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Evaluation of Operational Risk Factors at Runway High Speed Exits

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Abstract

Increasing demand in aviation sector has increased the need for capacity improvements at airport. However, due to several constraints such as environmental, land acquisition etc. expansion of airports and addition of new runways to increase capacity is becoming increasing difficult. Therefore, airports look to optimize the capacity of existing runway systems to meet the growth in air traffic demand. One such option is to increase the use of high speed exits on runways which would reduce the runway occupancy time of aircrafts thereby increasing its operational capacity. Moreover, with introduction of newer air navigation technologies and reductions in in-trail separation standards, Runway Occupancy Time (ROT) of landing aircrafts will become a critical capacity determinant in future. Historically, majority of aviation accidents have occurred in airports, and it is significantly high during the landing phase. Thus, the increased utilization of high-speed exits may contribute to the overall operational risks at the airport. Therefore, this study aims to develop a framework to evaluate the excursion risk at high speed exists considering different turn off speeds, locations and turn off configurations. The study focuses on computing the aircraft veer-off probability for different operating conditions to assess the relative risks of veer-off incidents at high speed exists due to operational parameters. The framework can be adopted to incorporate risk considerations in planning high speed exits in runways.

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Keywords: Runway Occupancy Time; wake turbulence; Turn off, veer off

1. Introduction

Air transportation is the fastest mode of transport for people and goods. As per the International Air Transport Association (IATA), annual air passengers and flights movement growths in 2015 are 7.4 %, and 5.4% respectively. IATA 2016 annual report further revealed that 3,568 million air passenger travels in 2015 and equivalent 34.8 million aircraft movements in the same year. The increase in aircraft movements will create significant operational issues at airports which are often faced with capacity, safety and other operational constraints.

Nomenclature

A	High Speed Exit
B	Turn off
C	Side Friction Coefficient
D	Scrubbing Factor
E	Wake vortices

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The airside capacity of an airport is governed by factors related to its runway system and the airspace above and around the airport, as well as the terminal area ATC and navigation equipment and procedures. Design factors such as number of runways, layout, length and operational factors such as wake separation, weather condition, air navigational flight rules are key determinant for airside capacity. In addition to design limitations, aircraft wake separation minimum and ROT are the two main contributors to runway capacity. According to Horonjeff, there are some important factors which influence runway occupancy time and resultant runway capacity, 1) In-trail separations 2) Aircraft population mix 3) Exit locations and their configurations. These factors can contribute to change runway occupancy by 20% (Barrer & Diehl, 1988). Thus, reducing Runway Occupancy Time (ROT) will have a great opportunity to increase runway capacities. The time elapsed between an aircraft crossing the runway threshold and the time when the same aircraft crosses the imaginary plane of a runway exit paved area is defined as the ROT (Trani, 1990). When an airplane leaves the runway speedily, another airplane would have opportunity to use the same runway and cause to improve the runway capacity.

High speed exits are one airside design improvement that is introduced to improve the runway capacity. High Speed exit is a taxiway connected to a runway at an angle and designed to allow landing airplanes to turnoff at higher speeds than those achieved on other exit taxiways, thereby minimizing runway occupancy time (ICAO Design manual, 2005). Since inter-arrival airplane separation is one of the main limiting factors for runway capacity, the advantage of high-speed exits could be explored from alternating landing and departing operations. For high speed exit taxiways, airplane population mix, approach speed and braking performance are decision making factors. According to aviation accident statistics, about 58% of aviation related fatal accidents have occurred at airports (L. Guerra, T. Murino, and E. Romano, 2008). Aircraft overrun and veer-off events are very common types of accidents. However, with future air traffic demand when high speed exits are regularly used as an option to runway capacity improvement, potential aircraft accidents at high speed exits will be a key issue in future.

At high speed turnings, aircraft exit speed is considerably higher than the conventional 90 degree exits. Airplane landing performances are not consistent and more or less deviate from the intended design characteristics. Further, at high speed exits where airplane high speed direction changes create extra complications at the curvilinear turnoff segments. Therefore, a portion of accidents can distribute in to high speed exits from conventional 90-degree turnoffs. According to Airport Corporative Research Program 51 (Risk Assessment Method to Support Modification of Airfield Separation Standards, 2011) most of the taxiway and taxi-lane accidents and incidents have occurred in curved segments. In such situations, lateral forces are significant and airplane veer-off possibilities are significant.

However, the ongoing studies on airport risk analysis focus on airplane overrun and veer-off risk on runways. There are several studies on high speed exit taxiways, their configurations in capacity improvement standpoint. Yet, there are no studies focused on risk considerations at high speed exits. Thus, this study addresses relevant research gap on aircraft veer off risks at high speed exits and it highlights critical design and operational parameters. Further it establishes a suitable risk analysis framework along with airport design elements and critical operational factors affecting veer off risk at high speed exits.

2. Aircraft Accidents at High Speed Exits

2.1. Aircraft Runway Excursions

Aircraft related accidents and incidents is a major concern in the air transport industry. According to International Civil Aviation Organization (ICAO), accident rate is the primary indicator for global air transport safety. In 2015 global jet accident rate (hull losses) was 0.32 per million flights (IATA Safety performance, 2015). Among the 58% of fatal accidents occurred at airports, 28% accidents have occurred on runways and 24% of accidents occurred in aprons. Further, from the fatal accidents reported in 2006 – 2015, 47% of accidents were within the final approach and landing phases (Boeing, 2016). As per the Global Safety Information Exchange (GSIE) defined Harmonized accident rate, accidents belong to runway safety category record the highest number of incidents, and the majority of them were in the landing and take-off flight phases. According statistics from 1995 to 2004, 71% of world jet aircraft accidents also occurred during the landing and take-off phases (ACRP 03, 2008).

Landing overrun (LDOR), landing undershoot (LDUS), landing veer-off (LDVOFF), take-off overrun (TOOR) and take-off veer-off (TOVOFF) are five possible accident types can occur during landing and takeoff phases. Overrun and undershoot events are some sort of longitudinal displacements along the runway and veer-offs due to lateral displacements. These overrun or veer-off aircrafts may collide with surrounding obstacles, or become standstill after traveling certain distance beyond the ends of runways unless any obstacles. As per overrun incident statistics, 95% of overrun events stopped within 1000 feet from the runway end (ACRP, 2008). In addition to landing and takeoff phases, according to IATA accident records, about 27,000 ramp accidents annually occur and it was 1 per 100 departures.

Adverse weather conditions, low surface friction, tail and cross wind, low visibility and unfavorable runway slopes are identified as critical contributing factors. Similarly, human error, incorrect approach speed, deviated approach height, improper touchdown location, inappropriate runway distance availability, aircraft system faults, excess weight and etc. are identified as casual factors (ACRP 03, 2008). The highest landing overrun risk generates due to excess approach speed and consequent long landings. (G.W.H. van Es, 2005).

2.2. Risk Factors for Aircraft Accidents at High Speed Exits

High Speed exit taxiways are concerned airplane veer-off incidents could be the most common type of accident when taxi-in to taxiway segment. Since high speed exits are always located in the middle part of the runway where aircrafts still have chance to use 90 Degree exit taxiway at the end of the runway if in case of missed turn offs at high speed exits. In addition to excursion accidents, incursion accidents are also possible when taxi-out to parallel taxiway. Table 4 give a summary of accidents reported at high speed exits. Considering the causal factors the most recurring issue is high exit speeds and the surface frictional condition are the main causal factors for the reported incidents at high speed exits.

Table 1 Aircraft accidents at high speed exits

Airport	Date	Incident Description	Possible causal factor(s)
Prestwick UK	23 December, 2009	B737 operated by Irish airline from Dublin to Prestwick, landing gear sunk into the adjacent wet grass prior to turning on to the designated taxiway.	Icy surface
Bengaluru, India	12 September, 2013	A320 operated by White Skye Leasing Limited, Ireland from Delhi to Bengaluru International airport veer off at the turnoff from active runway to rapid exit taxiway.	Heavy rain, wet runway and wind
Amsterdam, Netherland	12 August, 2006	B737 at Amsterdam Airport Schiphol veer off when exiting via a high speed exit after landing	Not Identified
Changi Airport Singapore	2 December, 2011	B747 at Singapore Changi Airport on runway 2L veered to the right side of the runway when trying to vacate the runway via rapid exit taxiway W.	High exit speed
Hohbot Baita Airport, Chaina	7 July, 2018	B737 operated by Chinese Shenzhen Airlines veered off the runway after landing when it was attempting to vacate via the rapid exit C.	Wet runway
Taipei, Taiwan	12 August, 2012	A330 by China Airlines from Hong Kong to Taipei, hit runway edge lights before vacate the runway via high speed exit S3	Hydraulic failure, wet slippery runway
Copenhagen Denmark	21 September, 2012	A319 landed on Copenhagen Denmark veered when attempting to make a turn off the rapid exit taxiway.	Inappropriate taxi speed
Narita Airport, Japan	01 February, 2019	B787 operated by Japan Airlines safely landed at while exiting via high speed exit slid to the left.	Icy runway
Mumbai Airport, India	29 August, 2011	A340 operated by Turkish Airways from Istanbul to Mumbai veered off (skid off the taxiway) at rapid exit taxiway	Bad weather

2.3. Risk Analysis of Aircraft Excursion

With respect to aircraft landing and takeoff operations; there are three distinct types of risk models for estimating likelihood of accident occurrence, accident location and consequences of accidents. Most of these risk analysis approaches rely on accident data and normal operation data to use logistic regression analysis or similar approaches to develop the risk models. Following Table 2 presents a summary of models derived to evaluate the aircraft excursion risk on runways.

Table 2 Development of Risk Models

Study	Model Description
Kirkland et al (2001)	Models have been introduced for evaluating landing and takeoff overrun probabilities as below, $P(landing\ overrun) = \frac{1}{1+e^{-(11.091-0.66D)}}$ $P(takeoff overun) = \frac{1}{1+e^{-(-32.290+0.172W)}}$ where D is the availability of the percentage of runway excess distance and W is percentage of aircraft takeoff weight.at the takeoff for evaluating probability of overrun at landing and takeoffs respectively. Lack of metrological normal operation data is a major shortcoming of this work. Information available for different airports was compared by using a normalization procedure, to transform existing data to standard nominal airport. Normalization was conducted for the effects of terrain on wreckage location using the models developed by Kirkland.
Wong et al (2006)	The use of Normal Operation Data (NOD) for accident frequency models was initiated by Wong et al (2006). Probability of

	overrun at landing is highlighted as below, $P(landing\ overrun) = \frac{1}{1+e^{-Z}}$ Z = -16.295+0.486(Heavy acft) – 1.631(L arg commuter Acft) +0.893 (Medium acft) + 1.951(Small Acft) + 1.050 (Turboprop Acft) + 0.934(FreightOp) + 0.835 (GAOp) – 1.565 (ForeignOD) – 0.014 (CeilingHeight 00ft) + 1.443 (Visibility< 2 SM) - 0.239 (Visibility 2 – 4 SM) – 1.429 (Visibility 4 -6 SM) + 0.276 (Visibility 6 – 8SM) + 2.437(Fog) + 0.486 (DownDusk) + 0.089 (Crosswind knts) + 2.1164 (Icing condition) + 1.860 (snow) + 0.588 (Non hub Apt) + 0.417(significant Terrain) In addition to landing overrun, models for takeoff overrun, takeoff crash and landing undershoot have also been introduced.
Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas (ACRP 03) - Hall et al (2008)	A model consists with fourteen risk factors with NOD. Models were introduced for landing overrun probability, landing Undershoot probability and takeoff overrun probability. $P(landing\ overrun) = \frac{1}{1+e^{-Z}}$ Z = -15.456+0.551(Heavy acft) – 2.113(Commuter Acft) -1.064 (Medium acft) - 0.876(Small Acft) + 0.445 (Turboprop Acft) – 0.857 (ForeignOD) + 1.832 (CeilingHeight < 1000ft) 1.639 (CeilingHeight 1001-2500ft) + 2.428 (Visibility< 2 SM) + 1.186 (Visibility 2 – 4 SM) + 1.1741 (Visibility 4 -6 SM) + 0.322 (Visibility 6 – 8SM) - 0.532 (Crosswind 2 -5 knts) + 1.566 (Crosswind 5-12knts) + 1.518 (Crosswind> 12knts) + 0.986 (Elect Storm) + 1.926(Icing Conditions)+1.499(Snow) - 1.009 (Temp<5C) – 0.63(Temp5 -15C) + 0.265(Temp>25C) + 1.006(NonhubApt) + 0.924(Significant Terrain)
Improved Models for Risk Assessment of Runway Safety Areas (ACRP 50) – Manuel Ayres (2011)	One significant improvement in this study relative to the models presented in ACRP Report 3 is the use of tailwind and headwind. In addition to those two factors, runway criticality factor was also included. The basic idea was to include a new parameter that could represent the interaction between the runway distance required by the aircraft and the runway distance available at the airport. This study introduced models for landing overrun probability, landing undershoot probability, takeoff overrrun probability, landing veer off probability and takeoff veer off probability. $P(landing\ overrun) = \frac{1}{1+e^{-Z}}$ Z = -13.065+ 1.539 (User Class G) – 0.498 (UserClass T/C) – 1.013 (Aircraft Class A/B) + 0.935 (Aircraft Class D/E/F) – 0.019(Ceiling less than 200ft) – 0.772 (Ceiling 200-1000ft) – 0.345 (Ceiling 1000-2500ft) +2.881 (Visibility< 2SM)+1.532 (Visibility 2 – 4SM)+ 0.200 (Visibility 4 -8SM) – 0.913 (Xwind 5-12kt) – 1.342(Xwind 2 -5kt) - 0.921 (Xwind >12kt) +0.786 (Tailwind>12kt) + 0.043 (Temp< 5C) – 0.019 (Temp 5 – 15C) – 1.067 (Temp >25C) + 2.007 (Icing conitions) + 0.449 (Snow) – 1.344 (Thunderstorm) + 0.929 (Foreign OD) + 1.334 (Hub/Non-Hub Apt) + 9.237 (Log Criticality fct) $P(landing\ veer\ off) = \frac{1}{1+e^{-Z}}$ Z = -13.088+ 1.682 (User Class G) – 0.770 (Aircraft Class A/B) – 0.252 (Aircraft Class D/E/F) +2.143 (Visibility< 2SM) + 0.653 (Xwind 5-12kt) – 0.091 (Xwind 2-5kt) + 2.192(Xwind >12kt) + 0.066 (Tailwind 5 -12kt) + 0.98 (Tailwind>12kt) + 0.558 (Temp< 5C) – 0.453(Temp 5 – 15C) + 0.291 (Temp >25C) + 2.67 (Icing conditions) – 0.126 (Rain) + 0.548 (Snow) – 0.103 (Frozen Precipitation) – 0.036 (Guts) + 1.74 (Fog) – 2.517 (Turboprop) - 0.334 (Foreign OD) + 4.318 (Log Criticality fct) -1.36 (Night condition)
Risk Assessment Method to Support Modification of Airfield Separation Standards (ACRP 51) – Jim W Hall (2011)	ACRP 51 study introduced a model for takeoff veer off probability and followed the same model which had been derived by ACRP 50. $P(landing\ veeroff) = \frac{1}{1+e^{-Z}}$ These logistic regression models are a technique for multivariate analysis, when dichotomous outcomes (incident or non-incident) with multiple predictor variables. Regression coefficients represent different casual or contributing variables. Most of the events with large lateral deviations occurred during poor weather conditions and situations of low surface friction (low visibility, rain and ice)
Runway Protection Zones (PPZ) Risk Assessment Tool (ACRP) – Transportation Research Board of the National Academies (2016)	This particular study introduced a model for evaluating probabilities for landing overrun, landing undershoot, takeoff overrun. $P(landing\ overrun) = \frac{1}{1+e^{-Z}}$ Z = -11.96 - 3.32(Hub)+ 1.71 Foreign(O/D) – 1.18 (Aircraft A) + 2.55 (Piston Acft) – 1.22(Prop Acft) + 1.60 (Fog) + 1.5 (Icing) + 1.61 (night) + 0.76 (Rain) + 1.57 (Snow) – 1.23 (Electric storm) + 1.6 (Visibility< 2SM) + 0.98 (Visibility 2 – 4SM) – 0.47 (Xwind 5-12kt) – 1.11(Xwind 2 -5kt) + 3.22 (Tailwind>12kt) + 0.94 (Tailwind 5-12knt) – 0.86 (Temp >25C) + 5.82 (Log Criticality fct) In overrun model regression coefficients represent different casual or contributing variables as shown above. The model consists with runway criticality factor the logarithm of the ratio between the distance required for the operation and the distance available. For correctly identify the distance required, it is adjusted for elevation, temperature, wind and various contaminated surface conditions.
Victor A Hasang (1975)	According to a study on nine airports with different thirteen types of aircrafts revealed that the average taxiway deviations on 30.5 m wider taxiways are about 0.94 m. The same study has explored the deviations corresponding to aircraft landing operations are 0.24 right to 0.7m left with maximum 3.4 m standard deviation. Deviations at high speed exits are highly affected by airplane flow pattern and exit configurations whereas standards deviation notice averagely 3.2 m.

With the use of normal operations data (NOD) and accident data, above regression models have been derived for evaluating overruns and veer offs probabilities at landing and take off operations. According to this research focus, models derived by studies on Risk Assessment Method to Support Modification of Airfield Separation Standards (ACRP 51) by Jim W Hall (2011) and Runway Protection Zones (PPZ) Risk Assessment Tool (ACRP) by Transportation Research Board of the National Academies (2016) were the latest models for probabilities for landing veer off and landing overrun respectively.

However, a model for evaluating aircraft accident risk (any type of accident) at high speed exiting operations have not yet been developed due to unavailability of high speed exits related accident data and normal operation data. Therefore, in this research a theatrical approach is developed for analyzing potential veer off risk at high speed exits.

2.4. Airport Safety Areas

Overruns and veer offs occur due to the deviations of airplane travel path from its designated travel facility. Thus, runway safety areas strengthen aircraft safety when overruns, undershoots and veer-offs, and turning potential accidents into minor incidents (AC 150/5300-13, 1989). Airport safety areas have been introduced for airport airside facilities such as runways, taxiways, aircraft approach path, initial climb path and etc. for improving aircraft safety at airports. Those safety areas are tabulated as below.

Table 3 Runway Safety Areas

Safety Areas	Purpose of Area
Runway Shoulder	mitigate foreign object damage to jet engines
Runway Strip	provides an area clear of objects which may endanger aero planes
Runway End Safety Area (ICAO) / Runway Safety Area (FAA)	adequately supporting any aircraft which overruns or undershoots the runway
Clearways/ Stopways	Alternative options for increased runway lengths
Approach surfaces (Conical, Inner Horizontal, Inner Approach, Transitional, inner transitional)	Three dimensional obstacle limitation surfaces free from obstacles for approach aircrafts
Take off climb surface	Three dimensional obstacle limitation surfaces free from obstacles for departing aircrafts

Most of the available studies focus on the runway excursion risk related to overrun and veer-off accidents during landing and take-off operations and landing under shoot accidents. However, there is no study carried out to evaluate risks related to high speed excursions.

3. High Speed Exit Design

3.1. Overview on High Speed Exit Design

The purpose of an acute-angled exit taxiway is to enhance airport capacity (ICAO Design Manual, 2005, Tamas Kolos-Lakatos, 2013). Therefore, world busiest airports by aircraft movements are equipped with high speed exit taxiways with different configurations. Following table summarize different exit configurations and their characteristics.

Table 4 Exit Geometry Design

Exit Type	**Exit Geometry and Exiting speed**	**Geometry specifications**
Right Angle Exit	Base line centerline radius 75 m, Recommended exit speed is 5 – 8 m/s	Pavement edge radius varies according to the runway width, this design is adequate low volume of traffic < 30 operations /hr
45 Degree Angle Runway Exit	Nominal Centerline radius 240 m and 180 m pavement edge radius and recommended exit speed is 8 – 15 m/s	This design has been discontinued by FAA, This is only useful for busy general aviation airports
30 Degree Angle Constant Radius Exit	Centerline radius 540 m, Recommended exit speed is 15 – 21 m/s	This design was proposed by Robert Horonjeff (1959). This design is proposed for traffic volumes > 30 operations /hr
30 Degree Angle Spiral Design Exit	Centerline radius 420 m, Recommended exit speed is 15 – 23 m/s	In this design the pavement edge radius varies. This was introduced in 1990s. This design is proposed for traffic volumes > 30 operations /hr
30 Degree Angle Exit (Current Design)	Centerline radius 550 m for Design Group 3 & 4, Recommended exit speed is 26.7 m/s	FAA went back to constant radius design in 2013. The transition centerline radii dimensions change at the junction with the parallel taxiway. Radii dimensions vary according to the Design Group and Taxiway Design Group. This design is proposed for traffic volumes > 30 operations /hr

3.2 High Speed Exit Geometry

ICAO has introduced two separate high speed exit geometries airplanes belong to code number 1, 2 and 3, 4. Acute angles, radius of curvature are completely distinct features as shown in Figure 1.

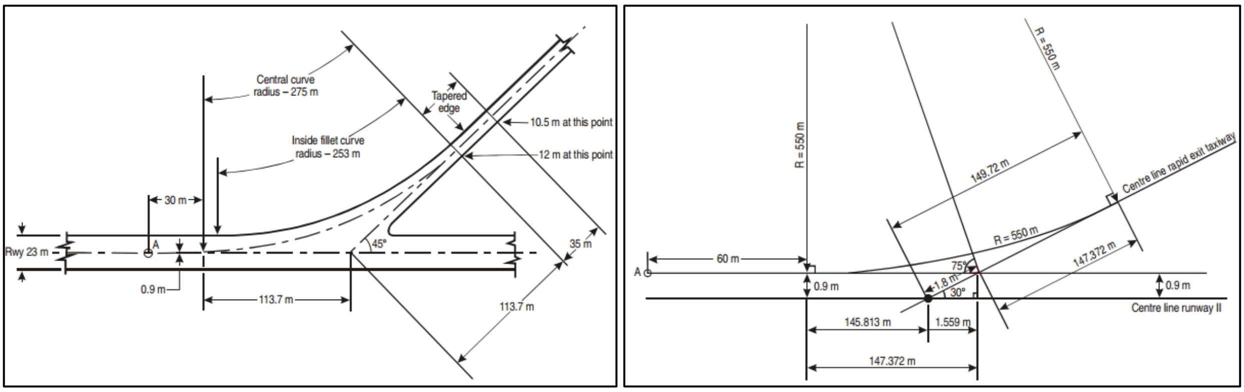


Figure 1 Design for High Speed Exit Taxiway for (a) code 1 & 2 (b) code 3 & 4(Source ICAO Design Manual)

3.3 High Speed Exit Locations

Locating high speed exits at the ideal location is important for optimizing ROT. Exit locations mainly depend upon the fleet mix. Percentages of aircrafts from each approach category determine the best exit location unless it is built an exit for each approach category. In addition to fleet mix, exit geometry is another critical parameter which determines the design exit speed. According to current FAA high speed exit design (Table 4), exit speed for aircrafts belongs to Aircraft Design Group 3 and 4 is 26.7 m/s.

Runway Occupancy time can be computed as a summation of five phases such as air phase, braking phase, turn off phase and two free roll phases. Braking phase takes the major share of the runway occupancy time. Free roll phases are averagely 2 to 3 seconds. Aircraft speed at the beginning of the turn off phase depend on various factors such as approach speed, runway surface condition, aircraft deceleration settings etc. However, the aircraft exit speed should match with the corresponding design exit speed for a safe exiting maneuver.
Aircraft approach speed is the most influencing parameter for all above segments and factors such as head, tail wind factors, flight path angle, and aircraft weight decide the air phase distance. Free roll distances are time based transition segments. Braking distance depends upon the aircraft deceleration rate. Again the deceleration rate is a function of runway friction coefficient, aircraft weight, weather factors and etc. Turn off distance is calculated as an integration function of instantaneous heading angle and instantaneous speed of aircraft.

Hence, in real operational conditions, when varying the operational parameters, aircraft actual turn off paths can vary.

3.4 Evaluation of Turning Radius at High Speed Exits

Before beginning a turning maneuver, aircraft should be within a defined lateral deviation with respect to runway centerline. Allowable lateral deviation depends on the exit geometry and type of aircraft. In this study, due to lack of sufficient data, the analysis is conducted with first principles attached to nose landing gear turning dynamics. When an aircraft is at the turning speed at which aerodynamic forces are insignificant, and therefore the forces acting on the nose gear are taken in to the account.

According to Schoen et. al, in 1983, there are three side force contributions acting on aircraft nose landing gear 1) Centripetal force 2) Aircraft inertia 3) Tire scrubbing resistance to turn. Thus these forces based relationship is developed with nose gear tire skid friction coefficient (f_{skid}), tire scrubbing coefficient (f_{sc}), aircraft inertia contribution to the nose gear skidding friction coefficient (f_{Izz}), Centripetal acceleration contribution to skidding (fc) are used for aircraft turn off stability analysis at high speed exits.

$$f_{skid} = f_{Izz} + fc + f_{sc} \quad (1)$$

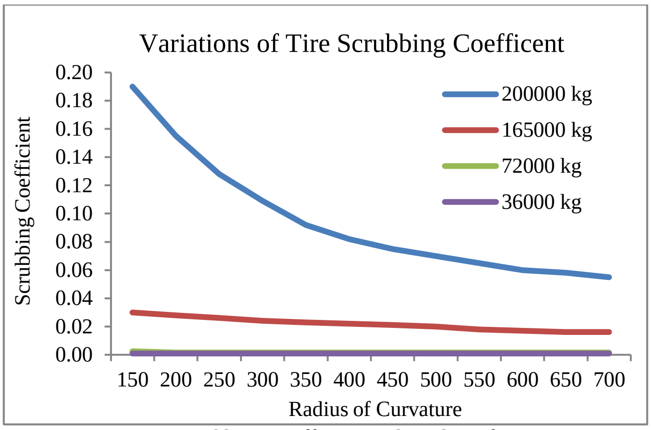


Figure 2 Tire Scrubbing Coefficient with Radius of Curvature

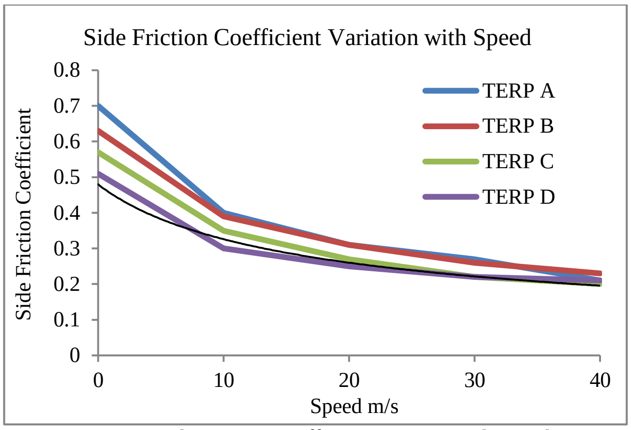


Figure 3 Side Friction Coefficient variation with Speed

Tire scrubbing resistance determined by aircraft weight (m) and instantaneous radius (R) (Figure 2). The side friction coefficient is a function of aircraft Terminal Instrument Category (TERP) and speed (v) (Harin, 1958: Wong, 1978).

$$f_{Izz} = \frac{I_{ZZ}\ \dot{\varepsilon}}{m\ R^2\ g\ wb\frac{lm}{100}\left(1-\frac{lm}{100}\right)} \tag{2}$$

where Izz is the moment of inertia around the z axis, V is the aircraft speed, Im is the percent load on the main gear, wb is the aircraft wheel base, $\dot{\varepsilon}$ is the angular acceleration.

$$fc = \frac{V^2}{g\,R} \tag{3}$$

where v is the aircraft instantaneous speed at turnoff, R is the instantaneous radius of the curvature, g is the acceleration of gravity.

$$f_{sc} \quad = f(R, m) \tag{4}$$

$$f_{skid} \quad = f(V, TERP) \tag{5}$$

$$\dot{R} = \frac{f_{Izz}\ m\ R^2\ g\ wb\frac{lm}{100}\left(1-\frac{lm}{100}\right)}{I_{ZZ}\ V} \tag{6}$$

$$f(V, TERP) - f(R, m) = \frac{V^2}{g\,R} + \frac{I_{ZZ}\,\dot{\varepsilon}}{m\ g\ wb\,\frac{lm}{100}(1-\frac{lm}{100})} \tag{7}$$

In Eq (7), V = ∞ R, a = $\dot{\varepsilon}$ R where ∞ is the angular velocity, $\dot{\varepsilon}$ is the angular deceleration at the curvilinear turn off segment.

$$f(V, TERP) - f(R, m) = \left(\frac{I_{ZZ}\ a}{m\ g\ wb\,\frac{lm}{100}\left(1-\frac{lm}{100}\right)} + \frac{V^2}{g}\right) x\,\frac{1}{R} \tag{8}$$

$$R(demand)\ = \left(\frac{I_{ZZ}\ a}{m\ g\ wb\,\frac{lm}{100}\left(1-\frac{lm}{100}\right)} + \frac{V^2}{g}\right) / \ [f(V, TERP)\ -\ f(R, m)] \tag{9}$$

According to above Equation (9), demand radius of curvature depends on several parameters. Tire scrubbing coefficient is very small and assumed as constant values for aircrafts with 72000 kg and 36000 kg weight (Figure 2). For a given aircraft, moment of inertia (Izz), aircraft wheel base (wb), percentage of aircraft mass loaded on main gear (lm) are fixed values. Parameters such as aircraft speed and deceleration are aircraft operational variables and side friction coefficient is a dependent of aircraft speed and TERP category.

ICAO guideline for rapid exit taxiway minimum radius of curvature for code number (3 & 4) and (1 & 2) are 550 m and 275 m respectively. The relationships in between aircraft speed and radius of curvature at the corresponding 30 degree turnoff geometry at 0.113 friction coefficient is shown below Table 5.

Table 5 Speed Radii Relationship

Radii (m)	V (m/s)
40	7.1
60	8.7
120	12.3
160	14.4
240	17.5
375	22.1
550	26.7

Aircraft landing performance can vary due to various reasons, and therefore actual aircraft exit speeds may more or less deviate from the 26.7 m/s designed exit speed. A study on flight simulations of high speed runway exits conducted by Verginia Tech University research team (Trani, 1992) has developed a model for Cumulative Probability Density Function for exiting speed of transport type aircraft as follows,

$$CPDF = \frac{1}{1+\alpha e^{-\beta(V-\gamma)}} \tag{10}$$

where CPDF is the cumulative value of the exit speed probability density function, α, β, γ are model parameters and V is the exit speed in meters per second. Parameters α, γ are taken as constants 99, 6 respectively and β is mathematically calculated as below.

$$\beta = 3381(d)^{-1.765} \qquad \text{for } 122 < d < 183 \tag{11}$$

where d is the distance between the centerline of the runway and the nearest parallel taxiway (in meters).

The calibration has been done with data collected from three airports (Washington National, Atlanta and Charlotte), five different transport type aircrafts (Boeing 727-200, 737-300, 400 and 200 series, 757-200, Douglas DC9-30 and McDonnell Douglas MD-80). Below Figure (4) shows the cumulative Density function for aircrafts turn off speeds at Atlanta International airport.

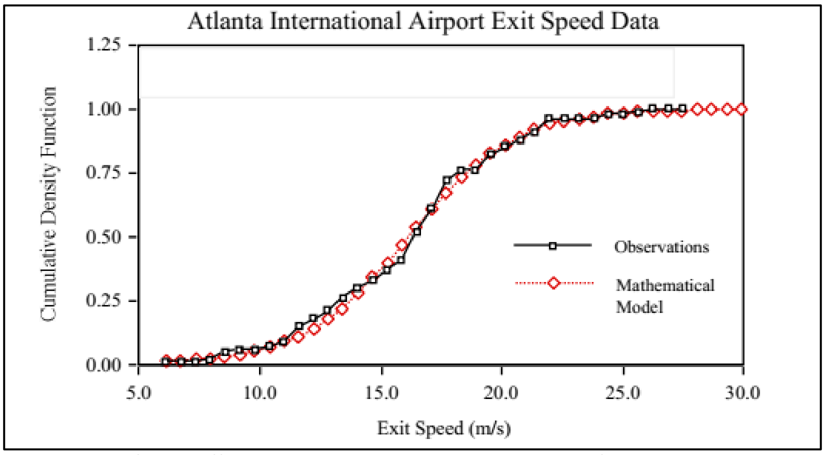


Figure 4 Aircraft Turn off Speed CPDF (Source: Flight Simulations of High-Speed Runway Exits)

A relationship for rate of change of turnoff radius (time variations) R° has developed by Schoen et.al (1984) including skidding friction, lifting force, yaw inertia, centripetal force and scrubbing force terms. Additionally, instantaneous radius R is constrained by normal acceleration a_N and jerk J_N factors as well.

$$\dot{R}^{\circ}_{min} = \frac{\left(f_{skid} - \frac{V^2}{gR} - f_{sc}\right)(m - 5\sigma V^2 S C_L)\, R^2 g\, wb \frac{lm}{100}\left(1 - \frac{lm}{100}\right)}{I_{ZZ}\, V} \quad \text{or} \tag{12}$$

$$= \frac{R\, J_N}{a_N}$$

where σ is the air density, S is the aircraft gross wing area, CL is the average lift coefficient in the landing ground roll configuration (low angle of attack and large flap deflection).

4. Methodology

According to high speed exit configuration for code number 3 & 4, the design radius of curvature is 550 m. It is the geometric centerline from the turn off initiation at the runway centerline to completion of the turning maneuver at the taxiway centerline. However, the actual turn path can deviate from the geometric path as per the variations of parameters defined in above relationship (9). Thus, aircraft position at the end of the curvilinear path would decide whether it enters in to the high speed exit taxiway or it is beyond the taxiway boundary. Aircraft position at the taxiway entry can be computed with rate of change of turn off radius R(dot) and its integration over the time. Therefore, the final R depends on Equation (6) and (12) and the average time for a turn off about 9 to 16 seconds. However, the R(dot) based computations is highly unsteady and are not fair to proceed a risk analysis. Therefore, the methodology is developed based on the demand turn off radius at the beginning of the turning maneuver when the airplane is still on the runway.

1. The methodology is continued with the above equation (9) based airplane nose wheel turnoff stability. Nose wheel turnoff radius depends on the variables such as aircraft deceleration rate, airplane turning speed, friction coefficient and tire scrubbing coefficient.
2. The analysis is based on the FAA standard rapid exit geometry for Code number 3 & 4. Airplane types B727, and B737 and B757 are used in this analysis. According to 550 m design radius of curvature, design exit speed is 26.7 m/s.

3. Side friction coefficients are calculated from Figure (3) based below Equation (12) and (13).

$$\text{When Turn off speed } V = < 10 \text{ m/s}, \quad \text{Side Friction Coefficient} = 0.6233\text{-}0.0323\ V \tag{13}$$

$$\text{When Turn off speed } V > 10 \text{ m/s}, \quad \text{Side Friction Coefficient} = 0.3483\text{-}\ 0.0025\ V \tag{14}$$

4. Aircraft turn off speeds are taken from the CPDF based Equation (10) and (11).

5. Calculation steps are mentioned under following I to VII

   I. Check Aircraft Lateral Deviation on the runway (before initiating turn off) - Figure (5)
      - Aircraft lateral deviation with respect to runway centerline < ½ Taxiway width – ½ wheel base

   II. Aircraft Turnoff speed selection
      - Turn off speed probability is chosen from the Cumulative Density Function Eq. (10) and Eq.(11)

   III. Monte Carlo simulation technique for generating random variables
      - Side friction coefficient is a dependent on the turning speed. As per figure (3), side friction coefficient is selected according to the respective TERP category. TERP category depends on the aircraft weight.
      - Airplane linear decelerations are generated as random values in the range [(-1.2) (-(0.4)] as per aircraft characteristics for airport planning.
      - Tire scrubbing coefficient is selected from figure (2). This is based on the aircraft mass and instantaneous radius of curvature. The following aircraft types which have been chosen for this analysis have almost constant scrubbing coefficients.
      - For B 727 aircraft, Izz = 4.90 x 106kgm2, m = 73025 kg, wb = 16.70 m, Im = 92.50 %
      - For B 737 aircraft, Izz = 2.76 x 106kgm2, m = 51710 kg, wb = 12.35 m, Im = 92.50 %
      - For B 757 aircraft, Izz = 7.14 x 106kgm2, m = 89810 kg, wb = 25.60 m, Im = 94.00 %

   IV. Step A - Calculate air plane nose demand radius of curvature
      - Generate variables as above (speed, deceleration)
      - Aircraft speed values are generated through CPDF.
      - Side friction coefficient value is taken from Eq. (13) or Eq.(14)

   V. Step B **-** Calculate air plane nose gear travel path radius of curvature
      - Aircraft turn off speed based exit location is chosen. It is supposed that after touch down, aircraft travel under constant linear deceleration along the runway until reach to a specified turn off speed.

   VI. Calculate number of events (N) where R(demand) > R(design)
      - R(design) is design radius of curvature (aircraft code number based value)

   VII. Calculate Aircraft veer off probability (Pv)
      - Pv = Ratio between above N and total number of simulations

5. Analysis

5.1 Sample Analysis

Aircraft's maximum allowable lateral deviation (at the beginning of the turn off) with respect to runway centerline is calculated. With respect to ICAO airplane reference code C, required taxiway pavement width is 18 m for B727 aircrafts. The study supposes that any taxiway centerline deviation (for reference code C) beyond 9 m does not enter in to the straight taxiway segment even after the 550 m curvilinear turning radius. However, the same airplane can sustain up to 22.5 m maximum one side deviation from the runway centerline when it is on the runway before beginning the turnoff.

According to aircraft position on the runway, there is 0.09 veer off probability unless any pilot intervention during the turning maneuver. Further, when an aircraft turning in to a high speed exit without any pilot intervention to initial turning radius (550m), only 91% of aircraft (according to B727 type and corresponding airport design) can enter in to the straight taxiway segment after completing (the 550 m) curvilinear segment even though it does follow the 550 m design turning radius from beginning to end.

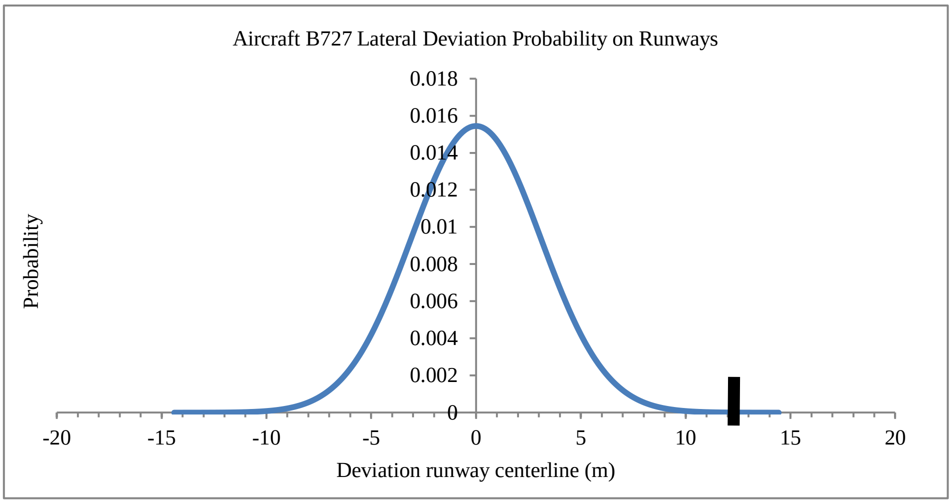


Figure 5 Aircraft Location Distribution on Runways

Table 6 Aircraft position on Runway before Turn off

Reference Code C, B727		
Taxiway Pavement + shoulder width	25.0	m
Taxiway Pavement one side available tolerance	12.5	m
B727 Main Gear Wheel base	16.8	m
B727 nose gear allowable tolerance in the taxiway (12.5-8.4)	4.10	m
When B727 is on the runway,		
Runway width	45.0	m
Nose gear allowable maximum lateral deviation (22.5-8.4)	14.4	m
Standard deviation (Aircraft lateral deviation) (Source A)	3.10	m
Aircraft lateral deviation probability beyond 4.1 m on runway	0.09	

Here, aircraft lateral deviation with respect to runway centerline is taken from field surveys conducted by Field Survey and Analysis of Aircraft Distribution on Airport Pavements (1975).

In the analysis, aircraft demand turning radius is computed by Equation (9). Side Friction coefficient values are taken from the Equation (13) and (14) as per the turning speed. Values for turn off speeds are generated from the Cumulative Probability Distribution Function. Thus,

Aircraft mass (m)	-	73,025 kg	(constant)
Wheel base (wb)	-	16.7 m	(constant)
Percent mass on main gear (lm)	-	92.5%	(constant)
Moment of inertia around the z axis (I_{zz})	-	4.9×10^6 kgm^2	(constant)
Deceleration (a)	-	-1.075 ms^{-2}	(simulated value)

Turnoff speed (v)	-	28.68 ms^{-1}	(simulated value)
Scrubbing coefficient (f_{sc})	-	0.001	(from figure 2)
Side friction coefficient (f_{skid})	-	0.28	(from figure 3 based Equation (13) or 14))

According to Equation (9), computed aircraft demand radius R(demand) = 253.65 m. Since the design radius of curvature for the respective exit geometry 550 m higher than the demand radius of curvature, turnoff path deviation will not lead to a veer off.

$$X = 253.65 – 550.00 = (-296.35)\ m$$

Similarly, 8000 aircraft operations are simulated and respective demand radius values are taken in to the consideration. In this analysis all positive deviations are considered as possible veer offs and negative events are supposed to be safe turning maneuvers. Turning speed, side friction coefficient, deceleration and scrubbing coefficient are variables and other factors are considered as constants for a given aircraft type.

5.2 Results

1. Aircraft turn off speed distribution for B727 is computed with respect to Atlanta International Airport exit speed data based Figure 4 Cumulative probability density function.

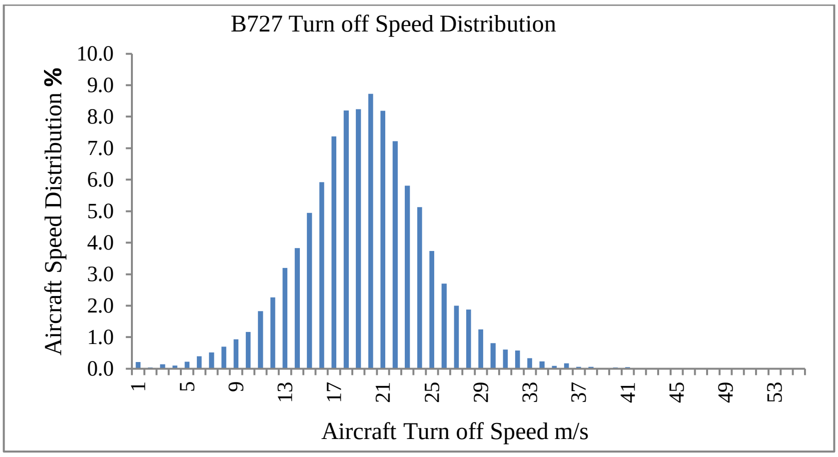


Figure 6 B727 Aircraft turn off speed distribution

2. The above veer off speed based demand turning radius are calculated and resultant veer off probabilities are as below.

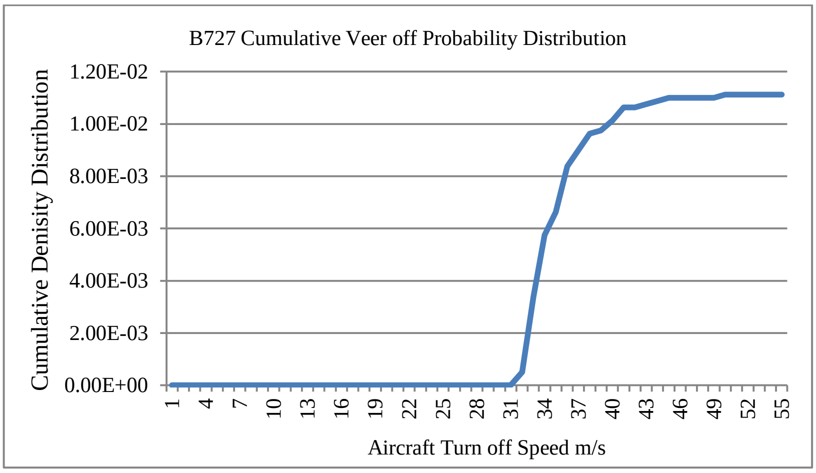


Figure 7 - B727 Cumulative veer off probability distribution

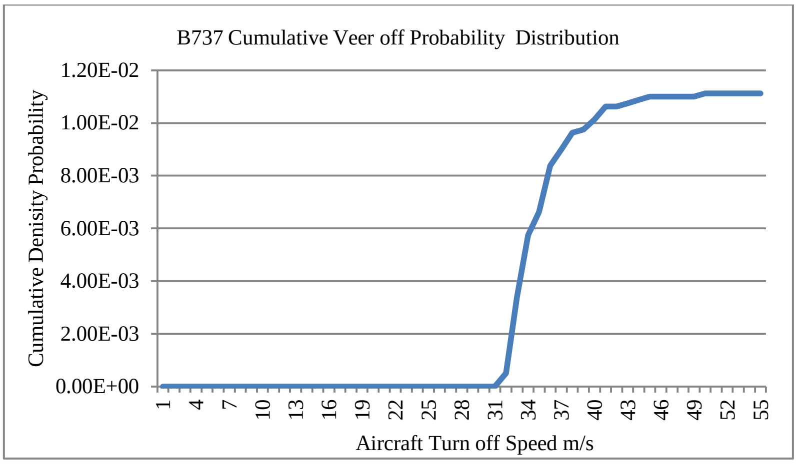
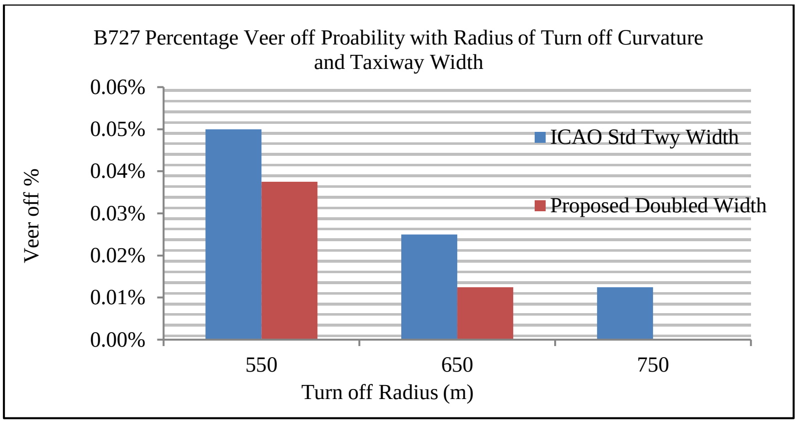
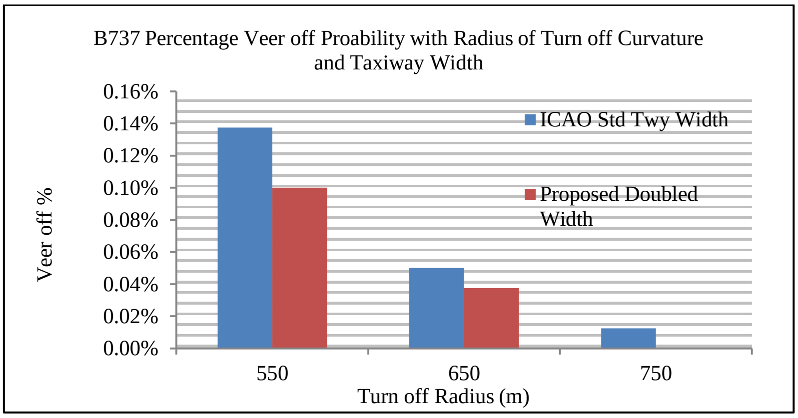


Figure 8 - B737 Cumulative veer off probability distribution

3. Veer offs probabilities are calculated at different high speed exit radius of curvature. Thus, one of the crucial design parameter the radius of curvature of rapid exit is increased up to 650 m instead of current ICAO recommended 550 m radius. A similar simulation was conducted and veer off probabilities were graphed. It could be found that aircraft veer off probabilities reduce at all turn off speeds at improved 650 m and 750 m design radius instead of original 550 m.





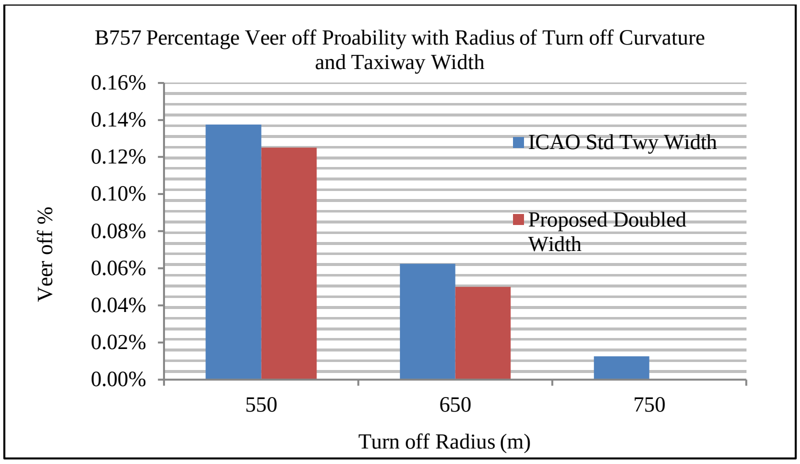


Figure 9 Aircraft Veer off probability in different Turn off Radius

4. Taxiway pavement width is increased by 200% (from current 25m up to 50m), larger radius of curvatures minimize veer-offs probabilities. It implies that the same turnoff speeds result not less than 0.1% lower veer-off probabilities when wider taxiway pavements are designed.

   Wider taxiways and improved turnoff radius are airport design alternations and they can reduce potential veer off risk at any operational condition. Thus, this paper emphasis that improved airport facilities can reduce accident and incident risks. However, it is still true that those veer-off probabilities are going up when turnoff speeds are purposely increased while maneuvering.

5. Exit location is one of the critical parameter in the use of high speed exits. The purpose of the use of rapid exit taxiways is for runway capacity improvement. Since higher exit speeds can reduce runway occupancy times, based on the fleet mix, locating rapid exits closer to runway threshold is promoted. In this study, exit speed based rapid exit locations are identified and consequently an exit location vs aircraft lateral deviations relationship is developed as below. These hypothetical deviations figure out for following three operational conditions. The results depict higher lateral deviations irrespective of the condition at advanced exit locations towards the runway threshold. In the categorizing of veer off events out of the total simulated events, it is assume that there is no pilot intervention during the maneuver and initial turning radius remain constant until complete the curvilinear turning cycle.

Condition A – Turn off geometry design condition 0.113 Side Friction coefficient is applied.

Condition B – Turn off speed based Side Friction Coefficient is applied (Figure 3)

Condition C – With condition B at improved linear deceleration 1.2 m/s^2 is applied for immediate exits

The following deviation results of aircraft demand turn off radius show that they are highly dependent on the factors of turn off speed and friction coefficient. In any condition, corresponding deviations increase when advanced turn off locations are designed. However, improved side friction coefficients record lower deviations with respect to 0.113 friction coefficient (Ex: Condition C is above the condition B at all)

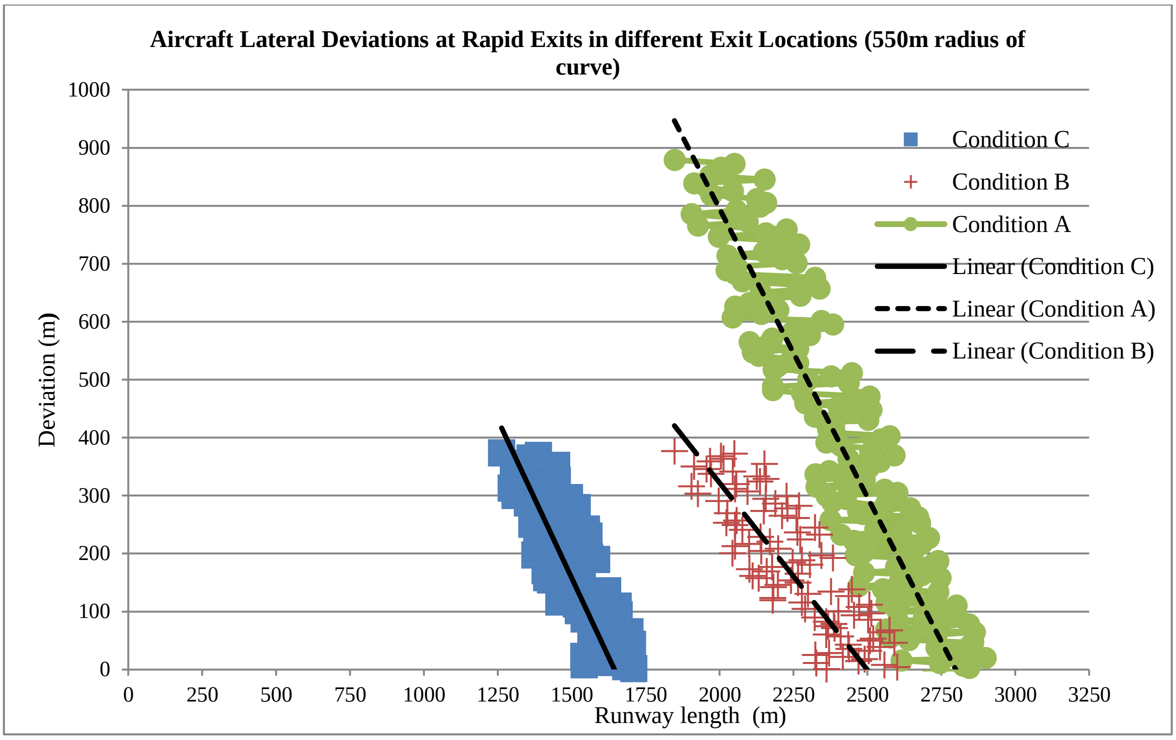


Figure 10 Aircraft lateral deviations at rapid exits in different exit location

The analysis has shown that aircraft lateral deviations are high at higher turn off speeds. However, wider taxiway pavements and larger turn off radius can minimize corresponding veer off risk at different circumstances. The research identified that the deviations of exit speeds with respect to design speed is a critical operational risk. Identifying the range of these variations of turn off speeds is also important. Higher turn off speeds can also be survived by improved exit geometries having higher design radius. Higher variations need wider taxiways geometries to minimize corresponding veer off events. Therefore, the next step of this research is for identifying the variability of turn off speeds at different exit locations.

6. Conclusion

As rapid exit taxiways are located for growing air traffic demand, potential veer off events could be one of the major threat. This paper described aircraft nose landing gear stability based theoretical approach on aircraft veer off risk analysis at high speed exits. By considering the aircraft and airport design parameters and aircraft key operational factors such as approach speed, landing mass, aircraft veer off risk can be computed. This information is useful for configuring high speed exits on airport runways with least risk.

There are key operational parameters such as aircraft turn off speed, friction coefficient factor and aircraft code number which influence turn path radius and resultant lateral deviations along the curved segment of rapid exit taxiways. According to the analysis, it could be identified that,

1) Veer off probability decrease at least by 3% when side friction factor increases by 10 % (side friction factor operating range from 0.05 to 0.70)
2) Veer off probability start to increase when turn off speed increases (after 26.7 m/s the design turn off speed)

These airplane turnoff speed vs veer-off probability curves show that veer-off probabilities increase with turn off speeds. Further, improved side friction coefficients always help for exiting at higher turnoff speeds while minimizing veer-off risks. Runway surface friction is a key design factor which influences airplane tire wear off and maintenance factors. Consequently, airplane lateral deviations are higher, when the exit locations are getting closer to runway threshold. However, corresponding modifications for airport design factors such as rapid exit taxiway width and turn off radius of curvature can reduce potential veer off risks considerably at all operational conditions.

Thus, designing wider rapid exit taxiways and larger turn off radius comparatively allow higher exiting speeds without compromising aircraft safety at rapid exits. However, the optimize design limitations depend on the variability of turn off speeds at different exit locations and contribute to reduce runway occupancy times and resultant capacity improvements.

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