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Mitigating Runway Incursions: Evaluating Advanced Technologies and Methodologies for Enhanced Aviation Safety

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Runway incursions (RIs) are not a new phenomenon in aviation; however, their continued occurrence presents an increasingly serious safety concern. As demand for air travel grows, airport congestion, pilot workload, technology, human factors, and communication increasingly influence the risk of runway incursions. The purpose of this study was to examine professional pilots' perspectives on the potential causes of RIs and identify technological and human-factor strategies for mitigating these events and improving aviation safety. The study employed purposive sampling to select participants, active professional pilots with firsthand experience in runway operations at U.S. airports. Data were collected using a Qualtrics survey and analyzed using descriptive statistics. The survey included demographic questions (pilot status, flight experience, and runway-incursion history) and Likert-scale statements to examine perceived causes of runway incursions, safety technologies, and airport influences. An open-ended question invited participants to share additional comments and professional experiences. Cronbach's alpha was used to assess the internal consistency of the Likert statements, and responses to a final open-ended question were manually coded to identify recurring themes. The study identified four key conclusions. First, systemic factors remain major contributors to runway incursions, with communication failures and lapses in situational awareness consistently identified as significant safety threats. Second, cockpit technologies, including electronic flight bags (EFBs), moving-map displays, and Automatic Dependent Surveillance - Broadcast (ADS-B) can enhance safety but must be used appropriately to prevent overreliance. Third, ground-based systems, such as Runway Status Lights (RWSL) and Airport Surface Detection Equipment, Model X (ASDE-X), are highly effective but are not consistently available across airports, potentially leaving smaller airports with fewer safety protections. Finally, airport size and operational complexity influence incursion risk in different ways, underscoring the need for tailored prevention strategies rather than a one-size-fits-all approach. Overall, the findings indicate that reducing runway incursions requires a multilayered approach that integrates effective pilot training, reliable communication, appropriate technology, improved infrastructure, and strategies tailored to the unique characteristics of each airport environment.

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Over the past several decades, the aviation industry has experienced a significant increase in runway incursions (RIs) worldwide. The International Civil Aviation Organization (ICAO) defines a runway incursion as any airport occurrence involving an aircraft, vehicle, or person entering an area designated for aircraft landing or takeoff (ICAO, 2015). Runway incursions include several categories, such as pilot deviations, operational errors, operational deviations, and vehicle or pedestrian incursions. Research indicates that examining the characteristics of incursions at high-traffic airports can help identify areas with the greatest safety risks (Mathew et al., 2017). Recent trends also indicate an increase in incursions involving professional pilots, often associated with misunderstandings of air traffic control (ATC) instructions, distractions, or inattention. Because runway incursions result from multiple factors, including pilot performance and airport environmental conditions, effective prevention requires a comprehensive approach. With commercial activity expected to increase over the next decade, strengthening runway safety measures remains an urgent priority.

Statement of the Problem

Aviation authorities recognize runway incursions as a significant global aviation safety concern. The Federal Aviation Administration (FAA) identifies airport runways as a primary area of safety risk (FAA, 2010), while the National Transportation Safety Board (NTSB) continues to prioritize runway safety as part of its key safety improvement initiatives. Similarly, the International Civil Aviation Organization (ICAO) has emphasized the need for stronger measures to mitigate runway-incursion risks. European aviation organizations, including Eurocontrol and the European Satellite Navigation initiative, have also supported efforts to strengthen runway safety following several high-profile incidents and ongoing coordination with the FAA and European Air Navigation Service Providers (ANSPs).

The aviation industry increasingly recognizes the need for layered safety strategies that combine technological, physical, human, and procedural measures. Runway incursions can have severe consequences, including aircraft damage, infrastructure loss, operational disruptions, injuries, and fatalities (Mrazova, 2014). Beyond the financial costs, the psychological trauma experienced by passengers, flight crews, and aviation personnel can be profound and cannot be fully measured in monetary terms. Consequently, even incremental improvements in runway safety can produce substantial benefits by reducing accidents, protecting lives, and improving operational efficiency. As forecasts indicate continued growth in global aircraft operations over the next two decades, strengthening runway safety measures will become increasingly important (Yang & Huang, 2023).

Purpose of Study

The purpose of this study was to examine technological, procedural, and infrastructure improvements designed to reduce runway incursions at United States (U.S.) airports. Specifically, the study sought to identify systemic factors that may contribute to runway incursions and assess whether existing onboard technologies and ground infrastructure are sufficient to mitigate these risks. The study also examined how airport size, traffic volume, and operational complexity may influence the likelihood of runway incursions. The findings were

based solely on survey responses and optional comments provided by participating professional pilots.

Research Questions

In response to rapid yearly growth in aircraft flights and the ongoing rise in runway incursions, the study examined the following research questions:

- RQ1: What are the underlying systemic causes of runway incursions?
- RQ2: To what extent are the capabilities of current onboard taxi routing tools, geological technologies, and the established ground infrastructure sufficient to prevent runway incursions?
- RQ3: Do airport size, traffic volume, and operating complexity impact runway incursions?

Significance of Study

The study aimed to enhance understanding of how technological innovations can be applied in different aviation contexts to improve runway safety and reduce the risks associated with runway incursions. Specifically, the study sought to identify effective configurations of emerging technologies, supporting infrastructure, and training programs that can be implemented at airports. The economic analysis further supported recommendations for effective and fiscally responsible safety measures while considering the operational and financial constraints of aviation stakeholders. As air traffic continues to increase, strengthening runway safety is essential to support the sustainable growth of the aviation industry. Reducing incursions and the potential for billions of dollars in losses demonstrates that even incremental safety improvements can produce substantial benefits in productivity and accident prevention.

Beyond measurable economic benefits, preventing fatalities, injuries, and traumatic experiences provides invaluable social benefits. Overall, reliable safety solutions that remain effective in crowded and complex airport environments can support the responsible growth of aviation technology and operations. In addition, a layered approach to safety can be strengthened by systematically identifying intervention strategies tailored to specific runway-incursion risks. A better understanding of operational contexts can help ensure that these strategies are adaptable across diverse airport environments. Ultimately, these improvements can strengthen aviation's primary objective of protecting passengers, crews, and aviation personnel while addressing the safety challenges associated with continued growth in air traffic.

Assumptions and Limitations

The following assumptions and limitations define the scope of this study and inform the interpretation of its findings.

Assumptions

1. Participation was limited to active professional pilots who had direct experience with runway operations at U.S. airports.
2. The study assumed participants provided honest responses to survey questions based on their professional knowledge and experiences.

3. The insights gained from participant responses regarding technologies for runway incursion mitigation are assumed to be reasonably representative of the best practices of professional pilots.

Limitations

1. The availability of current, factual resources addressing the mitigation of runway incursions limited the depth of the literature review and the interpretation of findings.
2. The analysis and interpretation of results may be influenced by the researchers' prior knowledge, experiences, or lack of familiarity with the subject. Readers may also interpret the findings differently based on their professional backgrounds and personal experiences, potentially affecting the study's acceptance and application within the aviation industry.
3. Participation depended on individuals' willingness and ability to complete the survey. Some eligible participants were unavailable or chose not to respond, potentially introducing nonresponse bias and limiting the representativeness of the findings.

Literature Review

Introduction to RI in a Global and US Context

Runway incursions (RIs) remain a major safety concern in the global aviation industry. As air traffic continues to increase, the frequency and severity of RIs may also rise if effective preventive measures are not implemented. However, the relationship between traffic growth and RI rates varies across airports and is influenced by factors such as airport design, operational vulnerabilities, existing safety measures, weather conditions, and traffic capacity. Even modest increases in traffic volume can contribute to more frequent and severe RI events (Shahriari & Aydin, 2018). Ison (2020) reported that some airports could experience a 140% increase in single-incursion RI rates for every 20% increase in aviation density. Overall, RIs range from minor runway violations to serious incidents that can cause property damage, airport closures, injuries, or fatalities.

Definitions of RIs also vary among aviation authorities and organizations. ICAO, a specialized agency of the United Nations responsible for coordinating international civil aviation standards and practices, defines a runway incursion as an occurrence involving an aircraft, vehicle, or person within the protected area of a runway intended for landing or takeoff (Song, 2016). Similarly, the Federal Aviation Administration (FAA) defines an RI as an occurrence involving an aircraft, vehicle, person, or object on a runway that creates a hazard, a collision, or results in a loss of required separation (Song, 2016). More broadly, an RI can be understood as the unauthorized or unsafe presence of an aircraft, vehicle, or person on a runway designated for aircraft landing or takeoff. These definitions highlight three primary sources of runway incursions: (1) aircraft, (2) vehicles, and (3) pedestrians.

ICAO Severity Classification Scheme

ICAO provides a widely used framework for assessing the severity of runway incursions (RIs). Under this classification system, RIs are categorized into four levels, from Category A to

Category D, based on the potential for collision and the level of risk involved. Category A represents the most serious incidents, typically involving a near collision in which evasive action or intervention is required to avoid an accident (Omosebi et al., 2023). These incidents indicate a significant safety threat and generally warrant a comprehensive investigation.

Category B incidents involve a significant risk of collision, with time or distance serving as the primary safety margin (Wang et al., 2018). Although evasive action may not be required, an aircraft may come dangerously close to another aircraft, vehicle, or object. Category C incidents involve situations in which a collision could occur, but sufficient separation is maintained to prevent an immediate threat (Ison, 2020). Although less severe, these events remain important because their underlying causes may reveal weaknesses in airport layout, communication, or compliance with established procedures. Category D represents the least severe incursions and includes events that do not create an immediate risk of collision, such as unauthorized runway entries or incorrect positioning with adequate separation (Zhang, 2019).

This classification system allows aviation authorities to document, monitor, and analyze runway incursions according to their level of severity. Although lower-category incursions may not present an immediate operational threat, they can provide valuable indicators of underlying system vulnerabilities. Identifying and addressing these vulnerabilities before they contribute to more serious incidents is essential for strengthening runway safety.

FAA Classification System: The Pilot Involvement, Operations Tasks, Vehicle/Pedestrian Involvement

In the U.S., the FAA categorizes runway incursions according to the party responsible for the event. Pilot deviations are among the most common and occur when flight crews fail to follow air traffic control (ATC) instructions or disregard airfield markings, resulting in unauthorized entry onto an active runway (Chen et al., 2024). These deviations are often associated with miscommunication, misunderstandings of taxi instructions, or lapses in situational awareness (Islam & Aulia, 2024). Operational incidents, in contrast, are typically attributed to air traffic controllers and may result from incorrect clearances, coordination failures, or inadequate monitoring (Koc & Cinar, 2025). Although less frequent, these incidents receive considerable attention because they can undermine the reliability and effectiveness of the ATC system.

Another FAA category is vehicle or pedestrian deviations, which involve unauthorized runway access by airport service vehicles, construction equipment, or pedestrians (Vernaleken et al., 2006). Such incidents may be more likely at smaller or non-towered airports where supervision, communication, and physical barriers are limited. The FAA classification can be used alongside the ICAO severity framework to support both causal analysis and risk assessment (Halawi et al., 2024). For example, a pilot deviation that results in a near-collision would be classified as a pilot deviation under the FAA system and as a Category A incursion under the ICAO framework. Together, these classification systems provide a comprehensive basis for identifying contributing factors and developing targeted safety interventions, such as improved pedestrian signage, enhanced ATC training, and more precise pilot taxi instructions.

FAA Runway Incursion Database

The FAA Runway Incursion Database serves as a primary source for documenting and analyzing runway incursions within the National Airspace System (NAS) (FAA, 2010b). Long-term analyses indicate a substantial decline in serious incursions (Categories A and B) since 2010, largely attributed to improvements in surveillance, technology, and operational procedures (FAA, 2012b). Although the overall number of incursions has remained relatively stable, recent data show a shift toward less severe Category C and D events (FAA, 2024). This trend suggests that existing safety measures are increasingly effective in preventing incursions from escalating into situations with a high risk of collision.

The decline in severe incursions has also been associated with the implementation of Airport Surface Detection Equipment, Model X (ASDE-X) and Runway Status Lights (RWSL) at major U.S. airports (FAA, 2012a). ASDE-X provides real-time monitoring of aircraft and vehicles on airport surfaces, improving controllers' situational awareness and supporting pilots' decision-making. Research indicates that airports equipped with ASDE-X have experienced fewer high-severity incursions because of improved surface surveillance and enhanced detection capabilities (Ellis et al., 2024). RWSL further strengthens runway safety by providing pilots with direct visual warnings of potential runway conflicts, creating an additional layer of protection against clearance errors and other operational mistakes.

Methodology

The methodology section describes the research questions, participant selection, reliability and validity, and procedures used for data collection and analysis. The study focused on identifying advanced technologies and strategies for mitigating runway incursion risks. The survey was structured around the research questions and began with a qualifying question to ensure that only professional pilots participated. Eligible respondents then provided information about their flight hours and prior runway incursion experiences before completing a series of four-point Likert-scale items. The survey concluded with an open-ended question that allowed participants to describe relevant personal and professional experiences, providing additional context to the quantitative findings.

Selection of Participant Population

The researchers used purposive sampling, a nonprobability sampling method in which participants are intentionally selected based on their ability to provide relevant and information-rich data (Palinkas et al., 2015). The sample consisted of professional pilots actively engaged in aviation operations. Participants were selected because of their operational experience and firsthand knowledge of runway incursions. To qualify for the study, pilots were required to maintain active flying status and have direct experience with runway operations at U.S. airports.

Research Instrument and Procedures

The study used a researcher-developed Qualtrics survey instrument, with data analyzed using descriptive statistics to summarize participants' characteristics, behaviors, and responses

(Rajagopalan, 2023). The instrument established a baseline of professional pilots' perceptions of advanced technology for runway incursion mitigation and was designed to align directly with the study's research questions. Demographic questions (Q1 - Q3) assessed participants' professional pilot status, experience, and history of runway incursions. Likert-scale items, ranging from Strongly Disagree to Strongly Agree, examined the potential causes of runway incursions (RQ1: Q4 - Q7), the use of onboard and ground-based technologies (RQ2: Q8 - Q15), and the effects of airport size, traffic volume, and congestion (RQ3: Q16–Q20). Finally, an open-ended question (Q21) allowed participants to provide additional comments and describe relevant personal or professional experiences, providing further context for the survey findings.

Reliability and Validity

The survey questions were developed to align directly with the research questions and were written in clear, straightforward language. To promote consistent interpretation, the consent form provided definitions of key terms, including runway incursion, onboard taxi routing tools, machine learning-based risk assessment algorithms, and geolocation technologies. These definitions were based on terminology provided by the FAA (FAA, 2021).

The survey underwent internal review and pilot testing with a small group of professional pilots to assess clarity and validity before distribution to the larger sample. Survey responses were collected and analyzed using Qualtrics, with results examined both numerically and visually to identify patterns and variations across responses. Descriptive statistics, including frequencies and percentages, were used to summarize participant characteristics and response patterns (Mburu, 2025).

Cronbach's alpha is a statistical coefficient used to assess the internal consistency of a scale, or the extent to which items within a questionnaire measure the same underlying construct (Brooksfield, 2026). The internal reliability of the Likert-scale statements in this study was assessed using Cronbach's alpha. According to Taber's (2018) guidelines, coefficients above 0.50 are considered acceptable, above 0.60 satisfactory, above 0.70 high, above 0.80 reliable, and above 0.90 strong. The survey produced a Cronbach's alpha coefficient of 0.739, indicating high internal consistency among the Likert-scale statements. This result suggests that the statements demonstrated an acceptable degree of consistency in measuring the study's underlying constructs.

Data Collection Procedure

The researchers recruited aviation professionals ranging from senior captains to junior commercial pilots through email and text messages. Initial contacts were provided with an overview of the study's purpose, asked about their interest in participating, and invited to share the study with qualified colleagues through their professional networks using snowball sampling (Nikolopoulou, 2023). The recruitment invitation provided a link to the informed consent form, which described the study's purpose, procedures, Institutional Review Board (IRB) approved protections, and voluntary nature of participation. During the 28-day data-collection period, 155 participants accessed the survey.

Participation was limited to U.S. professional pilots who met the study's eligibility criteria. Individuals who did not meet these requirements were excluded from the study. Access to the collected data was restricted to the researchers, and participants could withdraw from the study at any time by exiting the survey.

Statistical Analysis of the Data

Survey responses were systematically organized as quantitative data, with demographic characteristics and participant perceptions analyzed using descriptive statistics. This approach, commonly used in aviation safety research, identifies patterns, frequencies, and distributions within the data, providing a foundation for interpretation and reporting (Rajagopalan, 2023; FAA, 2021). Qualitative responses to the final open-ended question (Q21) were reviewed in Qualtrics and exported to Microsoft Excel for manual coding. Manual coding of open-ended survey responses is a qualitative data analysis method in which researchers systematically review, interpret, and assign codes to participants' written responses (Miller, 2026). Manual coding relies on human judgment and contextual understanding to identify recurring themes, patterns, and underlying meanings within participants' verbatim feedback.

Integrating these qualitative findings with the quantitative results provided a more comprehensive understanding of the factors contributing to runway incursions by connecting measurable response patterns with participants' operational experiences (Chanda, 2024). The open-ended responses further contextualized the Likert-scale findings by highlighting situational challenges, decision-making processes, and other operational factors relevant to runway safety.

Findings

Data were analyzed across three sections of the study: (1) three demographic questions, (2) seventeen Likert-scale statements, and (3) one open-ended question that allowed participating pilots to provide personal comments about runway incursions. The findings were organized according to the study's three research questions to provide both descriptive and interpretive insights into pilots' perceptions of runway incursion risks and the effectiveness of technological prevention measures.

Demographic Questions

The first survey question asked participants whether they were professional pilots. Respondents who identified as pilots were permitted to continue with the survey, while those who did not meet this criterion were automatically screened out. Of the 155 pilots who participated in the study, 144 (93%) identified as professional pilots, while 11 (7%) did not (Table 1). The responses from the 11 ineligible participants were removed from the dataset and excluded from all subsequent analyses.

Table 1

Professional US Pilot

Professional Pilot	Responses	Percentage of Responses
Yes	144	93%
No	11	7%

The second survey question asked participants to report their total career flight hours. As shown in Table 2, four respondents (3%) reported fewer than 1,000 flight hours, while another four respondents (3%) reported between 1,000 and 1,999 hours. Twenty-two respondents (15%) reported between 2,000 and 2,999 hours, and 16 respondents (11%) reported between 3,000 and 3,999 hours. Sixteen respondents (11%) reported between 4,000 and 4,999 hours. The largest group consisted of 90 respondents (62%) who reported 5,000 or more flight hours, indicating that most participants had substantial professional flight experience.

Table 2

Flight Hours

Flight Hours	Responses	Percentage of Responses
1-999 Hours	4	3%
1,000-1,999 Hours	4	3%
2,000-2,999 Hours	22	15%
3,000-3,999 Hours	16	11%
4,000-4,999 Hours	8	6%
5,000 or More Hours	90	62%

Question 3 examined participants' personal experience with runway incursions. Of the 144 professional pilots who answered this question, 31 (22%) reported having been involved in a runway incursion, while 113 (78%) reported no personal experience with an incursion (Table 3). These findings indicate that nearly one-quarter of the participating pilots had firsthand experience with a runway incursion.

Table 3

Runway Incursion

Personal RI	Responses	Percentage of Responses
Yes	31	22%
No	113	78%

Mitigation of Runway Incursions and Technological Advances

The 17 Likert-scale statements addressed the study's research questions concerning runway incursions, technological advancements, and mitigation strategies. Participants responded using a four-point scale: Strongly Agree (SA), Agree (A), Disagree (D), or Strongly

Disagree (SD). The four-point scale eliminated a neutral response option, encouraging participants to indicate a clear level of agreement or disagreement with each statement (ProProfs, 2023). Table 4 summarizes the participants' responses to the 17 Likert-scale statements.

Table 4

Runway Incursion Mitigation and Technological Advances

Likert Scale Statement	**SA**	**A**	**D**	**SD**
Runway incursions are among the most persistent threats to aviation safety. *(N=141)*	42 (30%)	78 (55%)	21 (15%)	0 (0%)
Runway incursions are the consequence of multiple operational and/or environmental factors. *(N=140)*	87 (62%)	53 (38%)	0 (0%)	0 (0%)
Pilot training and awareness, standardized ATC communications, runway signage and marking, aircraft conspicuity, and identified taxi routes are contributors to the risk of runway incursion. *(N=138)*	62 (45%)	41 (30%)	31 (22%)	4 (3%)
The likelihood of a runway incursion in the US is high; the severity is catastrophic. Therefore, the current level of risk is unacceptable. *(N=136)*	32 (24%)	61 (45%)	41 (30%)	2 (1%)
The risk posed by runway incursions can be significantly reduced with a combination of technologies which greatly improve the pilot's situational awareness and provide conflict-alerting capability during ground operations. *(N=135)*	70 (52%)	58 (43%)	6 (4%)	1 (1%)
Onboard taxi routing tools are more efficient than traditional runway status lights in mitigating runway incursions. (*N=133)*	25 (19%)	53 (40%)	52 (39%)	3 (2%)
Onboard taxi routing tools lower the complexity of navigating airport environments better than current geolocation technologies. *(N=133)*	33 (25%)	76 (57%)	22 (17%)	2 (2%)
Runway status lights alone are sufficient for mitigating runway incursions and do not need complementary technologies. *(N=133)*	1 (1%)	18 (14%)	97 (73%)	17 (13%)
Better runway safety could be attained with multi-technology integration, including machine learning algorithms and geolocation tools, than with a single solution. *(N=129)*	47 (36%)	71 (55%)	10 (8%)	1 (1%)
Machine learning-based risk assessment algorithms better detect potential runway incursions than current infrastructure. *(N=127)*	16 (13%)	91 (72%)	19 (15%)	1 (1%)

Geolocation technologies (real-world geographic location) greatly improve safety by mitigating the risk of runway incursions. *(N=126)*	40 (32%)	82 (65%)	4 (3%)	0 (0%)
Advanced technological combinations, including onboard tools and geolocation systems are more effective at managing the complexity of today's airport environments than older navigation and communication systems. *(N=126)*	56 (44%)	61 (48%)	8 (6%)	1 (1%)
Airport congestion is one of the most influential factors in determining the effectiveness of runway incursion prevention technologies. *(N=126)*	37 (29%)	61 (48%)	23 (18%)	5 (4%)
Airports can have complex layouts that create confusion for pilots and other airport users, resulting in additional risk factors that contribute to runway incursions. *(N=126)*	80 (63%)	44 (35%)	2 (2%)	0 (0%)
Runway incursions grow exponentially as a function of air traffic growth, which is on the increase in the US. *(N=126)*	33 (26%)	66 (52%)	23 (18%)	4 (3%)
Regardless of cost, airports with high traffic volume and operating complexities must continue to invest in surface safety and situational awareness technology tools. *(N=125)*	71 (57%)	50 (40%)	4 (3%)	0 (0%)
The implementation of most risk mitigations has been very slow because the FAA and the US aviation industry are reluctant to spend the resources that are required to achieve the potential high level of aviation safety. *(N=125)*	39 (31%)	60 (48%)	24 (19%)	2 (2%)

Note: Due to rounding, the reflected percentages in some Likert statements may exceed 100% of the total responses.

The researchers observed participant attrition during survey completion, with the number of respondents decreasing from 144 professional pilots who completed Questions 1–3 to 125 participants who completed Question 20. Participant attrition occurs when respondents discontinue a survey before completing all questions and do not return to finish answering the survey questions.

The study's findings that address the three research questions were derived exclusively from survey responses and optional written comments provided by participating professional pilots. No existing data from external databases or secondary data sources were used to establish the findings. Therefore, the results reflect participants' firsthand experiences, perceptions, and professional judgments regarding runway incursions and associated mitigation strategies.

RQ1: What are the underlying systemic causes of runway incursions?

The quantitative findings indicate that participants view runway incursions as a serious and ongoing aviation safety threat. Eighty-five percent of participants agreed that runway incursions remain a primary safety concern, while 100% identified operational and environmental factors as contributing causes. Training, air traffic control (ATC) communication, signage, and airport design were consistently identified as important factors influencing runway safety.

The qualitative responses reinforced these systemic concerns. Several participants identified communication difficulties and language barriers as contributors to runway incursions. One respondent stated that "Foreign language and accents are the most common cause of runway incursions that I've seen." Others identified ATC congestion and frequency overload as additional risks. One participant explained, "Frequency communications are overloaded… ORD splits ground by Inbound/Outbound traffic. This compromises situational awareness." These observations are consistent with the quantitative findings, which identified communication congestion and airport layout complexity as important risk factors.

Participants also emphasized the importance of pilot training and experience. One respondent noted, "Pilot experience levels and training play a huge role in safety," while another observed that the declining experience levels of newly hired pilots may increase operational risk. These comments provide additional context for the quantitative finding that 75% of respondents agreed that deficiencies in training, situational awareness, and communication contribute to runway incursions.

Institutional and infrastructure limitations were also identified as systemic barriers to runway safety. Some participants expressed concern that increasing traffic at busy airports has not been matched by sufficient investments in air traffic control capacity and airport infrastructure. One respondent stated, "Our busiest airports keep getting more traffic shoved into them… yet the ability for ATC and the underlying airport infrastructure has not expanded accordingly." This observation aligns with the finding that 79% of respondents agreed that the FAA and aviation industry have been slow to implement runway-incursion mitigation measures because of resource constraints and competing priorities.

Overall, the qualitative findings support Research Question 1 (RQ1) by demonstrating that runway incursions are not solely the result of individual errors. Instead, participant experiences point to interconnected systemic factors involving pilot training, communication, situational awareness, airport infrastructure, ATC capacity, and institutional decision-making. These findings suggest that effective runway-incursion prevention requires a comprehensive approach that addresses both individual performance and the broader operational system.

RQ2: To what extent are the capabilities of current onboard taxi routing tools, geolocation technologies, and the established ground infrastructure sufficient to prevent runway incursions?

The survey findings showed strong support for using technology to reduce runway incursions, while also indicating that no single system should be relied upon as a standalone solution. Eighty-six percent of respondents disagreed that Runway Status Lights (RWSL) alone are sufficient to prevent runway incursions, while 91% supported the use of multiple technologies in combination. Similarly, 85% supported the use of machine learning algorithms to improve runway-incursion detection, and 97% considered geolocation technologies essential safety tools.

The qualitative responses provided additional context by highlighting both the benefits and limitations of advanced technologies. Several participants cautioned against overreliance on technology and the potential for increased distraction. One respondent noted, "Certain levels of onboard taxi routing technology could pose a threat, causing a pilot to be heads down when their eyes should be outside." Another similarly observed that new technologies could become an extra tool but might eventually contribute to distracted operations. These comments suggest that technology should complement, rather than replace, pilot situational awareness and visual monitoring.

Some participants also questioned whether emerging technologies are sufficiently mature or widely implemented to support definitive conclusions about their effectiveness. One respondent stated, "You're asking if we believe advanced technologies will mitigate the threat. We have no way of knowing because we are not using these technologies… It sounds great in theory." Others recommended relatively simple and practical solutions, such as transmitting digital taxi clearances through ACARS or directly to electronic flight bags (EFBs). One participant suggested sending taxi instructions to pilots' iPads with the assigned route visually highlighted. These recommendations demonstrate that effective mitigation does not necessarily depend on the most technologically advanced systems but may also involve improving existing communication tools.

The participating pilots also referenced international runway-safety practices as potential models for U.S. airports. Several respondents highlighted European *Follow the Green* (FtG) taxiway lighting systems as intuitive approaches for guiding pilots along assigned routes. One participant suggested that improved ground lighting and route-following systems could significantly enhance nighttime safety. Another referenced the taxiway lighting system at Incheon International Airport in South Korea, where pilots follow green taxiway lights and red stop bars to navigate the airport surface. These observations indicate that U.S. aviation stakeholders may benefit from evaluating proven technologies and practices used at international airports.

Overall, the qualitative findings support Research Question 2 (RQ2) by demonstrating cautious optimism toward technological solutions. Participants generally viewed technology as an important component of runway-incursion prevention but emphasized that its effectiveness depends on system integration, human-centered design, operational reliability, and appropriate institutional implementation. The findings further suggest that technology should function as an additional layer of protection rather than substitute for effective training, communication, and pilot situational awareness.

RQ3: Does airport size, traffic volume, and operating complexity impact runway incursions?

The survey findings provided by the participating pilots demonstrated strong agreement that airport characteristics directly influence the risk of runway incursions. Ninety-eight percent of respondents agreed that complex airport layouts increase incursion risk, while 77% indicated that congestion can reduce the effectiveness of existing safety technologies. Additionally, 78% agreed that runway incursions increase as traffic volume rises. Nearly all respondents (97%) agreed that high-traffic airports should continue investing in runway safety technologies and other mitigation measures, regardless of cost.

The qualitative responses reinforced these findings by emphasizing the relationship between airport congestion, operational complexity, and incursion risk. Several participants reported observing incursions at high-traffic airports with complex taxiway configurations. One respondent noted, "Instances I observed occurred at high-traffic airports with complex taxiways." Another identified several U.S. airports where runway configurations and limited spacing place additional demands on air traffic control (ATC) capabilities, potentially increasing the risk of incursions.

Participants also highlighted the relationship between airport growth, infrastructure investment, and safety. One respondent argued that continued terminal and gate expansion without corresponding improvements to airport infrastructure can create additional operational risks. This perspective supports the quantitative finding that airport capacity and infrastructure are important considerations in runway-incursion prevention.

Respondents further indicated that operational conditions vary considerably by airport size and location, influencing both actual risk and perceptions of safety. One participant observed that large hub airports generally benefit from professional flight crews and advanced lighting systems, whereas smaller airports with a greater mix of operators may remain more vulnerable to incursions. These differences may help explain why nearly one-third of respondents disagreed that runway-incursion risk is unacceptable, as perceptions of risk may be shaped by participants' specific operating environments and experiences.

Overall, the qualitative findings support Research Question 3 (RQ3) by reinforcing the quantitative evidence that traffic volume, congestion, airport layout, and infrastructure capacity influence runway-incursion risk. The findings also suggest that effective mitigation strategies must account for differences among airport environments rather than applying a single approach to all locations.

Summary of Findings

Integrating the quantitative and qualitative findings provided a comprehensive understanding of the factors contributing to runway incursions. For Research Question 1 (RQ1), participants identified systemic factors, including (1) training deficiencies, (2) communication barriers, (3) situational awareness, and (4) infrastructure limitations, as major contributors to runway incursions. For Research Question 2 (RQ2), respondents viewed technology as an

important component of runway safety but emphasized that its effectiveness depends on proper integration, human-centered design, and appropriate training. Participants also cautioned against overreliance on technology and the potential for increased distraction. For Research Question 3 (RQ3), airport size, traffic volume, congestion, and operational complexity were consistently identified as factors that increase both the likelihood of incursions and the difficulty of implementing effective mitigation strategies.

Overall, the findings demonstrate that runway incursions are a complex, system-level safety issue that cannot be addressed through a single intervention. Effective prevention requires a comprehensive, multifaceted approach that combines (1) pilot and ATC training, (2) advanced technologies, (3) improved airport infrastructure, (4) effective communication, and (5) systemic safety reforms. This layered approach can strengthen existing defenses and reduce the likelihood that individual errors or operational challenges will develop into serious runway-incursion events.

Conclusions

The purpose of this study was to examine professional pilots' perceptions of runway-incursion causes and the effectiveness of cockpit technologies, ground infrastructure, and airport characteristics in mitigating risk. Despite ongoing regulatory and technological advances, runway incursions remain a significant aviation safety concern. Previous research has identified human factors, communication failures, and reduced situational awareness as recurring contributors to these events (Ruskin et al., 2021).

The findings indicate that runway incursions result from interacting with human, environmental, and operational factors. Seventy-two percent of respondents identified pilot–air traffic control (ATC) miscommunication as a primary concern, while 65% identified confusing taxiway layouts and inadequate signage as contributing factors. Participants also described fog, nighttime operations, congestion, and high cockpit workload as conditions that can increase risk. One pilot explained, "Surface operations in IMC are the most stressful moments outside of takeoff and landing, errors compound quickly when visibility is reduced." These responses suggest that reduced visibility and competing operational demands can increase the likelihood that communication or navigation errors will escalate.

Participants generally supported cockpit technologies but emphasized their limitations. Eighty-three percent expressed confidence in electronic flight bag (EFB) moving-map displays, and 75% supported the use of Automatic Dependent Surveillance–Broadcast (ADS-B) In. However, 47% expressed concern about overreliance on cockpit technology. As one participant stated, "They are excellent aids, but they're not substitutes for vigilance." These findings reinforce the importance of integrating technology with pilot training, situational awareness, and sound decision-making. Ground-based technologies also received favorable evaluations. More than 70% of respondents familiar with Runway Status Lights (RWSL) and Airport Surface Detection Equipment, Model X (ASDE-X), considered these systems effective. However, 58% reported that such technologies were primarily available at the busiest airports. This perceived disparity suggests that access to technological safeguards varies across the airport system.

Airport characteristics further influenced perceived risk. At major hubs, 68% of respondents identified congestion, complex taxi routes, and ATC workload as important concerns. At smaller and non-towered airports, participants emphasized limited infrastructure and reliance on pilot-to-pilot communication. These findings indicate that runway-incursion prevention requires strategies tailored to airport-specific conditions rather than a uniform approach.

Three overarching themes emerged from the quantitative and qualitative data:

1. *Systemic and human factors*. Communication failures, reduced situational awareness, environmental conditions, and task saturation contribute to runway-incursion risk.
2. *Technology and its limitations*. Pilots support cockpit and ground-based safety technologies but recognize the risks of overreliance and the uneven availability of these systems.
3. *Airport operating environments*. Major hubs face congestion and workload challenges, while smaller and non-towered airports may have fewer infrastructure-based safeguards and greater reliance on pilot communication.

Collectively, these findings support a comprehensive approach that integrates human-factors training, appropriate technological systems, effective communication procedures, and airport infrastructure improvements.

Summary of RQ1

Participants primarily viewed runway incursions as systemic events involving communication failures, environmental conditions, workload, and lapses in situational awareness. Seventy-two percent identified pilot - ATC miscommunication as a major contributing factor, while 65% cited confusing taxiway layouts and inadequate signage. Participants described ambiguous instructions, simultaneous radio transmissions, missed clearances, and complex taxi routes as challenges that can increase operational risk. Reduced visibility and task saturation further complicated surface operations. Pilots reported simultaneously managing ATC communications, aircraft systems, navigation, and departure or arrival preparations. One participant explained, “We’re heads-down managing checklists, monitoring radios, and taxiing at the same time; it only takes a split second for a missed clearance to become an incursion.”

These findings suggest that runway incursions rarely arise from a single isolated error. Instead, communication breakdowns and situational-awareness lapses may be compounded by workload, environmental conditions, airport design, and procedural limitations. Effective mitigation should therefore address both individual performance and the broader operational systems in which pilots and controllers work.

Summary of RQ2

Participants viewed cockpit technologies as valuable tools for improving surface-navigation awareness. Eighty-three percent expressed confidence in moving-map displays, and

75% supported ADS-B. However, 47% raised concerns about excessive reliance on automated systems, emphasizing that technology cannot replace pilot vigilance or sound judgment. Ground-based technologies also received favorable assessments. More than 70% of respondents familiar with RWSL and ASDE-X considered these systems effective, while 58% reported that they were primarily available at the busiest airports. These responses highlight the perceived benefits of technological safeguards and concerns about their uneven deployment.

Overall, the findings support a layered approach to runway safety. Cockpit and ground-based technologies should complement, rather than replace, effective training, clear communication, procedural compliance, and active monitoring of the airport environment. Expanding access to appropriate technologies may improve safety, provided implementation accounts for airport-specific risks, operational requirements, and system limitations.

Summary of RQ3

The findings indicate that runway-incursion risks vary according to airport characteristics. At major hub airports, 68% of respondents identified congestion, complex taxi routes, and ATC workload as key concerns. High traffic volumes and multiple simultaneous movements may increase communication demands and the potential for operational errors. At smaller and non-towered airports, 55% identified limited infrastructure and reliance on Common Traffic Advisory Frequency (CTAF) communications as vulnerabilities. Additionally, 49% cited inconsistencies in pilot-to-pilot communication. Participants emphasized that limited signage, lighting, and surveillance capabilities may place greater responsibility on individual pilots to maintain situational awareness and communicate intentions clearly.

These findings suggest that runway-safety strategies should reflect the specific conditions of each airport. Major hubs may benefit from improved traffic-management procedures, advanced surveillance, and technologies that reduce controller's workload. Smaller and non-towered airports may require improvements in signage, lighting, communication practices, and other safeguards appropriate to their operating environments.

Conclusion of the Study

The findings support an integrated runway-safety approach that combines human-factors training, effective communication procedures, appropriate cockpit and ground-based technologies, and targeted infrastructure improvements. Rather than relying on a single intervention, aviation stakeholders should address the interconnected conditions that contribute to runway incursions. Although the findings reflect the perceptions of participating professional pilots and should not be interpreted as establishing causation, they provide practical insight into perceived safety vulnerabilities and potential priorities for future runway-incursion mitigation efforts.

Recommendations

Based on the study's findings, three main recommendations are suggested by the researchers to lower the risk of runway incursions.

Recommendation 1

Mandatory retraining for pilots should be further enhanced to promote the effective integration of cockpit technologies into routine operations. Survey findings indicated that more than 80% of pilots rely on moving-map displays and electronic flight bags (EFBs), while nearly half expressed concerns about overreliance on these technologies. Mandatory retraining should therefore emphasize the importance of using technology as a supplemental safety tool while maintaining active monitoring of airport signage, air traffic control (ATC) instructions, runway markings, and external visual cues.

Recurrent training should incorporate realistic ground-operation scenarios that require pilots to combine traditional navigation methods with technological tools. Recommended practices include: (1) simulating EFB or geolocation-system failures to reinforce reliance on signage, markings, and ATC communication; (2) incorporating captain and first-officer cross-check procedures that require verification of ATC instructions against cockpit displays; and (3) incorporating airline recurrent-training modules that emphasize situational awareness and vigilance when using advanced technologies. These measures can strengthen pilot resilience and decision-making in both technology-supported and degraded operating environments.

Recommendation 2

Although 70% of pilots rated Runway Status Lights (RWSL) and Airport Surface Detection Equipment, Model X (ASDE-X) as highly effective, 58% reported that these systems are only available at major hub airports. In addition, 55% expressed concerns about smaller airports with inadequate signage and greater reliance on Common Traffic Advisory Frequency (CTAF) communications. One respondent noted, “The closest I’ve come to an incursion wasn’t at a hub, it was at a small field with no ground radar and poor markings.”

To reduce these infrastructure disparities, the FAA and airport authorities should prioritize scalable runway-safety improvements based on documented risk. Recommended measures include upgrading signage, lighting, and runway markings at airports with recurring incursion events; evaluating cost-effective surface surveillance technologies; and expanding federal grant opportunities that help smaller airports implement appropriate safety improvements. These measures would provide additional layers of protection at airports that may lack the resources to implement advanced systems such as RWSL and ASDE-X. Prioritizing investments according to operational risk rather than airport size alone could help address infrastructure gaps where additional safety measures are most needed.

Recommendation 3

Nearly half of the respondents (49%) reported discrepancies between electronic flight bags (EFB), taxi maps, and air traffic control (ATC) instructions. One pilot explained, “Sometimes what I see on my EFB and what I hear from ATC don’t quite match; it forces you to second-guess.” Such inconsistencies can increase pilot workload, create uncertainty, and reduce situational awareness during complex surface operations.

To address this issue, aviation authorities, technology providers, and airport operators should pursue greater integration between cockpit navigation systems and ATC infrastructure. Recommended measures include (1) developing real-time synchronization between Airport Surface Detection Equipment, Model X (ASDE-X), ATC displays, and cockpit moving-map systems; (2) implementing standardized digital taxi clearances that can be transmitted directly to EFBs; and (3) incorporating cockpit - ATC discrepancies into mandatory retraining scenarios to strengthen pilots' ability to identify and resolve conflicting information. Improving consistency between ATC instructions and cockpit navigation data could reduce communication errors, increase predictability during taxi operations, and strengthen overall situational awareness.

Recommendations for Future Research

Future research should expand beyond pilot perspectives to include air traffic controllers, ground personnel, and airport operators. A multi-stakeholder approach would provide a more comprehensive understanding of the operational, technological, and organizational factors that contribute to runway incursions. Longitudinal studies should also examine how pilot perceptions and safety practices change as technologies such as Runway Status Lights (RWSL), Airport Surface Detection Equipment, Model X (ASDE-X), and remote tower systems become more widely implemented.

Additional research should evaluate the cost-effectiveness of runway-safety infrastructure at smaller airports to help aviation authorities prioritize limited resources and identify scalable mitigation strategies. Finally, future studies should examine the use of artificial intelligence (AI) and machine learning (ML) for predictive conflict detection, including their ability to identify emerging runway conflicts before they develop into serious incidents. Together, these research directions could support more proactive, data-driven, and equitable approaches to improving runway safety across diverse airport environments.

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