped with intersections and 20 airports without intersections (Johnson et al., 2016). For these airports accounts that incursion observations and movement data need to be available for the same measurement period.

Lastly, the study period is set from January 1st, 2007 until December 31th 2017, because the current ICAO severity classification for runway incursions was implemented in 2007. Thus, data from 2006 and earlier may not be recorded and justified according to the contemporary standards. Also, the data may be confused with surface incidents, as incursions were designated at that time. Since the 2018 incident and operation data is not yet available for all airports at the time of the study, this year is excluded from the analysis.

As starting point for this research, a few questions are answered first during the literature review, which is covered in the next chapter:

- How are runway incursions defined?
- What is currently known from previous studies about the causal and contributory factors to incursions?
- In which area can this study contribute to a better understanding of infrastructure based causal factors?
- Which research questions can be defined?
- What data and information sources are available for this study and how is it collected?
- Which method can be used to answer the research question?

1.6 Reading guide

This report is divided into ten chapters. In the next part (Chapter 2) the results of the literature review are discussed. Then, in Chapter 3, the research approach is explained, after which Chapter 4 covers the results from the expert panel consultation. Subsequently, the process of data collection and preparation is explained in Chapter 5, after which in Chapter 6 the high-level analysis results are discussed. The model development is covered in Chapter 7. Thereafter, the case studies are presented in Chapter 8. The conclusion and recommendations can be found in Chapter 9. Finally, a discussion on the results is given in Chapter 10.

Throughout this report, the sub conclusions are presented in blue boxes.

2 Literature review

This chapter covers the results from the literature study on contributory factors to the occurrence of runway incursions, with special focus on airport characteristics.

2.1 Background

ICAO defines a runway incursion as "any occurrence at an aerodrome 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." (ICAO, 2007). This means that occurrences where, for example, a runway is obstructed by an animal, are not considered as incursion (e.g. bird strike).

Runway incursions are considered as one of the most important safety risks at airports as their consequences can be catastrophic. Such incidents have led to serious accidents with significant loss of life (ICAO, 2007). In 1977, an incursion between two Boeing 747's on the airport of Tenerife resulted in a major loss of life with 574 fatalities (Raad Voor De Luchtvaart, 1977). It became known as one of the largest disasters in aviation history, considering the number of fatalities.

Globally, runway incursions are known as safety themes in which large investments are made. To reduce the risk of incursions, aviation safety programmes have been implemented globally, in which there is special focus on prevention measures. Several international organisations introduced extensive runway incursion prevention programmes (EUROCONTROL, 2017; FAA, 2015a).

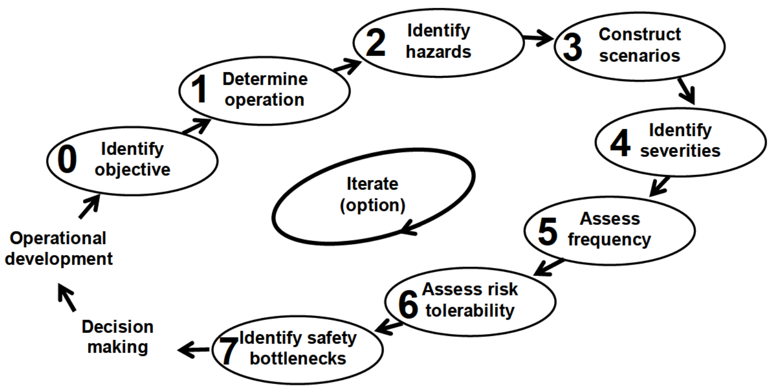


Figure 2-1: Safety Risk Assessment cycle (Blom et al., 2008)

In 2001, the ICAO Air Navigation Commission took action to address the problem of runway incursions by the identification of several critical areas related to overall runway safety in which further research was necessary. ICAO embarked on an education and awareness campaign to improve the situation with respect to incursions and to encourage the implementation of relevant provisions. In the following years, several seminars were given by the ICAO about aerodromes, air traffic management and flight operations with the aim of disseminating information on the prevention of incursions. One of the recommendations from the seminars was to provide a manual containing incursion prevention guidelines.

A recommendation formulated during the Eleventh Air Navigation Conference in 2003 in Montreal described that states must take appropriate action on the prevention of incursions through the implementation of runway safety programmes. It was recommended that capacity-enhancing procedures at aerodromes should only be implemented after appropriate studies on the effects of runway safety have been conducted.

In 2017, the Manual on the Prevention of Runway Incursions was published by ICAO to provide sector parties[2] with a systemic standardised approach to consider latent conditions in the system as well as active failures on the front lines of operations. It includes standardised reporting methods, a high-level discussion on causal factors, best practices and toolkits. Core to these initiatives is the uniform application of ICAO-provisions, which ensure consistency of safe

[2] I.e. regulators, aerodrome designers and planners, aircraft operators, air navigation service providers, aerodrome operators and investigation boards

operations on the manoeuvring area. A part of the guidelines is related to aerodrome layout and characteristics, where this chapter will elaborate further on.

In general, risk mitigation measures for any type of incident in the aviation industry are implemented in multiple steps. An overview of the steps taken in this safety risk assessment is given in Figure 2-1. This cycle has been developed over many years at the Netherlands Aerospace Centre (Blom et al., 2008). The approach proposed in this research is based on this roadmap, however, the decision-making component is excluded.

2.2 Severity classification

ICAO divides runway incursions in four types of severity categories. Additionally, sometimes a category ‘E’ is mentioned. Figure 2-2 explains the severity indicators. The classification of a runway incursion is based on different characteristics. Most importantly, it depends on the proximity to the other aircraft or vehicle.

Figures show that most incursions concern low severity incidents, in which a single aircraft or vehicle is involved without risk of collision. Only a relatively small number of serious incursions can be related to the safety of the air transport system each year. For example, 0.20 category A and B incidents per million operations were observed in 2013 in the US (Wilke et al., 2015b). At AMS, the most recent category A incident took place in 2009 (LVNL).

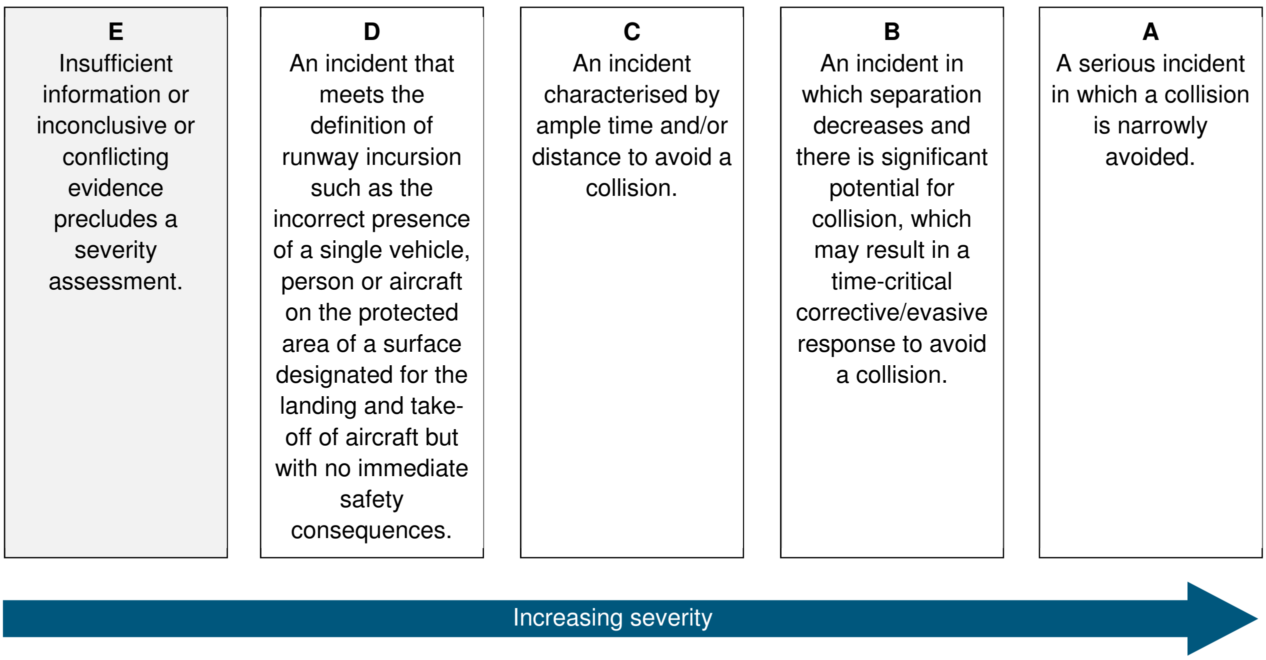


Figure 2-2: Severity classification runway incursions (ICAO, 2007)

Also, the geometry of the encounter is taken into consideration. Another aspect is whether an evasive or corrective action took place and how much reaction time was available. Environmental conditions, weather, visibility and surface conditions are considered as well. Lastly, factors that affect the system performance are considered.

Often, a category can be directly assigned to an incident. For instance, in case no other aircraft or vehicle is involved in the incident, it can be designated as a category D incident. However, in many cases a post-incident assessment is required to find the best applicable severity category. In order to conduct this assessment, ICAO developed a Runway Incursion Severity Classification calculator (RISC).

2.2.1 RISC

In case all characteristics of the incident are known, the severity is calculated using the RISC tool. The model, on which the calculator is based, was developed by Sheridan (2004). It explains how for example the circumstances, proximities between aircraft/vehicles and evasive actions interact with the determination of the severity level. For a detailed understanding of the factors that determine the severity class, an extensive discussion of the model can be found in Appendix A1.

Use of the RISC calculator will enable a most as possible objective and consistent assessment to be made of the severity of runway incursions. This makes comparison possible on a global standardised base and supports sharing incursion ratings (ICAO, 2007).

2.3 Safety risk

The main risk of a runway incursion is a collision. The impact of incursions can be significant since aircraft or vehicles involved in a conflict could move at a considerably speed. Outside the runway area boundaries, aircraft and vehicles move usually at a relatively low speed, meaning a lower risk on severe consequences.

Generally, for all incidents, a corresponding safety risks applies. An explanation of these standards is given in Appendix A2.

2.4 Types of incursions

Three types of incursion scenarios can be distinguished, namely Air Traffic Controller (ATCO)-induced, flight crew-induced and vehicle/driver-induced scenarios. In an ATCO-induced scenario, also known as an operational incident (OI) (FAA, 2012), the action of an ATCO results in insufficient spacing between two aircraft or vehicles, or for example clearing an aircraft to take-off or land on a closed runway. A flight crew-induced scenario (pilot deviation, PD) (FAA, 2012) exists when the flight crew enters or crosses a runway without clearance. Thirdly, a vehicle-induced situation exists when a vehicle driver or pedestrian enters any portion of the airport movement area (runways/taxiways) without authorisation from Air Traffic Control (ATC), also called a vehicle/pedestrian deviation (V/PD).

Common scenarios of runway incursions include (ICAO, 2007):

- an aircraft or vehicle crossing in front of a landing aircraft;
- an aircraft or vehicle crossing in front of an aircraft taking off;
- an aircraft or vehicle crossing the runway-holding position marking;
- an aircraft or vehicle unsure of its position and inadvertently entering an active runway;
- a breakdown in communications leading to failure to follow an Air Traffic Control instruction;
- an aircraft passing behind an aircraft or vehicle that has not vacated the runway.

2.5 Current practice measures

To avoid runway incursions, multiple mitigation measures have been implemented worldwide. Globally, it is advised to have Runway Safety Teams (RST) in place, which assess safety issues and implement mitigation measures. These teams are, for example, advised to define hot spots[3] at the aerodrome by investigation reports based on improved incident data collection, analysis and dissemination. For this, determining the number, type and, if available, the severity of incursions is required.

Generally, after a hot spot has been identified and defined, the subsequent tasks include, for instance, the launch of awareness campaigns to the stakeholders. Also, additional visual aids, such as signs, markings and lighting can be installed. Furthermore, infrastructure adjustments are possible considerations (Le Bris, 2016). Another example is the prevention of blind spots for the ATC tower. During operation, the use of alternative routings can be considered.

Other defences on the risk of runway incursions are among others the maintenance of situational awareness by pilots and ATCO's. For both parties, it is important to always have good understanding of the actual position relative to active runways and to other aircraft and vehicles. The mapping of hot spots on clear aerodrome charts is a way to improve the crew's understanding of the airport layout. Incursion avoidance and alerting systems are another approach to increase the awareness of pilots (Jones & Prinzel, 2007; Young & Jones, 2001).

Globally, multiple alerting systems have been developed over the years, which are widely used to prevent and detect incursions (Archer et al., 2009; Squire et al., 2009). These are for example Surface Guidance Systems (SGS), radar and visual monitoring systems and ATC alert systems (Dabipi et al., 2010). It is shown that SGSs have a minor influence on the prevention of incursions. At AMS, for example, Runway Incursion Alerting System Schiphol (RIASS) is installed, which acts as a 'safety net' in the system of tower-led ATC at the airport, warning of potential conflicts between aircraft

[3] *ICAO definition of a hot spot is "a location on an aerodrome movement area with a history or potential risk of collision or runway incursion, and where heightened attention by pilots/drivers is necessary." (ICAO, 2007)*

or vehicles on the runways and at its entrances and exits. It generates two kinds of alerts: alarms and warnings. The system is only able to generate alerts in respect of aircraft and vehicles fitted with a working transponder (LVNL, 2018).

Figure 2-3: Take-off Hold Lights (left) and Runway Threshold Lights with an aligned taxiway (right)

Another measure is the implementation of improved runway markings and taxiway surface markings and signs (Le Bris, 2016), in accordance to the ICAO standards. The same applies for the installation of additional runway lighting, known as Runway Status Lights (RSL). Examples of additional lighting includes: Runway Entrance Lights (REL, also known as Runway Guard Lights), Take-off Hold Lights (THL) and Runway Intersection Lights (RIL). Examples are depicted in Figure 2-3 and Figure 2-4.

The RSL-system is fully automated and provides runway status information to pilots and surface vehicle operators to indicate when it is unsafe to enter, cross, or take-off from a runway. It processes the information from surveillance systems to control the light modes (FAA, 2015a).

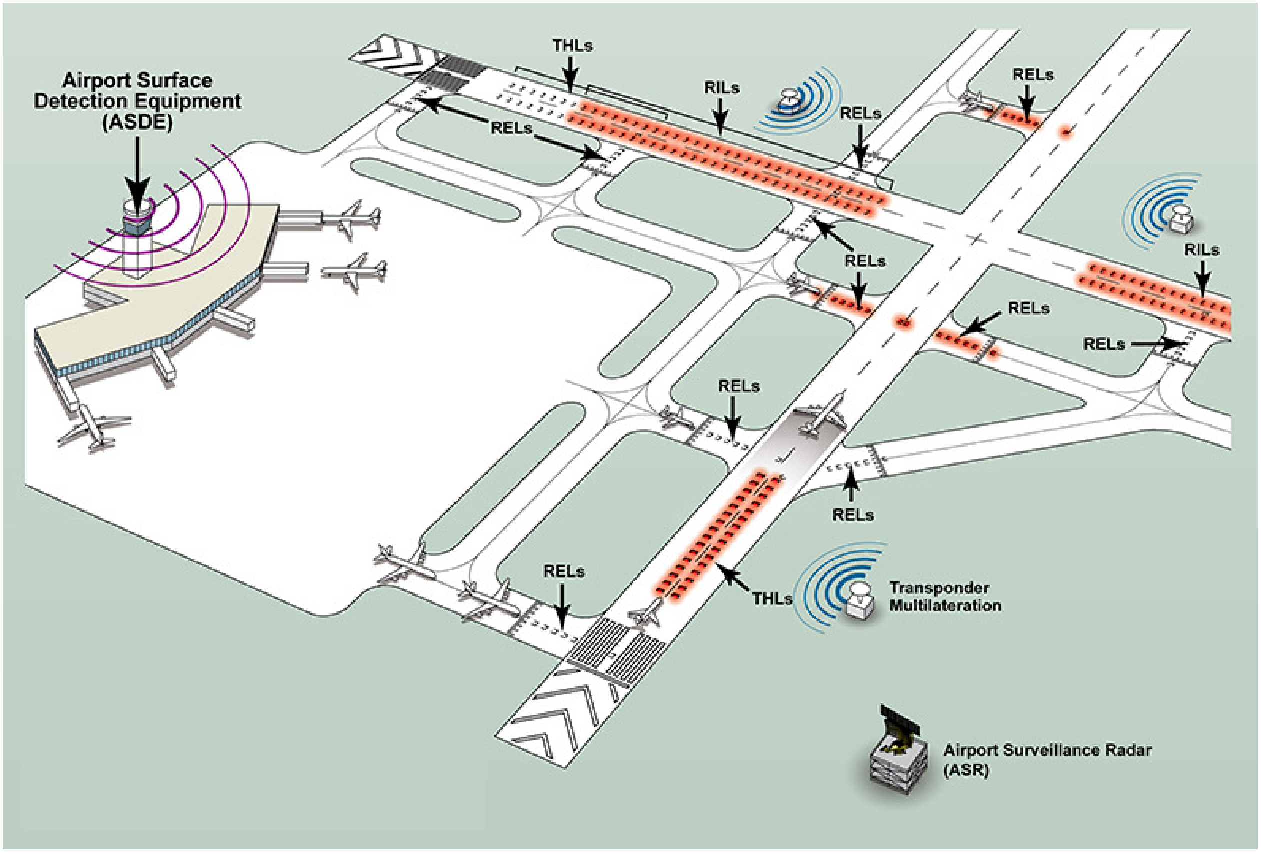


Figure 2-4: Overview of additional airport lighting (FAA, 2015b)

2.6 Contributory factors

This section discusses the contributory factors to the occurrence of runway incursions. First, a broad and general explanation is given, covering different factor areas. Thereafter, the focus is more on aerodrome design and airport characteristics.

2.6.1 SHELL

In general, six categories of contributing factors to incursions can be distinguished, which are human factors, airport geometry, technical factors, airport characteristics, environmental factors, and organizational factors (Wilke et al., 2014a). It is suggested that human factors (Knott et al., 2000) and airport geometry account for the most contributing factor to the occurrence of runway incursions.

As an incursion may be the consequence of multiple factors, analysing these incidents can be executed using the ICAO SHELL Model, in which attention is not drawn to the different components in isolation, but to the interface between the human elements and the other factors. The model is a conceptual framework which is often used in the aviation industry. It was developed by Edwards in 1972 and Hawkins modified the diagram in 1975 into the current model, which is depicted in Figure 2-5. It is used to illustrate the different components of human errors and to provide a basic understanding of the interactions.

S = Software (procedures, rules, written documents, etc.)
H = Hardware (displays, functional systems)
E = Environment (social, economic and natural)
L = Liveware (human beings in the system)

Figure 2-5: Shell Model, Hawkins, 1975

For instance, human errors in the L-L relation, include aspects of communication, teamwork, support and cooperation. The L-H interaction represents human-machine interface issues. For example, occasions in which an ATC-system does not technically responds to the input given by the controller. The L-E interaction covers for example the physical environment in which an aircraft operates and how people or equipment can be protected. An example of the L-S relation is an occasion in which the phraseology described in the procedures given by the ATCO is misunderstood by the pilot.

The airport surface[4] is shaped by five main stakeholders (Liveware-element) and the surface infrastructure. These are shown in Figure 2-6.

2.6.1.1 Software

All procedures, rules and written documents form the Software-element. For pilots for instance, loss of situational awareness and consequently crossing the hold short line without authorisation are the most common causal factors of runway incursions. Also, poor standards and inadequate supervision between controllers and pilots, between controllers and between pilots are considered to have negative impact on the incursion likelihood (Zhang & Luo, 2017).

For example, the use of a multiple simultaneous line-up procedure, increases the risk of runway incursions. This procedure allows at least two aircraft to take-off from the same runway using different entry ramps. In combination with low visibility for example, the risk of incursions may be even increased, because of the impossibility for pilots to visually observe the other aircraft. Also, simultaneous use of intersecting runways is an example of a risk-increasing procedure. Although the procedure is seldom used, it causes a significant risk for collisions, as aircraft usually do not visually observe each other from their starting position. Frequent ATC-procedure changes are also seen as a causal factor for an increased risk on incidents and can compromise safe ATC. As a result of increasing environmental pressure, the ATC at AMS is faced with these operational limitations (Dutch Safety Board, 2017b).

[4] The part of an aerodrome to be used for take-off, landing and taxiing of aircraft, excluding aprons

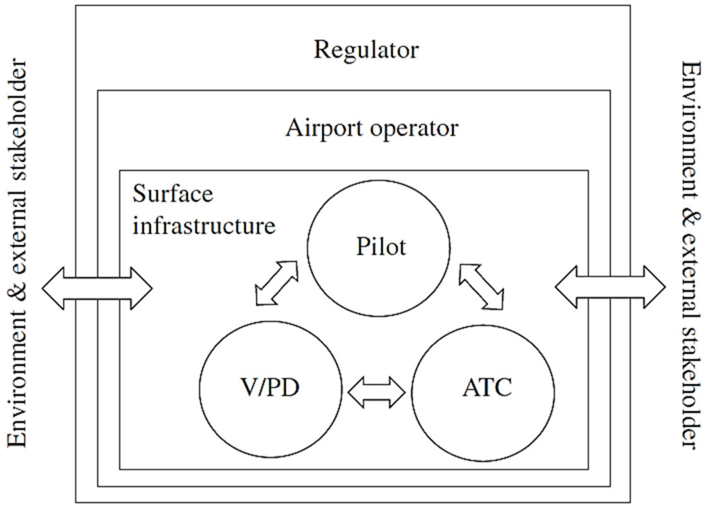


Figure 2-6: Airport surface and its stakeholders (Wilke et al., 2014a)

Furthermore, conditional clearances that are issued by the ATC, contribute to an increasing risk on incursions. These are clearances that do not become effective until a specified condition has been satisfied. For example, an aircraft receives permission or take-off behind another identified aircraft. If the identification is misunderstood by the flight crew, a possible incursion emerges.

Another influencing factor is the way in which and what type of phraseology is used (EUROCONTROL, 2015). A discrepancy between the used phraseology and the standard phraseology between the ATCO and the flight crew may lead to mistakes because of clearance confusion and misunderstanding. Also, the concurrent use of multiple languages for ATC-communication increases incursion risk. Some international airports, for example, allow locally-based users to communicate with the ATCO in the local language, while foreign aircraft have to speak English. This may lead to a misunderstanding of information such as the relative position to other traffic or conditional clearances. Moreover, misinterpretation of taxi clearances as a result of pilots whose native language is not English and their level of aviation English is insufficient, still occur (ICAO, 2007).

Furthermore, the situational awareness of pilots can decrease due to high workloads (Jones, 2002). For instance, immediately after landing, pilots have to orientate themselves with respect to their actual position, the airport layout and the taxiways. During this period, pilots are faced with a higher workload. The workload is also increased during preparation for departure, when pilots have to finish different tasks, such as the preparation for take-off checklist, configuring the aircraft systems, informing cabin crew and passengers and receiving detailed departure instructions from the ATC. Late issues and changes of clearances are an example in which the workload is also increased.

In addition, high workloads can be a problem for Air Traffic Controllers. ATCO's often have to handle multiple aircraft at the same time and have little time to confirm that, for instance, the aircraft are taxiing according to the clearances. Wilke et al. (2015a) showed that OI and PD incursions were significantly more likely to result in a high severity incident than V/PD. Also, a combination of at least two actors increase the risk of high severity incursions, with the pilot-ATC interaction being the most common for communication errors.

Moreover, distraction has a direct relation to the cause of runway incursions. Causes for pilots include for instance missing a turn or taking a wrong exit, and for controllers forgetting about an aircraft or a closed runway. Furthermore, research has shown that pilots may be unfamiliar with airports, resulting in loss of situational awareness. Inadequate and/or confusing airport signs and markings are known as an important contributing factor to runway incursions (Rogerson & Lambert, 2012).

2.6.1.2 Hardware

Failures of displays, functional systems and parts of the aircraft or vehicle are a possible causal factor for runway incursions as well. This study does not further elaborate on that. However, it must be mentioned that communication problems (Liveware) may also be caused by technical problems. Frequency congestion, blocked or partially blocked voice communications, and a high rate of false alarms from Airport Movement Area Safety System are examples of technical errors. A high rate of false warnings has resulted in the ignoring of justified alerts by controllers.

2.6.1.3 Environment

Aerodrome design is one of the main factors contributing to the occurrence of runway incursions. According to ICAO (2007), the probability of an incursion increases significantly as a result of complex or inadequate aerodrome design. For example, the design determines whether aircraft have to cross runways to access a specific area at the airport. The complex layout of AMS is one of the main contributing factors to the likelihood of incursions (Dutch Safety Board, 2017b).

The complexity of airport layouts can increase due to intersecting runways, intersections of runways and taxiways, the number of conflict points and complex intersections. Other factors include insufficient spacing between parallel runways, departure taxiways that fail to intersect active runways at right angles, short taxi routes, short thresholds, T-intersecting runways and no end-loop perimeter taxiways (REL) to avoid runway crossings (ICAO, 2007). Alternative design options such as perimeter taxiways, that allow aircraft to taxi around the approach end of a runway and avoid the crossing of active runways, are supported (FAA, 2009).

Besides that, daylight, glare and weather circumstances have been identified as a contributing factor (Rogerson & Lambert, 2012). In case of low visibility, pilots may be disoriented during taxiing. This could result in a situation in which pilots become unaware about their actual position and route. Low visibility is also a risk for ATCOs as this restrict the ability to observe and follow an aircraft. In addition, Mathew et al. (2017) found that in the US, the probability of category D incursions at GA airports is on average higher during winter.

The next section elaborates further on airport characteristics in detail, based on a review of earlier research.

2.7 Airport characteristics

This section focusses in more detail on airport characteristics that influence the occurrence of incursions, according to research literature. This part excludes ATC-procedures in further detail, since this topic is not part of the study scope.

2.7.1 Operations

Besides the air traffic volume at an airport, also the mix of air traffic influences the incursion likelihood. The primary type of traffic handled at the airport and the number of airlines that have their home base at the airport, influence the risk in this respect. A low number of airlines ensures e.g. that all flight crews are trained equally (Wilke et al., 2015a). It is shown that the number of operations during peak hours increases the potential of occurrences.

Redzepovic (2009) studied the effects of joint use aerodromes (i.e. airports used by both military and civil air traffic) on the occurrence of runway incursions. It concluded that those airports are not significantly more vulnerable for incursions than civil airports. Nevertheless, a civil-military Local Runway Safety Team is advised to address the local runway safety issues.

Also Mathew et al. (2017) examined the factors that correlate with runway incursions, using statistical methods. The study explored the relation between the airport type and the incursion severity and type, using a multinomial logit model with random parameters. The analysis was based on observation data for 3331 airports in the US between 2002 and 2015. Three groups were defined: large, medium/small and GA/non-hub/reliever/non-primary commercial service. Due to limited data for severity A and B incursions, which accounted for less than 4% of all incidents, these categories were combined. The study confirmed that incursion characteristics vary depending on the airport size. It was found that at large airports, PD are less likely for cat. B incursions, and that OI had an increased probability of resulting in a cat. A and C incursion. V/PD at large hub airports were found to be more likely to result in C and D incursions, while PD were less likely to result in B incursions. Furthermore, 93% of the incursions at large hub airports involving a commercial aircraft were less likely to result in an incursion of cat. A, and more likely to result in incursions of cat. B, C or D. And, for 7% of the incursions at large hubs, the incursions involving a commercial aircraft are more likely to result in cat. A incursions.

Another studied factor, the number of years since 2002, showed a statistically significance at all airports for cat. A incursions. The likelihood of the most severe incidents has diminished since 2002. One limitation of the research, is that it did not explicitly account for the fact that ICAO changed the definitions in 2007. It is advised to use the proposed methodology again for future research, when more data becomes available.

According to Ju (2011), category A and B incursions are mainly caused by V/PD and PDs are the key factor influencing category C and D incursions.

2.7.2 Signage, marking and lighting

Also, inadequate aerodrome design standards, signage, markings and lighting contribute to the increase in incursion likelihood (ICAO, 2007). Goodheart (2018) found the presence of irregular signage being a causal factor.

Chang and Wong (2012) mapped key human risk factors, identified from literature, in line with the SHELL Model. By means of empirical analysis using questionnaires, 56 preliminary risk factors were compared between the pilots' opinion and the airline management level experts' opinion. Ten of the top thirteen risk factors were matching, the others did not match. The pilots, for instance, considered operation deviation/negligence, teamwork, and pilot fatigue control as highly important, while the airline management level experts did not. Instead, the airline management level experts considered decision making ability; flight dynamics surface guidance systems and runway incursion prevention systems of high importance. It was concluded that pilots tended to place more emphasis on their core ability or interactions with others, while airline management level experts focused primarily on the interaction between pilots and hardware.

A grid of four quadrants (top priority implementation, possible integration zone, key challenge zone and long-term promotion zone) was used to map the risk factors according to the pairing of their relative importance against their improvement-achievability scores. Two airport characteristic related risk factors: runway/taxiway marking and signs and airport illumination were placed in respectively the key challenge zone and the top priority implementation.

2.7.3 Geometry

A simulation exercise for Los Angeles International Airport (LAX) reveals the significance of airport geometry in explaining runway incursions. Madson (2004) noted that the highest proportion of incursions at LAX occurs when an aircraft fails to stop before crossing the hold-short line at one of the runways and going through the high-speed exits.

Taxiways are an important part of the airport infrastructure and confine the airport routes designed for aircraft moving from one point on the airport to another. Within a taxiway planning and design process, two main targets are to minimise the number of runway crossings and to provide sufficient turning radius (e.g. Rapid Exit Taxiways (RET), which is used to increase the runway capacity). FAA guidelines suggest that angled taxiways (less or greater than 90 degrees) used for crossing the runway increase the probability of incursions exponentially because of visual hindrance for the pilots (FAA, 2014). The presence of a RET resulted in a large accident in 2000 at Paris Charles de Gaulle Airport (CDG), as the angle between the access taxiway and the runway made it impossible for the flight crew to perform a visual check before entering the runway (Le Bris, 2016). Since then, line ups from any RET were prohibited at the airport by the ATC. Furthermore, a large-scale taxiway reconfiguration was executed where RETs were replaced by 90-degree taxiway intersections. A drawback of using only right-angled taxiways is that it may cause longer runway occupancy times.

Other unfavourable design factors include taxiways that cross high-speed exits, taxiways that cross wide-throated runways and that intersect with multiple runways, since it may decrease the situational awareness of pilots. Also, intersections with more than three nodes are discouraged (FAA, 2012b). Pilots should ideally have only three options at an intersection: left, right and straight ahead. The FAA also insist designers to avoid layouts that lead to a narrow spacing between two parallel runways, to avoid airfield configurations which may allow vehicles or aircraft to cross an active runway, and to avoid taxiway layouts that lead taxiing aircraft onto runways when not landing or taking-off.

Johnson et al. (2016) studied the relationship between runway intersections and the number of incursions at specific airports in the US by means of statistical analysis. The study used the principle of parsimony since the number of airports was relatively small. A one-sided test for two proportions was used to analyse the data. It also compared, by means of best subsets regression, normalised incursion data with four geometry aspects for each airport: crossing-taxiway intersections per runway, high-speed taxiway intersections (RET) per runway and right-angle taxiway intersections per runway. It was assumed that there was only one incursion possible for each operation reported, and that each operation is independent. The study showed that airports with intersecting runways and with runways intersecting taxiways have a higher incidence in incursions than airports without such intersections. For further research, it is suggested to include a larger sample of airports and to distinguish runway incursions per type and severity category.

Galle et al. (2010) clustered 80 airports into five groups based on runway geometry, to analyse the impact of runway geometry in general. Surprisingly, the study concluded that runway geometry is not a significant predictor for incursions. However, the study falls short on the fact that runway geometry is considered as one variable. No specific geometry characteristics were tested on their influence. Neither, the impact on incursion severity and type is assessed.

A research by Wilke et al. (2015a); (2015b) modelled the relationships between airport characteristics and the incursion severity and type. The number of runways, taxiway segments and the number and type of intersections were used as factors. The obtained incident data covered the period between October 2007 and 31th December 2009. The scope existed of airports in the US, Norway, Australia and the UK. However, only US data was shown to be most appropriate for regression analysis, since the data of all countries were not homogeneous, and aggregation was therefore not possible. This resulted in the collection of airport characteristics for 19 US airports and 288 related occurrences (also other types of surface incidents), instead of the target sample of 57 airports for all countries. The population of A and B occurrences appeared to be too small for statistical analysis and were combined with category C incidents. It was suggested for future research to expand the incident sample in order to analyse A and B incidents separately.

Strikingly, it was found that the rate of incidents was hardly associated to airport characteristics, which is at odds with the other studies. Nevertheless, the study showed that the severity of incidents is associated with these factors. Also, the study built up evidence that there is a link between the factors and the type of incursions, although the prediction model showed a poor fit. The relationships between the variables associated with the severity and type were modelled on three levels (from number of general intersections to number of specific types) using logistic regression. The severity was best predicted by the factors: number of runways, number taxiway segments and the number of TWY-RWY conflict points. The incursion severity increased when the number of runways increased, when the number of runway intersections increased and when the number of TWY-RWY intersections increased. Categorisation of airports, according to their design complexity was shown to be not a suitable factor to measure the influence on the severity of occurrences. This because, for instance, airports with a small number of runways could similarly show a low, medium, or high number of taxiway segments and conflict points, and vice versa.

Wilke et al. (2015b) advices to extend the analysis and to include a larger sample, in order to generalise the findings. Also, case studies are advised to underpin and validate the obtained findings. Furthermore, the advantage of investigating all incidents on individual level was shown, in addition to airport-level analysis.

Another study that examined incursion severity was conducted by Biernbaum and Hagemann (2012), where statistical analysis was performed on incident-level. According to the authors, the research was the first systematic statistical analysis on runway incursions. It concluded that additional runway intersections increase the likelihood of a severe event, but more total runways decrease the likelihood of a severe occurrence. More parallel (non-intersecting) runways may be a way to reduce the likelihood of severe events, according to the conclusions. Moreover, incidents during take-off are 2.5 times more likely to be severe when compared to taxiing. Incidents during landing are 1.7 times as likely to be severe when compared to taxiing. The conclusions are based on narratives from the period 2001-2010, thus also data is used which is not compliant to the current ICAO severity classification. This study is limited to the contextual factors that were present at the time of the incidents, such as aircraft type, pilot demographics and workload. Among other things, the study suggests for future work to focus on refining complexity measures.

Mrazova (2014) defined, by reviewing several airport layouts and global advisories, a diagram of non-recommended types of taxiways, which include: direct access from a ramp/terminal to the runway, a taxiway crossing a high-speed exit (i.e. RET), a taxiway connecting to a V-shaped runway, high-speed exits leading directly onto another runway, aligned taxiways and Y-shaped taxiway crossings. The study underlines the importance of mitigation initiatives that have been implemented in the last years.

Goodheart (2018) used Bayesian Belief Networks to identify causal paths of incursions and to predict the risk of occurrences. It aimed to close the gap between earlier research that used methods which investigated discrete events and did not address the interaction dynamics between causes that impact safety risk. From this perspective, a comprehensive risk model was developed in which a mixed-method approach was introduced. It was found that complex intersections are strongly correlated to runway incursions. Also, the presence of airport constructions was found to have an influence on incursions. However, further distinction in airport characteristics has not been made.

A research executed by (Rogerson & Lambert, 2012) used multiple stakeholder perspectives to build a contributory factor hierarchy, with emphasises on airport geometry, operations, weather, geography, and days since last safety review. After the factors were collected, the hierarchical factor relationships of each expert - based on their given factor weights - were aggregated into a final hierarchy. One of the factors found by the experts is that the greater the number of hot spots at an airport is, the more likely that airport is to observe a runway incursion. The number of incursions per intersection-operation was also mentioned to be a causal factor. Furthermore, airport geometry in general and cumulative airport count were considered, covering the aspects crossing runways, intersections, T-intersecting runways, intersecting Runway Safety Areas, taxiways crossing many runways and close thresholds.

Claros et al. (2017) developed a safety model for determining the expected number of incursions, based on a data analysis of 137 US airports for the period 2009-2013. It aimed to address the lack of a quantification method for incursion likelihood, besides the existing qualitative expert experience studies, that can be used for the development of safety management systems. The model can be applied to a wide range of US airports. Geometric variables included in the models are length of runways, type of runway (single, parallel, crossing, or mixed), type of taxiway (entry–exit or RET), and hot spots. Also, the presence of construction projects was incorporated in the model. In the model estimation, severities A, B, and C were aggregated because of a shortage in observations. However, severity distribution factors were obtained to distinguish each of those three severities. Validation with data from 2014 showed that the model performed well and provided accurate frequency estimates. The research paper describes the result as a comprehensive example for further incursion modelling, for which the application of other and/or additional variables with a larger set of incident data is encouraged.

In Table 2-1 below, the findings of the literature studies are summarised.

Table 2-1: Research on airport characteristics interactions with runway incursions (table continuous on the next page)

Study	Characteristics	Method/findings
Biernbaum and Hagemann (2012)	• Intersecting runways • Number of runways • Number of hot spots • Operational procedures • Traffic complexity	Statistical analysis Additional runway intersections increase the likelihood of a severe event, but more non-intersecting runways decrease the likelihood of a severe event.
Chang and Wong (2012)	• Marking and signs • Airport illumination	Likert scale questionnaires TWY-RWY marking and signs and airport illumination are placed in respectively the key challenge zone and the top priority implementation
Claros et al. (2017)	• Type of operations • Length of runways • Types of runway configurations • Type of TWY-RWY intersections • Number of hot spots • Number of construction occurrences	Frequency model based on negative multinomial probability Runway incursion frequency prediction model
Galle et al. (2010)	• Geometry complexity	Clustering A general runway geometry complexity measure is not a significant predictor of the likelihood of runway incursions
Goodheart (2018)	• Complex intersections • Construction occurrences • Marking and signs	Mixed-method approach Bayesian Beliefs Network Complex intersections are strongly correlated to runway incursions and the presence of airport constructions has an influence on the incursion rate
Johnson et al. (2016)	• Intersecting runways • Type of TWY-RWY intersections • Number of crossing-TWY intersections	Statistical test for proportions Airports with intersecting runways and with runways intersecting taxiways have a higher incidence in runway incursions than airports without such intersections
Mathew et al. (2016)	• Airport size • Operation types • Time of day	Multinomial logistic regression analysis The size and type of and airport contributes to the likelihood of runway incursions
Mrazova (2014)	• Types of taxiways	Literature and airport review The types of taxiways contribute to the likelihood of runway incursions
Rogerson and Lambert (2012)	• Intersecting runways • T-intersecting runways • Intersecting Runway Safety Areas	Quantitative review based on expert perspectives The greater the number of hot spots on an airport, the more vulnerable the airport is to runway incursions. Also, the number of incursions per intersection-operation is a causal factor.

	• Taxiways crossing runways • Number of TWY-RWY intersections • Number of intersection-operations • Number of hot spots • Close thresholds	
Wilke et al. (2015a); (2015b)	• Number of runways • Number of taxiway segments • Number of TWY-RWY intersections • Type of TWY-RWY intersections	Tests for associations Logistic regression analysis Airport characteristics in general hardly determine the likelihood of runway incursions; however, the severity and type of incidents is associated with these factors. The severity increases when the number of runways increase, when the number of runway intersections increase and when the number of TWY-RWY intersections increase.

2.8 Concluding

As the literature review showed, multiple airport characteristics have been demonstrated to relate to the likelihood of runway incursions. Causes can be found in a variety of areas, such as communication, signage, operations and geometrics. Hence, these latter two categories are most appropriate with regard to the research objective.

Generally, two main types of research were found in this field: qualitative and quantitative studies. Especially qualitative studies were performed in the earlier stages of research on runway incursions (Chang & Wong, 2012; Goodheart, 2018); Rogerson and Lambert (2012).Therefore, the existence of certain interactions with characteristics have been revealed and substantiated by multiple studies. In recent years, quantitative methods became a more commonly used approach, in particular because of the greater availability of incursion data, especially since the introduction of the current definition in 2007. These statistical studies gave better insight in the interactions between certain factors and incursions, and made the prediction of incidents possible.

However, the literature study revealed demand for further research, in particular regarding airport geometry where detailed analyses on certain airport elements lack, such as complex intersections and runway crossings. Mathew et al. (2017) analysed the relationships between certain factors and incursion rates, but faced data shortage issues and advised therefore to repeat the methodology as soon as more data becomes available. Johnson et al. (2016) also suggested to increase the sample of data by extending the number of airports, to allow subdivision per severity and type. Wilke et al. (2015a); (2015b) analysed the influence of geometrics in more detail and showed similar demand for scope expansion, especially to make separate analysis of A and B incidents possible, which was not yet achieved. Striking is the conclusion of this study, which states that airport characteristics hardly correlate with the incident rates, contradicting conclusions of other studies. Therefore, the researchers encourage to validate the findings by means of statistical analysis and case studies. The developed frequency model of Claros et al. (2017) showed a good performance after validation of an additional study year. However, it appears to not accurately predict incursion rates, in particular at larger airports. Further modelling is encouraged, by means of other and/or additional variables with a larger incursion dataset. According to the authors, the model addresses the lack of quantification of incursion likelihood. Notwithstanding, especially regarding airport planning, improvement and refining is expedient, due to the small share of geometric attributes used in the model.

Based on the proven potential for further statistical analysis on this topic, the difficulty to achieve additional relevant findings from a qualitative approach and the objective to better understand the influence of airport characteristics from the perspective of airport planning, it was decided to conduct a data analysis, extended with a partly qualitative validation. Hence, obviously, in this respect solely analysis of incursions at Schiphol (AMS) would not contribute to the achievement of the research aim and the broader research question. Therefore, the analysis of an airport sample is proposed. The methodology and the further reasoning behind the approach is discussed in Chapter 3.

To conclude, the selection of potential relevant airport characteristics for this research are listed in Table 2-2. From the literature study, these variables appeared to either have a statistical relationship with the incursion rate (total, per type and/or severity) or to be mentioned as relevant aspects in guidelines and qualitative studies. Because it is assumed that geometrics cannot be treated in isolation, but should be considered in relation to airport usage, also operational characteristics are selected from the theory.

Table 2-2: Relevant airport characteristics for the research

Characteristic	Statistically analysed	Demand for analysis	Proposed quantification for analysis
Operational			
Airport size	✓	a	Large hub/medium hub/small hub/non-hub/other
Air traffic mix			Percentage of aircraft per size (ADG)
Operation types	✓	a	Percentage of general aviation air traffic
Geometry			
Aligned taxiways			Presence of aligned taxiways
Construction occurrences	✓	b	Annual number of construction occurrences
Direct access			Presence of direct access
Hot spots	✓	b	Number of hot spots
Number of runways	✓	b, c	Number of runways
Parallel runways	✓	b	Ratio parallel runways
RETs leading to other RWY			Ratio of RETs leading directly to another runway
Runway crossings	✓	b, c	Number of RWY-crossings per runway-km
Runway length	✓	b	Average runway length
Runway intersections	✓	b, c	Ratio intersecting runways
			Presence of T-intersecting runways
			Presence of intersecting Runway Safety Areas
TWY-RWY intersections	✓	b, c	Number of TWY-RWY intersections per runway-km
			Ratio of non-right-angled intersections
			Presence wide expanses of pavement
			Complex TWY-RWY intersections
Other			
Runway Status Lights (RSL)			Presence of RSL
Influences outside scope			
Weather and visibility			Percentage low visibility circumstances

a Because of data shortage in earlier research
b Validation of research suggested
c Contradicting results between earlier research

3 Research approach

Throughout this chapter, the framework of the research is discussed in chronological order. The set-up of the study method is explained, as well as the research phases, such as the data collection and preparation, and the proposed method for statistical modelling.

An overview of the research process is depicted in Figure 3-1. On the next pages, each of the steps is explained and substantiated.

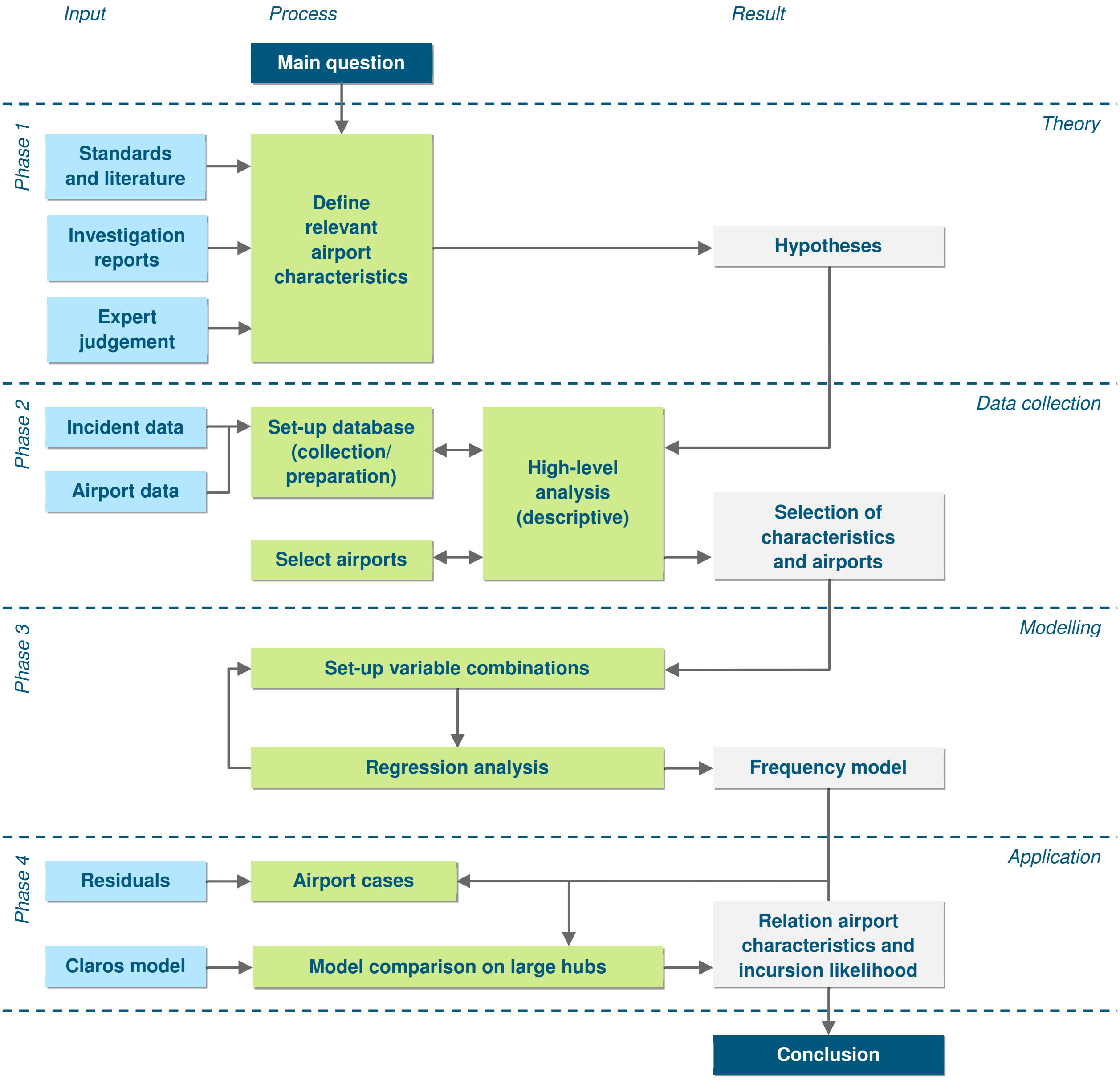


Figure 3-1: Research framework

3.1 Definition of relevant characteristics

The first step is the definition of relevant airport characteristics for the research. This phase elaborates on the findings from the literature study, which has been discussed in the previous chapter. Before these characteristics are analysed, they are validated first.

3.1.1 Literature and investigation reports

The first part of the study (phase 1) covers the definition of relevant airport characteristics. In order to answer the research questions and to develop a model, it needs to be clarified which aspects are relevant. The characteristics are the result of a combination of literature (earlier research and global standards) and incident reports, which have been discussed in Chapter 2.

As explained, some airport characteristics have already been studied in relation to runway incursions. Though, multiple studies made suggestions for future research (Claros et al. 2017; Mathew et al., 2017; Mathew et al. 2017; Wilke et al. 2015a; 2015b) and several qualitative studies (Rogerson and Lambert 2012; Goodheart 2018; Chang and Wong 2012) indicated possible relations between airport characteristics and the incursion frequency, which were not yet statistically substantiated.

Furthermore, the literature review also incorporated global standards, which provide advice on incursion-preventive airport design. From these directives, relevant characteristics are also obtained. In addition, various incident investigation reports give an indication of characteristics that played a role in the occurrence of the incident.

3.1.2 Pre-analysis expert judgement

In order to validate the results from the literature review, an expert panel was created in which each of the previous described airport actors, was represented. The aim for this was to substantiate the relevance for the collected characteristics with regard to the influence on the incursion likelihood. In this way, theory from research, knowledge from earlier incidents and practical experience from the airport users is combined. From this, relevant airport characteristics are selected for the data analysis.

To create a panel which provides an appropriate representation of the airport actors, it is decided to follow the type classification of runway incursions (operational incidents (OI): air traffic controller, pilot deviations (PD): pilot, vehicle/pedestrian deviation (V/PD): airside authority). In this way, the analysis of incursions can be substantiated by representatives from each of the type groups. Moreover, this division is justified by the stakeholder definition of the main airport users (Wilke et al., 2014a). For the expert panel, a pilot, an air traffic controller and an airport vehicle driver were invited. For the experts hold that they have more than twenty years of practical experience in their working field.

The panel was consulted for both the validation of the airport characteristics and the results from the data analysis to avoid misinterpretation of the characteristics. The panel consultation was performed by means of a qualitative interview methodology first, after which the list of characteristics was validated and eventually extended. The consultation of the panel is not considered to represent a qualitative side-study; it is an extension of the data-analysis, to select appropriate variables, to understand the results and to avoid misinterpretations. For further qualitative input will be referred to earlier qualitative research. Therefore, the possible restriction on shared knowledge to does not affect the research process.

Besides the panel, also an interview was conducted with researchers of the Dutch Safety Board, which executed the safety investigation at Schiphol, as explained in the introduction. This input was also used for the clarification of the findings.

3.1.3 Hypotheses

From the combination of the literature review and the input from the panel, hypotheses are developed for the effects of airport characteristics on the incursion likelihood. The hypotheses are described in the second part of Chapter 4, where also the expert judgement is discussed. These hypotheses are not stated for each of the characteristics, because for multiple characteristics comparable hypotheses apply. Therefore, it was decided to create general hypotheses for groups of characteristics, where is referred to in the subsequent parts of the research. The hypotheses are used to give guidance for the choice of characteristics, for the definition and expression of characteristics (e.g. Airplane Design Group as indicator for large aircraft) and for the understanding of obtained results.

3.2 High-level analysis

After the data has been collected in the database, a high-level analysis is performed to understand the data characteristics and to acquire an understanding of the data distributions, i.e. descriptive statistics. In addition, the relations between airport characteristics and runway incursions are analysed on an aggregated level, to find the first indications of interactions and to exclude irrelevant aspects for the further research. The main objective is to select appropriate indicators and a relevant airport subset, which can be used for the proposed frequency model.

3.2.1 Airport characteristics

All 420 airports within the research scope are considered in the high-level analysis. For these airports, the incidents are normalised for the number of aircraft movements and graphically presented to get a first indication of the dispersion. For the airport characteristics, all incursion severity classes are aggregated in this phase. The study is performed as univariate analysis (normalised number of incursions) and bivariate analysis (incursion likelihood versus demand). The data is presented, depending on the characteristics, by means of chatter plots, bar charts and frequency tables.

3.2.2 Multicollinearity

The avoidance of multicollinearity in a regression model is of great importance to provide significant attributes (Slinker & Glantz, 1985). Because of the assumption that some characteristics relate to each other, a test for collinearity is conducted. For instance, the share of parallel runways versus the share of intersecting runways would result in redundant variables. Therefore, this step is required to avoid multicollinearity during the model development. Hence, the aim is to apply independent attributes into the model, that are hardly correlated.

3.2.3 Selection of model attributes

The conclusion of the high-level analysis is the selection of airport characteristics that appear to have a relation with incursion likelihood. This selection is also based on the results of the collinearity test and provides therefore only relatively independent attributes, that describe incursion frequencies. Also, a subset of airports is selected for further analysis, in order to avoid low representative data points, such as airports with a small share of commercial air traffic.

3.3 Modelling

Then, phase 3 covers the development of the frequency model. Until this phase, all incursions were aggregated for airport size, severity classification and incursion type. From here, the distinction between the variations of incursions is considered as well. In this phase, it is decided for which type of incursions the most accurate model can be proposed. To achieve this, association tests are conducted, outliers are identified and the regression method is chosen.

3.3.1 Association tests

A selection of characteristics from the previous phase is analysed in more detail during the tests for associations. This implies an analysis on the correlation between each characteristic individually and the multiple definitions of incursion frequencies (incursion rates per severity, type and the total rate). The results of the association tests provide correlation values and significance levels.

For the selection of associating characteristics, the confidence level for the tests has to be chosen. Whether H_0 is rejected depends on whether the difference between the groups is statistically significant (i.e. the probability value p does not exceed the significance level α). Thus, if $p < \alpha$, H_0 is rejected. The α-value is set to 0.05, which is conventional in scientific (and ATM related) research. Thus, in case $p > \alpha$, the difference between the groups is not statistically significant and H_0 is valid.

The dependence between two variables (dependent Y and independent X) will be analysed as the Pearson's r correlation coefficient or the Spearman's rho rank correlation coefficient, depending on the data distribution. Thereafter, simple regression is used to analyse the correlation between the variables. In order to choose the applicable analytical test, it is required to consider the degree of normality in the data populations. This step does not apply for binary and categorical data, such as presence of Runway Status Lights.

To test for normality of the continuous data, the Kolmogorov–Smirnov test and the Shapiro-Wilk test are executed, which compares the empirical cumulative distribution function (CDF) with the theoretical CDF of a normal distribution, the null hypotheses. These tests are considered to provide good estimates of the normality. For data that is categorical or not normally distributed, non-parametric statistical tests are required. An overview of the statistical tests is provided in Appendix A16.

3.3.2 Outliers

Since the dataset can consist of outliers for certain characteristics that influence the correlation between variables, it is necessary to decide how to deal with these data points (airports). For this study, outliers are defined as values that exceed ±3σ of the residuals, a conventional threshold value. Observed outliers are not further analysed; the selection of case studies is discussed in the next section.

Since each airport, independent of the size, is treated equally across the dataset (no weighting factors are applied), the effect of a large airport outlier is equal to that of a small airport. However, the effect of large airports is more important and reliable because of its generally larger intensities, both in terms of movements and incursions. Therefore, it was decided to create three separate datasets; one in which outliers are included, one in which all outliers are excluded and one in which only ‘non-hubs’ and ‘other airports’ outliers are excluded (semi-complete). The purpose of this approach is that the effects of outlier removal on the correlations in the association tests become clear and that the most appropriate dataset can be chosen for the model estimation. Possibly, for example, a smaller dataset (i.e. ‘non-hub’ and ‘other airports’ outliers excluded), covering a larger share of hub airports, appears to be the most appropriate for the model development. Hence, all data for the modelling is sourced from the same dataset.

Relevant to mention, it was chosen to not treat each size of airport with a different weight factor in order to avoid side-effects from this method, which would not be observable in the results. By creating a smaller airport sample, in which more relevant airports based on their characteristics are added, it was aimed to reduce potential ‘unfair’ comparison with equal weight factors.

3.3.3 Regression analysis

Since associations have been demonstrated between certain groups, the relationships can then be further analysed by the estimation of the frequency model. The estimation is executed using the SPSS software tool. First, models are developed for the total incursion rate and for all severities and types of incursions, by means of the forced entry method in which the correlating variables are added simultaneously. Then, the chosen model is further developed according to the stepwise multiple linear regression method. By this, a continuous outcome (dependent variable Y) model can be obtained which describes the incursion rate. As explained in the literature review, multiple studies (e.g. Wilke et al. 2015a; 2015b; Mathew et al. 2016) used logistic regression to estimate the probability that a binary outcome occurs, in order to understand the influence and contributions of attributes to the result (i.e. probability event). Off course, this does not allow to develop a frequency model, which is desired since the study of Claros et al. (2017) and because of the possibility to assess airports (e.g. current situation and forecasted).

In the first place, a linear model was developed, in which it is assumed that there exists a linear correlation between the incursion frequency and a certain airport characteristic. In order to improve the model fit, the attributes are analysed on potential non-linear relationships, which are subsequently used for the development of a non-linear fit model.

Lastly, potential interactions between variables are analysed. Hence, possibly, some characteristics have an influence on other characteristics. For instance, the effect of required runway crossings could be stronger in case the share of intersecting runways is larger. Interactions are modelled by the application of interaction terms into the model.

3.3.4 Post-analysis expert judgement

As explained before, the consultation of the expert panel is also used for the post-validation of the analysis. Based on this input, the clarification of the obtained results through the research is stated.

3.3.5 Model comparison

After the regression model has been developed, it is compared and applicated. The comparison is conducted to the existing model developed by Claros et al. (2017), who developed a prediction model in which multiple airport characteristics are taken into account. The model is less focussed on geometry aspects, but incorporates also weather variables. Therefore, it is interesting to analyse whether the model manages to provide more accurate estimations, in comparison to the observations. Model validation using an additional dataset (e.g. comparison with a sample of similar airports or with data from a different time interval) is not chosen, because of qualitative data availability issues.

3.4 Airport cases

Thereafter, the model is applicated in two ways. Airport cases are analysed to observe the differences between the estimations and the observations. Using incident report narratives, all runway incursions are geographically mapped onto the airport diagram, to perform an incident-level analysis. Incident mapping was recommended for further understanding of incursion causes Wilke et al. (2015b) and is commonly used for the determination of hot spots. Descriptive statistics are used to indicate the most critical locations for each airport, per severity category and incursion type. From this, it can be observed which aspects are not covered by the model and in which way further research could improve the estimation ability. Case airports are selected from a residual analysis, where three large hub airports are selected: one with a higher observed incursion frequency than estimated by the model, one with the lowest difference to the estimation and one airport which was the best predicted by the model.

To test the potential of the model application on existing airports, Schiphol (AMS) is selected as case airport. For AMS certain scenario forecasts are proposed, based on geometrical adjustments. From the observation years, the incursion rate is extrapolated along the forecast period.

4 Expert judgement and hypothesis

In this chapter, a summary is presented of the results from the conducted interviews with the airport actors from the expert panel. Also, the resulting hypotheses are discussed in the second part.

4.1 Panel review

In Table 4-1, the results from the review of airport characteristics, obtained from the literature study, are shown. Four categories were defined on which the actors could value their expected relationship between the characteristic and the occurrence of runway incursions: 1. Improbable, 2. Questionable, 3. Probable, 4. Likely. For some aspects, the results are very different per expert. This can be the cause of diverging interpretations of the factors.

The characteristics indicated with the check mark (✓) are analysed in the high-level analysis of the research. This selection is based on the result from the panel consultation, the availability of data and the contribution to other characteristics. The characteristic was considered if at least one panel expert mentioned 'probable', or two experts mentioned 'questionable'. In case no appropriate dataset could be formed for the analysis of characteristics, it was excluded. Lastly, characteristics were in some cases merged to better express their influence, such as 'airport utilisation' and 'number of runways' resulting in 'movements per runway'. One exception was made for taxi delay, since it is assumed that the designation 'improbable' especially accounts for US airports. Lastly, airport surface was added as possible indicator, since the data became available after the panel interviews.

Table 4-1: Relevant characteristics (table continues the next page)

	Expert panel			
Characteristics	Pilot	ATC	V/PD	**Analysed**
Airport size (L, M, S, N, O)	Probable	Probable	Probable	✓
Operation types (GA, commercial, military)	Improbable	Very likely	Probable	✓
Air traffic mix (size and/or type of aircraft)	Probable	Probable	Questionable	✓
Geometry				
Number of runways	Very likely	Very likely	Questionable	
Intersecting runways	Very likely	Very likely	Very likely	✓
Parallel runways	Very likely	Probable	Probable	✓
Intersecting Runway Safety Areas	Probable	Probable	Probable	
Runway crossings	Very likely	Probable	Very likely	✓
Runway/Taxiway intersections (number and type)	Very likely	Probable	Very likely	✓
Complex TWY-RWY intersections	Very likely	Probable	Very likely	✓
Runway length	Improbable	Probable	Probable	
Runway width	Improbable	Improbable	Questionable	
Need to cross runways (to access other runways), presence central terminal area	Very likely	Very likely	Very likely	✓
Special elements				
Aligned taxiways	Questionable	Probable	Probable	
Direct access	Questionable	Probable	Probable	
Displaced thresholds	Questionable	Probable	Probable	
RETs leading directly onto another runway	-	-	Improbable	
Presence wide expanses of pavement	-	Probable	Probable	
Mitigation measures				
Presence of Runway Status Lights	Very likely	Probable	Probable	✓
Edge light intensity	Questionable	-	Improbable	
Presence of surface detection equipment	Very likely	-	Probable	

Other				
Runway material	Probable	-	-	
Construction occurrences	Probable	Very likely	Probable	
Hot spots	Improbable	Probable	Questionable	
Influences outside scope				
Weather and visibility	Very likely	Very likely	Very likely	✓
Added by review				
Airport utilisation	Very likely			✓
Taxi delay	Improbable	-	-	✓
Added after review				
Airport surface				✓

The corresponding interview reports can be found in Appendix A4.

4.2 Hypothesis

Below, the hypotheses developed from the literature study and the panel consultation are summarised. The blue boxes give the shortened hypothesis as conclusion.

H1: Runway crossings

Airports that require aircraft to cross runways in order to reach other parts of the airport area would be generally more vulnerable for runway incursions. For example, a centrally located terminal area may increase the need to cross runways, in order to reach cargo terminals, hangars or parking areas. This latter situation occurs often when the airport is in shortage of gates. In case an airplane is on the ground for a few hours and there are enough gates available, the aircraft does not require to be parked temporarily on the other side of the airport before moving back to the gate.

Thus, the necessity to cross runways is an important characteristic for incursion likelihood, more than only the infrastructure (the crossing) itself. Also, the use of the crossing runways plays a role. If active runways have to be crossed, the impact is more severe than when the runway is inactive.

> More runway crossings relate to higher incursion rates, if these crossings are required at runways which are in operation. The crossing of non-operational runways would not result in higher incursion likelihoods. Also, the necessity to cross runways relates more to higher incursion rates than the presence of these crossings itself.

H2: Intersecting runways

It is expected that the likelihood of runway incursions is stronger related to the number of runway intersections than the ratio of intersecting runways, because runways and TWY-RWY intersection are used simultaneously, which is not necessarily the case for two intersecting runways. In this latter case, the ATC forms a strong safety net, preventing from the unauthorised use of two runways simultaneously. However, the likelihood of incursions is assumed to be higher for intersecting runways than for independent runways.

> Intersecting runways relate to higher incursion rates compared to non-intersecting runways, if these runways are used simultaneously. If not, the risk is much lower.

H3: Infrastructure not cleared

A large share of the low severity incursions, category D, is represented by the unauthorised presence of an aircraft or vehicle on a part of the runway. These incidents are often the result of errors in communication and do not relate directly to geometry.

> Uncleared infrastructure in which only one aircraft or vehicle was involved contribute to a large share of incursions (category D). These incidents do not relate to the infrastructure.

H4: TWY-RWY intersection density
The lower the number of TWY-RWY intersections, the easier it is for the pilot, because there are less possibilities to make mistakes. However, from the operational perspective, the availability of runway exits can be a limiting factor for the throughput, since there are less possibilities to clear the runway, resulting in longer runway occupancy times and higher likelihood of loss of separation.

A higher number of TWY-RWY intersections per runway-km creates more possibilities for aircraft to clear the runway for the subsequent aircraft in the landing sequence, minimising the likelihood of a loss of separation. For departing aircraft, higher intersection numbers could increase the incursion likelihood as there are more possibilities to take the wrong taxiway.

H5: TWY-RWY intersection types
The effect of right-angled, non-right-angled intersections and RETs is different, depending on the way it is used. For aircraft that depart, visual hindrance is an important aspect during lining-up for the runway. If the runway is used for operations in the opposite direction of the RET exit, the visual hindrance is reduced, both for pilots and vehicle drivers. If aircraft use the same direction of the RET and arrive from the back, then the line of sight is decreased. The situational awareness of the users is increased when one enters a right-angle intersection, because the user has to physically make a turn and look around where to go.

For landing traffic, the presence of non-right-angled intersections and RETs could be advantageous in reducing the likelihood on incursions, since it stimulates to shorten the runway occupancy time, same as for TWY-RWY density. The aim is to have aircraft as quickly as possible off the runway. For a conventional right-angle exit, it is required to brake to a complete standstill, before exiting from the runway. This requires more time.

For departing aircraft, right-angled TWY-RWY intersections lower the incursion risk because visual hindrance is avoided for aircraft that hold short. For landing aircraft, right-angled intersections increase the risk, since aircraft have to make a full stop on the runway before it can leave the runway, with a potential loss of separation. In this latter case, high speed exits will lower the incursion likelihood.

H6: Traffic intensity
Traffic intensity is a good indicator of the airport complexity, because after landing the communication with ground control can become complex for pilots due to a growing number of infrastructure users, which use the same communication network. The ATC always evaluates which size of traffic volume they can handle for each specific sector, at any given time. So actually, this is the limiting factor of the airport usage. Therefore, movement figures itself will not explain higher incursion frequencies because of ATC capacity.

Traffic intensity is mainly related to the ATC, where the capacity of the handled flights is determined. Higher intensities generally relate to higher workloads, also for pilots because of more disturbance during communication. This relates to a higher incursion likelihood. Though, movement figures will not explain this effect, since the airport capacity is determined by the ATC.

H7: Large aircraft more involved
Larger aircraft are relatively more often involved in runway incursions, because pilots of small aircraft are often frequent visitors of an airport since they fly mainly short-haul. They are often very familiar with all procedures and communication channels at that airport. Flight crew of wide-body aircraft fly predominantly long routes, and visit airport less often. Furthermore, at the time of their arrival they are becoming tired and less alert compared to short-haul pilots.

Large aircraft are more involved in incursions since the pilots are less familiar with the airport and are often less alert during arrival of a long-haul flight.

H8: General aviation
The presence of GA traffic is not directly observable from the incursion likelihood. All GA-pilots should have obtained an equal level of pilot's licensing as commercial pilots. Furthermore, generally GA-pilots could conduct an even more

extensive pre-flight preparation than airline pilots, and they could also be more familiar with the airport, when they are based there.

> The presence of GA traffic does not impact the incursion likelihood.

5 Data collection and preparation

A major part of the research covers the data collection and preparation and the definition of the airport characteristic measures. First, incursion data is required, and second, the related airport characteristics need to be collected. This chapter covers the process of data collection, preparation and describes the definitions which are defined.

5.1 Incident data

The runway incursion incident data was obtained from the Aviation Safety Information Analysis and Sharing (ASIAS) system of the Federal Aviation Administration (FAA), the Air Navigation Service Provider (ANSP) of the US. This database was used because the FAA follows international standards, the assessment of incursions is conducted by qualified and trained analysts, and the assessment process is audited (FAA, 2009). Also, the US is known for its proactive safety culture (Wilke et al., 2015b). Furthermore, the database provides the only publicly available overview of all runway incursions at the important US airports, since it is mandatory to record incidents in the system. Also, important to mention, comparable databases in terms of size are not publicly available for other countries or regions in the world. The collection of all incident records in the study period (1 January 2007 until 31 December 2017) resulted in a dataset with a total 17,147 incidents over 513 airports. Accidents (i.e. collisions) were not found in the data.

For each incident record, variables such as the date on which the incursion occurred, the severity class, the FAA airport identifier, the type and a descriptive narrative of the occurrence, were obtained. The overview of information variables that was collected is listed in Table 5-1.

Table 5-1: FAA RWS incident information

Variable	Description
Type	PD/OI/VPD
Event date	Date of incident
Severity	A/B/C/D/E
Airport	Alphanumeric FAA LID code
Location	Airport location
Aircraft 1, type	ICAO code of first aircraft type
Aircraft 2, type	ICAO code of second aircraft type
Aircraft 1, Flight Conduct Code	FAR part under which the first aircraft was operated
Aircraft 2, Flight Conduct Code	FAR part under which the second aircraft was operated
Weather	Reported weather at time of the event
Runway	Runway on which the event occurred
Description	Narrative of the incident

The data was collected as .csv file from the online RWS database of the FAA Runway Safety Office as, using the study timeframe as search criterium. Excel was used as tool to prepare the data. In addition, to include AMS in the comparison with the other airports, also incursion records from AMS are required. This data was collected using the annual reports of the LVNL. Here, the annual number of incidents per severity category is available.

5.1.1 Preparation

After the incident data was collected, data preparation was required before it could be used in the analysis. This implied the selection of airports that fit in the study scope, the review of data consistency, the data validation and the data completeness check. Data completeness checks are required to ensure the internal validity of all data and the appropriateness for statistical analysis (Wilke et al., 2014b).

5.1.1.1 Selection of scope airports

The first step in the data preparation was the selection of scope airports. Thus, incidents that occurred at military- and GA-only airports had to be removed, as well as incidents at non-towered airfields and airports without commercial air traffic. For this, the incident dataset was reviewed using the NPIAS report, in which all US airports are listed with their designations, i.e. hub size (FAA, 2018b). Airports that are in any case included in the research are the large, medium and small hub airports, which are airports that account for respectively >1.0%, between 0.25% and 1.0%, and between 0.05% and 0.25% of the annual passenger boardings in the US (FAA, 2018a). The database check on military airfields resulted in the exclusion of 1 airport, which accounted for 15 incidents. One airport (Charleston International Airport, CHS) is defined as a joint-use aerodrome and was not excluded. The review on GA-airports showed that 75 airports were designated as GA-airport; these were excluded. The airports are responsible for 1005 incidents.

Also, the database was reviewed for the presence of commercial air traffic for at least one of the years in the analysis period. Airports labelled as Commercial Service – Primary CS and Commercial Service – Non-Primary in the NPIAS report were selected to remain in the database. In addition, airports designated as reliever airport[5] were kept, the remaining airports were filtered out. This resulted in the exclusion of one airport, responsible for one incident. Hence, the most airports were already filtered out in the previous step. Lastly, a review of the dataset for the presence of an ATC tower led to the exclusion of one airport, responsible for one incident. The check on presence of ATC was conducted using the AirNav (2018) database.

Furthermore, it appeared that one airport was designated with the two airport codes HCF and HNL (Honolulu Int'l). These were combined, since HCF consists only of a ATC-facility responsible for HNL. At this airport 234 incidents were observed during the time interval. The airport Panama City–Bay County International Airport (PFN) was excluded since it was temporarily closed during the analysis period, and because of that, no recent incident data was collected. This led to the exclusion of one incident. Lastly, Lake Hood Seaplane Base (LDH) was excluded since it comprises an airport with incomparable characteristics than the others, although it meets the scope requirements. LHD is an airport used by seaplanes and does not consist of taxiways and runways. Consequently, 47 incidents were removed.

To summarise, these database review filtered out 81 airports and 1,072 incidents in total. Resultantly, 431 airports responsible for 16,077 incidents were obtained for the next phase of the data preparation.

5.1.1.2 Data completeness and consistency

Then the incident dataset was checked for completeness. Some data records contained empty fields which could easily be filled without further information (like missing airport code, while airport name was known). A few data records used multiple names for the same airport code. For these cases, the names were modified to a standard name. Also, multiple datum formats were found, which had to be standardised. Records were only removed in case the incursion type, the date or the airport was unknown. Some type cells were also labelled as unknown (UNK). This led to the exclusion of 120 incidents. One data error was found in the database; for Charlotte Douglas, International Airport (CLT) one 'N/A-incident' was mentioned 160 times for the same datum. These records were removed.

In the database, the severity classifications are codified as A until E, according to the assessment standards. E-incidents were removed, meaning the filtering out of 8 records and one airport. Some records are labelled with a "P", meaning that the severity assessment is pending, or an "S", which stands for a surface incident, instead of a runway incursion, for which severity is not assessed. For the 4 P-incidents, the severities were calculated using the RISC-tools. S-incidents, were already filtered out during the earlier preparation steps. Also, some incident records were labelled as N/A. This means that for some reason the severity classification is not applicable, since the incident circumstances do not meet the requirements for a runway incursion severity class distinction. This resulted in the exclusion of 3,816 incidents over 9 airports. However, for the high-level analysis where no severity distinction is necessary, the N/A runway incursions are kept. Subsequently, a sample-wise check on the consistency of the incident data was done to test whether incident information corresponds with the airport characteristics during the occurrence. For example, the description of the weather circumstances was validated.

Furthermore, for each incident record in the database, the type of the occurrence is mentioned. The following distinction is made: operational error (OE), operational deviation (OD), operational incident (OI), pilot deviation (PD), vehicle/pedestrian deviation (V/PD) and other (OTH). OTH is used when an event does not meet the OE/OD/OI, PD, or V/PD criteria; it applies for 614 incidents. OTH were only excluded for the analysis of the type of RI, in all other cases the OTH occurrences were taken account for the total number of incidents. For each airport, the cumulative numbers were determined according to OI, which are OE/OD/OI incidents combined, PD and V/PD.

In the end, a prepared incident database for the data analysis was obtained. The incident records were transformed into the main datasheet, with for each airport the number of incursions in total and per year, per severity class (total) and per type (total). The following step comprises the check on weather circumstances.

5.1.1.3 Visibility conditions

The incident data also consists a METAR codex which describes the reported weather condition during the incident. The reporting method is predominantly used by pilots as part of a pre-flight weather briefing and consists of highly standardised language according to ICAO regulations. Generally, METAR codex describes (among other things) the location, the date and time of the report, the surface wind, visibility, runway visual range, weather, amount of cloud and

[5] An airport that is built or designated to provide relief or additional capacity to an area when the primary commercial airport(s) reach capacity

temperature. The reported weather description is shortened, but contains elements according to the METAR codex. It contains respectively the following variables: visibility, cloud layers, wind direction and speed and any obstructions to weather. For example: $10\ \mathrm{SM}\ \mathrm{FEW030}\ \mathrm{BKN045}\ \mathrm{20010G12KT}$, where $10\ \mathrm{SM}$ is 10 statute miles (1609 m), $\mathrm{FEW030}$ is few at 3000 ft, $\mathrm{BKN045}$ is broken at 4500 ft and $\mathrm{20010G12KT}$ is 200 degrees true/10 kts gusting to a maximum of 12 kts.

Since the circumstances can differ greatly among airports because of their geographical location and related climatological influence, weather should be taken into consideration when comparing airports on their relationship between geometry and incursion rates. For example, the effect of intersecting runways versus parallel runways cannot be reliably compared between an airport with 99% good visibility conditions and an airport with 75% of good visibility conditions.

For further preparation of the dataset, it was therefore decided to analyse the incidents on their visibility conditions. Because airports are compared on their characteristics in relation to incursion rates, an unfair comparison would emerge if airports with hardly any low visibility conditions are compared to airports with above average unfavourable weather. In these comparisons, the weather could have had the biggest impact on incursion likelihood, rather than the airport characteristics. To avoid this, it was decided to exclude incidents that occurred during unfavourable weather for all airports. Simultaneously, for each airport the share of operations during these conditions were excluded. As a result, only good weather incursions and operations remained in the database.

Two types of weather, which includes visibility conditions, were defined: unfavourable weather conditions and good weather conditions V_c, of which the first category was filtered out. ICAO defines the weather situation according to which flight rules have to be used. It distinguishes VFR for visual meteorological conditions and IFR for instrument meteorological conditions, respectively for good visibility weather and less good visibility conditions. Here, the distinction which is used in the US is applied, since it provides two addition categories (Marginal VFR and Low IFR), and is thus more precise in terms of visibility categories. To each of the incidents, one of the four labels was assigned.

In Table 5-2, the used definition is explained. The overview of the METAR codex on which all descriptions were analysed, is attached in Appendix A2, as well as the visibility classification of the FAA.

Table 5-2: Defined weather (visibility) categories

Weather categories	Characteristics
Unfavourable weather conditions	All operations during Low Instrument Flight Rules (LIFR) or Instrument Flight Rules (IFR) during heavy snow (+SN) and/or heavy rain (+RA) and/or mist (BR) and/or fog (FG)
Good weather conditions	All operations during Visibility Flight Rules (VFR) or Marginal Visibility Flight Rules (MVFR) or Instrument Flight Rules (IFR) in the absence of heavy snow (+SN) and/or heavy rain (+RA) and/or mist (BR) and/or fog (FG)

In multiple cases, the METAR used a different format, meaning that the visibility identifiers had to be extracted. For this a special rule was written to collect all visibility related codex of the METAR. Some METARs used ‘miles’ instead of SI, thus, also MI references were extracted. Subsequently, all visibility distances were calculated to miles and the corresponding visibility categories were assigned.

It appeared that 441 incursions occurred during the unfavourable weather conditions, and were thus excluded for airport comparison analysis. Of these incidents, 181 occurred during IFR conditions and a weather element obstructing the visibility, and 260 occurred during LIFR conditions of which the weather was not further examined. All other incidents were labelled as good weather, with favourable visibility conditions. Wind was not considered because of data shortage issues.

The collected weather data is summarised in Table 5-3. Further descriptives of the incursions are presented in the first part of the high-level analysis, in Chapter 6.

5.1.1.4 Runway incursion rate

Hence, the number of incursions and the number of movements at an airport are strongly related to each other. A certain number of incursions does not imply any risk or likelihood level, because it should be considered in the light of the airport utilisation. In other words, an airport with 3 incursions and 100,000 movements during one observation year performed better than an airport with 5 incursions and 90,000 movements.

Table 5-3: Weather descriptives

Weather characteristics	Type	N	Min	Max	Mean	Std. dev.
Percent composition VFR/year	Cont.	420	63.4	99.7	83	7.13
Percent composition MVFR/year	Cont.	420	0.1	24.9	10	4.59
Percent composition IFR/year	Cont.	420	0.0	9.4	4	2.03
Percent composition LIFR/year	Cont.	420	0.0	12.6	3	1.74
Percent composition 'good visibility conditions'	Cont.	420	87.4	100	97	1.74

To make airport comparable, and to give a justified indication of the situation at an airport regarding runway incursions, the incursion rate R_{rate} is introduced. Throughout the analysis, runway incursions are explained by this rate, unless otherwise indicated.

For each airport, the proportion of the airport operations resulting in incursions per severity classification and type is calculated on a scale of 100,000 operations (5-1), which is a common measurement on airport level. Here, R_i is the number of incursions for year i and T_i the number of operations for year i at a given airport. Furthermore, $i = 1$ for 2007 and $n = 11$ for 2017.

$$R_{rate} = 10^5 \frac{\sum_{i=1}^{11} R_i}{\sum_{i=1}^{11} T_i} \tag{5-1}$$

5.2 Airport data

The collection of airport characteristics comprises of operational information such as the number of operations (aircraft movements) and the traffic mix, and the geometrical characteristics. In this paragraph, for both groups of characteristics, the process of data collection and preparation is discussed. Also, in order the use the data for analysis, measures are defined.

Airport operation data for the US airports was obtained from the FAA Air Traffic Activity System (FAA, 2018c). Aircraft movement statistics from AMS were collected using the annual traffic reports (Royal Schiphol Group, 2018). All data was collected in the main datasheet, in which the incursion overview is included.

5.2.1 Preparation

After collecting the number of annual movements per airport, it appeared that for some airports, part of the operation data was not known. This was the case for 12 airports. These airports were checked using their annual reports, and if the data was available, the corresponding blank fields in the database were filled. For a few airports, no traffic figures were known for a specific year because the airport was closed during that period, and some airports were first opened during the research period. These airports remained in the database, hence, the average R_{rate} for these airports is less accurate because it was based on a shorter time interval. San Bernardino International Airport (SBD) was removed because the first commercial flights have not been performed yet. The opening of the airport was repeatedly delayed. Because of this, no incidents at SBD were observed. For the airports with complete data records, the operation figures were sample-wised checked using the airports annual reports. No data discrepancies were found.

Then, to each of the remaining airports, a category label was assigned, by means of the NPIAS report. The airports were labelled according to their size: large hub (L), medium hub (M), small hub (S), non-hub (N) and other (O). The definition for each category is mentioned in A2.3. Also, to each airport their GPS coordinates were assigned for the geographical airport mapping. The Lat/Lon coordinates (in decimal degrees) were collected using the open source database of OpenFlights (2018). In this study, the airports are referred to with their FAA LID, since not all airports have an IATA code. However, some databases use IATA identifiers, such as OpenFlights. Twelve airports in the database use deviant FAA codes, compared to IATA codes. For these airports, the coordinates were found manually. To validate the coordinates, all coordinates were automatically mapped using the chart maker in Google Maps. All coordinates proved to be valid.

In Figure 5-1, an overview of the examined airports in the high-level analysis is depicted. The entire list of airports is attached in Appendix A5.

5.2.2 Operations

First, the averaged number and percentage of commercial air traffic in the analysis period was obtained using the OBSNET operation database. Here the annual number of aircraft departures and arrivals per air traffic category was available. The percentage commercial traffic was determined by summing all the departure and arrival movement figures per airport, and relating this to the cumulative number of aircraft movements, which was determined earlier for each airport. This resulted in the averaged percentage to acquire representative figures.

Also, the percentage of operations per Airplane Design Group (ADG) was determined using traffic counts. For this, the FAA Traffic Flow Management System database was used. It consists of aircraft counts per ADG, per airport. However, a large share of the data appeared to have a large deviation from the traffic figures from the other database: the sum of all movements (ADG and year) was in some cases for example less than 50 percent of the total traffic count. The reasoning behind this discrepancy is that for most of the smaller airports, figures for some years lack. In order to obtain for those airports estimated percentages, the sum of ADG movements was used as reference.

Lastly, taxi delay data was collected from the FAA Traffic Flow Management System, in which the average taxi time for inbound and outbound traffic was given, as well as the percentage of the flights that delayed during taxing (in+outbound). It was decided to only consider taxi delay, since taxi time is strongly related to the size of the airport and not by definition to the utilisation and geometry.

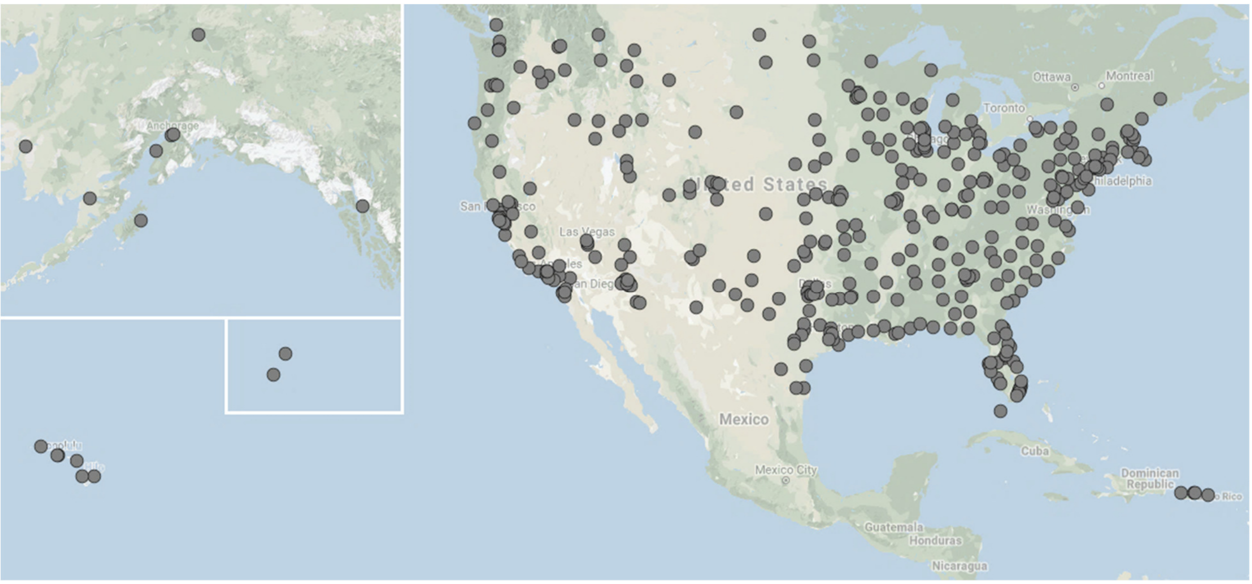


Figure 5-1: Geographical overview of selected scope airports

5.2.2.1 Proposed definitions

In order to apply the collected data in a justified way, it is partly transformed into applicable measures for airport comparisons. This insists for example the normalisation of the data in such a way that airports can be compared, as was also done for the incursion frequency (R_{rate}). For this reason, the subsequent described definitions are proposed for the data analysis.

Hourly airport and runway movements

Since airports may have differing operational regimes, a yearly figure may not describe this utilisation precisely in such a way that comparison between airports is relevant. For instance, an airport with 100,000 yearly movements and 168 operational hours per week has a lower hourly utilisation than an airport with 80,000 annual movements and 50 operational hours per week.

Therefore, one of the measures on which airports can be compared in relation to their number of incursions is by means of hourly airport movements T_h. This gives a more accurate figure of the air raffic handled per hour for each airport, compared than annual traffic figures, because an operational component is added. It is determined by (5-2):

$$T_h = \frac{1}{n}\sum_{i=1}^{n} T_{y,i}\left[\frac{1}{365 * 24O_w/168}\right] \quad (5\text{-}2)$$

Here, the number of operational hours per week O_w is considered, where the maximum number of 168 applies. Furthermore, T_y is the number of movements for year i of n at a given airport. Furthermore, $i = 1$ for 2007 and $n = 11$ for 2017. In this way, the hourly figures increase as the number of operational hours decrease, in case the number of movements is the same. This result gives thus the average airport utilisation and does consider peak hour intensities, since this strongly depends on the airport usage and is complicated to capture from data.

Using the same method, the number of runway movements is determined. For this, the value for T_h is devided by the number of runways at an airport. This result gives thus the average runway utilisation and does not incorporate runway preferences and resulting varying utilisations for each runway per airport. Hence, peak hour values would also give a different indication of the utilisation. However, because of data availability issues (only annual movement figures and operational hours were available for all scope airport), the average values were used.

General aviation and heavy aircraft

Furthermore, the share of general aviation traffic is used as characteristic for the analysis. For each airport, this is determined as follows (5-3):

$$T_{GA} = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{T_{h,i}}{1 + \%GA_i}\right] \quad (5\text{-}3)$$

Here, the share of general aviation traffic is used as determining factor for the estimation of the share commercial traffic. Furthermore, T_{GA} is the number of movements for year i of n at a given airport. Furthermore, $i = 1$ for 2007 and $n = 11$ for 2017. It is assumed that only these two categories of traffic type remained in the database, since other airports were filtered out in the scope preparation. Hence, a small share of other traffic types (such as military), may still be represented at some airports. These small shares are commercial traffic in the study.

Using this method, also the share of heavy aircraft can be determined. Heavy aircraft is defined as the cumulative of ADG E and F aircraft (5-4):

$$T_{HVY} = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{T_{h,i}}{1 + \%ADG_{E,i} + \%ADG_{F,i}}\right] \quad (5\text{-}4)$$

Taxi delay

The characteristic taxi delay is expressed as the cumulative percentage of in- and outbound flights that was delayed during taxiing. For this, the mean percentage for the entire study period is used as value. No further transformation is defined for this characteristic.

5.2.2.2 Data overview

The collected operational data is summarised in Table 5-4.

Table 5-4: Operational descriptives

Operational characteristics	Type	N	Min	Max	Mean	Std. dev.
Number of movements 2007-2017	Cont.	420	163,505	10,183,961	1,227,345	1,258,652.6
Operational hours per week	Cont.	420	21	168	142	34.01
Percent composition commercial traffic	Cont.	420	0.0	98.4	29	29.05
Number of Large hubs	Nom.	30				
Number of Medium hubs	Nom.	31				
Number of Small hubs	Nom.	71				
Number of Non-hubs	Nom.	152				
Number of Other airports	Nom.	136				

5.2.3 Geometry

Then, the characteristics for geometry which could be used as performance indicator for the airport, were defined. This task mainly consisted of the categorisation of geometry elements and the counting of these elements. Also, the presence of incursion mitigating techniques were addressed.

5.2.3.1 Elements

In order to compare airports, the infrastructure was divided into general geometry elements, which were subsequently counted by means of airport diagrams. The proposed geometry elements are schematically shown in Figure 5-2.

All elements per airport were counted using diagrams. Afterwards a second check was conducted using google earth satellite footages. Characteristics such as geometry factors (e.g. the number of perpendicular taxiway intersections) were collected by visually examining airport diagrams, which are available from the FAA (FAA, 2018a). For AMS, an aerodrome chart is available (LVNL, 2013).

Subsequently, the geometrical data was verified with respect to modifications during the analysis period. Since airport characteristics may have changed over time, it was necessary to consider incidents that occurred at that airport before and after the change. For example, if at a certain airport a new runway was opened, the incursion rate before the opening is considered separately from the incidents after the change. In these cases, the airport was added twice to the data set. This only applied to changes of the studied characteristic, since incorporating all adaptions for every characteristic would result in a too complex and fragmented dataset. Because the available airport diagrams only show the current layout, the changes were observed using a combination of ancient satellite footages from Google Earth and the historical FAA database.

An example of the counted geometry elements for La Guardia Airport is shown in Figure 5-4.

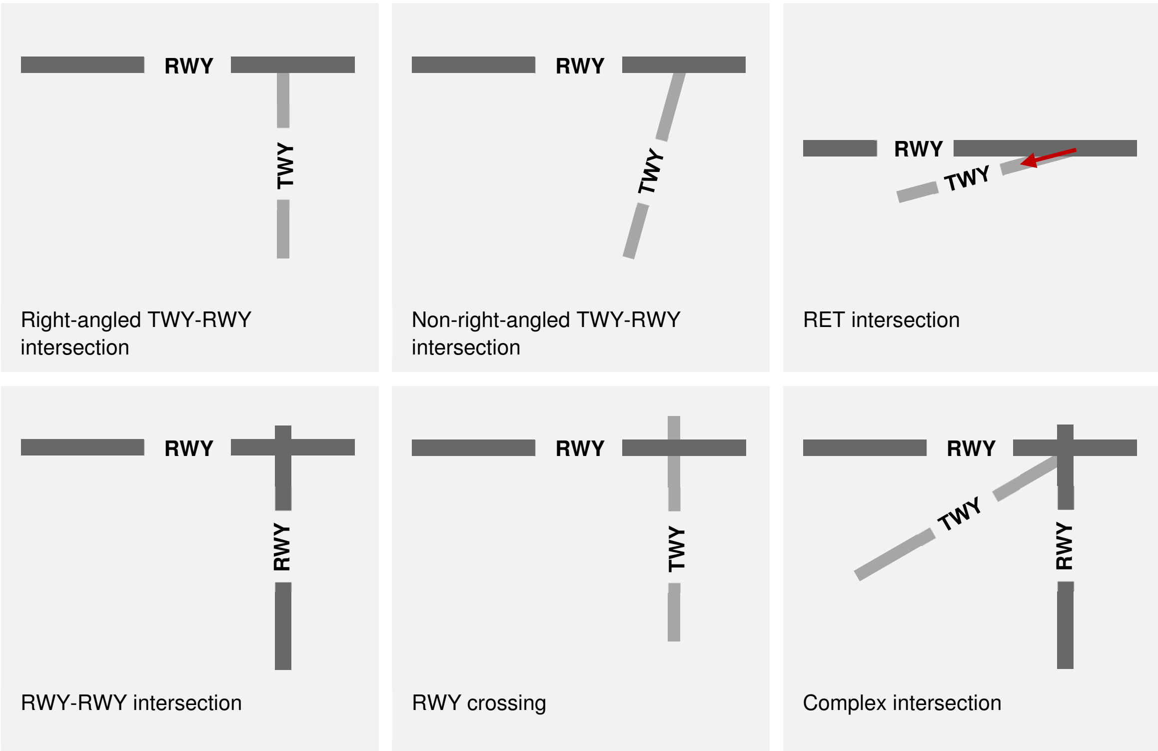


Figure 5-2: Schematic overview of defined geometry elements

Besides the visual examination of airport diagrams, detailed runway related characteristics were obtained from the FAA airport database. This runway database, consisting of more than 22,000 runway records was used to obtain runway characteristics. By counting the number of records per site number, the number of runways was determined. The number was sample-wise checked. Some discrepancies were found as helipads were also counted. Also, water runways were still found for some airports, such as Honolulu HNL. These runways were excluded across the database. The data was also used to calculated whether runways are situated parallel or intersect each other.

From the literature study and the consultation of the expert panel it became clear in general, airport complexity is related to the likelihood of runway incursions. However, complexity of an airport can be described in various ways. Throughout this section, multiple indicators for complexity are proposed in the light of the input from the previous research phase.

5.2.3.2 Proposed definitions

To use the collected data in a justified way, it is transformed into applicable measures for airport comparisons. This part discusses the measures on which the geometry data is expressed.

Required crossings

One of the aspects that increase the risk of incursions is the need to cross runways. In order to describe airports on this characteristic, an indicator was defined which explains the maximum number of required runway crossings to reach the farthest runway, measured from the terminal acreage. In Figure 5-3, a schematic representation is given for the indicator.

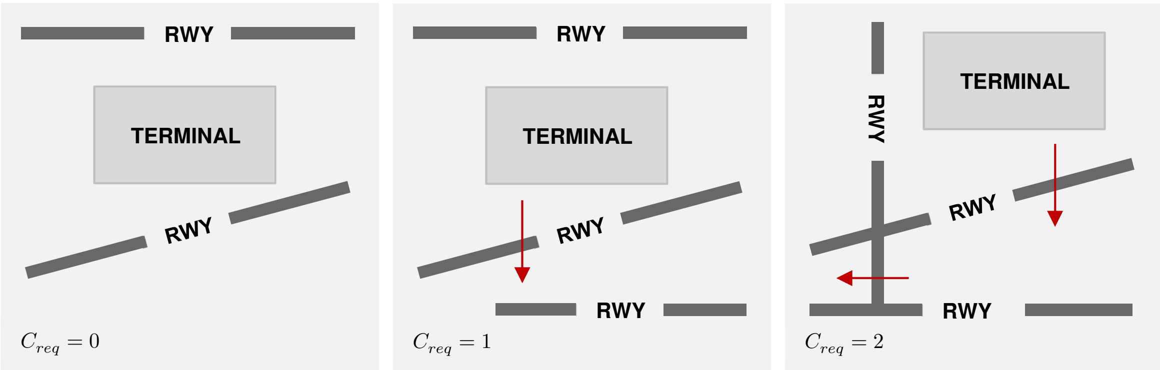


Figure 5-3: Schematic examples of variable definition 'maximum required runway crossings'

Number of TWY-RWY intersections

The number of geometry elements, such as TWY-RWY intersections is related to the size of the airport. Intuitively, the total number of intersections is larger for airports with more runways and a longer total runway length. To normalise the number of intersections based on runway length, the density of the intersection number I_n is expressed per runway-km. For this applies (5-5):

$$I_n = \frac{1}{L_{tot}} \sum_{i=1}^{n} I_{n,i} \tag{5-5}$$

Here, $I_{n,i}$ stands for the ith TWY-RWY intersection of the total n and L_{RWY} stands for the total runway length at a given airport. This data conversion also applies for the number of crossings.

Ratio intersecting runways

Also, the degree in which runways intersect, the ratio intersecting runways I_r, is analysed in relation to the number of incursions. This measurement is proposed since it gives a normalised description of the characteristic, independent of the airport size (e.g. the number of runways and the runway length) to avoid collinearity with this factor. For I_r, the total number of RWY-RWY intersections per airport is divided by the total number of runways. The following applies (5-6):

$$I_r = \frac{\sum_{i=1}^{n} I_{RWY_i}}{\sum_{j=1}^{n} RWY_j} \tag{5-6}$$

Here, I_{RWY_i} stands for the ith RWY-RWY intersection of the total n and RWY_j stands for the jth runway of the total n at a given airport. Likewise, the ratio of parallel runways and certain types of TWY-RWY intersections (non-right angled, RET) is determined. For the ratio non-right intersections for example, the total number of non-right intersections is divided by the total intersection count.

Hectare per runway-km

Lastly, the average airport area per length of runway is determined, using the equation below (5-7). Here A_{RWY} stands for the surface per runway-km, A_{tot} means the total airport surface and L_{tot} represent the total runway length (5-7):

$$A_{RWY} = \frac{A_{tot}}{L_{tot}} \tag{5-7}$$

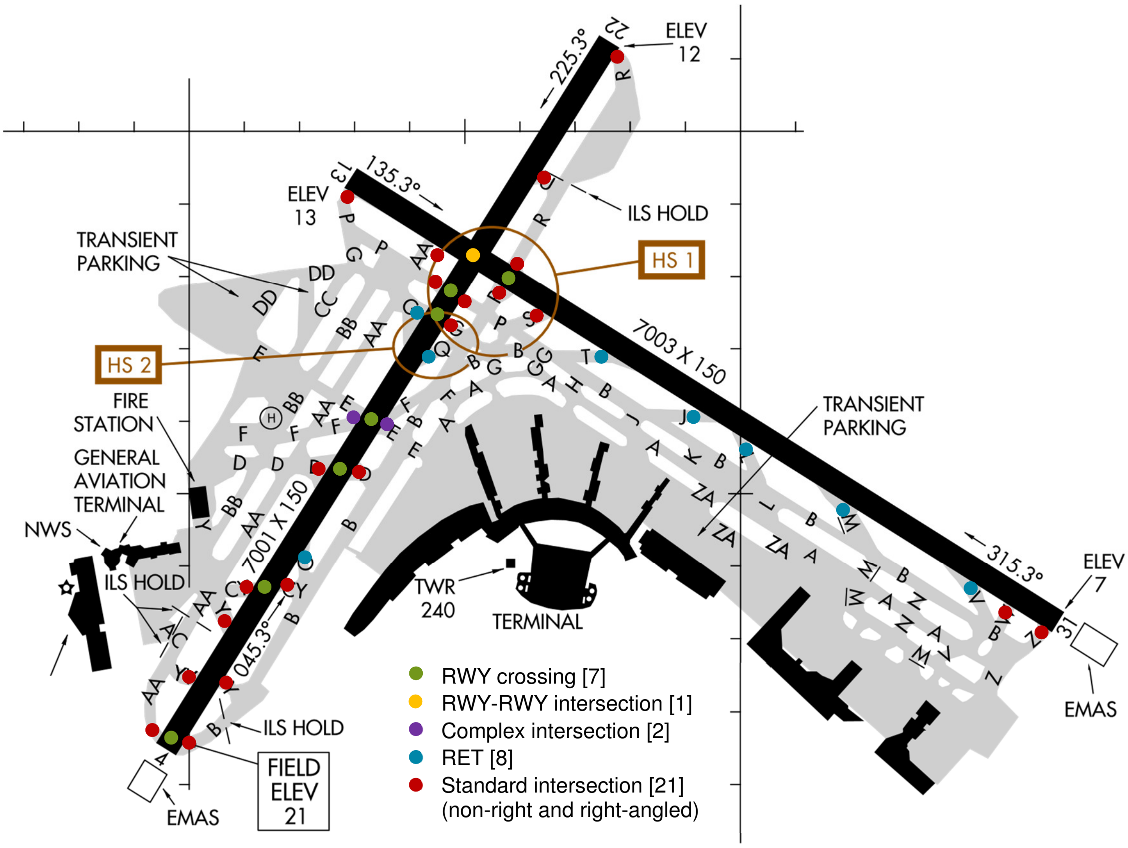


Figure 5-4: Example La Guardia (LGA): airport diagram with defined geometry elements indicated

5.2.3.3 Data overview

The collected geometrical data is summarised in Table 5-5.

Table 5-5: Geometrical descriptives (continuous on the next phase)

Geometry characteristics	Type	N	Min	Max	Range	Mean	Std. dev.
Runways							
Number of runways	Cont.	420	1	7	6	2.35	0.95
Total runway length in m	Cont.	420	745	24507	23762	4968.26	2991.75
Average runway length in m	Cont.	420	745	4298	3553	2087.13	620.89
Number of parallel runways	Cont.	420	0	7	7	0.85	1.27
Number of runway intersections	Cont.	420	0	6	6	0.89	1.01
Taxiways							
Right angle TWY-RWY intersections (I_n)	Cont.	420	2	92	90	14.69	10.09
Non-right angled TWY-RWY intersections (I_n)	Cont.	420	0	41	41	5.47	6.84
Number of Rapid Exit Taxiways	Cont.	132	0	37	37	4.08	6.01
Number of complex intersections	Cont.	420	0	9	9	0.41	0.94
Number of runway crossings	Cont.	420	0	40	40	6.15	5.98
Number of hot spots	Cont.	420	0	11	11	1.32	1.65
Number of required runway crossings (C_{req})	Cont.	420	0	3	3	1.00	0.70
Other characteristics							
Covered land area in acres	Cont.	420	80	33531	33451	1972.35	2555.02
Number of airports with RSL	Nom.	20					

6 High-level analysis

After the data is collected, prepared and expressed according to the chosen definitions in the previous chapter, the next phase consists of the high-level analysis of the complete dataset. The aim of this is to understand the incident data, the trends, the differences per airport size, incursion severity and type. The main results of this analysis are discussed in the first paragraph (6.1).

The second objective is to understand the interaction between incursions and airport characteristics and to find appropriate airports and relevant characteristics for the model estimation. In order to avoid multicollinearity in the model, also the correlation between airport characteristics is assessed, after which variables are excluded.

Besides obtaining an understanding of the relations, part of the hypotheses from the literature and the expert panel is answered.

The chapter is divided into the following three parts:

6.1 Incursion characteristics

This paragraph covers the descriptive analysis of all incident in the measurement period. First, the general trends are considered, after which the incursion frequencies per airport, per severity and type are analysed. In Table 6-1, the frequency table of the incidents can be found.

6.1.1 Incursion frequencies

Over the years, the number of aircraft movements has shown a steadily decrease until 2014, which can be clarified by a smaller demand for air traffic during the international financial crisis. This is visible in Figure 6-1, where the annual number of movements and incursions for hub airports and the total populations of airports are depicted. Since 2014, the number of movements showed a minor growth rate until 2017. Meanwhile, the number of incursions, has except of 2009, constantly increased during the studied period. According to the panel, the minor growth in aircraft can be explained by the fact that a large share of the older aircraft in the US are replaced by newer and often larger aircraft. This is for instance the case for the replacement of the MD80's. Also, in the US, the majority of the movements is represented by domestic flights. This means growth in terms of passengers, but not necessarily in movements since these fleet renewals take particularly place for these markets.

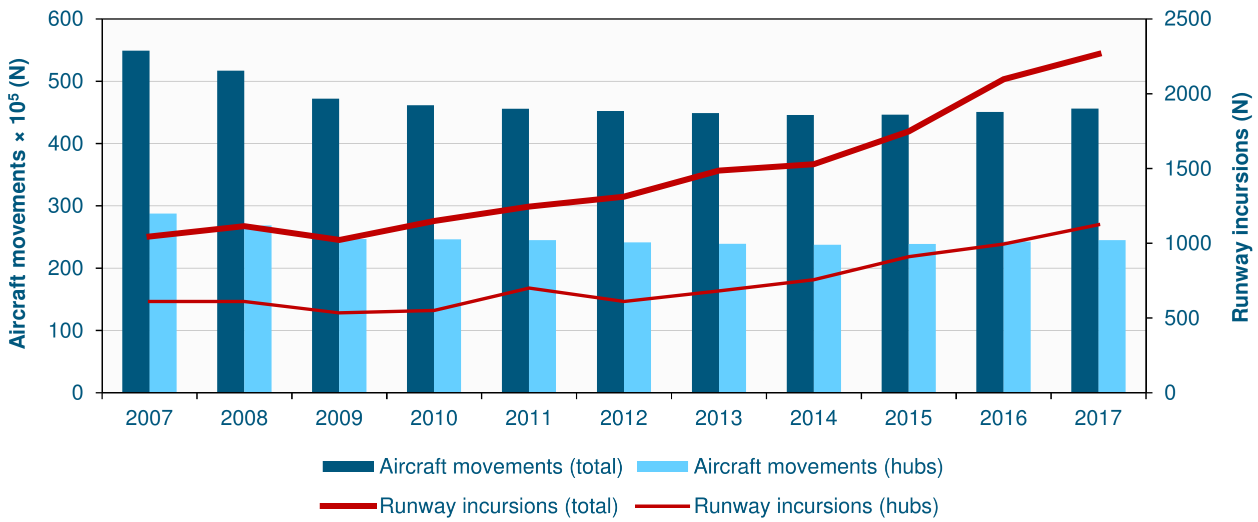


Figure 6-1: Annual movements and runway incursions

Both trends in movements and incursions generally also apply when only hubs are considered (lower red line). Though, the number of incursions showed more fluctuations until 2012, after which the level increased annually. For this, no clear explanation was found yet.

Table 6-1: Runway incursion data overview

Data	N	Data	N
Total number of incursions	15910	OI incidents	2723
Severity cat. A incidents	82	PD incidents	9208
Severity cat. B incidents	72	V/PD incidents	3427
Severity cat. C incidents	5168	Other incidents	552
Severity cat. D incidents	6928		
Severity cat. E incidents	3660		

6.1.2 Incursion rates

To indicate the importance of incursion numbers, the incursion frequencies are expressed as R_{rate}, where the total number of incursions (A-D) is normalised against the number of movements. The results are shown in Figure 6-2. Annual aggregates were defined for each of the five airport sizes: large hub, medium hub, small hub, non-hub and other. To incorporate both weather and operational hours, incursion rates are based on the number of incursion that occurred during good visibility conditions per operational hour. Therefore, incursions during low visibility conditions (LIFR) are not considered. For example, for New York JFK, the standard normalisation resulted in a R_{rate} of 1.94. Considering the operational hourly airport movements during good visibility conditions resulted in a more precise R_{rate} of 1.87. The effect of visibility is further elaborated in 6.1.4.

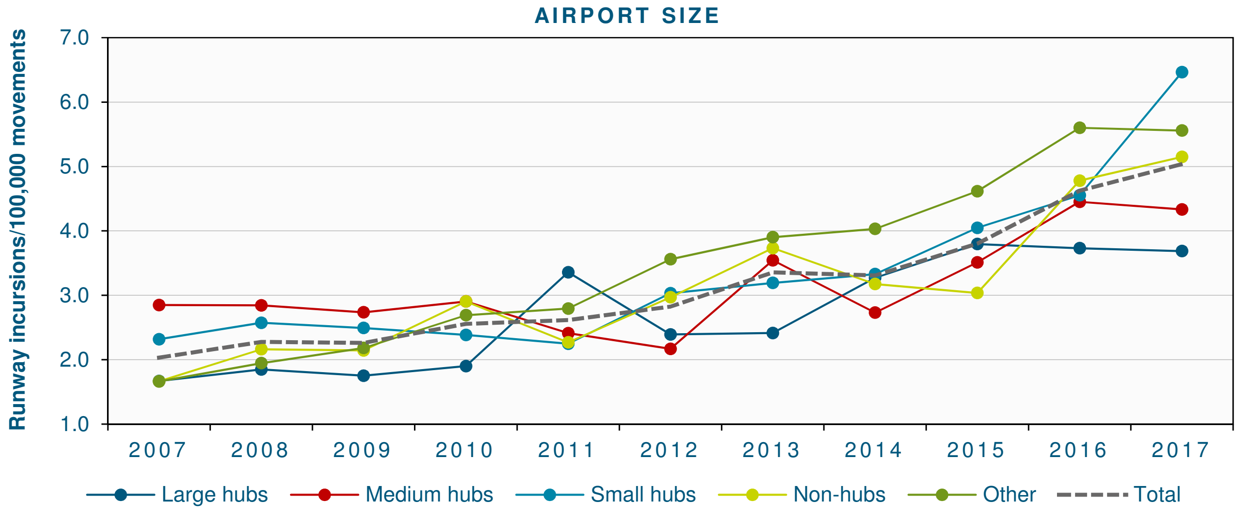


Figure 6-2: Annual incursion rates per airport size

The graph shows a general increase over the years, for the total incursion rate. Since 2007, the incursion rate has more than doubled. Looking at the individual airport rates, all airports show an increasing tendency, though rather large fluctuations are visible. Strikingly, large hubs show relative low incursion rates, except of 2011. In this year, the number of operational incidents was remarkably high compared to other years.

The large deviations between airport sizes can be caused by severe weather impact during certain years, and because of the implementation of the current classification system for runway incursions shortly before 2007. This could insist unfamiliarity at certain facilities for the application of the system. Also, the increasing incursion rates can be partly explained by the stricter and more accurate, and therefore more frequent reporting of incidents; a growing number of smaller airports got equipped with technologies (Archer et al., 2009; Dabipi et al., 2010; Xin-min et al., 2013), such as Airport Surface Detection Equipment (FAA, 2015a), that increase the ability to detect and warn for incursions. Also, large hub airports are more likely to have a technology platform that can be leveraged to implement NextGen and advanced technology based solutions, the commercial aircraft that utilize these large hubs are more likely to have the equipment required to utilize them (Mathew et al., 2017) and an increasing number of aircraft got equipped with transponders that are required to detect their position Furthermore, the establishment of Runway Safety Teams (RST) increase the aim to consider incursions (ICAO, 2007). This effect is smaller at the hubs, presumably because at these airports more often high standard equipment is available and dedicated RSTs are present.

To obtain more accurate incursion rates in the further analysis, the yearly figures were aggregated into the mean for the entire study period. By this, the deviations caused by certain variables, which are not covered in the research scope, can be avoided. One of the results from this is shown is in Figure 6-3, where all airports are labelled per type and placed for the number of incursions versus the hourly movement figure to understand the relationship between incursions and movements on airport level. Here, there is a flattening trend between both variables; as the number of hourly movements increase, the incursion frequency grows at a slower pace. Based on the input of the panel this can be explained by the assumption that higher movement numbers not by definition relate to higher incursion likelihood; a steady sequence of landing or departing aircraft can provide structured and natural traffic flow, instead of more sudden arrivals and departures (gaps in the traffic sequence) throughout the day.

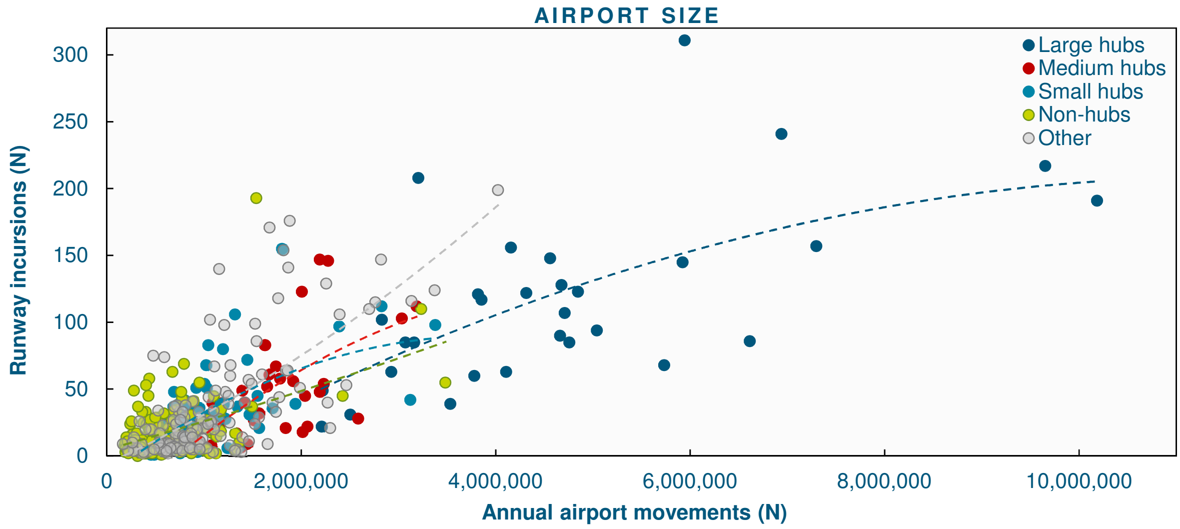


Figure 6-3: Number of incursions versus annual airport movements per airport size

The trend is visible across all airport sizes, except of non-hub airports. This deviation can be explained by the fact that non-hubs are represented by rather varying airport characteristics, such as large and low shares of commercial traffic. Furthermore, this airport category is less representative for the proposed model, since a large share consists of small general aviation airports. Therefore, this trendline is less reliable than the other hub types. Similarly, 'other' represents airports which are complicated to analysis on aggregated bases, because of the large variations in characteristics.

Next, the R_{rate} values are determined per airport and plotted against the number of hourly movements to understand the influence of normalisation across airport sizes. The results are presented in Figure 6-4.

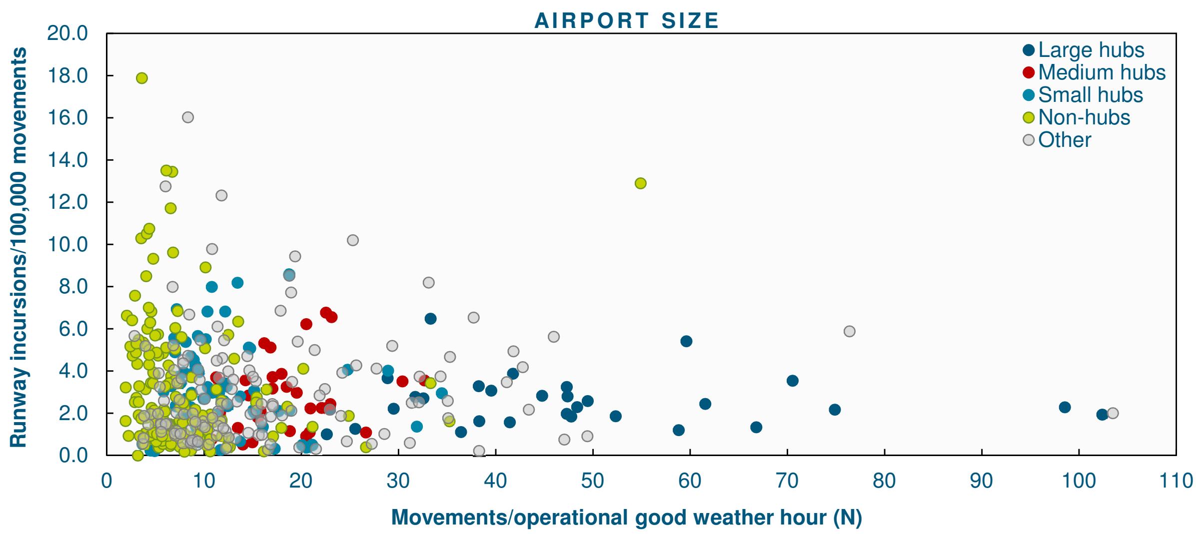


Figure 6-4: Incursion rates versus hourly airport movements per airport size

It is shown that there seems to be a relation between airport size and the incursion rate. The general trend explains that the larger the airport, the lower the incursion rate increases for a higher number of flights. The same explanation as given for the previous graph applies; larger traffic flows support expectation patterns and avoid straggling traffic situations. The only exception here is the category 'other' airports, which shows a spread across the entire scatter. Also, this can be explained by the large variation in the airport characteristics of which it consists.

The presented graphs are a first indication that *Hypothesis H6* is valid. Traffic intensity (airport size) appears to be no direct indicator for higher incursion rates, and is therefore not a relevant complexity indicator. From the literature phase, higher complexity is assumed to relate to higher incursion rates.

6.1.3 Severity and type

Until here, only total incursion rates are presented; severities and types are aggregated in the previous part. Intuitively, this does not clearly explain the situation at certain airports. When only high severity incidents are considered, the graphs could have an entirely different shape. Therefore, this section discusses the types and severities and its interactions. Table 6-2 shows the percentage composition of the incursion severities and types. As shown, the share of A and B is relatively low. Therefore, complications are expected during airport specific analysis, since many airports did not report any of these incidents during the study period.

Table 6-2: Runway incursions per severity and type

Severity (S_R)	**Share (%)**	**Type (E_R)**	**Share (%)**
A	0.67	OI	17.12
B	0.59	PD	57.88
C	42.19	V/PD	21.54
D	56.56		

Similar as for the annual representation of the total incursion rates, the graphs in Figure 6-5a and b, brake down the division per incursion type and severity classification. Because of the low figures for A and B incidents, it was decided to index the annual figures as a percentage of the total for each severity and type. In this way, the percental growth of the R_{rate} can be visually considered. The graphs incorporate differences in frequencies, and are therefore not based on the same sample. This is caused by incomplete data records, in which for certain incidents the incursion type was known, while the severity was unavailable and it was impossible to calculate using the RISC tool, due to a shortage of descriptives. Hence, because of this, both graphs should not be compared.

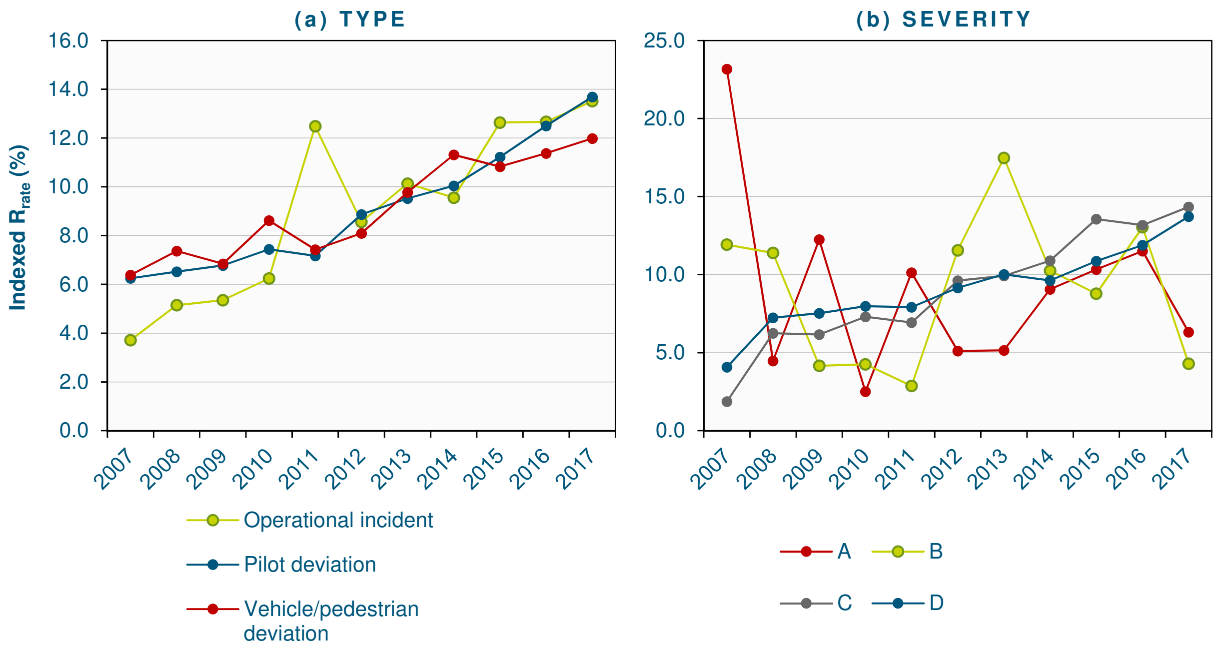


Figure 6-5: Incursion rates per type (a) and severity category (b), aggregated by total airports

From the first graph, it can be observed that for types of incursions the rates for operational incidents (OI), vehicle/pedestrian deviation (V/PD) and pilot deviation (PD) incidents all increase with a similar growth rate, across the total population of airports Strikingly, 2011 is characterised by a large increase in OI incidents, which corresponds to the increase of incursion rate at large hubs. From the graph can be concluded that incursion types are not clearly remarkable for further analysis with respect to the research aim. Therefore, incursion type is not considered in the next phase.

Considering severity, the deviations between the categories and the observation years is much larger, and more complicated to draw a trend from. As explained before, A and B incidents represent a minor share of the total incursion numbers and are therefore less reliable in terms of trend analysis than C and D incidents. Despite the low shares of A and B incidents, it can be seen that their incursion rates do not clearly grow during the measurement period, in contrast to C and D incidents, for which an equal growth rate is visible between 2007 and 2017. Therefore, the stricter reporting of incursions, as explained earlier, relates mainly to C and D incidents. The decrease in severe incidents is substantiated by Mathew et al. (2017). Severity appears to be an important aspect to consider for the model development. Therefore, the differences between the associations for airport characteristics per severity class will be examined in the next research phase.

Also, the interactions between incursion severity and type are examined, but do not contribute to the research objective. Therefore, these results are attached in Appendix A6.

Next, airport sizes are taken for a decomposition of the incursion characteristics, to consider the differences per airport group, based on the confirmation of Mathew et al. (2017) that incursion characteristics vary depending on the airport size. From this can be learned whether the individual analysis of interactions with airport characteristics is more important for certain airport sizes. In Figure 6-6 results are shown. Since the number of A and B incidents are too small for visual representation, the indexed incursion rates are given. Severity classes and incursion types cannot be compared to each other, but should be considered per category. For instance, it can be observed that the highest C incursion rates occurred at large hubs.

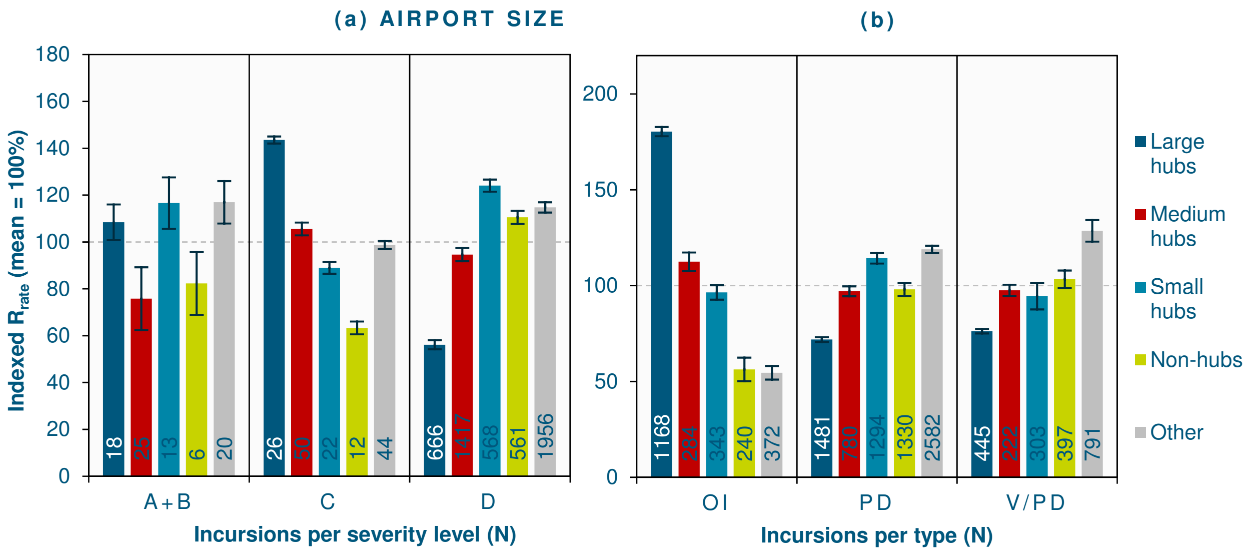


Figure 6-6: Incursion rate index for severity category (a) and type (b) per airport size, including ±1σ errors

Because of the marginal share of A and B incidents, it was decided to combine these categories for the graphical representation. This because disaggregation into airport size would result in not significant composition values and a separated graph presentation of the categories showed contradicting results. For instance, A incidents showed the highest rate for small hubs, while this airport category represented the second-lowest figure for B incidents. Hence, this contradiction is not plausible, but is the result of data shortage. The A+B category shows thus more reliable R_{rate} shares.

Consideration of the graph reveals that for A+B incidents, the trend across airport sizes is hard to conclude because of the deviations across the categories. Meanwhile, for C and D incidents, there is a clear trend visible. For C incidents, it is shown that the smaller the airport size, the lower the R_{rate}. For D incidents, the contrary trend is observed. Hence, we should be careful when drawing conclusions from this representation, since airport size is based on national passenger shares. Though, a correlation between airport size and share of passengers may be expected in further analysis. An explanation for this trend of C and D incidents, based on panel consultation, is that larger airports are generally characterised by more complex layouts, meaning a larger likelihood that mistakes are made that result in a runway incursion. At smaller airports, the layout is often much more simplistic and the traffic intensities are lower and therefore higher separations and less severe incidents because the Closest Horizontal Proximity (CHP) is still relatively large. Or, there may be even no other aircraft in the arrival sequence at that moment. Therefore, less incidents for the more severe C classification are to be expected. Consequently, these incidents are assigned as D incidents. This indicates a contradiction with *Hypothesis H6*; while higher traffic movements do not by definition relate to higher incursion frequencies, it appears to do correlate with higher severity.

Looking at the type compositions, the largest deviation is visible for operational incidents at large hubs. Clearly, there is a relation between the number of flights and the number of operational incidents, other than for PD and V/PD. As known form the expert panel and literature, the ATC workload is mainly determined by the number of flights that have to be handled, especially during peak hours, while this does not necessarily imply higher workloads for the pilot and a vehicle driver. For PD incidents, the trend is contrary to that of OI incidents; at smaller airports, higher incursion rates were observed. This is contradicting the expectations from the panel, since it is assumed that also for pilots, larger airports require higher workloads because of the higher frequency of radio communications between aircraft, which can be a disturbing factor. At smaller airports, it is expected that pilots are less disturbed by communication with other aircraft. Meanwhile, the higher rate composition could be a consequence of higher shares of general aviation traffic at smaller airports. Though, this relationship cannot be directly drawn from this representation. Finally, V/PD incidents do not show remarkable outcomes. *Hypothesis H6* is clearly substantiated by the results from the graph; a clear link between airport size (movement numbers) and OI incidents exist.

6.1.4 Visibility

From literature and the consultation of the expert panel it is known that weather has a significant impact on the operations at an airport, and consequently also on the likelihood of certain incidents, such as runway incursions. In the respect of runway incursions, visibility is considered to be the most important aspect. To observe the effects of visibility on the occurrence of incursions, incidents are analysed on the weather circumstances during the event, as described in the previous chapter. Analysis of the weathers circumstances during the incursions showed that 81.2% of all incidents occurred during VFR conditions, 13.7% occurred during MVFR, 2.9% during IFR and only 2.2% during LIFR. Further results and discussion on the impact of weather can be found in Appendix A6. This analysis concludes that the character and occurrence of incursions differs depending on the visibility. This justifies the choice to only analyse good weather incidents, and thus not the aggregation of good and unfavourable weather conditions.

To summarise this section, when considering incursion rates the size of airport should be considered, because of the different relationships. This accounts for the total rates, per type and especially between C and D incidents. Also, low visibility incidents should be analysed separately. Therefore, for the model estimation, a selection of airports is created and association tests are conducted for the different incursion variants in the next phase.

6.2 Airport characteristics

This part covers the analysis of the chosen airport characteristics. It consists of the collinearity analysis of the characteristics and the high-level analysis of the associations with the incursion rates.

6.2.1 Multicollinearity between characteristics

In this paragraph, the interactions between airport characteristics are analysed, in order to avoid the application of multicollinear variables in the model, which is estimated in the next phase. This part is divided into sections in which correlations between groups of associated airport characteristics are tested.

6.2.1.1 Parallel runways

First, the correlation between airports that have parallel runways and airports shaped by intersecting runways is examined. Figure 6-7a represents a scatterplot of the ratio intersecting runways versus the ratio parallel runways. Here the dot size, explains the number of airports that have a certain value, with larger dots representing higher frequencies. Because many airports share an equal ratio, a conventional scatterplot would not visualize the distribution of the data points. The characteristics show a significant correlation (sig.: .000) of $R^2 = 0.451$, adjusted $R^2 = 0.447$ and $r_s = -0.672$.

From this, it can be concluded that the individual application of the intersecting runway ratio to the model will be a justified complexity indicator. The simultaneous application of the parallel runway ratio would emerge collinearity between the model attributes. The ratio parallel runways is not used for regression modelling because it the definition of this variable is less accurate. Whether runways are parallel depend on the maximum spacing which was not defined.

6.2.1.2 Complex intersections

Next, the variable complex intersections is defined to be important, but is also difficult to measure due to the low numbers per airport. Therefore, potential correlation with other more reliable variables is tested. For this, the characteristics given in Table 6-3, are found. As also visible in Figure 6-7b, the presence of complex intersections shows a correlation with other airport characteristics. Intuitively, complex intersections are mainly present at airports with large numbers of TWY-RWY intersections. Since the variable runway crossings is potentially also related to the number of TWY-RWY intersections, this characteristic was analysed too. In addition, for the correlation of complex intersections, the number of non-right TWY-RWY intersections is tested, since this also contributes to the total number of TWY-RWY intersections.

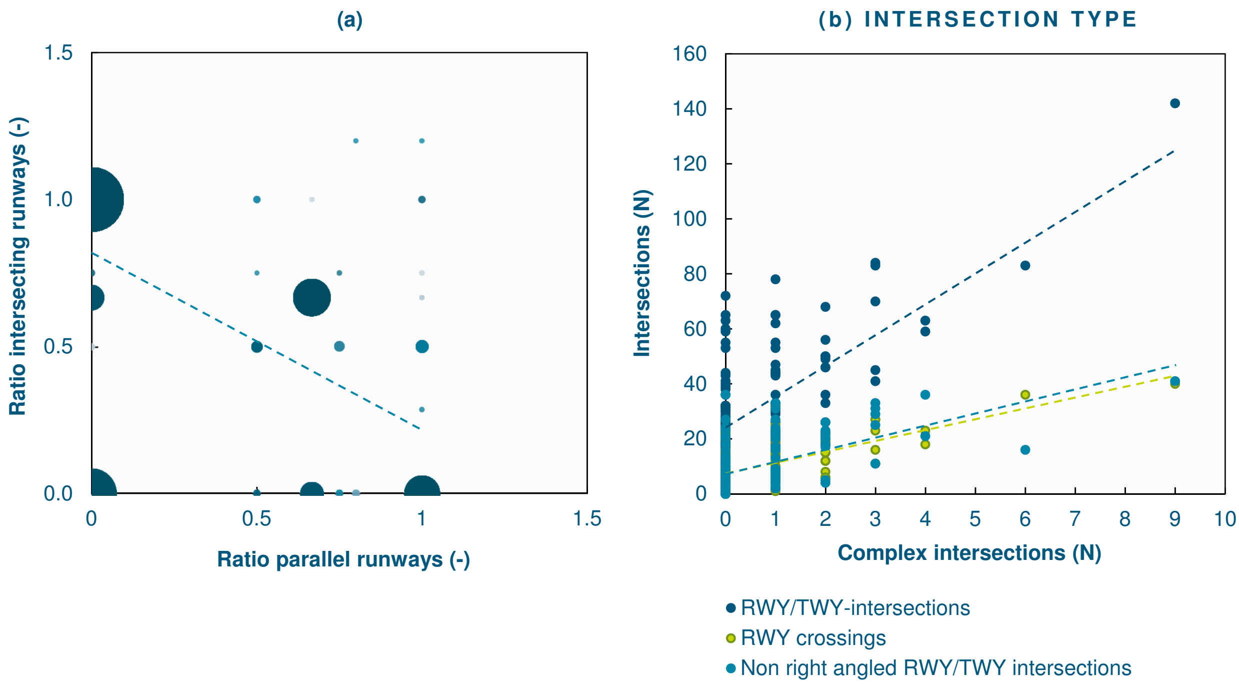


Figure 6-7: Scatterplot ratio intersecting versus ratio parallel runways (a) and number of intersections per type versus number of complex intersections (b)

In the table, rather high correlation values are obtained for complex intersections versus crossings and intersections. Hence, this also indicates a possible correlation between crossings and intersections. The characteristics complex versus total number of intersections show a significant correlation (sig.: .000) of $R^2 = 0.309$, Adjusted $R^2 = 0.307$ and $r_s = 0.556$. From this, the indicator presence of complex intersections is not further analysed; it is explained by both the number of crossings and the number of intersections.

Table 6-3: Correlation matrix associations with complex interactions

	Spearman's rho correlation r_s			
Characteristics	Complex intersections	Runway crossings	Total TWY-RWY intersections	Non-right intersections
Complex intersections	1.00			
Runway crossings	0.60*	1.00		
Total TWY-RWY intersections	0.67*	0.91*	1.00	
Non-right intersections	0.58*	0.74*	0.83*	1.00

*Significant associations at 95% confidence interval

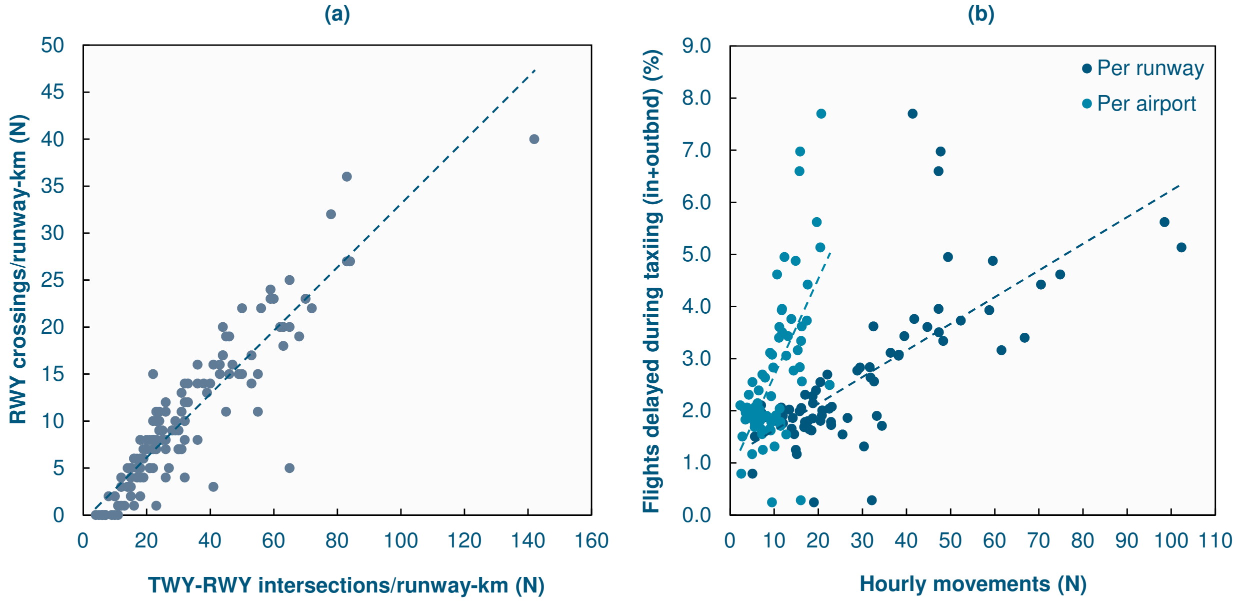


Figure 6-8: Scatterplot number of runway crossings versus number of TWY-RWY intersections per runway-km (a) and percentage delayed flights during taxiing versus hourly number of movements (b)

6.2.1.3 Runway crossings

Then, the relation between TWY-RWY intersections and runway crossings is considered, since in line with the expectations a high correlation was found in Table 6-3. As visually substantiated in Figure 6-8a, there exists a strong correlation between these characteristics. The variables show a significant correlation (sig.: .000) of $R^2 =$ 0.830, Adjusted $R^2 =$ 0.828 and $r_s =$ 0.910. Since TWY-RWY intersections can be part of a runway crossing, but not the opposite, the number of intersections is a more precise indicator for geometry complexity. Moreover, the database also contains airports which have no runway crossings, while there are intersections present. Therefore, the number of runway crossings is not used for model estimation.

6.2.1.4 Taxi delay

Lastly, taxi delay is analysed on multicollinearity with other characteristics, based on input from the panel. As can be seen in the correlation matrix in Table 6-4, there appears to be a strong correlation between hourly airport movements, runway movements and taxi delay. Furthermore, taxi delay seems to be related to the number of TWY-RWY intersections, however this is already determined to be a justified indicator in the model previously.

Table 6-4: Correlation matrix for associations with taxi delay

	Spearman's rho correlation r_s						
Characteristics	Taxi delay	Hourly airport movements	Hourly runway movements	RWY crossings	TWY-RWY intersections	Required crossings	Complex intersections
Taxi delay	1.00						
Hourly airport movements	<u>0.73</u>*	1.00					
Hourly runway movements	<u>0.64</u>*	0.74*	1.00				
RWY crossings	0.46*	0.60*	0.35*	1.00			
TWY-RWY intersections	0.63*	0.78*	0.38*	0.88*	1.00		
Required crossings	0.02	0.08*	-0.04	0.37*	0.26*	1.00	
Complex intersections	0.39	0.42*	0.21*	0.61*	0.65*	0.30*	1.00

*Significant associations at 95% confidence interval

The aim is to apply at least one utilisation-related attribute into the model, to explain the movement figures at an airport. For this, hourly movements is kept as indicator since this appears to provide a more accurate explanation of incursion rate than hourly runway movements. The characteristics indicate a significant correlation (sig.: .000) of $R^2 = 0.536$, Adjusted $R^2 = 0.530$ and $r_s = 0.730$. The related scatterplot is visible in Figure 6-8b.

Note that discrepancies in between r_s values the correlation matrices are given, because of varying sample sizes used for the tests. This was required, because of the aim to develop correlation matrices in which all characteristics are based on equal sample sizes. For taxi delay, for example, data was only available for a select number of airports.

6.2.1.5 Concluding

The analysis for multicollinearity learned which airport characteristics are not appropriate to apply in the model simultaneously. This would result in high correlations between attributes and therefore not-significant variables. To summarise, the airport characteristics in Table 6-5 are selected for high-level analysis in the next part. Also, the excluded characteristics are analysed, these results can be found in Appendix A6.

Table 6-5: Remaining airport characteristics from the high-level analysis

Remaining characteristics	Excluded characteristics because of correlation
Share heavy aircraft	
Share general aviation traffic	
Hourly airport movements	*Taxi delay*
	Runway movements
Required runway crossings	
Ratio intersecting runways	*Ratio parallel runways*
Number of TWY-RWY intersections	*Number of runway crossings*
Ratio non-right angled TWY-RWY intersections	
Ratio Rapid Exit Taxiways	
Hectare per runway-km	
Presence Runway Status Lights	

6.2.2 Incursion analysis on characteristics

In this paragraph, after the incidents are analysed and mutual independent airport characteristics are selected, the interactions between the incursion rates and airport attributes are analysed. The characteristics are stepwise discussed.

6.2.2.1 Share heavy aircraft

First, the relation between incursion rates and the aircraft size is analysed. Hence, this analysis is conducted independently of the airport size, although a clear relation may be assumed between the size of an airport and the size of aircraft. In other words, for example, code E and F aircraft are mainly seen at the large hubs.

From the analysis of the incursions in the database, 465 aircraft types were identified. According to the ICAO standards, these aircraft were assigned to one of the airplane design groups. Figure 6-9a depicts the normalised total incursion rates per airplane design group (heavy indicated in dark blue). Here, it becomes clear that, in line with *Hypothesis H7* from the expert panel, large (heavy) aircraft show the largest R_{rate} values. Thus, the data justifies the expectation that larger aircraft are relatively more involved in runway incursions. This can be explained by the fact that pilots of small aircraft are generally frequent visitors of an airport since they fly mainly short-haul. They are often much more familiar with the local procedures and communication habits at that airport. Flight crew of wide-body aircraft fly predominantly long routes, and visit airport much less often. Furthermore, at the time of their arrival they are often becoming tired and less alert compared to short-haul pilots, as is evidenced by the panel.

Furthermore, cat. A shows a higher rate, which could be represented by the general traffic. However, by the panel it was not expected that GA traffic has a big impact on the incursion rate (*Hypothesis H8*). Though, research have demonstrated that the presence of GA traffic could have an impact (Mathew et al., 2017). Below, the presence of GA traffic is analysed specifically.

6.2.2.2 Share general aviation traffic

General aviation appears to have an influence on runway incursions. In order to better understand the effect of GA traffic, the share of this category of traffic is considered next. Since two types of air traffic were distinguished in this research (commercial and general aviation) and military was already excluded by definition of the scope, these two traffic mixes are considered below.

Figure 6-9b shows the effects of the share of GA traffic on the incursion rates. It can be observed that the incursion rates have the highest values among airport with more than 20% share of GA traffic. Between the range of 20-80% no clear differences are visible, taking the standard errors into account. To conclude, this representation of the data underlines the assumption that GA traffic has an impact on the occurrence of runway incursions. Therefore, to reduce the effect of GA traffic at the model estimation, it is decided to create a sample of airports where the share of GA traffic is at maximum 20%.

6.2.2.3 Hourly airport movements

From the analysis of hourly runway movements, which is discussed in Appendix A6, it can be assumed that runway usage is not by definition a good indicator for incursion rate. This is substantiated by the collinearity analysis. Instead, hourly airport movements gives a more reliable view of the effects. For the further analysis, hourly movements is used as categorisation for airports, instead of size, since this definition is based on passenger statistics.

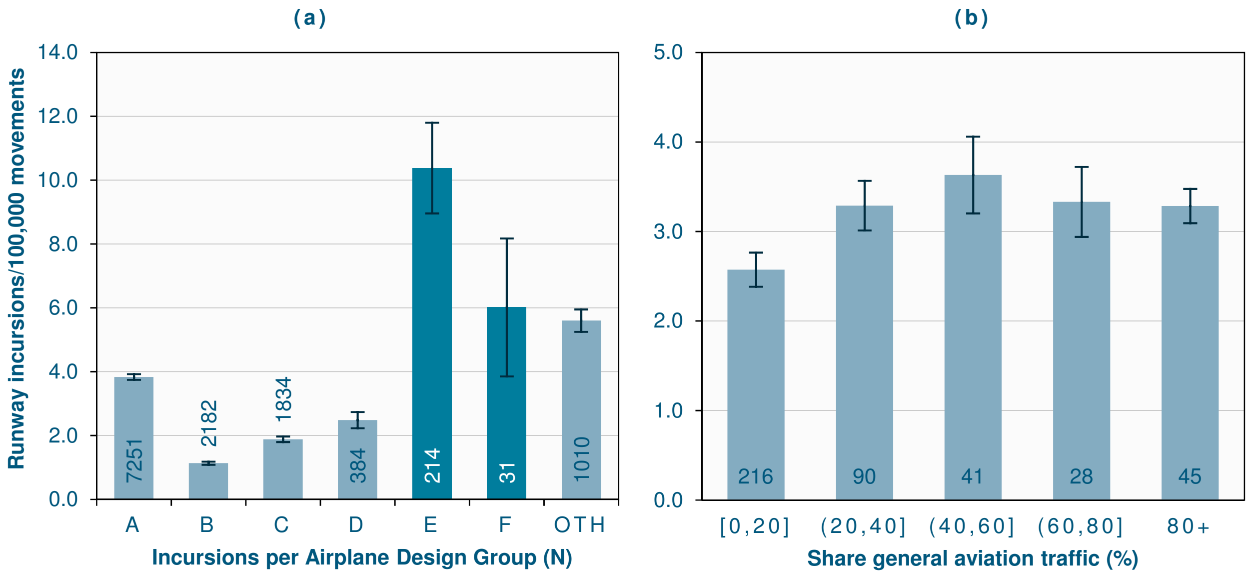


Figure 6-9: Incursion rate composition per Airplane Design Group (a) and share GA traffic (b), including 1σ errors

6.2.2.4 Required runway crossings

Then, the number of required runway crossings C_{req} is assessed. Four categories were defined: no crossings required and respectively 1, 2 and 3 crossings required. The number of airports per C_{req} are given in the charts (Figure 6-10a). Since only 8 airports require 3 runway crossings, this group as aggregated with 2, into 2+. The results underpin *Hypothesis H1* that the number of required crossings influence the incursion rate.

6.2.2.5 Ratio intersecting runways

At multiple airports, required crossings are the consequence of runways that intersect each other. In order to examine whether intersecting runways show an effect on the incursion rate, the ratio intersecting runways I_r is also tested as indicator. In Figure 6-10b, the corresponding graph is depicted. As this ratio increases, the total incursion rate increases too. This trend cannot be directly drawn from the airport movement categories; only <10 underpins this trend. Small shares of data could be the underlying cause. Referring to *Hypothesis H2*, it can be assumed that intersecting runways relate to higher incursion rates compared to non-intersecting runways, in line with the findings of Johnson et al. (2016) that airports with intersecting runways have a higher incursion likelihood. Also Biernbaum and Hagemann (2012) found similar results. However, as was detected, the operational procedures are related to the presence of crossing runways; if crossing runways are used simultaneously, the incursion likelihood would be higher than if these are not. Rogerson and Lambert (2012) mentioned the importance of assessing operational procedures. Nonetheless, this aspect is not covered in the analysis, because data of this level of detail was not available for all airports.

6.2.2.6 Number of TWY-RWY intersections

Then, the density of TWY-RWY intersections I_n is tested to be a justified and relevant performance indicator. For this, the number of intersections per runway-km are determined and aggregated into three categories, which are shown in Figure 6-11a.

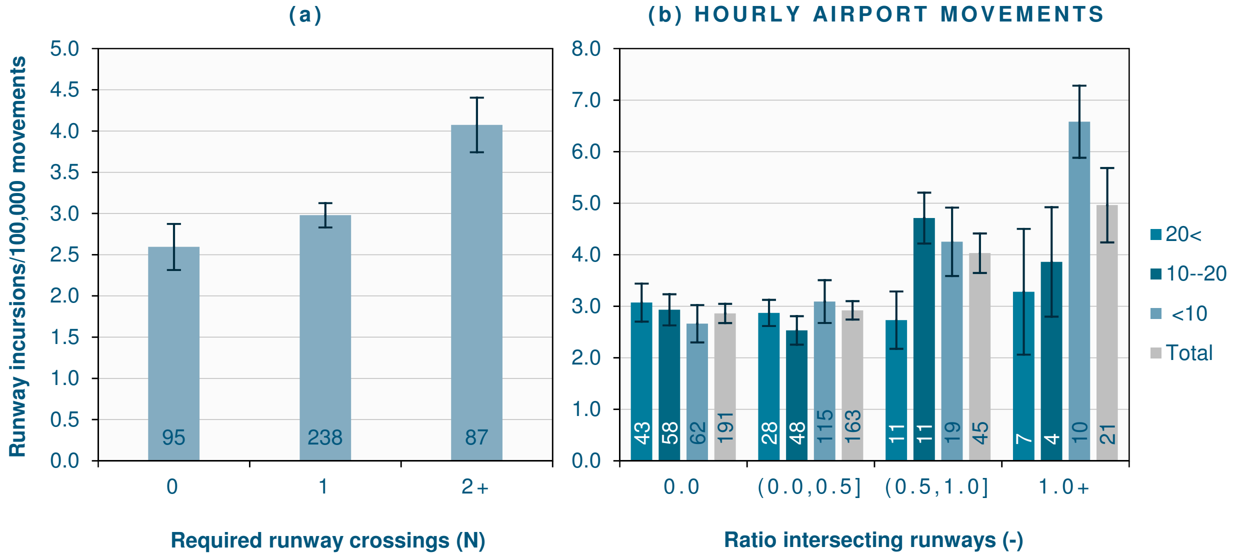


Figure 6-10: Incursion rate for number of required runway crossings (a) and ratio intersecting runways per hourly airport movements category (b), including 1σ errors

In line with *Hypothesis H4*, the general tendency shows an increasing incursion rate for an increasing number of intersections per runway-km. Wilke et al. (2015a); (2015b) found similar results. It is visible that airports with large hourly traffic volumes have lower incursion rates for the first and second category. This could be caused by the factors such as a larger number of runways. The rapid R_{rate} increase from 6+ intersections can be explained by the assumption that a higher density of intersections does not necessarily insist a higher likelihood on human error. For arrival aircraft, the presence of a higher number of intersections can be advantageous, since more options are available to exit the runway, such was mentioned by the panel. This reduces the risk of loss of separation between to the subsequent aircraft in the landing sequence. Therefore, it can be concluded that the incursion likelihood is related to the way the airport it is operated. Moreover, the angle of intersection can play a role, as this improves the runway clearance throughput even further. Nonetheless, higher shares of non-right-angled intersections could, once again have a negative effect for departing aircraft, because of visual hindrance (FAA, 2014). Therefore, the ratio non-right intersections is tested next.

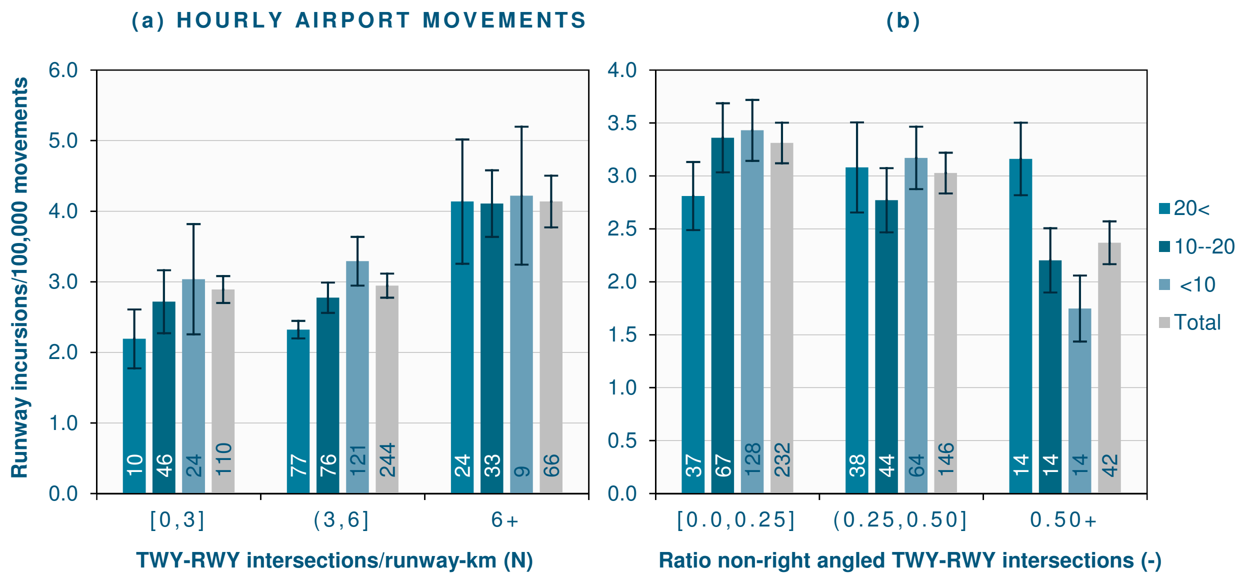


Figure 6-11: Incursion rate for number of TWY-RWY intersections per runway-km (a) and ratio non-right angled TWY-RWY intersections per hourly airport movements category (b), including 1σ errors

As the collinearity analysis revealed, there is a strong correlation in the dataset between the number of runway intersections and the number of runway crossings. Of course, this also applies for the normalised data where the number of both elements is expressed per kilometre of runway. Because of this correlation, similar incursion rates are obtained for the number of crossings. Across all movement categories, there is an increase in R_{rate} visible as the number of crossings per runway-km increases. For instance, airports without runway crossings have a total incursion rate of 3.0, while airports with more than 2 crossings represent a R_{rate} of 3.9. I was also found that this increase is stronger for airports with higher movement intensities.

6.2.2.7 Ratio non-right angled TWY-RWY intersections

Different types of TWY-RWY intersections exist, potentially relating to differing incursion likelihoods. Each of the types known from the literature study is analysed. First, the non-right-angled TWY-RWY intersection is considered. The results are shown in Figure 6-11b. A remarkable difference to the total number of intersections per runway-km is visible; as the ratio non-right-angled intersections increase, the incursion rate decreases. This underlines the assumption that non-right-angled intersections have an advantageous effect for arriving aircraft *Hypothesis H5*. It should be noted that RETs are included here, which are aimed to reduce the likelihood of incursions by shortening the runway occupancy time (FAA, 2014). Repetition of this analysis with RETs excluded also indicated a positive effect of non-right-angled intersections. For the ratio of non-right-angled taxiways of [0.0,0.25], the mean $R_{rate} =$ 3.6. For airports with a share of 0.25+ applied $R_{rate} =$ 2.6. Therefore, this additional check also justifies *H5*.

6.2.2.8 Ratio Rapid Exit Taxiways

In the same way, the ratio RETs is evaluated, using the ratio RETs of the total number or TWY-RWY intersections. By means of this representation, the effect of a larger ratio of RETs can be considered, for airports that are equipped with these elements. Figure 6-12a shows the results. Since low numbers of airports were found for airport movement categories, it was decided to aggregate to incursion rates into total airports. Also, here the advantage of RETs on the mitigation of runway incursions is shown with a decreasing R_{rate} as proportion to an increasing ratio.

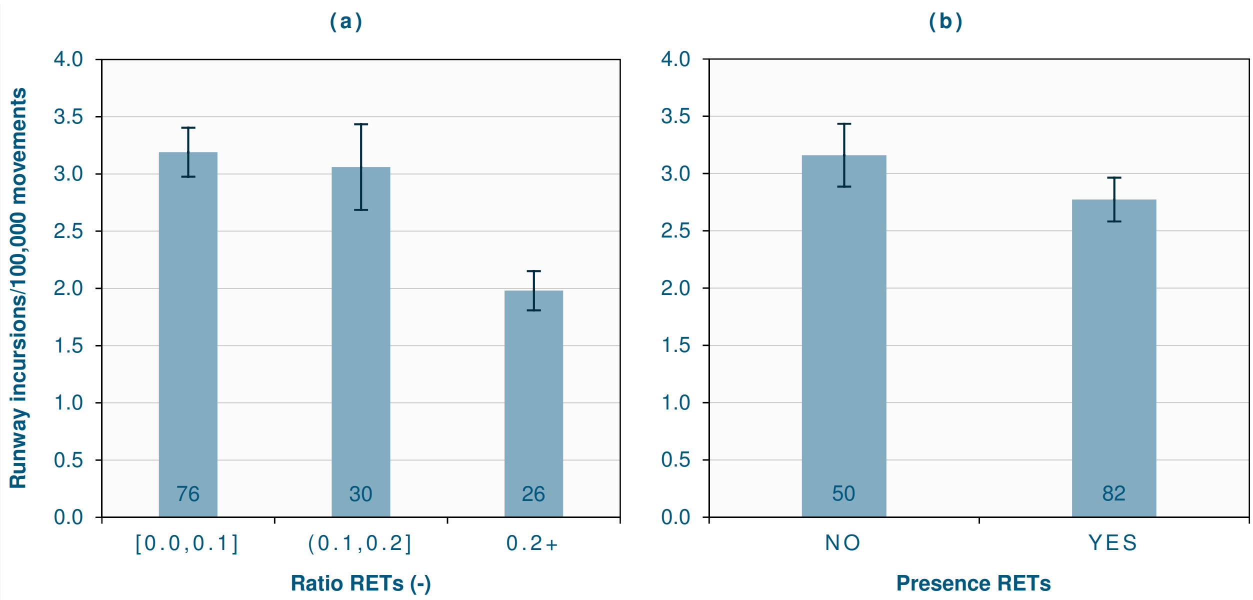


Figure 6-12: Incursion rate for ratio RETs (a) and for presence of RETs (b), including 1σ errors

6.2.2.9 Presence Rapid Exit Taxiways

Intuitively, the effect of RETs can also be examined by considering the presence of these elements. Hence, presence does not explain the number of RETs and could therefore arguably be not a useful measure. Nonetheless, the presence of RETs generally explains that an airport is equipped with multiple elements of this type. In other words, airports equipped with only one RET represent hardly exist. From graph (Figure 6-12b) can be concluded that airports equipped with RETs tend to have a lower incursion rate, which is in line with the earlier stated assumptions.

6.2.2.10 Hectare per runway-km

Another discussed characteristic during the panel meeting was the effect of a small airport surface in combination with high traffic intensities. For instance, at Schiphol, the small airport surface area was defined to be one of the factors that

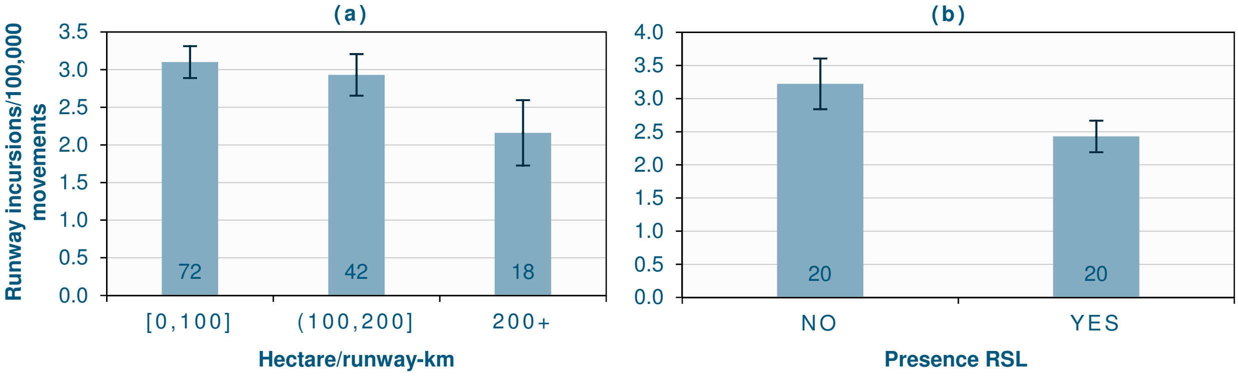


Figure 6-13: Incursion rate for hectare per runway-km (a) and presence of RSL (b), including 1σ errors

contribute to the high complexity Dutch Safety Board (2017b). To examine this interaction, the airports are analysed on total surface area. Since the number of intersections are expressed in relation to runway length, it is chosen to also express the airport surface in relation to the runway length (runway-km). Three suitable categories were defined, which can be found in Figure 6-13a. The measure is only applied for hub airports, because of the assumption that non-hubs and other are often large low-density fields in terms of infrastructure. From the graph, it can be seen that an increasing surface area per runway-km relates to a decreasing incursion rate. This validates the assumption from the panel meeting. Therefore, the aspect is considered to be a relevant aspect for further analysis in the next phase.

6.2.2.11 Presence Runway Status Lights

Lastly, the presence of Runway Status Lights (RSL) is analysed in respect to the incursion rates. For this, the airports were ranked according to their hourly airport movement figure. All airports equipped with RSL were selected, as well as the remaining top 20 airports based on the highest number of movements, since only large hubs in the dataset are equipped with RSL. This resulted in the selection of 40 airports. The results are given in Figure 6-13b. It is shown that airports with RSL relate to an on average lower incursion rate (Eggert et al., 2016). Though, the effectiveness of RSL could also be analysed by considering the incursion rates at airports equipped with RSL, before and after the implementation of the measure. However, due to data shortage issues (multiple airports implemented RSL in the most recent years of the study period, which means the absence of incursion data for the post-implementation period), it was decided not to conduct this test.

To summarise this section, airport characteristics and geometry in particular appeared to have an influence on the incursion frequency. Therefore, the research objective maintains justified, since the potential for modelling has been indicated. The analysis gives a first argument to reject the conclusion of Galle et al. (2010) and Wilke et al. (2015a); (2015b) that geometry is not a sufficient indicator for incursion frequency. The assumption of Wilke et al. that the severity of incidents is associated with these factors, has still to be analysed. By this, the aim to further analyse the interactions in the next phase is substantiated.

6.2.3 Concluding

Based on the high-level analysis and the results from the collinearity check, the remaining airport characteristics taken for the model estimation are presented in Table 6-6. The symbols frequently used as reference in the next parts are also mentioned. Lastly, the effect of an increase per characteristic on the R_{rate} is shown, based on the analysis output. It is assumed that hourly airports movements can describe the utilisation of the obtained geometry characteristics.

Table 6-6: Remaining airport characteristics from the high-level analysis

Selected airport characteristics	Type	Symbol	Effect on R_{rate}
Hourly airport movements	Operational	T_h	▲/▼
Share commercial traffic	Operational		▼
Share heavy aircraft	Operational		▼
Ratio intersecting runways	Geometry	I_r	▲
TWY-RWY intersections/RWY-km	Geometry	I_n	▲/▼
Ratio non-right angled	Geometry		▼
Ratio RETs	Geometry		▼
Required crossings	Geometry	C_{req}	▲
Presence RSL	Other		▼
Hectare per runway-km	Geometry		▼

7 Model development

This chapter describes the process of the model estimation. First, the used method is explained, then the remaining airport characteristics are prepared and tested on their associations with the different types of incursion rates. Subsequently, the model development is discussed.

7.1 Multiple linear regression model

The relationship between the collected airport characteristics and incursion rates is modelled by means of multiple linear regression, which is an extension of simple regression, known in the form $\widehat{Y}_i = b_0 + B_1 X_i + \varepsilon_i$. Because in the proposed model, multiple characteristics will be added, the effect of multiple independent variables on the predictor variables need to be estimated. The general multiple linear regression equation applies (7-1).

$$\widehat{Y}_i = b_0 + B_1 X_{1i} + B_2 X_{2i} + \dots + B_k X_{ki} + \varepsilon_i \tag{7-1}$$

Here, $\widehat{Y}_i$ represents the predicted variable of ith observation with $i = 1, 2, \dots, n$, b_0 is the estimated Y_i intercept, B_k describes the slope coefficients for independent variable k. Furthermore, X_i is the predictor variable and ε_i represents the error term. The effect of binary data in the determination model can be added by the introduction of dummy variables d_{ki}. Hence, variables could also have a non-linear relationship with the incursion rate. For this, in order to improve the model fit, polynomial linear regression could be used. This is modelled as (7-2):

$$\widehat{Y}_i = b_0 + B_1 X_{1i} + B_2 X_{2i}^2 + \dots + B_k X_{ki}^k + \varepsilon_i \tag{7-2}$$

7.1.1 Goodness of fit

To measure good the model performs in relation to the set of observations, the goodness of fit is determined, in which the squares of the sum of residuals is aimed to be minimal. For this, the considered model is tested with the likelihood ratio index, where it is measured how the model fits compared to the baseline model, where all predictor variables are equal to zero ($\widehat{Y}_i = \beta_0 + u_i \longrightarrow \widehat{Y}_i = \bar{Y}$). The ratio is determined by (7-3):

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{7-3}$$

Here, SS_{res} describes the residual sum of squares and SS_{tot} the total sum of squares. Also, an improved version of the likelihood ratio index exists, which incorporates the degrees of freedom. It is known as the adjusted R-squared, where k is number of estimation parameters (7-4):

$$Adjusted\ R^2 = 1 - \frac{SS_{res} - k}{SS_{tot}} \tag{7-4}$$

For the research, both measures of R^2 are used to indicate the model fit. The aim is to have a result as close as possible to 1.0. However, because of the large expected variation due to characteristics which are not covered by the scope, it is expected to have a much lower value for this.

7.1.2 Airport sample

From the high-level analysis, it was concluded to create a smaller airport sample were airports with more comparable operational characteristics were added, such as the minimal share of commercial traffic. Also, it became clear that the high severity incidents are scarce in the database, and should therefore be aggregated. This part discusses the final selection of airports and incidents for the model development.

7.1.2.1 High severity aggregation

The incident database consists of small shares of the highest severity categories, with 0.67% A incidents, 0.59% B incidents and 42.19% C incidents. The remaining share 56.56% is represented by D incidents. A and B incidents occurred at a total of airports of respectively 58 (of which 29 at hubs) and 59 (of which 26 at hubs). Therefore, it is not possible to execute a separate analysis on the relation between airport characteristics and either A of B incidents; many airports have not recorded any of these incidents during the study period. For this analysis, it was decided to combine

A, B and C into ‘high severity’, and to analyse this separate from the D incursions, because of its naturally different characteristic.

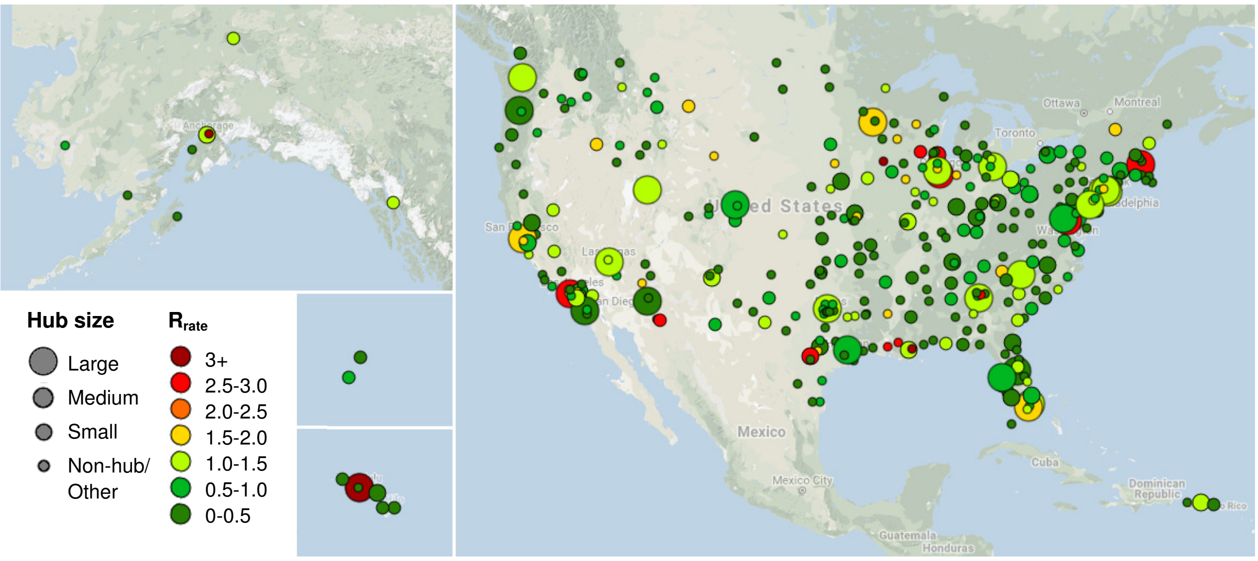


Figure 7-1: High severity incursion rates for all airports

The aggregation of the high severity incursions was translated into a visualisation of the airport’s incursion rates, as depicted in Figure 7-1. Here, the size of the dot represents the size of the airport, and the colour indicates the high severity incursion rate. It can be observed that the majority of the airports performed in the green range.

7.1.2.2 Interaction between incursion severity categories

Although the percentage composition of A and B incidents is low and not applicable for analysis on airport attributes, it can be analysed on the correlation with C incidents. Intuitively, it may be expected that C incidents are strongly related to A and B incidents, as the most important component that explains the differences is the Closest Horizontal Proximity (CHP). This is explained in more detail in Appendix A1. Thence, it is expected that in many cases the difference between an A, B or C incident was explained by the separation during incident, and that this is not directly a result of the geometry. Thus, at airports with large shares of C incidents, a higher likelihood for B and A incidents is expected. Likewise, A incidents are expected to occur more often at airports with higher numbers of B incidents.

To test the interactions, the correlations between the incursion severities were determined, of which the results are shown in Table 7-1. For all pairs, a positive S_R exists. C and D are strongly correlated, thus airports with large shares of D incidents, generally also observe large shares of C incidents. Considering the high severity pairs, A and B show a rather low correlation, which also applies for the relation of A-C, and B-C incidents. In the table, three correlation matrices are combined; in the first one, all airports are included regardless of whether an A or B incident was recorded, the second matrix is only based on airports where A incursions occurred and in the third matrix only airports where B incidents occurred are presented. The correlation between A and B, determined in this way, is 0.39 ($N = 17$) and not siginifcant. To conclude, relation between A, B and C incidents may be assumed, although it is not strongly justified by the data.

Table 7-1: Correlations between incursion severity classifications

	Spearman’s rho correlation r_s									
	N = 420				N = 58			N = 59		
Severity (S_R)	A	B	C	D	A	C	D	B	C	D
A	1.00				1.00					
B	0.19*	1.00						1.00		
C	0.32*	0.37*	1.00		0.59*	1.00		0.35*	1.00	
D	0.32*	0.34*	0.81*	1.00	0.54*	0.76*	1.00	0.30*	0.80*	1.00

*Significant associations at 95% confidence interval

To apply an additional check on the presence of interaction between these severity pairs, while coping with these low frequencies, it was decided to conduct a binary logistic regression. In this way, the independent variable is the number of C incidents and the dependent variable the presence of an A or B incursion (1 = yes, 0 = no). From this, the output indicates whether higher numbers of C incidents lead to a higher probability of an A or B incident being observed. Hence, this does not indicate how many of these incursions will occur for certain numbers of C, because this cannot be determined as result of the low correlations, partly due to low frequencies per airport.

For the probability that A occur, given C occurred applies: $P(A) = 1/(1 + e^{2.339-0.031C})$, $R^2 =$ 0.073 (Cox & Snell), $R^2 =$ 0.132 (Nagelkerke), Hosmer and Lemeshow: .125 ($X^2 =$ 11.334). Likewise, for B accounts: $P(B) = 1/(1 + e^{2.425-0.036C})$, $R^2 =$ 0.097 (Cox & Snell), $R^2 =$ 0.174 (Nagelkerke), Hosmer and Lemeshow: .001 ($X^2 =$ 24.890). Only the regression model for $P(A)$ appeared to be significant from the Hosmer and Lemeshow test. This is once again the consequence of the small share of A and B observations. However, it is shown that higher numbers of C incidents result in a higher probability on A and B incidents. For example, in case 10 C incidents are observed, $P(A) =$ 0.12, and when 100 C incidents are recorded, $P(A) =$ 0.68.

Mathew et al. (2016) used mixed logit models using 200 Halton draws for a 90% confidence intervals to analyse the differences in correlations between severities, in order to deal with the shortage of A and B incidents (measurement period: 2002 until 2015). Although it found that the proposed models cannot provide statistical confirmation of all types of runway for all severity levels, the relationship between A, B and C incidents was indicated per airport size. However, only one aspect was found to be significant for A incidents: the reduction of occurrences since 2002. It should be noted that the researchers obtained an even higher share of A and B incidents from their measurement period, 4% compared to approximately 1.2% in this study, which is the result of the decreasing rate.

7.1.3 Data selection

Based on the assumption from the high-level analysis about the influence of general aviation traffic on the occurrence of runway incursions, a selection of airports was used for the further modelling. Here, the large, medium and small hubs are selected, since they all represent a dominant share of commercial traffic. In this sample, the airport with lowest number of commercial movements was found (33,902). This value was then used as threshold for the selection of additional airports from the remaining population of other and non-hubs. Airports representing a number of commercial flights of at least this threshold value within the same time window, were added to the sample. This resulted in the selection of 268 from the total population of 420 airports. An overview of these airports can be found in Appendix A5.

It was decided to not consider the percentage of commercial traffic, since airports were found with high shares of commercial traffic, though representing rather low traffic numbers. These airports are logically, not representative. Another aspect to note is that purely considering the airport size designation does not give a clear indication on the airport traffic, since the definition is based on the percentage of national passenger boardings. This means, that freight hubs, with large numbers of commercial freight traffic, could have be designated as a small hub or other, while their commercial traffic figures are comparable to that of medium or large hubs.

7.2 Analysis for associations

This paragraph describes the results of the analysis for associations between the airport characteristics and the incursion rates. This is conducted to observe possible differences between the severities and types of incursions. For example, it is expected that the share of large aircraft has a different correlation with pilot deviation (PD) incursion rates compared to that of vehicle/pedestrian deviation (V/PD).

7.2.1.1 Normality

First, to select the most appropriate correlation test for the assessment of associations of characteristics, the continuous data was tested for normality to justify whether the data shows a normal distribution. For association tests, the Spearman's rho method is preferred for the non-normally distributed data, since outliers are better incorporated compared to Pearson's r, because outliers are less weighted (Hauke & Kossowski, 2011). The results can be found in Appendix A7. As the figures show, none of the continuous data characteristics appeared to have normal distribution. Therefore, it was determined to use the Spearman's rho for association tests. For the correlations with the presence of Runway Status Lights, the Mann–Whitney U Test was used, because of its binary character.

7.2.1.2 Outliers

To test the effect of outliers on the results, it was decided to create three separate datasets, one with all outliers included, one with outliers excluded and one with the exclusion of outliers which are no hub airports (semi-complete data set).

Outliers are defined as standardised residuals of at least 3.0 with regard to the mean. Conventionally, the effect of outliers is tested as an iterative effect during modelling. However, to assess the effects of the outlier removal it was decided to compare the association results per characteristics systematically. For instance, the correlation of hourly movements for total incursion rate is considered for each of the three datasets. Consequently, the semi-complete database could provide the best fit. After comparing all characteristics, the dataset providing the majority of the highest correlations is selected.

Off course, another way to deal with outliers, instead of the data point removal, is to treat these points as missing values. In this way, the outlier values are replaced with the means of the dataset. It was decided to not apply this method for hub airports, since transformation results in the loss of important characteristic information. The observed outliers in the final dataset are designated in the airport overview, which can be found in Appendix A12.

7.2.1.3 Associations

The following step is to test for associations between the airport characteristics and the incursion rates. Table 7-2 gives an overview of significant correlations between the characteristics and the total R_{rate}, the rate for high severity, cat. D, and type OI, PD and V/PD incidents. The results are presented for the three datasets. The related correlations, significance levels and sample numbers can be found in Appendix A7.

Consideration of the outliers revealed that these airports are generally represented by non-hubs and other airport; these were thus removed in accordance to the previous explained assumption. Only 43 outliers are either L, M or S airports, of which HNL was found 9 times and HOU 8 times for high severity incursions. The data check resulted in no requirement for adaptions.

The exclusion of outliers influences the strength of the correlation between the airport attributes and the incursion rates. Exclusion of all outliers increased a major share of the correlations, however some correlations became less strong. For example, the correlation between the share of large aircraft versus the incursion rate for cat. D incidents showed to be stronger and more significant when the complete dataset including outliers was considered. However, for number of intersections versus high severity R_{rate}, the r_s increased because of the outlier removal. Also, some data pairs became not significant for the 95% confidence interval after the outlier removal. Exclusion of only N and O airports, improved some of the significant correlations even further. For example, the share of commercial traffic became a significant indicator for high severity incidents. Since the semi-exclusion of outliers resulted in a stronger correlation matrix and a more representative sample of airports, this data set was preferred above the others. Next part elaborates on the analysis of this data set.

Table 7-2: Summary of significant associations per dataset

	Complete data set						Outliers excluded						Semi-complete data set					
	S_R		E_R				S_R		E_R				S_R		E_R			
Characteristics	Total	High	D	OI	PD	V/PD	Total	High	D	OI	PD	V/PD	Total	High	D	OI	PD	V/PD
Hourly movements		•	•	•		•		•	•	•				•	•	•		
Share commercial traffic			•	•	•				•	•				•	•	•		
Share heavy aircraft	•		•	•	•	•			•	•	•	•			•	•	•	•
Ratio intersecting runways	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•
TWY-RWY intersections/RWY-km	•	•		•	•		•	•		•	•		•	•		•	•	
Ratio non-right angled		•		•				•		•				•		•		
Ratio RETs		•		•	•			•		•				•		•		
Required crossings	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Presence RSL	•		•		•				•		•				•		•	
Hectare per runway-km		•		•				•		•				•		•		

● Significant associations at 95% confidence interval

Incursion rates

Then, the correlations are considered per incursion rate. Surprisingly, according to the results in Table 7-2 and Appendix A7, more than half of the data pairs for the total R_{rate} are not significant. Only the r_s of significant characteristic required crossings is higher than 0.3. Because of the minimal number of significant airport attributes, it was decided to not further analyse the total R_{rate}. The main reason for this is the absence of any operational component that describes the utilisation of an airport.

Contrary to the total incursion rate, many of the attributes show a significant correlation with high severity rates. This once again explains the influence of D incidents on the total incursion numbers, in line with the assumption from the previous chapter that D incidents less relate to geometrics. Apparently, high severity incidents could be better modelled and predicted separately from the total number of incursions. Wilke et al. (2015a); (2015b) and Claros et al. (2017) also noted the different associations per severity level. Therefore, it was chosen to not further elaborate on the R_{rate} of D. It is chosen to further analyse the high severity model, because of the higher correlations and the fact that all types of incidents are captured.

The table also learns that most of significant associations are found for operational incidents (OI) and that vehicle/pedestrian deviations (V/PD) is the most complicated to predict, because of the less associations. A possible explanation for this result is that airport vehicles naturally use the infrastructure in a different way than aircraft. Also for ground vehicles, often dedicated roads are available, which minimise the need for to use the taxiways. These infrastructure variables are not captured by the analysis.

Airport characteristics

Also, the correlations with airport characteristics are clarified individually. Some remarkable results are explained below.

The share commercial traffic is only correlated to the frequency of severity D incidents. This could be caused by the share of GA aviation, which might be more vulnerable to D incidents. Furthermore, it shows correlation with OI and PD incidents, and not with V/PD. In line with *Hypotheses H8*, the incursion rate with pilot errors shows a decrease when the share of commercial air traffic increases. Furthermore, it shows negative correlations for all R_{rate} values, except of OI. Remarkably, the share of heavy aircraft is correlated with all incursion rates, except of high severity incidents. Thus, an increasing share of heavy aircraft seem to be correlated with an increasing OI rate.

Also, higher ratios of non-right-angled intersections and RETs relate to higher incursion numbers, which is in line with *Hypotheses H5*. The variable required crossings is the only characteristic that correlates to all incursion rates, and is apparently an important determinant, such as was expected (*Hypotheses H1*). Hectare per runway-km only correlates with high severity rates and OI rates. There is a negatively relationship, thus, the more surface area per runway km, the larger the lower the incursion rates. This justifies the assumption from the high-level analysis.

Lastly, for the presence of Runway Status Lights, a correlation was found for D incidents and PD. This can be substantiated by the fact that RSL is especially implemented for the main users; the pilots. Low severity D incidents imply the unauthorised presence of aircraft or vehicles on the runway, often without danger for collisions. The aim of RSL is to prevent this from happening. For arrival aircraft, which contribute for a large share to the high severity incursion statistics, the presence of RSL is not directly useful.

7.2.2 Concluding

To conclude this paragraph, the potential for characteristics to be used as model attributes has been indicated for certain incursion groups. As explained, only the high severity interactions are modelled using the semi-complete dataset. Association results validate some of the hypotheses, which contributes to the answering of the research questions. One of these shows the need to exclude share of heavy aircraft and the presence of RSL as model variable, and are therefore not further examined. Thus, now the final selection of model attributes and the estimation variable are known for the estimation in the next part.

7.3 Model estimation

Throughout this paragraph, the process of the model estimation is discussed. The described steps include the definition of assumptions, the stepwise modelling, the improvement of the model fit and the consideration of interactions. The final selection of potential model attributes to be assessed can be found in Table 7-3.

7.3.1 Collinearity

During the regression modelling, not only the model fits R^2 are examined. Also, a collinearity check is taken into consideration for the review of the model. The models are tested for collinearity, by observing the collinearity coefficients given in SPSS. The tolerance per variable should be higher than 0.10 and the variance inflation factor lower than 10.0. Furthermore, correlations between variables in the model should not exceed 0.70.

7.3.2 Forced entry for all incursion rates

In the first stage, all incursion rates were modelled using the corresponding significant correlating characteristics. In order to obtain an overview of possible relevant models for further improvement (possibly for future research), it was decided to create models for all incursion types, independently of their number of significant characteristics. For this, the forced entry method was applied, in which all variables are added simultaneously, without considering the effects on significance levels. The results of the models can be found in Appendix A8.

As expected, because of the small numbers of significant correlating characteristics, multiple models have low adjusted R^2 values and large standard estimation errors. The model for V/PD shows by far the lowest prediction performance, followed by that of PD and low severity (D) incidents. Also, the total incursion rate model is not accurate with an adjusted R^2 of 0.142. The best model fits are found for high severity incidents for OI incidents (Adjusted R^2 = 0.364 and 0.233). Therefrom, it was decided to take the high severity model of further improvement in the next section.

7.3.3 High severity incursion rate model

Instead of the forced entry method, used in the previous part, the model estimation for the high severity incursion frequency is conducted in steps. This process is explained below. First the distribution of the incursion rates is visualized in Figure 7-2. Considering the distribution histogram, a non-normally distributed dataset is observable.

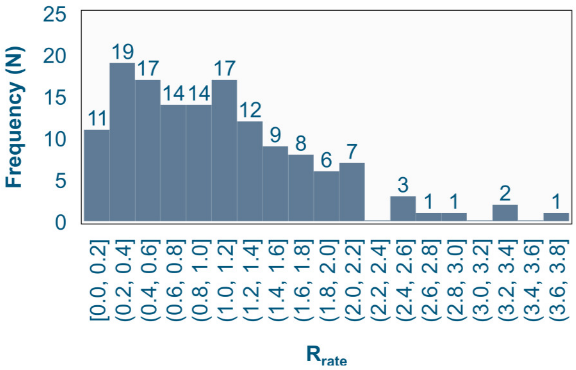


Figure 7-2: Data distribution high severity incursion rates

Table 7-3: Ranking airport characteristics on correlation

Variable	r_s	Sig.
TWY-RWY intersections/runway-km	0.436	.000
Hourly movements	0.351	.000
Required crossings	0.351	.000
Ratio intersecting runways	0.261	.000
Ratio non-right angled	0.225	.000
Hectare per runway-km	-0.205	.001
Ratio RETs	0.201	.002
Share commercial traffic	0.124	.043

The high severity runway incursion data appears to have a positive skewness. Outliers are found in the higher ranges of R_{rate}, with the highest rate observed at HNL (3.62).

As explained, the model estimation for the high severity rate is conducted in steps. This implies that first a simple regression model is estimated, in which the highest correlating attribute is used. Then, the attribute with the second-highest r_s is applied. This proces is repeated until one of the independent variables in the model becomes not significant for example because of multicollinearity. To determine the sequence of the variable application into the model, the attributes are ranked based on their correlation value, as can be found in Table 7-3. Since the presence of Runway Status Lights represents a binary factor, the effect was afterwards tested by the implementation of a dummy variable.

The results of the stepwise models are listed in Table 7-4. Here, model IV appeared to provide the highest significant R^2 values. Moreover, collinearity does not occur. As shown, the model incorporates four attributes, of which hourly movements represents the only remaining utilisation factor. The full overview of estimations for each model can be found in Appendix A9. Residual analysis

7.3.4 Model fitting

Until now, the regression analysis was based on only linear relationships for each of the variable as $\widehat{R_{rate}} = b_0 + a_1T_h + a_2I_n + a_3C_{req} + a_4I_r + \varepsilon$. However, plausibly some variables show non-linear relations which have not yet been analysed. In other words, certain variables might show a non-linear function for the high severity rate. Furthermore, intuitively, hourly movements could be a function of (part of) the geometry variables, since it describes the utilisations of the geometry elements. Nevertheless, it might also be possible that geometrical attributes have a non-linear relationship. To achieve insight in these factors, residual analysis was conducted, which is covered next.

Table 7-4: Summary of stepwise regression model results

	Summary				
Model	Added variable	R^2	Adj. R^2	Sig.	Std. Error
I	TWY-RWY intersections/runway-km	0.160	0.157	.000	0.58082
II	Hourly movements	0.201	0.195	.000	0.56738
III	Required crossings	0.315	0.307	.000	0.52661
IV	Ratio intersecting runways	0.346	0.336	.000	0.51638
V	Ratio non-right angled*	0.345	0.333	.000	0.51580
VI	Ratio RETs*	0.351	0.338	.000	0.51536
VII	Hectare per runway-km*	0.346	0.333	.000	0.51642
VIII	Share commercial traffic*	0.346	0.333	.000	0.51672

*Not significant at 95% confidence interval (p>.050)

Because the simple linear form currently used might not result in the best model fit, further analysis is conducted on the function of the variables itself and their interaction. Firstly, the residuals were studied for each of the four variables. For each attribute, small ranges were defined for the x-axis to plot against the y-axis. All data point within these ranges were aggregated and plotted as observations, i.e. the average of the aggregates, thus the mean of ΔRI. The corresponding regression estimates were obtained from the model output. Then, the difference between the observations and the estimates were depicted on the y-axis $\Delta R_{rate} = R_{rate,obs} - R_{rate,est}$.

TWY-RWY intersections per runway-km

Firstly, the attribute TWY-RWY intersections per runway-km is analysed on residuals. The results are graphed in Figure 7-3.

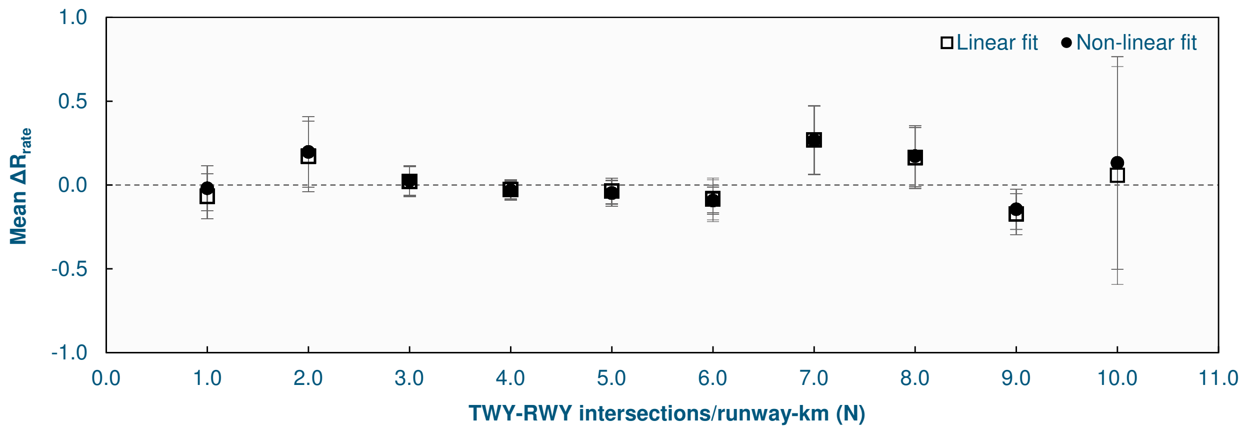


Figure 7-3: Plot of mean residuals for number of TWY-RWY intersections per runway-km variable

It can be observed that for the range [1,6] intersections, a steady growth in R_{rate} was recorded; i.e. a linear growth. In the range from 6 intersections per runway-km, a greater variance is visible. Considering the related scatter plot (I_n vs R_{rate}), a reduced growth figure was found above this threshold of 6. Multiple non-linear functions were tested on residuals, of which ${I_n}^{0.8}$ is shown in the graph above. For each of these functions applied that the correlation decreased. Therefore, it was concluded that the relation with this variable the best is described by a linear function. Thus applies $I_n \longrightarrow aI_n \Longrightarrow \widehat{R_{rate}} = b + aI_n$.

Hourly airport movements

During the high-level analysis, a trend was visible between the total number of incursions and the number of movements; the growth rate of the positive trendline decreased a fraction for the higher ranges of traffic numbers. The residual plot in Figure 7-4 reveals that also for high severity incursions a decreasing growth rate is observed as the number of hourly movements increases. From approximately 40 movements per hour, a deviation is visible in the data aggregates. It is shown from the scatterplot that the influence of traffic movements on the rate decreases for high values. This can be explained by the fact that from a certain range, the separation times and the ATC become the limiting factor. Therefore, at large airports often more runway are available for a spread of the movements. The flattening increase in incursion rates showed the best fit as $T_h \longrightarrow aT_h{}^{0.5} \Longrightarrow \widehat{R_{rate}} = b + aT_h{}^{0.5}$. $\ln \widehat{R_{rate}} = b + a \ln T_h$ was considered but did not result in an improved model fit.

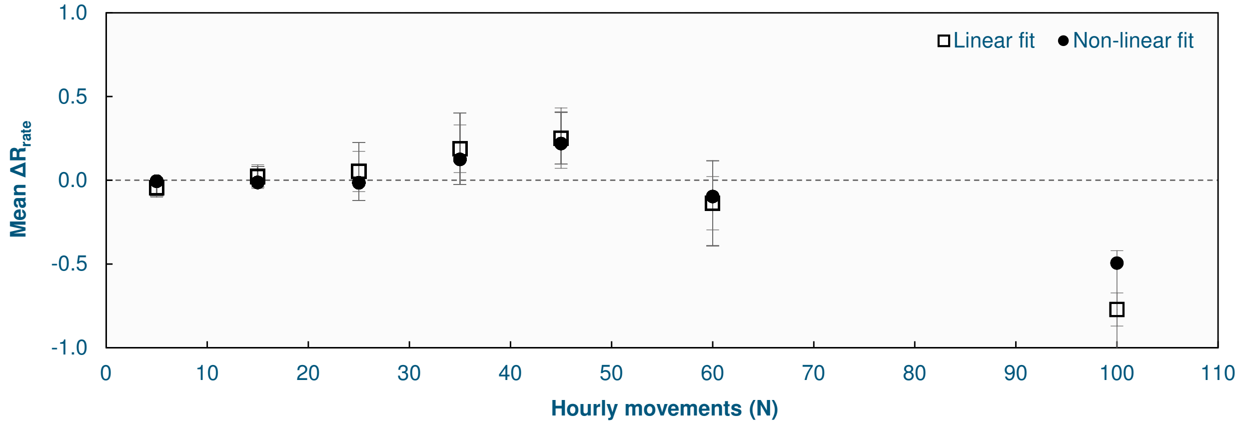


Figure 7-4: Plot of mean residuals for hourly movements variable

Required crossings

Previous analysis showed the importance of required runway crossings for the estimation of runway incursions. Though, it may be assumed that the effect is strengthened as the number of crossings increase. The residual plot in Figure 7-5a shows that for 3 required crossings a large deviation from the linear trend is observed, although large standard errors are found. From this can be assumed that a linear relationship does not result in the best fit. Fitting resulted in $C_{req} \longrightarrow aC_{req}{}^{2.2} \Longrightarrow \widehat{R_{rate}} = b + aC_{req}{}^{2.2}$ to provide the most accurate results.

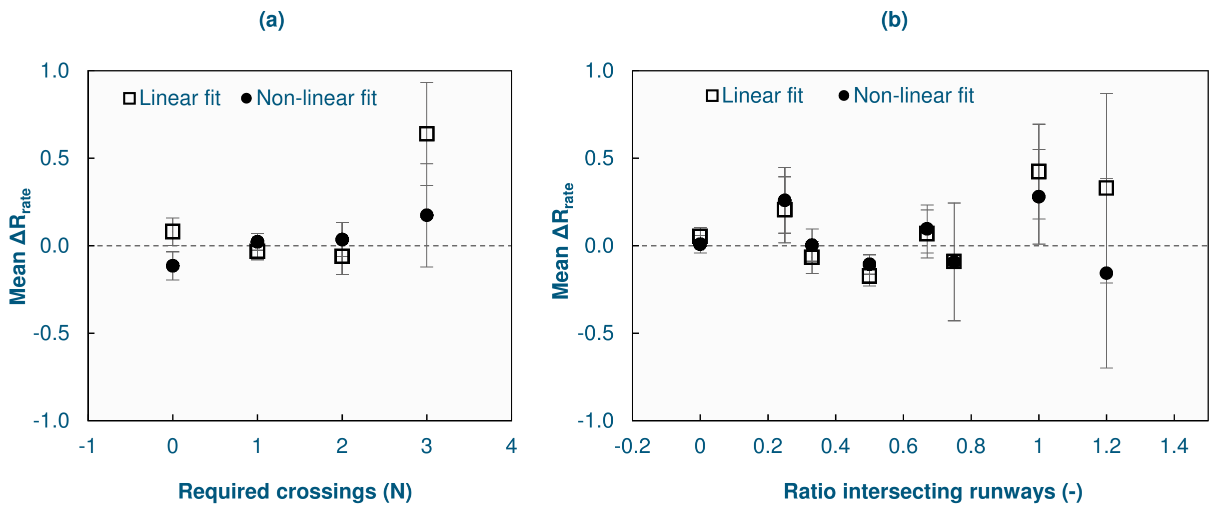


Figure 7-5: Plot of mean residuals for variables maximum required crossings (a) and ratio intersecting runways (b)

Ratio intersecting runways

Lastly, the relationship between ratio intersection runways and the R_{rate} was examined (Figure 7-5b). From the first observation of the residuals, not a clear relationship could be extracted. However, clearly a linear trendline does not provide the most optimal fit; instead a quadratic relationship is considered here first. After fitting, $I_r \longrightarrow aI_r{}^{1.9} \Longrightarrow \widehat{R_{rate}} = b + aI_r{}^{1.9}$ was found to provide the most accurate relationship, while overfitting was avoided. From this can be said that the effect of higher ratios of intersecting runways lead to a bigger growth in incursion rate.

From the previous residual analysis, we arrive at the improved model (7-5):

$$\widehat{R_{rate}} = b_0 + a_1 T_h{}^{0.5} + a_2 I_n + a_3 C_{req}{}^{2.2} + a_4 I_r{}^{1.9} + \varepsilon \qquad (7\text{-}5)$$

7.3.5 Interaction

Intuitively, the utilisation attribute hourly movements should be a function of at least one of the geometry variables, rather than a linear component of the multiple regression equation. Furthermore, it is possible that geometrical attributes influence each other. For instance, the effect of a higher intersection density could be larger for an increasing number of required crossings. Therefore, the interaction between each of the variables it analysed in this part.

To test for interactions, interaction terms were developed, which consists of a product of two attribute values that describe the interaction effect. The application of the interaction term into the model shows a shift in the significance levels for the variables. If the interaction term appears to be significant, this implies a possible interaction between the variables. The main effects of the two variables are kept in the model, regardless of the significances. The only requirement is that the multiplicative terms are significant.

In Table 7-5, the proposed interaction terms are listed. Model runs resulted in the corresponding significance levels, which are also given in the table. Strikingly, there appeared to be no interaction between hourly movements and one of the geometric attributes. As can be seen, the interaction terms TWY-RWY intersections × Required crossings and TWY-RWY intersections × Ratio intersecting runways appeared to be significant. The terms were added into the model in sequence. Currently, the following model form applies (7-6), for which the interaction terms G_i (with i indicating the term) are determined next:

$$\widehat{R_{rate}} = b_0 + a_1 T_h{}^{0.5} + a_2 I_n + a_3 C_{req}{}^{2.2} + a_4 I_r{}^{1.9} + G_i \tag{7-6}$$

Table 7-5: Interaction terms and corresponding significance levels

Interaction term		Sig.
Hourly movements × TWY-RWY intersections		.831
Hourly movements × Required crossings		.793
Hourly movements × Ratio intersecting runways		.495
TWY-RWY intersections × Required crossings	G_1	.032
TWY-RWY intersections × Ratio intersecting runways	G_2	.028
Required crossings × Ratio intersecting runways		.311
TWY-RWY intersections × Required crossings × Ratio intersecting runways		.150

To understand the indicated interactions between variables, scatterplots were produced for the two terms. These are shown in Figure 7-6a an b. First, it was shown that the incursion rate increases for an increasing number of TWY-RWY intersections, however, differences are found for the interaction with required crossings. The growth rate of incursions is smaller in case no crossings are required. In case 1, 2 or 3 crossings are required, the growth rates are equally higher. The use of a dummy variable for the presence of required crossings was tested, but resulted in a similar significance.

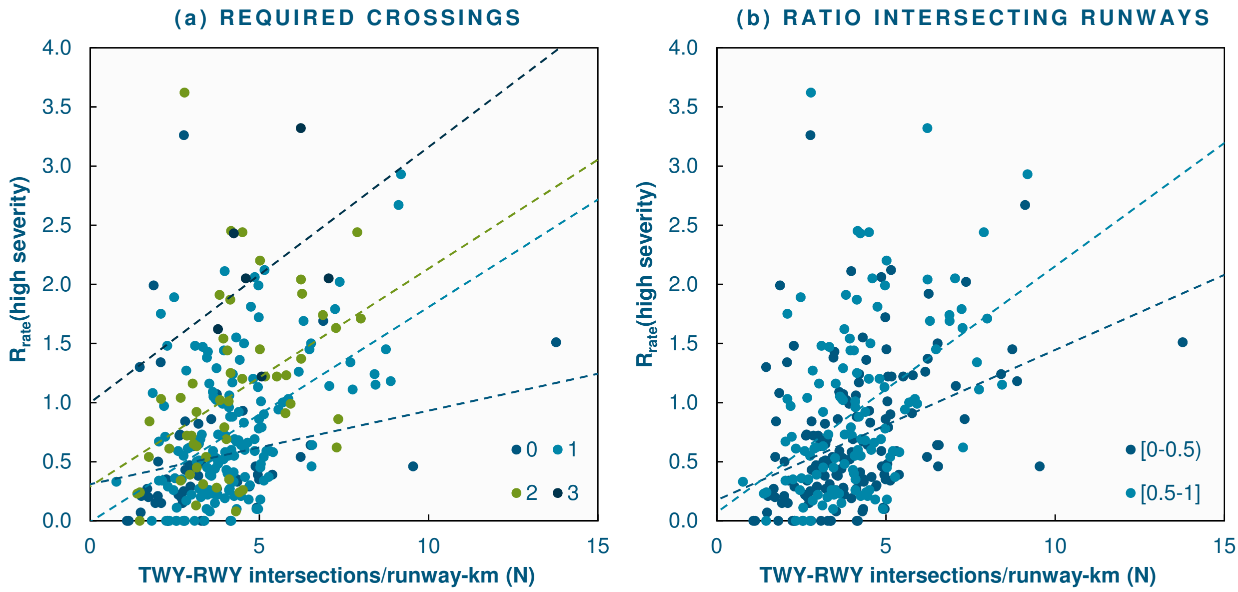


Figure 7-6: Interaction effects between independent variables number of TWY-RWY intersections and required runway crossings (a), number of TWY-RWY intersections and ratio intersecting runways (b)

The second graph reveals that also the ratio intersecting runways influences the impact of high intersection numbers per runway-km. For higher shares of crossing runways, the growth of R_{rate} is also larger. In other words, for airports without intersecting runways, the effect on incursion likelihood is smaller when TWY-RWY intersections are added. As can be seen in the scatter plots, there is a large variation after the subdividing each of the categories and therefore rather low correlation values are found. However, the product of the variables (i.e. interaction term) increases the correlations to significant levels.

7.3.6 Model comparisons

After the execution of the model fitting procedures, the models are compared in this section.
This equation can be shortened by factorization $\Longrightarrow \widehat{R_{rate}} = \cdots + {I_r}^{119}(a_4 + a_5 I_n)$
Table 7-6 provides an overview of model estimates R^2 values for the baseline model (linear fit model from the stepwise regression), the non-linear fit model and the extended non-linear fit models with interaction terms. Also, the application of both interaction terms simultaneously ($G_1 + G_2$) was tested, but caused collinearity between the terms and therefore not significant attributes. As the table below shows, the fourth model shows the best fit ($R^2 =$ 0.381 and adjusted $R^2 =$ 0.369), therefore this was selected as the final model (7-7). Here, $a_1 =$ 0.088, $a_2 =$ 0.080, $a_3 =$ 0.064, $a_4 =$ -0.045, $a_5 =$ 0.133 and the $b_0 =$ -0.084.

$$\widehat{R_{rate}} = b_0 + a_1 {T_h}^{0.5} + a_2 I_n + a_3 {C_{req}}^{2.2} + a_4 {I_r}^{1.9} + a_5 I_n {I_r}^{1.9} \quad (7\text{-}7)$$

This equation can be shortened by factorization $\Longrightarrow \widehat{R_{rate}} = \cdots + {I_r}^{1.9}(a_4 + a_5 I_n)$

Table 7-6: Overview of model estimates for linear model versus improved models

	Linear fit model [I]		Non-linear fit model [II]		Non-linear fit model + interaction term 1 [III]		Non-linear fit model + interaction term 2 [IV]	
Variables	B	Std. Error	B	Std. Error	B	Std. Error	B	Std. Error
(Constant)	*-0.139	0.092	-0.139	0.098	*-0.171	0.101	*-0.084	0.110
TWY-RWY intersections/runway-km (I_n)	0.107	0.021	0.105	0.021	0.104	0.021	0.080	0.023
Hourly movements (T_h)	0.010	0.002	0.098	0.023	0.091	0.023	0.088	0.023
Required crossings (C_{req})	0.186	0.057	0.474	0.125	0.055	0.024	0.064	0.018
Ratio intersecting runways (I_r)	0.443	0.127	0.071	0.018	0.386	0.152	*-0.045	0.266
Interaction term								
$I_n \times C_{req}$ (G_1)					*0.031	0.031		
$I_n \times I_r$ (G_2)							0.133	0.060
Summary								
R^2	0.346		0.370		0.372		0.381	
Adjusted R^2	0.336		0.360		0.360		0.369	
Model significance	.000		.000		.000		.000	
Std. error of estimate	0.51638		0.50692		0.50689		0.50317	

*Not significant at 95% confidence interval ($p >$ .050)

In Figure 7-7, the residual plots are given for the baseline model (I) and the final model (IV), with the observed R_{rate} values on the y-axis and the fitted rates on the x-axis. It is clearly visible that after model fitting still a great amount of variation is visible. Moreover, both scatters show rather similar results, which is the consequence of a minor increase adjusted R^2 of 0.033 from 0.336 to 0.369. Though, it is visible that in particular for the lower R_{rate} ranges a bend towards the zero-line occurred. Before the model fitting, a large share of the incursion rates was underestimated, in other words, the linear model attributes estimated a lower R_{rate} than was observed. This is the result of the exponentiation of the attributes C_{req} and I_r. For the higher R_{rate} ranges, there was less improvement of the estimation.

In general, the model improved by means of fitting, with data points shifting towards the zero line. In both graphs, the airports equipped with RETs are highlighted in red. Since the red dots are spread across the chart, the effect of RETs cannot be directly extracted from this. Therefore, the model is extended in the next section by a binary variable for the presence of RETs.

A representation of the standardised residuals in Figure 7-8a and b shows in more detail the differences between the first model and the final model. According to the procedure for the selection of case airports, large hubs were drawn from Figure 7-8b, where the highest residual, the lowest residual and the smallest residual was considered. This resulted in the selection of HNL (5.15), IAH (-0.03) and PHX (-1.35).

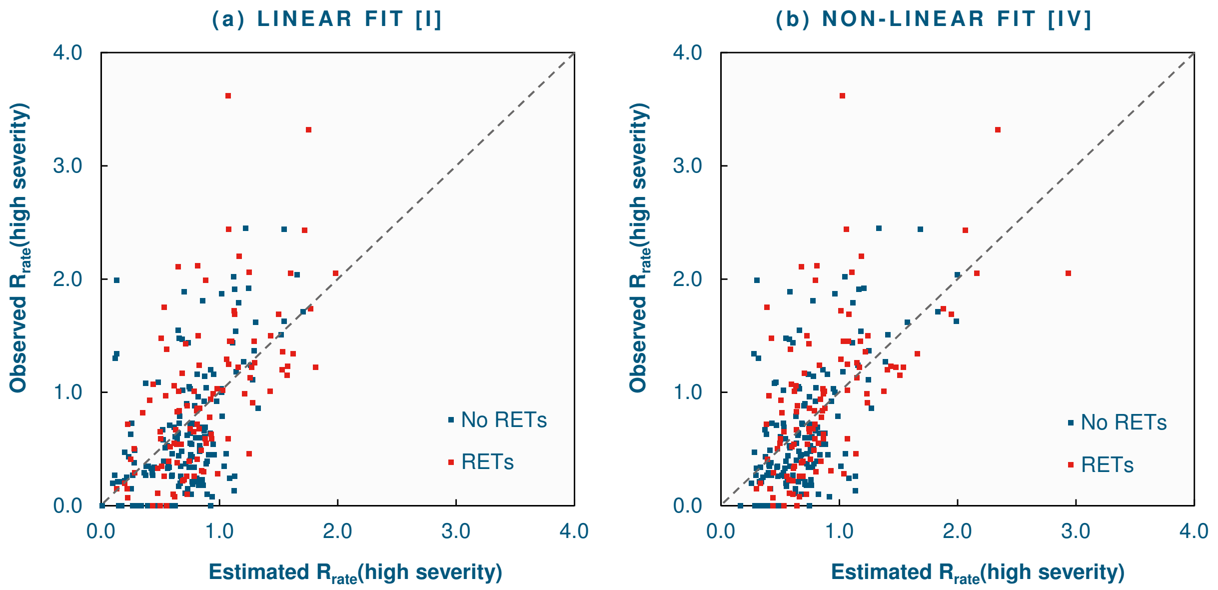


Figure 7-7: Observed versus estimated high severity incursion rates for linear fit model (a) and non-linear fit model (b)

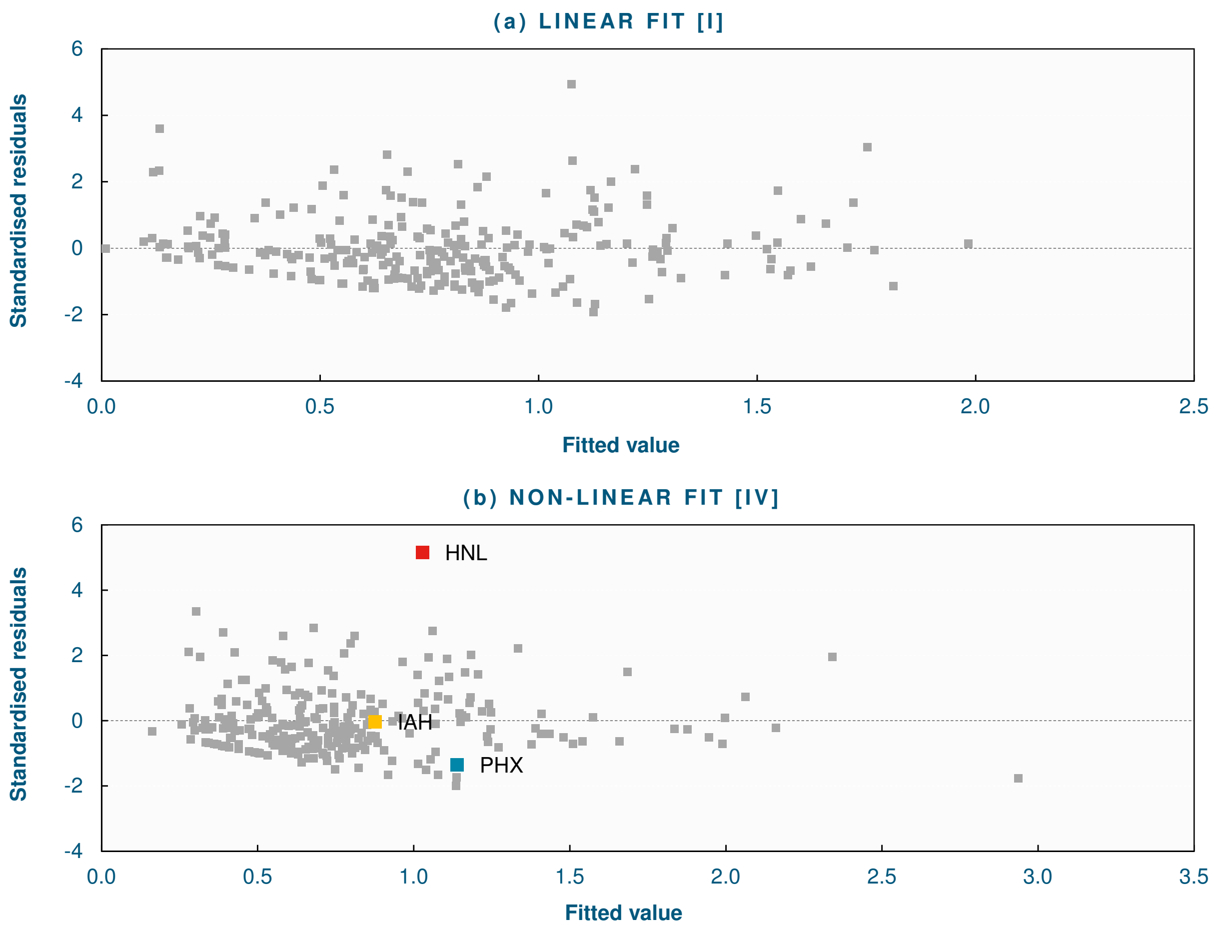


Figure 7-8: Standardised residuals versus fits plot for linear fit model (a) and non-linear fit model (b)

7.3.7 Additional variables

Because RETs are mainly found in large numbers, rather than only intersection of this type, it was tested whether the presence of RETs would influence the total incursion rate. In the same way, also the influence of the presence of RSL is tested. The results are described below.

7.3.7.1 RSL

From the high-level analysis, it became clear that airports equipped with Runway Status Lights recorded less runway incursions, than comparable airports without RSL. In the regression model (IV), this effect can be tested by adding a dummy variable, with 1 = RSL present, and 0 = RSL not present. The resulting model showed an improved fit with adjusted R^2 = 0.371. The B-value is -0.191, insisting a decrease in R_{rate} when RSL is present. However, the RSL attribute appeared to be not significant (.209). This is presumably the cause of the small sample of 20 airports equipped with RSL.

7.3.7.2 RETS

Then, the presence of RETs is modelled likewise, with 1 = RETs present, and 0 = RETs not present. Also, the application of this dummy predictor resulted in a higher adjusted R^2. Meanwhile, all independent variables maintained significant. The B-value for the attribute is 0.178, meaning that the incursion rate is higher for airports equipped with RETs. Possibly, for high severity incursions this negative influence is the consequence of operational procedures for departing aircraft, because for total incursion rate it was shown that the R_{rate} was lower at airports with RETs. This implies that the effect of RETs is particularly positive for the prevention of D incidents. The model estimates can be found in Table 7-7.

Table 7-7: Model estimates high severity model extended with RET dummy variable

	Model R_{rate}(high severity)				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.082	0.109		.451	
TWY-RWY intersections/runway-km	0.085	0.023	0.223	.000	0.177
Hourly movements	0.067	0.026	0.159	.009	0.128
Required crossings	0.061	0.018	0.206	.001	0.166
Ratio intersecting runways	0.022	0.267	0.011	.934	0.004
TWY-RWY intersections × Ratio intersecting runways	0.124	0.060	0.272	.041	0.100
Presence RETs	0.139	0.072	0.108	.055	0.094
Model summary					
R^2	0.390		Model significance	.000	
Adjusted R^2	0.376		Std. error of estimate	0.5052	

Lastly, the presence of RETs and RSL were added simultaneously. This resulted in an improved significance of both variables. Though, the presence of RSL was still not significant (.151).

To conclude, the final model is (7-8) given below:

$$\widehat{R_{rate}} = b_0 + a_1 {T_h}^{0.5} + a_2 I_n + a_3 {C_{req}}^{2.2} + {I_r}^{1.9}(a_4 + a_5 I_n) \quad (7\text{-}8)$$

And with the extension of the RET element (7-9):

$$\widehat{R_{rate}} = b_0 + a_1 {T_h}^{0.5} + a_2 I_n + a_3 {C_{req}}^{2.2} + {I_r}^{1.9}(a_4 + a_5 I_n) + a_6 d_1 \quad (7\text{-}9)$$

where dummy variable $\boldsymbol{d_1}$ for indicates the presence of RETs:

$$\boldsymbol{d_1} = \begin{cases} 0, & \text{if no RETs present} \\ 1, & \text{if RETs present} \end{cases}$$

7.4 Sensitivity analysis

In this section, the attributes in the final model are compared in a standardised form, to understand how factors contribute to the estimation of an incursion rate. From the final model estimates the standardised betas can be derived, which describe the mutual effect on the estimated outcome. Hence, the model exponents lapse in this situation, the standardised model is given below (7-10). The corresponding results are depicted in Figure 7-9.

$$\widehat{R_{rate}} = -0.084 + 0.208T_h + 0.211I_n + 0.218C_{req} - 0.021I_r + 0.293I_nI_r \tag{7-10}$$

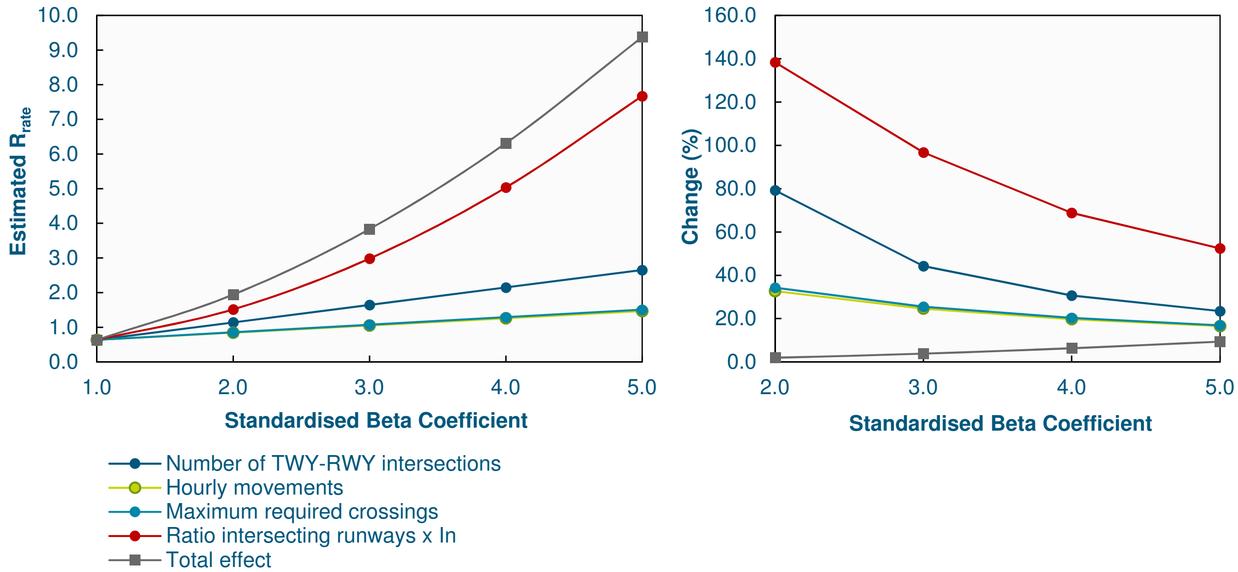


Figure 7-9: Effects of standardised betas for model attributes

Here, for each characteristic the incursion rate is shown for the standardised input variable from 1.0, where all other betas are equal to 1.0. From here, we can conclude that the interaction of number of TWY-RWY intersections per runway-km with the ratio intersecting runways generates the strongest impact.

In Appendix A10, a transformation of the model into a probability form on a binary outcome (0 and 1 for a given probability event) is proposed. Here the probabilities for certain incursion rates are assigned to the airports, based on their characteristics, and compared with the actual observed rates.

7.5 Model comparison

To conclude this chapter, the model is compared to the existing runway incursion frequency model, developed by Claros et al. (2017). The model can be found in Appendix A13. The model consists of multiple attributes, among which airport operations, runway configuration, number of TWY-RWY intersections, weather, number of hot spots and the presence of constructions sites. Thus, the Claros et al. model is less focussed on the geometry and captures also general circumstances. The model estimation is based on 137 airports and an analysis period of 5 years (2009 to 2013). Validation was performed for the year 2014.

Both models share two variables: the number of intersections and the number of movements. However, in both models, different measurements for these variables are used, i.e. annual movements versus hourly movements and number of intersections (RETs + right-angled) versus number of intersections per runway-km. In order to compare both characteristics, input was used from Houston IAH, as this appeared to be the best estimated airport by the model. The following standard parameters were used for the Claros et al. model: $\vartheta_s = 0.98072$, $\delta_e = 1.0$, $\varphi_{other} = 0.90304$ (given in Appendix A13). The figures in Table 7-8 represent the input variables that were used for the comparison as start value.

In Figure 7-10a and b, the results for the comparison on the two common variables are presented. Clearly, for higher movement numbers, the Claros et al. model shows an increasing growth of the R_{rate}, while the own model shows a flattening trend. One of the explanations for this deviation is that Claros et al. treats the variable as a product of the other attributes, while the own model incorporates hourly movements as linear component. Considering the number of intersections, a similar trend is visible.

Table 7-8: Input variables for model comparison, case Houston (IAH)

	Model input, Houston airport (IAH)	
Attribute	Claros et al. (2017)	Own
Number of annual operations	520,986	520,986
Airport configuration	Single runway	-
Number of runways	-	5
Runway length	50,403 ft	15.36 km
Number of TWY-RWY intersections	-	55
Number of right-angled TWY-RWY intersections	31	-
Number of RETs	24	-
Number of RWY-RWY intersections	-	0
Number of annual operations	0	0
Precipitation per year	49.8 inch	-
Snowfall	0.1 inch	-
Operational hours per week	-	168
Share general aviation traffic	3.3%	-

Attributes mentioned in italic are not applied in the own model

Next, the models were tested on the residuals for the prediction of R_{rate} for large hubs. Weather data was obtained from the meteorological office of the US, and indicates the annual average amount of precipitation and snow in inches. As can be observed in the scatterplot in Figure 7-11, the Claros et al. model shows much larger deviations between the observed and the estimated incursion rates. Strikingly, the model produces also negative values for certain airports. Analysing these values, explain that these airports have runway lengths of at least 40,000 feet. Since too large length values for airports produce negative R-values, the R_{rate} will also be negative. All coefficients for airport configuration types are negative, instead of mixed layouts. Though, large values for this variable, lead to unrealistically high rates.

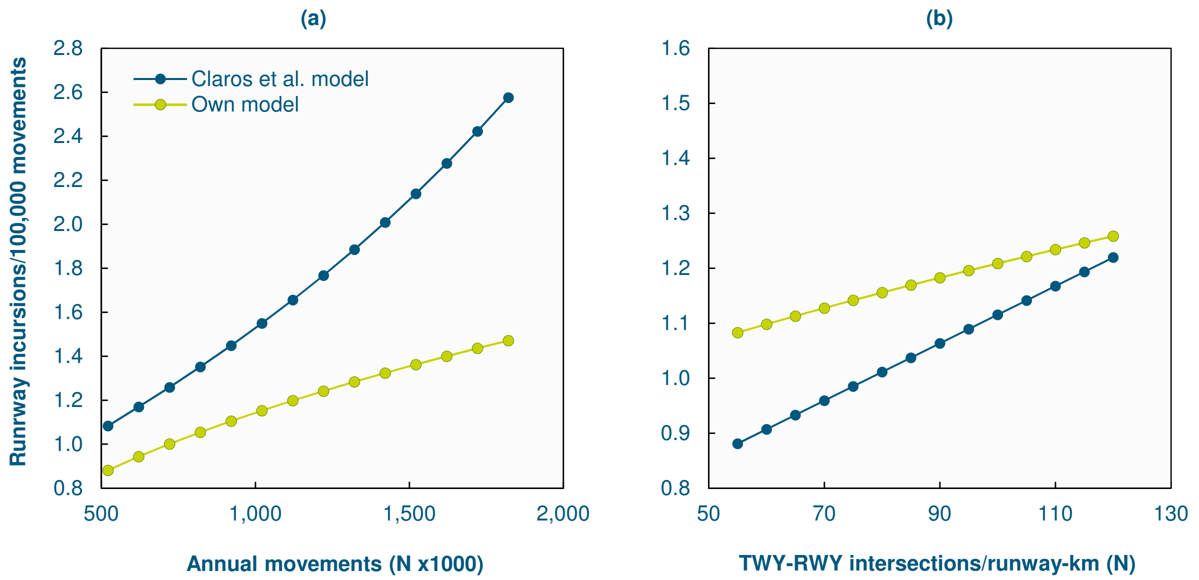


Figure 7-10: Estimated incursion rates Claros et al. and developed model for annual movements (a) and number of TWY-RWY intersections per runway-km (b)

To conclude, it can be assumed that the Claros et al. model performs better on the estimation of R_{rate} for smaller airports, in the range until 40,000 feet of total runway length. The own model is a more accurate estimator for the total range of airports, while a weather and general aviation share component is not included.

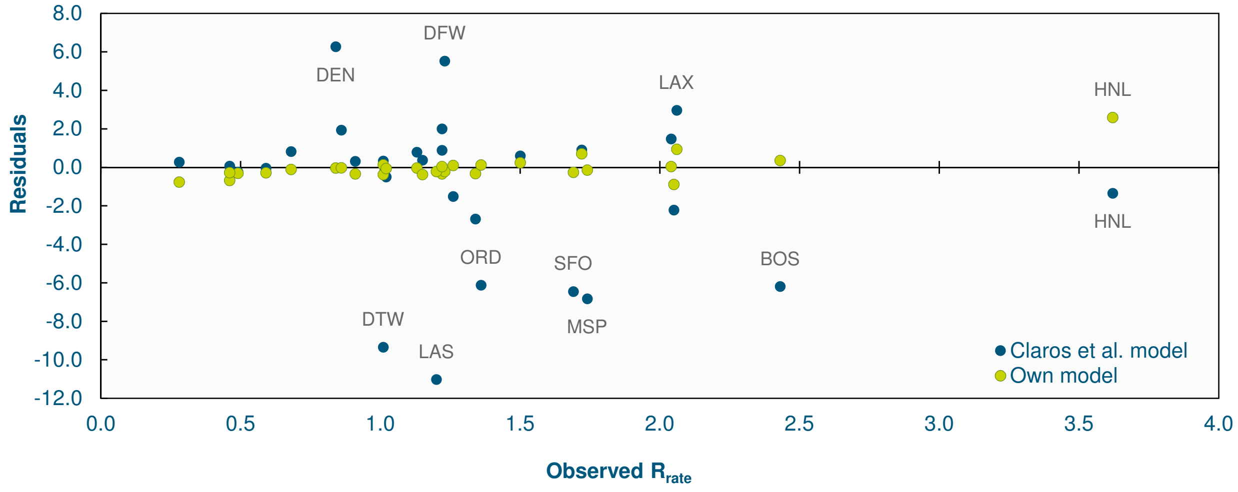


Figure 7-11: Residuals model Claros et al. and developed model versus observed incursion rate

8 Airport case studies

In this chapter, the model is compared to the three selected airport cases to find variations that are not captured. Furthermore, in order to consider the applications of the model, it is used to develop forecast scenarios for certain geometric adjustments at Schiphol (AMS).

8.1 Incident mapping

This paragraph describes the results of the analysed case airports (Figure 8-1). The aim of the airport case studies was to apply the model on the characteristically airports, that were found from the residual analysis during the model development. The model was applied to Honolulu, which performed worst against to the prediction from the model, Phoenix, which performed better compared to the model, and Houston which was the best predicted large hub by the model. For all airports, the incursion rates during the research period were examined and clarified. All incidents were geographically mapped and described. By this, the aim was to also consider airport elements that increase the likelihood of incursions according to the literature study and the expert panel, but was not modelled.

Honolulu $R_{rate}(obs, est) =$ 3.62, 1.03 **Houston** $R_{rate}(obs, est) =$ 0.86, 0.88 **Phoenix** $R_{rate}(obs, est) =$ 0.46, 1.14

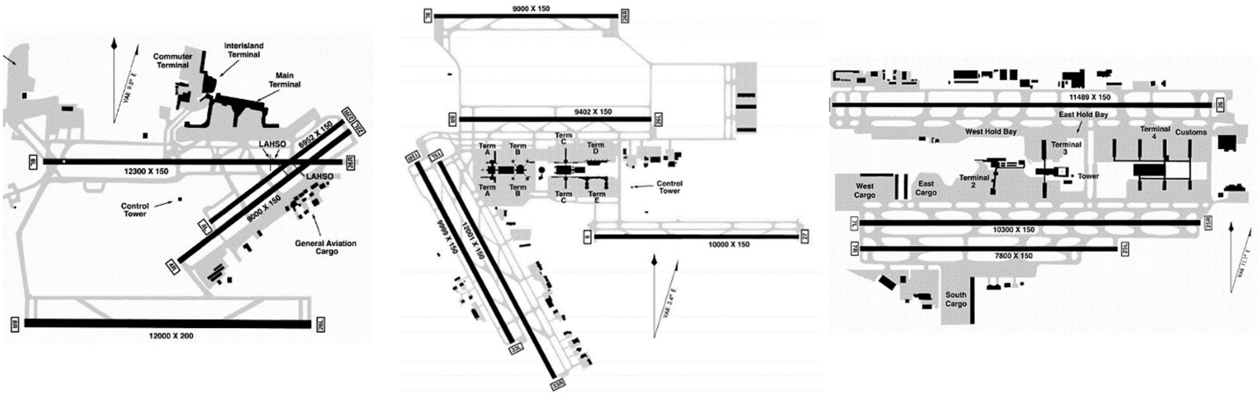


Figure 8-1: Analysed airport cases with observed (obs) and estimated (est) incursion rates

All incidents for the case airports were mapped by means of the narratives, which describe the sequence of events that occurred which led to the incursion. Here, the locations are also described. Before the incidents were mapped on the airport layout, the data had to be prepared first. This incorporated the check on visibility circumstances during the event, as well as the check on light conditions. This was required in order to make separate maps for day and night.

To check the light circumstances during the incident, the component of the date and time was checked according to the sunrise and sunset data of each airport. First, the incidents were filtered according to the latest sunrise and the earliest sunset, for each year. All incidents in this time in this time window are classified as daylight incidents. For the remaining incidents, an additional selection was made based on the latest sunset and earliest sunrise. The incidents in this time window are classified as being night incidents. This resulted in an overview with incidents occurring during night and during day, for each airport. This is in all cases the period from sunset civil twilight and sunrise civil twilight, since the visibility conditions contribute to the light conditions. For this reason, no further distinction is made into nautical twilight, astronomical dusk and night. Moreover, the number of incidents during these light phases are minimal.

In the subsequent parts, for each case airport, the incident mapping for day occurrences is shown. In Appendix A14 the night incident mappings and related airport diagrams can be found.

8.1.1 Honolulu – HNL

In Figure 8-2 an overview of all runway incursions during daylight conditions in the study period is shown. Analysis of the incidents revealed that none of the incursions occurred during unfavourable weather conditions, consequently, no additional map was created. In Table 8-1, the frequencies of the incursions are given for three defined infrastructure groups per type and severity. From this, the geometry type with the largest contribution to incursion numbers is highlighted.

From the map, it can be seen that the main concentration of the incidents (18%) is located around the two RWY-RWY intersections, known as one of the hot spots. The ratio intersecting runways has a relative large contribution to the occurrence of incursions, according to the standardised betas from the model. From the map, it can be assumed that the effect is possible impacted by the closely situated parallel runway, creating a double RWY-RWY intersection. This cannot directly be extracted from the intersection ratio I_r, because for instance, if one of the runways would only intersect the southern runway, the value maintains 0.5, while the effect may be positive for the incursion likelihood. Consequently, there is possibly aggravated effect when parallel runways are combined with runway intersections, as is the case at HNL.

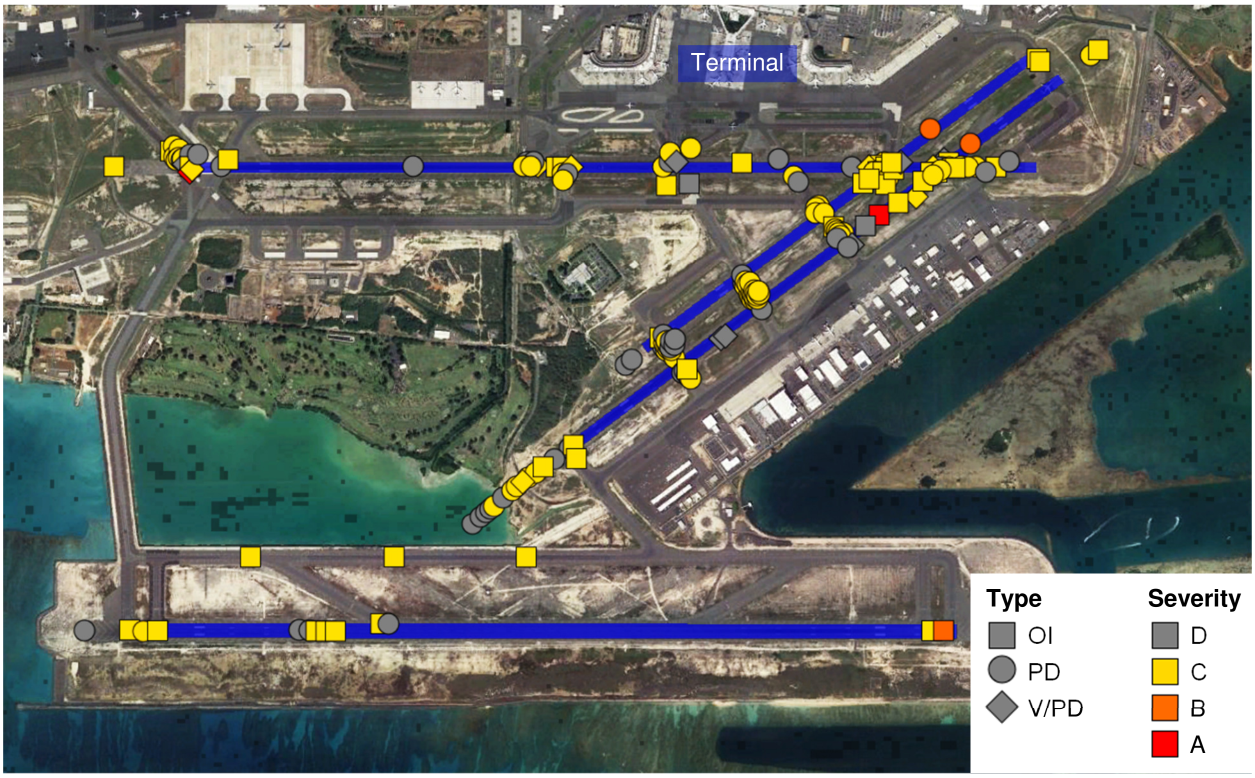


Figure 8-2: Runway incursion map Honolulu (HNL) airport 2007-2017

The largest share of incursions was recorded at TWY-RWY intersections (58%). Clearly, a large concentration of the incidents is located besides and between the parallel runways. The consequence of the short distance between the runways is that in many occasions the flight crew failed to brake before the hold line of the other runway. Similar incidents were observed at Los Angeles LAX, according to Madson (2004). Another frequently observed cause was that large aircraft were too long, meaning that the aft side of the aircraft overhang the crossed runway, meaning that it was not cleared yet. Often, the ATC gave the instruction to hold short, while there was not enough space for that aircraft (OI incident). The expert panel underlines these problems from the closely situated parallel runways, which are especially seen in the US.

Furthermore, a remarkable type of incident for HNL is the loss of separation between landing aircraft. A frequent error type found in the incident descriptions is an approach for the wrong runway. Pilots are often confused with the parallel runways, after which they land on the runway which they were not cleared for. Or this reason, the biggest proportion of these incursions is PD. According to the panel, an explanation is that in the US, rather often VFR operations are used for aircraft. This means that the landing is performed on sight, resulting in higher risk on errors, which could be avoided by IFR landings, on which the approach is automated by the instrument landing system (ILS). However, according to the panel, in the US visual landings are often preferred because this insists a higher landing capacity and shorter separations. For the use of ILS, certain larger separation distances are required.

Also, one of the relevant characteristics from the literature study is the intersection of Runway Safety Areas (RSA). At HNL, the southern runway is intersected by the approach paths of the parallel runways. Indeed, multiple (OI) incursions occurred as aircraft were cleared to cross the RSA, while an aircraft was approaching one of the parallel runways. This resulted in a loss of separation.

Lastly, RET's leading directly onto another runway are considered as an incursion risk increasing characteristic. This type of RET is present at HNL and connects with two intersecting runways. The incursion map shows indeed a relatively high concentration of incursions, caused by this complex element. This area is known as hot spot 2, highlighted on the airport diagram.

Table 8-1: Frequency table incidents Honolulu (HNL) airport 2007-2017

Incident type/severity		Infrastructure category: RWY-RWY intersection	TWY-RWY intersection	RWY threshold (separation)	Other	**Total**	**Hot spot**
OI		**15**	**21**	**6**	**6**	**48**	**18**
	A	-	-	-	1	1	1
	B	-	1	-	1	2	-
	C	15	19	6	4	44	16
	D	-	1	-	-	1	1
PD		**14**	**79**	**13**	**17**	**123**	**72**
	A	-	-	-	-	-	-
	B	2	-	-	-	2	-
	C	9	51	6	7	69	49
	D	3	28	7	10	38	23
V/PD		**4**	**9**	**-**	**4**	**17**	**6**
	A	-	1	-	-	1	1
	B	-	-	-	-	-	-
	C	2	5	-	-	7	3
	D	2	3	-	4	5	2
Total		**33**	**109**	**19**	**27**	**188**	**90**

8.1.2 Houston – IAH

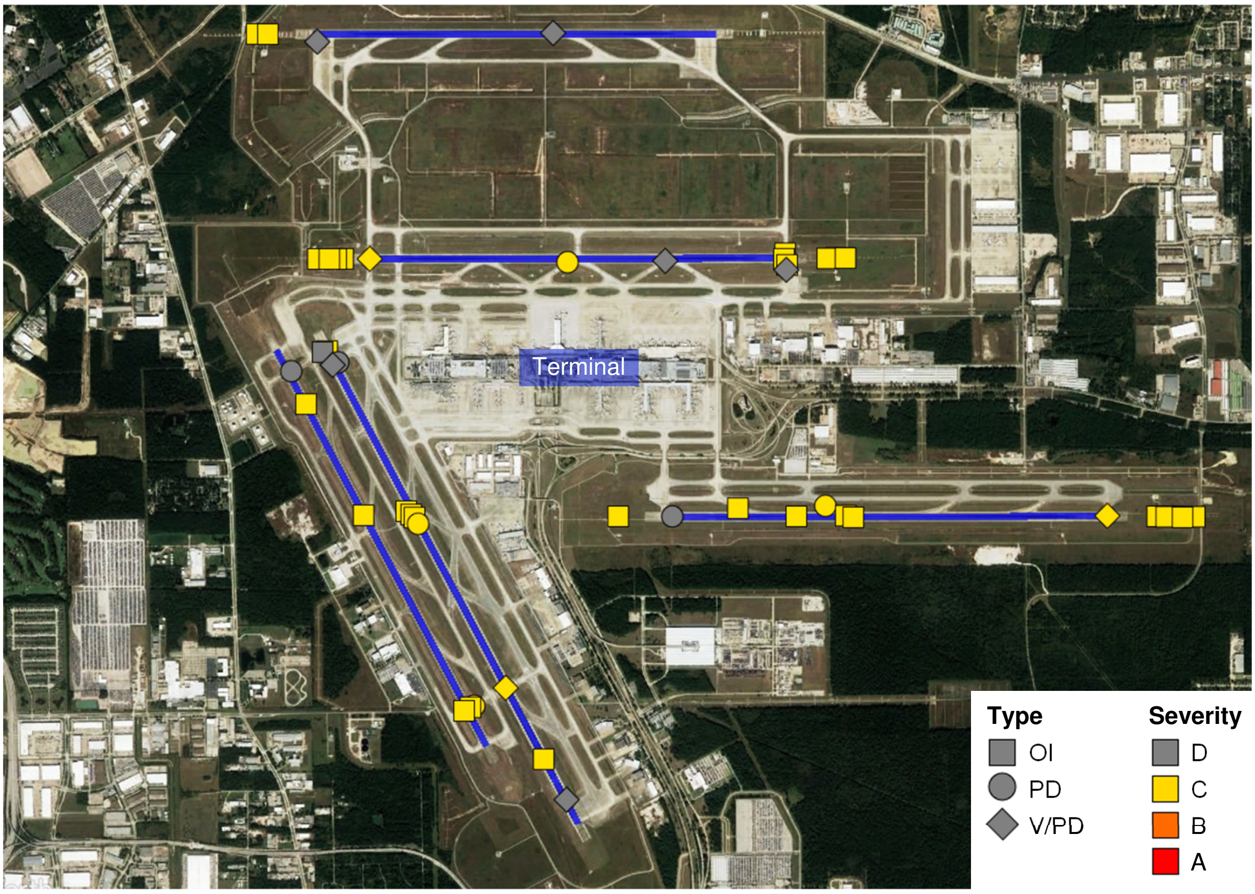


Figure 8-3: Runway incursion map Houston (IAH) airport 2007-2017

Figure 8-3 gives an overview of all runway incursions during daylight conditions in the study period is shown. Only one incident occurred during LIFR conditions and it was therefore decided to not create an additional map for this single incursion. In Table 8-2, the frequencies of the incursions are given for two defined infrastructure groups per type and severity. Note that because of the absence of RWY-RWY intersections, no group was created for these incidents. The same applies for incidents in hot spots. From the table, the geometry type with the largest contribution to incursion numbers is highlighted.

Strikingly, the share of operational incidents at IAH is rather large. The majority of OI incident was related to the loss of separation between landing aircraft. These incidents are to a lower degree related to geometry than for example incidents because of RWY-RWY intersections. Though, the possibility for aircraft to exit the runway faster reduces the risk of separation losses. For this reason, a higher density of intersections could be positively related to lower incursion rates, since aircraft have more options to clear the runway. In line with this assumption and *Hypothesis H5*, non-right-angled intersections are advantageous, since aircraft are able to exit with higher speeds. Clearly, at IAH a low share of incursions is caused at TWY-RWY intersections by PD, since all entrance taxiways are constructed at a 90-degree angle to the runway, avoiding visual hindrance. The higher rate of incursions here is caused by the ATC, which could be caused by aspects that are not necessarily related to geometry. From the perspective of runway incursions, it could have a mitigating effect when more RETs are available on the high-speed sections of the runway, in order to reduce the loss of separation incidents.

A second aspect that can be seen is that the presence of parallel runways does not emerge in higher incursion numbers, since the runways can be used independently $C_{req} = 0$. Hardly any PD incident was recorded in this area.

Table 8-2: Frequency table incidents Houston (IAH) airport 2007-2017

Incident type/severity		Infrastructure category: TWY-RWY intersection	RWY threshold (separation)	Other	Total	Hot spot
OI		**15**	**18**	**5**	**38**	**n/a**
	A	-	-	-	-	
	B	-	-	-	-	
	C	14	18	5	37	
	D	1	-	-	1	
PD		**7**	**-**	**4**	**11**	**n/a**
	A	-	-	-	-	
	B	-	-	-	-	
	C	3	-	1	4	
	D	4	-	3	7	
V/PD		**7**	**-**	**3**	**10**	**n/a**
	A	-	-	-	-	
	B	-	-	-	-	
	C	3	-	-	3	
	D	4	-	3	7	
Total		**29**	**18**	**12**	**59**	**n/a**

8.1.3 Phoenix – PHX

Figure 8-4 shows the incursion mapping of PHX during daylight circumstances. No incursions during low visibility LIFR were found. In Table 8-3, the frequencies of the incursions are given for two defined infrastructure groups per type and severity. Since there are no RWY-RWY intersections, this group is excluded in the table. From the overview, the geometry type with the largest contribution to incursion numbers is highlighted.

Although there are two parallel runways at PHX, the incursion map reveals that this does not relate to higher incursion concentrations around these runways with more crossing traffic. Biernbaum and Hagemann (2012) indeed found more parallel runways to be an incursion rate reducing factor. From the model, it is expected that the closely related runways cause higher incursion rates around these runways. Though, overserved figures show the contrary. This can be clarified by the reason that the way in which runways are operated, play an important role in the determination of C_{req} (see: case AMS). At PHX, the southern runway is scarcely used by traffic from the main terminal in the central acreage. The runway is designated for the terminal on the southern side of the airport, where cargo flights are handled. Since these aircraft are predominantly smaller in size, a shorter runway fulfils the requirements.

Furthermore, a low number separation incidents is seen at PHX. This may be explained by the large number of 'higher speed' exits, which provide multiple possibilities for aircraft to exit the runway after landing.

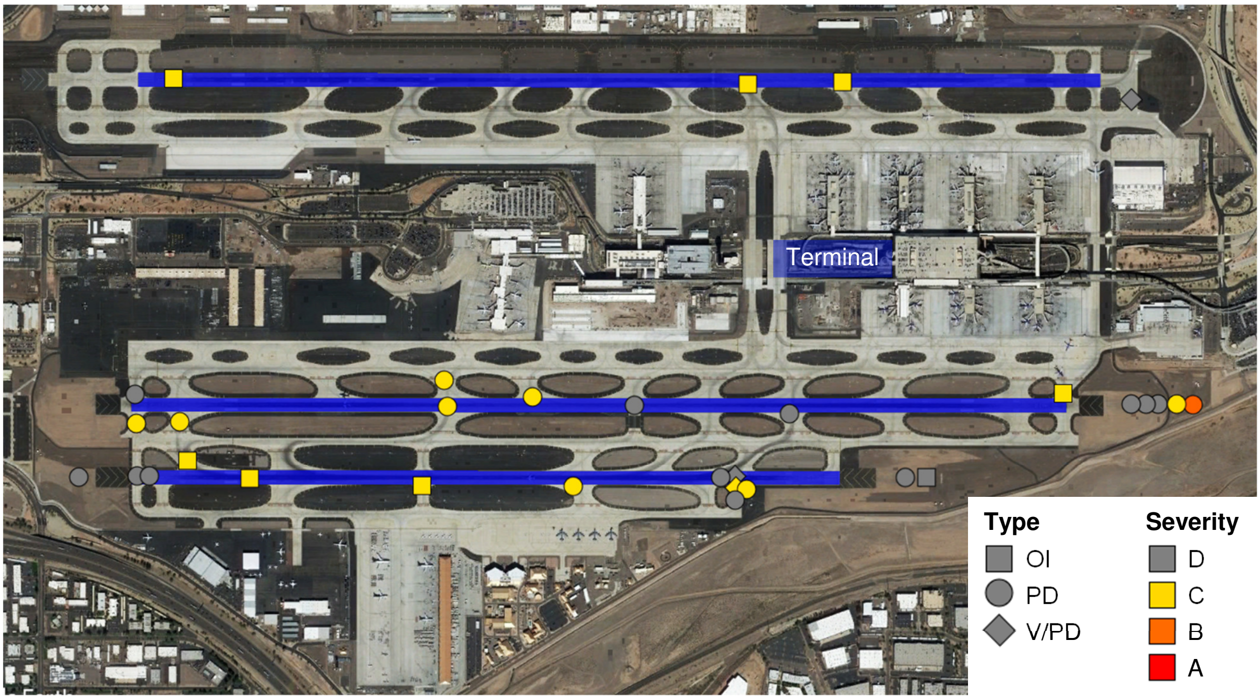


Figure 8-4: Runway incursion map Phoenix (PHX) airport 2007-2017

Table 8-3: Frequency table incidents Phoenix (PHX) airport 2007-2017

Incident type/severity		Infrastructure category: TWY-RWY intersection	Infrastructure category: RWY threshold (separation)	Total	Hot spot
OI		**11**	**4**	**15**	**1**
	A	-	-	-	-
	B	-	-	-	-
	C	11	4	15	1
	D	-	-	1	-
PD		**22**	**8**	**30**	**11**
	A	-	-	-	-
	B	-	1	1	-
	C	8	2	10	2
	D	14	6	20	9
V/PD		**4**	**-**	**4**	**1**
	A	-	-	-	-
	B	-	-	-	-
	C	1	-	2	-
	D	3	-	1	1
Total		**37**	**12**	**49**	**13**

8.1.4 Concluding

To conclude this paragraph, from the incident mapping and the panel consultation some explanation for the variation in the model estimations are found. It is shown that there is a significant effect of closely situated parallel runways and double RWY-RWY intersections, i.e. a runway that intersects multiple runways. Also, reducing factor was found for the incursion rate; higher number of non-right-angled TWY-RWY intersections has a different effect than the total intersection number I_n. Lastly, the need to assess operational procedures is demonstrated. For further research, it is therefore suggested to take these aspects into account.

8.2 Forecast study Schiphol (AMS)

Schiphol Airports is the international airport of Amsterdam and home base of KLM, the national airline carrier of the Netherlands. It accounts for the largest share of air traffic at the airport. In 2017, 48.2% of the aircraft movements were conducted by KLM (Royal Schiphol Group, 2018b). Other large airlines at AMS are easyJet (7,5%), Transavia (6,6%), Flybe (2,5%) and Delta Air Lines (2,4%). AMS is connected with 305 non-stop passenger destinations and 21 cargo destinations worldwide (figures from 2017), of which respectively London Heathrow, Frankfurt and Paris Charles de Gaulle are the most important. In 2017, AMS handled more than 68.5 million passengers via 496,748 aircraft movements. It is Europe's third busiest airport in terms of passenger volume and the eleventh in the world. Almost 37% of the passengers use AMS as transfer airport.

8.2.1 Operations

Between 2007 and 2017, AMS handled a total of 4,904,835 flights. On average, this means a traffic number of 445,894 annually. The hourly number of flights at the airport T_h is 49.5, in which the number of operational hours per week O_w was set to 168 and the share share good weather $V_g = 96.2$.

During the study period, 393 runway incursions were counted, of which 3 severity cat. A, 9 of cat. B, 44 cat. C and a rather large share of 338 for cat. D. The high share of cat. D incidents can be explained, according to the panel, by the stringent reporting culture for incidents. For example, a large share of D incidents is represented by a sequence of aircraft that used infrastructure that was not yet cleared, while there was an absence of any danger of accidents. Since the beginning of 2018, the definition of this characteristic type of incursions at Schiphol, has been adapted, such that more relevant information is collected for incursions. However, the higher severity incidents give a more accurate view of the situation for Schiphol. The high severity R_{rate} at AMS is 1.15. The scatterplot in Figure 8-5 gives a comparison of AMS in perspective to the analysed airports in the US. Here, the airport performs rather average on the incursion rate. Information regarding types of incursions for Schiphol is not available.

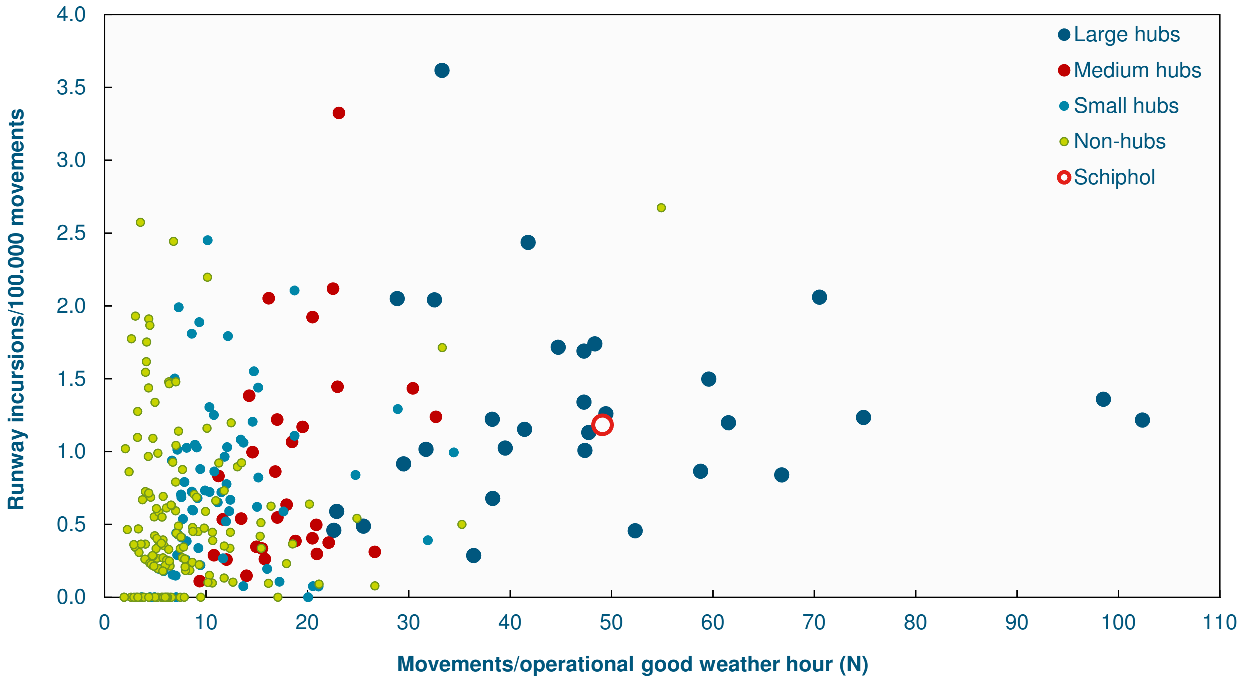


Figure 8-5: High severity incursion rates: Schiphol in perspective to the analysed US airports

8.2.2 Geometry

The layout of AMS is shaped by six runways with a total length L_{tot} 19.5 km. Per runway-km, the surface area is xx hectare. Characteristic is the central terminal area Schiphol Centrum, where all passenger flights depart and arrive, according to the 'one-terminal concept'. The terminal consists of three departure halls, one main arrival hall and seven piers. The six runways are situated according to a tangential runway concept, except of the Polderbaan and the Oostbaan (04/22). This concept was developed by Jan Delleart for the large airport expansion in the 50's. The objective was to minimise the impact of unfavourable wind situations. As it is preferred to take off and land in the direction of the wind. The airport diagram of AMS can be found in Appendix A15.

Four runways have displaced thresholds. There are no closely related parallel runways and two runways intersect each other ($I_r = 0.17$). The TWY-RWY intersection density I_n is 2.67. The runways can be crossed by aircraft at 14 possible locations. For passenger flights, the number of required crossings C_{req} is 0, while for cargo traffic there is an exception because of the geographical location of their cargo apron Sierra, resulting in a C_{req} of 1. For this, the required crossings of operational runways are considered. Though, the model does not make this distinction, and therefore relies on $C_{req} = 1$ for all air traffic.

The ratio non-right angled TWY-RWY intersections is 0.42. There are 17 RETs present at AMS. Furthermore, one area can be classified as complex intersection. Lastly, four locations are known as hot spot and there is no RSL system in operation. Though, a special warning system is implemented which aims to avoid runway incursions, the Runway Incursion Avoidance System Schiphol (RIASS).

8.2.3 Forecast

The developed model is applied to make a forecast for high severity incidents under various scenarios. An overview of the results is depicted in Figure 8-6. The same as for the other case airports (Appendix A14), the R_{rate} shows large variations during the study period. The model performed rather precise in the prediction of the incursion rate, with an estimated R_{rate} of 0.82, while the observed values is 1.15 and considering the fluctuations (solid grey line).

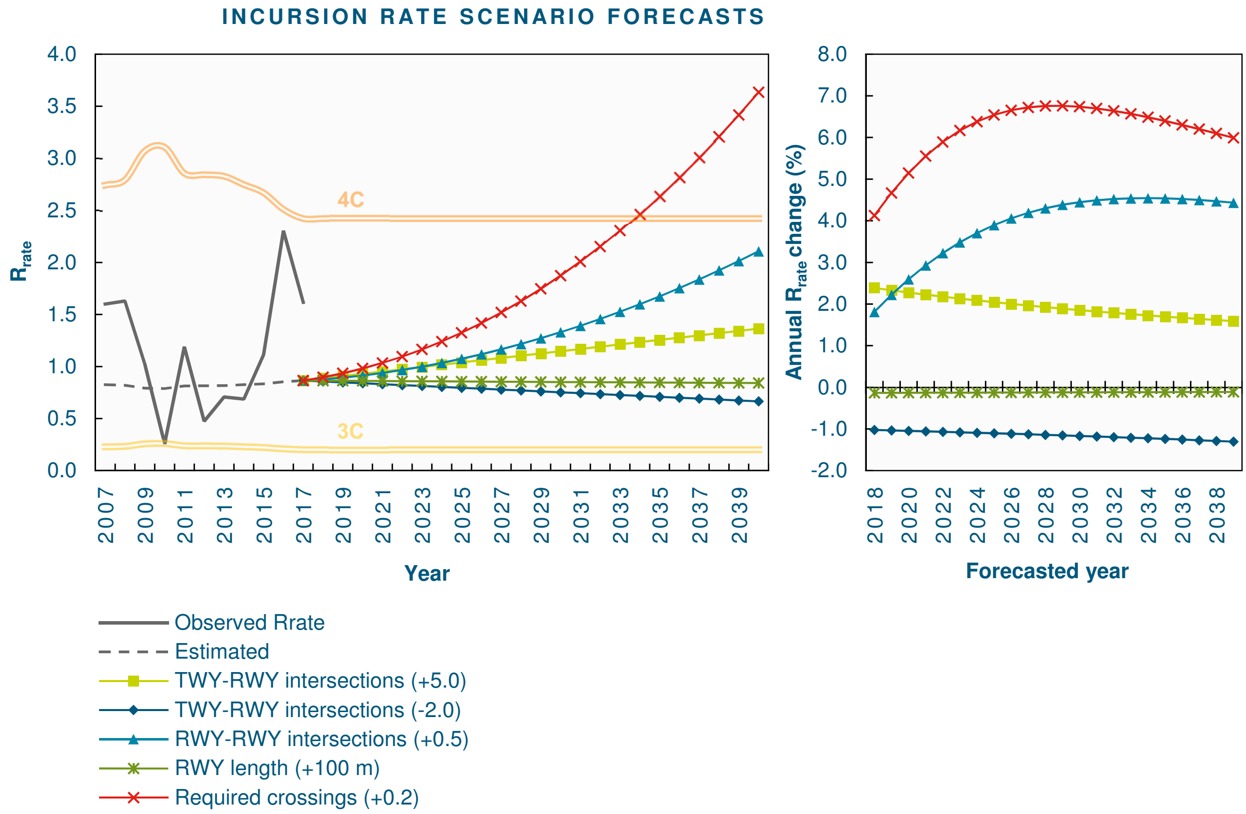


Figure 8-6: Schiphol (AMS) incursion model scenario forecasts

For the forecast period, five scenarios are developed to analyse the effects on the R_{rate} values. The threshold lines for risk frequencies are shown in the graphs. In Appendix A11, the method for the determination of the risk category is explained. These correspond to the frequency related risk matrix for major incidents C3 and C4. As can be seen in the graph, the risk threshold fluctuates over the observation years, since the applicable risk measure is based on the number of movements.

Furthermore, it can be observed in the figure, that only a yearly addition of 0.5 RWY-RWY intersections would result in the exceedance of the C4 threshold by 2034. The annual percentage of change is depicted in the second graph in

Figure 8-6, since the effects are non-linear. Also for AMS, the estimated R_{rate} does not reduce to below C3 in any of the scenarios.

To conclude, this section showed the potential for the application of the model for given airport cases. For the long term, the effect of modification scenarios can be charted. Though, deviations in observations, which are not captured by the model, should be kept in mind. Stricter reporting and chancing operational procedures are example causes for this variance.

9 Conclusions and recommendations

The aim of this research was to “obtain knowledge on how airport characteristics influence the likelihood of runway incursions, based on historical incident data”. This objective emerged from the problem definition, for which the research has been executed: “to expand airports for growth of traffic volumes, and to design green field airports in a way such that the probability of runway incursions is reduced, it is necessary to have an understanding of the relation between the geometric factors and elements of an airport and the probability of runway incursions.” To give guidance to the study, research questions were developed as part of the research proposal. In this chapter, the research questions are answered and the conclusions are drawn.

The results are compared to the hypothesis and the research proposal. Furthermore, recommendations for future airport planning with regard runway incursion mitigation are provided.

9.1 Research questions

First, the defined sub questions are answered, before the main research question is considered in the next section. For each sub question, a brief conclusion is provided in the blue boxes.

SQ1 *What do global standards direct and advice regarding incursion risk mitigating airport design?*
The threat of the directives, published by ICAO, the FAA and the EASA, is to restrain the need to cross runways. Airport layouts determine whether runways have to be crossed to access certain areas of the airport, such as hangars, terminal areas, etcetera. Therefore, airport layouts should be designed in such a way that these required crossings are limited.

Furthermore, directives suggest minimising the number of non-right TWY-RWY intersections, because of its side-effect of visual hindrance for pilots (PD) and vehicle drivers (V/PD). Right-angled intersections are preferred. Also, the number of conflict points such as TWY-RWY intersections is defined to be a relevant factor. The number should be minimised, according to the standards. Furthermore, it is discouraged to design airports which incorporate intersecting runways. Also, the implementation of complex intersections is discouraged and inadequate signage is stated to be an influencing aspect.

Lastly, the FAA launched a campaign that encourages airport designers to avoid direct access, wide expanses of pavement near runways, Rapid Exit Taxiways (RET) leading directly onto another runway, short thresholds, short taxiways, aligned taxiways and insufficient spacing between parallel runways. As mitigation tools, Runway Entrance Lights (REL) are promoted.

> The number of any type of intersections should be minimised, non-right angled TWY-RWY intersections are discouraged and additional airport illumination can support the mitigation of incursions.

SQ2 *Which airport characteristics are defined as causal factors for incursions in incident investigation reports?*
Investigation reports broadly underpin the directives for airport design. In the end, the need to cross runways is known as the underlying cause of a large share of the incursions. The location of the maintenance area or cargo platforms, for example, determines the necessity for aircraft to cross runways in order to access the terminal apron, and is therefore important aspects to consider during the planning of an airport.

Also, locations were multiple taxiways and runways intersect lead to potential complex situations. Pilots of large aircraft may have a better overview of the situation than small aircraft and vehicle drivers. This should be kept in mind when designing intersections of more than three nodes. Conventional right-angle exits are generally known as disadvantageous, since it requires aircraft to brake to a complete standstill after landing, before leaving the runway. This contradicts with the encourage to implement right-angled taxiways, which avoid visual hindrance for departing traffic. Lastly, the discourage to implement closely situated parallel runways, was justified by reports from Honolulu (HNL), where insufficient spacing between the runways caused a large share of the incursions.

> Investigation reports underline the importance of aspects discussed in the design standards. However, some discouraged elements (e.g. non-right angled TWY-RWY intersections) could also have a positive effect, as has been demonstrated by incident mappings and reports.

SQ3 *Which airport characteristics are relevant for data analyses?*

From literature and consultation of the expert panel, both geometrical and operational aspects were shown to be relevant for the analysis of incursion likelihoods. Operational aspects include the type of flights (general aviation, commercial), the air traffic mix (size of aircraft), the size of the airport in terms of handled passengers (indicator for size) and the number of flights. Visibility conditions are a relevant variable in this respect, since it determines the intensity of operations. Taxi delay was another relevant aspect for analysis, since it was assumed that incursions are not related to this characteristic.

Relevant geometrical elements include the presence of intersecting runways and parallel runways, the presence of runway crossings, TWY-RWY intersections (both number and type), complex crossings and the need to cross runways. Runway length and width are assumed to have minor impact on the incursion likelihood. Nonetheless, runway length is important for the expression of certain elements, such as the density of intersections. Likewise, the number of runways is used for expression of runway movements. Intersecting Runway Safety Areas is also an important factor. However, because of data collection issues, this was excluded.

Lastly, the presence of Runway Status Lights (RSL) was assumed to be a relevant characteristic. Special elements, such as direct access, aligned taxiways, wide expanses of pavement and the number of construction occurrences were defined to be relevant. Though, not enough data was available for statistical analysis.

Both operational and geometrical characteristics are related to the likelihood of runway incursions and are therefore analysed. Since not for all aspects an appropriate data sample was available, these characteristics are not examined.

SQ4 *What is the influence of the airport characteristics on the rate of runway incursions?*

Analysis showed that part of the characteristics relates to the likelihood of incursions. Some aspects showed a positive correlation, while others appeared to have a negative correlation.

Firstly, the operational aspects. It was shown that the highest total incursion rates were observed at airports with a larger share of general aviation traffic. Also, Airplane Design Group (ADG) cat. A aircraft showed a higher incursion rate, indicating general aviation traffic. Consideration of the airplane size revealed that large aircraft are relatively more often involved in incursions, regardless of the severity and type of incursions. Taxi delay appeared to have no relation with the occurrence of incursions, especially when the US operational culture is considered. Hourly airport movements was found to be a significant estimator of incursion likelihood. As the number of movements increases, the high severity incursion rate increases as well. Nonetheless, there appeared to be a flattening of this trendline; the incursion rate growth reduces for higher movement numbers.

Regarding geometrics, it was shown that the number of required runway crossings is an important estimator for incursion likelihood. The incursion rate increases as the number of required crossings increases. Also, the incursion rate increases as the ratio intersecting runways grows, and likewise, as the density of TWY-RWY intersections increases. However, as the ratio non-right angled TWY-RWY intersections increases, the total incursion rates reduce. This assumption applies for both RETs and non-right-angled intersections which are not defined as RET. In other words, airports which are equipped with RETs tend to have a lower total incursion rate.

Furthermore, assessment of interactions between characteristics and high severity incursion rates indicated that the influence of the number of TWY-RWY intersections per runway-km depends on both the number of required runways and the ratio intersecting runways. If runway crossings are not required, the incursion rate shows less growth for higher intersection densities than in case crossings are required. Likewise, the incursion rate increases stronger for a higher density of intersections as the ratio intersecting runways is larger.

Lastly, the main airport density, expressed as the availble airport surface per runway-length, showed a relation with the frequency of incursions. It can be seen that an increasing surface area relates to a decreasing incursion rate. Moreover, the presence of complex intersections and runway crossings contribute to higher incursion likelihoods. Also, airports equipped with RSL showed to have lower incursion rates, than comparable airports in terms of movement numbers, without this technology.

Higher total incursion rates if:

- Larger share GA traffic
- Larger share heavy aircraft
- Larger number of hourly airport movements
- Larger number of required runway crossings
- Larger number of TWY-RWY intersections
- Larger number of complex intersections

Lower total incursion rates if:

- Larger ratio of non-right angled TWY-RWY intersections and RETs
- Larger airport surface per runway-km
- Presence of Runway Status Lights

SQ5 *How do the results differ depending on the severity and type?*

It is shown that there is a wide variation across the types of incursion rates: total, high severity (A+B+C), low severity (D), PD, OI and V/PD type. The total incursion rate appeared to be not an appropriate estimation variable for the selected characteristics, as most characteristics showed no association. It was concluded that D incidents have a strong influence on the total frequency. This can be explained by the fact that a large share of D incidents is not the cause of the infrastructure; it is often the consequence of communication errors and other unexplained variance. Observation of the correlations for incursion types learned that the majority of significant associations are found for OI.

Also, the correlations with airport characteristics showed differences across the types of incursion rates. Hourly airport movements is only associated with high severity and D incidents, OI and V/PD incursions. This seems plausible, as Air Traffic Control (ATC) is higher utilised when the number of movements is high, while this does not necessarily affect the performance of the pilot. The share commercial traffic is only associated with the frequency of severity D incidents, which could be caused by the share of GA aviation; the type of traffic which is assumed to be more vulnerable to D incidents. In line with the hypotheses, the incursion rate for PD shows a decrease when the share of commercial air traffic increases. Meanwhile, OI seem to be related to an increasing share of commercial traffic. Associations also showed that an increasing share of heavy associates with an increasing OI rate.

Furthermore, the ratio intersecting runways is significantly associated with all rates except of V/PD. Higher intersection ratios seem to be correlated with higher incursion rates for both total and high severity. This also applies for larger numbers of TWY-RWY intersections per runway-km. For OI and PD, intersection numbers are positively correlated to the incursion rate. The ratio non-right-angled intersections correlates with only high severity and OI incursions. The same applies for the ratio RETs. Higher ratios of non-right-angled intersections and RETs relate to higher incursion numbers, which is in line with the hypothesis. The variable required crossings correlates to all incursion rates. For each applies that the incursion frequency increases as the number of required crossings increases. And for the variable hectare per runway-km applies (for high severity and OI rates) that larger surface areas per runway-km available imply lower incursion rates.

Lastly, the likelihood of D and PD and incidents is lower for airports equipped with RSL. For the other incursion rates, no associations were found, which can be substantiated by the fact that RSL is especially implemented for the main users: the pilots.

Total incursion rates should not be considered for in-depth analysis, because of the large differences between high severity and D incidents. Also for incursion type, disaggregation is preferred since only for OI incidents the most associations were found; PD and V/PD have a large influence on the total incursion rate.

SQ6 *Are there significant airport outliers in the regression models? How does Schiphol perform compared to the model?*

Three datasets were created in order to test the effects of outliers on the model. The results explained in the previous sub question are based on the dataset in which non-hub outliers were excluded. It was shown that for this dataset, higher correlations exist between the data pairs. Incorporation of all outliers in the model resulted in the absence of correlations for some data pairs. Therefore, it was chosen to use the semi-parallel dataset.

Based on the residual analysis (difference observed and estimated incursion rate) for the model, airport cases were extracted. From this, the hub airport with the highest positive residual (HNL), the hub with the lowest residual (PHX) and the hub with the smallest residual value was selected (IAH). These airports were further analysed as case studies.

Lastly, Schiphol (AMS) was analysed in more detail. It appeared from the mapping of AMS in perspective to the scope airports, based on high severity incursions, that the airport performed rather average between the large hubs. This underlines the assumption that the use of total incursion rates results in distorted outcomes on the performance, because of the large influence of D incidents. Indeed, AMS recorded a relatively high number of D incidents, which was substantiated by the input from the expert panel.

The exclusion of unimportant outliers (non-hub and other airports) resulted in higher correlations and additional associations between airport characteristics and incursion rates. Because of their importance, hub airport outliers have a positive contribution to the data set.

SQ7 *How can these outliers be clarified?*

The differences between the observed and the estimated incursion rates for HNL can be explained by airport characteristics that were considered in the model. For HNL, the presence of parallel runways resulted in a large number of incursions. Nonetheless, parallel runways were not modelled because of the collinearity with intersecting runways. Furthermore, the combination of parallel runways and intersecting runways seem to have an interaction; the impact of double intersections at one runway is possible greater than for a single crossings runway.

At PHX, the presence of a higher TWY-RWY density resulted in a lower frequency of runway incursions. Instead on the assumption from the model that higher intersection numbers lead to higher incursion rates, the overserved rates for PHX are contrary. This is explained by the large number of 'higher speed' exits, which provide multiple possibilities for aircraft to exit the runway after landing. Departing aircraft use right-angled intersections at the runway-ends. Since the ratio of non-right TWY-RWY intersections was not added as a characteristic in the model, the potential positive contribution could not be modelled. To conclude, the type of intersections is important to distinguish, as well as the position at which it is implemented along the runway.

The incursion rate for IAH was the best predicted by the model. This can be explained by the rather standard layout elements and the absence of special elements, such as closely situated runways.

Certain geometry aspects of an airport layout are not captured by the model.

9.2 Conclusion

In this section, the main research question is answered and recommendations are given for incursion-preventive airport planning, sorted per theme and presented in the grey boxes on the next pages.

RQ *Which airport characteristics influence the likelihood, the severity and the type of runway incursions and which recommendations can be made for incursion-preventive planning?*

As stated in the beginning, this study aimed to perform a statistical analysis to obtain insight in the relations between airport characteristics, with a special focus on geometrics, and the likelihood of the types and severities of runway incursions. From the results can be seen that this objective was largely fulfilled.

First, by the development of a frequency model that provides accurate estimations of high severity incidents at any given airport. The potential for the application of the model on airport cases has been demonstrated, as well as the transferability onto cases outside the US. Although further improvements are found, to cope with the variation in the estimations, existing airports can be analysed on their incursion likelihood. Likewise, designs for future green field airports, can be judged on the mitigation of runway incursions. The analysis that led to the model estimation, the model on its own and the theory and substantiation by the expert panel, provided general recommendations for incursion-preventive airport planning. Therefore, the scope expansion beyond Schiphol, to obtain a more general understanding of the topic and to plot AMS in the spectrum of other airports, has been demonstrated to be valuable.

Also, by the clear differences that were found between the associations with airport characteristics and different types of incursion rates (total, high severity, low severity, OI, PD, V/PD). However, the share of the highest severity categories A and B was such small that appropriate statistical analysis was impossible. Despite of the long-studied time interval (2007-2017), the same problem was faced as earlier research on runway incursions dealt with. Given that A and B incidents rarely occur, it is not expected that a longer time interval would allow statistical modelling of these incidents. Moreover, the number of these high severity incidents show a decreasing trend, and therefore, category C maintains the most interesting category for analysis of airport characteristics.

To deal with the data shortage, A, B and C incidents were aggregated into a high severity category, because of their similar character; the main difference is explained by the Closest Horizontal Proximity between two objects, and D incidents represent often a different character of incident. It was found that the influence of airport characteristics on the likelihood of incursions depend on expression of the incursion rate. The total number of incursions normalised for the number of aircraft movements cannot be properly modelled with regard to airport characteristics. However, the high severity incursion rate is associated to the majority of the airport characteristics, including the geometry variables, and the likelihood of D incidents is generally not explained by the infrastructure. Likewise, OI, PD and V/PD incidents should be treated separately. Only for operational incidents, most of the characteristics showed an association. For PD and V/PD various outside-the-scope circumstances play a role. Although in-depth analysis and regression modelling was not possible for all the severity and type categories, the preceding high-level analysis resulted in valuable insight in the interactions between airport characteristics, incident circumstances and incursion types. Also, the combination with the qualitative reviewing by the panel resulted in a better understanding of runway incursions.

From this research, the conclusion of Galle et al. (2010) stating that geometry is not a significant predictor of runway incursions, can clearly be refuted. In that study, geometry was considered as one factor. In this research, disaggregation into geometry elements resulted thus in a contrary conclusion. Also, partly contrary to the results of Wilke et al. (2015a); (2015b), stating that the incursion rate hardly associates with airport characteristics, and conformable with other studies, the incursion rate does appear to be affected by the airport characteristics.

9.3 Recommendations

From the results, general recommendations can be given for incursion-preventive airport planning. These follow both from the high-level analysis and the model estimation. Below, preferred and discouraged geometry elements are discussed and clarified by example airports. In the first box, the geometric are ranked according to their importance.

Here, two variants are given; first the geometrics in isolation (effect on incursion rate for an increase per characteristic) followed by the combined effects in the model (based on standardised beta coefficients).

Importance of individual geometrics

1. Required runway crossings
2. Ratio intersecting runways
3. Number of TWY-RWY intersections per runway-km

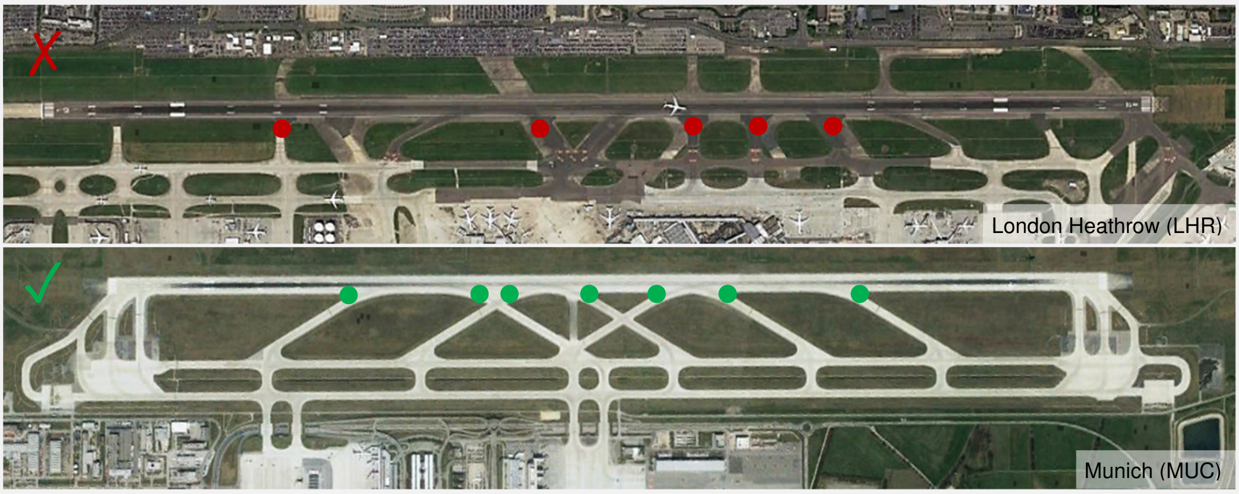
Importance of geometric attributes in the model (standardised contribution to the estimation %)

1. Number of TWY-RWY intersections per runway-km × ratio intersecting runways (29.3)
2. Number of TWY-RWY intersections per runway-km (21.1)
3. Required runway crossings (21.8)
4. Ratio intersecting runways (-0.02)

The remaining 20.8% is represented by hourly airport movements

TWY-RWY intersections

- Position right-angled intersections only near the runway-ends, such that these are predominantly used by departing aircraft.
- Position non-right-angled intersections only in the mid-range of the runway, such that these are predominantly used by landing aircraft.
- Higher densities of intersections are only encouraged for the mid-range of the runway and if there are no required runway crossings.



Runway crossings

- Avoid runway crossings.
- If needed, position runway crossings only on the runway-ends, not in the centre of the runway: avoid high energy crossings.
- If needed, construct runway crossings always as double right-angled intersection.
- If needed, additional runway crossings have lower impact in case no required runway crossings are present.

Intersecting runways

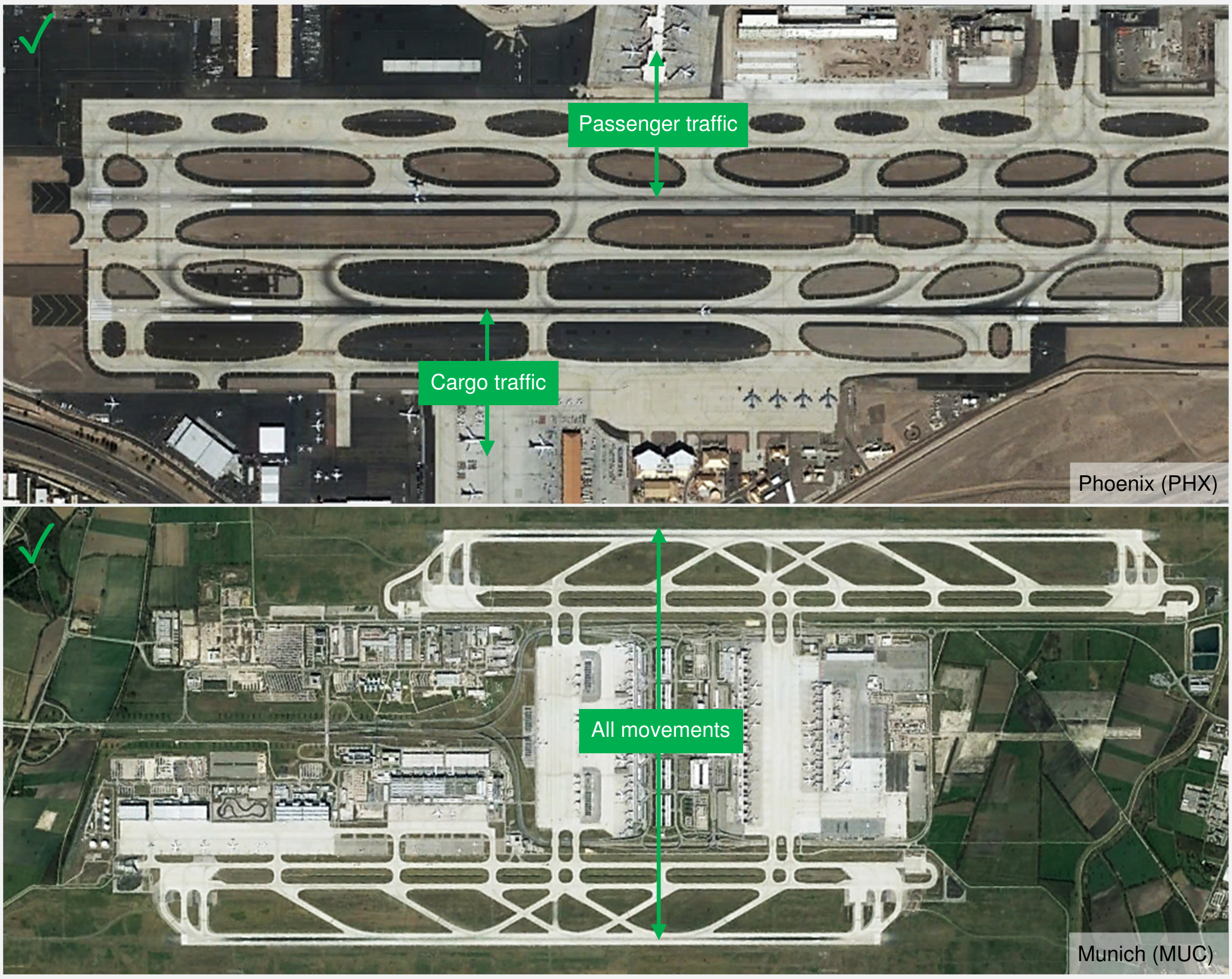
- Avoid intersecting runways.
- If needed, construct intersecting runways only if their operations are independent of each other.
- If needed, in case intersecting runways are operated simultaneously, the implementation of RSL.

Complex intersections

- Avoid complex intersections.
- Avoid aligned taxiways, direct access, RETs leading directly onto another runway and wide expanses of pavement.

Layout

- Position aircraft related areas (hangars, parking aprons) on the same side of the runway as the terminal acreage.
- Construct designated runways for certain terminals, airport areas or air traffic types.



10 Discussion

This part of the report evaluates the results, conclusions and research method, which have been explained earlier. The discussion is divided into two main parts. First as evaluation, the limitations that were found during the research process are discussed. Thereafter, suggestions for further research are presented.

10.1 Evaluation and limitations

The topic of runway incursions has shown to be very broad; many circumstances determine the risk of an incursion, i.e. the component of severity and likelihood. Even the estimation of incursion likelihoods requires many variables that are complicated to capture. Although multiple qualitative and quantitative research have been conducted on the causes of runway incursions, it was concluded from the literature study that it is hard predict these incidents. This is somewhat logical, since various studies are bounded to a certain topic, such as communication, weather and infrastructure. The aim to connect the dots of the knowledge into an encompassing tool has been tried, such as by means of Bayesian Beliefs Networks. Though, it appeared to be complex to capture all variables that play a role in the modelling of incursions. Nonetheless, it is known that the characteristics of an airport, and especially the geometry, represent an important share of the causes. In this area of research, a gap of knowledge still existed, such became clear from the literature study.

From this, and taking in mind that a large share of the variation in the results could not be explained, a statistical analysis was conducted that incorporated both geometry and operations, since it was assumed that these types of information are strongly intertwined. Obviously, this study was not the first research to focus on the influence of airport characteristics on runway incursions. Though, the literature study indicated that various geometrics were only qualitatively analysed and not by means of data. Also, earlier studies used much smaller airport samples (maximum of 137) and shorter study periods. Therefore, the results presented in this research are assumed to give a more accurate estimation, which was also shown in the comparison phase, using the Claros et al. (2007) model. The final model achieves to explain almost 40% of the variability of the response data and is therefore, based on comparable studies in the field, quite accurate. Apparently, airport geometry represents a major share in the occurrence of the incidents.

Though, when comparing the model estimations with the observed incursion rates for certain airports during the study period it appeared that the mean rates were quite well predicted. However, often large fluctuations are shown in the incursion frequencies; for some years, small numbers of incursions were recorded, while for the subsequent years large numbers occurred. This could be the consequence of various factors, which are not covered in the study. For instance, the model is based on good visibility conditions to reduce noise on the airport characteristics, therefore weather impacts for certain years could explain part of the variation.

It is a consideration whether to implement additional variables into a model, leading to a lower significance level, or to maximise the number of variables within the confidence interval. In this study, the latter case is chosen. Though, in order to extend the model further, a larger data sample is needed to improve the correlations. Then, for example, also a weather component could be included. Nevertheless, this will imply many difficulties in data collection, because of the small share of incidents during bad weather and the complication of collecting data from multiple countries.

Another point to mention is that the model is predominantly focused on the geometric attributes. Although the number of hourly movements is incorporated as well, the model is not appropriate to be used for the entire theoretical extent. In other words, for unrealistic high movement numbers and equal geometry input, the incursion rate would not result in remarkably high values. This is the consequence of the rate being expressed per 100,000 movements. Hence the infrastructure is limited to a maximum number of flights which can be handled, based on ATC requirements, separation, etcetera. Therefore, the model can be a useful tool to acquire a general view of the incursion likelihood at an airport which already exists or after a proposed airport design has been approved by means of conventional modelling software.

In addition, operational procedures with regard to the ATC are not covered in this research. For instance, the procedure in which runways are used; two crossing runways might be never used simultaneously (lower incursion risk), while this could be daily practice at other airports. This effect, for example, is not captured in the analysis. The main reasoning for this decision was the complexity to collect the procedural information for all the scope airports. Also, procedures could have changed during the study period. Consequently, a much smaller airport sample would be obtained, meaning that a reduced power to estimate geometrics based on potential unreliable information.

Likewise, from the high-level analysis it was chosen to exclude the variable ratio parallel runways for the model estimation, as it showed a correlation with ratio intersecting runways. By excluding this aspect, the interaction between parallel runways and intersecting runways was not tested, while there could be a reinforcing effect on the influence of incursion likelihoods. Also, the presence of closely situated runways has a negative effect as the case study of HNL showed, which is not covered by the model.

Last point to raise is the chosen method of research validation by means of expert judgement. This method was found to be valuable, since many of the results could be understood from the experience from the airport users. Though, it can be argued that a larger panel, with more representatives for the chosen stakeholders, would be more valuable since different views and opinions can then be considered for each actor. Because of a broad existing basis of qualitative studies, it was chosen to not extent this qualitative part of the study, but rather to use it as additional tool to understand and explain the results.

10.2 Directions for further research

Throughout this research, various starting points were found for further research. Partly based on the evaluation and limitations discussed above, it is suggested to expand the analysis by adding a larger dataset. Hence, in terms of representative airports, this must be found outside of the US. But also, in terms of incursion numbers, additional yearly data would provide an improved model.

As mentioned earlier, the problem for the modelling of the relationship between A, B and C severity incidents is clear. The rarity of A and B incidents make them complicated to predict. In order to acquire additional justification for the presence of a relationship, it is recommended to perform an analysis solely on the severity of incursions, regardless of the airport characteristics. Hence, for this it is required to sample airports and incursion characteristics from airports around the world (not only US), in order to have an appropriate dataset.

Another suggestion is to expand the scope of an airport to the control zone around the airport (Controlled Traffic Region). In this way, variables that determine the aircraft separation in the air, could be considered. For example, runways which do not physically intersect each other might still have intersecting Runway Safety Areas, such as was seen in the case study for HNL. This could then be modelled as well.

Furthermore, a different the definition of airport utilisation can be applied. In this study, the number of aircraft movements is expressed as the hourly mean. Though, plenty large airports have to cope with peak hours, in which the hourly traffic figure may be more than doubled. Hence, this could imply a deviating likelihood on runway incursions. Therefore, a peak hour incursion model could be proposed.

As shown in the test for associations, operational incidents (OI) appeared to be correlated with the majority of the airport characteristics. Because of that, a frequency model could also be developed for this type of incidents. Likewise, a model could be developed for low visibility conditions, although airports do not operate according to their standard (and thus representative) procedures. Also, as said, this requires data collection of additional airports outside the US.

The selection of US airports for this case study has been underpinned by the availability of a large and reliable dataset. However, it can be argued that these results could differ from other airports around the world. Therefore, the developed model could be validated by means of an additional dataset, for example including all large hubs globally. Matter of course, this would require much effort to collect all necessary data.

Finally, a separate model could be proposed in which the airports are treated differently in the database, depending on their size or another measure of importance, i.e. weighted regression fitting. These results could act as valuable validation tool for the existing model. Moreover, it can be adapted for certain airport target groups, such as the small hubs.

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A1 Runway Incursion Severity Classification calculator

RISC is a computer programme (Figure A-1) that classifies the outcome of runway incursions into one of three severity categories “A”, “B”, or “C”. When only one aircraft, vehicle or pedestrian is involved in the incident, it is automatically defined as a category “D” RI. The programme does not story data, but it provides a standardised way to rate the severity of RI’s. An advantage of RISC is that the outcome is more objective compared to when using an assessment form, as severity judgements can change from person to person and from time to time. Because the rating (output) is standardised to the input, the ratings are consistent. Such consistency is essential to being able to examine trends over time or see the effects of mitigation strategies (ICAO, 2007).

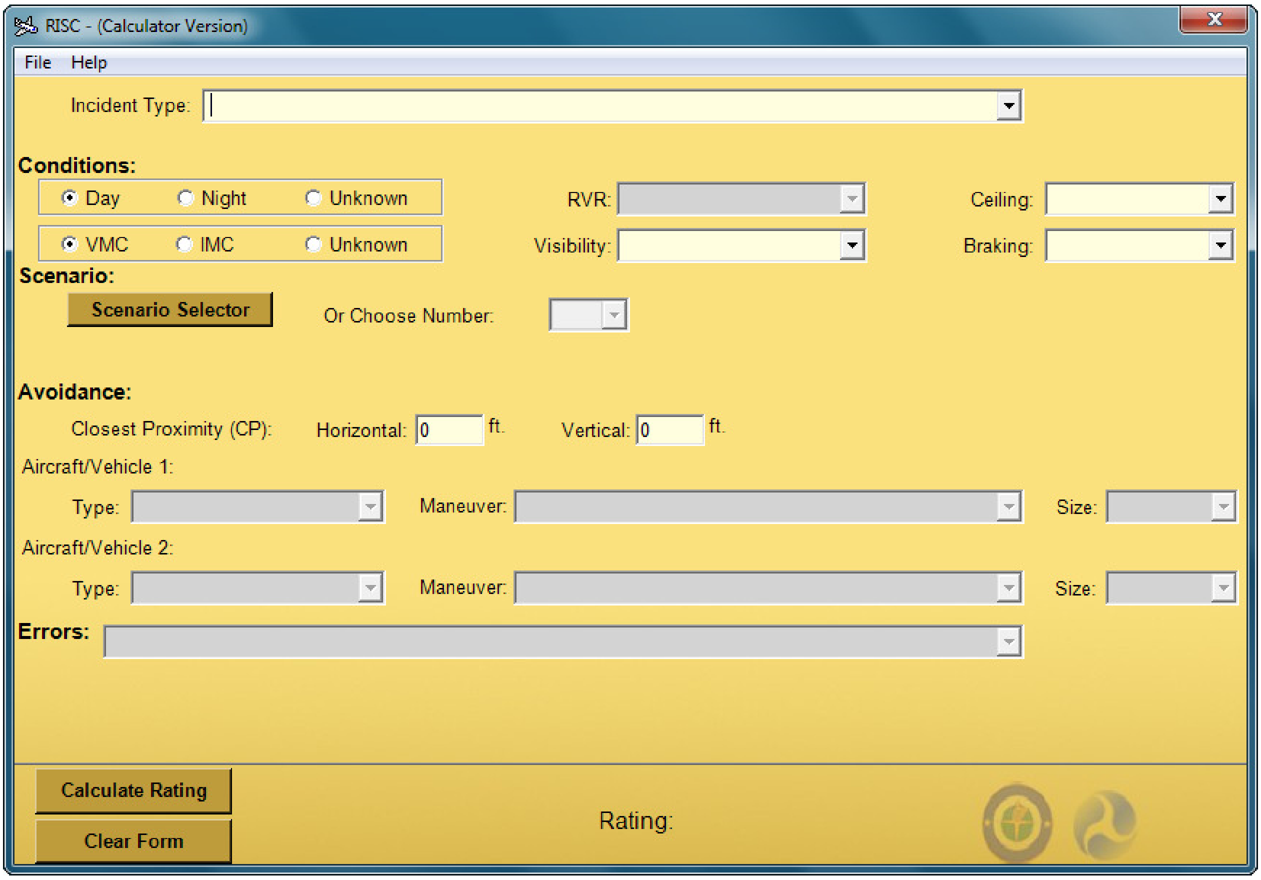


Figure A-1: RISC incident input interface

A1.1 Factors

RISC calculates a rating based on the characteristics of the incident, which has to be submitted via the input interface. The severity is defined as the outcome of the incursion in terms of the closest proximity (horizontal or vertical) that an aircraft came, or might easily have come, to a collision with another aircraft, vehicle or object on the runway. The severity calculation is based on:

- Closest proximity: the closest distance between the aircraft and the other aircraft, vehicle or pedestrian;
- Factors that affect the probability of a collision:
  - Visibility
    - Runway Visual Range (RVR)
    - Reported ceiling height and visibility
    - Day/night
  - Type of aircraft (dimensions and/or performance characteristics)
  - Characteristics of avoidance manoeuvre executed (including time available for pilot response)
  - Runway characteristics and conditions

- The width of the runway in situations in which an aircraft on the runway conflicts with an aircraft or vehicle approaching it from the side
- Dry
- Wet
- Braking action reported as poor or fair

- Degree to which the situation was controlled or uncontrolled (e.g., type of pilot/controller errors involved, whether all parties were on frequency, whether the controller was aware of all the parties involved)

A1.2 Rating

RISC aims to provide an outcome that represents the risk incurred, based on the stated factors above. For instance, the risk on a collision is larger in low visibility conditions when two aircraft on intersecting runways, compared to the same situation during clear weather conditions. The calculator does not base the rating on the worst possible or least credible outcome; it is not based on everything that could have gone wrong. RISC takes critical sources of variability within the scenario into account, on which of each of the factors, and to each element within the factor, a weight is assigned to.

Apart from defining a severity category, RISC also calculates a numerical value of the severity, specifying the runway incursions rating more accurately.

RISC is based on a set of predefined scenarios that cover all types of RI's. Each scenario describes the action of the parties that are involved in the incident. A specific set of factors are associated with the scenarios, which are subsumed with elements.

It is not applicable to helicopters and other aircraft that take-off and land vertically. Furthermore, the assessment tool cannot provide severity ratings in cases where more than two aircraft (or between aircraft and a vehicle or pedestrian) are involved.

A1.3 Mathematical explanation of severity determination

In this section, the mathematics behind the RISC model are explained, based on the theory by Sheridan (2004).

Severity S is a continuous scale of 1 to 4, with classifications A, B, C and D corresponding to severities of respectively 4, 3, 2 and 1. A 'plus' adding of 0.3 and a 'minus' subtracting of 0.3 is allowed, corresponding with a '+' and '-' (B+ = 3.3). A+ is not used, as it correspondents to an accident, instead of an incident.

Furthermore, 52 independent scenarios, categorized under the headings listed in Table A-1, are used to subsume broadly all incursion types. Per scenario, a predefined set of severities is available. Closest proximities are expressed as CHP (horizontal) and CVP (vertical).

Each scenario is further characterised by scalable factors, as listed in Table A-1. The factors are scaled by a variable potential P, ranging between 0 and 10. For the equations, the P values are divided by 10 (thus ranging between 0 and 1). Not all factors are applicable for each scenario. $P = 0$ means that there is no influence of that factor to make the severity of the given incursion greater than what is evident from the closest proximity CP. Thus, in the ideal situation in which there is not any influence from the factors, all P values are 0, and the S is represented by the 'best case' CHP or CVP. On the other hand, in case all factors are worst, then all P values are 10, meaning that the S is represented by the 'worst case' CHP or CVP.

Table A-1: Scenario categories and factors

Categories
Two landing aircraft
One landing aircraft, one taxiing aircraft
One landing aircraft, one aircraft taking off
Two aircraft taking off
One aircraft taking off, one taxiing
Modifications to these when vehicles and/or pedestrians are involved

Factors
Visibility/RVR/ceiling
Take-off or landing aircraft #1 (weight and thrust characteristics)
Take-off or landing aircraft #1 (weight and thrust characteristics)
Controller erroneous communications or actions
Pilot erroneous communications or actions
Extraordinary remedial action taken by pilot

For each scenario, the best possible combination of factors is called S_b, and the worst possible combination of factors is called S_w. For example (see: Table A-2), when $CHP = 100$, $S_b = B$ when all P values are 0, and $S_w = A$ when all P values are 10. All factors are called S_i with 'i-th factor'. No S_i rating can be smaller than S_b or larger than S_w. When $S_b = S_w$ than $S_b = S_i$ and $S_w = S_i$. Combined factor influences can never push the severity rating beyond S_w.

Table A-2: A scenario with corresponding severity ratings per factor and closest proximity

Scenario #3: Two landing aircraft on intersecting runways, both landed, converging at CHP							
			Given factor S_i is worst case. All other factors are best case.				
CHP	S_b	S_w	Visibility/ RVR/ Ceiling	Information communication	Exceptional actions	Take-off A/C or A/C 1	Landing A/C or A/C 2
50	A (4)	A (4)					
100	B (3)	A (4)	A- (3.7)	A- (3.7)	A (4)	A- (3.7)	A- (3.7)
500	D (1)	A- (3.7)	A- (3.7)	B+ (3.3)	A- (3.7)	B- (2.7)	B- (2.7)
1000	D (1)	B+ (3.3)	C+ (2.7)	B (3)	B+ (3.3)	C (2)	C (2)
2000	D (1)	C (2)	C (2)	D+ (1.3)	C (2)	D+ (1.3)	D+ (1.3)
3000	D (1)	D (1)					

From here, an algorithm is used to calculate the exact numeric value for any given CHP, and a given set of P values, using the information that is available in each scenario table. The algorithm needs to combine and interpolate between the known information components. Several algorithms are presented and tested by Sheridan (2004), according to whether or not they violate the stated assumptions and to which degree they correspond to a reasonable sample of expert judgements.

The paper concludes that experiments have suggested that Equations 3, 4 and 5 are the best candidates for severity calculations.

Since D is the bottom of the S scale, S_i starts from 1, thus S can be calculated by (A-1):

$$S = S_b + P_1(S_1 - S_b) + [_{i=2\ldots n}P_i(S_i - 1)/_{i=2\ldots n}(S_i - 1)](S_w - S_1) \quad \text{(A-1)}$$

With the factor having the greatest P_iS_i product, called the 'primary factor', treated separately from the remaining factors, using an additional term $P_i(S_1 - S_b)$. This implies that if the other P_iS_i are 0 and $P_1 = 1$ than $S = S_b + (S_1 - S_b) = S_1$. Any remaining P_iS_i add their influence over the residual 'potential S distance' $(S_w - S_1)$. A schematic view of the components is shown in Figure A-2.

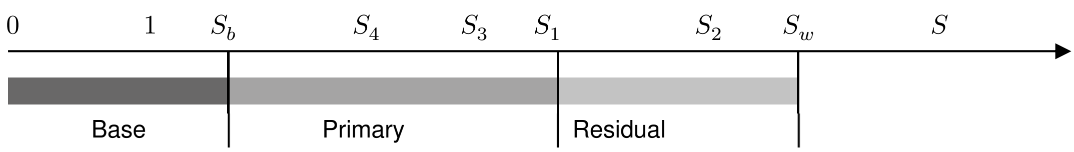


Figure A-2: S components used in the equations

Alternatively, S can be considered as a multidimensional space of independent factor influences, with three severity vertices, as depicted in Figure A-3.

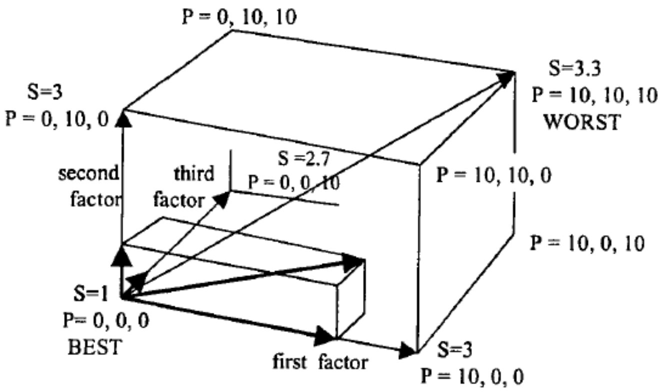


Figure A-3: Three factor severity space (Hannon & Sheridan, 2005)

For this method, S can be determined with (A-2):

$$S = S_b + P_1(S_1 - S_b) + [_{i=2...n}{P_i}^2(S_i - 1)^2/_{i=2...n}(S_i - 1)^2]^{0.5}(S_w - S_1) \quad \text{(A-2)}$$

Sheridan (2004) also suggests the following equation, derived from conventional combinatorial statistics (A-3):

$$S = K\{1 - _{all\ factors}[1 - P_i S_i / S_w]\}S_w \quad \text{(A-3)}$$

using K as a scaling factor

In case the CHP or CVP lies somewhere between the tabled values, S can be calculated by interpolation between CP_{lower} and CP_{higher}, as stated in the table. The following equation applies (A-4):

$$S(CP^*) = \left[\frac{CP^* - CP_{lower}}{(CP_{higher} - CP_{lower})}\right]\left(S_{CP_{higher}} - S_{CP_{lower}}\right) \quad \text{(A-4)}$$

A2 Definitions

This appendix covers all definition to which is referred in the report. First, the risk definitions are described, after which other general definitions are listed.

A2.1 Risk

ICAO classifies incidents (also other than RI) according to five safety risk severity categories, with the most severe category designated for an accident (ICAO, 2013). It is defined as the extent of harm that might reasonably occur as a consequence or outcome of the identified hazard[6].

Furthermore, a division is defined for the probability of occurrences. Safety risk probability is defined as the likelihood or frequency that a safety consequence or outcome might occur. Table A-4 gives an overview of the severity categories of ICAO.

Table A-3: Safety risk severity categorisation (ICAO, 2013)

Severity	Description	Value
Accident	An incident involving circumstances indicating that an accident occurred.	A
Serious incident	An incident involving circumstances indicating that an accident nearly occurred. Note: The difference between an accident and a serious incident lies only in the result.	B
Major incident	An incident associated with the operation of an aircraft, in which safety of aircraft may have been compromised, having led to a near collision between aircraft, with ground or obstacles (i.e., safety margins not respected which is not the result of an ATC instruction).	C
Minor incident	An incident involving circumstances indicating that an accident, a serious or major incident could have occurred, if the risk had not been managed within safety margins, or if another aircraft had been in the vicinity.	D
No safety effect	An incident which has no safety significance.	E
Not determined	Insufficient information was available to determine the risk involved or inconclusive or conflicting evidence precluded such determination.	

Table A-4: Safety risk probability categorisation (FAA, 2010)

Likelihood	Qualitative definition	Quantitative definition	Value
Frequent	Likely to occur many times (has occurred frequently)	Expected to occur more than once per week or every 2500 departures	5
Probable	Likely to occur sometimes (has occurred infrequently)	Expected to occur about once every month or 250,000 departures	4
Remote	Unlikely to occur, but possible (has occurred rarely)	Expected to occur about once every year or 2.5 million departures	3
Extremely remote	Very unlikely to occur (not known to have occurred)	Expected to occur once every 10-100 years or 25 million departures	2
Extremely improbable	Almost inconceivable that the event will occur	Expected to occur less than every 100 years	1

ICAO does not define a quantitative likelihood definition on which the airports can be plotted. Though, the FAA has quantifications defined for likelihoods, for multiple applications. Two distinct quantifications are known which are applicable for airport operations, since the other quantifications are related to incidents during flights, outside the airport scope. These are listed in Table A-4. For each likelihood category applies that the highest likelihood label of the two measures the one that counts, in other words for some airports the number of departures determines the likelihood, while for other airports this is the number of incidents per time window.

[6] A condition or an object with the potential to cause death, injuries to personnel, damage to equipment or structures, loss of material, or reduction of the ability to perform a prescribed function.

From the combination of the severity and probability of an incident, the safety risk can be derived. It is defined as the projected likelihood and severity of the consequence or outcome from an existing hazard or situation. In Table A-5, the ICAO safety risk matrix is shown. To each projected risk, a tolerability category is assigned. The risk indices shown in red form the 'intolerable region'. The yellow area is defined as the 'tolerable region'. Lastly, the green risk area is designated as the 'acceptable region'. A more precise description of the risks and tolerability categorisation can be found in Table A-6.

Table A-5: ICAO safety risk matrix (severity x probability)

Probability		**Severity** Accident A	Serious incident B	Major incident C	Minor incident D	No safety effect E
Frequent	5	5A	5B	5C	5D	5E
Probable	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Extremely remote	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Table A-6: Risk acceptability (ICAO, 2013)

Risk index	**Tolerability**	**Description**
5A, 5B, 4A	Extreme risk	Stop operation or process immediately. Unacceptable under the existing circumstances. Do not permit any operation until sufficient control measures have been implemented to reduce the risk to an acceptable level. Top management approval required.
5C, 4B, 3A	High risk	Caution. Ensure that risk assessment has been satisfactorily completed and declared preventive controls are in place. Senior management approval of risk assessment before commencement of the operation or process.
5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D, 2A, 2B, 2C, 1A	Moderate risk	Perform or review risk mitigation as necessary. Departmental approval of risk assessment.
3E, 2D, 1B, 1C	Low risk	Risk mitigation or review is optional.
2E, 1D, 1E	Negligible risk	Acceptable as is. No risk mitigation required.

The safety risk matrix can be adapted by service providers, using alternate descriptors, or more subdivisions. However, the previous explained system is meant as global standard.

A2.2 ICAO Airplane design group

Group	**Wingspan (m)**	**Tail height (m)**	**Typical aircraft**
A	< 15 m	< 6.1 m	Cessna 421, Learjet 35
B	15 m - < 24 m	6.1 m - < 9.1 m	Beech B300, Cessna 550
C	24 m - < 36 m	9.1 m - < 13.7 m	Airbus A320, Boeing 737, Embraer E190
D	36 m - < 52 m	13.7 m - < 18.3 m	Airbus A300, Boeing 757, 767,
E	52 m - < 65 m	18.3 m - < 20.1 m	Airbus A330, A340, A350, B787, B777, B747-400,
F	65 m - < 80 m	20.1 m - < 24.4 m	Airbus A380, Boeing 747-8

A2.3 FAA airport categories

Category	(Percentage of total) annual passenger boardings/definition
Large hub	1% or more
Medium hub	At least 0.25%, but less than 1%
Small hub	At least 0.05%, but less than 0.25%
Non-hub	More than 10,000, but less than 0.05% (primary)
Other	At least 2,500 and no more than 10,000 (nonprimary)
Reliever	An airport that is built or designated to provide relief or additional capacity to an area when the primary commercial airport(s) reach capacity

A2.4 METAR codex

Visibility		Cloud layers		Wind direction and speed	
1SM (measure used in the US)	1 statute mile (1,609 m)	• Each cloud layer ordered from lowest to highest altitude • Code plus 3-digit cloud height in hundreds of feet • Okta is a unit of measurement used to describe the amount of cloud cover		• Wind direction in tens of degrees • Wind speed in knots (KT)	
		Codes		23018KT	230 degrees true/18 kts
		SKC	Sky clear	+G30KT	Gusting to a maximum of 30 kts (in case the mean wind speed by 10kts or more in the 10 minutes preceding the time of the report)
		CLR	Clear below 12,000 ft		
		FEW	Few (1-2 oktas)		
		SCT	Scattered (3-4 oktas)		
		BKN	Broken (5-7 oktas)	VRB05KT	Variable/5 kts
		OVC	Overcast (8 oktas)	0000	Calm

Weather and/or obstruction to visibility

-	slight	+	Heavy	BC	Patches	BL	Blowing
BR	Mist	DR	Low Drifting	DS	Dust Storm	DU	Widespread
DZ	Drizzle	FG	Fog	FC	Funnel Cloud		Dust
FZ	Freezing	GR	Hail		(e.g. Tornado)	FU	Smoke
IC	Ice Crystals	MI	Shallow	GS	Small Hail	HZ	Haze
RA	Rain	SA	Sand	PL	Ice Pellets	PO	Dust Devils
SN	Snow	SQ	Squall	SG	Snow Grains	SH	Shower
VA	Volcanic Ash	VC	In the vicinity	SS	Sandstorm	TS	Thunderstorm
				UP	Unidentified	RE	Recent
					Precipitation		

A2.5 Low visibility procedures

Category	Visibility	Ceiling
VFR	> 5 mi	and > 3000 ft AGL
Marginal VFR	Between 3 and 5 mi	and/or Between 1,000 and 3,000 ft AGL
IFR	1 mi or more but less than 3 mi	and/or 500 ft or more but less than 1,000 ft
Low IFR	< 1 mi	and/or < 500 ft

A3 Examples of runway incursions per severity category

In this section, an example of a near-incident in the past is presented for each severity classification category. All examples are incidents at Schiphol.

A3.1 Cat. A: Airbus A319, Schiphol Airport, 2007

On the 5th of March 2007, an Airbus A319 nearly collided with a Boeing 747, while accelerating on the runway for take-off. According to an investigation by the Dutch Safety Board (2010), the flight crew of the A319 started their take-off acceleration assuming that they received permission for this. Meanwhile, the taxiing Boeing 747 was nearly crossing the same runway as was used by the A319. The crew of the A319 was directed to stop on the runway, while they stopped their take-off run as they observed the 747. In Figure A-4 an overview of the situation is depicted.

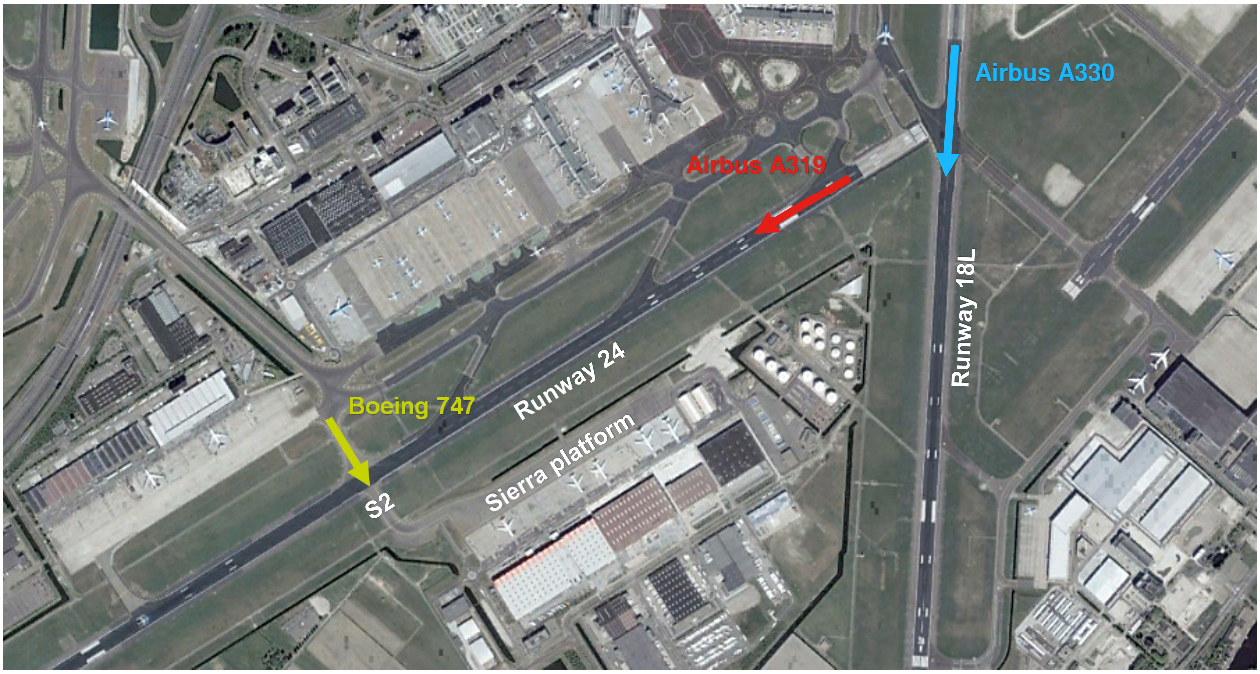


Figure A-4: Overview cat. A runway incursion Schiphol, 2007

The Boeing 747 was taxiing to the Sierra platform, on the other side of the runway. In 2007, the only opportunity was to cross Runway 24, at intersection S2. Since the intersection is located halfway the length of the runway, the impact of a collision could be catastrophic as the speed of the accelerating aircraft is almost at its maximum before the take-off rotation. Currently, an additional taxiway is available to reach the platform via the other end of the runway.

Also, a third aircraft was involved in the incident. An Airbus A330 was lined up at Runway 18L, ready for take-off. It received a take-off clearance from the air traffic controller; however, the crew of the A319 assumed that the clearance was intended for them.

A3.2 Cat. B: Bird control, Schiphol Airport, 2017

On the 31th of 2017, the ground vehicle Kiviet (bird control) was cleared for a runway inspection of Runway 36L, and the vehicle drove towards the runway end for the inspection (Dutch Safety Board, 2017a). A short while later, a Bombardier Regional Jet CRJ9 arrived from the terminal at Runway 36L for take-off. The ATC cleared the Bombardier for take-off from taxiway V3, while the bird control was still on the runway, near the runway end. The ATC did not take notice from this. Because the bird control reported that it had not left the runway, the take-off clearance was withdrawn. The situation is shown in Figure A-5.

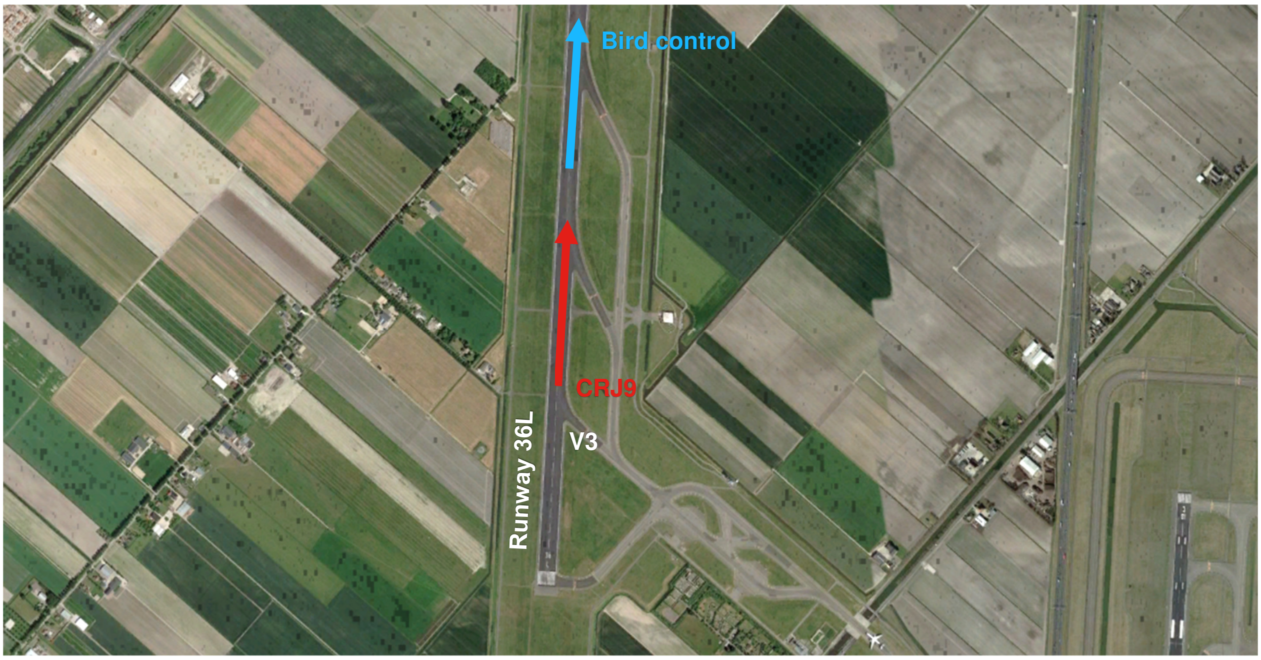


Figure A-5: Overview cat. B runway incursion Schiphol, 2017

A3.3 Cat. C: Airbus A330, Schiphol Airport, 2012

On April the 12th 2012, an Airbus A330 landed on Runway 18R at Schiphol Airport and taxied to the gate at the central terminal area (Dutch Safety Board, 2013). To reach this area, it is necessary to pass Runway 18C. The ground controller instructed the pilots to cross the runway area via taxiway Z2, which is located on the southern side of the runway. However, the crew assumed they have got permission to cross Runway 18C at the southern point, which was at that moment in use for landing traffic. The Airbus A330 crossed the runway via W11, which resulted in a runway incursion. Since the next landing aircraft on Runway 18C was still at a distance of 3 nautical miles, there was no danger of collision. RIASS was not activated because of the large spacing. The DSB investigation concluded that human factors played a causal role in the incident, and the pilots were unaware of the situation. Figure A-6 gives an overview of the situation.

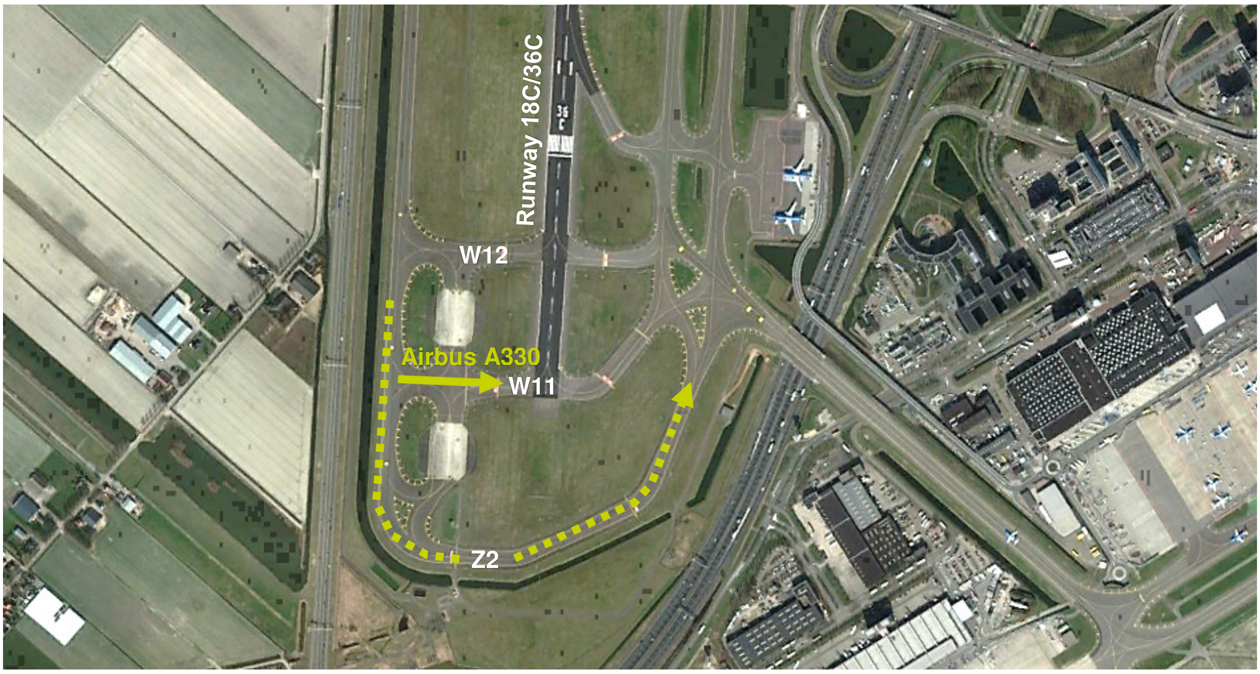


Figure A-6: Overview cat. C runway incursion Schiphol, 2012

At the time of the incident, the area around W11 was designated as hot spot. Earlier, as a measure to reduce the number of hot spots at Schiphol, the RST advised to change the markings in the area. However, this did not prevent aircraft from taking the exit. Afterwards, the lay-out was reconstructed such that W11 and W12 taxiways were closed.

A3.4 Cat. D: Airbus A320, Schiphol Airport, 2015

On 13 June 2015, Runway 18L was prepared to put into operation. However, the runway was not yet made available to the Air Traffic Control (ATC) by the Airside Operations Manager, because of an ongoing runway inspection (Dutch Safety Board, 2015). After the runway was inspected and approved, the ATC did not immediately contact the airport, since the first departure from the runway was not yet expected. However, the ATC gave an Airbus A320 permission to start from Runway 18L, after the ATC was informed about the not available runway. Since the runway was not occupied, the ATC decided not to abort the take-off.

In Figure A-7 the location of the incident can be seen.

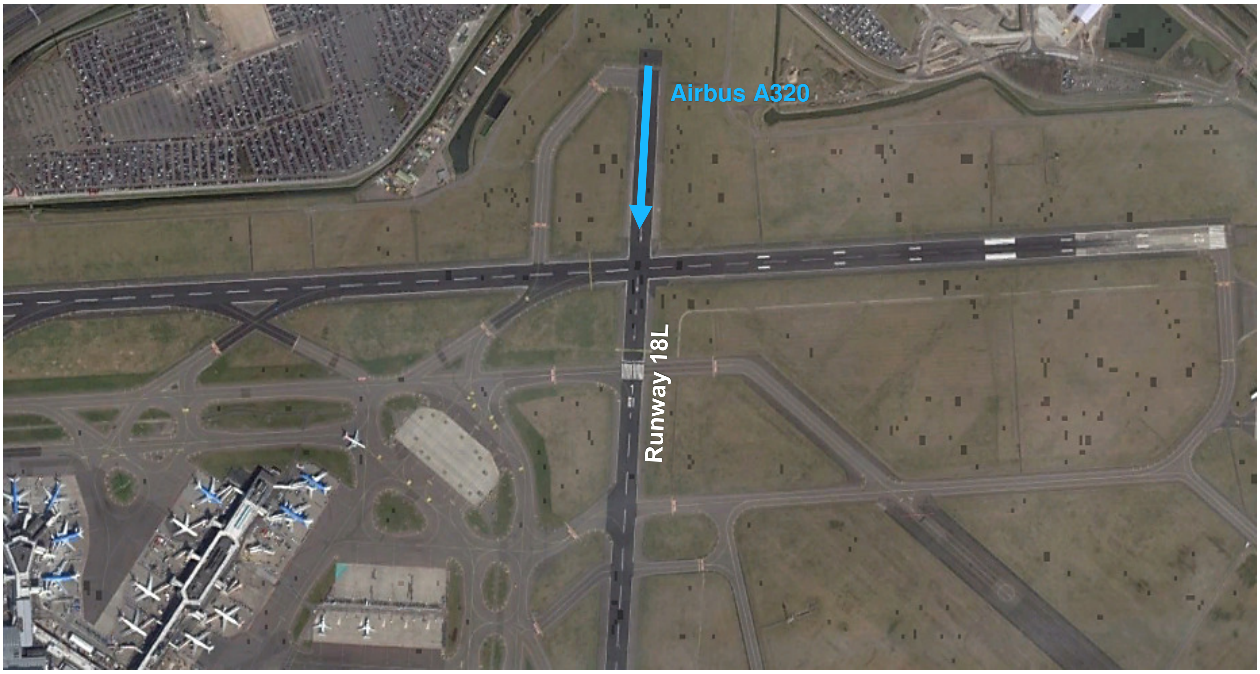


Figure A-7: Overview cat. D runway incursion Schiphol, 2015

A4 Interview reports

This section contains the full reports of the interviews which have been conducted during the panel consultation in phase 1 of the research. Post-analysis input is described throughout the report and is not worked out into an interview report. Also, the interview with investigators of the Dutch Safety Board, as part of the literature study, is added.

A4.1 Pilot

Profile	
Functions	Senior airline pilot at KLM Chairman of the Flight Technical Affairs Committee at Dutch Airline Pilots Association (VNV)
Experience	+20 years: first officer Boeing 747, Fokker 70/100, captain and instructor Boeing 737
Date	November 2018

What is your general view on the causal factors of runway incursions?
This very much depends on the definition one uses for a runway incursion. The definition used at Schiphol has recently been adapted; the new definition is in place since the beginning of this year. Two of my people are involved in the Runway Safety Team (RST) of Schiphol (AMS). Until recently, this was part of Veiligheidsplatform Schiphol (VpS), the organisation who oversees the overall safety at AMS. However, partly due to the publication of the investigation report by the Dutch Safety Board, AMS is changing its safety organization structure. From now, a Safety Management System (SMS) will be implemented, which is a more advanced safety structure. In the meantime, the RST still exists. Within the RST, incursions are already an important topic. The RST distinguishes different types of runway incursion (other than explained in this research). AMS is the owner of the infrastructure, the LVNL is one of the main users. But AMS has to hand over the infrastructure to the LVNL, before they are allowed to use it. AMS also has to determine whether the LVNL can use it. It is a sort of three-party structure, with the LVNL, the airport and the airline involved. I am not sure how this exactly interacts, however according to my information, the LVNL has an interface on which the available infrastructure is shown. A few times it happened that the LVNL used a runway before it received clearance from AMS. This incident was recorded as a runway incursion, because aircraft landed on a runway which was not cleared. At AMS, with almost 20 runway configuration changes per day, this is an important contributor to the incursion counts. In fact, this is not an unsafe situation by definition. Sometimes, two or three incursions were counted in a row, before the ATC experienced that the runway was not yet cleared. And, I believe, those incursions are not recorded anymore since the new definition at Schiphol.

ICAO defined severity classifications. Are the explained incident records all assigned as cat. D incursions?
I do not know the exact details of the statistics, but indeed, it was visible in these kinds of incursions. I do not know whether airports abroad use the same system for the clearance of infrastructure. In case the other airports in the research scope use a different procedure, it could be that AMS therefore shows a large contrast with the others.

Are there other characteristic incursion scenarios at AMS to point out?
Yes, there are. It often occurred that an aircraft landed on a runway which was at that moment not cleared by the preceding aircraft. In case an aircraft is hanging with its rear part of the fuselage over the red hold short line, which defines the Runway Safety Area (RSA), while the subsequent aircraft touches down on that runway, it is recorded as an incursion.

At AMS, this is kind of incursions is more of less encouraged. Quite characteristically for AMS is that immediately after landing, the pilot themselves has to contact ground control via the runway-specific frequency. AMS is not the only airport to use this procedure, however, there are only a few airports using this system. In most cases, the ATC tower gives the pilot shortly after landing the instruction to call ground control, mentioning which frequency to use. Sometimes, even a taxi instruction is immediately given. At AMS it sometimes happens that, especially foreign airline pilots, that do not fly frequently to AMS and are therefore less aware of this system, hold short before the red line and wait until the tower provides them with further instructions. Simply because they do not know which taxiways to use. Meanwhile, the tower already cleared the subsequent aircraft for landing on the same runway. Consequently, a runway incursion occurs. Recently, AMS implemented a mitigation measure by specifically stating in the Air Traffic Information System, to never stop on the runway for such reasons. I belief that this category of incidents strongly decreased after the implementation.

When was this measure implemented?
I am not sure, but I think this year. However, you could look it up in the statistics. It was for example clearly visible that during strong westerly winds, these incursion numbers rose, because only one runway was used then. Especially when holding short on a Rapid Exit Taxiway (RET), a large part of the wing and tail intersects the RSA.

Are there other scenarios to mention?
Another striking category is characterised by the towing traffic that crosses the runways, while there is not an optimal alignment in the communication between the tower controller and the towing controller who is in charge of the towing traffic. Although AMS is not the only airport using this separated communication procedure, where the towing traffic is handled on a different frequency than the taxiing air traffic, the system is rather unique. To give an example of the problem, in case an aircraft is being towed in front of my aircraft, I am not directly prepared for this instruction. I am dependent on the communication from the ATC. Before, this traffic was aligned between both controllers at LVNL, however they were not physically located close to each other. This has recently changed, in order to improve the communication alignment between the controllers. However, the separated frequencies are still used. We as VNV have repeatedly argued to use only one frequency. Then the pilots know directly that another aircraft will cross the runway in front of them. Nowadays, the tower informs pilots about the towing traffic, but they do not hear the direct conversations, such as pilots are able to hear from other aircraft.

Since a long time, we argue for the 'One Runway - One Frequency - One Language' concept, also known as 'Triple One'. The aim is, besides this one-frequency procedure, to also use the same language. Currently, communication to towing traffic is mainly performed in Dutch. However, LVNL does not yet want to implement this concept. A research concluded that all the towing drivers would have to acquire an IT-license comparable to that of pilots, since their current communication standards are not appropriate to communicate with pilots. By using two frequencies, drivers are still allowed to speak in Dutch. This category of incursions, is partly the result of choices that have been made for the system at AMS. It is a culture that developed over the years. It makes it rather easy, to just talk in your own language. And, it is also a way to less burden the tower. I would suggest asking the LVNL for more details about this topic.

Which developments do you specifically see at AMS?
Currently, there are plans to lower the usage and removal of the high-energy runway crossings. For example, there are plans to construct a perimeter taxiway, around the end of the Kaagbaan. Similar taxiways were build earlier on both ends of the Zwanenburgbaan, to detour the majority of the traffic flows to and from the Polderbaan around this runway. Also, the proposed parallel runway of the Kaagbaan could be a way to mitigate the high-energy crossings.

Could you mentioned specific characteristics that relate to the emerge of runway incursions?
At AMS, there is a specific spot where a relatively large share of the incursions occurs, namely at the N2/E6 intersection (see Appendix A15). Pilots have often difficulties reading the signage, which is not clearly visible from all angles. It has been decided to replace this angled taxiway intersection with a perpendicular one. This must prevent from situations that occurred earlier, where aircraft turned immediately right on the runway, instead of crossing the runway towards the designated take-off position.

The specific locations you mentioned are defined as hot spots. Is a hot spot based on a standard definition, or may it differ from airport characteristics abroad?
No, this is specific for each airport. These areas are determined within the RST. Hot spots are repeatedly evaluated, based on the incidents that occurred. Sometimes hot spots are lifted, a new one arises, because incursions happened frequently at a specific location.

And other mitigation measures?
There is a good example of Paris Charles de Gaulle (CDG), where they implemented Runway Status Lights (RSL). For AMS it was also studied, whether this would be a valuable technology. However, it was concluded that this system is particularly appropriate for airports equipped with parallel runways. Because for parallel runways, each one is often used at simultaneously for take-off and landing. Aircraft that are lined up at the runway observe the red-light signal on the runway when a landing aircraft crosses this take-off runway. As soon as the sensors do not measure a passing aircraft anymore, the red lights will turn off. With the conventional stop bars, aircraft are only warned when not to enter a runway. Because stop bars are automatically controlled, meaning that after an aircraft left the runway, they immediately shift from green to red. Sometimes the braking distance is too short because of the red-light signal that suddenly appears. This sometimes results in the unauthorised crossing of the red line. While the runway was no even in use, this is measured as a runway incursion.

Another example, at London Heathrow (LHR) they implemented a system called 'follow the greens'. This system is also used during visual conditions, but only in the dark. As soon as it starts to dusk, the system is activated. Here, after landing, the pilots get a taxi clearance and the taxiway centre lines are switched on in segments, according to the taxi clearance. In fact, pilots only have to follow their green lights. With this, LHR is a bit of an exception to the rule, because navigation here is easier in the dark with the system in use, compared to during the day without it.

Also, AMS studied on this, but it appeared that this was not a fully automatic system. The lights have to be manually controlled. LHR was the first with this system, nowadays more airports study improved versions of it. Of course, it is less complicated to control such a system at an airport with only two parallel runways, instead of AMS with six runways of which one intersecting. By the way, LHR uses a very efficient system, in which the only two runways are utilised with very short separation times. One is used for take-off and one for landing, which makes it traffic situation very clear.

Considering the characteristics that I listed as a result of literature study: to which degree do they influence the incursion likelihood?
For the types of operations, I do not immediately see a clear link. For example, on Rotterdam The Hague (RTM) with flight schools and a large share of GA, commercial and GA traffic alternates each other quite smoothly. The types of aircraft may have an influence. Pilots of small aircraft are often frequent visitors of an airport because they fly mainly short-haul. They are often very familiar with all procedures and communication channels at that airport. Flight crew of wide-body aircraft fly predominantly long routes, and visit airport much less often. Furthermore, at the time of their arrival they are becoming tired and less alert compared to short-haul pilots. Consequently, they may be more vulnerable to cause mistakes that result in incursions. Also large aircraft, because of their size, earlier intersect the red line, compared to a small aircraft.

Aligned taxiways: It may be that the ATCO has to adapt the separation time, as aircraft could use the entire runway length. However, it is questionable whether this relates to runway incursion. In the past, complex intersections have caused confusion by pilots. For example, at Brussels Airport, where a taxiway intersected at the crossing of two runways. It happened that aircraft took off from that point on the wrong runway.

The type of runway material could be a good explanator for confusion of pilots as well. It the US, pilots are much more often cleared to land on visual. Thus, if runways are made of concrete, like that of taxiways, it could be confusing leading to aircraft landing on the taxiway instead of the runway. However, in case ILS is used, this mistake cannot be made, due to the automatic autopilot approach. Construction occurrences could also lead to confusion, especially if temporary charts and/or procedures are in place. Sometimes, NOTAMs are such extensive that pilots would never read it entirely. This increases the workload. Edge light intensities could be influential, for example during low visibility. Sometimes, lights can be too intense as well, leading to a blurry view. For example, modern runway lights in led, such as at AMS, are often considered by pilots as being too intense, because its light intensity is complicated to adjust.

Traffic intensity is a good indicator for the airport complexity, besides the geometry, because after landing the communication with ground can become complex due to a growing number of infrastructure users, who also use the same communication network. This may kind of overload the physical and non-physical systems. Taxi delay in the US is difficult to compare to the situation as we have in Europe. This is the result of planning. In the US, aircraft are often released from the gate, while the infrastructure is already very busy. This means that they have to enter the waiting queue. In Europe, aircraft leave the gate according to a predefined slot time window.

A4.2 Air traffic controller

Profile		
Functions	Ground controller at Schiphol	LVNL
Experience	+20 years: tower control at Rotterdam Airport, ground controller at Schiphol	
Date	December 2018	

How would you describe Schiphol in relation to runway incursions?
Schiphol is a very complex airport. In general, the idea behind the design is quite good, because of the central terminal surrounded by the converging runways, which are in general easily accessible from the terminal. However, this makes it also sensitive for incidents such as runway incursions, but also go arounds which can result in a mid-air conflict.

Could you describe a typical scenario in which an incursion emerges, for example at Schiphol?
Schiphol is a complicated airport, especially for users that do not use the airport frequently. Foreign pilots have much more often than Dutch pilots difficulties to find their way on the airport, which is quite understandable when looking at the airport map (Appendix A15). A clear example of an incursion is when an aircraft lands on a runway which has not yet been cleared to the aircraft, because it is still in use by the preceding aircraft.

During other interviews, I learned that quite a number of incursions took place because the infrastructure was not yet cleared to the ATC, while it was already cleared to the aircraft. Could you explain this?
What happened in the past is that an aircraft used the runway which was not yet available for us from the FMA, the operational responsible party of the airport. If they make a particular runway available to us, we are allowed to use it for everything we want. This also means that the airport is responsible to keep the runway clear of birds. However, if an aircraft lands on a runway which we have not received from the airport, this is called a runway incursion. Nowadays, all runways that are available to us, are visible on a digital screen. Hence, this is a very different kind of incursion without any danger. Worth mentioning, for the crossing of runways we do not need permission from the FMA. In general, a check of the infra availability is part of the procedure before we give clearance to an aircraft.

Schiphol has a ground radar. During low visibility conditions, is this the only system that shows the location of the taxing aircraft?
Indeed. Often the upper side of the tower is not visible from the ground, meaning that we cannot observe aircraft visually. We use the ground radar for that. However, the system is not an alerting system for runway incursions. For that, a special warning system is developed for Schiphol, called RIASS. This is a totally different system compared to the ground radar. RIASS gives a warning when two aircraft come to close to each other, for instance when two runways are in use and one of the aircraft has a too long roll-out distance after landing. Then we see two red dots on the screen and we receive a voice alert calling 'runway incursion'. After the warning, we determine how to respond. RIASS also works when for example a vehicle is on the runway while too close to an aircraft.

Which characteristics of an airport are related to the occurrence of runway incursions in your opinion?
What we see at Schiphol is a big shortage of gates at the terminal. This means that there is a lot of towing traffic between the terminal area and parking platforms, for example at Schiphol Oost, during the period an aircraft is on the ground for a longer period. Throughout the whole day there is towing traffic, increasing the utilisation of the airport. For example, the Surinam Airways aircraft arrives in the morning and leaves again in the evening. The aircraft cannot stay at the gate whole day, thus it has to be moved to the parking area by a towing vehicle. Then, the towing vehicle drives back to the terminal area, and has to drive to the parking area to tow the aircraft back to the terminal before the evening departure. In many cases runways have to be crossed, to access the parking area. If possible, towing vehicles use their own dedicated infrastructure to minimise the number of runway crossings and disturbing the air traffic operations.

Is visual hindrance from the tower a problem, for example because of distance?
The airport is equipped with cameras which allow us the see all necessary spots of the airside, also during night. In general, everything within my handling area is therefore visible from the tower.

Complex airports are more vulnerable for incursions. What would be good indicators for complexity?
For Schiphol, this is especially determined by the converging runways, the limited area, the presence of multiple stakeholders in the field. For example, beside the Air Traffic Control there is the towing control, which is not part of LVNL, but of the airport.

The number of TWY-RWY intersections, would that be a good indicator?
In general, the less intersections, the easier it is for the pilot, because there are less possibilities to make mistakes. However, from the operational perspective, the availability of runway-exits can be a limiting factor for the throughput, since there are less possibilities to leave the runway, resulting in longer runway occupancy times. Small aircraft for instance require less runway length. Longer occupancy times than predicted could result in an incursion because of loss of separation. For this reason, RETs have the advantage that aircraft can leave the runway at higher speed, so that the runway is cleared earlier than compared to other types of intersections.

At Schiphol, are RETs also used for runway line-up?
Yes, this is done so that the take-off sequence can be performed in the most optimal way, for example depending on the size of the aircraft and their separation requirements, by means of multiple line ups. Indeed, the pilots of the aircraft using the RET for line up do not see the aircraft lined up at the beginning of the runway, however they are informed about their presence. We are allowed to have two aircraft lined up at the same runway.

In the US, Land and Hold Short Operations on intersecting runways are frequently used. How is this for the two intersecting runways at Schiphol?
Depending on the wind direction we use intersecting runways simultaneously. For lining up, we prefer aircraft to take the entrance taxiway, such that the crossing of the runway is not required. However, for some aircraft types this is not possible since they require additional runway length. Then we take the risk of an incursion for granted, because this may sometimes avoid a conflict in the air, as for instance aircraft have to head for different directions.

Many airports have designated hot spots. Is there special attention from the Air Traffic Control for hot spots during the operation?
Hence, a hot spot is an area of which we know that it can be complicated for the pilot. However, there are no special procedures for the operation at hot spots. We want to prevent mistakes of course everywhere on the airport, not only in hot spots.

Is the Air Traffic Control involved in the designation of hot spots at Schiphol?
Yes, our safety department, which investigates all incidents that occurred, is involved in this process.

A4.3 Airside operations

Profile	
Functions	Airside operations manager at Schiphol
Experience	+20 years: airside operations, GA pilot
Date	November 2018

How would you describe a runway incursion?
Of course, it depends on the definition you use for a runway incursion. Sometimes, there is confusion whether an incident was a runway incursion or not. For example, in case two vehicles are unauthorised present on the same runway at the same time, this is called a runway incursion. In fact, there was not any danger for a severe incident.

At Schiphol, sometimes cat. D incursions were counted while the infrastructure was not yet cleared to the ATC. In this way, high numbers of incursions may be registered, in which there was not any danger, right?
Indeed, in those cases there was no danger during the occurrence. Then the question arises: how was this miscommunication possible? And, instead of counting these incursions separately, you could also say that it was just one handling that went wrong which resulted in three incursions.

Since this year, Schiphol uses a different method to count incursions, in order to avoid these false counts. Could you explain this new procedure?
I do not know the exact details about that. The LVNL makes the severity distinction in more detail, I suggest asking them for further details.

Worth mentioning, from our role, we do not conduct any severity assessment. We have to make notice of an incursion to the Dutch Safety Board, the ILT and the board of Schiphol, but the severity is then determined by other parties at the back office. They conduct the incident investigation. Meanwhile, we have to act on what we did wrong in order to learn from it, and to prevent it from happening in the future.

From your role as airside authority, which factors influence the probability of an incursion?
This is mainly related to workload; i.e. capacity plays a role. The weather has a big impact, especially visibility conditions. Communication and IT is a very important aspect, and also unambiguity in communication. Generally, it is mainly related to human factors; think of distraction. And circumstances deviating from normal, such as construction occurrences.

I would say, incidents are mainly related to human factors, because the infrastructure itself is in fact built to avoid mistakes. You could ask yourself whether additional measures such as markings, signage and lighting would mitigate incidents, because this could also result in an overload of information, which consequently increases the chance on mistakes.

And an overload of communication frequencies?
Possibly not the number of frequencies itself, but the way they are used. For instance, the moment on which one has to change frequency could be an influencing factor, such as during taxiing when the workload is already high due to the

take-off preparation. We as airside authority use the runway channel for communication with the ATC. Pilots use the VHF-frequencies.

Which other aspects play a role?
The used language in aviation is English. However, we as airside authority use Dutch for communication with the tower. Intuitively, it would be better to use only one language, but this requires a large transition effort before all participants understand the entire system in English. This could, once again, increase the chance on mistakes.

How is a hot spot determined?
There is not an unambiguous global definition for a hot spot, and the way it is defined differs per situation. In general, the determination is based on an incident trend analysis, not only runway incursions. For example, there is data available from the LVNL about locations were the ATC has to undertake the most frequent corrective actions. And there are notices from unsafe occurrences known. Based on this, the Runway Safety Team defines the current situation and thinks of possible mitigation measures. One of the measures is to add the hot spot to the AIP, to increase the degree of attendance. Thus, preferably, there a not too many hot spots assigned at an airport.

Could you give an example by which the alertness of pilots is influenced?
For instance, at Schiphol there is a platform in the GA area, where the runway is closely situated to the apron (direct access). As a result, pilots have scarce time to prepare for take-off during taxiing, as they arrive quite early for the line-up. A taxi routing with multiple angles could increase the awareness of pilots, because they have to continuously orientate themselves in the area.

Does taxiway intersection geometry influence visual hindrance, for example by the angle on which a taxiway intersects a runway?
Well, I think that this really depends on the way in which the runway is used. If the runway is used for operations in the opposite direction of the RET exit, the view may be even better, both for pilots and vehicles. If aircraft use the same direction and arrive from the back, then your line of sight is obviously decreased. Based on this, you could say that right-angle intersections are on average the most save option.

Also, you could note that the situational awareness of the users is increased when one enters a right-angle intersection, because one has to physically make a turn and look around where to go.

Would the presence of a larger share general aviation influence the likelihood of incursions?
I think this does not necessarily relate to incursions, because all pilots should have obtained an equal level of pilot's licensing. Furthermore, generally GA-pilots could conduct an even more extensive pre-flight preparation than airline pilots and they could also be more familiar with the airport if they are based there.

And runway intersections versus crossing runways?
I expect that the likelihood of incursions is stronger related to the number of runway intersections than the number of crossing runways, because runways and TWY-RWY intersection are used simultaneously, which is not necessarily the case for two crossing runways. In this second case, the ATC creates a strong safety net, preventing from the unauthorised use of two runways simultaneously.

Runway length?
I think that this is quite much related to the size of an aircraft. For instance, a small aircraft in the farthest distance of a long runway is probably impossible to observe, instead of a large aircraft. For runway width, this is the case to a much lesser degree. Hence, the time to cross a wider runway may be a bit longer, but any unauthorised presence on the runway is an incursion. Thus, crossing time is not a justified measure.

The presence of Runway Status Lights?
This only shows whether the infrastructure is available, not whether it is used. To a certain degree, it increases the situational awareness of pilots, but too many measures works counterproductive. Then it loses its primary function, and users could too much rely on it.

Displaced thresholds?
I do not see a clear relation with the presence of displaced thresholds, because the runway is in any case only cleared for one aircraft or one vehicle. Thus, when an aircraft enters the displaced threshold, this is already counts as a runway incursion if it happens unauthorised.

Do you think that the results from the data analysis based on US airports are applicable on other airports worldwide?
On a high level, this comparison can be made since the infrastructure and aircraft are primarily the same. However, focusing on specific aspects, such as communication shows differences in for example language and visual instructions. These cannot be directly compared with other countries.

A4.4 Dutch Safety Board

NOT FOR PUBLICATION

NOT FOR PUBLICATION

NOT FOR PUBLICATION

A5 All scope airports

FAA ident	Size	FAA ident	Size	FAA ident	Size	FAA ident	Size	FAA ident	Size	FAA ident	Size
ABE	N	**CMI**	N	GKY	O	**LIT**	S	**PHF**	N	**SQL**	O
ABI	N	CNO	O	GLH	O	**LNK**	N	**PHL**	L	**SRQ**	S
ABQ	M	**COS**	S	**GLS***	O	LNS	O	**PHX**	L	SSF	O
ABY	N	**CPR**	N	**GNV**	N	LOU	O	**PIA**	N	STC	N
ACK	N	**CPS**	O	GPI	N	**LRD**	N	**PIE**	S	**STL**	M
ACT*	N	CRG	O	GPM	O	**LSE***	N	**PIH**	N	**STP**	O
ACY	S	**CRP**	N	**GPT**	N	**LUK**	O	**PIT**	M	**STS**	N
ADQ	N	**CRW**	N	**GRB**	N	LVK	O	PKB	O	**STT**	S
ADS*	O	CSG	N	GRI	N	LWM	O	PNE	O	**SUN***	N
AEG	O	**CVG**	M	**GRR**	S	**LWS**	N	**PNS**	S	**SUS**	O
AFW	O	CWA	N	**GSN**	S	**LYH**	N	POC	O	SUX	N
AGC*	O	CXO	O	**GSO**	S	LZU	O	PRC	O	**SWF**	N
AGS	N	CXY	O	**GSP**	S	**MAF**	S	**PSC**	N	SWO	N
AKN	N	**DAB**	N	**GTF***	N	**MBS**	N	**PSP**	S	**SYR**	S
ALB	S	**DAL**	M	GTR	N	**MCI**	M	**PTK**	O	**TEB**	O
ALN	O	**DAY**	S	GTU	O	**MCO**	L	**PVD**	S	TKI	O
ALO	N	DBQ	N	**GUM**	S	**MDT**	S	PVU	N	**TLH**	N
ALW	N	**DCA**	L	GYR	O	**MDW**	L	PWA	O	TMB	O
AMA	N	**DEN**	L	**HEF**	O	**MEM**	S	**PWK**	O	TOA	O
ANC	M	**DFW**	L	HFD	O	**MFE**	N	**PWM***	S	**TOL**	N
ANE	O	DHN	N	HGR	N	**MFR**	N	RAL	O	**TPA**	L
APA	O	**DLH**	N	HHR	O	**MGM**	N	**RAP**	N	**TRI**	N
APC	O	DPA	O	HIO	O	MHK	N	RBD	O	TTD	O
ARR	O	**DSM**	S	**HLN**	N	**MHR**	O	**RDD**	N	**TTN**	N
ASE*	N	DTN	O	**HND**	N	**MHT**	S	**RDM**	N	**TUL**	S
ASH	O	DTO	O	**HNL***	L	**MIA**	L	**RDU**	M	TUP	O
ATL	L	**DTW**	L	HOB	N	MIC	O	**RFD**	N	**TUS**	S
ATW	N	DVT	O	**HOU***	M	**MKC**	O	RHV	O	**TVC**	N
AUS	M	DWH	O	**HPN**	S	**MKE**	M	**RIC**	S	**TWF**	N
AVL	S	DXR	O	HQZ	O	MKG	N	RNM	O	TXK	N
AVP	N	EAU	N	**HRL**	N	MKL	O	**RNO***	S	**TYR**	N
AZO	N	**ECP**	S	**HSV**	S	**MLB**	N	RNT	O	**TYS**	S
BBG	O	**EGE**	N	HTS	N	**MLI***	N	**ROA**	N	TZR	O
BCT	O	**ELM**	N	HVN	N	**MLU**	N	**ROC**	S	UES	O
BDL	M	**ELP**	S	HWD	O	**MMU**	O	**ROW**	N	UGN	O
BED	O	EMT	O	HWO	O	**MOB**	N	**RST**	N	**UNV**	N
BET	N	**ENA**	N	**HXD**	N	MOT	N	**RSW**	M	VCV	O
BFI	N	ENW	O	**HYA**	N	MQY	O	RVS	O	**VGT***	O
BFL	N	**ERI**	N	HYI	O	**MRI***	N	RYN	O	**VNY**	O
BGM	N	**EUG**	S	**IAD**	L	**MRY**	N	RYY	O	VRB	O
BGR	N	EVB	O	IAG	N	**MSN***	S	SAC	O	WHP	O
BHM	S	**EVV**	N	**IAH***	L	**MSO**	N	**SAF**	N	**XNA**	S
BIL	S	**EWB**	O	**ICT**	S	**MSP**	L	**SAN**	L	**YIP**	O
BIS	N	**EWN**	N	**IDA***	N	**MSY**	M	**SAT**	M	YKM	N
BJC	O	**EWR**	L	IFP	N	MTN	O	**SAV**	S	YNG	N
BKL	O	**EYW**	N	ILG	O	MVY	N	**SAW**	N		
BLI	S	**FAI***	S	**ILM**	N	MWA	N	**SBA***	N		
BMI	N	**FAR**	N	**IND**	M	MWC	O	**SBN***	N		
BNA	M	**FAT**	S	IPT	N	MYF	O	**SBP**	N		
BOI	S	**FAY**	N	ISM	O	**MYR**	S	**SBY**	N		
BOS	L	FCM	O	**ISP**	S	NEW	O	SCK	N		
BPT	N	FDK	O	**ITH**	N	**OAK**	M	**SDF**	S		
BQN	N	**FFZ**	O	**ITO**	S	OGD	N	**SDL**	O		
BTR*	N	**FLG**	N	**IWA**	S	**OGG**	M	SDM	O		
BTV	S	**FLL**	L	IXD	O	OJC	O	**SEA**	L		
BUF	M	FLO	N	**JAC**	N	**OKC**	S	SEE	O		
BUR	M	FMY	O	**JAN**	S	**OMA**	M	**SFB**	S		
BVY	O	**FNT**	N	**JAX**	M	OMN	O	SFF	O		
BWI	L	FOE	O	**JFK**	L	**ONT**	M	**SFO**	L		
BZN	S	**FSD**	S	JLN	N	**OPF**	O	**SGF**	S		
CAE	S	FSM	N	**JNU**	S	**ORD**	L	**SGJ**	N		
CAK	S	FTG	O	JRF	O	**ORF**	S	SGR	O		
CCR	O	FTW	O	**KOA**	S	**ORL**	O	**SHV**	N		
CDW	O	FTY	O	LAL	O	**OSU**	O	**SIG**	N		
CGF	O	FUL	O	**LAN**	N	OTH	N	**SJC**	M		
CHA	S	**FWA**	N	**LAS**	L	OUN	O	SJT	N		
CHD	O	FWS	O	LAW	N	OWB	N	**SJU**	M		
CHS	S	**FXE***	O	**LAX**	L	PAE	O	**SLC**	L		
CID	S	GCK	N	**LBB**	S	PAH	N	**SLN**	O		
CKB	N	GCN	N	**LCH**	N	PAO	O	**SMF**	M		
CLE	M	**GEG**	S	**LEX**	S	**PBI**	M	SMO	O		
CLL	N	GEU	O	**LFT***	N	**PDK**	O	SMX	N		
CLT*	L	**GFK**	N	**LGA**	L	PDT	O	**SNA**	M		
CMA	O	GGG	N	**LGB**	S	**PDX**	L	SPG	O		
CMH	M	**GJT**	N	**LIH**	S	**PGD**	S	SPI	N		

*Airports labelled as outliers

(Airports indicated in bold have been used for the model estimation)

A6 Additional high-level analysis results

This appendix covers the remaining results from the high-level analysis, which contribute to the understanding and justification of the hypotheses, but are not used for the remainder of the research phasing. The section follows the similar structure as Chapter 6.

A6.1 Incursion severity versus type

After considering the interactions between airport size and incursion characteristics, the relation between severity and type are examined. Figure A-8a shows the related incursion rate index. Also for this graph, it was decided to combine A+B incidents to provide higher accuracies.

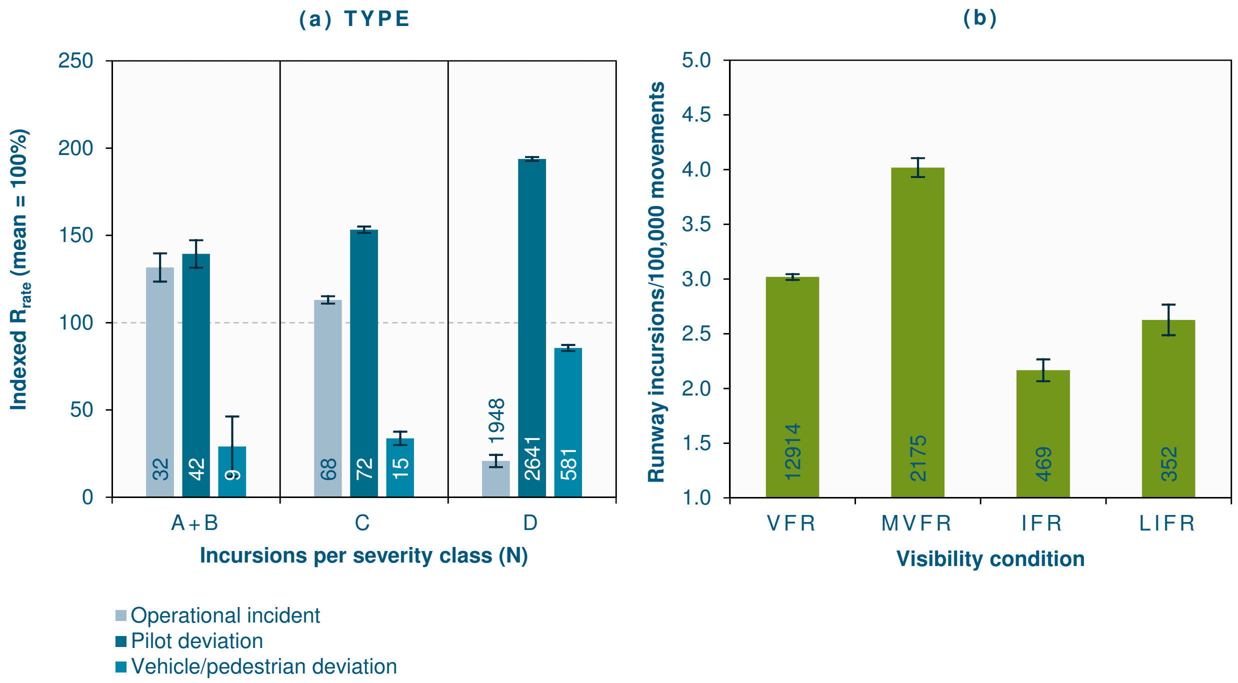


Figure A-8: Incursion rate composition for severity per incursion type, including ±1σ standard errors (a) and composition per visibility condition (b), including ±1σ errors

It is visible that category A+B incidents are hardly caused by vehicles/pedestrian deviations (V/PD). Across all severities, pilot deviations (PD) caused the largest share of incursions. This underlines the finding of Ju (2011) who found that PDs are the key factor influencing C and D incursions. However, it also concluded that A and B incidents are mainly caused by A and B incidents, which contradicts with the results. Hence, the minor share of A+B incidents should be kept in mind, meaning a large standard error.

The larger share of V/PD incidents for cat. D can be clarified by the fact that vehicle drivers often use the runway infrastructure in periods that it is not in use by aircraft, for example because of runway inspections. Then, the unauthorised presence of the vehicle on the runway is registered, however, it did not cause any dangerous situation since no aircraft was involved. These kinds of incidents are clear examples of category D incursions.

In general, there appears to be a relationship between incursion type and severity, although it is complicated to model because of data shortage. Wilke et al. (2015a); (2015b) found the same conclusion. Since these findings does not contribute to the development of the frequency model, it is not further analysed.

A6.2 Visibility

From literature and the consultation of the expert panel, it is known that visibility has a significant impact on the operations at an airport, and consequently also on incursion likelihood. Analysis of the weathers circumstances during the incursions showed that 81.2% of all incidents occurred during VFR conditions, 13.7% occurred during MVFR, 2.9%

during IFR and only 2.2% during LIFR. The low percentage for the lowest visibility conditions LIFR can be clarified by the assumption that the airports are used with different operational procedures. Normalisation to incursion rates using the annual mean percentages that the visibility conditions occur for the entire airport sample (VFR: 83.0%, MVFR: 10.5%, IFR: 4.2% and LIFR: 2.6%), resulted in the graph shown in Figure A-8b. The chart shows that the largest incursion rates for MVFR, followed by VFR and LIFR. The results indicate not a clear relation between the visibility conditions and the R_{rate}. Appearantly, other factors have a larger impact on the incursion rates. According to the panel, it can be explained by the fact that for LIFR larger separations are applied.

That low visibility circumstances do not necessarily relate to higher incursion rates can also be explained by earlier research on runway excursions[7]. Often, it is assumed that these incidents mainly occur at short runways. However, when considering the statistics, it is observed that most of these excursions occurred on average length runways and during good visibility circumstances, such as VFR. During these circumstances, pilots may be less concentrated on the situation, since pilots then often rely on their previous experience at the airport, while the situation could have changed (lower situational awareness). For landings at short runways, pilots are more prepared for unexpected situations.

Also, the air traffic intensity is reduced by the cancellation of flights and all actors are generally more aware of the situation. Pilots have to taxi at a lower speed during low visibility conditions and do additional visual checks. For example, an incursion occurs when an aircraft lands on a runway which was not yet cleared by the previous aircraft. Hence, this type of incursion is much more likely to occur when the separation distances are short, which is not the case during LIFR. In these situations, the runway has to be cleared for the subsequent aircraft, because it often has to land by means of the automatic landing system. For this, the radio signal from the ILS is required, which becomes only available when the runway is clear of other traffic. To conclude, slower moving traffic, lower intensities and lower workloads for the ATC and relate therefore not by definition to a higher likelihood for incursions.

Next, since the weather characteristics are known during the incidents, an incursion rate composition for both severity and type was also made for each visibility condition, similar to the type of incident. The resulting graphs are visible in Figure A-9. Similar as for previous graphs, A+B incidents are aggregated to provide significant results.

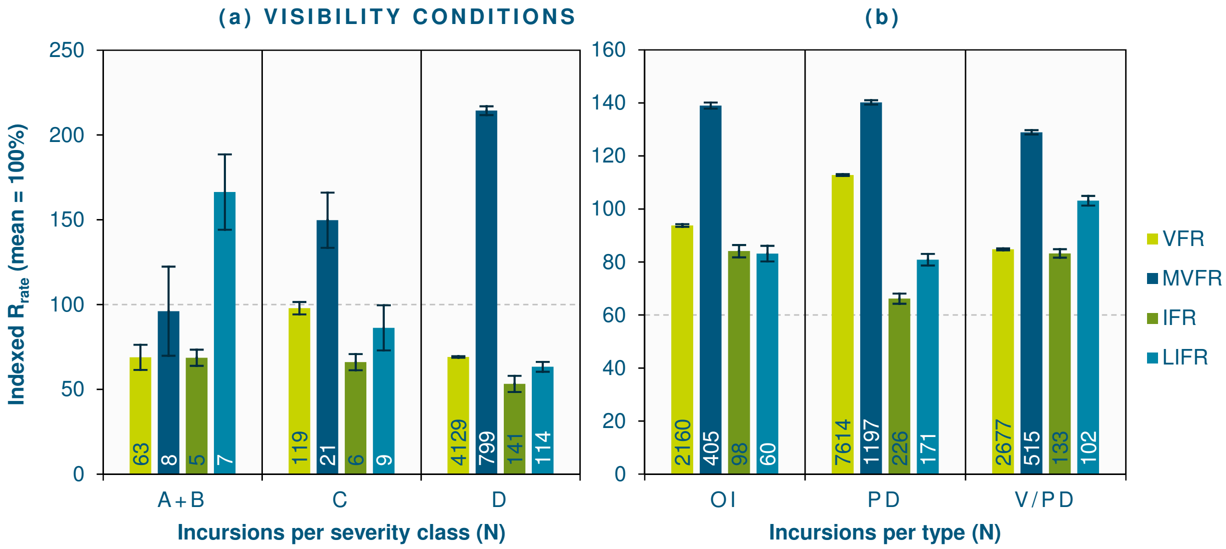


Figure A-9: Incursion rate composition for severity and type per visibility condition, including ±1σ errors

The clearest outlier in the severity graph is seen for category A+B incidents, where the largest incursion rate is observed during LIFR conditions, i.e. the lowest visibility condition. Severity incidents C and D are not related to low visibility. Considering the incursion types, MVFR shows the highest shares of incursion rates across all categories. No clear explanation could be extracted from this trend, since the differences appeared to be rather small. Though, it can be concluded that the distribution of the incursion rates per visibility condition is similar to the total rates as shown in Figure A-8. Thus, the expounding of R_{rate} values per type does not result in divergent results. Lastly, consultation of the panel learned that only LIFR will have a significant impact on the operations, because the remaining conditions V_c do not imply an adapted operation. For instance, IFR and VFR are generally not related to the visibility conditions, but it determines

[7] *A veer off or overrun off the runway surface*

that flight rules that apply for a certain flight. Although the visibility conditions may be good, IFR can be required at some airports.

To conclude, the need for separated assessment of incursions for low visibility and good visibility conditions has been demonstrated. A decomposition of good visibility into VFR, MVFR and IFR is shown to be unnecessary.

A6.3 Share heavy aircraft: Airplane Design Group decomposition

Also, the incursion rates per Airport Design Group were analysed for incursion severity and type. As can be seen in the results in Figure A-10 with regard to Table A-7, ADG E aircraft shows the highest incursion rates amongst all severity classifications. Another remarkable result is the outlier for category F aircraft in severity C. Hence, it should be noted that the small population of incursions for A and B imply less reliable results. Though, in general it can be said that large aircraft are relatively more often involved in all severity classes of incursions.

The results for the incursion types show also the highest portions of rates for large aircraft, in particular for ADG E airplanes (Figure A-10b). Another remarkable result is the higher incursion rate for small aircraft (cat. A) caused by pilots (PD). This, once again, highlights potential influence from general aviation traffic. Both decompositions in severity and type underpin the explanation for large aircraft being relatively more vulnerable for involvement in runway incursions.

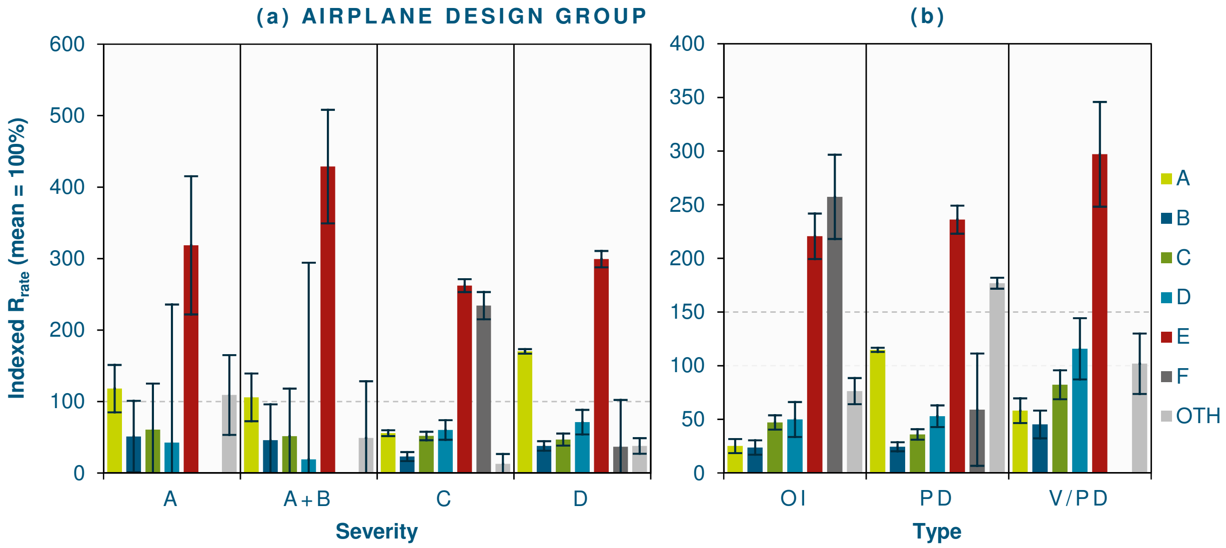


Figure A-10: Incursion rate composition for severity and type per airplane design group, including ±1σ errors

Table A-7: Frequency table percentage delayed flights during taxiing

	Incursions per severity class (S_R)				Incursions per type (E_R)		
Delay (%)	N(A)	N(B)	N(C)	N(D)	N(OI)	N(PD)	N(V/PD)
A	34	34	2184	3391	752	5709	233
B	15*	15*	919	770	724	1240	185
C	9*	8*	1046	481	726	920	170
D	1*	0*	193	116	122	215	38
E	1*	2*	112	65	72	128	13*
F	0*	0*	25	2*	21	8*	0*
OTH	3*	0*	48	72	218	839	39

*Does not meet requirement of $N > 20$

Because of data shortage, A and B incidents were aggregated into A+B. However, class. F incidents were not recorded for A+B.

A6.4 Airport characteristics

Lastly, airport characteristics that were excluded as a result of the collinearity analysis are analysed in more detail next.

A6.4.1 Runway movements

The utilisation of runways is tested, based on the combination of airport movements and the number of runways. The average number of hourly movements per runway is used as indicator here. Partly contradictory to *Hypothesis H6*, a decrease is observable when the hourly runway movements increase. For instance, the R_{rate} showed a value of 3.4 for 0-5 hourly runway movements, while for 10-15 hourly movements, the R_{rate} was 2.6. Though, from 15< hourly runway movements, the incursion rate increased a fraction. This variation can be clarified by the fact that the number of movements is not directly related to the number of runways. In many cases, the number of runways is determined from wind preferred flight routings and noise mitigating objectives, rather than a higher capacity. In other words, operational factors play an important role in this respect. For example, Schiphol (AMS) consists of six runways, while a maximum of four runways is used during peak hours. Moreover, airports with four runways could handle less aircraft that an airport with only two.

A6.4.2 Presence complex intersections

A complex intersection is another example of TWY-RWY intersections which has been analysed in relation to the incursion rates. Since these kinds of intersections are generally not present in large numbers per airport, it is not useful to express it in number per runway-km. To test on the effect on incursion rate, the presence of complex intersections is used as indicator. Since also here low numbers of airports were found for airport movement categories, it was decided to aggregate to incursion rates into total airports. Figure A-11a shows the results.

The results underpin the assumption that airports with complex intersections are more vulnerable for incursions. As can be seen in the graphs, the aggregated incursion rates are higher at airports which have complex intersections. Goodheart (2018) concluded that airports are strongly correlated with complex intersections, in line with these findings.

A6.4.3 Taxi delay

Lastly, taxi delay is analysed for airports of which the corresponding data was available. Based on earlier knowledge, it is assumed that taxi delay does not necessarily imply complex situations or high airport utilisations, especially for airports in the US. Indeed, as shown in Figure A-11b, there is only a minor difference in incursion rates among the two delay categories. The absence of a strong interaction between these aspects is that taxi delay, especially in the US does not depend on gate capacity. In the US, aircraft are often released from the gate, while the infrastructure is already congested. This means that aircraft have to join the waiting queue of airplanes taking off. In Europe aircraft leave the gate according to predefined slot time allocations, and consequently performs much more smoothly. Therefore, taxi delay could be a better indicator for European airports, however, this is outside this research scope.

To conclude, taxi delay does not seem to be a good performance indicator for airport complexity, which is in line with the expectations from the expert panel.

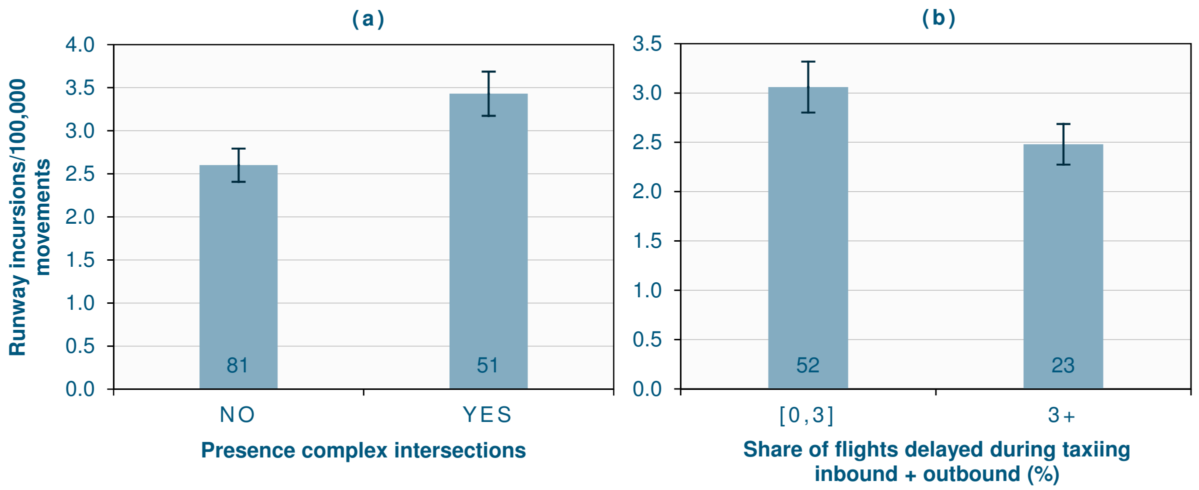


Figure A-11: Incursion rate composition for presence of complex intersections (a) and share delayed flights during taxiing (b), including 1σ errors

A7 Associations between incursion rates and airport characteristics

A7.1 Test for normality

	Kolmogorov-Smirnov			Shapiro-Wilk		
Characteristics	Statistic	df	Sig.	Statistic	df	Sig.
Hourly movements	.199	268	.000	.704	268	.000
Share commercial traffic	.124	268	.000	.906	268	.000
Share heavy aircraft	.273	268	.000	.619	268	.000
Ratio intersecting runways	.256	268	.000	.839	268	.000
TWY-RWY intersections/runway-km	.097	268	.000	.924	268	.000
Ratio non-right angled	.086	268	.000	.954	268	.000
Ratio RETs	.328	268	.000	.671	268	.000
Required crossings	.299	268	.000	.819	268	.000
Hectare per runway-km	.152	268	.000	.683	268	.000

A7.2 Complete dataset

	Correlation, N=268					
		S_R		E_R		
Characteristics	Total	High	D	OI	PD	V/PD
Hourly movements	$r_s = -0.026$, p (2-tailed) $= 0.677 > 0.05$	$r_s = 0.354$, p (2-tailed) $= 0.000 < 0.05$	$r_s = -0.212$, p (2-tailed) $= 0.000 < 0.05$	$r_s = 0.355$, p (2-tailed) $= 0.000 < 0.05$	$r_s = -0.034$, p (2-tailed) $= 0.579 > 0.05$	$r_s = -0.212$, p (2-tailed) $= 0.000 < 0.05$
Share commercial traffic	$r_s = -0.80$, p (2-tailed) $= 0.190 > 0.05$	$r_s = 0.101$, p (2-tailed) $= 0.098 > 0.05$	$r_s = -0.079$, p (2-tailed) $= 0.198 > 0.05$	$r_s = 0.261$, p (2-tailed) $= 0.000 < 0.05$	$r_s = -0.130$, p (2-tailed) $= 0.033 < 0.05$	$r_s = -0.079$, p (2-tailed) $= 0.198 > 0.05$
Share heavy aircraft	$r_s = -0.150$, p (2-tailed) $= 0.014 < 0.05$	$r_s = -0.26$, p (2-tailed) $= 0.675 > 0.05$	$r_s = -0.160$, p (2-tailed) $= 0.009 < 0.05$	$r_s = 0.178$, p (2-tailed) $= 0.003 < 0.05$	$r_s = -0.169$, p (2-tailed) $= 0.006 < 0.05$	$r_s = -0.160$, p (2-tailed) $= 0.009 < 0.05$
Ratio intersecting runways	$r_s = 0.212$, p (2-tailed) $= 0.000 < 0.05$	$r_s = 0.215$, p (2-tailed) $= 0.000 < 0.05$	$r_s = 0.106$, p (2-tailed) $= 0.082 > 0.05$	$r_s = 0.213$, p (2-tailed) $= 0.000 < 0.05$	$r_s = 0.191$, p (2-tailed) $= 0.002 < 0.05$	$r_s = 0.106$, p (2-tailed) $= 0.082 > 0.05$
Number of TWY-RWY intersections per runway-km	$r_s = 0.212$, p (2-tailed) $= 0.000 < 0.05$	$r_s = 0.426$, p (2-tailed) $= 0.000 < 0.05$	$r_s = 0.027$, p (2-tailed) $= 0.658 > 0.05$	$r_s = 0.330$, p (2-tailed) $= 0.000 < 0.05$	$r_s = 0.198$, p (2-tailed) $= 0.001 < 0.05$	$r_s = 0.027$, p (2-tailed) $= 0.658 > 0.05$
Ratio non-right angled	$r_s = -0.016$, p (2-tailed) $= 0.790 > 0.05$	$r_s = 0.215$, p (2-tailed) $= 0.000 < 0.05$	$r_s = -0.014$, p (2-tailed) $= 0.822 > 0.05$	$r_s = 0.217$, p (2-tailed) $= 0.000 < 0.05$	$r_s = -0.061$, p (2-tailed) $= 0.324 > 0.05$	$r_s = -0.014$, p (2-tailed) $= 0.822 > 0.05$
Ratio RETs	$r_s = -0.053$, p (2-tailed) $= 0.387 > 0.05$	$r_s = 0.188$, p (2-tailed) $= 0.002 < 0.05$	$r_s = -0.052$, p (2-tailed) $= 0.401 > 0.05$	$r_s = 0.316$, p (2-tailed) $= 0.000 < 0.05$	$r_s = -0.132$, p (2-tailed) $= 0.031 < 0.05$	$r_s = -0.052$, p (2-tailed) $= 0.401 > 0.05$
Required crossings	$r_s = 0.269$, p (2-tailed) = $0.000 < 0.05$	$r_s = 0.334$, p (2-tailed) = $0.000 < 0.05$	$r_s = 0.134$, p (2-tailed) = 0.029 < 0.05	$r_s = 0.281$, p (2-tailed) = $0.000 < 0.05$	$r_s = 0.251$, p (2-tailed) = $0.000 < 0.05$	$r_s = 0.134$, p (2-tailed) = $0.029 < 0.05$
Presence of RSL	$U = 127.000$, p (2-tailed) $= 0.048 < 0.05$ $N = 40$	$U = 155.500$, p (2-tailed) $= 0.229 > 0.05$ $N = 40$	$U = 187.000$, p (2-tailed) $= 0.725 > 0.05$ $N = 40$	$U = 144.000$, p (2-tailed) $= 0.130 > 0.05$ $N = 40$	$U = 105.000$, p (2-tailed) $= 0.010 < 0.05$ $N = 40$	$U = 187.000$, p (2-tailed) $= 0.725 > 0.05$ $N = 40$
Hectare per runway-km	$r_s = -0.110$, p (2-tailed) $= 0.073 > 0.05$	$r_s = -0.207$, p (2-tailed) $= 0.001 < 0.05$	$r_s = -0.098$, p (2-tailed) $= 0.110 > 0.05$	$r_s = -0.128$, p (2-tailed) $= 0.036 < 0.05$	$r_s = -0.102$, p (2-tailed) $= 0.095 > 0.05$	$r_s = -0.098$, p (2-tailed) $= 0.110 > 0.05$

*For presence of RSL $N = 40$ because 20 airports have RSL implemented, 20 without are added with equal movement figures.

A7.3 Incomplete dataset (all outliers excluded)

	Correlation					
		S_R		E_R		
Characteristics	Total	High	D	OI	PD	V/PD
Hourly movements	r_s = -0.009, p (2-tailed) = 0.888 > 0.05 N = 262	r_s = .339, p (2-tailed) = 0.000 < 0.05 N = 264	r_s = -.184, p (2-tailed) = 0.003 < 0.05 N = 261	r_s = 0.365, p (2-tailed) = 0.000 < 0.05 N = 264	r_s = -0.004, p (2-tailed) = 0.949 > 0.05 N = 261	r_s = -0.201, p (2-tailed) = 0.001 < 0.05 N = 259
Share commercial traffic	r_s = -.067, p (2-tailed) = 0.279 > 0.05 N = 262	r_s = 0.112, p (2-tailed) = 0.069 > 0.05 N = 264	r_s = -0.161, p (2-tailed) = 0.009 < 0.05 N = 261	r_s = 0.253, p (2-tailed) = 0.000 < 0.05 N = 267	r_s = -0.120, p (2-tailed) = 0.053 > 0.05 N = 261	r_s = -0.067, p (2-tailed) = 0.284 > 0.05 N = 258
Share heavy aircraft	r_s = -.102, p (2-tailed) = 0.101 > 0.05 N = 262	r_s = -.044, p (2-tailed) = 0.473 > 0.05 N = 264	r_s = -.152, p (2-tailed) = 0.014 < .05 N = 260	r_s = .176, p (2-tailed) = 0.004 < 0.05 N = 267	r_s = -.132, p (2-tailed) = 0.032 < 0.05 N = 261	r_s = -.123, p (2-tailed) = 0.048 < 0.05 N = 259
Ratio intersecting runways	r_s = 0.257, p (2-tailed) = 0.000 < 0.05 N = 263	r_s = 0.250, p (2-tailed) = 0.000 < 0.05 N = 263	r_s = 0.199, p (2-tailed) = 0.001 < 0.05 N = 262	r_s = 0.216, p (2-tailed) = 0.000 < 0.05 N = 267	r_s = 0.200, p (2-tailed) = 0.001 < 0.05 N = 262	r_s = 0.133, p (2-tailed) = 0.033 < 0.05 N = 258
Number of TWY-RWY intersections per runway-km	r_s = 0.228, p (2-tailed) = 0.000 < 0.05 N = 261	r_s = 0.441, p (2-tailed) = 0.000 < 0.05 N = 267	r_s = 0.103, p (2-tailed) = 0.095 > 0.05 N = 261	r_s = 0.323, p (2-tailed) = 0.000 < 0.05 N = 267	r_s = 0.215, p (2-tailed) = 0.000 < 0.05 N = 261	r_s = 0.052, p (2-tailed) = 0.403 > 0.05 N = 258
Ratio non-right angled	r_s = 0.017, p (2-tailed) = 0.780 > 0.05 N = 262	r_s = 0.220, p (2-tailed) = 0.000 < 0.05 N = 264	r_s = -0.094, p (2-tailed) = 0.132 > 0.05 N = 260	r_s = 0.213, p (2-tailed) = 0.000 < 0.05 N = 267	r_s = -0.046, p (2-tailed) = 0.461 > 0.05 N = 261	r_s = 0.023, p (2-tailed) = 0.708 > 0.05 N = 259
Ratio RETs	r_s = -0.053, p (2-tailed) = 0.395 > 0.05 N = 263	r_s = 0.191, p (2-tailed) = 0.002 < 0.05 N = 264	r_s = 0.048, p (2-tailed) = 0.443 > 0.05 N = 260	r_s = 0.309, p (2-tailed) = 0.000 < 0.05 N = 266	r_s = -0.111, p (2-tailed) = 0.073 > 0.05 N = 261	r_s = -0.062, p (2-tailed) = 0.319 > 0.05 N = 261
Required crossings	r_s = 0.323, p (2-tailed) = 0.000 < 0.05 N = 263	r_s = 0.345, p (2-tailed) = 0.000 < 0.05 N = 264	r_s = 0.250, p (2-tailed) = 0.000 < 0.05 N = 263	r_s = 0.282, p (2-tailed) = 0.000 < 0.05 N = 267	r_s = 0.266, p (2-tailed) = 0.000 < 0.05 N = 262	r_s = 0.159, p (2-tailed) = 0.011 < 0.05 N = 248
Presence of RSL	U = 127.000, p (2-tailed) = 0.077 > 0.05 N = 39	U = 155.500, p (2-tailed) = 0.332 > 0.05 N = 39	U = 118.500, p (2-tailed) = 0.045 < 0.05 N = 39	U = 144.000, p (2-tailed) = 0.196 > 0.05 N = 39	U = 105.000, p (2-tailed) = 0.010 < 0.05 N = 40	U = 187.000, p (2-tailed) = 0.933 > 0.05 N = 39
Hectare per runway-km	r_s = -0.0084, p (2-tailed) = 0.175 > 0.05 N = 262	r_s = -0.191, p (2-tailed) = 0.002 < 0.05 N = 265	r_s = -0.0002, p (2-tailed) = 0.975 > 0.05 N = 260	r_s = -0.135, p (2-tailed) = 0.026 < 0.05 N = 267	r_s = -0.075, p (2-tailed) = 0.227 > 0.05 N = 262	r_s = -0.0087, p (2-tailed) = 0.113 > 0.05 N = 258

A7.4 Semi-complete dataset (non-hub outliers excluded)

	Correlation					
		S_R		E_R		
Characteristics	Total	High	D	OI	PD	V/PD
Hourly movements	r_s = -0.009, p (2-tailed) = 0.888 $>$ 0.05 N = 262	r_s = 0.351, p (2-tailed) = 0.000 $<$ 0.05 N = 266	r_s = -.184, p (2-tailed) = 0.003 $<$ 0.05 N = 261	r_s = 0.364, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = -0.004, p (2-tailed) = 0.949 $>$ 0.05 N = 261	r_s = -0.196, p (2-tailed) = 0.001 < 0.05 N = 260
Share commercial traffic	r_s = -.067, p (2-tailed) = 0.279 $>$ 0.05 N = 262	r_s = 0.124, p (2-tailed) = 0.043 $>$ 0.05 N = 266	r_s = -0.161, p (2-tailed) = 0.009 $<$ 0.05 N = 261	r_s = 0.253, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = -0.120, p (2-tailed) = 0.053 $>$ 0.05 N = 261	r_s = -0.065, p (2-tailed) = 0.298 $>$ 0.05 N = 259
Share heavy aircraft	r_s = -.102, p (2-tailed) = 0.101 $>$ 0.05 N = 262	r_s = 0.046, p (2-tailed) = 0.450 $>$ 0.05 N = 267	r_s = -.152, p (2-tailed) = 0.014 $<$ 0.05 N = 260	r_s = .176, p (2-tailed) = 0.004 $<$ 0.05 N = 267	r_s = -.132, p (2-tailed) = 0.032 < 0.05 N = 261	r_s = -0.122, p (2-tailed) = 0.009 < 0.05 N = 260
Ratio intersecting runways	r_s = 0.257, p (2-tailed) = 0.000 $<$ 0.05 N = 263	r_s = 0.261, p (2-tailed) = 0.000 $<$ 0.05 N = 265	r_s = 0.199, p (2-tailed) = 0.001 $<$ 0.05 N = 262	r_s = 0.216, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = 0.200, p (2-tailed) = 0.001 $<$ 0.05 N = 262	r_s = 0.124, p (2-tailed) = 0.045 $<$ 0.05 N = 260
Number of TWY-RWY intersections per runway-km	r_s = 0.228, p (2-tailed) = 0.000 $<$ 0.05 N = 261	r_s = 0.436, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = 0.103, p (2-tailed) = 0.095 $>$ 0.05 N = 261	r_s = 0.323, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = 0.215, p (2-tailed) = 0.000 $<$ 0.05 N = 261	r_s = 0.042, p (2-tailed) = 0.506 $>$ 0.05 N = 259
Ratio non-right angled	r_s = 0.017, p (2-tailed) = 0.780 $>$ 0.05 N = 262	r_s = 0.225, p (2-tailed) = 0.000 $<$ 0.05 N = 266	r_s = -0.094, p (2-tailed) = 0.132 $>$ 0.05 N = 260	r_s = 0.213, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = -0.046, p (2-tailed) = 0.461 $>$ 0.05 N = 261	r_s = 0.014, p (2-tailed) = 0.828 $>$ 0.05 N = 260
Ratio RETs	r_s = -0.053, p (2-tailed) = 0.395 $>$ 0.05 N = 263	r_s = 0.201, p (2-tailed) = 0.002 $<$ 0.05 N = 266	r_s = 0.048, p (2-tailed) = 0.443 $>$ 0.05 N = 260	r_s = 0.315, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = -0.111, p (2-tailed) = 0.073 $>$ 0.05 N = 261	r_s = -0.067, p (2-tailed) = 0.284 $>$ 0.05 N = 259
Required crossings	r_s = 0.323, p (2-tailed) = 0.000 $<$ 0.05 N = 263	r_s = 0.351, p (2-tailed) = 0.000 $<$ 0.05 N = 265	r_s = 0.250, p (2-tailed) = 0.000 $<$ 0.05 N = 263	r_s = 0.282, p (2-tailed) = 0.000 $<$ 0.05 N = 267	r_s = 0.266, p (2-tailed) = 0.000 $<$ 0.05 N = 262	r_s = 0.158, p (2-tailed) = 0.011 $<$ 0.05 N = 259
Presence of RSL	U = 127.000, p (2-tailed) = 0.077 $>$ 0.05 N = 39	U = 155.500, p (2-tailed) = 0.332 $>$ 0.05 N = 39	U = 118.500, p (2-tailed) = 0.045 $<$ 0.05 N = 39	U = 144.000, p (2-tailed) = 0.196 $>$ 0.05 N = 39	U = 105.000, p (2-tailed) = 0.010 $<$ 0.05 N = 40	U = 187.000, p (2-tailed) = 0.933 $>$ 0.05 N = 39
Hectare per runway-km	r_s = -0.0084, p (2-tailed) = 0.175 $>$ 0.05 N = 262	r_s = -0.205, p (2-tailed) = 0.001 $<$ 0.05 N = 266	r_s = -0.0002, p (2-tailed) = 0.975 $>$ 0.05 N = 260	r_s = -0.135, p (2-tailed) = 0.026 $<$ 0.05 N = 267	r_s = -0.075, p (2-tailed) = 0.227 $>$ 0.05 N = 262	r_s = -0.083, p (2-tailed) = 0.183 $>$ 0.05 N = 259

A8 Forced entry models

In this part, the forced entry model estimates for all incursion rates are summarised.

	Model R_{rate}(total)				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	1.162	0.342		.001	
Ratio intersecting runways	0.838	0.462	0.127	.071	0.104
TWY-RWY intersections/RWY-km	0.198	0.071	0.163	.005	0.161
Required crossings	0.725	0.210	0.244	.001	0.197
Model summary					
R^2	0.152		Model significance	.000	
Adjusted R^2	0.142		Std. error of estimate	1.92782	
			No collinearity	✓	

	Model R_{rate}(high severity)				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.178	0.122			
Hourly movements	0.010	0.003	0.235	.000	0.177
Share commercial traffic	0.000	0.001	-0.008	.892	-0.007
Ratio intersecting runways	0.441	0.129	0.214	.001	0.168
TWY-RWY intersections/RWY-km	0.121	0.021	0.320	.000	0.285
Ratio non-right angled	0.033	0.196	0.009	.867	0.008
Required crossings	0.181	0.059	0.195	.002	0.151
Hectare per runway-km	-0.001	0.001	-0.026	.624	-0.024
Model summary					
R^2	0.381		Model significance	.000	
Adjusted R^2	0.364		Std. error of estimate	0.51837	
			No collinearity	✓	

	Model R_{rate}(low severity)				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	2.062	0.231		.000	
Hourly movements	-0.019	0.008	-0.162	.025	-0.130
Share commercial traffic	-0.005	0.004	-0.088	.230	-0.070
Share heavy aircraft	-0.014	0.014	-0.065	.322	-0.057
Ratio intersecting runways	0.147	0.392	0.027	.707	0.022
Required crossings	0.663	0.178	0.273	.000	0.216
Model summary					
R^2	0.139		Model significance	.000	
Adjusted R^2	0.122		Std. error of estimate	1.59323	
			No collinearity	✓	

	Model R_{rate}(operational incidents)				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.088	0.093		.345	
Hourly movements	0.008	0.002	0.263	.000	0.196
Share commercial traffic	0.002	0.001	0.146	.035	0.114
Share heavy aircraft	0.001	0.004	0.014	.825	0.012
Ratio intersecting runways	0.328	0.100	0.226	.001	0.177
TWY-RWY intersections/RWY-km	0.041	0.016	0.156	.011	0.137
Ratio non-right angled	-0.088	0.152	-0.035	.561	-0.031

Required crossings	0.054	0.045	0.082	.238	0.063
Hectare per runway-km	0.000	0.001	0.009	.871	0.009
Model summary					
R^2	0.256		Model significance	.000	
Adjusted R^2	0.233		Std. error of estimate	0.40114	
			No collinearity	✓	

	Model R_{rate}(pilot deviations)				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	0.735	0.252		.004	
Share heavy aircraft	-0.024	0.011	-0.126	.033	-0.126
Ratio intersecting runways	0.304	0.335	0.065	.366	0.053
TWY-RWY intersections/RWY-km	0.179	0.050	0.211	.000	0.209
Required crossings	0.360	0.153	0.169	.019	0.138
Model summary					
R^2	0.121		Model significance	.000	
Adjusted R^2	0.107		Std. error of estimate	1.38543	
			No collinearity	✓	

	Model R_{rate}(vehicle/pedestrian deviations)				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	0.621	0.067		.000	
Share heavy aircraft	-0.007	0.002	-0.185	.006	-0.169
Ratio intersecting runways	0.000	0.004	-0.003	.966	-0.003
TWY-RWY intersections/RWY-km	-0.012	0.128	-0.007	.926	-0.006
Required crossings	0.104	0.058	0.139	.074	0.110
Model summary					
R^2	0.046		Model significance	.017	
Adjusted R^2	0.031		Std. error of estimate	0.51686	
			No collinearity	✓	

A9 Stepwise model development

This appendix gives the chronological process of the high severity R_{rate} model development, according to the stepwise regression methodology.

First, the model was developed by the application of one attribute (model I), the number of TWY-RWY intersections per runway-km, which showed the strongest correlation with R_{rate}.

	Model R_{rate}(high severity) [I]				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	0.164	0.094		.084	
Number of TWY-RWY intersections per runway-km	0.152	0.022	0.400	.000	0.400
Model summary					
R^2	0.160		Model significance	.000	
Adjusted R^2	0.157		Std. error of estimate	0.58082	
			No collinearity	✓	

A low adjusted R^2 of 0.157 was achieved. The model is significant, thus the next attributes: hourly movements and required crossings are added in sequence (model II and III), because both variables show the same correlation with R_{rate}.

	Model R_{rate}(high severity) [II]				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	0.138	0.094		.138	
Number of TWY-RWY intersections per runway-km	0.123	0.022	0.323	.000	0.302
Hourly movements	0.009	0.003	0.218	.000	0.204
Model summary					
R^2	0.201		Model significance	.000	
Adjusted R^2	0.195		Std. error of estimate	0.56738	
			No collinearity	✓	

Number of TWY-RWY intersections per runway-km appears to be an important variable, considering the standardised betas.

	Model R_{rate}(high severity) [III]				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.103	0.093		.271	
Number of TWY-RWY intersections per runway-km	0.109	0.021	0.286	.000	0.266
Hourly movements	0.008	0.002	0.185	.000	0.172
Required crossings	0.307	0.047	0.341	.000	0.337
Model summary					
R^2	0.315		Model significance	.000	
Adjusted R^2	0.307		Std. error of estimate	0.52661	
			No collinearity	✓	

The adjusted R^2 improved strongly to 0.307. Considering the standardised betas, required crossings appears to be a twice as much important predictor of the incursion rate than hourly movements. The model is significant, thus the next attribute: ratio intersecting runways is added (model IV).

	Model R_{rate}(high severity) [IV]				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.139	0.092		.136	

Number of TWY-RWY intersections per runway-km	0.107	0.021	0.279	.000	0.259
Hourly movements	0.010	0.002	0.228	.000	0.207
Required crossings	0.186	0.057	0.208	.001	0.164
Ratio intersecting runways	0.443	0.127	0.220	.001	0.174
Model summary					
R^2	0.346		Model significance	.000	
Adjusted R^2	0.336		Std. error of estimate	0.51638	
			No collinearity	✓	

The adjusted R^2 improved even further to 0.336. The standardised betas show that the contribution to the model estimation for each independent variable became equal. The implementation for this variable is important because it gives an important description of the airport layout. The attribute distinguishes airports with central terminal acreages and other airports. The remaining attributes have comparable r_s values, and are for this reason applied alternately (model V, VI, VII and VIII).

	Model R_{rate}(high severity) [V]				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.141	0.094		.136	
Number of TWY-RWY intersections per runway-km	0.106	0.021	0.278	.000	0.257
Hourly movements	0.010	0.002	0.226	.000	0.199
Required crossings	0.186	0.058	0.207	.001	0.162
Ratio intersecting runways	0.438	0.128	0.219	.001	0.173
Ratio non-right angled	0.031	0.192	0.009	.872	0.008
Model summary					
R^2	0.345		Model significance	.000	
Adjusted R^2	0.333		Std. error of estimate	0.51580	
			No collinearity	✓	

	Model R_{rate}(high severity) [VI]				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.129	0.092		.162	
Number of TWY-RWY intersections per runway-km	0.113	0.021	0.297	.000	0.270
Hourly movements	0.009	0.002	0.217	.000	0.195
Required crossings	0.187	0.057	0.208	.001	0.164
Ratio intersecting runways	0.440	0.127	0.220	.001	0.174
Ratio RETs	-0.449	0.316	-0.073	.157	-0.071
Model summary					
R^2	0.351		Model significance	.000	
Adjusted R^2	0.338		Std. error of estimate	0.51536	
			No collinearity	✓	

	Model R_{rate}(high severity) [VII]				
Variables	B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.093	0.117		.425	
Number of TWY-RWY intersections per runway-km	0.104	0.021	0.272	.000	0.248
Hourly movements	0.010	0.002	0.229	.000	0.208
Required crossings	0.182	0.058	0.203	.002	0.158
Ratio intersecting runways	0.435	0.128	0.217	.001	0.172
Hectare per runway-km	-0.001	0.001	-0.033	.536	-0.031
Model summary					
R^2	0.346		Model significance	.000	
Adjusted R^2	0.333		Std. error of estimate	0.51642	
			No collinearity	✓	

Variables	Model R_{rate}(high severity) [VIII] B	Std. Error	Std. Betas	Sig.	Corr. part
(Constant)	-0.150	0.103		.144	
Number of TWY-RWY intersections per runway-km	0.107	0.021	0.281	.000	0.259
Hourly movements	0.009	0.003	0.218	.001	0.165
Required crossings	0.188	0.057	0.209	.001	0.165
Ratio intersecting runways	0.439	0.127	0.220	.001	0.174
Share commercial traffic	0.000	0.001	0.017	.780	0.014
Model summary					
R^2	0.346		Model significance	.000	
Adjusted R^2	0.333		Std. error of estimate	0.51672	
			No collinearity	✓	

The adjusted R^2 improved further across all models. However, each model resulted in non-significant variables. Therefore, model IV was kept for further improvement and fitting.

A10 Sensitivity analysis using probability function

The developed model can also be used to determine the probability that a specified scenario occurs, given specific airport characteristics. Instead of predicting the continuous variable R_{rate}, the variables could be used to predict an outcome of different variable type, i.e. binary outcome. For this, logistic regression analysis is used, using the generic logistic regression equation (A-5):

$$ln\left(\frac{p_{yes\,=\,1}}{p_{no\,=\,0}}\right) = b_0 + b_1X_{1i} + b_2X_{2i} + \cdots + b_kX_{ki} \qquad \text{(A-5)}$$

Rewriting into a probability model form gives (A-6):

$$P(Y_i) = \frac{1}{1 + e^{-(b_0 + b_1X_{1i} + b_2X_{2i} + \cdots + b_kX_{ki})}} \qquad \text{(A-6)}$$

Here, the model coefficients are determined by means of the maximum likelihood estimation.

From the simulation in SPSS, the goodness of fit was obtained for the developed models. The output provides the results of a Chi-Square test, which compares the -2 Log Likelihood value of the model with the estimated value of a model with only one variable. The difference is the value for Chi-Square. Furthermore, the pseudo R^2 values are given for Cox & Snell and Nagelkerke. Generally, R^2 are relatively low compared to linear regression. Also, the Hosmer and Lemeshow Goodness-of-Fit Test results are provided. Here, the aim is to obtain non-significant values, meaning that the data fits the model sufficiently.

Same as for linear regression, the B-values describe the function for the model. These parameter values are estimated by means of the maximum likelihood estimation (MLE), which selects coefficients that maximise the probability that the observed results are obtained. In de model, B shows the effect on the logit, i.e. the probability that the scenario is met. Preferably, probability ratios are considered instead of logits, because these are easier interpretable. Therefore, exp(B)-values were obtained, which describe the contribution of the variable on the probability that the specified scenario occurs. Here, values above 1.0 explain a positive contribution of the variable to $P(Y_i)$.

Since severity A, B and C incidents were aggregated into high in the earlier phase of the research, predictions for incursion rates for each severity class individually, cannot be made. However, it is possible to define specific scenarios that describe a certain intensity of high severity incursions. Based on the distribution of the incursion rates, four R_{rate} events have been defined: $R_{rate} \leq 0.5$, $R_{rate} \leq 1.0$, $R_{rate} \leq 1.5$ and $R_{rate} \leq 2.0$. For these, the probabilities were determined for the likelihood that the event occurs at a given airport.

In equation (A-7), the linear function retrieved from the multiple regression model is expressed in logit terms. The equation provides a probability of scenario Y occurring, in which Y is described by binary value true $= 1$ or false $= 0$, i.e. whether the prediction scenario occurs. Note that the non-extended model is applied.

$$P(Y_i) = \frac{1}{1 + e^{-(b_0 + a_1{T_h}^{0.5} + a_2I_{km} + a_3{C_{req}}^{2.2} + a_4{I_r}^{1.9} + a_5I_{km}{I_r}^{1.9})}} \qquad \text{(A-7)}$$

In Table A-8, the B-coefficients, the corresponding standard errors and the exp(B) estimates are listed for each of the four events. Also, the corresponding goodness-of fit figures are provided.

As can been seen in the table, multiple variables appeared to be not significant at the specified 95% confidence interval. However, each model, was found to be significant, with overall percentages of predicted success of 69.2, 83.3, 90.1 and 96.2. Strikingly, the model for $R_{rate} \geq 1.5$ shows rather deviating prediction coefficients. However, their exp(B) values show generally comparable results to the other models. One characteristic deviation is visible in the effect of ratio intersecting runways. Though, the effect of this variable is already exposed by the interaction term, $I_n \times I_r$.

To visualise the probabilities for each of the model attributes individually, graphs were produced in which per variable the probability is plotted for the corresponding range of change, for each event. These graphs are depicted in Figure A-12. In order to show the effect for the individual variables, the means were used as input for the remaining variables.

Table A-8: Logistic model estimates per event

Model (event)	(Constant)	TWY-RWY intersections/ runway-km	Hourly movements	Required crossings	Ratio intersecting runways	$I_n \times I_r$
	B (S.E.) Exp(B)	B (S.E.) Exp(B)	B (S.E.) Exp(B)	B (S.E.) Exp(B)	B (S.E.) Exp(B)	B (S.E.) Exp(B)
$R_{rate} \geq$ 0.5	-2.554 (0.567) 0.078	º0.214 (0.123) 1.239	0.400 (0.132) 1.492	º0.215 (0.108) 1.24	º-2.697 (1.96) 0.067	1.279 (0.587) 3.593
	R^2 (Cox & Snell): 0.129, (Nagelkerke) 0.379, Hosmer and Lemeshow: .668 ($X^2 = 5.811$), Significance: .000					
$R_{rate} \geq$ 1.0	-4.799 (0.688) 0.008	0.336 (0.127) 1.4	0.467 (0.123) 1.596	º0.152 (0.097) 1.164	º0.305 (1.949) 1.357	º0.631 (0.504) 1.879
	R^2 (Cox & Snell): 0.283, (Nagelkerke) 0.396, Hosmer and Lemeshow: .143 ($X^2 = 12.182$), Significance: .000					
$R_{rate} \geq$ 1.5	-4.757 (0.842) 0.0092	º0.314 (0.144) 1.369	º0.072 (0.148) 1.074	º0.192 (0.103) 1.211	-1.678 (1.718) 0.187	1.008 (4.755) 2.739
	R^2 (Cox & Snell): 0.213, (Nagelkerke) 0.391, Hosmer and Lemeshow: .981 ($X^2 = 2.007$), Significance: .000					
$R_{rate} \geq$ 2.0	-6.445 (1.419) 0.002	º0.163 (0.246) 1.177	º0.320 (0.180) 1.378	0.318 (0.115) 1.375	º0.018 (2.013) 1.018	º0.338 (0.421) 1.402
	R^2 (Cox & Snell): 0.121, (Nagelkerke) 0.207, Hosmer and Lemeshow: .609 ($X^2 = 6.338$), Significance: .000					

ºNot significant at 95% confidence interval

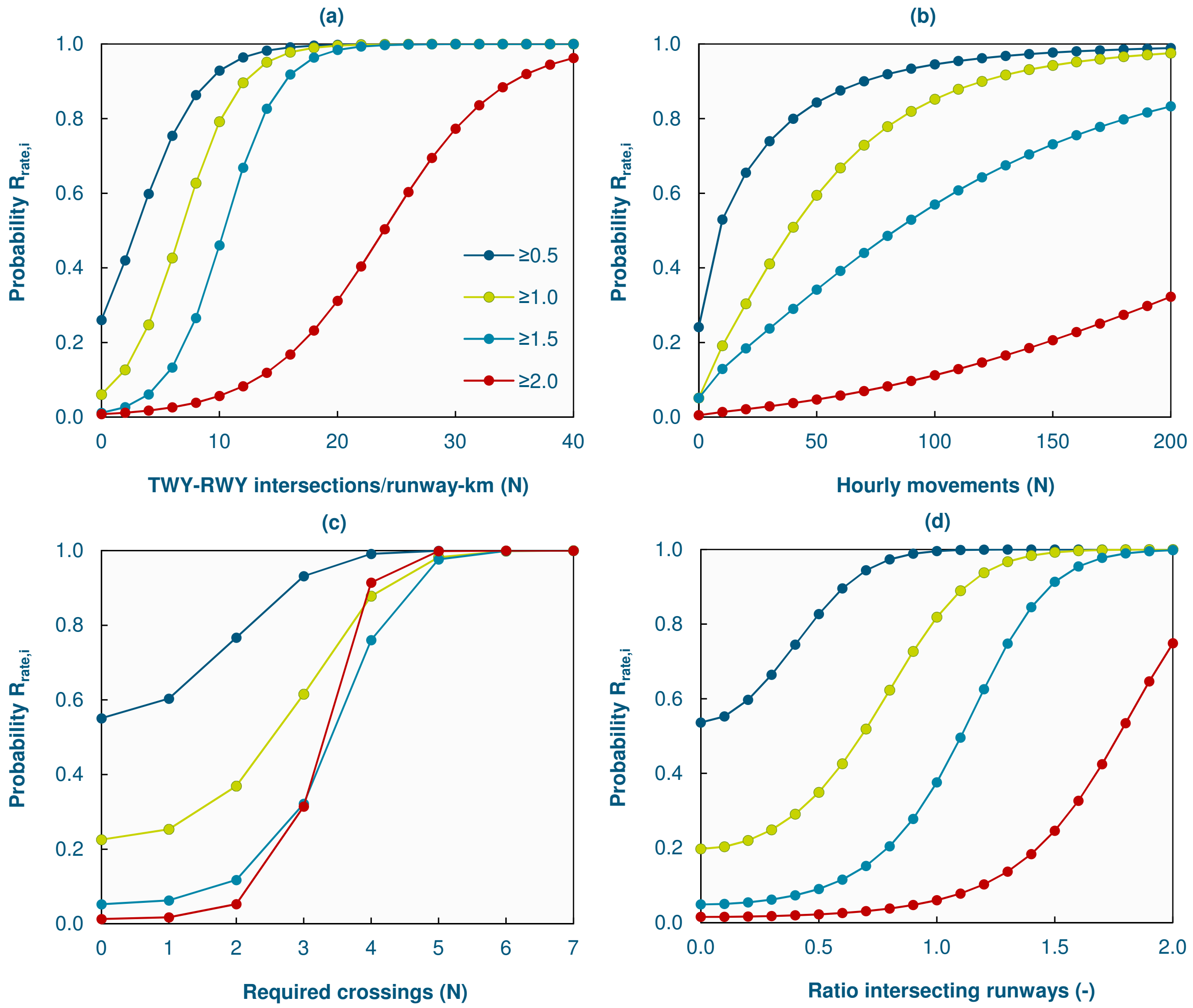


Figure A-12: Probability graph for model characteristics (a-d) per incursion rate event: $P(R_{rate} \geq i), i = 0.5, 1.0, 1.5, 2.0$

To compare the effects of each individual variable, it is required to use standardised betas instead of adding absolute values for the variables. Since for logistic regression no standardised betas are estimated, this was calculated manually, according to the method of Menard (2011). For each variable applies in this case (A-12):

$$P(Y_i) = \frac{B\ SD\ R}{SD_{logitY}} \qquad \text{(A-8)}$$

where:

$$logitY = ln\left(\frac{P(Y_i)}{1 - P(Y_i)}\right)$$

And R stands for the square root from Cox and Snell's R^2.

Hence, this procedure has to be applied for each scenario model. Since, the model for $R_{rate} \geq 1.0$ appeared to be the most accurate for estimation, it was chosen to only standardize this model. The effect of the change in $P(Y_i)$ for an increasing standardised input value X can now be compared between the variables, as is shown in Figure A-13. Each line in the graph shows the probability effect for a specific variable, where all other variables were set to 0. Also, the total effect is shown in grey.

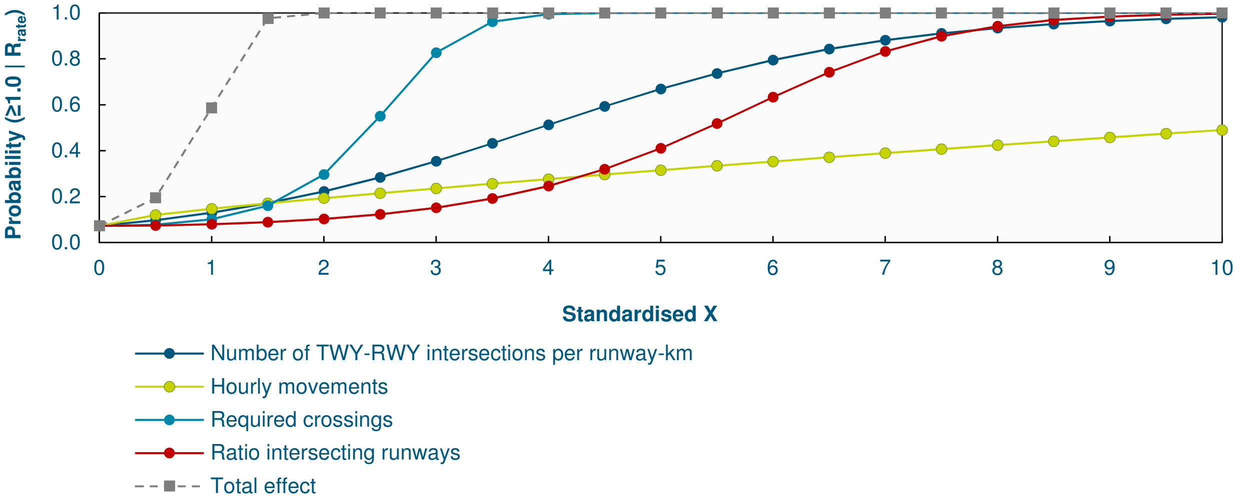
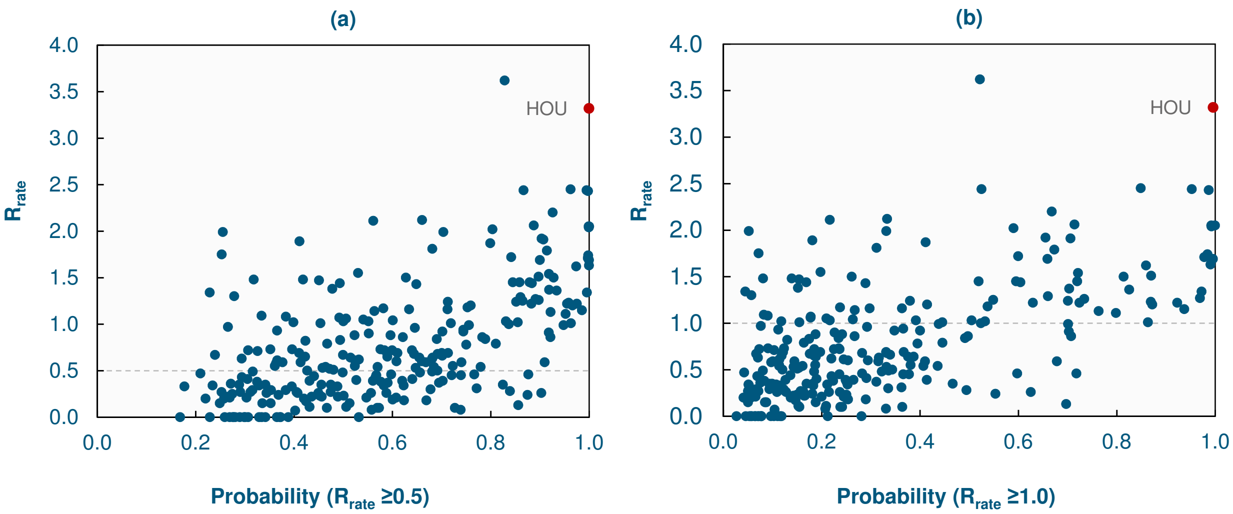


Figure A-13: Probability graph for incursion rate event R_{rate} > 1.0 per characteristic for standardised X

Next, similar to the probability results presented in Figure A-12, the probabilities for each airport is estimated per event. These results are depicted in the graphs below (Figure A-14). As can be observed, for higher incursion rate events a large share of the airports represents low probabilities. Though, certain airports have low probabilities and meanwhile high R_{rate} values. As example, William P. Hobby Airport (HOU) is indicated in red for each of the plots.



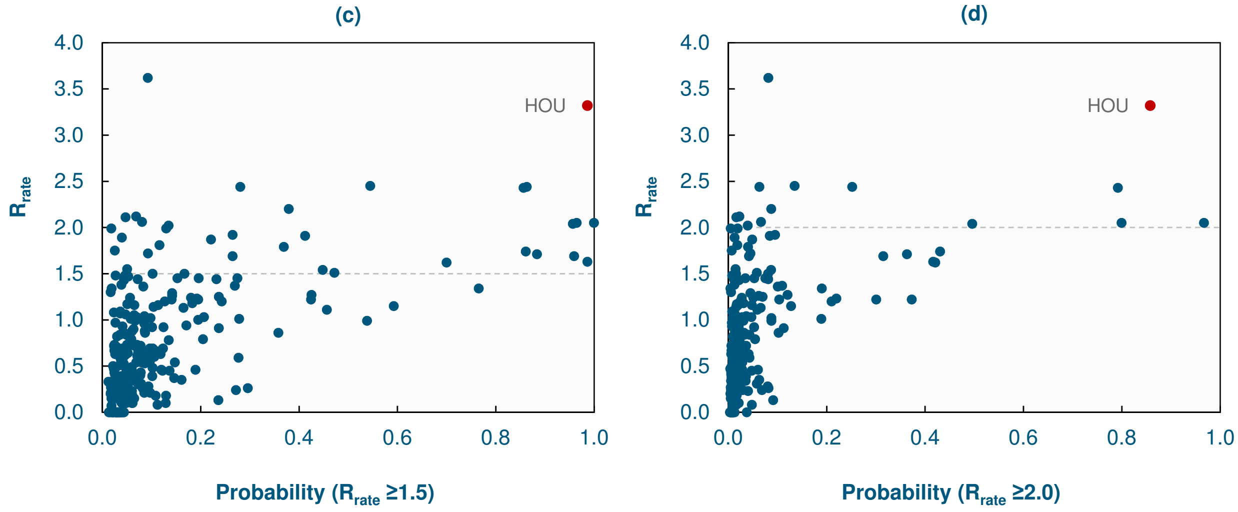


Figure A-14: Probability plots for incursion rate events R_{rate} ≥ 0.5 (a), R_{rate} ≥ 1.0 (b), R_{rate} ≥ 1.5 (c) and R_{rate} ≥ 2.0 (d)

A11 Risk mapping

To see how the observed incursion rates at the airports translate to incursion risks, the components for severity and likelihood were determined according to the risk definitions by the FAA. From this, it can be seen which airports perform, based on the observed incidents, within respectively the green, the yellow and the red regions, indicating whether preventive action is needed.

Since all A, B and C incidents were aggregated into high severity, no accurate predictions can be made for the risk on these individual incursion categories. However, it is known that all incidents belong at the lowest to category C, which corresponds to major incident in the risk matrix, as is shown in Appendix A2. In this respect, D incidents can be related to either 'minor incident' or 'no safety effect'. All model estimation airports are assigned to one of the codes in the risk matrix. For this, mapping is conducted for the C column of the matrix. This is in line with the assumption that airports with large portions of C-incidents, are also more vulnerable for A and B incidents.

The determination of the position in the risk matrix, i.e. the risk code, is based on the following equations (A-9) (A-10):

$$N_{dep}(f_{\mathcal{L}}) = \frac{R_{rate} f_{\mathcal{L}}}{5.0 * 10^5} \quad \text{(A-9)}$$

In here, N_{dep} stands for number of incursions per $f_{\mathcal{L}}$ departures and $f_{\mathcal{L}}$ represents the number of departures for $\mathcal{L}$: frequent ($\mathcal{L} = 2500$), probable ($\mathcal{L} = 2.5 * 10^6$), remote ($\mathcal{L} = 2.5 * 10^7$), improbable $\mathcal{L} = 2.5 * 10^8$ and extremely improbable ($\mathcal{L} = 2.5 * 10^9$). In case $N_{dep}(f_{\mathcal{L}}) \geq 1.0$, the corresponding $\mathcal{L}$ category applies.

$$N_{tot}(t_{\mathcal{L}}) = \frac{1}{n} \sum_{i=1}^{n} R_y \left(\frac{1}{t_{\mathcal{L}} O_{wk}/168} \right) \quad \text{(A-10)}$$

N_{tot} is the number of incursions per $t_{\mathcal{L}}$ time window and R_y respresent the number of incursions per year. The $t_{\mathcal{L}}$ gives the time window ratio for $\mathcal{L}$: frequent ($\mathcal{L} = 52$), probable ($\mathcal{L} = 12$), remote ($\mathcal{L} = 1$), improbable ($\mathcal{L} = 0.1$) and extremely improbable ($\mathcal{L} = 100$). Operational hours are presented by O_w. Also, $i = 1$ for 2007 and $n = 11$ for the study period. In case $N_{tot}(t_{\mathcal{L}}) \geq 1.0$, the corresponding $\mathcal{L}$ category applies.

From the results of both equations accounts that the value $max\{N_{tot}(t_{\mathcal{L}}), N_{dep}(f_{\mathcal{L}})\}$ applies.

This method can also be used for forecast models, which are applied in the airport cases in the next section. The effects of geometrical modifications can therefrom be tested on the risk categories.

In Table A-9, the modified risk matrix is shown, in which the airports are mapped for three severity categories and according to the two measures discussed above. To determine the applicable risk category, the highest frequency position for each airport between the measures has to be found.

Since airports were found for the red region, although not being large hubs, it was decided to indicate these airports in the matrix. Underlined airport codes represent non-large hubs. Two airports are indicated in bold, since these only depend on one additional incursion to be assigned to the higher frequency range: the red zone B4. The complete series of results from the mapping can be found in Appendix A12, where the applicable risk codes are listed for the three severity groups.

To visualise the effects of each of the airport characteristics in the model on the position in the risk matrix, a mean airport was determined, based on the average values for each of the characteristics. In addition, the theoretical minimum value and maximum value for the variables resulting in a different probability category are used as input, while the other variables remain constant. Table A-10 shows the effects of the variables on the risk group. The mean airport is based on the following characteristics: $T_h =$ 15.7, $I_n =$ 4.10, $C_{req} =$ 1.04 and $I_r =$ 0.32. The positions are based on $max\{N_{tot}(t_{\mathcal{L}}), N_{dep}(f_{\mathcal{L}})\}$.

Table A-9: Risk matrix for observed incursions at large hubs (frequency and time window)

Probability		Severity: Accident A	Serious incident B	Major incident C	Minor incident D	Severity: Accident A	Serious incident B	Major incident C	Minor incident D
Frequent	5								
Probable	4			LAX - ORD			ATW - ERI - HLN - JAC - MKC - MLI - SBN	ATL - BOS - BWI - CLT - DCA - DEN - DFW - DTW - EWR - FLL - HNL - IAD - IAH - JFK - LAS - LAX - LGA - MCO - MDW - MIA - MSP - ORD - PDX - PHL - PHX - SAN - SEA - SFO - SLC - TPA	ATL - BOS - BWI - CLT - DCA - DEN - DFW - DTW - EWR - FLL - HNL - IAD - IAH - JFK - LAS - LAX - LGA - MCO - MDW - MIA - MSP - ORD - PDX - PHL - PHX - SAN - SEA - SFO - SLC - TPA
Remote	3		ORD	ATL - BOS - BWI - CLT - DCA - DEN - DFW - DTW - EWR - FLL - HNL - IAD - IAH - JFK - LAS - LGA - MDW - MIA - MSP - PDX - PHL - PHX - SAN - SEA - SFO - SLC - TPA	ATL - BOS - BWI - CLT - DCA - DEN - DFW - DTW - EWR - FLL - HNL - IAD - IAH - JFK - LAS - LAX - LGA - MCO - MDW - MIA - MSP - ORD - PDX - PHL - PHX - SEA - SFO - SLC - TPA		BWI - CLT - DEN - DFW - DTW - EWR - FLL - ***HNL*** - IAD - LAX - LGA - MDW - MSP - ***ORD*** - PHL - SAN - SFO		
Extremely remote	2		CLT - DEN - DFW - DTW - ERI - FLL - HLN - HNL - IAD - JAC - MKC - LAX - LGA - SFO	MCO	SAN		PHX		
Extremely improbable	1		ATL - ATW - BOS - BWI - DCA - EWR - IAH - JFK - LAS - MCO - MDW - MIA - MLI - MSP - PDX - PHL - PHX - SAN - SBN - SEA - SLC - TPA				ATL - BOS - DCA - IAH - JFK - LAS - MCO - MIA - PDX - SEA - SLC - TPA		

Table A-10: Influence of model characteristics and incursion risk

Probability		Severity: A	Serious incident B	Major incident C	D	E
Frequent	5			$T_h = 310$ · $C_{req} = 14$ · $I_r = 6.85$ · $I_n = 207$ · MEAN		
Probable	4			$T_h = 0$ · $C_{req} = 0$ · $I_r = 0$		
Remote	3					
Extremely remote	2					
Extremely improbable	1			$I_n = 1$		

A12 Airport characteristics and model results

FAA ident	Size	R_{rate}(high) Observed	Estimated	$P(R_{rate} > 2.0)$	Risk level Serious	Major	minor	Characteristics I_r	I_n	C_{req}	T_h
ABE	N	0.66	0.80	0.02	3B	4C	4D	0.50	4.7	1	11.0
ABI	N	0.59	0.50	0.01	1B	4C	4D	0.00	3.6	1	7.0
ABQ	M	1.22	1.48	0.37	3B	4C	4D	0.33	5.1	3	17.0
ACK	N	0.34	0.77	0.04	3B	4C	3D	0.33	2.7	2	12.3
ACT	N	0.27	0.43	0.01	1B	4C	4D	0.00	3.2	1	4.6
ACY	S	0.34	0.47	0.01	3B	4C	4D	0.50	2.0	1	9.2
ADQ	N	0.00	0.75	0.04	1B	1B	4D	1.00	1.5	2	9.5
ADS	O	3.26	n/a	n/a	3B	4C	4D	0.00	2.8	0	11.8
AFW	O	0.53	0.58	0.01	1B	4C	4D	0.00	3.7	1	11.8
AGC	O	0.58	n/a	n/a	1B	4C	4D	0.50	5.4	1	7.2
AGS	N	0.00	0.39	0.01	1B	1B	4D	0.50	2.3	1	3.1
AKN	N	0.33	0.30	0.01	1B	4C	4D	0.50	0.8	1	7.4
ALB	S	0.68	0.74	0.02	1B	4C	4D	0.50	4.4	1	9.2
AMA	N	0.27	0.29	0.01	1B	4C	4D	0.00	1.7	0	7.7
ANC	M	1.43	0.74	0.02	3B	4C	4D	0.00	3.5	1	30.4
APA	O	1.24	0.83	0.03	3B	4C	4D	0.00	4.2	1	34.3
ASE	N	0.93	0.50	0.01	1B	4C	4D	0.00	4.5	0	6.7
ATL	L	1.22	1.54	0.30	1B	4C	4D	0.00	5.5	2	102.4
ATW	N	0.26	0.54	0.01	4B	1B	4D	0.50	3.4	1	4.0
AUS	M	0.50	0.48	0.01	1B	4C	4D	0.00	2.0	0	20.9
AVL	S	1.99	0.30	0.01	1B	4C	4D	0.00	1.9	0	7.3
AVP	N	0.00	0.51	0.01	1B	1B	4D	0.50	2.8	1	6.1
AZO	N	0.99	1.23	0.09	1B	4C	4D	0.67	5.9	2	5.2
BCT	O	0.29	0.53	0.01	1B	3C	4D	0.00	4.7	0	7.1
BDL	M	0.53	0.76	0.02	1B	4C	4D	0.67	3.5	1	11.6
BED	O	1.16	0.74	0.02	1B	4C	4D	0.50	3.5	1	17.0
BET	N	0.51	0.58	0.01	1B	4C	4D	0.00	3.2	1	15.4
BFI	N	0.54	0.85	0.02	1B	4C	4D	0.00	6.2	0	24.9
BFL	N	0.39	0.55	0.01	1B	4C	4D	0.00	3.5	1	10.7
BGM	N	1.02	0.53	0.01	1B	4C	4D	0.50	3.7	1	2.0
BGR	N	0.20	0.26	0.00	1B	4C	4D	0.00	1.7	0	5.3
BHM	S	0.78	0.85	0.02	3B	4C	4D	0.50	5.0	1	12.0
BIL	S	1.89	0.58	0.01	3B	4C	4D	0.67	2.5	1	9.3
BIS	N	0.00	0.47	0.01	1B	3C	4D	0.50	2.6	1	5.6
BKL	O	0.00	0.53	0.01	1B	1B	4D	0.00	4.2	1	6.1
BLI	S	0.41	0.39	0.01	1B	4C	4D	0.00	2.9	0	7.6
BMI	N	0.67	0.37	0.01	1B	4C	4D	0.50	2.0	1	3.7
BNA	M	0.30	0.80	0.02	1B	4C	4D	0.25	4.7	1	20.9
BOI	S	1.55	0.66	0.01	3B	4C	4D	0.00	4.3	1	14.7
BOS	L	2.43	2.06	0.79	1B	4C	4D	1.00	4.2	3	41.8
BQN	N	0.00	0.36	0.01	1B	1B	4D	0.00	2.2	1	5.2
BTR	N	2.20	1.18	0.09	1B	4C	4D	0.67	5.0	2	10.1
BTV	S	1.81	0.78	0.02	1B	4C	4D	0.50	4.8	1	8.6
BUF	M	0.54	0.88	0.03	1B	4C	4D	0.50	5.1	1	13.5
BUR	M	1.00	0.96	0.03	3B	4C	4D	0.50	5.7	1	14.6
BWI	L	0.91	1.24	0.11	3B	4C	4D	0.33	5.8	2	29.5
BZN	S	0.72	0.75	0.03	1B	4C	4D	0.25	2.9	2	10.3
CAE	S	1.50	0.73	0.02	1B	4C	4D	0.50	4.5	1	6.9
CAK	S	0.60	0.76	0.02	1B	4C	4D	0.50	4.6	1	8.7
CHA	S	0.94	0.84	0.02	1B	4C	4D	0.50	5.6	1	6.6
CHS	S	0.96	0.75	0.02	3B	4C	4D	0.50	4.1	1	11.8
CID	S	0.71	0.47	0.01	1B	4C	4D	0.50	2.2	1	7.5
CLE	M	1.17	0.70	0.02	3B	4C	4D	0.00	4.2	1	19.5
CLT	L	1.50	1.24	0.08	3B	4C	4D	0.25	6.5	1	59.6
CMH	M	0.33	0.61	0.01	1B	4C	4D	0.00	4.3	0	15.5
CMI	N	1.16	0.90	0.05	1B	4C	4D	0.67	3.0	2	10.1
COS	S	0.82	0.51	0.01	3B	4C	4D	0.00	3.2	0	15.2
CPR	N	1.75	0.39	0.01	1B	4C	4D	0.50	2.1	1	4.1
CPS	O	0.27	0.61	0.01	3B	4C	4D	0.00	4.1	1	11.4
CRP	N	0.73	0.43	0.01	1B	4C	4D	0.00	2.7	0	11.8
CRW	N	0.35	0.48	0.01	3B	4C	3D	0.00	4.3	0	5.9
CVG	M	0.41	0.75	0.02	1B	4C	4D	0.25	4.2	1	20.5
DAB	N	1.71	1.83	0.36	3B	4C	4D	0.67	8.0	2	33.3
DAL	M	2.12	0.81	0.02	1B	4C	4D	0.00	5.2	1	22.5
DAY	S	0.44	0.56	0.01	3B	4C	4D	0.33	3.7	1	7.1
DCA	L	2.04	2.00	0.50	1B	4C	4D	1.00	6.2	2	32.5

DEN	L	0.84	0.86	0.03	3B	4C	4D	0.00	2.8	0	66.8
DFW	L	1.23	1.43	0.22	3B	4C	4D	0.00	5.8	2	74.9
DLH	N	1.48	0.55	0.01	1B	4C	4D	0.50	3.1	1	6.3
DSM	S	1.05	0.65	0.01	1B	4C	4D	0.50	3.6	1	8.9
DTW	L	1.01	1.38	0.19	3B	4C	4D	0.67	4.1	2	47.4
ECP	S	0.00	0.29	0.00	1B	4C	4D	0.00	2.3	0	4.5
EGE	N	0.49	0.42	0.01	1B	4C	4D	0.00	3.3	0	7.3
ELM	N	0.34	0.33	0.01	1B	4C	4D	0.33	2.1	1	3.0
ELP	S	0.65	0.53	0.01	3B	4C	4D	0.00	3.2	1	11.2
ENA	N	0.00	0.37	0.01	1B	1B	4D	0.00	1.1	0	17.1
ERI	N	0.73	0.53	0.01	4B	4C	4D	0.50	3.3	1	4.0
EUG	S	0.43	0.38	0.01	1B	4C	4D	0.00	2.8	0	7.2
EVV	N	0.39	0.81	0.04	1B	4C	4D	0.67	2.9	2	5.3
EWB	O	0.17	0.55	0.01	1B	3C	4D	0.50	2.8	1	8.6
EWN	N	0.55	0.63	0.01	1B	4C	4D	0.50	4.1	1	4.9
EWR	L	1.34	1.66	0.19	3B	4C	4D	0.67	7.7	1	47.3
EYW	N	0.15	0.42	0.01	1B	3C	3D	0.00	2.7	0	10.3
FAI	S	1.08	0.45	0.01	1B	4C	4D	0.00	1.9	1	13.4
FAR	N	0.48	0.76	0.02	1B	4C	4D	0.67	3.8	1	8.7
FAT	S	1.06	0.63	0.01	3B	4C	4D	0.00	4.1	1	13.7
FAY	N	0.21	0.71	0.02	1B	4C	4D	0.50	4.5	1	6.4
FFZ	O	2.02	1.05	0.04	3B	4C	4D	0.00	7.4	1	29.3
FLG	N	0.00	0.41	0.01	1B	1B	4D	0.00	3.4	0	6.5
FLL	L	1.01	0.87	0.02	3B	4C	4D	0.00	5.8	0	31.7
FNT	N	0.20	0.55	0.01	1B	4C	4D	0.50	3.3	1	5.3
FSD	S	0.69	0.53	0.01	1B	4C	4D	0.33	3.3	1	7.6
FWA	N	0.63	0.86	0.04	1B	4C	4D	0.67	3.1	2	6.6
FXE	O	2.93	n/a	n/a	1B	4C	4D	0.50	9.2	1	18.8
GEG	S	0.26	0.69	0.02	1B	4C	4D	0.50	4.1	1	8.0
GFK	N	0.50	0.78	0.03	3B	4C	4D	0.25	3.1	1	35.2
GJT	N	0.35	0.41	0.01	1B	3C	4D	0.50	2.3	0	7.8
GLS	O	0.26	0.48	0.01	1B	4C	4D	0.50	2.5	1	6.8
GNV	N	0.00	0.49	0.01	1B	3C	3D	0.00	3.4	1	7.5
GPT	N	0.33	0.54	0.01	1B	4C	4D	0.00	4.2	1	6.3
GRB	N	0.59	0.55	0.01	1B	4C	4D	0.50	2.6	1	10.0
GRR	S	0.22	0.61	0.01	1B	4C	4D	0.33	3.8	1	9.4
GSN	S	0.29	0.40	0.01	1B	4C	4D	0.00	2.3	1	7.2
GSO	S	0.88	0.64	0.01	1B	4C	4D	0.33	4.1	1	9.4
GSP	S	0.20	0.33	0.01	1B	3C	4D	0.00	2.7	0	5.3
GTF	N	0.97	0.40	0.01	1B	4C	4D	0.50	2.2	1	4.3
GUM	S	0.54	0.73	0.03	1B	4C	4D	0.00	3.4	2	7.7
HEF	O	0.10	0.72	0.02	1B	3C	4D	0.00	5.0	1	15.4
HLN	N	0.61	0.77	0.03	4B	4C	4D	0.75	2.3	2	6.1
HND	N	0.90	0.71	0.02	1B	4C	4D	0.00	5.1	1	13.1
HNL	L	3.62	1.03	0.08	3B	4C	4D	0.50	2.8	2	33.3
HOU	M	3.32	2.34	0.86	3B	4C	4D	1.00	6.2	3	23.1
HPN	S	1.11	1.25	0.06	3B	4C	4D	0.50	7.8	1	18.7
HRL	N	0.79	0.99	0.05	1B	4C	4D	0.67	4.0	2	7.0
HSV	S	0.38	0.42	0.01	1B	4C	4D	0.00	3.2	0	8.1
HXD	N	0.27	0.39	0.01	1B	4C	4D	0.00	3.3	0	5.7
HYA	N	0.10	0.82	0.02	1B	1B	3D	0.50	4.9	1	10.6
IAD	L	0.68	0.77	0.03	3B	4C	4D	0.00	3.1	1	38.3
IAH	L	0.86	0.88	0.03	1B	4C	4D	0.00	3.6	0	58.8
ICT	S	0.19	0.71	0.02	1B	3C	4D	0.33	4.0	1	16.0
IDA	N	0.25	0.35	0.01	1B	4C	4D	0.00	2.8	0	6.1
ILM	N	1.47	0.58	0.01	1B	4C	4D	0.50	3.3	1	6.4
IND	M	0.39	0.69	0.01	1B	4C	4D	0.00	5.0	0	18.8
ISP	S	1.44	1.11	0.08	1B	4C	4D	0.67	4.1	2	15.1
ITH	N	0.00	0.39	0.01	1B	1B	4D	0.00	3.3	0	5.7
ITO	S	0.11	0.63	0.02	1B	3C	4D	0.50	2.6	1	17.2
IWA	S	0.84	0.79	0.04	1B	4C	4D	0.00	1.8	2	24.7
JAC	N	1.34	0.28	0.00	4B	4C	4D	0.00	2.1	0	5.0
JAN	S	0.15	0.30	0.00	1B	3C	4D	0.00	1.9	0	6.7
JAX	M	0.29	0.44	0.01	1B	4C	3D	0.00	3.0	0	10.8
JFK	L	1.13	1.15	0.07	1B	4C	4D	0.50	5.0	1	47.8
JNU	S	1.30	0.32	0.01	1B	4C	4D	0.00	1.5	0	10.3
KOA	S	0.07	0.44	0.01	1B	3C	3D	0.00	1.5	0	21.1
LAN	N	0.69	0.78	0.03	1B	4C	4D	0.33	4.0	2	4.5
LAS	L	1.20	1.41	0.21	1B	4C	4D	0.50	4.5	2	61.5
LAX	L	2.06	1.11	0.07	3B	4C	4D	0.00	4.9	1	70.5
LBB	S	0.72	0.38	0.01	3B	4C	4D	0.00	2.6	0	8.6
LCH	N	0.00	0.44	0.01	1B	1B	4D	0.00	3.1	1	5.8
LEX	S	0.79	0.63	0.01	1B	4C	4D	0.00	5.1	1	7.9

LFT	N	2.44	1.06	0.06	3B	4C	4D	0.67	4.5	2	6.8
LGA	L	1.15	1.51	0.13	3B	4C	4D	0.50	8.4	1	41.4
LGB	S	0.99	0.87	0.03	3B	4C	4D	0.33	3.9	1	34.4
LIH	S	0.08	0.66	0.02	1B	3C	3D	0.00	3.5	1	20.5
LIT	S	0.67	0.64	0.01	1B	4C	4D	0.00	4.3	1	12.4
LNK	N	1.48	0.43	0.01	3B	4C	4D	0.33	2.3	1	7.0
LRD	N	0.45	0.90	0.05	1B	4C	4D	0.67	3.2	2	9.2
LSE	N	1.62	1.57	0.42	1B	4C	4D	1.00	3.8	3	4.1
LUK	O	0.65	0.75	0.03	1B	4C	4D	0.33	3.1	2	7.9
LWS	N	0.58	0.50	0.01	1B	4C	4D	0.00	4.0	1	5.3
LYH	N	0.10	0.68	0.02	1B	3C	3D	0.50	3.4	1	12.6
MAF	S	1.03	0.86	0.05	1B	4C	4D	1.00	2.1	2	8.1
MBS	N	0.36	0.41	0.01	1B	4C	4D	0.50	2.5	1	2.9
MCI	M	0.26	0.66	0.02	1B	4C	4D	0.33	3.5	1	15.8
MCO	L	0.28	1.04	0.08	1B	4C	4D	0.00	3.7	2	36.4
MDT	S	0.00	0.33	0.01	1B	3C	4D	0.00	2.3	0	7.1
MDW	L	2.05	2.94	0.97	3B	4C	4D	1.20	7.0	3	28.9
MEM	S	0.39	0.84	0.02	3B	4C	4D	0.00	5.4	0	31.9
MFE	N	0.48	0.66	0.01	1B	4C	4D	0.00	5.0	1	9.8
MFR	N	0.22	0.34	0.01	1B	4C	4D	0.00	2.6	0	6.0
MGM	N	0.43	0.67	0.01	1B	4C	4D	0.50	4.0	1	7.3
MHR	O	0.21	0.34	0.01	3B	4C	4D	0.00	1.5	0	12.2
MHT	S	0.15	0.63	0.01	1B	4C	4D	0.50	3.7	1	7.0
MIA	L	1.72	1.01	0.05	1B	4C	4D	0.25	5.0	1	44.8
MKC	O	1.99	0.80	0.02	4B	4C	4D	0.50	5.0	1	8.3
MKE	M	2.05	2.16	0.80	3B	4C	4D	1.20	4.6	3	16.2
MLB	N	0.34	0.74	0.02	1B	4C	4D	0.00	5.1	1	15.4
MLI	N	1.91	1.16	0.08	4B	4C	4D	1.00	3.8	2	4.3
MLU	N	1.54	1.18	0.09	1B	4C	4D	1.00	3.9	2	4.0
MMU	O	0.69	0.81	0.02	1B	4C	4D	0.50	4.3	1	15.9
MOB	N	0.10	0.61	0.01	1B	3C	3D	0.00	4.3	1	10.2
MRI	N	2.67	n/a	n/a	3B	4C	4D	0.00	9.1	1	54.9
MRY	N	1.14	0.78	0.02	1B	4C	4D	0.00	7.1	1	7.3
MSN	S	2.45	1.33	0.14	1B	4C	4D	1.00	4.2	2	10.2
MSO	N	1.44	0.61	0.01	1B	4C	4D	0.50	4.0	1	4.3
MSP	L	1.74	1.88	0.43	3B	4C	4D	0.75	6.9	2	48.4
MSY	M	1.38	0.59	0.01	1B	4C	4D	0.00	3.5	1	14.2
MYR	S	0.00	0.64	0.01	1B	1B	4D	0.00	4.1	0	20.1
OAK	M	0.31	0.93	0.06	1B	4C	4D	0.00	3.3	2	26.6
OGG	M	0.35	1.01	0.06	1B	4C	4D	0.50	4.1	2	15.0
OKC	S	0.08	0.92	0.05	1B	3C	4D	0.25	4.3	2	13.7
OMA	M	0.26	1.14	0.08	1B	4C	4D	0.67	4.5	2	12.0
ONT	M	0.83	0.64	0.01	1B	4C	4D	0.00	4.5	1	11.2
OPF	O	0.64	0.65	0.01	3B	4C	4D	0.00	4.5	1	13.0
ORD	L	1.36	1.22	0.10	3B	4C	4D	0.14	4.4	1	98.5
ORF	S	0.73	0.68	0.02	1B	4C	4D	0.50	3.8	1	9.9
ORL	O	1.45	1.03	0.03	1B	4C	4D	0.50	6.5	1	12.8
OSU	O	1.27	1.39	0.12	1B	4C	4D	1.67	2.8	1	11.5
PBI	M	0.86	1.27	0.10	3B	4C	4D	0.33	7.3	2	16.8
PDK	O	2.44	1.69	0.25	3B	4C	4D	0.67	7.9	2	17.8
PDX	L	0.49	0.78	0.02	1B	4C	4D	0.33	3.8	1	25.5
PGD	S	0.00	0.39	0.01	1B	1B	4D	0.33	2.5	1	3.6
PHF	N	0.35	0.58	0.01	1B	4C	4D	0.50	2.7	1	11.8
PHL	L	1.26	1.15	0.06	3B	4C	4D	0.25	6.2	1	49.5
PHX	L	0.46	1.14	0.06	2B	4C	4D	0.00	6.5	1	52.3
PIA	N	1.09	0.46	0.01	1B	4C	4D	0.00	3.6	1	4.8
PIE	S	0.62	0.65	0.02	3B	4C	4D	0.50	2.9	1	15.0
PIH	N	0.00	0.34	0.01	1B	1B	4D	0.00	1.8	1	6.1
PIT	M	0.55	0.82	0.02	1B	4C	4D	0.50	4.3	1	17.0
PNS	S	1.03	0.95	0.03	1B	4C	4D	0.50	5.9	1	12.1
PSC	N	0.92	0.93	0.05	1B	4C	4D	0.67	3.1	2	11.3
PSP	S	1.01	0.62	0.01	1B	4C	4D	0.00	5.0	1	7.2
PTK	O	1.18	1.03	0.03	1B	4C	4D	0.00	8.9	1	15.0
PVD	S	0.72	0.69	0.02	1B	4C	4D	0.50	4.0	1	8.6
PWK	O	1.63	1.99	0.42	3B	4C	4D	1.00	7.3	2	9.5
PWM	S	1.03	0.66	0.01	1B	4C	4D	0.50	3.7	1	9.1
RAP	N	0.22	0.56	0.01	1B	4C	4D	0.50	3.5	1	4.8
RDD	N	0.22	0.58	0.01	1B	4C	4D	0.50	3.0	1	9.3
RDM	N	0.88	0.70	0.02	3B	4C	4D	0.50	4.2	1	7.7
RDU	M	0.38	0.68	0.02	3B	4C	4D	0.00	3.6	1	22.1
RFD	N	0.61	0.50	0.01	1B	4C	4D	0.50	2.9	1	5.1
RIC	S	0.72	0.79	0.04	1B	4C	4D	0.33	3.0	2	11.5
RNO	S	1.25	1.07	0.07	3B	4C	4D	0.67	4.1	2	10.8

ROA	N	0.18	0.72	0.02	1B	3C	4D	0.50	4.7	1	5.7
ROC	S	0.86	0.74	0.02	3B	4C	4D	0.33	5.0	1	10.8
ROW	N	0.21	0.32	0.01	1B	4C	4D	0.00	2.0	0	7.9
RST	N	0.23	0.58	0.01	1B	4C	4D	0.50	3.6	1	4.6
RSW	M	0.11	0.58	0.01	1B	3C	4D	0.00	4.9	0	9.4
SAF	N	0.13	1.13	0.09	1B	3C	4D	1.00	3.1	2	11.8
SAN	L	0.46	0.72	0.02	3B	4C	4D	0.00	4.9	0	22.6
SAT	M	1.92	1.21	0.10	1B	4C	4D	0.33	6.3	2	20.5
SAV	S	1.20	0.86	0.02	1B	4C	4D	0.50	4.8	1	14.6
SAW	N	0.00	0.16	0.00	1B	1B	4D	0.00	1.1	0	3.3
SBA	N	0.62	n/a	n/a	1B	4C	4D	0.67	7.3	2	16.4
SBN	N	1.87	0.96	0.05	4B	4C	4D	0.67	4.1	2	4.4
SBP	N	0.37	0.72	0.02	1B	4C	4D	0.00	4.6	1	18.5
SBY	N	0.45	0.68	0.02	1B	4C	1D	0.50	3.5	1	12.4
SDF	S	0.59	1.07	0.04	1B	4C	4D	0.67	5.2	1	17.6
SDL	O	0.46	1.05	0.03	1B	4C	4D	0.00	9.5	0	18.0
SEA	L	1.22	1.17	0.10	1B	4C	4D	0.00	5.2	2	38.2
SFB	S	1.29	1.01	0.05	3B	4C	4D	0.75	3.7	1	28.9
SFO	L	1.69	1.94	0.32	3B	4C	4D	1.00	6.9	0	47.3
SGF	S	0.18	0.76	0.02	1B	3C	4D	0.50	5.0	1	5.8
SGJ	N	0.23	0.76	0.04	1B	3C	4D	0.67	1.4	2	17.9
SHV	N	0.40	0.64	0.01	1B	3C	3D	0.50	4.1	1	5.1
SIG	N	0.64	0.83	0.02	1B	4C	4D	0.00	6.5	0	20.2
SJC	M	0.64	0.88	0.02	1B	4C	4D	0.00	6.6	1	18.0
SJU	M	1.07	0.59	0.01	1B	4C	4D	0.00	3.7	0	18.5
SLC	L	1.02	1.07	0.09	1B	4C	4D	0.00	3.8	2	39.5
SLN	O	0.24	0.68	0.03	1B	4C	4D	0.75	1.5	2	8.7
SMF	M	0.15	0.41	0.01	1B	3C	4D	0.00	2.1	0	14.0
SNA	M	1.24	1.16	0.05	3B	4C	4D	0.00	8.4	1	32.7
SQL	O	1.51	1.41	0.06	1B	4C	4D	0.00	13.8	0	19.6
SRQ	S	1.79	1.11	0.04	1B	4C	4D	0.50	7.2	1	12.2
STL	M	1.45	1.08	0.08	1B	4C	4D	0.25	5.0	2	23.0
STP	O	0.24	1.08	0.07	1B	4C	4D	0.67	4.4	2	8.8
STS	N	0.92	0.80	0.02	1B	4C	4D	0.50	4.4	1	13.5
STT	S	0.27	0.52	0.01	3B	3C	1D	0.00	3.7	0	11.7
SUN	N	0.63	0.38	0.01	1B	4C	4D	0.00	3.0	0	6.6
SUS	O	0.35	0.62	0.01	1B	4C	4D	0.00	5.0	0	12.0
SWF	N	0.55	0.50	0.01	1B	4C	4D	0.50	2.8	1	5.7
SYR	S	0.60	0.71	0.02	3B	4C	4D	0.50	4.2	1	8.6
TEB	O	1.69	1.08	0.04	3B	4C	4D	0.50	6.3	1	19.0
TLH	N	0.26	0.56	0.01	1B	3C	4D	0.50	3.5	0	7.9
TOL	N	0.21	0.65	0.01	1B	4C	4D	0.50	4.3	1	4.9
TPA	L	0.59	0.86	0.03	1B	4C	4D	0.33	4.9	1	22.9
TRI	N	0.37	0.79	0.02	1B	4C	4D	0.50	5.3	1	5.6
TTN	N	0.69	0.80	0.02	1B	4C	4D	0.50	4.9	1	9.1
TUL	S	0.59	0.79	0.02	1B	4C	4D	0.33	5.3	1	12.3
TUS	S	2.11	0.68	0.02	3B	4C	4D	0.00	4.0	1	18.7
TVC	N	0.45	0.84	0.02	1B	4C	4D	0.50	5.0	1	10.6
TWF	N	0.00	0.50	0.01	1B	1B	4D	0.50	2.8	1	6.0
TYR	N	1.04	0.80	0.04	1B	4C	4D	0.67	2.7	2	7.0
TYS	S	0.52	0.60	0.01	1B	4C	4D	0.00	3.9	1	12.0
UNV	N	0.47	0.28	0.00	1B	4C	1D	0.00	2.9	0	2.2
VGT	O	1.37	1.25	0.11	1B	4C	4D	0.33	6.2	2	25.3
VNY	O	1.45	1.18	0.05	1B	4C	4D	0.00	8.7	1	32.2
XNA	S	0.00	0.40	0.01	1B	1B	4D	0.00	2.8	1	4.9
YIP	O	0.54	0.61	0.02	1B	4C	4D	0.33	1.7	2	7.7

A13 Claros et al. (2007) model

The baseline definition is determined using the developed model of Claros et al. (2017). This runway incursion general frequency model determines the average number of incursions (N), using Equation (A-11), which is a function of the year-specific scale parameter (φ_y) and multiplicative variables accounting for measures of annual operations, runways, taxiways, weather, hot spots, and construction notices. The model coefficients were determined through maximum likelihood estimation.

$$N = \hat{E}\{u\} = \vartheta_s \times \delta_e \times \varphi_y \times [OP \times R \times TX \times W \times H \times C] \quad \text{(A-11)}$$

where:

$\hat{E}\{u\}$	=	expected number of runway incursion per year
ϑ_s	=	RI severity parameter
δ_e	=	event classification parameter
φ_y	=	scale parameter for a given year
OP	=	airport operations
R	=	runway
TX	=	taxiway
W	=	weather
H	=	hot spot
C	=	construction

Here, the scale parameter φ_y is used to make the model more accurate for the years of study y = 2009 to 2013. To make the model applicable for other observation years, a general scale parameter was developed. The variable airport operations OP represents the annual number of air traffic movement and the share of general aviation traffic and is determined by Equation (A-12):

$$OP = \left\{ \left(\frac{TO}{100{,}000}\right)^{\beta_1} exp\left[\beta_2 \left(\frac{TO}{100{,}000}\right)\right] \right\} \times [\beta_3 \%GA + \beta_4] \quad \text{(A-12)}$$

where:

TO	=	number of annual operations
$\%GA$	=	percentage general aviation traffic

Next, the runway predictor variable R incorporates the type of runway configuration and the length of runways. It is calculated by means of Equation (A-13):

$$R = \left\{ \sum_{j=1}^{4} \left[\beta_{j+4} \left(\frac{L_j}{10{,}000}\right)^2 + \beta_{j+8} \left(\frac{L_j}{10{,}000}\right) \right] \right\} + \beta_{13} \quad \text{(A-13)}$$

where:

j	=	runway type (1 = single, 2 = parallel, 3 = crossing, 4 = mixed)
L_j	=	runway length (L_j = 0 in case a specific type is not present at the airport)

Then, it is followed by the taxiway factor TX, which incorporates the effect of two types of TWY-RWY intersections: conventional exit-entry taxiways and RETs. The quantification is determined using Equation (A-14).

$$TX = [\beta_{14} T + \beta_{15} RET]^{\beta_{16}} \quad \text{(A-14)}$$

where:

T	=	number of conventional TWY-RWY intersections
RET	=	number of RETs

Also, a weather variable W is implemented in the model, Equation (A-15). Here, snowfall and precipitation are considered. Strikingly, visibility, which is an important weather characteristic for runway incursion risk, is not modelled because of data collection issues.

$$W = [\beta_{17} e^{\beta_{18} SW} + \beta_{19} SW] \times e^{\beta_{20} PR} \quad \text{(A-15)}$$

where:

SW	$=$	inches of snowfall per year
PR	$=$	inches of precipitation per year

Furthermore, the number of highlighted hot spots H is considered with Equation (A-16).

$$H = \beta_{21} HOT + \beta_{22} \quad \text{(A-16)}$$

where:

HOT	$=$	number of hot spots

Lastly, the number of construction notices C is applied in the model Equation (A-17).

$$C = \beta_{23} CON^{\beta_{24}} \quad \text{(A-17)}$$

where:

CON	$=$	number of construction notices per year

Variable	**Severity** A ($\vartheta_s = 0.00871$), B ($\vartheta_s = 0.00933$), and C ($\vartheta_s = 0.98072$)	D ($\vartheta_s = 1.00000$)	TOT ($\vartheta_s = 1.00000$)
Surface event (δ_e)			
OI	0.45274	0.08230	0.26706
PD	0.43595	0.71349	0.57506
VPD	0.11132	0.20421	0.15788
All	1.00000	1.00000	1.00000
Dispersion term ($\mathscr{b}$)	6.95547	4.18394	5.11075
Scale parameter			
φ_{other}	0.90304	1.40682	1.06638
φ_{2009}	0.76252	1.62284	1.07474
φ_{2010}	0.77734	1.29989	0.95817
φ_{2011}	0.80513	1.27129	0.95619
φ_{2012}	1.13105	1.30754	1.14011
φ_{2013}	1.04060	1.54800	1.20221
Predictor variable coefficient estimate			
β_1	1.13061	0.44682	0.66141
β_2	0.05409	0.03671	0.08002
β_3	0.01440	0.06392	0.06281
β_4	0.50999	0.83694	1.36719
β_5	-0.32682	-0.13363	-0.17175
β_6	-0.15203	-0.06977	-0.06579
β_7	-0.07307	-0.06027	-0.06779
β_8	0.65818	-0.11942	0.03549
β_9	0.03876	0.00346	0.01543
β_{10}	0.02311	0.00472	0.00405
β_{11}	-0.02007	-0.00834	-0.00885
β_{12}	-0.16207	0.01046	-0.02385
β_{13}	1.88207	0.89602	1.06127
β_{14}	0.04571	0.02759	0.05055
β_{15}	0.14693	0.01461	0.04367
β_{16}	0.37529	0.83421	0.65461
β_{17}	0.82277	0.80932	0.97253
β_{18}	0.01520	0.00825	0.01123
β_{19}	-0.01834	-0.00716	-0.01478
β_{20}	-0.00001	-0.00102	-0.00150
β_{21}	0.04402	0.07976	0.05456
β_{22}	0.73730	0.74039	0.65916
β_{23}	0.71205	0.96923	0.83182
β_{24}	0.01549	0.08184	0.05079

A14 Airport cases

A14.1 Honolulu, HNL

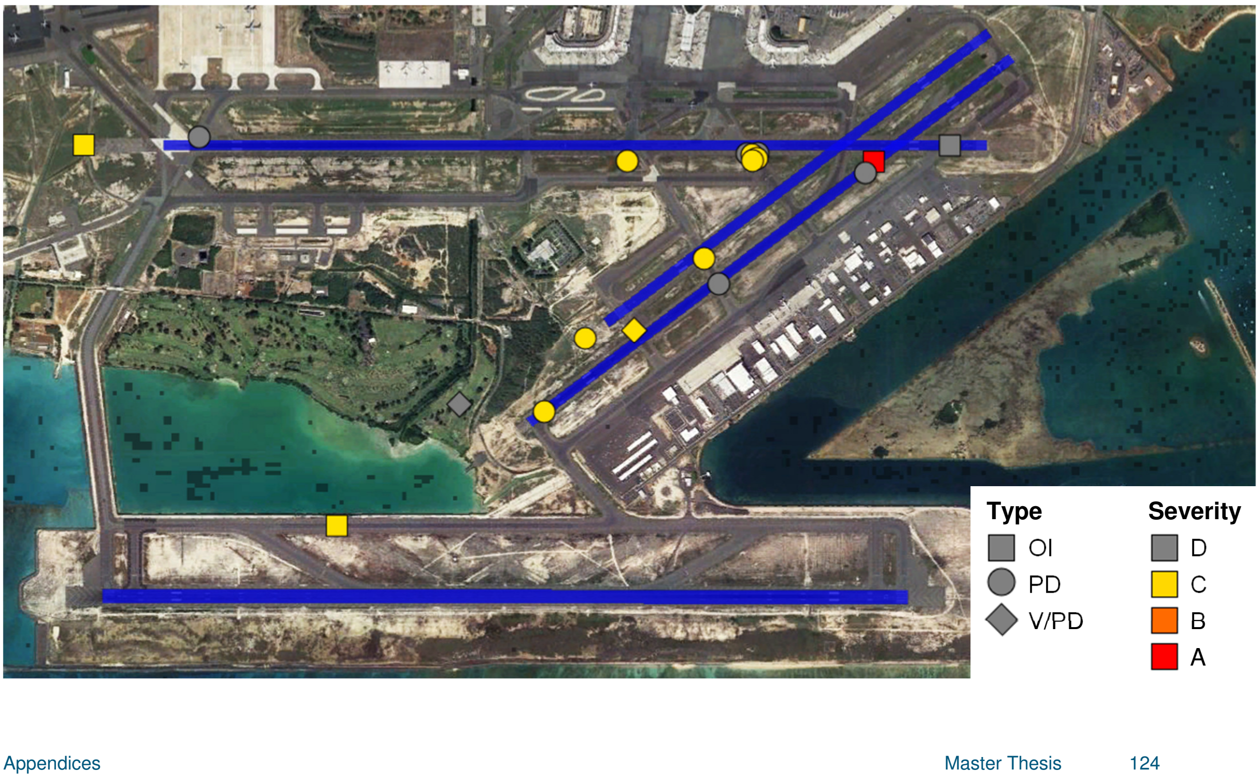
Daniel K. Inouye International Airport (HNL) is the international airport of Honolulu which opened in 1927 and belongs to one of the busiest airports in the United States in terms of passenger numbers. The airport is the home base and main hub for Hawaiian Airlines, which serves flights to short-haul destinations on Hawaii and long-haul flights, for example to the continental US. Because of its geographical location in the Pacific Ocean, a large share of the flights is represented by long-haul flights. This results in a relative large share of heavy aircraft (29%). The total share of commercial traffic is 78.2%.

A14.1.1 Characteristics

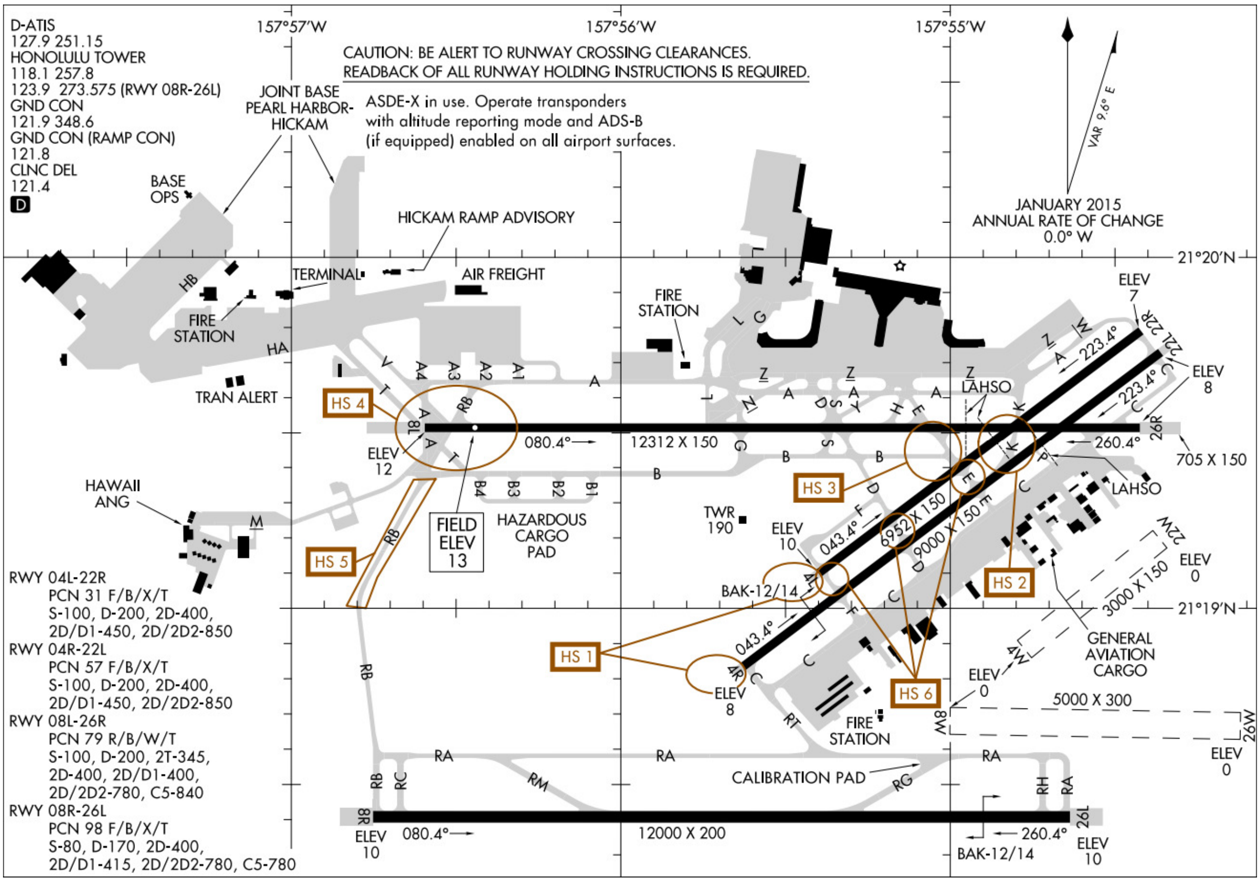
Between 2007 and 2017, the airport handled 3,202,108 flights, which means an average annual number of movements of 291,100. The airport is operational for 168 hours per week. Taking the percentage good weather per year into account (99.9%) results in hourly airport movements T_h of 33.3. During the study period, 191 runway incursions were recorded, of which 3 A-, 3 B-, 126 C- and 59 D-incidents. The share of operational incidents, pilot deviations and vehicle/pedestrian deviations was respectively 51, 123 and 17. The incursion rate for HNL during the period was 3.62 for high severity incidents. The airport defined capacity categories for the visibility conditions. During visual operations (VFR), the airport is theoretically able to handle 120 flights per hour with 4 runways in operation. For MVFR 105 operations per hour can be accommodated, using three runways. During IFR procedures, the number of aircraft is 60 flights per hour, by means of 3 runways. Hence, T_h is much lower since in reality, the airport has to cope with peak hours.

HNL consists of six runways, of which two are designated water areas for seaplane aircraft. The remaining four runways are made of asphalt and situated according to the diagram. The total runway length L_{tot} is 14.7 km and the surface area per runway-km is 13.9 hectare. Three of the runways intersect; none of the runways are equipped with displaced thresholds. Furthermore, two runways are parallel situated. Also, Runway Safety Areas intersect at multiple locations. The main terminal acreage is located on the north side of the airport area. Consequently, runways have to be crossed in order to reach other runways and the southern terminal area from the main terminal, meaning a C_{req} of 2. In total, 16 runway crossings are available. The ratio intersecting runways I_r is 0.5, the number of required crossings $C_{req} = 2$ and the number of TWY-RWY intersections $I_n = 2.8$. Three intersections are designed as RET. The ratio non-right TWY-RWY intersections is 0.27. Furthermore, the layout also consists of three complex intersections, six locations are defined as hot spots. No runway status light system (RSL) is in operation.

A14.1.2 Night incidents



A14.1.3 Airport diagram



A14.1.4 Model forecast

The developed model is applied in order to make a forecast for high severity incidents under various scenarios. In Figure A-15, the results from the model estimation are depicted. In the graph, it can be observed that the R_{rate} shows large fluctuations over the observation years. Between 2007 and 2013, the model estimates rather good incursion rates, in line with the averaged observed rates. However, the big increase in incursions between 2013 and 2017 resulted in the high incursion rate for the entire study period. Hence, this was not predicted by the model. The large increase in incursion rates can be explained by improved detection equipment that was implemented during the study period. Installed sensors at stop bars now detect whether an airport is at the right place. Before, if an aircraft stopped one meter over the hold-short line, that would not be detected, nowadays this would have reported as an error.

For the forecasted years, five scenarios are developed to see the effects on the incursion rates. The scenarios incorporate geometrical modifications, all attributes which are covered by the model. Between brackets, the yearly change in number is shown. For example, RWY length (+100m), represents the effect for a yearly increase of runway length of 100 meter. Since the effects are non-linear, the annual percentage of change is depicted in the second graph in Figure A-15. From the model, a modification effectiveness for the removal of five TWY-RWY intersections gives an incursion likelihood decrease of 4%.

Lastly, the threshold lines for risk frequencies are shown in the graphs. These correspond to the frequency related risk matrix for major incidents C3 and C4. As shown, for certain modifications the C4 threshold is crossed, in all cases HNL belongs to at least risk category C3. Though, the large observed incursion rates since 2013 resulted in a crossing of the C4 threshold.

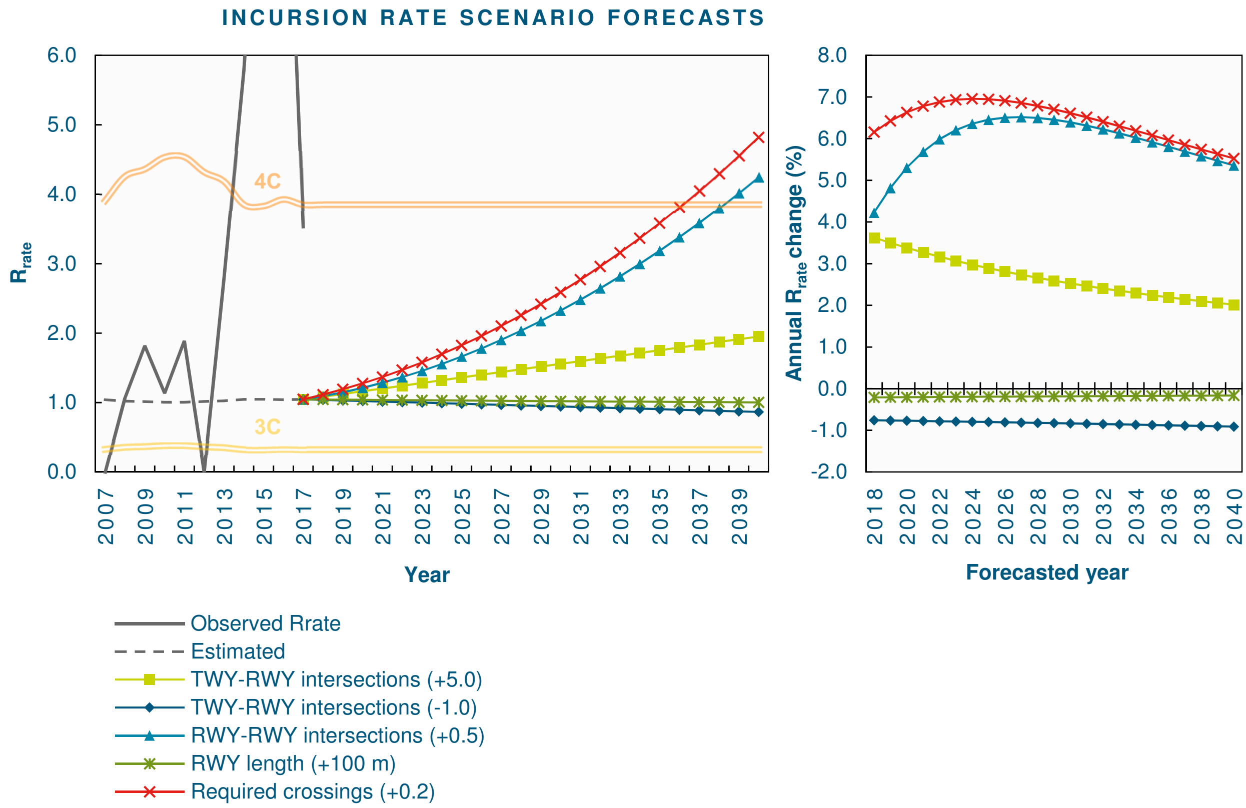


Figure A-15: Honolulu (HNL) incursion model scenario forecasts

A14.2 Houston, IAH

George Bush Intercontinental Airport (IAH) is the international airport of Houston, located 37 kilometres north of the downtown area of the city. The airport is the second largest passenger hub for United Airlines, behind O'Hare International Airport. Other important airlines include Spirit Airlines, United Express, ExpressJet Airlines and SkyWest Airlines. The airport opened in 1969. It belongs to the top 15 busiest airports in the US, in terms of passenger numbers.

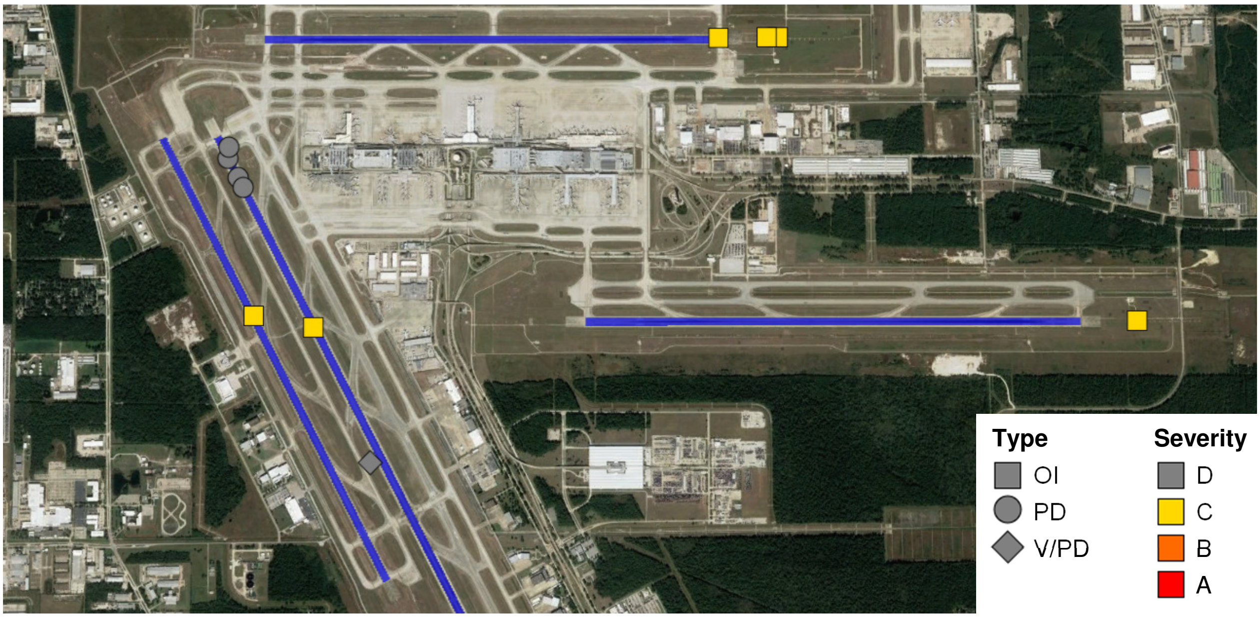
A14.2.1 Characteristics

IAH handled 5.730,848 flights between 2007 and 2017, which is on average 520,986 take-offs and landings per year. The hourly number of movements T_h is 58.8, based on 168 operational hours (O_w) and V_g of 98.6 (share good weather). The share of commercial traffic is rather high with 96.9%. Heavy aircraft represent 7.8% of the traffic. In the period, 67 incursions were recorded of which none of these was category A or B. The incidents for C and D incidents were respectively defined as 52 and 15. This results in a high severity incursion rate of 0.86. Of the total, 46 incidents were OI, 11 PD and 10 V/PD. During visual operations (VFR), IAH is theoretically able to handle 172 flights per hour with 5 operational runways. For MVFR 152 operations per hour can be handled, with 5 runways in use. During IFR procedures, the number of aircraft is 144 per hour, using 5 runways. Same as for HNL, T_h is significantly lower since in reality, the airport has to cope with peak hours.

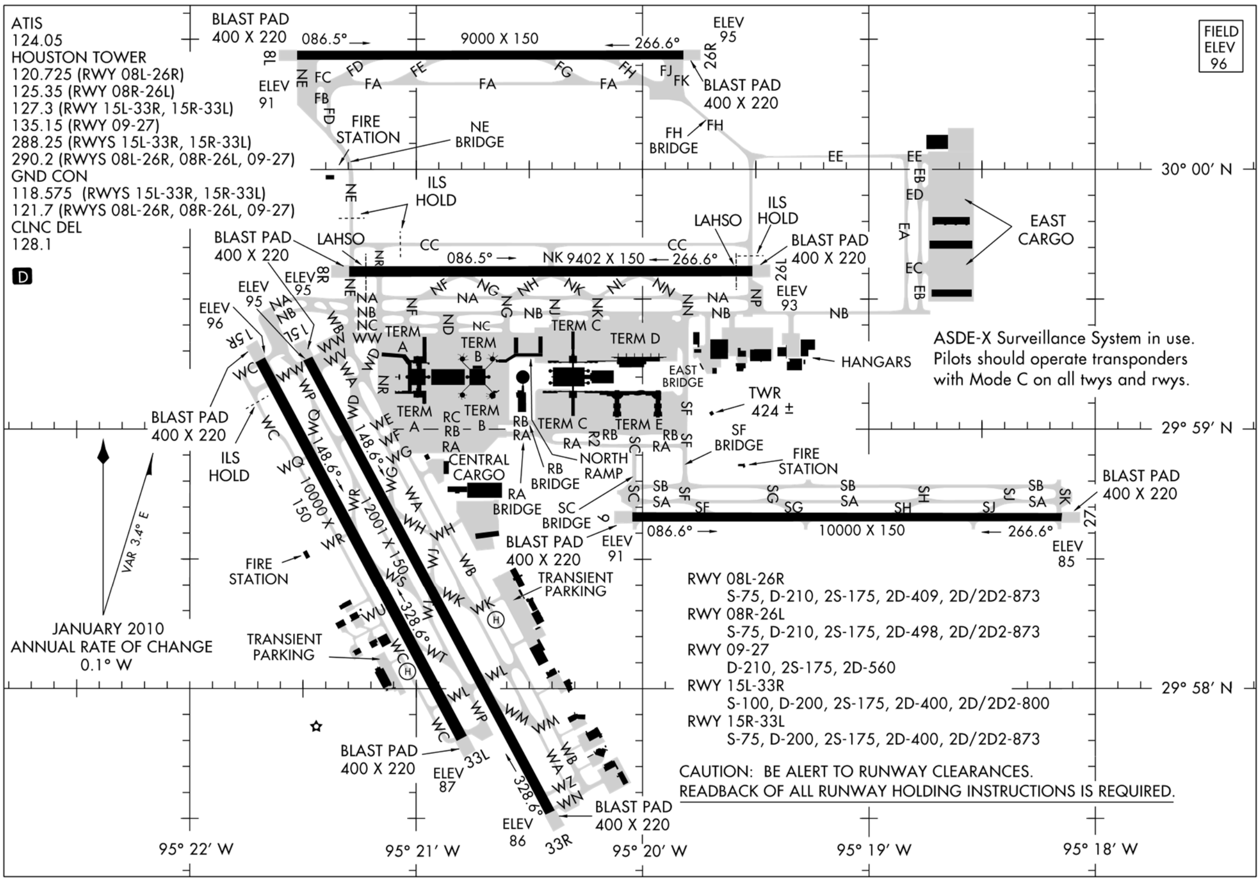
The airport consists of 5 runways, with a total length L_{tot} of 15.4 km. Per runway-km, the relative airport surface is 57.62 hectare. None of the runways is equipped with displaced thresholds. Two of the runways are parallel situated on the southern side of the area. There are no RWY-RWY intersections, which means an I_r of 0.0. Though, a runway status light (RSL) system is operational.

The number of TWY-RWY intersections per runway-km I_n is 3.6. There are 11 opportunities to cross runways, while there is an absence of the requirement for runway crossings, thus C_{req} is 0. In total, 24 intersections are embodied as RET. The ratio non-right-angled intersections is 0.44. For IAH, no hot spots are designated. Furthermore, there are no complex intersections in the layout.

A14.2.2 Night incidents



A14.2.3 Airport diagram



A14.2.4 Model forecast

The developed model is applied in order to make a forecast for high severity incidents under various scenarios. In Figure A-16, the results from the model estimation are shown. As can be seen from the observed incursion rates, there are large deviations recorded in the statistics, with high incursion peaks in 2011 and 2015, while in 2012 no incursions were counted. On average, the R_{rate} decreased a fraction, although the number of movements increased.

For the forecasted years, five scenarios are developed to analyse the effects on the incursion rates. The threshold lines for risk frequencies are also shown in the graphs. These correspond to the frequency related risk matrix for major incidents C3 and C4. As can be observed in the figure, a yearly addition of 0.5 RWY-RWY intersections would result in the exceedance of the C4 threshold in 2039. Because of the non-linear effects, the annual percentage of change is depicted in the second graph in Figure A-16. In none of the scenarios, the estimated R_{rate} reduces to below C3.

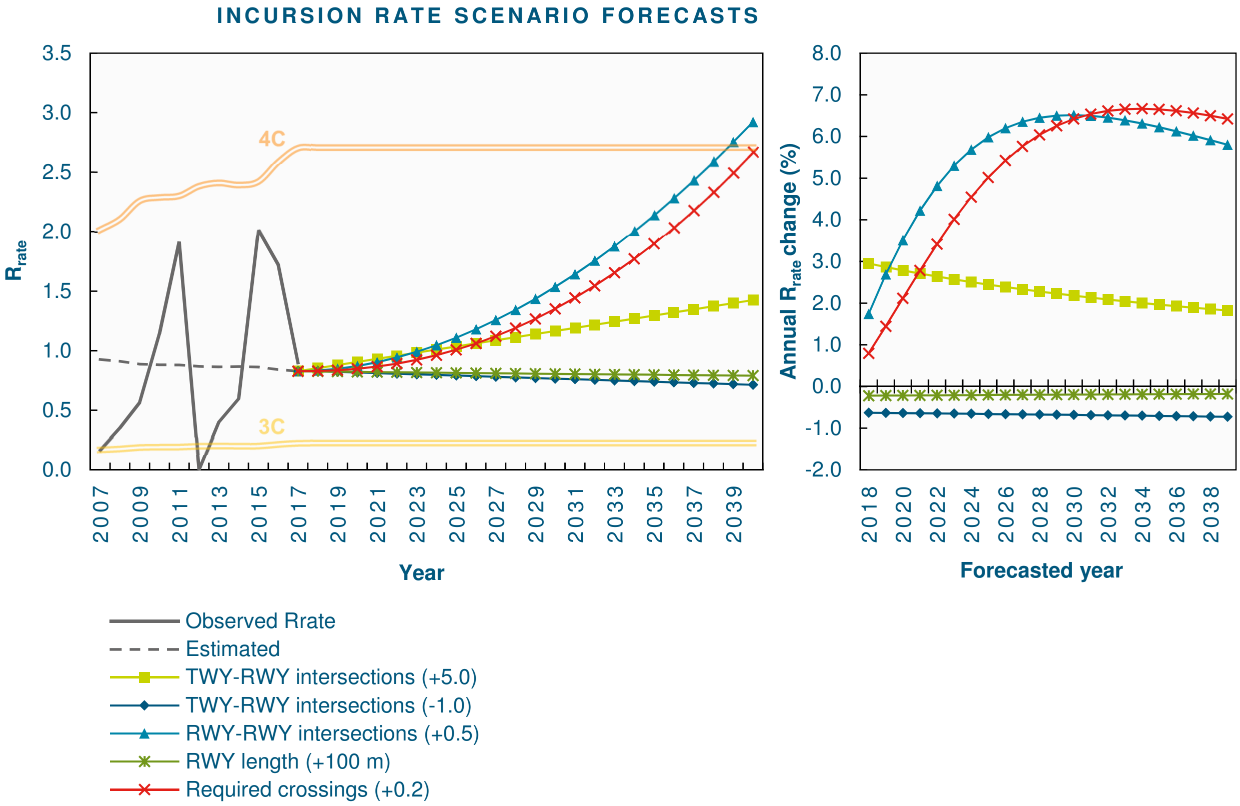


Figure A-16: Houston (IAH) incursion model scenario forecasts

A14.3 Phoenix, PHX

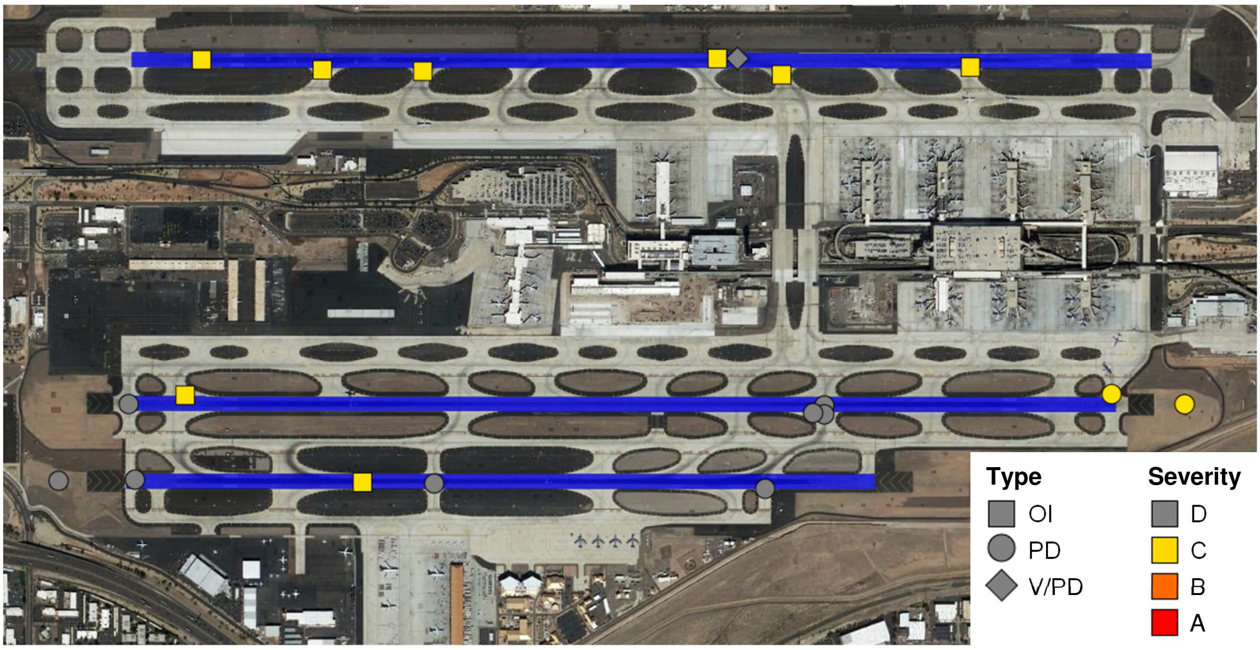
Phoenix Sky Harbor International Airport (PHX) is the international airport of Phoenix, located 4.8 km southeast of the downtown area. The airport is comparable to IAH in terms of size, handling almost 45 million passengers per year. PHX serves as one of the main hubs for American Airlines, which carries almost half of the passengers at the airport. For Southwest Airlines, PHX belongs to one of the largest bases. A small share of the traffic is represented by military operations.

A14.3.1 Characteristics

PHX served 5,039,128 flights between 2007 and 2017, which means an average of 458,103 flights per year. Per hour 52.2 flights take-off and land at the airport (T_h). This is based on 168 operational hours per week (O_w) and a share good weather V_g of 99.8. The average share of commercial traffic is 93.4%. Heavy aircraft belong to the share of 5.8% air traffic. During the study period, 51 incursions were recorded. A incidents did not occur in this period. Of the total number of incidents, 1 was classified as cat. B, 26 as cat. C and 24 as cat. The number of OI, PD and V/PD incidents was respectively 16, 31 and 4. The high severity R_{rate} is 0.46. During visual operations (VFR), the airport is theoretically able to handle 138 flights per hour with 3 runways in operation. During MVFR, 108 operations per hour can be processed, using three runways. For IFR procedures, the number of aircraft is 96 flights per hour, using all three runways. The T_h value is rather lower since the airport has to cope with peak hours during certain periods of the day.

The airport complex of PHX consists of 3 runways, with a total length L_{tot} of 9.0 km. Per runway-km, 33.37 hectare can be assigned. One of the runways is partly shaped as displaced threshold. Furthermore, the layout has two parallel runways and none of the runways intersect, thus I_r is 0.0. The number of TWY-RWY intersections I_n is 6.54. In total, there are 24 runway crossing possibilities, though the number of required crossings C_{req} is 1. The proportion non-right angled TWY-RWY intersections is 0.05. Though, as can be seen on the airport map, provide the intersections smooth transition curves from the runway to the taxiway, which provides aircraft the opportunity to leave the runway at higher speed, compared to conventional right-angled exits. However, for line-up the intersections ensure aircraft to enter the runway at (almost) 90 degree. PHX consists of only 3 RETs. There are no complex intersections, but three areas are designated as hot spot. The runways are equipped with runway status lights (RSL).

A14.3.2 Night incidents

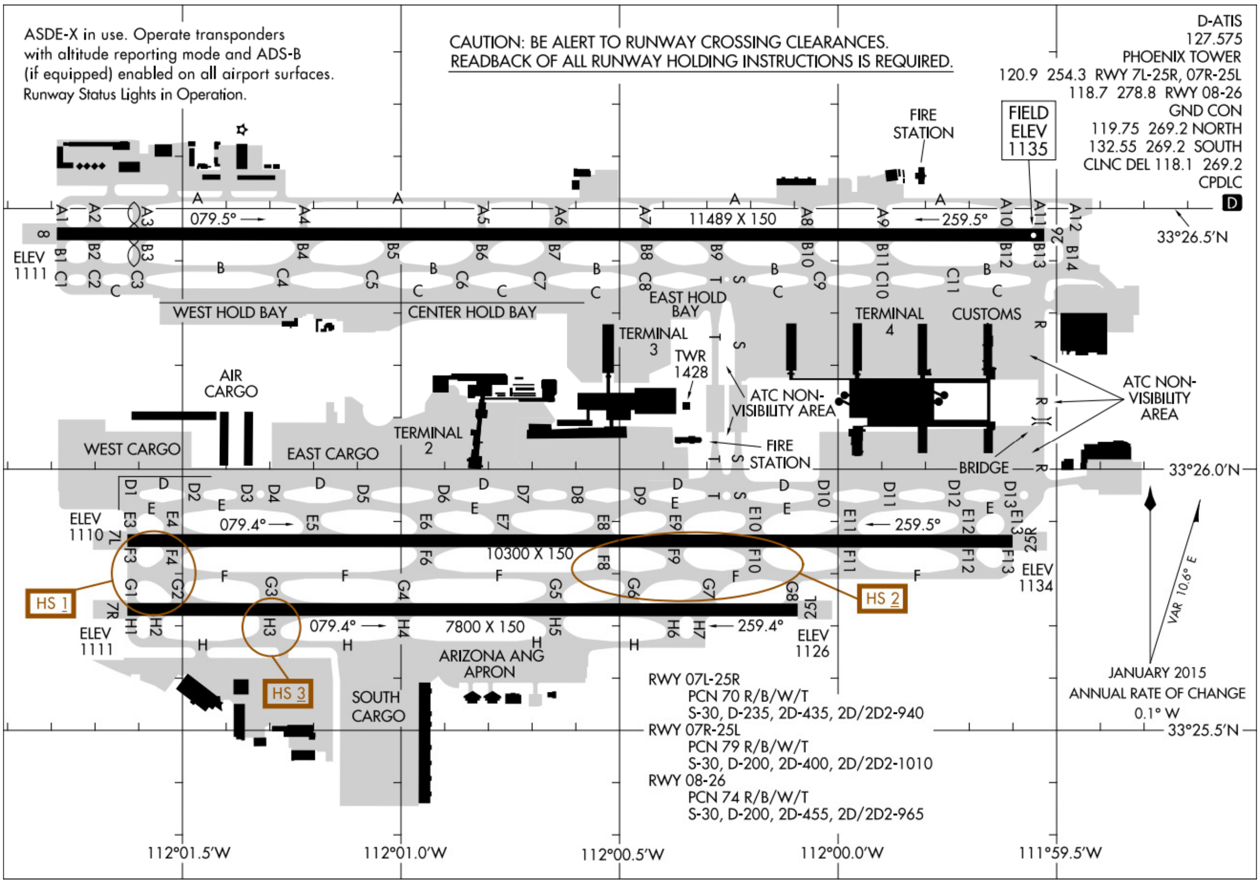


A14.3.3 Model forecast

In Figure A-17 below, the application results from the models are shown, taking multiple scenarios into account. It can be observed that the R_{rate} during the observation years remained below the estimation line. Higher movement numbers led to a slight decrease in the incursion rate.

For the forecast time interval, five scenarios are developed to test the effects on the R_{rate} values. The threshold lines for risk frequencies are added to the graphs. These correspond to the frequency related risk matrix for major incidents C3 and C4. As can be observed in the figure, a yearly addition of 0.5 RWY-RWY intersections would result in the exceedance of the C4 threshold in 2026. For a yearly increase in required runway crossings by 0.2, this threshold is exceeded in 2034. Because of the non-linear relations, the annual percentage of change is depicted in the second graph in Figure A-17. In none of the scenarios, the estimated R_{rate} reduces to below C3.

A14.3.4 Airport diagram



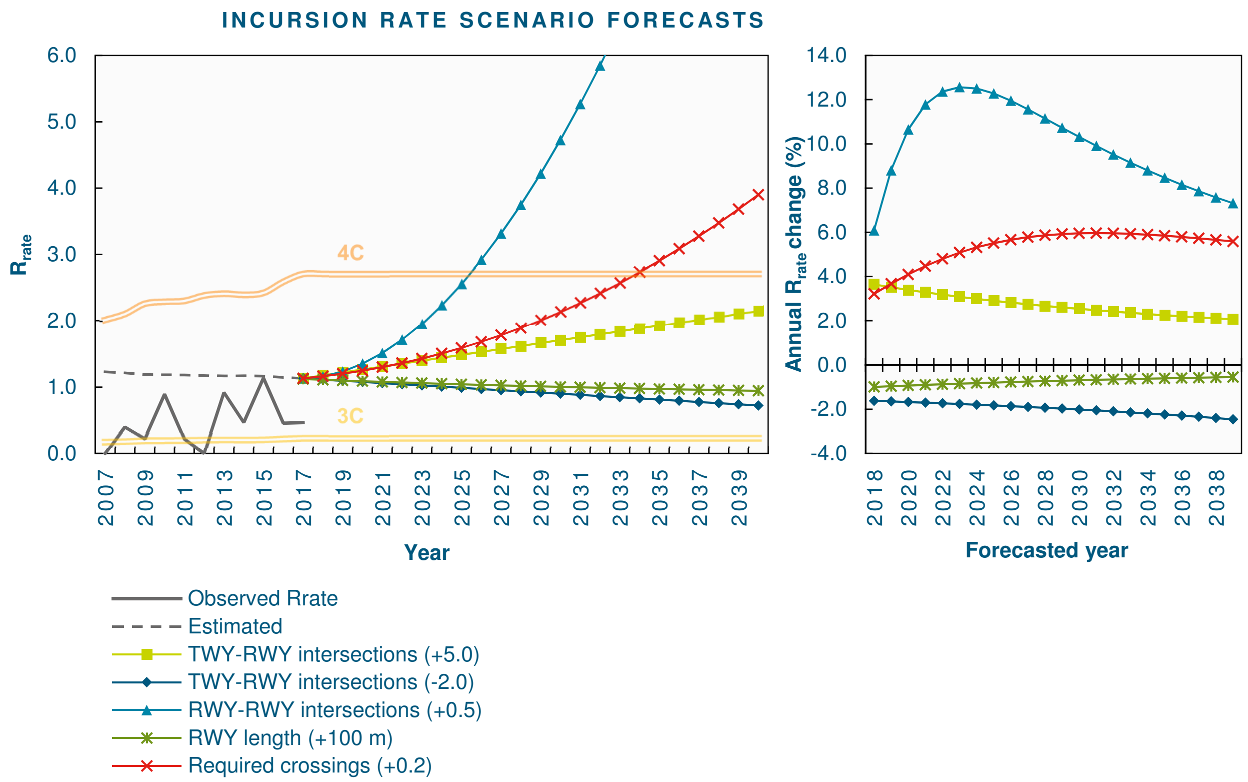
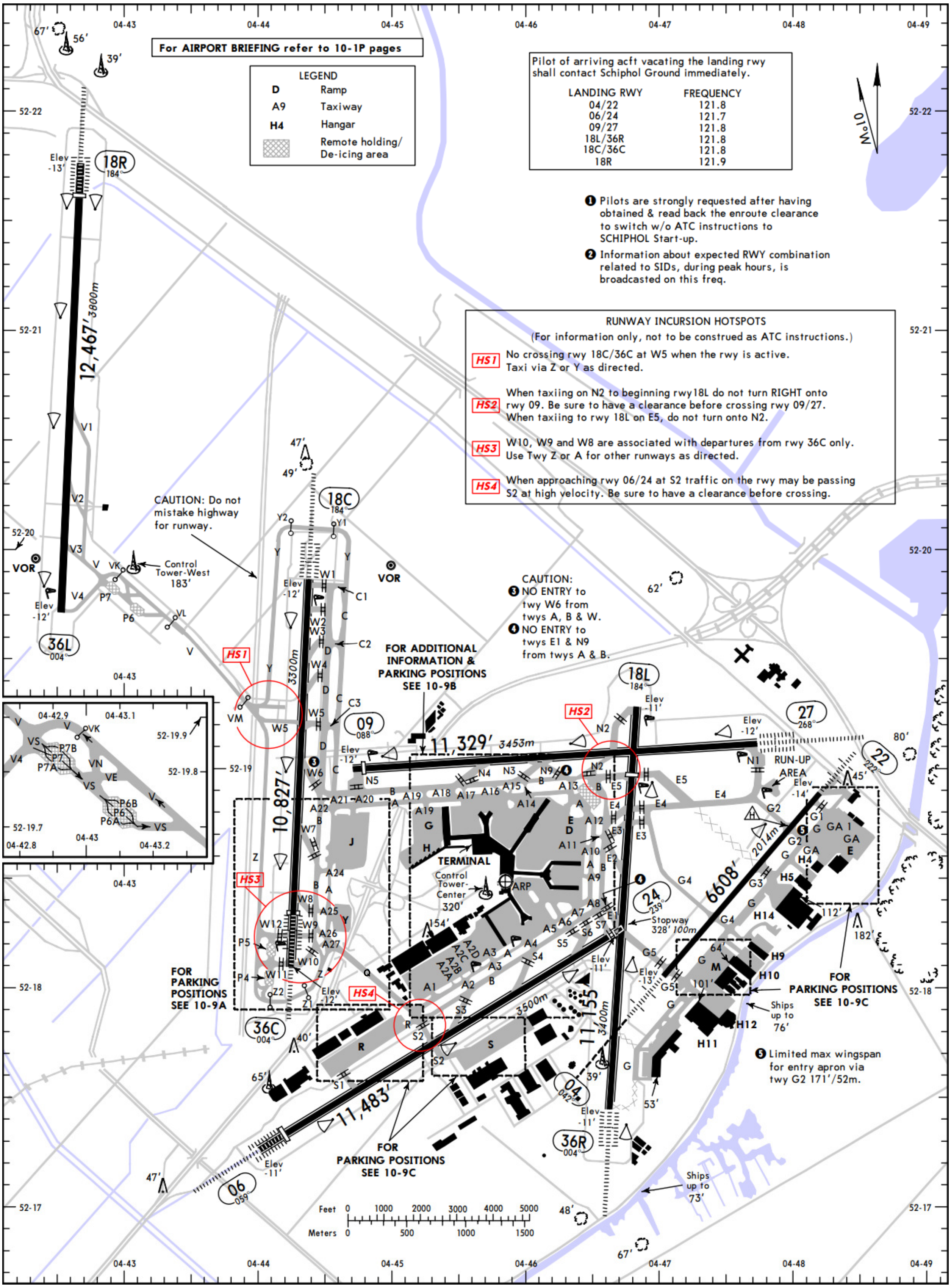


Figure A-17: Phoenix (PHX) incursion model scenario forecasts

A15 Airport diagram Schiphol Amsterdam, AMS



A16 Analytical methods

Mann–Whitney U Test (U):

$$U = n_1 n_2 + \frac{N_1(N_{1+1})}{2} - R_1 \quad \text{(A-18)}$$

where:

n_1	=	sample sizes from population 1
n_2	=	sample sizes from population 2
R_1	=	$\sum$ ranks from sample 1

Kruskal–Wallis test (H):

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{{R_i}^2}{n_i} - 3(N+1) \quad \text{(A-19)}$$

Pearson's Chi-Square test:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \quad \text{(A-20)}$$

where:

X^2	=	Pearson's cumulative test statistic
O	=	observed score
E	=	expected score
k	=	number of cells

Pearson's r:

$$\rho(X,Y) = \frac{cov(X,Y)}{\sigma(X)\sigma(Y)} \quad \text{(A-21)}$$

where:

$cov(X,Y)$	=	$E[(X - E(X))(Y - E(Y))] = E(XY) - E(X)E(Y)$
$\sigma(X)$	=	standard deviation of X
$\sigma(Y)$	=	standard deviation of Y

Spearman's rho:

$$r_s = 1 - \frac{6 \sum d^2}{n(n^2-1)} \quad \text{(A-22)}$$

where:

r_s	=	Spearman's rank correlation coefficient
d	=	difference in ranks
n	=	number of data pairs