Transportation Research Interdisciplinary Perspectives 12 (2021) 100480

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Evaluation of the impact of runway characteristics on veer-off risk at rapid exit taxiways

Sameera Galagedera [a,*], H.R. Pasindu [a], Varuna Adikariwattage [b]

[a] Department of Civil Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka
[b] Department of Transport and Logistics Management, University of Moratuwa, Moratuwa 10400, Sri Lanka

ARTICLE INFO

Keywords:
Rapid exits
Runway excursion
Veer-off risk
Runway design

ABSTRACT

Runway rapid exits are used as a method of reducing runway occupancy times of landing aircraft and thereby increasing its operational capacity. This is an important design improvement in the runway system of an airport that requires capacity improvement to meet the increasing demand. Due to the increased utilization of rapid exit taxiways, the number of accidents that could take place at rapid exits in the future could increase. The paper proposes a methodology to evaluate veer-off risks under different operational and design conditions at runway rapid exits. The method of analysis includes estimating veer-off probability along with the associated consequence. One of the key findings of this study is that a 30% increase in taxiway width and taxiway design radius result in 32% and 69 % reductions in veer-off risk respectively. The study provides a useful framework to incorporate veer-off risk when planning and design of rapid exit taxiways.

Introduction

Worldwide air passenger demand shows an average annual growth rate of 6.9% over the past few years (IATA, 2019). International Civil Aviation Organization's (ICAO) long-term air traffic forecast is approximately 10 billion by the year 2040, while airplane departures will also rise up to 90 million (International Civil Aviation Organization, 2018a). This forecasted growth in air traffic volumes would pose several operational issues, especially with respect to the capacity constraints prevailing in airports. Airport runway capacity is one of the variables that decide the limitation to capacity expansion. Thus, airports would look towards maximizing runway capacity utilization with the available infrastructure.

The need for rapid exit taxiways arises when operations exceed 30 operations per hour at which runway operational capacity is inadequate to cater to the air traffic demand (ICAO, 2005). For example, more than 85% of aircraft exits are through the rapid exits in the main runways of some airports (Meijers and Hansman, 2019). The recent commissioning of new rapid exit taxiways at Kolkata and Mumbai airports in India and Poland's Chopin airport are evidences that the airports are moving towards developing new rapid exit taxiways to meet the air side demand. Therefore, it's apparent that rapid exit taxiways will play a pivotal role in runway operations in the future. Therefore, improving the understanding of the operational risks at rapid exits is vital in this scenario.

The geometric characteristics of the rapid exit taxiways enable aircraft to exit at higher speeds which reduce runway occupancy times (ROTs) (ICAO, 2005; FAA, 2014). Several research studies have been initiated under the Airport Cooperative Research Program (ACRP) to evaluate the impact of runway geometric characteristics such as length, width, runway end safety areas, taxiway separation rules on aircraft excursion and incursion risks (Hall et al., 2011). They have contributed to evaluate the adequacy of runway end safety areas (Hall et al., 2008), taxiway design modifications in order to accommodate new large aircraft (Hall et al., 2011).

Nevertheless, only a limited number of research has been conducted to investigate aircraft excursion and incursion risks during high speed exiting operations taking into consideration runway characteristics and operational parameters. Moreover, with the potential increase in the usage of rapid exit taxiways, it is important to evaluate the relative influence caused by rapid exit design elements towards aircraft operational risk. Therefore, the research study proposes a model to evaluate the veer-off risk impact of key rapid exit taxiway design elements. The analysis incorporates variations in the runway surface conditions such as surface friction, as well as aircraft operational and design characteristics such as exit speed and main landing gear width, etc. The proposed

---

* Corresponding author.
E-mail addresses: 168008C@uom.lk (S. Galagedera), pasindu@uom.lk (H.R. Pasindu), varunaa@uom.lk (V. Adikariwattage).

https://doi.org/10.1016/j.trip.2021.100480
Received 18 December 2020; Received in revised form 20 July 2021; Accepted 27 September 2021

methodology enables to determine which of these design elements would have a relatively greater impact in reducing the aircraft veer-off risk.

The methodology developed for the purpose of evaluation of veer-off risk at rapid exits is in the third chapter of this paper. The illustrative example shown in the fourth chapter can be referred to be adapted the same methodology for any other airport setting. Additionally, the importance of rapid exit taxiway design features to be minimized the corresponding excursion risk is also discussed in the same chapter. The relevant advantages of the proposed methodology and future recommendations are summarized in the conclusion.

Runway operational risk

In air transport, the target level of safety (TLS) for landing operations is one accident per ten million operations (Feng and Chung, 2013). Among the worldwide aviation accidents, about 80% of accidents were reported to have occurred at airports or in the vicinity of airports. Nearly 39% of airport related accidents happened on runways, of which 25% occurred during landing and 14% occurred during takeoff (Boeing, 2019; Ayres et al., 2014). Considering the accidents during the landing roll, overruns and veer-offs are the most common types of accidents reported. They are categorized under runway excursions. Landing veer-offs are about 4 times more likely to occur than veer-offs during takeoffs (Lin et al., 2009). Regarding taxiway and taxi-lane related accidents, most of them have occurred at curved segments (Hall et al., 2011).

Historically, both quantitative and qualitative approaches have been adopted for aircraft excursion risk analysis. Most of them were site-specific studies that had limited applicability to other airports. Kirkland (2001) developed a quantitative risk assessment model to estimate landing overrun probability. In Kirkland's model, the only input variable was the percentage excess distance. It was estimated as the difference between the required landing length for an aircraft and the available runway length. A similar one-dimensional probability model was developed by Eddowes et al. (2001). Later Wong et al. (2007) developed a probability model using airport, aircraft and weather related multiple input variables. Wong's excursion risk estimation approach consisted three steps such as event probability, location probability, and event consequences. Under Airport Cooperative Research Program (ACRP) 03, Hall et al. (2008) conducted a study on aircraft overruns and undershoots for runway safety areas. ACRP applied Wong's approach to study on landing overrun and undershoot risk. Model estimation included variables such as airport related data, aircraft data, flight data, weather, wreckage information, consequences, and cost. Data was collected using previous accident records. In addition to Wong's probability model, factors such as ambient temperature and rain were included in this ACRP model. The same approach was used for veer-off risk modeling by Ayres et al. (2014) under ACRP 50 study. It included a new runway design related factor called "runway log criticality factor". Runway log criticality factor is a ratio between available runway length of a runway and the required runway length by an aircraft at the same runway. Further, it was extended by Hall et al. (2011) for risk assessments to modify airfield separation standards. In 2014, Ayres et al. modified veer-off and location probability models used for runway safety area risk assessments. Similarly, Shirazi et al. (2016) developed a runway protection zone risk assessment tool using modified landing and takeoff overrun and undershoot models. In this approach, presence of airport, aircraft and weather related conditions at the time of event occurrence were used to develop probability models.

Accident location models attempt to estimate the stopping location of the wreckage after the occurrence of an excursion event. ACRP studies have developed location probability models for individual overrun and veer-off events during landing and takeoff operations. They estimate the fraction of accidents involving locations exceeding a given distance from the runway edge using exponential decay functions. Hence, at given operational and design conditions, the probability of an event occurrence, and lateral and longitudinal location of an aircraft beyond a threshold point on the runway could be estimated using these models. Over the years these models have been modified by researches using new accident data or by introducing new risk factors.

Consequence of an accident is one of the main components of risk. The inclusion of the severity of injuries and loss of property is considered under consequences to quantify accident risk. Accident consequences depend on various factors such as accident location, speed, final stopping location and types of objects involved in an accident (Hall et al., 2008). Thus, higher the speed an aircraft collides with an obstacle, greater the consequences due to higher energy involved. The speed of the aircraft striking an object is related to the distance the same aircraft would travel beyond that point and stop if no obstacles is present in the area. Hence, the site condition and terrain are significant determinants for distinct consequences. The method used by ICAO for assessing veer-off accident consequences is based on the damages to human health and aircraft condition (International Civil Aviation Organization, 2018b). In the ACRP approach, consequences are categorized using aircraft wreckage locations. Therefore, in order to estimate risk, location models can be used to quantify qualitative assessments (Hall et al., 2008).

Landing overrun risk index was developed by Van Es (2005). The index weighted multiple risk factors and combined them to form a value (Van Es, 2005). According to Van Es, non-precision approach, touch down far beyond the threshold, excess approach speed, visual approach, tailwind, wet/flooded runway, and/or snow/ice/slush-covered runway are the key causal factors for runway excursions. Guerra et al. (2008) developed risk contours around airports, using touch down location and probabilistic analysis of the final stopping location. Jeon et al. (2016) modified event probability model developed by Ayres et al. previously in 2014, where the two risk factors "snow" and "rain" were split into three different factors such as light, moderate and heavy.

Moretti et al. (2017) developed a quantitative risk assessment methodology to evaluate the probability of an aircraft veer-off accident and the probability of the accident location exceeding a particular distance from the runway centerline. Using historical veer-off accident from 1980 to 2015, Moretti et al. estimated veer-off probability and developed exponential models to estimate veer-off location probabilities. Moretti et al. used frequentist approach to estimate event and location probabilities. Moretti et al. (2018) and Mascio et al. (2020) continued risk assessments at different airports using airport related characteristics such as air traffic, runway usage, wind distributions, landside building interferences and geotechnical features of the strip areas (Moretti et al., 2017, 2018; Mascio et al., 2020). In addition to the aircraft condition and human health based severity index, relating the effect of the soil bearing capacity into veer-off consequences was one of the significant improvement in the Moretti's severity index. Following this methodology, *iso*-risk curves can be developed for different airports. Trucco et al. (2015) developed a severity index based on the kinetic energy available at any given point beyond the runway paved surface (Trucco et al., 2015). The severity value is used to estimate the excursion risk at the vicinity of the runway.

Considering taxiway related excursions, FAA together with the Boeing conducted a project on taxiway centerline deviations of B747 (Scholz, 2003). By taking laser measurements in straight taxiway segments at two US based international airports, the study developed a formula to estimate the two-sided risk of exceeding a specified threshold for taxiing B747 aircraft.

Even though several risk models have been developed for runway excursion risk estimation, excursion risk estimation at rapid exit taxiways have been ignored. Instead, there are studies conducted for selection of suitable locations for rapid exit taxiways. A study on probabilistic assessment on aircraft turnoff paths was done by Schoen et al. (1985). Following the same approach, Trani et al. (1990) developed a computer based simulation program "Runway Exit Design Interactive Model (REDIM)" for optimally locating rapid exits. The REDIM was modified in 1992 for the added flexibility with user defined exit angles (Trani et al., 1992). Using fleet mix and aircraft landing performances, these were mainly focused on planning exit locations. Once runway design factors and exit design elements such as exit locations, acute angles are inserted into the REDIM, optimum new exit locations will be the given subject to the fleet mix and requested new number of exits. This can be used for existing runways as well as the new runway designs. Meijers and Hansman (2019) used Airport Surface Detection Equipment data from 36 largest airports in US to analyze ground conflicts. The study revealed that the exit location is the most influencing factor on ROT.

All previous rapid exits-related literatures primarily focus on runway capacity optimizations. However, the potential incident risk at runway rapid exits have not been considered thus far. This may be due to the lower number of incidents at rapid exits reported currently. Even though the runways related studies have developed excursion event and location probability models, they have not addressed the evaluation of veer-off risk at rapid exits. Accordingly, based on the literature review and the corresponding knowledge gap on incident risk at rapid exits, rapid exits related risk estimation is noteworthy.

Runway rapid exit

Aircraft risk at rapid exits

Aircraft veer-offs are defined as excessive deviations of aircraft travel path beyond the lateral limits of the respective facility (Hall et al., 2011). These extreme lateral deviations are not uncommon at rapid exit taxiways as well. Due to the resultant effect of speed and turning maneuver, complications may occur, especially at turn-in segments of rapid exit taxiways. Other than the excursion events, incursions may also be caused at high speed exit taxi-out locations when exit aircraft enter into parallel taxiways.

The possible chance of veer-off at high speed turning maneuver is identified when an aircraft moves outward from the taxiway paved surface and enter the adjacent unpaved terrain. Force imbalance on the nose gear wheel is the main cause for the initiation of this type of event. Due to variability in landing performance, aircraft operational parameters such as approach speed, aircraft mass, touchdown location, weather conditions, etc. may vary at each individual landing operation. These variations could cause extreme turn path deviations with regard to the intended travel path and can end up as a veer-off event. In order to illustrate relevant causal factors, a list of veer-off accidents that occurred at rapid exits are summarized in (Table 1) (Skybrary, 2020; FAA, 2019).

Common causal factors related to excursions at rapid exits are aircraft speed, deceleration, pilot error, etc. Factors such as approach speed, touchdown location, aircraft mass at landing, and deceleration influence aircraft speed at the exit location. Moreover, deceleration is influenced by the runway pavement condition, airplane aerodynamic effect, weather condition, and pilot preparation to exit. In addition to the above operational factors, exit location, exit angle, radius of curvature, runway-taxiway separations, and runway safety areas are airfield design related factors that may affect the probability of veer-off. Therefore, it could be envisaged that several other causal factors may have contributed for accidents at rapid exits. Additionally, these factors determine pilot acceptance and relevant utilization of rapid exit taxiways as well. A factor becomes a causal factor when the causality can be established in relation to the incident. The above mentioned factors are common causal factors for excursions, not only at rapid exits but also at straight runway and taxiway segments. These causal factors are prone to create excessive deviations from the taxiway centerline. Consequently, such extreme deviations may cause aircraft to deviate away from the paved runway or taxiway surface, and it is identified as an excursion event.

Rapid exit taxiways are identified as one of the leading factors for incursion type incidents (Green, 2013). Increasing number of ground movements cause higher incursion rates at taxi-out locations. Compared to 90-degree exists, acute angle exit taxiways reduce pilot's sight angle. When rapid exits include in airport airside layouts, the associated number of intersections may increase the potential for ground collisions (Johnson et al., 2016).

Airports take various measures to improve runway safety such as development of airfield safety area, runways taxiways and taxilane paving, navigation aids (ASDE-X), lighting and other visual aids, compliance to safety standards, etc. With numerous controlling and mitigating mechanisms, aircraft accidents still occur worldwide. Thus, design, operational, and human factor-based collective safety measures are important for continuous approach for accident prevention or minimization.

Rapid exit taxiway design

Exit angle (acute angle), design exit radius of curvature, and runway-taxiway separation distance are key geometrical features of rapid exit taxiways. Over the years, the acute angle has become smaller to improve the aircraft exiting speed and it aids to expedite aircraft vacation from the runway. ICAO recommends that acute angles should not be greater than 45-degrees, and preferably should be 30-degrees. Accordingly, ICAO recommended design features include 30-degree acute angle, 550 m design radius for code number 3 and 4 aircraft categories (Fig. 1), and a 26.7 ms^{-1} of exit speed (ICAO, 2005).

However, the FAA recommends the same 30-degree acute angle with 450 m radius of curvature for all Taxiway Design Groups (TDG) (Table 2). Taxiway Design Groups are a standardization of aircrafts for maneuvering. TDG classifies aircraft using pavement requirements for taxiways and the landing gear configurations. Aircraft Main Gear Width (MGW) and Cockpit to Main Gear distance (CMG) is used to define the

Table 1
Events at rapid exits.

Date	Aircraft Type	Airport	Accident Type	Severity	Causal Factors
29-Aug-2011	A340	Chhatrapati Shivaji International Airport, India	Veered-off from the rapid exit taxiway	Got struck in the adjoining mud	Taxiway surface condition
02-Nov-2011	B747	Changi Airport, Singapore	Veered-off when trying to vacate the runway via a rapid exit	No Information	Turn off speed, deceleration, pilot error
21-Sep-2012	A319	Copenhagen Airport, Denmark	Veered-off from the paved surface when attempting to turn to the rapid exit	No Information	Turn off speed, pilot error
21-Feb-2016	A320	Birmingham International Airport	Failed to negotiate the taxiway turn	Ran on to the adjoining grass	Turn off speed, wet surface, pilot error
21-Nov-2019	B737	Odessa Airport, Ukraine	Travelled off the side of the runway	Aircraft left main landing gear struck on the grass	Mechanical failure of the nose landing gear
05-Dec-2013	B767	Madrid Barajas Airport	Move out of the rapid exit taxiway	Stopped on the grassy area	Tire failure
02-Jul-2019	A320	Mangalore International Airport, India	Aircraft veered-off the taxiway when turning into rapid exit taxiway from the runway	No severe damages	Turn off speed, deceleration, pilot error

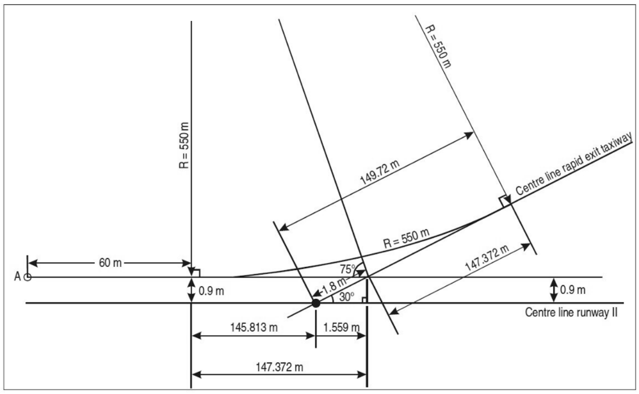


Fig. 1. Rapid exit design for code number 3 and 4 aircraft categories (Source: ICAO, 2005).

Table 2
Rapid exit taxiway design elements.

Design Element	Relevant Design Parameter	Aircraft Operations / Airside Design Characteristic relevant to the design parameter
Acute angle	30°	Exit speed, side friction coefficient, runway taxiway separation
Taxiway radius of curvature	450 m	Exit speed, side friction coefficient, tire scrubbing, runway taxiway separation
Taxiway width	Depends on Taxiway Design Group (TDG)	Airplane's undercarriage, Main Landing Gear Width, Cockpit to Main Gear Distance
Shoulder width	Depends on TDG, Taxiway Edge Safety Margin (TESM)	Airfield soil, paved shoulders required for ADG-IV and above
Runway taxiway separation	Depends on the Airplane Design Group (ADG) and TDG, Visibility minimum	When aircraft turn back to the reverse direction with a subsequent 150° turn after the initial 30° turn off

TDG classification. Considering 125 aircraft types and their longest CMGs and widest MGWs, eight TDGs are categorized. The purpose of taking CMG distance into TDG classification is the importance of aircraft length and steering characteristics for taxiway fillet designs. Using TDG, FAA defines standards for taxiway widths, shoulder widths, parallel taxiway separations, safety areas and Object free areas. The parallel taxiway separation is important for aircraft to reach safe taxiing speed or full stop prior to any intersection and reverse turn. As rapid exit taxiways are built in between a runway and a taxiway, runway, taxiway safety areas are still applicable to the rapid exit taxiways as well. Compatibility of the rapid exit design depends on several airport and aircraft operational characteristics. They need to be included in the risk-based evaluation of aircraft operations at rapid exits. Table 2 summarizes the factors which are relevant to each design element.

Methodology for risk evaluation

Considering the research gap on rapid exits related incident risk evaluation and related literature on airport risk assessment, a methodology is developed for excursion risk evaluation at rapid exits. The greatest challenge is the lack of incident data for developing statistical models. Hence, the methodology mainly depends on the aircraft nose gear lateral stability based dynamics. Using first principals of nose gear lateral stability a deterministic model is derived for the nose gear turn path radius. It is assumed that the variation in the causal variables induced by operational conditions would make aircraft to deviate from the intended curvilinear taxiway centerline path. Excessive deviations are the basis for potential excursion events. The methodology shown in Fig. 2 is developed to evaluate associated excursion risk at rapid exits incorporating the relevant operational factors, features of high speed exit and aircraft characteristics.

Evaluation of Veer-off risk

A condition or an object potential to cause or contribute to an aircraft accident or incident is defined as a hazard. Though there are various hazards in an airfield, they do not affect uniformly for each operation. Thus, risk incorporates the probability and severity of the consequences of being exposed to a hazard. The risk of veer off is given by Eq. (1).

$$R = P \times D \tag{1}$$

where, R is the veer-off risk. P is the event probability and *D* is the consequence. The vent in concern is defined as the main landing gear leaving the taxiway paved surface and reaching a certain distance (*Ls*) from the rapid exit taxiway centerline, Thus the probability (*P*) of the event describes the intersection of aircraft veer-off event (*P1*) and the aircraft traveling a certain distance (*Ls*) given the veer-off (*P2*).

Thus, the probability that an aircraft veers-off from the taxiway paved surface and come to a stop at a certain distance from the taxiway centerline can be computed by the Eq. (2):

$$P = P_1 \times P_2 \tag{2}$$

The methodology outlined in Fig. 2 consists with three main steps such as veer-off event probability estimation, location probability estimation and event consequences estimation.

Evaluation of the veer-off event probability (P1)

This section presents a relationship between exit design features and aircraft operational factors that determine aircraft nose landing gear stability during turning maneuvers. According to Schoen et al. (1985), centripetal force, aircraft inertia, and tire scrubbing resistance to turning are identified as three contributing factors for the lateral force acting outwards on the nose gear during turning maneuvers. For the lateral stability of the nose gear during turning maneuvers, the related three forces should be balanced by a counter force. Thus, side friction force is identified as the counter force laterally acting on the nose gear for maintaining the lateral stability. Schoen et al. used different coefficients to represent those forces and they are a) nose gear tire skid friction coefficient (f_{skid}), b) tire scrubbing coefficient (f_{sc}), c) aircraft inertia contribution to nose gear skidding friction coefficient (f_{Izz}), and d) centripetal acceleration contribution to skidding (f_c). Accordingly, the functional relationship among the coefficients is expressed by the Eq. (3). Aerodynamic forces are insignificant at these exiting speeds (Trani et al., 1992).

$$f_{skid} = f_{Izz} + f_c + f_{sc} \tag{3}$$

Here, tire scrubbing coefficient (f_{sc}) is determined by aircraft mass (*m*) and nose gear turn path's instantaneous radius (*R*). The sensitivity of the scrubbing coefficient to the radius of curvature increases for heavier aircrafts at landing such as the 200,000 kg or more aircraft masses. Aircraft belong to Airplane Design Group (ADG) E & F are some examples of this weight category. According to Trani et al. (1990), the side friction coefficient (f_{skid}) is identified as a function of aircraft speed (*V*) for different TERPS categories. TERPS stands for Terminal Instrument Procedures that prescribes minimum measure of obstacle clearance for landings and takeoffs. TERP categorization follows the same classification under Aircraft Approach Categories (AAC). Considering indicated airspeed at threshold at certified landing weight, aircraft split into different approach categories. TERPs are used in US based airports and ICAO PANS-OPS are used by the airports in other counties. However, there are less significant differences exist between them.

Similarly, f_{Izz} is dependent on factors such as aircraft instantaneous

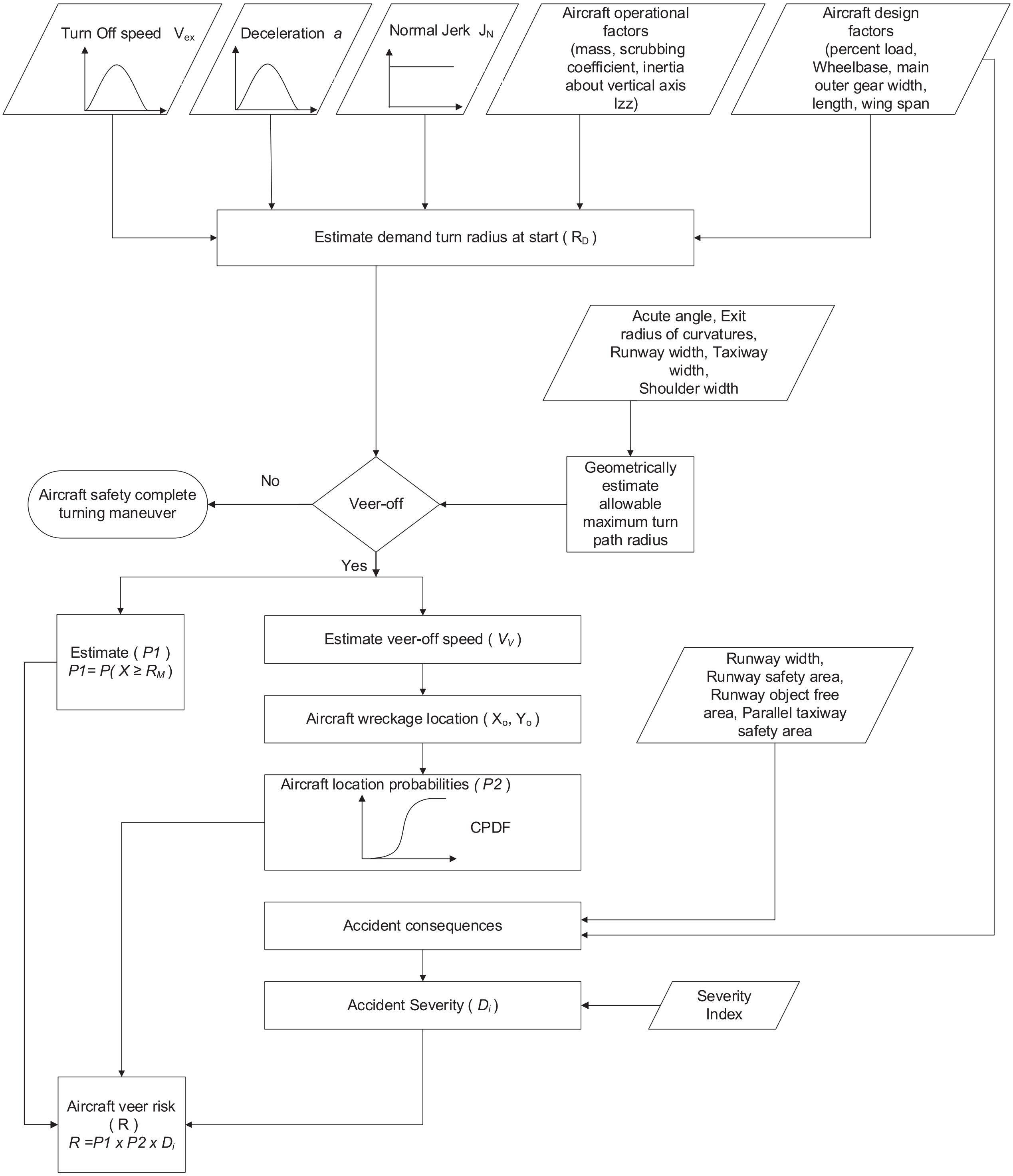


Fig. 2. Flow chart of the methodology.

radius, rate of change of radius, aircraft inertia, mass, wheelbase, and percent load on the main gear. Aircraft nose gear may follow different turn path radius and the instantaneous radius given by this relationship (Eq. (3)) is the minimum value pertaining to the limiting case of nose gear stability. Consequently, this minimum radius is the demand turn path radius (R_D) for maintaining nose gear wheel stability.

According to Schoen, R^o is presented by the Eq. (4):

$$R^0 = \frac{-\left(f_{skid} - \frac{V^2}{gR} - f_{sc}\right)\frac{mR^2 gWb\frac{lm}{100}\left(1-\frac{lm}{100}\right)}{I_{zz}} + RV^0}{V} \tag{4}$$

where, R - instantaneous radius of the curvature (m), g - acceleration of gravity (m/sec^2), I_{zz} -moment of inertia around the z-axis (kgm^2), I_m - percent load on the main gear (%), W_b - aircraft wheelbase (m), R^o - the rate of change of the turning radius (m/sec), V^o - instantaneous velocity rate of change of the nose gear (m/sec^2), V- instantaneous speed (m/

sec). Here, I_{zz}, I_m, and W_b are constants for a given type of aircraft.

Passenger comfort is an important design parameter when the maximum allowable rate of change of radius is considered. As shown in Eq. (5), it is constrained by the acceleration normal to the direction of velocity - normal acceleration (a_N) and jerk factor (J_N) for a given R. According to Trani, average accepted normal jerk and normal acceleration vary between 0.54 and 0.64 m/sec^3 and 1.18–1.47 m/sec^2 respectively (Trani et al., 1992). Hence, the maximum rate of change of radius (R^0_{max}) for a given turn off is given by,

$$R^{o}_{max} = (J_N \times R)/a_N \tag{5}$$

Here, $a_N = V^2/R$

At the beginning of the exit maneuver, the aircraft nose gear turning radius changes from infinity to the demand turning radius (R_D) for starting the exit maneuver. Thus, around this point maximum rate of change of radius (R^0_{max}) can be observed. Accordingly, in order to estimate the nose gear demand turning radius (R_D) at the initiation of the exit maneuver, the relationship given by Eq. (6) is derived by substituting $R^o{}_{max}$ to Eq. (4). At the point of exit, exit speed becomes the instantaneous speed and V^o is the linear deceleration in the taxiing direction.

$$R_D = \left(C \times V^2 + g \times V^o\right) / \left\{ g\left(C\left(f_{skid} - f_{sc}\right) - J_N/V\right) \right\} \tag{6}$$

Here, $C = \{m \times g \times W_b \times (l_m/100) \times (1 - (l_m/100))\}/I_{ZZ}$

The above (R_D) is the nose gear wheel minimum required turn path radius (demand turning radius of aircraft nose gear wheel) at the point of exit when the maneuver starts (Exit start) as shown in the Fig. 3.

Aircraft turning radius at different positions can be computed using demand turning radius (R_D) together with the rate of change of radius (R^o), Respective R^o and R_D can be used to estimate the nose wheel's position during the taxiing maneuver. However, this approach makes this methodology much complex. Hence, the study ignores pilot intervention to change the nose gear radius and therefore the rate of change of radius after the point of exit is assumed to be zero. Thus, estimated R_D continues along with the turning maneuver up to the end of the curved taxiway path. The deviation of the aircraft lateral position with respect to the taxiway centerline is a critical safety factor to complete the aircraft taxiing maneuver.

Using Eq. (6), an aircraft demand turning radius (R_D) at the point of exit can be estimated. Here, R_D is a dependent variable of various operational parameters such as touch down speed, deceleration in the landing roll, exit speed, aircraft mass, wheelbase, weather factors, etc. These parameters take randomly varying values under operational conditions. Thus the right hand side of Eq. (6) can be viewed as a function of random variables. As a result, R_D will be a random variable that can be modeled as a function of random variables in the right hand side of Eq. (6).

Given the non-linear nature of Eq. (6) and the heterogeneous random behavior of the causal variables, an analytical approach to model the probability distribution of R_D is intractable. Thus a numerical technique such as the Monte Carlo simulation method is used to estimate the probability distribution of R_D.

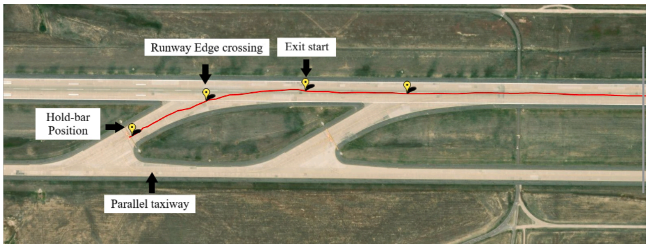


Fig. 3. Turn path locations.

Application of Monte Carlo simulation technique

I. The type of aircraft determines aircraft-related input parameters. Aircraft wingspan, length, wheelbase, inertia around the vertical axis, outer gear width, percent load on main gears, and aircraft mass are aircraft related design factors which remain as constants for a given type of aircraft. Aircraft exit speed and deceleration along the turning maneuver are aircraft related random variables.

II. Exit speed (V_{ex}) and deceleration (a) are assumed to be normally distributed as per the probability density function in Eq. (7). This probabilistic assumption was made by referring the landing event data for three distinct airports. Considering aircraft exit speed and deceleration data from the landing event database - REDIM (Air Transportation Systems Laboratory, 2020), the respective distribution patterns were studied. Accordingly, it was identified that the exit speed and deceleration are independent and normally distributed. Thus, respective mean and standard deviation values for speed and deceleration were calculated and illustrated in the example. Exit speed follows Eq. (7),

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad -\infty \leq x \leq \infty \tag{7}$$

where μ and σ are, respectively, the mean speed and standard deviation.

Similarly, aircraft deceleration also follows the normal distribution subject to mean and standard deviation values for deceleration.

III. Scrubbing coefficient (f_{sc}) depends on the turning radius and aircraft mass. By referring Trani et al. (1992), scrubbing coefficient remains as a constant in specified intervals of the turning radius. Thus, for aircraft heavier than 200000 kg, scrubbing coefficient f_{sc} follows following Eq. (8) where y denotes the nose gear turn path radius in meters (m).

$$g(y) = \begin{cases} 0.12, & 0 \leq y \leq 400\,m \\ 0.08, & 401 \leq y \leq 650\,m \\ 0.05, & 651 \leq y\,m \end{cases} \tag{8}$$

IV. There is no standard normal jerk value for aircraft ground movements during ground maneuvering. Due to lack of empirical evidence and lack of data, the study assumes that the normal jerk values for the aircraft high speed turnings are similar to the normal jerk values for the large ground moving vehicles during the high speed turning maneuvers. Considering road and rail transportation related standard normal jerk values, the respective upper and lower bounds are defined (Bae et al., 2019). Accordingly, the normal jerk (JN) follows the following uniform distribution in Eq. (9) where 0.3 and 0.9 are the respective lower and upper bounds of the uniform distribution and j denotes the normal jerk.

$$z(j) = \begin{cases} \dfrac{1}{(0.9 - 0.3)}, & 0.3 \leq j \leq 0.9 \\ 0, & otherwise \end{cases} \tag{9}$$

V. Side friction coefficient depends on the aircraft speed (Trani et al., 1990). Considering the aircraft speeds during high speed maneuvering, it varies between 10 and 45 ms^{-1}. In the speed range 10–45 ms^{-1} side friction coefficient depicts a linear relationship with the speed and side friction varies between 0.2 and 0.3 for the same speed range. Accordingly, the following linear relationship (Eq. (10)) is derived and for the side friction coefficient values for the given speeds (v).

$$h(v) = 0.446 - 0.007v \qquad 10 \leq v \leq 45\ ms^{-1} \tag{10}$$

VI. In each simulation run, random values of aircraft exit speed, deceleration, jerk, scrubbing factor, and side friction coefficient are generated according to the distributions specified above. By substituting values to Eq. (6), R_D is estimated within each simulation run.

This process repeated over multiple simulation runs can be used to develop a probability distribution *F(x)* of R_D given by:

$$F(x) = P(X \leq x), \qquad \text{where X denoting the possible values of } R_D \tag{11}$$

VII. Aircraft turning radius at the initiation of the exit maneuver R_D is the key determinant of airplane safety at the rapid exits. When an aircraft R_D is equal to the taxiway design radius (R_a), it can precisely complete the tuning maneuver and enter into the taxiway. The estimated R_D for a given operation is the lower bound of the turn path radius for that particular operation and all the turn path radiuses above R_D may inherently maintain the nose gear stability. Thus, R_D values less than the R_a (taxiway design radius) can also be increased up to taxiway radius R_a during the turning maneuver. However, the problem arises with the R_D values greater than the design radius R_a, which might deviate from the taxiway entrance. To confirm the potential entries of this higher R_D (>R_a) into the taxiway, the maximum allowable demand turning radius (R_M) is estimated. This maximum allowable turning radius is the demand turning radius that can complete the curvilinear taxiing maneuver within the paved taxiway surface. In all the demand turning radiuses (R_D) greater than this maximum allowable radius (R_M), aircraft directly enters the unpaved airfield terrain. For B747-400 aircraft, this maximum allowable turning radius is 775 m. Based on the aircraft dimensional characteristics such as wheelbase, track width, R_M is an aircraft type-specific value. The analysis assumes if R_D is greater than the R_M, it will be a missed opportunity beyond the pilot controllability and these larger turning radiuses can cause the aircraft to leave the taxiway paved surface and enter the adjacent unpaved terrain. These events are defined as aircraft veer-offs belonging to the excursion event category.

VIII. Veer-off probability (P_1) is given by:

$$P_1 = 1 - F(R_M) = P(X \geq R_M) \tag{12}$$

Evaluation of location probability (P2)

A consequence of an excursion event depends on the collision with an obstacle, airfield terrain, etc. As the areas where rapid exits are located have no obstacles, the potential consequences of veer-offs are due to the aircraft travel distance on the unpaved adjacent terrain. The shorter the travel distances, aircraft may stop within the runway safety area and longer the travel distances, it enables aircraft to enter into the object free area. However, these travel distances are determined by the veer-off speed and the point of the veer-off from the paved surface. To estimate veer-off speed and to identify the respective veer-off location, a curvilinear segments-based (A_1-A_{16}) geometrical approach is introduced.

As shown in Fig. 4, the taxiway paved area in between the runway centerline and taxiway curvilinear centerline (550 m taxiway design centerline) is divided into curvilinear segments. A perpendicular line is drawn to the taxiway centerline at the location where the taxiway centerline getting straight and the same perpendicular line is extended towards the runway up to the runway centerline. This perpendicular line is marked in 5 m intervals and those markings are joined with the point of exit by curvilinear lines. Accordingly, A_1 to A_{16} sixteen number of curvilinear segments are developed.

Referring to Table 3 and the above estimated turn path radius (R_D), for a given aircraft operation, the corresponding curvilinear segment out of the A_1-A_{16} segments can be identified. As R_D lesser than the R_M are not considered as veer-offs, R_D values belong to A_1 to A_5 segments can be neglected in the location probability estimation. However, with the effect of R^o, the corresponding radius of curvature at the point of veer-off might be in another segment. Assuming the change in the demand turning radius up to the point of veer-off is minimal, the effect of R^0 is neglected when allocating possible turn paths into segments. Thus, aircraft enter into the unpaved adjacent terrain from a particular segment is the same segment that the aircraft belong with regard to the R_D estimated at the point exit maneuver started.

To categorize aircraft wreckage locations where similar consequences cause, wreckage locations are estimated using initial turn path radius. Once turn path radius based curvilinear segment is identified, for each segment, the distance travel on the paved surface up to the point of veer-off (L), the x and y coordinates of the point of veer-off (x_j, y_j), and travel direction on the unpaved surface after veer-off (β_j) are important information on the final wreckage location. Thus, a runway centerline and rapid exit taxiway-based coordinate system is developed in (Fig. 5). With regard to each segment, there is a specific location at which paved to non-paved (from the runway /taxiway paved surface enter into the unpaved terrain) transition takes place. The corresponding transition point for any particular segment (A_j) is fixed and considered as (x_j, y_j). In (Fig. 5), the distances from the axis origin (O) in each X, Y directions to each segment's transition location are denoted as x_j, y_j. The curvilinear distance travel up to x_j, y_j in each segment is denoted as L_j. The paper further assumes that each veer-off takes place from any particular segment (A_j) always make a constant angle (β_j) with the runway centerline. For all sixteen segments, these distance L_j, veer-off point x_j, y_j, and angle β_j values are geometrically derived and shown in Table 3. These values aid to estimate final wreckage locations and it is shown in the later part of this methodology. The last three columns in the Table 3 show the respective veer-off lengths (in Y direction) on the adjacent unpaved areas up to the boundaries of safety area object area boundaries, and parallel taxiway are defined as Y_s, Y_o and Y_t for aircraft veer-off from different curvilinear segments A_j. These distances are important to classify different consequences.

As an example, during the turning maneuver if an aircraft follows 1024.3 m turn path radius, the respective turn path belongs to the segment A_9 in Table 3. An aircraft which belongs to the segment A_9, travels average $L_9 = 295$ m up to the point of veer-off (x_9, y_9). If aircraft possesses sufficient kinetic energy to travel this 295 m, the corresponding veer-off point locates 142.7 m from the origin towards X

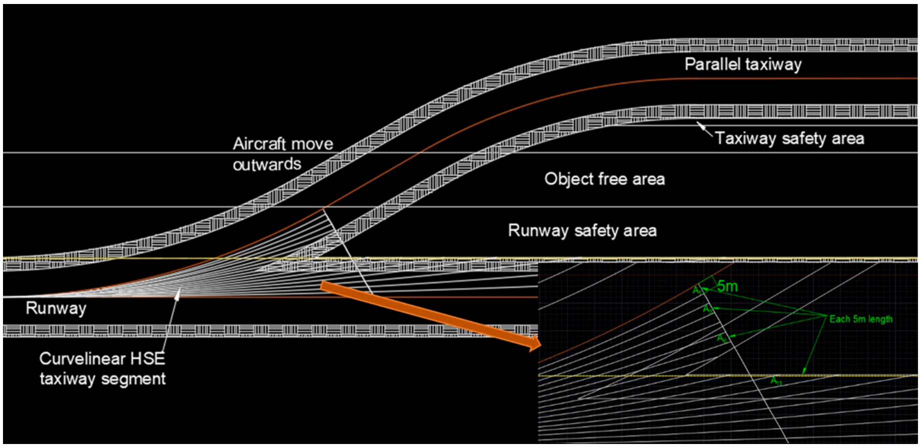


Fig. 4. Aircraft lateral deviation outwards the taxiway centerline.

Table 3
Wreckage location and safety area geometrical parameters.

Lateral segments Aj	Radius of curvature Rj (m)	Distance from the point of exit to the point of veer-off (Lj)	Distance from rapid exit taxiway centerline to veer-off location x_j (m)	Distance from runway centerline to veer-off location y_j (m)	Veer-off angle with respect to runway centerline (deg)	Y_s distance to Runway Safety Area (m)	Y_o distance to Object Free Area (m)	Y_t distance to Parallel Taxiway Safety Area (m)
1	550–588	288	130.1	71.5	29	–	–	–
2	589–628	289	132.6	67.2	27	–	–	–
3	629–664	291	135.1	62.8	25	–	–	–
4	665–709	292	137.6	58.5	23	–	–	–
5	710–775	293	140.1	54.2	21	–	–	–
6	776–820	295	142.6	45.5	20	75	120	182
7	821–905	287	136.5	36.1	18	75	120	182
8	906–1007	274	124.0	33.0	15	75	120	182
9	1008–1133	295	142.7	33.0	13	75	120	182
10	1134–1292	314	165.1	33.0	12	75	120	182
11	1293–1496	342	192.7	33.0	12	75	120	182
12	1497–1769	377	228.0	33.0	11	75	120	182
13	1770–2151	420	271.3	33.0	10	75	120	182
14	2152–2726	489	340.9	33.0	8	75	120	182
15	2727–3684	607	459.4	33.0	7	75	120	182
16	3685–5594	862	714.3	33.0	5	75	120	182

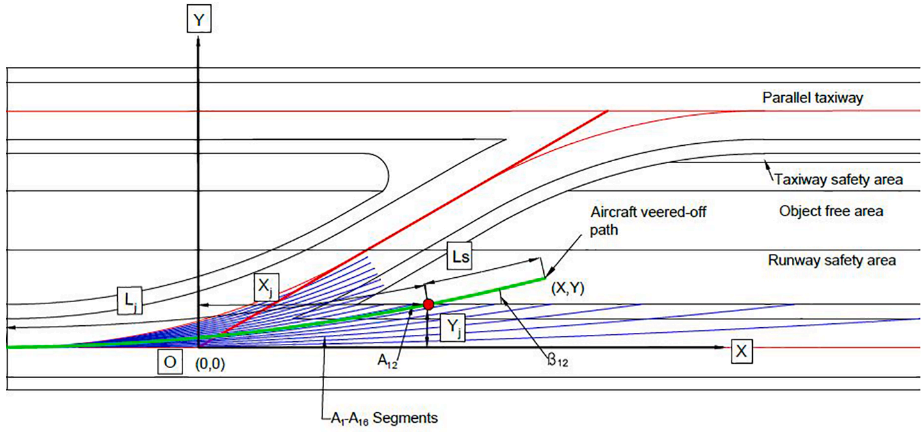


Fig. 5. Laterally divided segments of taxiway paved area.

direction and 33 m from the origin towards Y direction (Fig. 5).

In case of veer-off, aircraft travel distance on the unpaved terrain is one of the major findings of the estimation of consequences. Accordingly, aircraft speed at which aircraft enter the unpaved terrain is determined by the fundamental relationship in Eq. (13):

$$V_v^2 = V_{ex}^2 - 2\times a\times L \tag{13}$$

where, V_v - veer-off speed from the paved surface (m/sec), V_{ex} - turn off starting speed (the speed at Ex start) (m/sec), a - deceleration to the direction of movement (m/sec^2). L which is aircraft's mean travel distance on the paved surface up to the point of veer-off from the point of exit maneuver starts can be taken from Table 3.

According to Kirkland (2001), aircraft deceleration on wet/dry grass terrain can be computed by the following Eq. (14):

$$a_s = -0.0185 - 0.06749\times V_v \tag{14}$$

where, a_s – aircraft deceleration on the wet/dry grass terrain after veering off from the paved taxiway surface (m/sec^2).

Due to the effect of retardation of unpaved terrain, as shown in (Fig. 5) aircraft may stop a certain distance from the point of veer-off. Thus, aircraft wreckage location from the point of veer-off can be estimated by the fundamental equations of motion for uniform acceleration (Eq. (15)).

$$L_S = V_v^2/(2\times a_S) \tag{15}$$

where, L_s - stopping location from the point of veer-off

Using x_j, y_j values, and angle β attached to each segment (Table 3), aircraft wreckage locations can be converted for a common coordinate system. Eqs. (16) & (17) along with the individual travel distance (L_s) can be used for the conversion.

$$X = L_s\cos\beta_j + x_j \tag{16}$$

$$Y = L_s\sin\beta_j + y_j \tag{17}$$

If any known hazard/obstacle is available in the airfield area, potential wreckages conflict with the same obstacle can be estimated by this approach. The above conversion into a common coordinate system supports to the identification of corresponding wreckages that are in danger due to such an obstacle in the airfield. Here, *P2* is the percentage of wreckages in a selected airfield area out of the total veer-offs. For example, veer-offs stopping within the runway safety area is estimated by filtering respective Y coordinates as shown in Eq. (18). The respective limiting values of X and Y distances that belong to runway safety areas, object free areas and leads to parallel taxiway are also mentioned in the Table 3.

$$p_2 = \frac{Number\ \ of\ \ events\ where\ 33\ m\ <\ Y\ <\ 75\ m}{All\ \ veer\ \ off\ \ events} \tag{18}$$

Evaluation of event consequences (D_i)

As the entire curved taxiway section is located within the runway safety area, it is assumed that the aircraft's main landing gears are the critical aircraft components at the initiation of a veer-off event. Accordingly, whenever a landing gear in the opposite side to the turning direction leaves the taxiway paved area first is considered as the event initiation (P_1). The main landing gear is the critical component for the veer-offs through segments A_6 to A_8 (no veer-offs through A_1 to A_5 segments). Nose landing gear becomes the critical component in segments A_9 to A_{16}.

As similar to Moretti's approach, this paper proposes a severity index considering associated wreckage location-based mechanical consequences (Table 4) (Moretti et al., 2017). However, different obstacles in the adjacent terrain cause different consequences until veered-off aircraft come to a standstill at a wreckage location. Therefore, this severity index could be site-specific with regard to the probable damage to its critical component. In this paper, considering a standard runway safety area, it is assumed that there are no objects/obstacles other than the standard frangible navigational aids.

To estimate aircraft risk on potential event type (Table 4), respective severity values (D_i) are substituted to the Eq. (1).

The proposed methodology has key advantages over various other veer-off risk estimation methods explained in the literature review section. Veer-off risk analyses that consist historical accident data based frequency models have limitations when its adopted to completely different airport configurations and operating environments.

Table 4
Accident severity categorization.

Event	Damage	Critical Component	Severity	Maximum D %
Aircraft vacate through the rapid exit taxiway	No	Not applicable	No incident	0
Aircraft not follow the taxiway exit path, however aircraft can be stopped within the paved taxiway/runway surface (landing gears are still on the paved surface)	No	Outer main gear	Incident	0
Aircraft landing gear leaves the exit taxiway paved surface and engines not beyond the object free area (aircraft stops within the runway safety area)	Aircraft landing gear damage due to high stress at soft terrain	Aircraft landing gear	Major	25
Aircraft engine enters the object free area and wing tip not beyond the parallel taxiway safety area (aircraft within the runway object free area), applicable to aircrafts with wing mounted engines	Aircraft engines damage due to rough terrain	Aircraft engine	Hazardous	50
Aircraft wing tip enter the parallel taxiway safety area	Potential collision with a taxiing aircraft	Wing tip	Catastrophic	100

Other methods widely used include logistic regression model-based approaches. Lack of accident and normal operations data is identified as the key limitation to use logistic regression method for veer-off risk estimation at rapid exits. Compared to proposed methodology, statistical methods are highly data intensive. Thus, it's applicability to rare incident types such as high-speed exit related veer-offs is difficult. Machine learning techniques such as Bayesian networks also suffers with the same limitation. Whereas the analytical modeling approach allows to model the phenomena using conditions for the dynamic stability and fundamental equations of motion. The model can be developed using minimal empirical data, as well as it can be iteratively improved with the availability of empirical evidence. Furthermore, analytical modeling gives the flexibility to incorporate nonlinear links between the input variables and the output variable compared to very restrictive model specifications in statistical modeling methods.

Analysis

Illustrative example

Table 5 shows a single simulation run as an illustrative example developed to demonstrate the application of the proposed methodology. The input parameters and the output (for a given case) for each step of the methodology are outlined in the table. Three Airports (Cases) such as A, B, and C are used in the example representing different mean exit speeds. These were from direct measures of approximate 2000 real operations data from rapid exits related landing operations (Air Transportation Systems Laboratory, 2020).

Similarly, based on the wreckage locations (X, Y coordinates), potential aircraft veer-off risks can be evaluated. The methodology is useful to compare potential risks at various operational and design conditions such as different exit locations etc.

Results

Due to variation in operational conditions, even in the same airport, aircraft veer-off risks at individual high-speed turning maneuvers are different. Aircraft veer-off risks for different levels of consequence are estimated for B747-400 at three airport Cases A, B & C as shown in Fig. 6. Additionally, aircraft veer-off risks at different jerk values were estimated and the jerk factor contribution was found to be negligible. According to Fig. 6, Case C with the highest mean exit speed and standard deviation, records the highest veer-off probability which is approximately 9 times higher than the probability at Case A. The respective mean exit speed at the Case A is 15-percent lower than the that of the Case C.

According to Fig. 7, higher exit speeds cause increase in veer-off probabilities at rapid exit taxiways. Conversely, as depicted in Fig. 8, higher decelerations cause a reduction in relevant veer-off probabilities. Therefore, these two factors are crucial at high-speed turning maneuvers.

The study identified that the improved operational factors can alter the relevant veer-off risk at rapid exits. Thus, the sensitivity of the operational factors such as aircraft exit speed, deceleration to the travel direction, and jerk factor perpendicular to the travel direction is estimated. These findings are important at decision making at aircraft maneuvering to the rapid exit taxiways under minimum veer-off risk. Accordingly, the sensitivity of the exit speed, deceleration, and jerk factor for veer-off event probability with regard to the operating conditions in Table 6 is measured.

According to Table 6, the highest impact on the veer-off probability is due to the exit speed. Deceleration's impact is about 50-percent of the

Table 5
Aircraft veer-off probability calculation example.

Airport Data			
Airport (Case)	A	B	C
Runway Code FAA ADG / ICAO Code	V/ E	V/E	V/E
High speed exit taxiway - Acute angle	30°	30°	30°
Aircraft Data (Aircraft type B747-400) (26)			
Mean exit speed (m/s)	21.40	22.73	24.63
Speed standard deviation (m/s)	5.05	5.90	5.80
Deceleration		Ex start to Runway edge	
Mean deceleration (m/s^2)		0.65	
Dec. standard deviation (m/s^2)		0.21	
Aircraft Design Parameters			
Aircraft type			B747-400
Aircraft percent load on main gear			94%
Moment of inertia around vertical axis			$5.25x10^{7}$ Kgm^{2}
Wheelbase			26.6 *m*
Aircraft mass (load factor 0.5)			245,765 kg
Nose gear to outer main gear wheel distance (one side)			6.30 *m*
Operational Data - Variables			
Random Number Generation for exit speed, linear deceleration using CPDF Eq. (7):			
Aircraft turn off speed (from the generated random number for the example)			38.32 ms^{-1}
Aircraft deceleration (from the generated random numbers for the example)			0.61 ms^{-2}
Random number generation for Scrubbing coefficient Eq. (8):			
Chosen value for scrubbing factor (from the generated random numbers for the example)			0.0053
Random number generation for normal jerk Eq. (9):			
Chosen value for normal jerk for the example (from the generated random numbers for the example)			0.31 ms^{-3}
Side friction coefficient for the example Eq. (10):			0.19
Gravitational force			9.81 ms^{-2}
Veer-off probability estimation			
Estimated aircraft turning radius at the point of exit maneuver starts Eq. (6): (R_D)			1024.3 *m*
Taxiway design turn path radius maximum allowable (under geometric relationship) (R_a)			775.0 *m*
As 1024.3 m greater than 775.0, aircraft chance to veer-off			Yes
Considering number of events which generated through random numbers, all veer-off events are counted			
Veer-off probability (P_1) Eq. (12):			0.0002
The lateral deviation segment which belongs to the final turning radius 1024.3 m (Table 3)			A9
Location probability estimation			
For all veer-off events,			
Estimated aircraft speed at the veer-off Eq. (13):			4.35 ms^{-1}
Estimated aircraft deceleration on the unpaved terrain surface Eq. (14):			0.31 ms^{-2}
Estimated travel distance on the ungraded surface after veering off Eq. (15):			30.3 *m*
Aircraft wreckage location (X,Y) with regard to lateral segment A7 and travel distance 30.3 m,			
X = (30.3 Cos 13° + 142.7) - distance from the Y axis (Eq. (16)):			172.2 *m*
Y = (30.3 Sin 13° + 33) - distance from the X axis (Eq. (17)):			39.8 *m*
Since this wreckage location (172.2, 39.8) is within the runway safety area (Y < 75 m) (Table 5), it is a			Major event
Aircraft wreckage locations within the runway safety area with regard to total simulation,			
Probability out of the total veer-offs (Major events) - (P_2) **Eq. (18)**:			0.0001
Severity level (D_i) attached to Major events Table 4:			0.25
Event risk estimation ($P_1 \times P_2 \times D_i$)			
Aircraft veer-off risk of B747-400 on hazardous event at given 0.2 side friction coefficient at Airport C (Case C)			2.5×10^{-5}

exit speed whereas the jerk factor has very little effect. Even though the above estimations are done as point sensitivity values for the three factors for the base conditions in Table 6, the same sensitivity values can be used as average sensitivity levels. Except for catastrophic events for all the other types of consequences, the above sensitivity levels are applicable for the operating ranges of the exit speed 17–37 ms^{-1} deceleration 0.55–1.25 ms^{-2} and the jerk factor 0.08–1.10 ms^{-3}.

As in Table 4 of this analysis, airfield terrain type-based severities determine veer-off risk. With the percentage improvement of airfield design elements such as acute angle, radius of curvature, taxiway width, airfield safety area (runway safety area, object free area, distance up to parallel taxiway safety area), corresponding veer-off risk on the minor, major, hazardous and catastrophic consequences are evaluated. Those operational factors at the same base case condition (as above mentioned) are continued to compare the sensitivity of the design

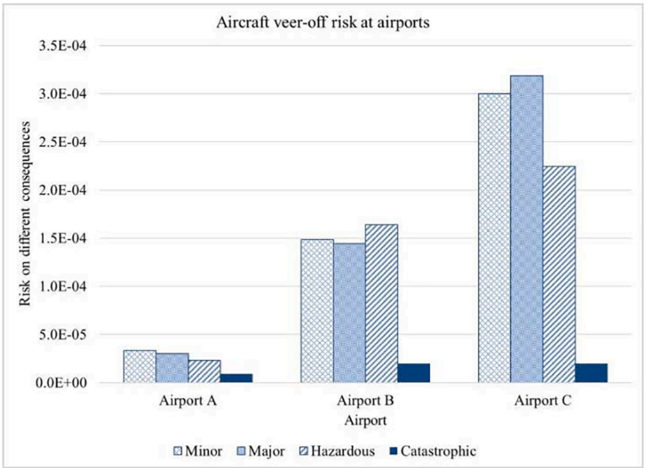


Fig. 6. Veer-off risk at three different airport settings.

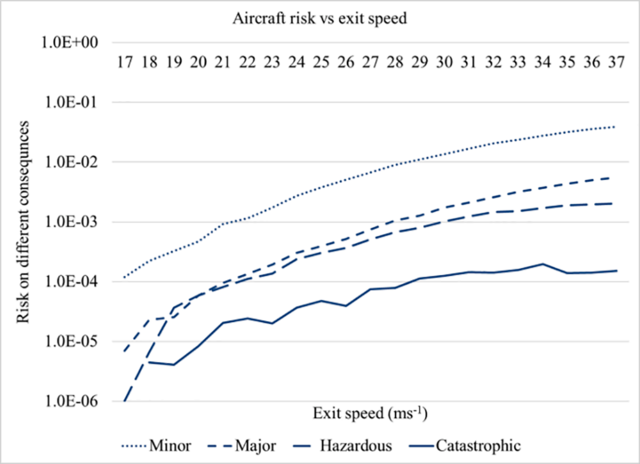


Fig. 7. Airport veer-off risk at different exit speeds.

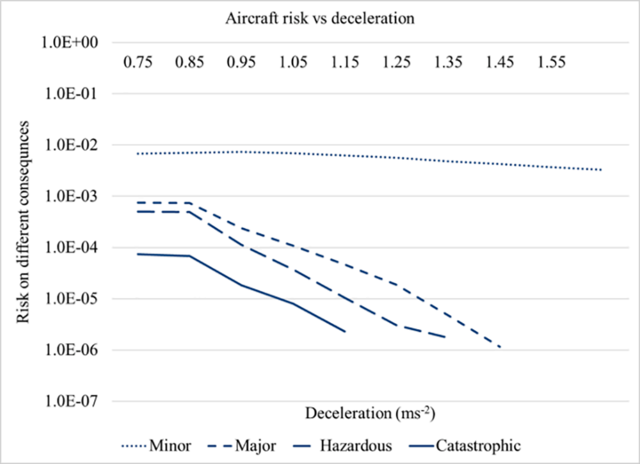


Fig. 8. Airport veer-off risk at different decelerations.

Table 6
Sensitivity of the operational factors.

Factor	Exit speed	Deceleration	Jerk factor	Sensitivity for + 10% change of the factor	Sensitivity for −10% change of the factor
Base Condition (BC)	(26.7, 5.6)	(0.75,0.25)	[0.50–0.70]	–	–
Exit speed	Mean speed change by 10 %	BC	BC	35.0%	−28.0 %
Deceleration	BC	Mean decel. change by 10 %	BC	−16.0%	14.0 %
Jerk factor	BC	BC	Range change by 10%	0.32%	−0.46%

elements of the rapid exit taxiways. (Table 7 & Fig. 9).

Rapid exit acute angle, taxiway radius of curvature, and taxiway width where design changes can reduce veer-off probabilities and consequent veer-off risks. Improvements of safety areas such as widening the runway safety area, object free area can minimize potential consequences of an occurrence. Taking sensitivities into account, design elements are successively prioritized in Table 8 from the most effective to the least effective for managing risk.

Conclusion

Use of rapid exit taxiway is becoming a preferred option for airports which require runway capacity improvements to meet the increasing air traffic demand. When usage increases, veer-off incidents could be identified as an associated risk on the aircraft safety. Accordingly, this paper described aircraft nose landing gear stability-based analytical approach on aircraft veer-off risk analysis at runway rapid exits. Monte Carlo simulation was used to study the random variation of the exit demand radius, which allowed to estimate probability of veer-off incidents. A novel approach was proposed in this research to estimate the location probability based on categorizing the veer-off trajectory into a set of known lateral deviation categories. One of the greatest challenges overcome by the study approach is the lack of operational data related to rapid exit related veer-off incidents. This study fills an important gap in the knowledge related risk involved in rapid exit veer-off incidents. The study findings can be used as initial approximation of rapid exit veer-off risk under different conditions. The input parameters can be further improved with the availability of the airport operational data and incident data, for which certain assumptions have been made in the study due to limited data availability. Moreover, incorporating the pilot behavior in opting for rapid exits under certain operating conditions could further improve the methodology.

Aircraft exit speed and deceleration in the taxiing maneuvers are identified as key operational parameters affecting accident risk. Aircraft veer-off risks significantly increase at higher aircraft exit speeds and lower decelerations. Based on the sensitivity of these operational factors, for a given aircraft type, exit speed is the most influential parameter which should be used to manage veer-off risk at high-speed turning maneuvers. Exit speeds beyond a certain value in the upper tail of the speed distribution will lead to excessive aircraft travel path deviations relative to exit taxiway centerline path. As per the findings, if the aircraft exit speed equals or less than the recommended exit speed of 26.7 ms^{-1} (for 550 m design radius), the aircraft can follow the exit taxiway centerline path. Further, if aircraft deceleration is greater than the 0.6 ms^{-2}, aircraft still have a chance to follow the taxiway centerline path for speeds up to 35 ms^{-1}. This is an important consideration for planning rapid exit location, as it directly affects the speed distribution at the exit location.

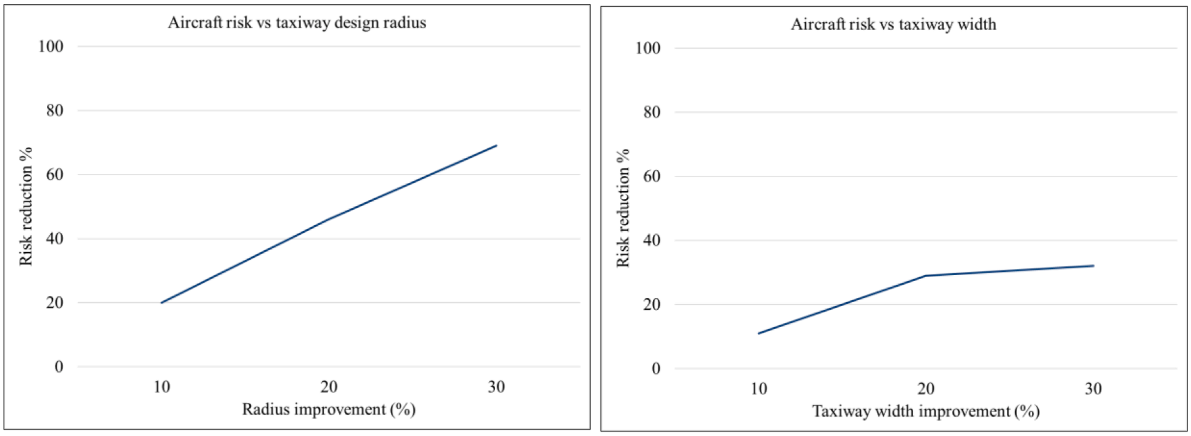
As shown in the analysis, changes to the high speed exit related design elements such as acute angle, design radius of curvature, runway-parallel taxiway separation, and runway safety area have varying impact on the reduction of veer-off risks. Acute angle, taxiway design radius, and taxiway width can minimize potential veer-off risks by minimizing the respective probability component of the risk. Runway safety area expansion is one approach that does not reduce the potential veer-off probability, which can only minimize event consequences such as the conversion of catastrophic events to major events. Reduction of taxiway acute angles (or increased design radius) and widened taxiways are the most effective approaches for managing high veer-off risks. This is in line with the recommendations given in the draft FAA Advisory Circular on Airport Design that recommends widening high speed exit throats (FAA, 2020). With respect the previous FAA Advisory circular (150–5300-13A), current draft circular has given more emphasis on rapid exit taxiways related design elements. For example, as shown in the illustrative example, a 30-percent increase in taxiway design radius and taxiway width reduce veer-off risk by 69-percent, and 32-percent respectively.

The rapid exit location is planned with the primary objective of minimizing the runway occupancy time. With the proposed approach the veer-off risk at varying locations can also be analyzed. Thus, for a given runway the veer-off risk at proposed locations can be evaluated and the results can be used to select the optimum location by considering the gain in veer-off risk against the additional gain in runway operational capacity.

Airport planners can use this methodology to simulate various operating conditions and find the corresponding sensitivity of each factor on the veer-off risk to evaluate design alternatives. Thus, the study provides a framework for risk-based approach to be adopted in rapid exit design during runway system planning.

Table 7
Sensitivity of design elements on veer-off risk.

Design element increase by 10%	Impacted other design elements	Event probability	Risk on major events	Risk on hazardous events	Risk on catastrophic events
Acute angle (27°)	Radius of curvature, parallel taxiway separation	−22%	−22%	−22%	−22%
Radius of curvature (605 m)	Acute angle, parallel taxiway separation	−20%	−20%	−20%	−20%
Runway width	Safety areas, parallel taxiway separation	–	–	–	–
Taxiway width	–	−11%	−5%	−10%	−48%
Runway safety area	Object free area, parallel taxiway separation	–	15%	−38%	–
Runway object free area	Parallel taxiway separation	–	–	8%	−72%
Runway safety area & object free area widen	(while maintaining the same runway – parallel taxiway separation)	–	15%	−32%	−58%



(a) (b)

Fig. 9. Veer-off risk reduction with increase of the rapid exit design radius (b) taxiway width.

Table 8
Ranking design element.

Design Element	Rank
Acute angle (-)	1
Radius of curvature (+)	2
Taxiway width (+)	3
Runway Safety area (+)	4
Runway width (+)	5

CRediT authorship contribution statement

Sameera Galagedera: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **H.R. Pasindu:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. **Varuna Adikariwattage:** Conceptualization, Formal analysis, Supervision, Writing – review & editing.

Funding sources

The authors wish to thank the University of Moratuwa, Senate Research Committee for providing support for research publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are highly thankful to the academic staff of the Department of Civil Engineering, University of Moratuwa, Sri Lanka who supported us immensely in numerous ways during this research.

References

Ayres, M., Carvalho, R., Shirazi, H., David, R., 2014. Airport Cooperative Research Program Report 107: Development of a Runway Veer-Off Location Distribution Risk Assessment and Reporting Template. Transportation Research Board, Washington, D.C., USA https://www.nap.edu/download/22411. (Accessed August 11, 2020).

Laboratory, A.T.S., 2020. Landing Events Database: Runway Exit Design Interactive Model (REDIM). Virginia Tech, Blacksburg https://www.atsl.cee.vt.edu/index.html. (Accessed September 12 2020).

Boeing Commercial Airplanes, 2019. Aviation Safety, Boeing Commercial Airplanes: Statistical Summary of Commercial Jet Airplane Accidents 1959–2016. Accessed September 2, 2020. https://www.skybrary.aero/bookshelf/books/4239.pdf.

Bae, I., Moon, J., Seo, J., 2019. Toward a comfortable driving experience for a self-driving shuttle bus. Electronics. 8 (9), 943. https://doi.org/10.3390/electronics8090943.

Eddowes, M., Hancox, J., MacInnes, A., 2001. Final Report on the Risk Analysis in Support of Aerodrome Design Rules. AEAT/RAIR/RD02325/R/002, Issue 1. (Accessed August 14 2020).

Feng, C.-M., Chung, C.-C., 2013. Assessing the risks of airport airside through the fuzzy logic-based failure modes, effect, and criticality analysis. Math. Probl. Eng. 2013, 1–11. https://doi.org/10.1155/2013/239523.

Federal Aviation Administration, 2014. Airport Design Advisory Circular 150/5300-13A. Accessed November 25 2020. https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5300-13A-chg1-interactive-201612.pdf.

Federal Aviation Administration, 2019. Accident and Incident Data. Accessed November 20 2019. https://www.faa.gov/data_research/accident_incident.

Federal Aviation Administration, 2020. Advisory Circular No: 150/5300-13B. Accessed November 2 2020. https://www.faa.gov/documentLibrary/media/Advisory_Circular/draft-150-5300-13B-industry.pdf.

Guerra, L., Murino, T., Romano, E., 2008. Airport system analysis: a probabilistic risk assessment model. Int. J. Syst. Appl. Eng. Dev. 2 (2), 52–65.

Green, L.L., 2013. Analysis of Runway Incursion Data. NASA Langley Research Center, Hampton, Virginia https://ntrs.nasa.gov/api/citations/20150018913/downloads/20150018913.pdf (Accessed 7 April 2021).

Hall, J., Ayres, M., Wong, D., Appleyard, A., Eddowes, M., Shirazi, H., 2008. Airport Cooperative Research Program Report 3: Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas. Transportation Research Board, Washington, D.C., USA https://www.icao.int/SAM/Documents/2011/AGAASEROSTUDIES/ACRP_rpt_003.pdf. (Accessed July 30 2020).

Hall, J., Ayres, M., Shirazi, H., Speir, R., Carvalho, R., David, R., 2011. Airport Cooperative Research Program Report 51: Risk Assessment Method to Support Modification of Airfield Separation Standards. Transportation Research Board, Washington, D.C., USA http://nap.edu/14501. (Accessed August 5 2020).

International Civil Aviation Organization, 2005. Aerodrome Design Manual Part 2 Taxiways Aprons and Holding Bays. ICAO-Doc 9157-AN 901. https://www.academia.edu/41316519/Doc_9157_Aerodome_design_manual_part_2_ taxiway_up_date. (Accessed September 20, 2020).

International Civil Aviation Organization, 2018a. ICAO Long-Term Traffic Forecasts, Passenger and Cargo. Accessed July 24 2020. https://www.icao.int/sustainability/Documents/LTF_Charts-Results_2018edition.pdf.

International Civil Aviation Organization, 2018b. Safety Management Manual. ICAO-Doc 9859-AN 474. https://www.icao.int/sam/documents/rst-smsssp-13/smm_3rd_ed_advance.pdf. (Accessed July 20, 2020).

International Air Transport Association, 2019. Industry Statistics Fact Sheet 2019. https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance—june-2020—data-tables. (Accessed August 8 2020).

Jeon, J., Song, J., Kim, H., Song, B., 2016. Research on the advanced risk assessment of runway safety areas with enhanced algorithm. Int. J. Eng. Sci. Technol. 5 (1), 67–70. https://doi.org/10.17950/ijset/v5s1/114.

Johnson, M.E., Zhao, X., Faulkner, B., Young, J.P., 2016. Statistical Models of Runway Incursions Based on Runway Intersections and Taxiways. JATE. 5 (2), 15–16. https://doi.org/10.7771/2159-6670.1121.

Lin, X., Fulton, N., Westcott, M., 2009. Target Level of Safety Measures in Air Transportation – Review, Validation and Recommendations. and Identification, Beijing, China.

Kirkland, I.D., 2001. The Risk Assessment of Aircraft Runway Overrun Accidents and Incidents. PhD Thesis Report. Loughborough University, England, 2001. https://repository.lboro.ac.uk/articles/The_risk_assessment_of_aircraft_runway_overrun_accidents_and_incidents/9456605 (Accessed November 2 2020).

Meijers, N.P., Hansman, R.J., 2019. Report 2019–14: Data-Driven Predictive Analytics of Runway Occupancy Time for Improved Capacity at Airports. International Center for

Air Transportation, Massachusetts Institute of Technology https://hdl.handle.net/1721.1/123677.

Moretti, L., Cantisani, G., Caro, S., 2017. Airport Veer-off Risk Assessment: An Italian Case Study. APRN J. Eng. Appl. Sci. 12 (3), 900–912.

Moretti, L., Mascio, P.D., Nichele, S., Cokorilo, O., 2018. Runway veer-off accidents: quantitative risk assessment and risk reduction measures. Saf. Sci. 104 (2018), 157–163. https://doi.org/10.1016/j.ssci.2018.01.010.

Mascio, P.D., Cosciotti, M., Fusco, R., Moretti, L., 2020. runway veer-off risk analysis: an international airport case study. Sustainability. 12 (22), 9360. https://doi.org/10.3390/su12229360.

Schoen, M.L., Preston, O.W., Summers, L.G., Nelson, B.A., VanderLinden, L., Reynolds, M.C., 1985. NASA Contractor Report: 172549: Probabilistic Computer Model of Optimal Runway Turnoffs. Langley Research Center, Hampton, Virginia.

Scholz, F., 2003. *Statistical Extreme Value Analysis of ANC Taxiway Centerline Deviations for 747 Aircraft.* The Boeing Company. (Accessed October 17, 2020).

Shirazi, H., Hall, J., Williams, B., Moser, S., Boswel, D., Hardy, M., 2016. Airport Cooperative Research Program Report 168: Runway Protection Zones(RPZ) Risk Assessment Tool Users' Guide. C., USA, Transportation Research Board, Washington D https://www.nap.edu/download/24662.

Skybrary, 2020. Accidents and Incidents. https://www.skybrary.aero/index.php/Accident_and_Serious_ Incident_Reports: _RE. (Accessed October 3 2020).

Trani, A.A., Hobeika, A.G., Sherali, H.D., Kim, B.J., Sadam, C.K., 1990. Report DOT/FAA/RD-90/32, I: Runway Exit Designs for Capacity Improvement Demonstrations Phase I Algorithm Development. Virginia Polytechnic Institute and State University, Virginia, Center for Transportation Research https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19910007752.pdf. (Accessed October 17, 2020).

Trani, A.A., Hebeika, A.G., Kim, B.J., Nunna, V., Zhong, C., 1992. Report DOT/FAA/RD-92/16, II: Runway Exit Designs for Capacity Improvement Demonstrations Phase II Computer Model Development. Virginia Polytechnic Institute and State University, Virginia, Center for Transportation Research https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920011919.pdf. (Accessed September 22, 2020).

Trucco, P., Ambrogg, M., Leva, M.C., 2015. Topological risk mapping of runway overruns: A probabilistic approach. Reliab. Eng. Syst. Saf. 142, 433–443. https://doi.org/10.1016/j.ress.2015.06.006.

Van Es, G.W.H., 2005. NLR Report-TP-2005-498: Running of runway - Analysis of 35 years of landing overrun accidents. National Aerospace Laboratory, Netherlands http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.967.9604&rep=rep1&type=pdf.