



AIRPORT GUIDE TO

Runway Safety Technologies

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Introduction

Purpose and Scope of This Guide

The purpose of this white paper is to evaluate the main factors that contribute to potential risk related with runway safety and to identify effective strategies and technologies to reduce runway-related incidents and accidents. It aims to provide a comprehensive understanding of the risks associated with runway operations.

The guide aims to:

- Raise awareness of runway safety as a key and critical component of overall aviation safety.
- Analyse trends and common causes of runway incursions, excursions, and confusion.
- Share best practices, lessons learned, and technological innovations that enhance runway safety.
- Support decision-makers, airport operators, and regulators in developing data-driven policies and procedures.
- Promote alignment with regulations and/or standards led by international and regional organizations such as ICAO (International Civil Aviation Organization), FAA (Federal Aviation Administration) and EASA (European Union Aviation Safety Agency).

The scope of this paper includes the following areas:

Types of runway safety events: runway incursions, excursions, confusion, related with the simultaneous use of one single runway or conflicts on crossings or converging runways.

Review of regulatory international or regional frameworks and global initiatives towards runway safety.

Human factors: Analysis of pilot, air traffic controller and ground personnel performance, including communication awareness, fatigue and training.

Airport infrastructure and design: Review of runways and taxiways layout, airfield ground lighting, markings and signage.

Technology and innovation: Evaluation of existing technology towards enhancing runway safety and potential innovation solutions to increase safety.

Case studies and lessons learned: Analysis of historical runway accidents and incidents related to runway safety and lessons learned.

Future challenges and recommendations: Identification of emerging risks (traffic growth, mixed operations, climate change impacts).

Definition of Runway Safety

According to the ICAO Runway Safety Team Handbook, the following definitions should be considered to frame the runway safety:

Runway Safety: The state in which risks associated with the operation of aircraft on runways are reduced and controlled to an acceptable level.

Runway Incursion: Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and take-off of aircraft.

Runway Excursion: Any occurrence at any aerodrome involving the departure, wholly or partly, of an aircraft from the runway in use during take-off, a landing run, taxiing or manoeuvring.

Runway confusion: An error when an aircraft makes “unintentional use of a wrong runway or taxiway for landing or take-off” usually due to lack of situational awareness.

Note: In the context of runway incursions, the protected area of a surface designated for the landing and take-off of aircraft is comprised of: the runway; the stop way; the runway end safety area (RESA); the area along each side of the runway whose width is the runway-holding position distance; and, if provided, the clearway.

Importance Of Runway Safety In Global Aviation

Whilst commercial air travel is agreed to be the safest mode of transportation, in the recent past the highest risk for a severe incident or accident is during take-off, landing or whilst crossing an active runway.

For many airports, especially at major hubs, runways have become the natural bottleneck of the entire operations during peak hours. According to the Eurocontrol Aviation Outlook 2050, demand for air traffic in Europe is expected to grow by 44% by 2050 compared to 2019 levels. However, Eurocontrol expects that European airports will be unable to accommodate between 3 and 12% of this forecasted demand by 2050.

In Europe, most of the Tier 1 and many Tier 2 airports are operated by private companies and, since it is very difficult and costly to increase runway capacity, there is a strong focus on making best use of the existing physical capacity through smart procedures and technology increasing the already high traffic on the runways even further.

This, together with the relatively high probability of fatalities with runway incidents and accidents, shows the importance of additional measures to maintain or even further increase the current level of runway safety at airports. The most common critical events on or around runways are Runway Incursions, Runway Excursions and Runway confusion, which are typically linked to the simultaneous use of a single runway or conflicts on crossing or converging runways.

Executive Summary

Runway Safety is one of the most critical challenges in global aviation today. While flying remains exceptionally safe, growing traffic demand combined with capacity constraints at airports, complex airfield layout and climate change leading to more frequent extreme weather conditions increase ground operations risks, especially those around runways (incursion, excursion and confusion). Hence, the main international organisations leading civil aviation (ICAO, FAA, EASA, Eurocontrol) have addressed runway safety through detailed reports (Global Runway Safety Action Plan – ICAO; National Runway Safety Plan 2024-2026 – FAA; Annual Safety Review 2025 – EASA; Global Action Plan for the Prevention of Runway Incursions – Eurocontrol).

Looking back, the available official statistics from existing aviation authorities and airport operators show that a ROM for the number of runway incursions per one million of flights can be around 33-62. Looking ahead, the increasing traffic and operational complexity will intensify runway safety challenges. To address these risks, traditional measures such as operational procedures, training and static safety infrastructure will no longer be sufficient. Airport operators, civil aviation authorities, air navigation service providers and other stakeholders, will need to accelerate the adoption of technological solutions that enhance situational awareness, reduce human workload, provide warnings and alerts and hence, reduce the risk of potential mistakes that can result in incidents on and around runways.

While covering the entire problem area of Runway Safety, this paper mainly focuses on the available and future technical solutions to prevent runway-ops related incidents. These solutions may vary depending on the local infrastructure and operations at a given airport, but generally airport operators and air navigation service providers take a layered approach to safety, introducing as many safety layers as possible and needed to reduce the likelihood and severity of runway events. These safety layers are composed of different technological solutions:

Standard Solutions that have already shown effectiveness and are widely implemented, like stop bars and lead-on/lead-off lights.

Regional Solutions that have been adopted regionally, like RWSL under FAA (type of ARIWS), that has shown significant results reducing runway incursions.

Early Adoption Solutions that have been adopted in few cases, like Follow-the-Greens, but that has also proven reduction of incursions after its implementation.

Innovative Solutions like Adaptive Airfield Lighting (already considered by Eurocontrol), that will add another safety layer to the airfield lighting system without significant CAPEX.

In conclusion, significant improvements in runway safety depend on a good risk assessment, a solid operational concept and safety culture, continuous training and the implementation of layered technological solutions and safety nets. By combining these elements, the aviation industry can preserve capacity, while progressing towards the long-term goal of reducing runway incursions and serious runway incidents to a minimum.

Runway Safety Overview

Types of Runway Safety Occurrences

1

Runway Incursions

Runway incursions are any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and take-off of aircraft. According to the “Manual on the Prevention of Runway Incursions” (ICAO), common scenarios include:

1. An aircraft or vehicle crossing in front of an aircraft landing.
2. An aircraft or vehicle crossing in front of an aircraft taking off.
3. An aircraft or vehicle crossing the runway holding position marking.
4. An aircraft or vehicle unsure of its position and inadvertently entering an active runway.
5. A breakdown in communications leading to failure to follow an air traffic control instruction.
6. Conflicting (ATC-)clearances leading to the unintended presence of two different aircraft or one aircraft and one ground vehicle on a runway simultaneously.
7. An aircraft passing behind an aircraft or vehicle that has not vacated the runway.

2

Runway Excursions

Runway excursions are any occurrence at any aerodrome involving the departure, wholly or partly, of an aircraft from the runway in use during take-off, a landing run, taxiing or manoeuvring. Most of the scenarios include:

1. A destabilized or long landing aircraft resulting in insufficient runway remaining for safe deceleration.
2. A contaminated or under slippery conditions runway leading to hydroplaning.
3. A high-speed rejected take-off with insufficient stopping distance available.
4. A loss of directional control during landing due to crosswinds, surface condition, including errors on runway condition assessment.

3

Runway Confusion

Runway confusion is any error when an aircraft makes “unintentional use of a wrong runway or taxiway for landing or take-off”. Most scenarios include:

1. An aircraft lining up or landing on the wrong runway, due to misidentification in complex runway layouts.
2. An aircraft using a taxiway instead of a runway for take-off or landing because of inadequate airfield lighting or markings.
3. Confusion between parallel or intersecting runways, particularly at airports with similar runway designators or geometry.
4. Misinterpretation of air traffic control clearances, leading to aircraft positioning for taking-off or landing on an unintended runway.
5. An aircraft operating under reduced or low visibility conditions (night operations, fog, glare, precipitation) causing loss of situational awareness during final approach, or taxiing.
6. Outdated, incorrect or misinterpreted aeronautical information or charts, resulting in incorrect runway selection.



Relevance for this guide.

This document focuses on operational measures as well as infrastructure and technology improvements for airports and Air Navigation Service Providers (ANSPs) to improve runway safety and mainly addresses Runway Incursions and Runway Confusion with the related mitigations and safety nets.

Runway excursions are an equally important safety hazard, whereas a large part of the related safety and training actions are with the aircraft operators and flight crews combined with Met-Services and runway condition reporting as well as proper runway maintenance by the airport which is not in the main scope of this document.

Global and regional safety analysis

Runway safety has been systematically addressed by international and regional organizations, such as ICAO, FAA, EASA and Eurocontrol:

- **ICAO:** The second edition of the Global Runway Safety Action Plan was released in February 2024. The Global Runway Safety Action Plan provides recommended actions for all runway stakeholders, with the aim of reducing the global rate of runway excursions and runway incursions.
- **FAA:** National Runway Safety Plan (NRSP), 2024-2026, released in May 2024. This NRSP describes how FAA, airport operators, and aviation industry stakeholders collaborate and use data-driven, risk-based decision making to enhance the safety performance in the runway environment and the NAS (National Airspace System).
- **EASA:** Annual Safety Review 2025. The European Union Aviation Safety Agency (EASA) published the Annual Safety Review (ASR) 2025, which provides a comprehensive analysis of aviation safety in 2024 and compares it with trends from the past decade.
- **Eurocontrol:** Global Action Plan for the Prevention of Runway Incursions (GAPRI), published on August 2024. This document consists of a general introductory part, followed by a part with detail recommendations per stakeholder and a longer part with guidance and explanatory material for various stakeholder groups.

Under the leadership of ICAO, IATA, ACI World, CANSO, Eurocontrol and the Flight Safety Foundation more than 200 aviation experts from 100 organisations have been involved in developing the Global Action Plan for the Prevention of Runway Incursions (GAPRI).

GAPRI lists the following findings as the most common contributors to runway incursion incidents:

Variability in human performance:

Events caused or negatively influenced by issues like distraction, miscommunication, misidentification, or misapplication of operational processes.

Lack of systemwide collision avoidance barriers:

Unlike the collision avoidance system (ACAS/TCAS) in the air, there is no universally implemented last line of defence against runway collisions.

Degraded runway status awareness:

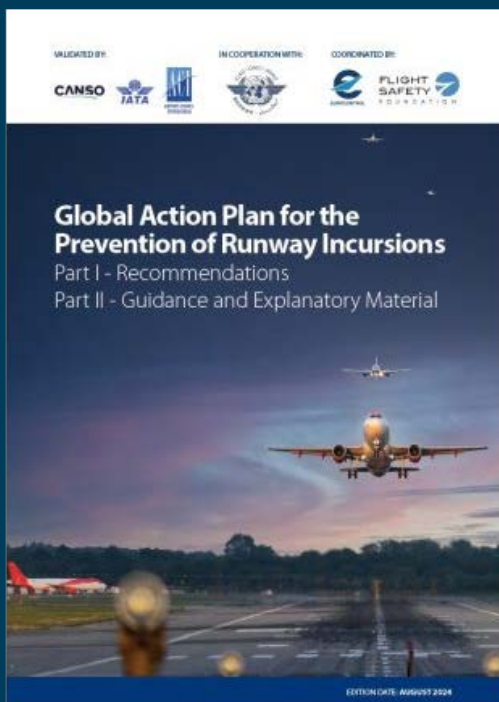
More than one-third of high-risk runway incursions could have been averted through better situational awareness technologies for pilots and air-traffic controllers. This includes technologies like stop bars, Runway warning lights and Alerting Systems and Safety-Nets for controllers.

Miscommunication and coordination:

A prevalent theme across incidents is the apparent breakdown in communication and coordination between air traffic control and pilots. This includes simultaneous clearances given to aircraft on the same runway, aircraft crossing paths due to misunderstood instructions, and inefficiencies in communication among manoeuvring area vehicle drivers because of language barriers or differing communication channels.

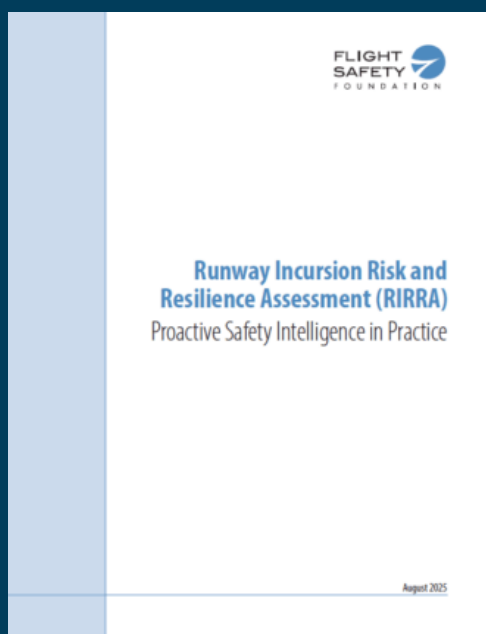
Challenges in surface navigation:

Incorrect positioning of aircraft or manoeuvring area vehicles on runways due to inaccurate position awareness or navigation routing points to potential procedural lapses, inadequacies in navigation capabilities and guidance, or insufficiencies in aerodrome signage, markings and lighting.



To address these findings, GAPPRI provides a set of >100 recommendations across stakeholder groups, including airport operators, ANSPs (Air Navigation Service Providers), aircraft operators, manufacturers, national governments and regulators as well as organisations involved in research and development. With the main target to address risks and provide resilience, the recommendations include:

- Training and equipment for staff.
- Risk mitigation through infrastructure design.
- Integration of advanced technologies.
- Enhanced procedures for runway operations.
- Enhanced aerodrome visual aids.



With contribution from numerous renowned experts from the aviation industry, GAPPRI has become the first reference document for runway incursion prevention. Therefore, this document builds upon the recommendations of GAPPRI with the aim to give a more detailed insight into the technical solutions available on the market to enhance airside operational safety, especially on and around runways.

▲ Past GAPPRI recommendations

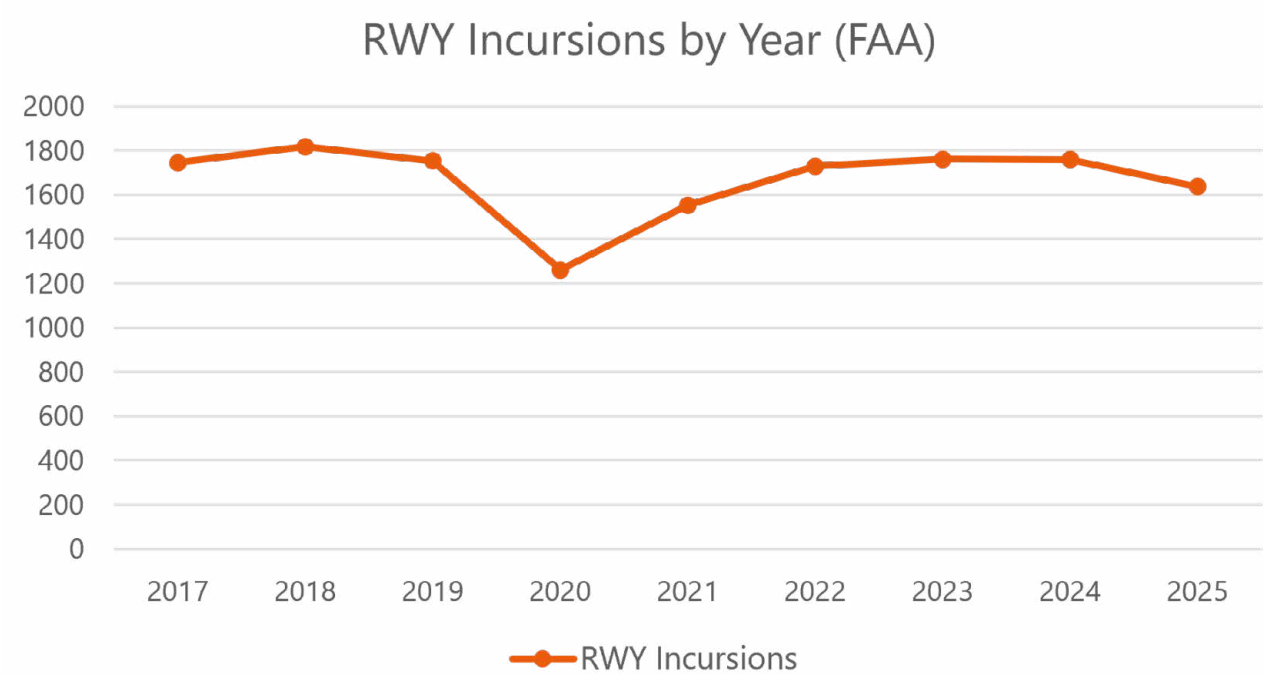
High-risk operational environments

Whilst there is no central reporting data hub providing comprehensive figures for Europe, FAA publishes the number of runway incursions by quarter, classified as operational incident, pilot deviation, vehicle or pedestrian deviation or others. For example, considering runway incursions alone, in 2025, the FAA recorded 1,636 events. The numbers can be assumed in a similar range, which explains why runway safety has become a key focus area of all aviation authorities, e. g. ICAO, FAA, EASA, Eurocontrol and others.

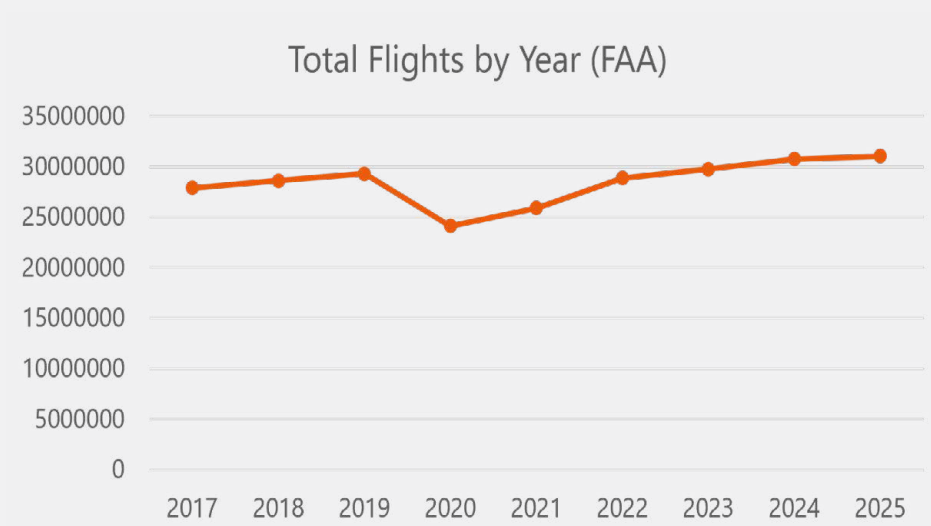
Considering FAA statistics, it can be assumed 6 runway incursions per 100,000 flights, which is aligned with other official statistics, for example, at Brussels Airport where Skeyes, in its “Runway Performance Report 2023”, indicated 6.2 runway incursions per 100,000 movements. According to the “Global Action Plan for the Prevention of Runway Incursions”, by Eurocontrol, the frequency of runway incursions during 2022 was 33 per one million take-offs and landings. Therefore, it can be concluded that a ROM for the number of runway incursions per one million of flights can be 33-62.

6 runway incursions per 100,000 flights

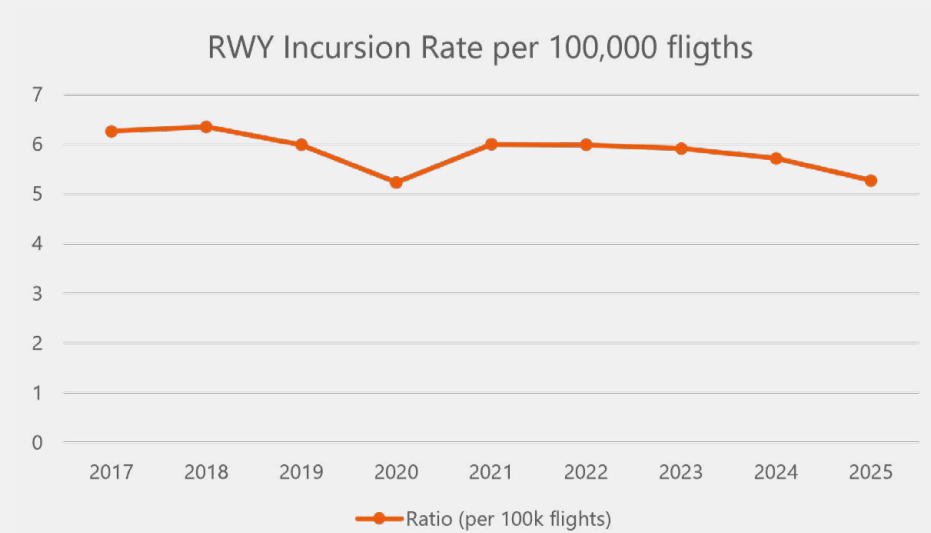
33-62 incursions per one million flights



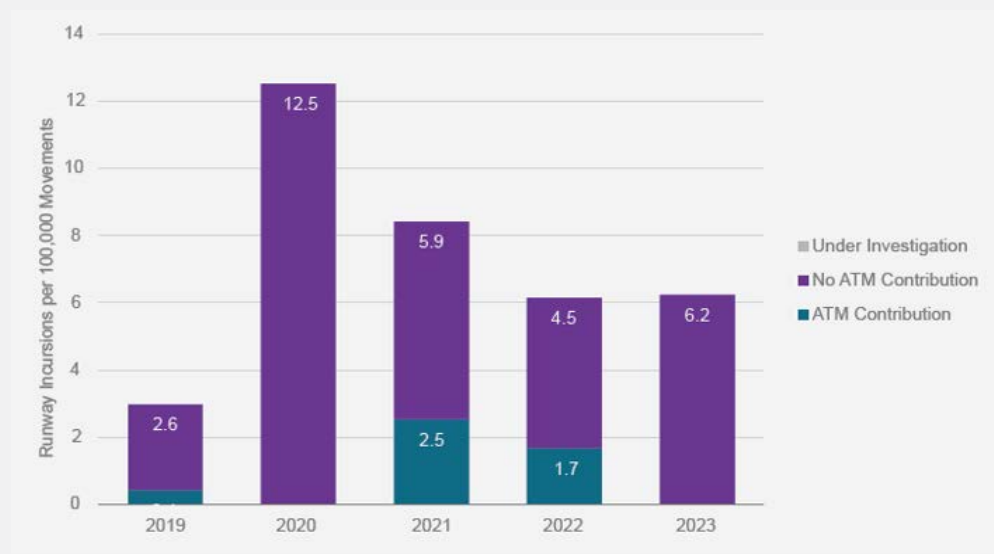
▲ Figure 1 – Runway Incursions by Year © by FAA (faa.gov/airports/runway_safety/statistics)



▲ Figure 2 – Total IFR Flights by Year © by FAA ([faa.gov/air_traffic/by_the_numbers](https://www.faa.gov/air_traffic/by_the_numbers))



▲ Figure 3 – Combination of values from figures 1 and 2



▲ Figure 4 – Yearly rates of runway incursions per 100,000 movements by ATM Contribution (Skeyes RWY Performance Report 2023 – Brussels Airport)

However, not all airports are affected at the same level. There are multiple factors determining the risk of critical events on runways including but not limited to:

- Traffic density.
- Predominant weather conditions.
- Airport layout and runway configuration.
- Operational procedures.
- Technical environment (Nav Aids, Surveillance, Lighting & Signage, etc.).
- Collaboration of stakeholders (Airport / ANSP).

As already mentioned, the risk of a critical event increases with the volume of traffic on a given runway, irrespective of whether it is a major multi-runway hub or a busy single runway airport. A higher traffic density does imply lower margins and thus less room for error.

Weather, especially low visibility, rain, snow or any combination of these events can drastically reduce the efficiency of visual aids such as markings, signage and lighting and lead to a loss of situational awareness, which is a frequent cause for runway incidents.

The layout of airport airside infrastructure is also a frequent and important cause of safety hazards. The first category of airports with an increased risk are those with crossing or converging runways, which naturally require a deconfliction for all aircraft using them. Some examples of this kind of layout are the airports of Zurich, Hamburg, Prague, Dublin, New York JFK, New York LGA, Washington Reagan, and Chicago Midway.

Another category are airports with closely spaced parallel runways which are typically used in a segregated mode (dedicated arrival and departure runways). This setup usually results in aircraft having to cross one of the runways either after landing or prior to take-off on the other. Examples of this runway layout are Frankfurt, London Gatwick, Paris CDG, Manchester as well as many of the North American hubs like Dallas, Atlanta, and Chicago O'Hare.

The third category of airports are those with terminal, cargo or maintenance infrastructure on different sides of one runway which increases the likelihood of unintended runway crossings by aircraft and vehicles. On the other hand, airports with a midfield Terminal and two parallel runways at the airport's perimeter such as Munich are less likely to see this kind of incursion.

Based on the risk factors mentioned in the previous paragraph, it can be concluded that Runway Safety is an important goal for airports of all sizes and categories. However, depending on the individual airport's infrastructure, meteorological conditions, operational procedures, technical equipment, safety culture, etc., the overall degree of risk as well as specific local risk categories may vary. Therefore, every single identified risk factor needs to be addressed by specific organizational, operational, and technical measures locally, with examples described in more detail in the following sections.

Regulatory and Standards Framework

International Standards and Guidance

The International Civil Aviation Organization (ICAO) has published several different documents addressing the design and safe operations of runways, the most relevant being:

- Runway Safety Programme – Global Runway Safety Action Plan.
- Annex 10 – Aeronautical Telecommunication.
- Annex 14 – Aerodromes.
- Annex 19 – Safety Management.
- Doc. 4444 – Procedures for Air Navigation Services (PANS) – ATM.
- Doc. 9157 – Aerodrome Design Manual.
- Doc. 9830 – Advanced Surface Movement Guidance & Control Systems.
- Doc. 9859 – Safety Management Manual.
- Doc. 9870 – Manual on the Prevention of Runway Incursions.
- Doc. 9881 – Procedures for Air Navigation Service (PANS) – Aerodromes.
- CIR 326 AN/188 – Assessment of ADS-B and Multilateration Surveillance to support ATS.

Regional and National Regulatory Requirements

The Federal Aviation Authority (FAA) has published several different documents addressing the design and safe operations of runways, the most relevant being:

- National Runway Safety Plan 2024-2026.
- AC 150/5210-20, Ground Vehicle Operations on Airports.
- FAA Order JO 7110.65BB – Air Traffic Control.
- Part 139 – Certification of Airports.
- AC 150/5340-1, Standards for Airport Markings.
- AC 150/5340-18, Standards for Airport Sign Systems.
- AC 150/534-30J Design and Installation Details for Airport Visual Aids.
- AC 150/5345-46E, Specification for Runway and Taxiway Light Fixtures.
- AC 150/534-26C, Maintenance of Airport Visual Aid Facilities.

The European Union Aviation Safety Agency (EASA) has comprehensive framework and guidance to minimize runway incursions and enhance runway safety in Europe, being the most relevant:

Regulation (EU) No 139/2014

Aerodromes, in particular, Annex III (Part-ADR.OPS), documents ADR.OPS.B.040 – Runway Incursion Prevention, and ADR.OPS.B.045 – Low Visibility Operations.

Regulation (EU) No 923/2012

SERA (Standardized European Rules of the Air), in particular, documents SERA.3210 – Right-of-Way & SERA.8005 – Operations of air traffic control service.

Regulation (EU) No 965/2012

Air Operations.

European Action Plan for the Prevention of Runway Incursions (EAPPRI), which was superseded by the Global Action Plan for the Prevention of Runway Incursions (GAPPRI).



Case Studies and Lessons Learned

Summary of latest runway accidents and incidents

The following list includes recent major accidents or incidents related to runway safety, including runway incursions and confusion. All examples are real incidents from the past 5 years which have been anonymized for the purpose of this paper.

Incident 1, February 2026

Runway confusion:

An Airbus A320 mistakenly lined up on a parallel taxiway confusing the taxiway with the runway (07R) during low visibility conditions (night operation), after taxiing through a complex intersection, classified as Hot Spot in the AIP Charts of the airfield. The aircraft then commenced a take-off roll which was aborted through intervention by ATC. The incident emphasized the need for hot spot alerts.

Incident 2, January 2024

Runway incursion, collision:

An A350 and a Dash 8 collided on runway (34R/16L) after the Dash 8 had entered the runway without clearance during low visibility conditions.

Incident 3, January 2023

Runway incursion, near-miss collision:

A B737 was cleared to take-off on runway (04L). Twenty seconds after the B737 plane began its take-off roll, a B777 crossed the runway without clearance. The Airport Surface Detection Equipment issued acoustic and visual alerts in the air traffic control tower, warning of a potential collision. Five seconds after the alerts, the controller cancelled the take-off clearance of the B737 aircraft, which quickly decelerated from its top speed as the B777 was crossing in front of it and avoided a collision.

Incident 4, February 2023

Runway incursion, near-miss collision:

A B767 was cleared to land on runway (18L) and had also approved a B737 to take-off using the same runway. The B767 crew realized they were about to land on top of the B737 and called for the B737 crew to abort the take-off. The B767 then aborted their landing.

Contributing factors and potential mitigation strategies

The main contributing factors and potential mitigation strategies for the mentioned accidents/incidents could be summarized as follows:

Incident 1, February 2026

Runway confusion:

Main Contributing Factors:

- Low visibility conditions (night operations).
- Hot Spot complexity (included in AIP Charts).
- Pilot stress level and loss of situational awareness.

Potential Mitigation Strategies:

- Hot Spot alert.
- Pilot briefing/training.
- Improved airfield ground lighting, signage, marking. (e.g. advanced ground lighting features (Adaptive Lights)
- Implementation of A-SMGCS Routing and Guidance Services (Follow-the-Greens).

Incident 3, January 2023

Runway incursion, near-miss collision:

Main Contributing Factors:

- Conflicting Air Traffic Control Tower clearances.
- Miscommunication.
- Lack of situational awareness.

Potential Mitigation Strategies:

- Implementation of RWSL (Runway Status Lighting System).
- Improved ATC Training.
- Better pilot/ATC alerting systems.

Incident 2, January 2024

Runway incursion, Collision:

Main Contributing Factors:

- ATC Communication breakdown.
- Low visibility conditions (night operations).
- Pilot misidentification.

Potential Mitigation Strategies:

- Advanced Surface Movement Guidance (A-SGMCS).
- Implementation of RWSL (Runway Status Lighting System).
- Stricter LVP protocols.
- Improved coordination
- Improved airfield ground lighting technologies or solutions.

Incident 4, February 2023

Runway incursion, near-miss collision:

Main Contributing Factors:

- Low visibility.
- Multiple simultaneous operations.
- Delayed detection by ATC (Air Traffic Control)

Potential Mitigation Strategies:

- Implementation of RWSL (Runway Status Lighting System).
- Better pilot/ATC alerting systems.
- LVP training.



Infrastructure and Airport Design

To minimize runway incursions or confusion, and, therefore, to enhance runway safety, one of the most important areas is the proper design of airside infrastructure, together with operational procedures and staff training to minimise risk of incidents in a way that is reducing the risk of incidents to a minimum. In addition to measures related with airside infrastructure design, technology also plays a key role and contributes to assuring required safety levels related to runway safety.

Location of Runways

From a design point of view, ideally runways should be positioned at the perimeter of the airport. With no operational areas beyond the runway, safety will increase automatically as there is no operational need for runway crossings by aircraft and vehicles. One good example of this kind of layout can be found at Munich Airport with a pair of parallel runways and the Terminal as well as all airside operational areas located between them.



Figure 8 – Areal picture of Munich Airport (MUC) © by Google

Perimeter Taxiways vs. Runway Crossings

For airports where this layout is not possible and where there is an operational need for aircraft and vehicles to get to the other side of an operational runway the safest method is to avoid runway crossings by designing a perimeter taxiway leading aircraft around the runway ends to the operational areas on the other side.



Figure 9 – Areal picture of Frankfurt Airport (FRA) © by Google

However, due to lack of space, building perimeter taxiways is not always possible in existing airport infrastructures. And where there is the required space, the expected safety benefits have to be carefully balanced with the considerable infrastructure costs and the increase in taxi-time resulting in additional fuel-burn and potentially ground delays.



Figure 10 – Areal picture of Paris CDG Airport (CDG) © by Google

Where there is no perimeter, a combination of operational and technical measures shall be used to safeguard the necessary runway crossings and reduce the risk of incidents to a minimum (see subsequent chapters).

Crossing Runways

A completely different challenge for Runway Safety is crossing or converging runways where departing and/or arriving aircraft are on crossing trajectories by design and the operational risk of a runway accident is considerably higher as in parallel operations. A very prominent example of this can be observed at Zürich airport (Switzerland) with crossing and converging runways as well as regular runway crossings by taxiing aircraft.



▲ Figure 11 – Areal picture of Zürich Airport (ZRH) with crossing and converging runways © by Google

Runway crossings are crucial parts of an aircraft or vehicle's ground trajectory as they involve an increased risk for severe incidents and accidents with fast moving aircraft on the runway. This is why ICAO recommends to limit crossings to a minimum. Where runway crossings are unavoidable, ICAO Annex 14, Attachment A, Chapter 22 gives clear guidelines on taxiway design for minimizing the potential for runway incursions. Some of the most relevant recommendations are:

Perpendicular crossings:

"The centreline of an entrance taxiway should be perpendicular to the runway centreline, where possible. This design principle provides pilots with an unobstructed view of the entire runway, in both directions, to confirm that the runway and approach are clear of conflicting traffic..."

Linear (straight) crossings:

"Build taxiways that cross a runway as a single straight taxiway. Avoid dividing the taxiway into two after crossing the runway. This design principle avoids constructing "Y-shaped" taxiways known to present risk of runway incursions".

No crossings at high energy points (mid-runway):

"This design principle helps to reduce the collision risks at the most hazardous locations (high energy location) because normally departing aircrafts have too much energy to stop, but not enough speed to take off, before colliding with another errant aircraft or vehicle."

Whereas points 1 and 2 are purely design aspects, point 3 also has an operational component requiring the definition of standard taxi-routes which take into account the principle of runway crossings at low-energy locations.



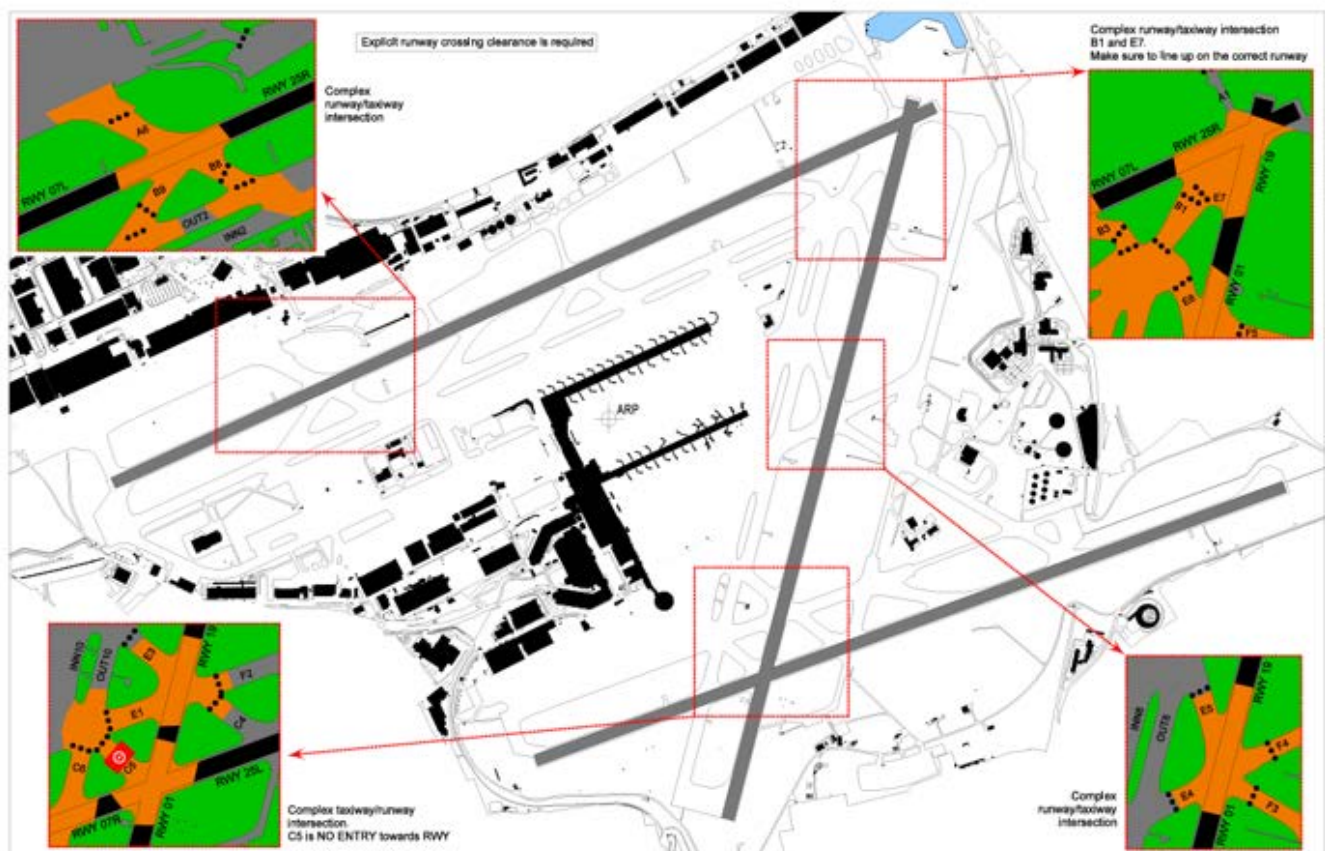
Hot spot identification and mitigation

Complex and critical areas of the airside infrastructure are usually described as “Hot Spots” in a special chart of the airport’s AIP to raise the attention of the flight crews and drivers.

Hot Spots are typically located at complex intersections, unusual taxiway layouts, or places where visibility, signage, or markings may be challenging.

As all other runway entries/crossing points these locations are highlighted and protected by airfield ground lighting, marking, signage and potentially additional technical systems, but due to the complex layout, pilots who do not often operate at the respective airport still may find difficult orientation and adherence to an assigned taxi-route.

It is essential to know the location of the Hot Spots to reduce the risk of runway incursions. These areas are classified due to a documented history, background or potential for confusion, miscommunication, or navigation errors that could lead to unauthorized runway entries. By identifying and highlighting these locations – both on airport charts and through pre-flight briefings – pilots, ground vehicle operators, and air traffic controllers can pay extra attention, anticipate possible risks, and exercise heightened vigilance when operating in or near them. This targeted awareness enables more cautious manoeuvring, better communication, and stricter compliance with clearances, all of which are critical for preventing potential runway or taxiway incursions. Ultimately, knowledge of the location of the Hot Spots supports staff involved in airport operations to proactively manage and mitigate the risks inherent in these vulnerable areas, enhancing overall runway safety.



▲ Figure 12 – Complex Runway entries and crossings at Brussels Airport (BRU) (Source: AIP Belgium)

Role of airfield ground lighting in runway safety

Airfield Ground Lighting (AGL) plays a crucial role in preventing runway incursions and reducing confusion for pilots and vehicle operators by providing clear, unambiguous visual guidance, especially at runway entrances, intersections, and taxiway crossings. Systems such as stop bars, runway guard lights, and lead-on/off lights ensure that only authorized movements occur onto active runways, supporting compliance with air traffic control clearances and minimizing the risk of uncontrolled incursions. By enhancing situational awareness and offering real-time, dynamic routes, airfield ground lighting significantly mitigates the potential for incursion events and operational misunderstandings.

However, while these lighting systems are highly effective for incursion prevention and avoiding misunderstandings when taking-off or landing, their influence on runway excursions (events where an aircraft overruns the runway), is limited, as excursions are more often related to factors such as weather, aircraft performance, and approach stability, rather than guidance or markings provided by ground lighting.



On the other hand, depending on the criteria of the civil aviation authority or international aviation regulators, runway entrance confusion (where an aircraft mistakenly enters an active runway without proper clearance or where an aircraft uses a taxiway as a runway), is often classified as a runway incursion. This type of event (runway confusion) can be considered within the definition of a runway incursion, as it represents an authorized presence on the runway, potentially creating hazardous conflicts with other aircraft movements and compromising overall runway safety.

Operational Procedures

General Recommendations

Regarding operational procedures and training, the Global Action Plan for the Prevention of Runway Incursions (GAPPRI) document provides a list of recommendations for Airport Operators and other stakeholders including but not limited to:

- Implementation and regular meetings of Local Runway Safety Teams (LRST).
- Ensuring harmonised awareness of runway incursion risk and sharing of lessons learned.
- Constant (re-)evaluation of the consistency of runway safety procedures for operations on the manoeuvring area of the aerodrome.
- Ensuring that new aerodrome infrastructure and changes to existing infrastructure and temporary infrastructure associated with aerodrome construction Works in Progress (WiP) are designed to reduce the likelihood of runway incursions.
- Including runway incursion risks and mitigations within initial and refresher/recurrent training of operational staff with periodical assessments and updates of the content.
- Define and re-assess training for manoeuvring area driver permits in a way it includes the most up-to-date requirements and infrastructure schemes.
- Constantly re-assess radio-communication procedures and language proficiency of drivers in the manoeuvring area where a language different to the local language is used on the communication channel.
- Reduction of the workload for runway- and ground-controllers, pilots and vehicle drivers to allow for a stronger focus on situational awareness.

Phraseology and communication standards

According to the European Action Plan for the Prevention of Runway Incursions from Eurocontrol, studies of investigation reports, and surveys regarding runway safety occurrences, communication issues are frequently a causal or contributing factor that affect runway safety. Some examples of factors leading to communication breakdown on the manoeuvring area include, among others:

- Complex instructions to different aircraft.
- Controller / pilot / service vehicle driver high speech rate.
- Two different languages being used.
- Use of non-standard EU / ICAO phraseology.
- Absent, poor or incomplete readback.
- Inadequate aviation English.
- Heavily accented English.
- Different frequencies associated with runway operations.

Entering a runway (to line up or cross) or landing without a valid ATC clearance will lead to incorrect presence of traffic on a runway and require a runway incursion to be reported.

Numerous studies and safety reports highlight that miscommunications between pilots, air traffic controllers, and ground service vehicle drivers contribute to runway incursions. Because verbal instructions can be misunderstood or misheard (especially in high workload or low visibility environments), implementing technologies that provide direct, unambiguous visual cues without relying on radio communications is crucial. Such systems deliver immediate, automated visual feedback about runway and taxiway status, reducing the risk of human error or misinterpretation. By eliminating the dependency on verbal exchanges for critical stop-or-go decisions, these technologies add a robust layer of safety, ensuring that essential information reaches pilots and vehicle operators clearly and instantly, thus significantly lowering the risk of runway incursions caused by communication breakdowns.

Low visibility and adverse weather operations

Regarding low visibility and adverse weather condition reports like the Global Runway Safety Action Plan (Runway Safety Programme, ICAO, February 2024) identify the Meteorology as a one of the Top Contributing Factors leading to runway incursions, including poor visibility, rain, snow, icing conditions (that may obscure visual aids and hinder visual observation), and it recommends the following action:

Action No. 7 to Aircraft Operators: “Equip aircraft with technologies to assist in improving situational awareness especially during low-visibility operations, such as Improved Resolution Airport Moving Maps, Electronic Flight Bags, Enhanced Vision Systems and Head up Displays (HUD) .”. (Contributing Factor: Active Human Performance; Meteorology: Runway Incursions).

Besides, the Global Action Plan for the Prevention of Runway Incursion (Eurocontrol) identifies “Follow-the-Greens” as a system that minimises the number of conflicts on taxiways enabling smoother traffic flows. The “Follow-the-Greens” system was validated as part of SESAR 2020 PJ03a-01 initiative and has been shown to be very effective in low visibility conditions. The system improves the situational awareness of pilots taxiing on the airfield, and, besides, it also helps reducing ATC workload.

Adverse weather and low visibility conditions increase the risk of runway incursions by degrading situational awareness and making it more difficult for pilots and vehicle drivers to navigate the airfield safely. In such environments, technologies that can provide and improve clear and real-time visual guidance offer a powerful means to prevent runway incursions or confusion even under the most challenging weather conditions, supporting both safety and continuity of operations when visibility is at its lowest.

Standard Operating Procedures (SOPs) and Stakeholder Collaboration

Based on the regulatory framework, technical standards and the recommendations highlighted in the previous chapters, the airport operator and the local ANSP need to derive a concept of operations and the resulting Standard Operating Procedures (SOPs) for the specific airport.

These SOPs are designed to guarantee the safe and efficient flow of aircraft from approach to departure and must take into account local specifics such as terrain, airport infrastructure, traffic mix and specific weather conditions.

The communication and training of these procedures as well as the collaboration between all stakeholders at the airport, including also airlines, military, maintenance & construction teams, ground handlers regulators and other state-entities, on a daily basis is absolutely essential to achieve a high level of safety.



Human Factors in Runway Safety

Human Factors and the coordinated involvement of all airport stakeholders (Aircraft operators and flight crew, Air Navigation Service Providers – ANSPs, ground vehicle operators) are key to improve runway safety and minimize any kind of runway incursions or confusions. Many incidents happen not only from technical failures, but from miscommunications or lack of proper communication, situational awareness, proper follow-up of procedures among pilots, air traffic controllers, ground vehicle operators, etc.

Each stakeholder brings unique perspectives and responsibilities, making collaboration vital for identifying risks and implementing effective solutions. Regular training, clear communication protocols, and a shared safety culture help ensure that everyone understand their role and can respond rapidly to changing conditions.

The Global Runway Safety Action Plan (ICAO) addresses the different actions related to Human Factors by groups of stakeholders to minimize runway incursions.

Aircraft Operators

The main actions related to Human Factors to be addressed by Aircraft Operators are:

1. Ensure flight crew complete Crew Resource Management (CRM) and Threat and Error Management (TEM) training addressing runway incursion prevention with emphasis on team decision making, effective monitoring and appropriate Pilot Monitoring (PM) intervention.
2. Implement policy and training that clearly define actions for Pilot Flying (PF) and Pilot Monitoring (PM), including intervention by PM.
3. Provide training and assessment for flight crew regarding aerodrome signs, markings and lighting.
4. Ensure pilots are made aware of any safety significant airport information.
5. Ensure flight crew awareness of relevant aerodrome works (WIP – Work In Progress).

Air Navigation Service Providers

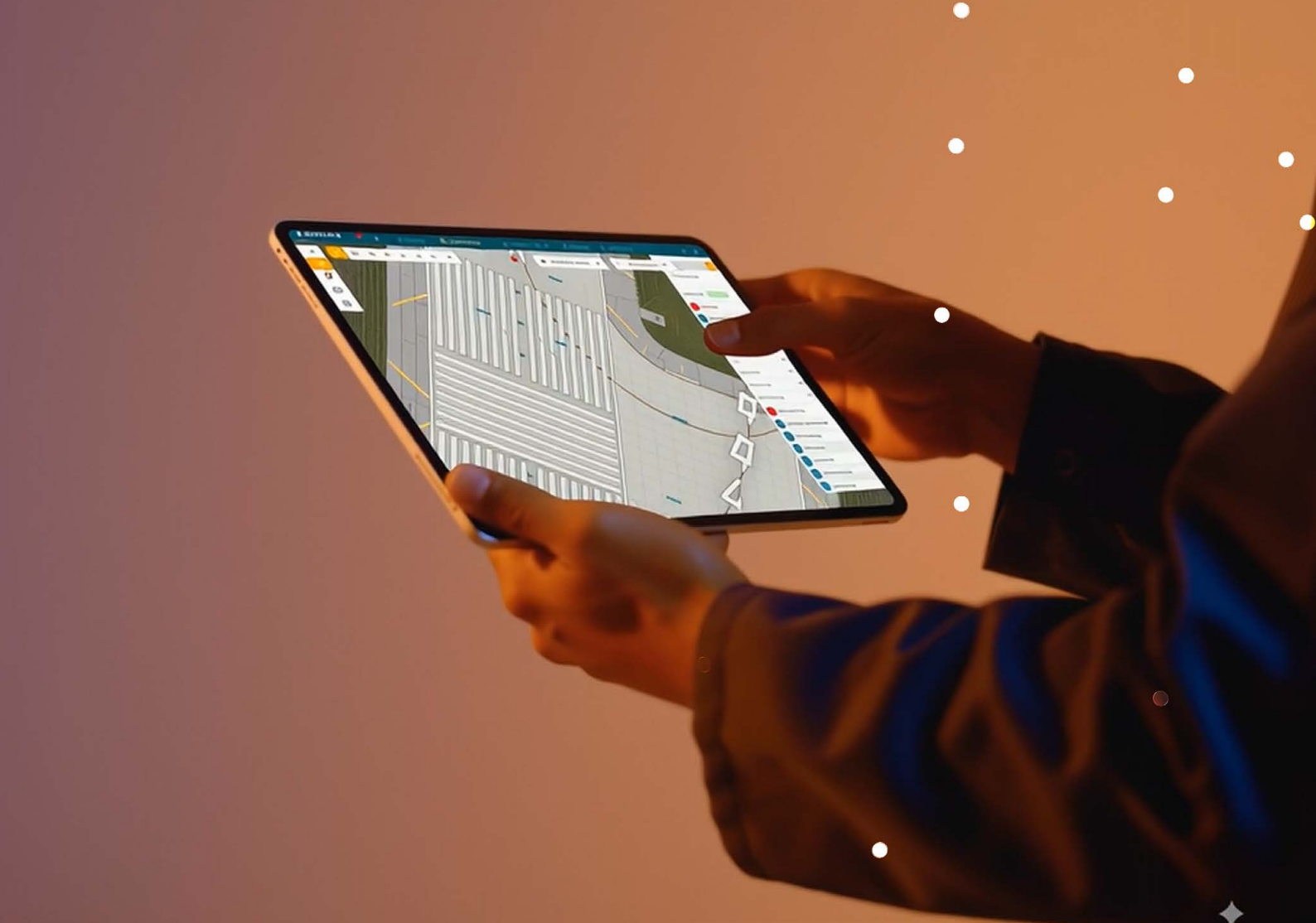
Human Factors are also a key topic for Air Navigation Service Providers with the main actions being:

1. Ensure that runway safety is included in initial and refresher training for Air Traffic Control staff.
2. Enable controllers to maintain a “heads up” visual observation of all parts of the manoeuvring area, as far as practicable, whilst taking into consideration the availability and use of technologies (e.g. A-SMGCS).
3. Ensure air traffic controllers are informed about aerodrome Work In Progress (WIP).
4. Ensure proper coordination and contingencies agreed with Aerodrome Operator during WIP.
5. Ensure that all air traffic controllers are aware of runway incursion “Hot Spots” (including changes) and associated mitigations.

Aerodrome Operator

For Aerodrome Operators, the main actions that should be addressed with regards to Human Factors are:

1. Conduct local runway safety awareness campaigns.
2. Establish and implement a formal “manoeuvring area driver training and assessment programme” and review driver guidelines with a focus upon: improving training in adverse weather conditions (particularly in low visibility) and driving at night, and ensuring that procedures for the control of all vehicles are developed and implemented in coordination with air traffic control.
3. Ensure effective and coordinated procedures for the activation and deactivation of Low Visibility Procedures (LVP) are in place.
4. Identify and periodically review local runway incursion “Hot Spots” using reports, investigation and other suitable data.
5. Ensure all relevant stakeholders (ANSPs, Operators, etc.) are properly informed of WIP, in advance.
6. Coordinate and communicate the WIP of risk analysis with relevant stakeholders.
7. Ensure that any signs that may cause confusion during WIP in progress are correctly concealed.



Technology and Systems

Infrastructure and operational measures lay the foundation for a safe and orderly operation of the airport's manoeuvring area. However, for most airports, these measures are complemented and enhanced by technological systems to guarantee an optimum level of safety. These systems can vary from simple installations such as lights and signs in combination with ground markings to more complex installations integrating the usage of Ground Surveillance Systems, Advanced Surface Movement Guidance Systems (A-SMGCS), Runway Status Lights (RWSL; type of ARIWS – Airport Runway Incursion Warning System) and others.

There are numerous technologies available today that play a key role to minimize the risk of runway incursions, each one adding a new protection layer to runway operations. The purpose of deploying different technologies is to overlap safety layers that work together to detect, prevent, and mitigate the potential of unauthorized runway entries.

Aviation accidents or incidents, such as runway incursions or confusions, are rarely due to one single cause, but a combination of different potential causes (weather conditions, miscommunications, maintenance issues, etc). The Swiss Cheese model, originally proposed by James Reason, is a risk management theory that illustrates accidents resulting from multiple, accumulated failures in layered defences. The principle of safety layers – where different systems complement and back up one another – means that if one layer is breached or a human error occurs, there are other technologies in place to provide alerts or automatically intervene.

In this case, the potential accident or incident would be a runway incursion or confusion, and the different layers will be technologies that can be implemented to minimize the risk of such situation:

- **Basic Runway Protection Systems**
 - Markings and Signage
 - Stop Bars and Runway Guard Lights.
 - Lead-on/Lead-off Lights.
 - Surveillance Systems (MLAT, ADS-B, SMR)
 - Onboard Vehicle Navigation System
 - Integrated Controller Working Position (iCWP)
- **Advanced Runway Protection Systems**
 - Sensor-based runway entry protection.
 - ARIWS (Airport Runway Incursion Warning System) &
 - RWSL (Runway Status Lights).
 - Runway Incursion Alerting System (RIAS)
 - Final Approach Runway Occupancy Signal (FAROS)
 - Follow-the-Greens (FtG).
 - Adaptative Lights (ADAL).



Basic runway protection systems

To protect runways from any type of incursions ICAO has foreseen so-called Runway-Holding Positions at entry and crossing points to runways (roads and taxiways). The location of such holding positions is described in detail in ICAO Annex 14 (chapter 3.12.):

“The location of a runway-holding position ... shall be such that a holding aircraft or vehicle will not infringe the obstacle free zone, approach surface, take-off climb surface or ILS/MLS critical/sensitive area or interfere with the operation of radio navigation aids.”

This implies that for CAT II/III instrument runways, at every runway entrance, there are usually 2 separate holding points in place, one closer to the runway for CAT I operations and one at a greater distance taking account of the wider ILS protection zone in CAT II/III operations.

There is a combination of basic measures and infrastructure to highlight runway-holding positions to aircraft pilots and vehicle drivers which usually include:

- Taxiway Markings and Signage
- Stop Bars and Runway Guard Lights
- Lead-on / Lead-off Lights

All of the above are efficient means to provide situational awareness and information on the potential danger of entering a runway ahead, without requiring any kind of on-board equipment in the aircraft or vehicle.

1. Taxiway Markings and Signage

Runway-holding position markings together with the respective signage as specified by ICAO Annex 14 are the standard means for situational awareness with regards to runways and build the first line of defense. Typical setups look as follows:



▲ Figure 13 – Markings and signage at CAT II/III Holding Position at Frankfurt Airport (Source: Fraport AG)

2. Stop Bars and Runway Guard Lights

The provision of stop bars will significantly increase the visibility of runway holding positions, especially at night and in low visibility conditions and should be part of effective runway incursion prevention measures.

Stop bars consist of a row of unidirectional, red, in-pavement lights spaced 3m. apart across a taxiway, plus elevated red lights on each side, indicating a mandatory stop before a runway. They are usually paired with green “lead-on” lights and are used in low visibility conditions (RVR,500m.). Runway Guard Lights (RGLs) are flashing yellow “wig-wags” (pair of elevated or row of in-pavement) used to highlight holding positions.

The installation aims to protect runway entries and reduce the risk of runway incursions in all weather conditions. Prior to entering a runway, pilots and vehicle operators are required to hold short of the stop bar and obtain a clearance from ATC (Air Traffic Control). Once the clearance is provided the stop bar will be switched off and the mobile can continue to enter the runway safely.

With regards to the usage of Stop Bars, recently, the European Union Safety Agency (EASA) issued a Safety Information Bulletin on 13th October 2025, stating that the Global Action Plan for the Prevention of Runway Incursions (GAPRI) recommends the implementation of continuous (H24) stop bar use, as it ensures that the critical boundary of the runway is clearly marked at all times.



Configuration of Stop Bars (ICAO/FAA):

- Lights: Unidirectional, showing red toward the approaching aircraft.
- Placement: Installed at runway holding points, typically perpendicular to the taxiway centreline.
- Operation: Activated by ATC; lights must be switched off to clear the aircraft to entry the runway.
- Components: In-pavement lights, plus elevated light on both sides of the taxiway.

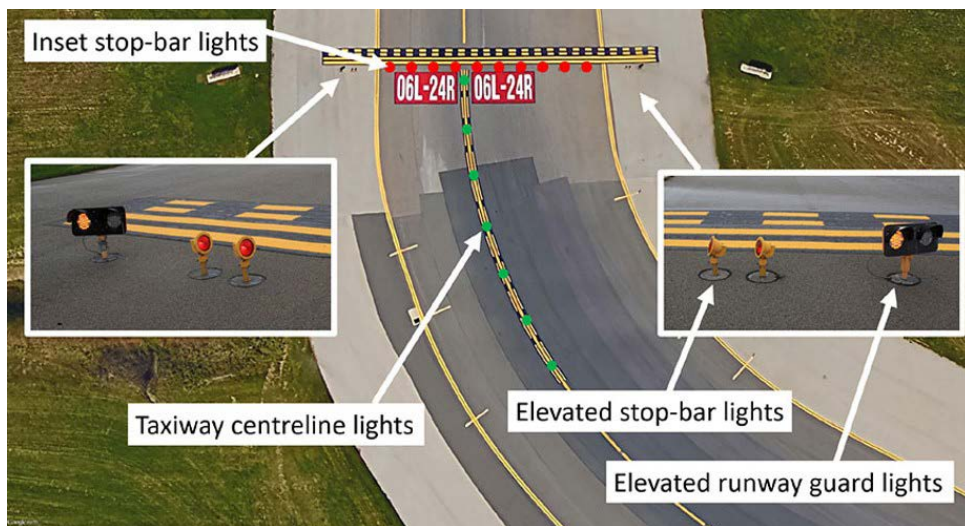
Configuration of Runway Guard Lights (RGL):

- Configuration A (Most Common): A pair of elevated, flashing yellow lights located on either side of the taxiway at the holding position.
- Configuration B: A row of in-pavement yellow lights across the taxiway.
- Operation: Flash at 30-60 cycles per minute, alternating (left side, then right side).
- Purpose: Increase situational awareness of the holding point, especially in low visibility conditions, but do not replace stop bars.

Operational integration:

- Stop bars: Require a complete stop of the aircraft in front of the stop bar until switched-off.
- Runway Guard Lights: Supplement stop bars to enhance visibility of the intersection.
- Interlocking: Stop bars are often linked with taxiway centreline lights (green) to provide a guided, safe path.

◀ *Figure 14 – Stop bar lights are an effective barrier, but often used only in LVC (Source: ICAO)*



◀ **Figure 15** – Stop bar lights and RGLs configuration with Taxiway Centerline lights (Source: tsb.gc.ca)

3. Lead-on/Lead-off Lights

Lead-off Lights are alternating green and yellow taxiway centreline lights that guide pilots to leave the runway through a taxiway. Lead-off lights direct aircrafts exiting the runway:

Lead-off lights guide the aircraft off the runway onto a taxiway, often a high-speed exit or rapid exit taxiway. These lights guide pilots from the runway centreline to a taxiway.

Appearance: these lights consist of alternating green and yellow lights embedded in the pavement.

Direction/Colour pattern: Green lights start on the runway centreline, transitioning to alternating green/yellow, and finally just yellow to lead the aircraft out of the runway hold area.

Safety purpose: These lead-off lights warn pilots they are within the runway safety area or Instrument Landing System (ILS) critical area.

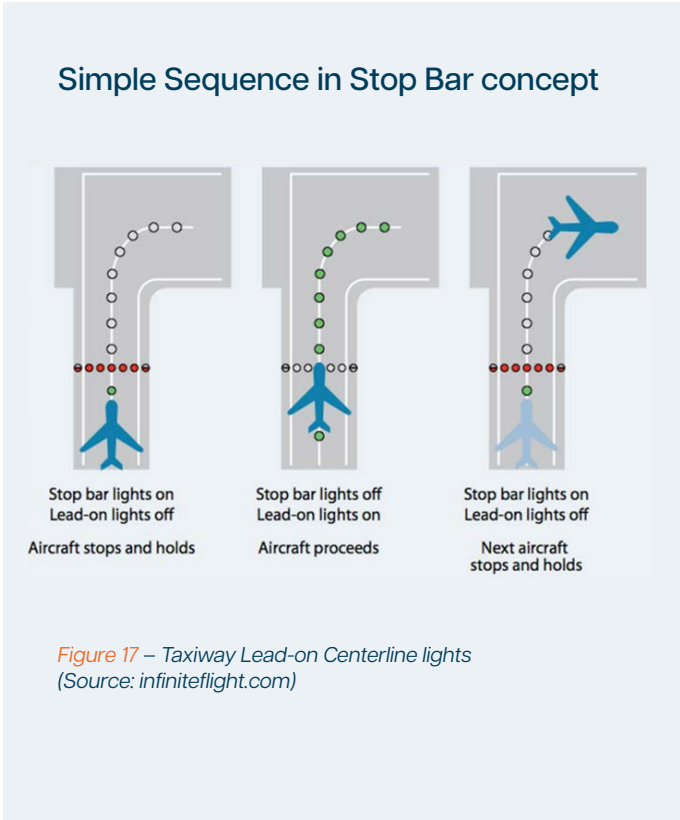
Lighting type: The fixtures used for these are often bidirectional, meaning the same light can function as a lead-on or lead-off light depending on the direction of travel.



▲ **Figure 16** – Taxiway Lead-off Centerline lights (Source: pilotinstitute.com)

Lead-on Lights are green taxiway centreline lights that guide pilots to enter the runway through a taxiway. Lead-on lights direct aircrafts entering the runway:

- Lead-on lights guide the aircraft on the runway through a taxiway, often a runway entry taxiway. These lights guide pilots from the taxiway, crossing the holding position, onto the runway centreline.
- Appearance: these lights consist of green lights embedded in the pavement.
- Direction/Colour pattern: Typically, these lights start at the taxiway and lead the aircraft onto the runway, often paired with stop bars to indicate the aircraft is approaching the runway hold position.
- Lighting type: The fixtures used for these are often bidirectional, meaning the same light can function as a lead-on or lead-off light depending on the direction of travel.



Lead-on lights can be switched on either automatically based on the selected taxi route or manually by ATC (Air Traffic Control). The lights then guide the pilot along their allocated route. These lights are typically controlled by the Airfield Lighting Control and Monitoring System (ALCMS) and are illuminated only when an aircraft has received clearance from ATC to enter, line up, or cross the runway. By providing a clear visual cue for pilots, lead-on lights help prevent unauthorized or accidental runway entries, significantly reducing the risk of runway incursions. Their potential integration into an Advanced Surface Movement Guidance and Control System (A-SMGCS) would enable dynamic, real-time management of runway access, reinforce procedures compliance and enhance runway safety.

Surveillance Systems (SMR, MLAT, ADS-B)

Surveillance systems at airports are essential for reducing the risk of potential runway incursions by providing real-time, comprehensive situational awareness of all aircraft and vehicle movements on the airfield. Technologies such as Surface Movement Radar (SMR), Multilateration (MLAT), and Automatic Dependent Surveillance - Broadcast (ADS-B) enable air traffic controllers to precisely track the position and identity of all ground traffic, even in complex layouts or low-visibility conditions. This enhanced visibility allows controllers to detect unauthorized entries, potential conflicts, or deviations from clearances early, enabling timely intervention before a dangerous situation develops.

Additionally, when integrated with advanced alerting systems and safety nets, surveillance data can automatically trigger warnings or activate specific lighting systems, further supporting proactive incursion prevention. By continuously monitoring and analyzing ground activity, surveillance systems form the backbone of an effective, layered defense against runway incursions.

1. Surface Movement Radar - SMR

SMR (Surface Movement Radar) is a conventional NON-cooperative surveillance sensor, specifically designed to detect all moving targets on the surface of an airport, including aircraft and vehicular traffic. The resulting comprehensive image is displayed on a radar indicator console in the control tower to augment visual observation of aircraft and/or vehicular movements on runways and taxiways by tower personnel.

In the absence of visual observation of all or part of the manoeuvring area or to supplement or (in poor visibility) replace visual observation, SMR may be utilised to:

- Enhance the controllers' situational awareness regarding the manoeuvring area.
- Monitor the movement of aircraft and vehicles on the manoeuvring area.
- Provide routing information to pilots and vehicle drivers as necessary; and
- Provide advice and assistance for the safe and efficient movement of aircraft and vehicles on the manoeuvring area.

The SMR uses the working principle of the Primary Surveillance Radar (PSR), i.e. emits a signal which is reflected by the target and the echo received is used to determine the range and bearing of the target. The SMR is often mounted on top of the ATC Tower which provides good visibility of the manoeuvring area. Despite the location, an important disadvantage of this technology is that the SMR's line of sight may be blocked by large airport terminal buildings, hangars and other obstacles, and it is also affected by heavy rain.

2. Multilateration Detection System- MLAT

MLAT (Multilateration) is considered a co-operative surveillance technique, combining a dependence on target-derived data for identification and altitude with ground-based calculation of position. MLAT is a key technology for precise real-time tracking of aircraft and vehicles on airport surfaces and in terminal airspace. MLAT can achieve a higher update rate than a typical rotating radar, determined by the intervals between aircraft transmissions (responses).

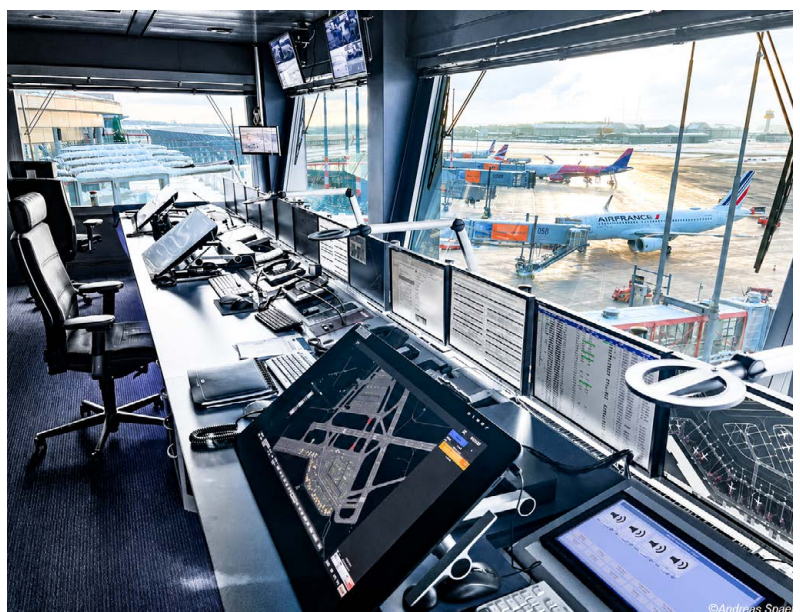
MLAT is particularly useful for tracking older aircraft not equipped with ADS-B, as it works with standard transponders, ensuring comprehensive, 3D surveillance on the ground. , An MLAT system consists of the following components:

- A transmitting subsystem that includes interrogation message generation and transmission function.
- An optional intelligent interrogation process that determines whether an MLAT interrogation is required.
- A receiving antenna array subsystem that receives the transmission from the target and timestamps receipt at each antenna.
- A central processor that calculates and outputs the MLAT tracks.

Multilateration is a proven technology that has been in use for many decades. It was developed for military purposes to accurately locate aircraft. Multilateration requires a number of ground stations which are placed in strategic locations around the airport to ensure proper coverage. MLAT ground stations receive replies from all transponder-equipped aircraft (Mode A/C/S transponder signals) and vehicles and determine aircraft position based on the time difference of arrival (TDOA) of the replies.

In addition to the position of an equipped mobile, MLAT also provides the identification of the target based on the transmitted transponder-ID which can be correlated with the aircraft registration and from there with further operational data, e.g. aircraft type, flight-number / callsign, origin / destination, etc. This together with label deconfliction and other advanced features led to a wide use of MLAT-based A-SMGCS installations at major airports globally, making a major contribution to the reduction of runway incursion incidents.

However, since MLAT is by nature a co-operative sensor which depends on the signals sent by the transponder of a mobile, it is usually complemented by a non-cooperative sensor such as an SMR to also detect mobiles without or with a non-functioning transponder. To guarantee only one single track per target with the best possible precision, the signals from the various sensors are weighed and fused by a Sensor Data Fusion (SDF) module before being displayed to the controller.



3. ADS-B (Automatic Dependent Surveillance-Broadcast)

ADS-B (Automatic Dependent Surveillance-Broadcast) is also considered a co-operative surveillance technique and is a key technology for precise real-time tracking of equipped mobiles on airport surfaces and in terminal airspaces. Aircraft and vehicles use GPS to calculate their position, which is then broadcast via a transponder along with identification, altitude and velocity data (ground speed) to ground-station receivers. ADS-B improves airport safety by tracking ground vehicles, reducing taxiway collisions, enhancing runway safety, and providing surveillance in areas when radar is not cost-effective or possible.

ADS-B relies on aircraft or airport vehicles broadcasting their identity, position, and ground speed from onboard systems. This signal (ADS-B Out) can be captured for surveillance purposes on the ground (ADS-B Out) or on board other aircraft (ADS-B In) in order to facilitate airborne traffic situational awareness, spacing, separation and self-separation (ADS-B In, also known as “ADS-B airborne surveillance”).

The ADS-B data transmitted are defined in the relevant standards and certification documents (e.g. EASA AMC 20-24 for ADS-B in Non-Radar Airspace or CS-ACNS for “ADS-B Out”). They include (among others) the following:

- Aircraft horizontal position (latitude/longitude).
- Aircraft barometric altitude (the same as for the SSR – Secondary Surveillance Radar).
- Quality indicators.
- Aircraft identification (Unique 24-bit aircraft address, Aircraft ID, Mode A code in the case of CS ACNS for “ADS-B Out”).
- Emergency status.
- SPI (special position indicator) when selected.

ADS-B based ground surveillance has recently entered regulation and standardization under the Eurocontrol Surface Movement Awareness System (SMAS) initiative. The main advantage over MLAT based surveillance is the relatively low installation cost with only very few ground stations needed for an entire aerodrome.

A major disadvantage of ADS-B / SMAS is its dependency on the GPS-derived position of the mobile, which does not come with an estimated level of accuracy of the mobile’s reported position. This involves the risk of compromised position data in case of defect GPS receivers or during events of GPS jamming or spoofing, which ultimately may result in an outage of the entire system.

4. Other Surveillance sensors

In a multi-sensor surveillance environment, typically at major airports, additional types of sensors may be deployed at specific points throughout the manoeuvring area, e.g. in the vicinity of runways, to add a layer of protection.

Typical installations consist of microwave radars, LIDAR sensors, earth-magnetic-field sensors, induction loops or a combination of several of these sensors. The installation can either be part of a local installation as for example a Sensor based Runway Incursion Protection (chapter 9.5.1) or embedded in an overarching A-SMGCS environment, acting as an additional data source for the Sensor Data Fusion.

Onboard Vehicle Navigation System

As a basic safety functionality, especially for complex and high traffic-density airports, all critical vehicles operating on runways and taxiways (e.g. fire-fighting, airside operations, snow removal, maintenance,...) are generally equipped with Mode-S transponders to ensure they will be tracked and identified by the surveillance system and can trigger alerts in the safety relevant systems.

Additionally, such vehicles can be equipped with a moving map display showing the vehicle's position on the airfield and providing basic alerting functions e.g. for entering restricted areas such as runway strips or ILS protection zones. If the system is connected to the security operations center and the airport's surveillance system, e.g. through a proprietary 5G connection, it can also display the mission target, route to the target as well as the position and ID of all other aircraft.



Showing the surrounding traffic in addition to the own position considerably increases the situational awareness of the drivers, and warnings and alerts provided by the on-board system add an additional layer of safety and help to prevent incidents on runways.

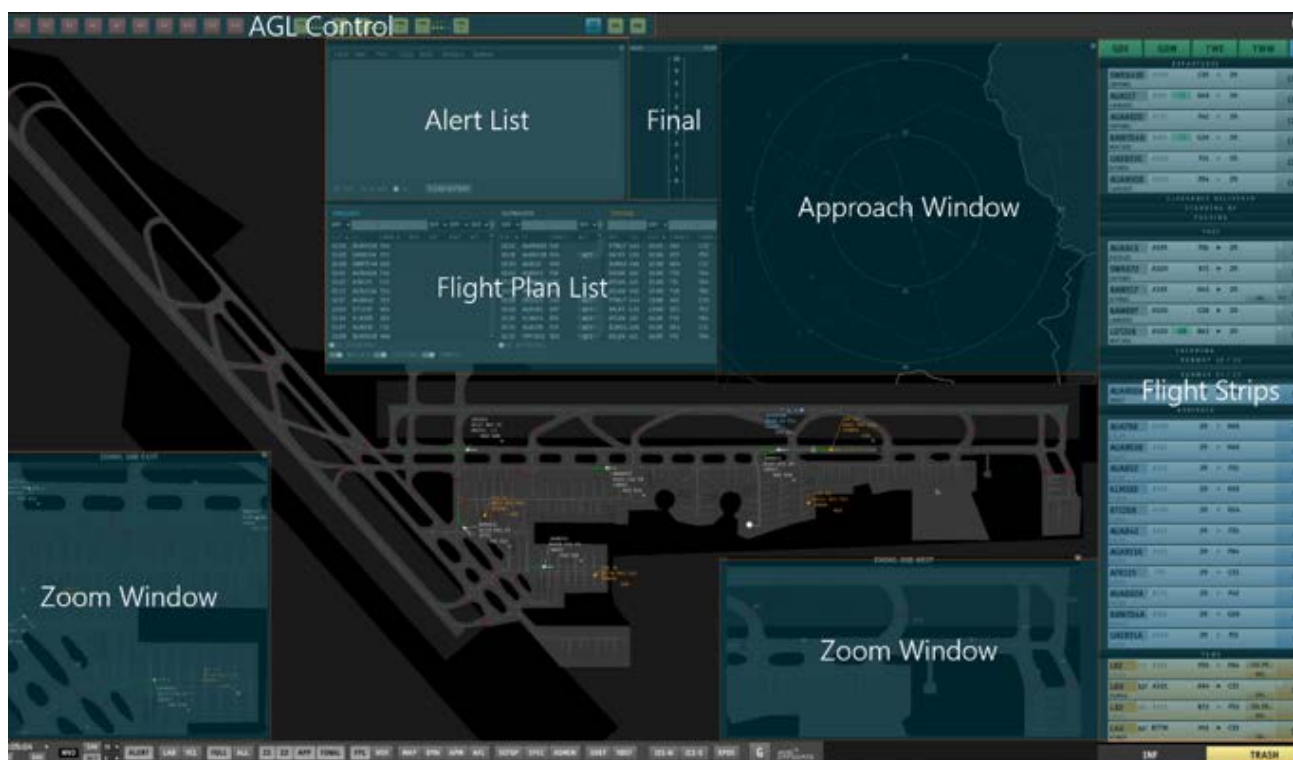
▲ Figure 18 – Airport Vehicle Onboard Navigation System (Source: www.rosenbauer.com)

Integrated Controller Working Position (ICWP)

Another key building block for a safe runway operations is an integrated Controller Working Position in the ATC Tower. An iCWP unites surveillance, communication, planning and decision support tools together into a single, Human-Machine Interface (HMI).

The iCWP integrates several core functions, which have previously been provided by separate systems, leading to an increased situational awareness and faster, more accurate decision making. These core functionalities include:

- **Approach Radar Picture** as received from ATC - usually in a separate window
- **Electronic Flight Strip (EFS) System** providing an overview of the status of all movements as well as the planned sequence of flights across all positions
- **Routing and Guidance Services** enabling de-confliction of traffic and automated switching of Airfield Ground Lighting (see 9.6 and 9.7)
- **Ground Surveillance Picture** with a detailed synthetic map of the airport layout and all identified labeled ground targets
- **Airport Safety Support Tools** providing all sorts of alerts and conflicts detected by the system to the controller and potentially also conflict resolution proposals
- **Digital Voice Communication System** (may also be provided on a separate console)



▲ Figure 19 – Integrated Controller Working Position for Vienna Airport (© ADB SAFEGATE)

The main advantages of combining all these functionalities in an iCWP are:

- **Real-Time Information Sharing:** All ATC (Air Traffic Control) controllers and relevant stakeholders see the same, up-to-date information instantly, improving coordination and situational awareness.
- **Automated Alerts and Safety Nets:** the iCWP will generate automatic warnings for conflicting clearances, missed readbacks, potential runway incursions or conformance monitoring.
- **Improved Efficiency and Reduced Workload:** Routine tasks such as strip marking, handover, and coordination are streamlined, saving time and reducing workload.
- **Comprehensive Data Recording:** Digital recordings provide a comprehensive and clear data-set for incident investigation and operational analysis.
- **Seamless Integration** with other systems allow for an easier management of intersecting runways, multiple taxi routes, and dynamic changes, especially at busy or complex airports.

Advanced runway protection systems

In addition to the basic runway protection infrastructure (chapter 9.1), there are several advanced systems on the market to further increase the safety of runway operations. All of them are either based on local sensors or input from surveillance systems and include different degrees of automation. The main different installation are described in the following paragraphs. Local installations may differ slightly in their setup and naming:

- Sensor-based Runway Incursion Protection
- Autonomous Runway Incursion Warning System (ARIWS)
- Runway status lights (RWSL)
- Runway Incursion Alerting System (RIAS)
- Final Approach Runway Occupancy Signal (FAROS)

1. Sensor-based Runway Incursion Protection

To minimize the risk of runway incursions, multiple suppliers have deployed sensor-based solutions to protect runway entries. These solutions involve installing local sensors such as microwave radars, LIDAR sensors, earth-magnetic-field sensors, induction loops or a combination of several of these sensors at a runway holding position (stop bar):

- The sensors located before the stop bar detect the presence of an aircraft correctly stopped before the holding position.
- Depending on the installed sensor(s) and their placement, the system can create a movement profile of the mobile and predict if it will still be able to stop before the designated holding-point (stop bar)
- The sensors located just after the stop bar detect if the aircraft has crossed the holding position.
- If the sensors located just after the stop bar detect the presence of the aircraft while the stop bar is still red (no ATC clearance), then the system will automatically generate an incursion alert transmitted via the ALCMS to the ATC Controllers.
- An optional third set of sensors can be used to switch off the taxiway centreline lead-on lights once the aircraft has entered the runway and it is lining up, to protect for another authorized entry.

This concept is commonly combined with stop bars at runway holding positions.

2. Autonomous Runway Incursion Warning System (ARIWS)

An **Autonomous Runway Incursion Warning System (ARIWS)** is a system which provides autonomous detection of a potential incursion or of the occupancy of an active runway and a direct warning to flight crew or vehicle operator (ICAO, Annex 14, Aerodromes).

The operation of an ARIWS is based upon a surveillance system which monitors the actual situation on a runway and automatically returns this information to warning lights at the runway (take-off) thresholds and entrances. The system provides the following warnings:



When an aircraft arriving at a runway is on short final or one departing from the runway has commenced its take-off roll, red warning lights at the runway entrances will illuminate, indicating that it is unsafe to enter or cross the runway.



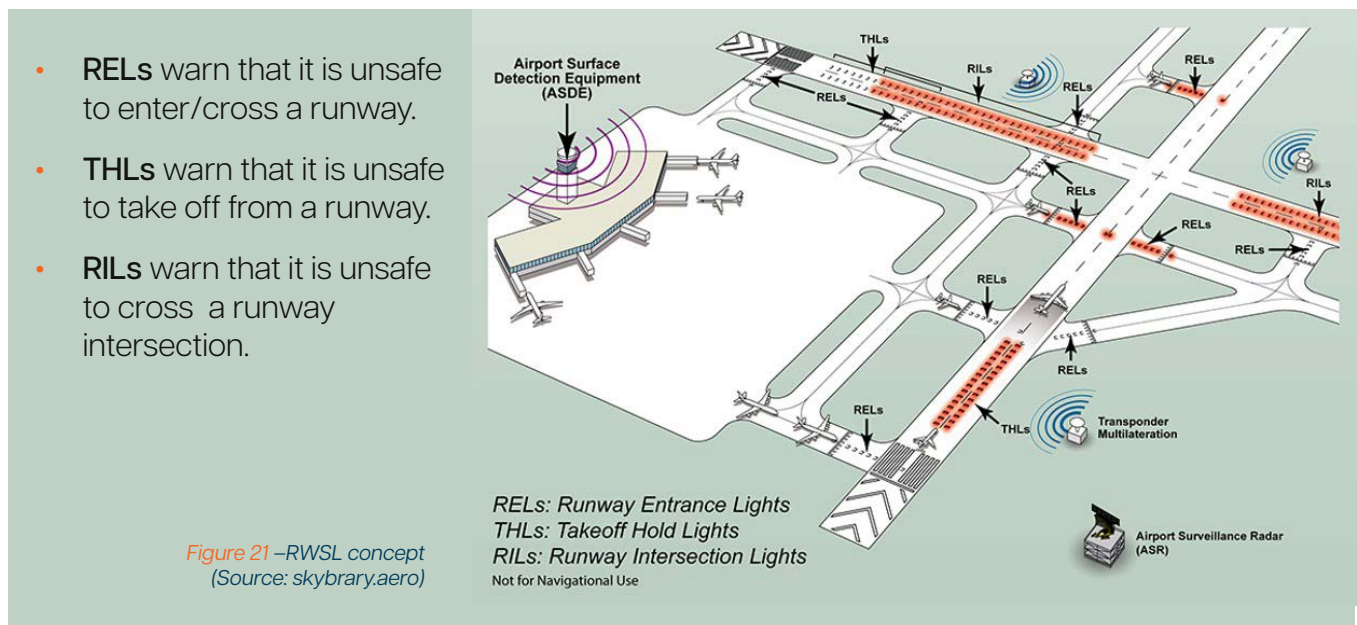
When an aircraft is aligned on the runway for take-off and another aircraft or vehicle enters or crosses the runway, red warning lights will illuminate indicating that it is unsafe to start the take-off roll.

Generally, an ARIWS consists of a surveillance system and a warning system (airfield lighting system) which are connected through a processor that generates alerts directly (autonomously, without ATC controllers' interaction) to the flight crew or vehicle operator independent of the ATC inputs or actions. Thus, when ARIWS lights are triggered, pilots and drivers are presented with a globally consistent signal meaning “STOP IMMEDIATELY”.

3. Runway status lights (RWSL)

Runway Status Light (RWSL) system is identified by ICAO as an Autonomous Runway Incursion Warning System (ARIWS). The primary goal of a Runway Status Light (RWSL) is to provide situational awareness to vehicles and aircrafts of ongoing or impending traffic on the runway strip. Practically, The RWSL system is an autonomous system, whose role is to prevent Aircrafts or Vehicles to move into or take-off at the runway strip in case it is occupied, illuminating dedicated red Runway Entrance Lights (REL), when the runway is unsafe for entry or crossing, or red Take-off Hold Lights (THL) when the runway is unsafe for departure. This is achieved by using a series of computers and industrial equipment interfaces that transfer the RWSL processor's commands to the various devices in the field; monitor their status and provide the appropriate feedback to the operator and maintenance staff.

This picture explains the concept and location of REL, THL and RIL:



The group of Runway Entrance Lights at one entrance that is operated simultaneously is called a REL segment. Similar, the group of Take-off Hold Lights at one runway which will be operated simultaneously are called a THL segment.

The control of this group of lights will be done by the RWSL field lighting process based on the surveillance data received from the A-SMGCS system. The RWSL field lighting process will send the necessary commands to the RWSL AGL system to switch ON and OFF the THL and REL group of lights.

The RWSL Logic allows the system to work autonomously, without adding workload to the Air Traffic Controllers for normal traffic. ATCs operations within the system are limited to intensity control and to turning the system “ON” or “OFF”. The last would only be needed in case of malfunctioning of the RWSL system.

The RWSL provides “calculation” of “events” based on surveillance data received from the external existing airport A-SMGCS and operates the RWSL-REL and THL ensuring pilots and drivers receive situation awareness about the use of the runway.

As noted, activation of RWSL components is completely independent and autonomous of ATC clearances and their activation is a backup safety net against human errors. However, when RWSL indications contradict clearances, pilots and vehicle drivers are expected to prioritize response to the status lights. On the other hand, the absence of RWSL indications does not equate to an ATC clearance to proceed.

To be highlighted, the Global Runway Safety Action Plan (ICAO) and the Global Action Plan for the Prevention of Runway Incursions (Eurocontrol) recommend the usage of an ARIWS (e.g. RWSL) to reduce the risk of runway incursions, in the following statements:

Global Runway Safety Action Plan (ICAO):

- Action No. 3 to Air Navigation Service Providers: “Make use of technologies (such as A-SMGCS, stop bars and ARIWS) to improve situational awareness and provide warnings of runway incursions to controllers, pilots and vehicle drivers”. (Contributing Factor: Active Human Performance; Runway Safety Priority: Runway Incursions).
- Action No. 7 to Aerodrome Operator: “In coordination with ATC, consider implementing available technologies such as A-SMGCS and ARIWS”. (Contributing Factor: Active Human Performance & Aerodrome Design; Runway Safety Priority: Runway Incursions).

Global Action Plan for the Prevention of Runway Incursions (Eurocontrol):

- Recommendation ADR20 to Aerodrome Operators: “In cooperation with ANSPs, implement H24 stop bars operation or other lighting systems (e.g., autonomous runway incursion warning system (ARIWS) at all active runway holding positions, providing an equivalent level of safety commensurate with the level and complexity of the operations and the potential risk of runway incursion.”.
- Recommendation ANSP28 to Air Navigation Service Providers: “In cooperation with aerodrome operators, implement H24 stop bars operation or other lighting systems (e.g., autonomous runway incursion warning system (ARIWS) at all active runway holding positions, providing an equivalent level of safety commensurate with the level and complexity of the operations and the potential risk of runway incursion.”.
- Recommendation AO23 to Aircraft Operators: “Aircraft operators should provide flight crews with guidance and training on ARIWS (e.g., runway status lights (RWSL)), where relevant to the operation. Guidance should include technical information, guidance on inclusion in flight crew briefings, and clear policy for dealing with activation (e.g., “Red means Stop”).”.

Recommendation REG7 to States and Regulators: “As part of the regulatory oversight, assess the operational use of aerodrome ground lighting (e.g., stop bars) to ensure a robust policy to protect the runway from the incorrect presence of traffic. Wherever practicable, the use of H24 stop bars at all runway’s holding positions should be considered, as this has been shown to be an effective runway incursion prevention barrier. The use of ARIWS at all runway’s holding positions should also be evaluated.”.

4. Runway Incursion Alerting System (RIAS)

The **Runway Incursion Alerting System (RIAS)** was developed and deployed at Frankfurt Airport by DFS and Fraport, RIAS is a sensor-based solution that monitors critical runway access points. When an unauthorized entry or crossing occurs, it issues simultaneous alerts to both controllers and pilots/vehicle operators. RIAS employs in-pavement Runway Entrance Lights (REL) at runway entry points but does not require THL along the runway itself. This localized lighting concept, combined with distributed sensors, minimizes infrastructure requirements while still delivering immediate and effective alerts. Compared with RWSL (Runway Status Lights), which proactively provides continuous occupancy status via REL and THL using airport-wide surveillance, RIAS is more targeted and reactive, detecting unsafe entries as they occur and issuing dual alerts. Its modular sensor-driven architecture makes it highly suitable for airports without comprehensive surface surveillance or those requiring more cost-efficient solutions. RIAS require stop bars.

5. Final Approach Runway Occupancy Signal (FAROS)

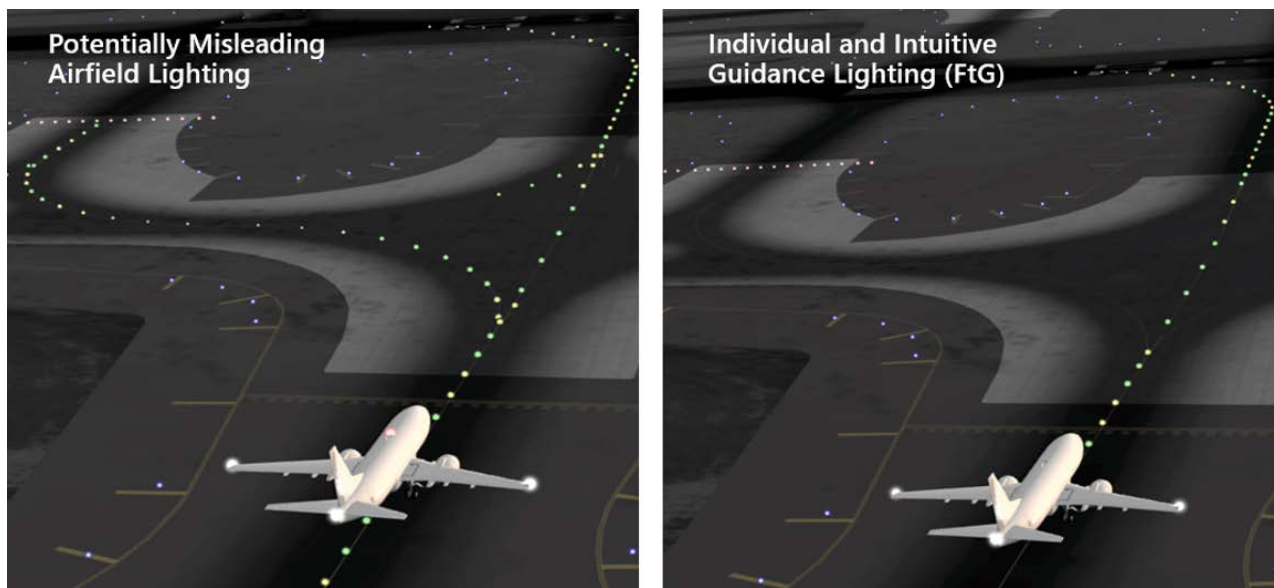
The Final Approach Runway Occupancy Signal (FAROS) was originally developed by the FAA under the Runway Incursion Reduction Program as a function of RWSL, FAROS alerts approach aircraft when a runway is occupied by flashing the Precision Approach Path Indicator (PAPI) lights, signalling pilots on final approach to execute a go-around if necessary. While FAROS is no longer part of the FAA's current Surface Safety Portfolio, ADB SAFEGATE maintains it as an active, deployable solution, enabling airports to benefit from a proven safety concept that complements other runway incursion prevention technologies with a targeted safeguard against landings on occupied runways.

Follow-the-greens (FtG)

Follow-the-Greens (FtG) is an advanced airfield guidance system that uses illuminated green taxiway centerline lights to visually direct pilots along a pre-cleared route. The system dynamically illuminates only the centerline segments relevant to each aircraft's clearance, updating in real time based on ATC instructions or advanced - surface movement guidance systems (A-SMGCS). This reduces confusion, minimizes ATC (Air Traffic Control) communication, reduces taxiway and runway incursions, and enhances situational awareness, especially in low visibility conditions or complex airport layouts.

By providing a clear, continuous visual path from runway to gate or vice versa, FtG helps prevent runway and taxiway incursions and allows for smoother ground movements, supporting both safety and operational efficiency. Unlike traditional operations, where pilots rely on static lighting and verbal communication with ATC controllers, FtG enables a continuous, unambiguous illuminated visual path that can be updated in real-time operations, based on the actual traffic on the airfield:

- Pilots follow an illuminated green path from runway to gate and/or vice versa.
- The route can be automatically updated by the Airfield Lighting Control System based on the clearances and instructions from ATC (Air Traffic Control) controllers or A-SMGCS.
- Only the taxiway centerline lights that are part of the selected route are illuminated; the rest of the lights are off, thus minimizing confusion and energy consumption.



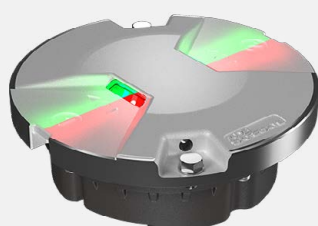
▲ Figure 22 –Improvement of situational awareness with FtG (Source: ADB SAFEGATE)

Adaptative lights (ADAL)

Adaptive Airfield Lighting is a new generation of lights that can produce multiple colour signals from a single fixture. The light's output colour can be dynamically changed between two colours via the series circuit powerline. These lights are designed to dynamically adjust colour, and operational logic based on real-time airport conditions. This functionality can be integrated with ALCMS platforms to support responsive runway and taxiway lighting control.

The aim is to improve the safety and efficiency of aircraft and vehicle movements on the airfield. Unlike static lights, adaptive lights use switchable colours to provide dynamic visual cues to pilots and ground vehicles, helping manage intersection, reducing the risk of runway incursions, hold positions, and temporary closures with greater precision.

The possible combinations of colours are:



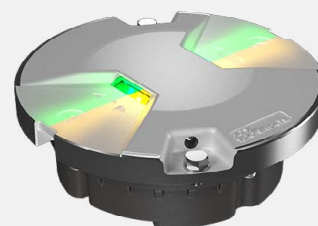
GREEN RED

Green/Red: The LEDs can change from Red to Green and vice versa. ADAL fixtures will show one colour (Green) in standard operation and red when required because of operational needs.



YELLOW RED

Yellow/Red: The LEDs can change from Red to Yellow and vice versa. ADAL fixtures will show one colour (Yellow) in standard operation and red when required because of operational needs.



GREEN YELLOW

Green / Yellow: The LEDs can change from Green to Yellow and vice versa. ADAL fixtures will show one colour (Green) in standard operation and yellow when required because of operational needs.

Side 1 of the ADALs can have a different colour combination than side 2.

Photometry and brilliancy output of ADAL are fully compliant with ICAO Annex 14 Stop Bars and Taxiway Centreline lights and applicable FAA airfield lighting standards. ADAL can be integrated with existing airport lighting systems (series circuits) and supports phased deployment strategies. The fixture operates within:

- Traditional series circuit airfield ground lighting systems with powerline communication.
- Centralised Airfield Lighting Control and Monitoring Systems (ALCMS).

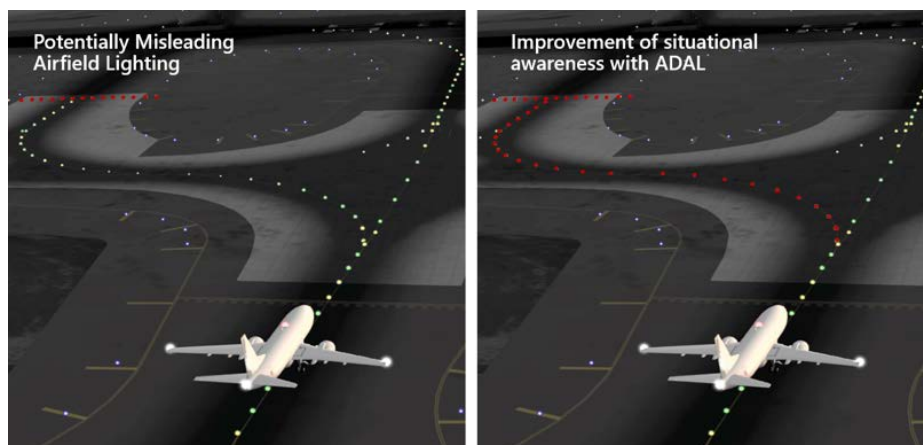
In their normal operation, these fixtures operate as standard green TCL lead-on / lead-off lights. However, when there is an alert or it is required to close a taxiway for avoiding potential runway incursions, it changes to red. When the lights are red, they clearly indicate to any pilot or airfield vehicle driver that they must stop immediately before entering an active runway or crossing a taxiway.

ADAL elevates safety functions by enabling individual lights (or groups of lights) to change colour, rather than relying solely on an ON/OFF function. This allows traffic to be warned (e.g., by switching lights to red) or cleared (by displaying green). All these actions can be fully automated and seamlessly managed by the A-SMGCS, eliminating any latency caused by user reaction while ensuring the user remains actively always involved in the process.

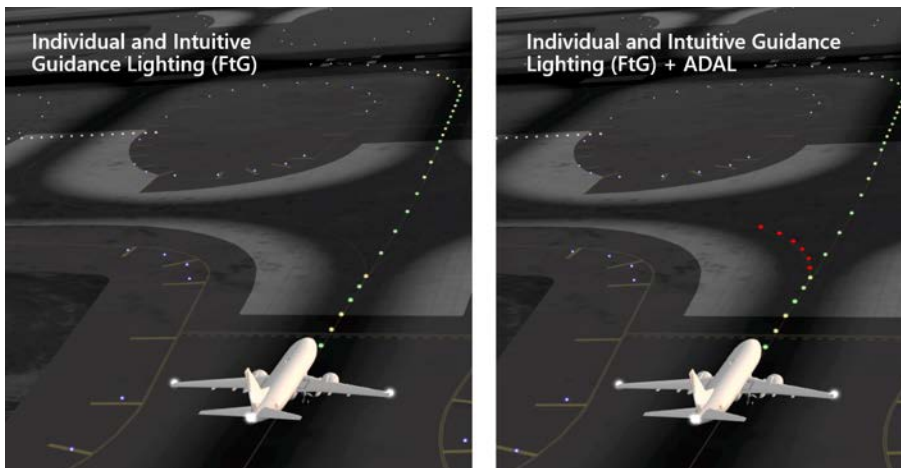
Typical operational uses cases that can be addressed with ADAL include:

- Service road safety systems, enhancing visibility during crossings.
- Dynamic holding positions, using ADAL as adaptative stop bar and holding logic based on aircraft traffic and operational needs.
- Apron pushback support, improving guidance during aircraft stand operations.
- Follow-the-Greens Operations, sequencing taxiway lighting (dynamic separation) controlled through ALCMS integration.

How can it minimize the risk of runway incursions? ADAL light fixtures reduce ambiguity for pilots and ground vehicle operators, especially in complex or low-visibility environments where situational awareness is challenged. By offering unambiguous, immediate feedback on movement permissions and routing, ADALs help prevent inadvertent or unauthorized entries onto active runways, thus serving as a proactive safety layer that complements other safety nets and surveillance technologies.

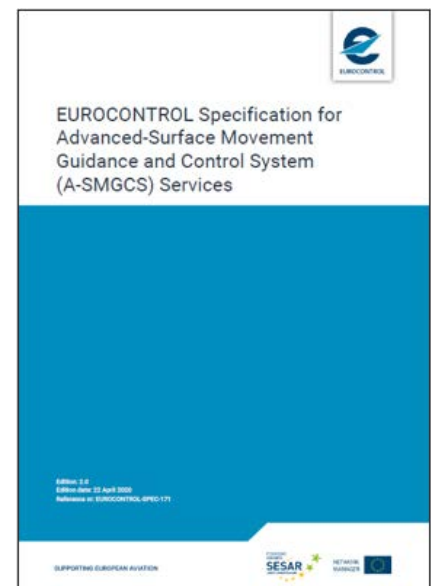


◀ *Figure 24 – Improvement of situational awareness with ADAL (Source: ADB SAFEGATE)*



◀ **Figure 25** – Improvement of situational awareness with FtG & ADAL (Source: ADB SAFEGATE)

The ADAL (Adaptative Airfield Lighting) concept, which enables taxiway centreline lights to change colour, is not yet explicitly included in current ICAO, FAA or EASA regulations. However, the idea aligns with the “Eurocontrol Specification for Advanced-Surface Movement Guidance and Control System (A-SMGCS) Services”. Specifically, under statement 4.3.4 Guidance Service, the specification note: “If there are no green (or alternating green and yellow) TCL; or if there are activated red TCL or there is a red stop bar, then they must stop the aircraft”. This means that when a pilot encounters either no coloured lights or red taxiway centreline lights, it is an unambiguous signal to stop. While not yet included in global standards or regulations, ADAL technology is consistent with the intent of these advanced guidance service requirements and offers clear operational benefits for runway safety.



4.3.4 Guidance Service

The Flight Crew read back the instructions detailed in section 4.2.4.1 and proceed as follows.

- If green (or alternating green and yellow) TCL are shown in front of the mobile they can follow the lights.
- If there are no green (or alternating green and yellow) TCL; or if there are activated red TCL or there is a red stop bar, then they must stop the aircraft.
- Yellow or flashing lights they exercise caution.

▲ **Figure 26** – Section 4.3.4 Guidance Service – page 53 (Source: Eurocontrol)

Emerging Risks and Future Challenges

Traffic growth and airport capacity constraints

Global Aviation continues its rapid recovery and expansion after the COVID-19 pandemic, and airports worldwide are facing the dual pressure of increasing traffic volumes but with limited infrastructure capacity. According to information from IATA (International Air Transport Association) and ACI (Airports Council International) many regions have already surpassed pre-pandemic levels, with steady annual global growth rates of 3-4% projected up to 2040, with particular growth in Asia-Pacific, the Middle East, some regions in Europe and North America. This growth, coupled with increase in aircraft movements and limited capacity for infrastructure expansion, will lead to a higher traffic-density and an increased operational complexity.

Airport capacity infrastructure limitations mean that more aircraft and ground vehicles must be managed within the same physical footprint. During peak periods, the human factor will have a significant impact, and pilots, ATC controllers, and ground personnel will be more susceptible to miscommunication and confusion. This situation has been well documented to be a precursor to runway incursions. Historical data from ICAO, FAA and EASA show that spikes in surface movement often correlate with periods of high traffic density and operational stress, particularly at major hub airports.

To address these challenges, airports and regulatory authorities must prioritize the deployment of advanced technological solutions capable of enhancing safety and situational awareness on the airfield. The automation of certain elements of aircraft guidance and safety nets reduces the workload of pilots, drivers and controllers in critical situations. Systems such as Advanced Surface Movement Guidance and Control Systems (A-SMGCS), Runway Status Lights (RWSL), Follow-the-Greens, and ADAL fixtures provide real-time automated guidance and conflict detection capabilities that help mitigate human limitations, particularly during periods of peak operational demand and under adverse weather or low visibility conditions.

In conclusion, the projected growth in traffic, combined with persistent capacity constraints, highlights the urgent need to implement measures to reduce the risk of runway incursions at airports worldwide.

Climate change and extreme weather impacts

Climate change is recognized as a critical factor impacting airport operations. Rising global temperatures, weather change patterns, more frequent and severe extreme weather events will be significant challenges for runway safety:

- Extreme weather events can degrade runway friction, and, therefore, the risk for runway excursion will increase.
- Heavy rainfall and flooding can lead to hydroplaning which can cause poor braking action, and the potential for a runway excursion.

- Snow, fog, smoke, and heavy precipitation reduce visibility conditions, which increase the yearly hours of low visibility conditions. It is more difficult for pilots and vehicle drivers to maintain situational awareness, increasing the risk of navigation errors and unauthorized runway entries.
- Also, climate-driven operational disruptions will force airports to implement temporary procedures, reroute traffic, or conduct emergency maintenance, all of which can add confusion to crews and ground staff.
- To address these evolving risks, airports must invest in resilient infrastructure, advanced technologies, enhanced training, etc., as operational environments become more unpredictable and challenging.

Automation, AI, and digital tower operations

As air traffic grows in volume and operational complexity, operational environments become more challenging due to infrastructure constraints or climate change. Advance technologies including automation and AI will become new tools to support human operators and create new layers of safety and situational awareness, with the ultimate objective to reduce all risk of runway incursions.

At present, the use of existing automation and AI tools within safety critical environments is still very limited. However, it is expected that these tools will evolve and increase their capabilities through machine learning by monitoring ground movements in real time. AI-powered surveillance systems will detect patterns or deviations in order to indicate potential runway incursion. These systems will generate predictive alerts for air traffic controllers, enabling rapid interventions before a potential conflict becomes real.

Digital tower operations are one of the focus points in this space. Equipped with high-definition cameras, real-time data feeds, and augmented reality, digital towers offer ATC controllers an enhanced view of the airfield, regardless of weather conditions or line-of-sight limitations. AI-powered analytical tools will offer automatic detection of potential hazards, track all moving objects on the surface, and support ATC controllers' decisions with additional information and recommended actions.

Voice Recognition functions using Large Language models can transform controllers' instructions given via voice communication and transform them into system inputs such as aircraft routings, clearances and time-stamps. This capability will significantly reduce the workload of controllers by eliminating parallel tasks.

Furthermore, these tools can analyse instructions and clearances by controllers, responses and read-backs from flight crews, vehicle driver communications, as well as conflicting clearances well in advance of the action which could potentially lead to an incident.

In summary, the adoption of automation, AI, and digital tower operations will significantly reduce of the cognitive load on air traffic controllers, standardizing responses to routine and emergency situations, and ultimately mitigate many of the human factors that contribute to runway incursions or confusion.

The ability of these capabilities to anticipate, detect, and prevent incursions in complex and demanding environments makes them key and critical components in the ongoing effort to minimize the number of runway incursions and maintain safety as the priority in Aviation.

Conclusions

Key conclusions and outcomes

- Despite aviation's overall strong safety record, runway safety (incursions, excursions and confusion) remains a critical topic addressed by the main international organizations in the aviation industry (ICAO, FAA, EASA, Eurocontrol).
- Traffic growth and capacity constraints are increasing runway risk, particularly at major hubs where, in addition, infrastructure expansion is limited, and operational margins are reduced.
- Human factors remain the dominant contributor to runway safety events, including miscommunication, loss of situational awareness, workload, fatigue, and inconsistent adherence to procedures across pilots, ATC, and ground personnel.
- Complex airport layouts – such as crossing or converging runways, closely spaced parallels, and mandatory runway crossings – significantly elevate risk and require tailored local mitigation strategies.
- Low visibility and adverse weather substantially degrade situational awareness and are recurring precursors to serious runway incidents and accidents.
- No single measure can prevent runway incidents, effective mitigation depends on a layered safety approach combining infrastructure design, procedures, training and implementation of technological existing and innovative solutions (Swiss Cheese model).
- Airfield ground lighting and visual aids (e.g. stop bars, runway guard lights, lead-on/lead-off lights) are proven, highly effective barriers against runway incursions, particularly when used continuously (H24).
- Autonomous safety systems such as ARIWS / Runway Status Lights provide a critical independent last line of defence by warning pilots and vehicle drivers directly, regardless of ATC clearances.
- Surveillance technologies (MLAT, ADS-B, SMR), when integrated with A-SMGCS, significantly enhance situational awareness and enable early conflict detection.
- Advance guidance solutions (e.g. Follow-the-Greens and adaptive lighting concepts – ADAL) reduce reliance on radio communication, lower controller workload, and minimize navigation errors, especially in complex or low-visibility environments.
- Training and competency development across all stakeholders are essential, with recurrent, scenario-based training focused on runway risk, human factors, and the use of modern safety technologies.
- Emerging risks – including climate change, extreme weather – require proactive investment in automation, resilient infrastructure and intelligent and connected systems.
- Collaboration among regulators, civil aviation authorities, airport operators, air navigation service providers (ANSPs), airlines, and industry is essential to achieve sustained improvements and move towards the long-term objective of zero runway incursions.

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