

Systematic literature review on autonomous ground vehicles for airport operations: Challenges, risks, and technological innovations

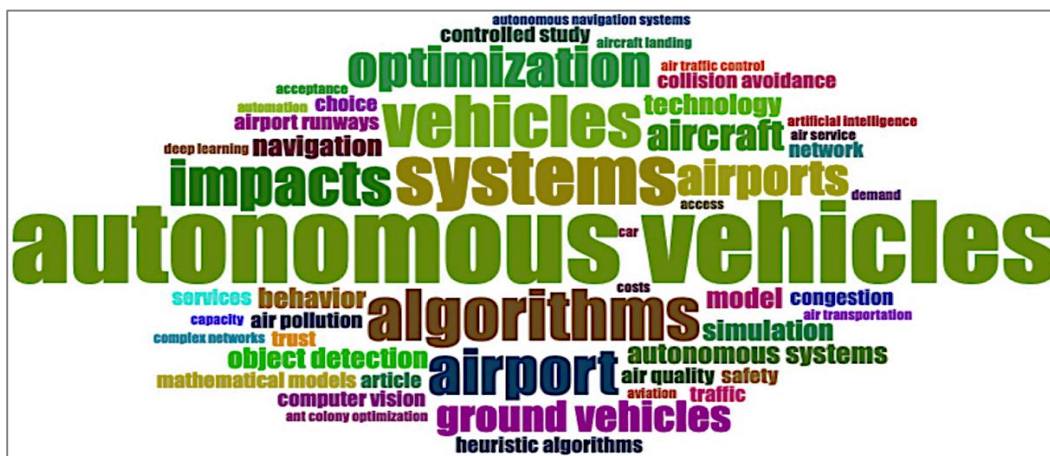
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Highlights:

- Challenges on the Autonomous Ground Vehicles in Airports
- Risk Area on the Autonomous Ground Vehicles in Airports
- Impact of Autonomous Ground Vehicles on Airport Efficiency and Safety

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Abstract

This systematic literature review explores the integration of Autonomous Ground Vehicles (AGVs) into airport operations, focusing on key challenges, associated risks, and enabling technological innovations. The adoption of AGVs promises significant improvements in efficiency, safety, and sustainability across tasks such as baggage handling, aircraft towing, and runway maintenance. However, deploying AGVs in the dynamic, complex environments of airports presents significant obstacles, including challenges related to perception accuracy, sensor limitations, real-time decision-making, and cyber security risks. We applied the PRISMA methodology to screen 206 peer-reviewed articles from major databases, including Scopus, Web of Science, and PubMed. After screening, 14 studies were selected based on the inclusion criteria. The findings highlight the importance of advanced perception systems, multi-agent coordination, and Artificial Intelligence (AI)-based algorithms in enhancing AGVs performance. Furthermore, emerging innovations such as sensor fusion, transfer learning, and simulation-based development have proven effective in improving reliability and operational efficiency. This review contributes to current understanding of AGVs applications in airports and provides practical insights and recommendations for future research and development.

Keywords: Autonomous Ground Vehicles (AGVs); Airport operations; Risk assessment; Baggage handling; Technological innovation

1. Introduction

Integrating Autonomous Ground Vehicles (AGVs) into airport operations has the potential to significantly enhance efficiency, safety, and sustainability in various tasks [1]. AGVs are gaining attention as they have the potential to assist or replace human drivers, aiming to reduce traffic accidents caused by human error and improve road safety [2], [3]. This technology encompasses the capability to operate a vehicle without active human oversight, offering a spectrum of automation levels where complete autonomy entails a system that manages all driving functions continuously [4]. Advancements in sensor technology and algorithms have driven the evolution of autonomous driving, promising safer and more eco-friendly transportation [5], [6]. The field has witnessed considerable progress in the last decade [7]. This pursuit is driven by the potential to curtail accidents, diminish energy consumption and pollution, alleviate traffic congestion, and enhance transportation accessibility. The automotive sector globally invests significantly in research and development to foster innovation and maintain a competitive edge in this rapidly evolving landscape [8]. The deployment of these vehicles in structured environments such as airports, however, requires careful consideration of several challenges, risks, and technological innovations [9].

Several challenges need to be addressed before AGVs can be widely adopted, including regulations, risks, public opinion, cost, the precision of onboard sensors, computing power, and algorithm limitations [10]. The path toward full autonomy is paved with safety hurdles that demand rigorous analysis and mitigation strategies [11]. These challenges encompass decision-making complexities and issues related to fleet management, highlighting scenarios where AGVs might navigate without passengers, inadvertently adding to traffic congestion, especially in densely populated urban settings [12]. Despite their potential, AGVs are still in the developmental stage, necessitating comprehensive testing and refinement before widespread deployment can be considered. The primary goal of developing AGVs is to improve safety, reduce accidents, enhance traffic flow, and lower environmental impact. To tackle these challenges, AGVs are equipped with advanced sensor systems, including cameras, radar, and LiDAR, coupled with sophisticated autonomous driving algorithms [13]. The integration of such systems allows for precise environmental detection and safe navigation under diverse conditions [14].

Central to AGVs technology is the concept of perception, involving comprehensive environmental analysis and extraction of pertinent navigational data [15]. This perception is facilitated through an array of sensors that capture information about the vehicle's surroundings, enabling the system to construct a detailed environmental model. The continuous enhancement and validation of Artificial Intelligence (AI) algorithms are pivotal in ensuring the dependability and efficacy of AGVs, reflecting the industry's commitment to safety and innovation. This involves analyzing and interpreting the environment around the vehicle to make informed decisions and plan driving paths [16]. Real-time processing and decision-making capabilities are vital for AGVs to respond promptly to changing conditions and potential hazards. Explainability is crucial for building trust in AGVs, especially as these vehicles can cause accidents. To improve trust and prevent potential risks, AGVs need to supply user-friendly interfaces for effective human-machine teaming [17].

The integration of AI algorithms is central to enabling AGVs to perceive their environment, make decisions, and navigate without human intervention. The evolution of AI algorithms in AGVs has led to increased decision-making capabilities without human involvement, facilitated by Internet of Things (IoT) connectivity for enhanced interaction with the driving environment [18]. However, these advancements also bring potential vulnerabilities, as the connectivity and AI-driven systems of AGVs can be targeted by cyberattacks [19]. Addressing these cybersecurity challenges is essential to ensure the safe and reliable operation of AGVs. Future AGVs will leverage data from various sensors to enhance self-driving algorithms and assist other vehicles in real-time decision-making [20].

The aviation industry is undergoing a transformative shift with the integration of autonomous systems, particularly in airport operations, where efficiency, safety, and sustainability are crucial. AGVs are expected to play a pivotal role in tasks such as baggage handling, aircraft towing, and runway maintenance. The application of AGVs in airports promises to revolutionize various tasks, including baggage handling, aircraft towing, and runway maintenance, by optimizing workflows and minimizing human error [21]. Addressing transportation challenges through AI applications can lead to improved productivity, safety on highways, and better corporate decision-making [22]. This approach ensures that AGVs not only perform their designated tasks efficiently but also

contribute to the overall safety and sustainability goals of airport operations. In the aviation sector, these vehicles are being developed and tested for various applications, including passenger transportation, cargo logistics, and aircraft maintenance, with the aim of reducing operational costs and improving service quality [23].

This systematic literature review not only provides an analysis of the challenges and risks but also highlights key technological innovations and practical solutions for the implementation of AGVs in airport operations, with actionable insights for policymakers, airport operators, and technology developers. This review seeks to address the following research questions:

- What are the main challenges associated with the implementation of AGVs in airport operations?
- What are the risks associated with the use of AGVs in airports, particularly in baggage handling and ground transport operations?
- How do AGVs and their technologies impact efficiency and safety in airport operations?

This paper is structured as follows: Section 1 introduces the context of AGVs in airport operations, emphasizing the significance of identifying and addressing the associated challenges, risks, and technological innovations. Section 2 examines the relevant literature on the application of AGVs in airport environments. Section 3 details the methodology used in conducting this systematic literature review. In Section 4, a comprehensive review of the current scientific literature is provided, focusing on the risk assessment and technological developments related to AGVs in airport operations. Section 5 concludes the paper by summarizing the key findings and offering insights based on the review.

2. Relevant Studies

The integration of AGVs into airport operations has been the focus of a growing body of research. Studies in this area have primarily addressed the key challenges, risks, and technological innovations associated with their implementation. This section reviews the most significant topics explored in the literature, including the operational applications of AGVs in airport settings, the safety and risk management issues involved, and the technological advancements that support their adoption. Specifically, research has focused on the efficiency improvements provided by AGVs, the risks related to vehicle autonomy in dynamic airport environments, and the innovations in sensor technology and automation systems that enable safer and more efficient operations. The following sections will examine these critical areas in detail, drawing from the most relevant findings in recent studies.

2.1. Autonomous Ground Vehicle Application in Airport Operations

The application of AGVs in airport environments has expanded significantly in recent years, driven by the need to enhance operational efficiency, reduce human dependency, and improve safety across a range of ground-handling operations. AGVs are now being explored for various use cases, including baggage handling, runway Foreign Object Debris (FOD) clearance, aircraft towing, curbside logistics, and intra-terminal transport. These applications rely on advanced perception systems, multi-agent coordination, and intelligent routing algorithms to execute tasks traditionally performed by humans, with the goal of optimizing turnaround time and minimizing operational risk.

In baggage handling, AGVs are deployed to transport luggage between terminals and aircraft bays, increasing precision and reducing the likelihood of handling errors. For instance, de Frutos Carro *et al.* demonstrated how synthetic data enhances visual perception systems, enabling AGVs to accurately recognize and navigate within apron environments [24]. Major airports and aviation stakeholders are increasingly piloting and deploying autonomous Baggage Towing Tractors (BTTs) to enhance the efficiency of airside logistics. At Toulouse-Blagnac Airport in France, for instance, a collaboration between EasyMile and Charlotte Manutention resulted in the deployment of TractEasy, an autonomous electric baggage tractor that operates safely in mixed-traffic environments alongside human-driven vehicles and pedestrians. Equipped with LiDAR and GPS-based localisation, the vehicle can navigate complex apron layouts while towing baggage carts between terminals and aircraft, significantly reducing turnaround times and emissions [25]. As part of ongoing digital transformation in aviation, Changi Airport in Singapore has identified automation as a strategic priority for the next three to five years. The Civil Aviation Authority of Singapore (CAAS) announced plans to scale up the use of AGVs, robotic baggage systems, and cleaning robots to mitigate labour shortages and strengthen operational resilience amidst growing passenger

demand [26]. In a parallel development, Cathay Pacific's cargo terminal in Hong Kong has become one of the first in the region to operationalise autonomous electric tractors for cargo transport [27].

AGVs are also transforming aircraft maintenance and support operations. Zhang *et al.* [28] introduced a detection and control framework for unpiloted Ground Support Equipment (GSE), utilizing virtual channel guidance to ensure precise vehicle movement within aircraft stands. This innovation minimizes the risk of human error during towing and docking procedures, contributing to safer and more standardized ramp operations. Similarly, Morris *et al.* [29] developed an autonomous pushback tractor system capable of towing aircraft between gates and runways, demonstrating the feasibility of integrating AGVs into critical taxiing operations while reducing emissions and pilot workload.

For runway maintenance, AGVs offer valuable contributions in the form of automated FOD clearance. Öztürk and Kuzucuoğlu [30] proposed a multi-robot coordination approach for simultaneous detection and removal of debris, demonstrating its ability to shorten runway closure times while maintaining stringent safety standards.

In more dynamic passenger-facing contexts, AGVs are increasingly used for managing traffic flow and transporting passengers or goods in terminal buildings and curbside zones. Cai *et al.* introduced a curiosity-driven navigation model that allows AGVs to adapt to real-time crowd movements, significantly improving localization accuracy and safety [31]. Complementing this, Ugirumurera *et al.* developed a simulation framework for managing curbside congestion using AGVs, reinforcing their potential role in sustainable airport mobility planning [32].

Building on these innovations, several airports have piloted self-driving shuttle services to improve passenger mobility while promoting environmentally friendly, contactless transport. In 2019, Charleroi Airport near Brussels tested the electric autonomous shuttle Navya for intra-terminal service. In 2020, Luxembourg Airport launched a similar driverless transit solution to accommodate growing passenger volumes. Plans were also made to introduce autonomous shuttle buses between Brussels city center and Brussels Zaventem Airport by 2021, though implementation was delayed by the COVID-19 pandemic [33].

Additional applications include automated trolley collection systems. Wang *et al.* [34] presented a coarse-to-fine object detection strategy that enables AGVs to locate and retrieve trolleys across varying environmental conditions. This automation not only reduces labor requirements but also enhances the responsiveness and reliability of ground services during high-traffic periods.

Collectively, these implementations underscore the growing maturity of AGVs technology across both operational and passenger service domains. As airports continue to evolve into highly automated and sustainable transport hubs, AGVs are poised to become integral to improving ground-handling performance, enhancing safety, and supporting decarbonization goals. However, the success of widespread adoption depends on the development of robust digital infrastructure, supportive regulatory frameworks, and close collaboration among stakeholders to ensure seamless integration, safety, and operational efficiency.

2.2. Previous Studies on Risk and Challenges

Although AGVs offer promising benefits for airport operations, their deployment faces a range of challenges. According to Alonso Tabares and Mora-Camino [35], these include operational complexities, regulatory limitations, industry conservatism, and unresolved technical issues.

Airports are dynamic environments where AGVs must operate amid changing weather, limited visibility, and strict time constraints, often alongside manually operated vehicles and personnel. This mixed-mode setting increases safety risks and complicates navigation. In some regions, regulations still prohibit fully autonomous operations on ramps, restricting wider adoption. The aviation industry's low tolerance for error further slows progress. AGVs must demonstrate near-faultless performance to gain certification, yet high development costs and limited investment from GSE manufacturers have resulted in a focus on retrofitting existing systems rather than developing fully autonomous fleets [35].

Technically, key challenges remain, including real-time coordination of heterogeneous fleets, precise path planning, communication protocols, and reliable operation in Global Navigation Satellite System (GNSS) compromised environments. Sensor fusion and emergency response mechanisms are still evolving to support safe and scalable AGVs deployment. Sunaryo and Basaria [36] further note that while automation in baggage and passenger handling has advanced, critical apron tasks such as aircraft taxiing, refueling, and emergency response remain largely manual due

to safety risks and system complexity. Their review also highlights the lack of cost-effectiveness studies and limited adoption in developing regions, indicating that broader implementation must be context-sensitive and supported by robust evaluation frameworks.

In addition to these high-level challenges, the literature identifies further risks that threaten AGVs deployment in real-world airport environments. For instance, environmental unpredictability, such as adverse weather, low-light conditions, and apron clutter, can degrade perception and localization systems, increasing the risk of collision or navigation failure [24], [37]. GNSS signals are often obstructed by infrastructure, requiring more advanced positioning technologies [38].

Another concern is the interoperability between humans and AGVs, particularly in shared workspaces where non-standard behaviors or delayed responses may pose safety threats. Öztürk and Kuzucuoğlu [30] emphasize the difficulty of ensuring safe coordination between autonomous and human-operated systems in high-density ground operations. Cybersecurity vulnerabilities also become more pronounced as AGVs rely on wireless communication and cloud-based management. Threats such as signal hijacking, unauthorized access, or service disruption could severely impact airport operations if not mitigated through robust encryption and control systems [19].

Overall, while the momentum for AGVs adoption is growing, these layered challenges suggest that a hybrid, phased approach—beginning with assisted automation and gradually scaling to full autonomy—may be the most feasible path forward. Success will require not only technological innovation but also regulatory adaptation, infrastructure investment, and close collaboration among aircraft manufacturers, airport operators, and technology providers.

2.3. Technological Innovations in Autonomous Ground Vehicles for Airports

Technological innovation plays a central role in enabling the reliable and efficient deployment of AGVs within airport environments. These advancements span a range of domains, including sensor integration, artificial intelligence (AI), real-time control systems, localization techniques, and vehicle coordination frameworks, all of which are designed to address the complex challenges inherent in airport ground operations.

A major innovation driving AGVs functionality is the use of multi-sensor fusion for enhanced environmental perception. By combining data from LiDAR, radar, cameras, and inertial measurement units (IMUs), AGVs can build a comprehensive, high-resolution understanding of their surroundings. This fusion is crucial in dynamic airport environments where lighting, occlusion, and object clutter can impede the effectiveness of single-sensor systems [14], [28]. For example, Baek *et al.* [39] implemented a conditional random field (CRF)-based sensor fusion algorithm to detect large occluding objects such as aircraft. Advanced perception systems now incorporate transfer learning and synthetic data augmentation to improve object recognition in conditions of low visibility and rare scenarios, thereby expanding operational reliability [24], [37].

In terms of navigation, GNSS integrity augmentation and virtual channel guidance systems have been proposed to improve localization precision in environments prone to signal degradation. These systems use supplementary sensors and geometric models to ensure real-time path correction and fault-tolerant navigation [28], [38]. Complementary approaches such as GPS-free route memory systems and vision-based mapping offer scalable alternatives where GNSS signals are unreliable or unavailable [40].

Control and decision-making algorithms have evolved significantly through the use of fuzzy logic, multi-agent simulations, and curiosity-based exploration models, enabling AGVs to adapt to variable traffic conditions, manage energy distribution, and optimize route planning. For example, Grosset *et al.* [41] demonstrated a fuzzy multi-agent system capable of dynamically allocating tasks and charging schedules, thus reducing vehicle idle time and energy waste. Likewise, Cai *et al.* [31] applied internal motivation-based algorithms to allow AGVs to navigate crowded terminal environments safely and efficiently.

Technological innovations have also focused on task-specific automation, such as automated trolley collection [34], runway FOD removal [30], and precision docking for aircraft service vehicles [28]. Notably, Elrayes *et al.* [42] developed a low-cost autonomous rover equipped with LiDAR and ultrasonic sensors, designed specifically for real-time FOD detection on runways. The system utilized off-the-shelf components, including Arduino Uno boards and HC-SR04 sensors, achieving reliable object recognition at a fraction of the cost of conventional systems (approx. \$300). It featured dual-mode communication (Bluetooth and GSM/GPRS), allowing alerts to be transmitted

in real time without interfering with airport operations. This approach highlights the feasibility of deploying cost-effective AGVs for safety-critical applications, particularly in resource-constrained settings.

At the system level, the integration of Internet of Things (IoT) infrastructure, cloud-based fleet management platforms, and edge computing has allowed real-time monitoring, diagnostics, and remote control of AGVs fleets. These technologies enhance scalability, enable predictive maintenance, and allow for centralized oversight across complex airport zones [32]. In support of such innovations, Kuroda *et al.* [43] conducted an empirical study at Tokyo International Airport by deploying Bluetooth Low Energy (BLE) beacons on over 2,200 ground support vehicles. Their analysis revealed distinct usage patterns across vehicle types, including frequent movement for towing tractors and prolonged idling for passenger steps. These insights are critical for simulating realistic deployment scenarios of autonomous BTTs and for identifying operational hotspots, route overlaps, and inefficiencies within the airside environment.

Furthermore, advances in human-machine interfaces (HMIs) have contributed to the trust and usability of AGVs. Explainable AI and operator-friendly dashboards are being developed to allow human supervisors to monitor AGVs status, intervene when necessary, and understand the rationale behind autonomous decisions [17].

Collectively, these innovations not only enhance the functional capabilities of AGVs but also contribute to the broader goals of sustainability, cost-efficiency, and safety in airport operations. As airports continue to evolve toward smarter, more automated infrastructures, the role of technological innovation in AGVs systems will remain foundational to achieving seamless and resilient ground operations.

3. Methodology

This review starts with an introduction that presents the background and objectives of the study, followed by a detailed methodology section. This section describes the extensive literature search process across multiple databases and specifies the inclusion and exclusion criteria applied to identify relevant studies, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [44].

This systematic literature review was conducted by searching through three major electronic databases: Scopus, Web of Science, and PubMed, chosen for their extensive coverage in both general and specialized fields. A combination of relevant keywords and Boolean operators was used to retrieve pertinent studies. The search terms included phrases such as ("autonomous vehicle*" OR "autonomous system*" OR "autonomous ground vehicle*" OR "autonomous transport") AND ("airport*" OR "ground handling" OR "airport operations" OR "baggage transport"). The search was confined to English-language publications, and there were no restrictions on publication dates, ensuring a comprehensive selection of relevant research related to AGVs in airport operations.

To be included in the review, studies had to meet certain criteria: they were required to be peer-reviewed, published in English, and focused on AGVs in the context of airport operations, specifically addressing challenges, risks, and technological innovations. Exclusion criteria were applied to remove studies that were not directly related to airport operations, those that discussed topics like charging infrastructure or environmental impact, and any non-peer-reviewed papers. The PRISMA flowchart illustrates the steps taken to identify, screen, assess eligibility, and include studies that met these criteria. The extracted data were synthesized by analyzing the key findings from the selected papers, comparing risk assessment methodologies, and identifying strengths and weaknesses. The review discusses the results, identifies gaps in current research, and offers recommendations for future studies, with a final conclusion summarizing the main insights gained from the review.

Figure 1 presents the PRISMA flowchart outlining the methodological process used in selecting studies for this systematic review. An initial total of 206 records was identified through comprehensive searches in three major academic databases—Scopus, Web of Science, and PubMed, selected for their extensive coverage of interdisciplinary and domain-specific literature. Relevant studies were identified through a structured search process across major academic databases, focusing on the use of AGVs in the context of airport operations. After deduplication, 130 distinct records remained and were subjected to a multi-stage screening process. During the title screening phase, 72 studies were excluded for not aligning with the scope of the review. The remaining 58 articles were screened based on abstracts, leading to the exclusion of 37 studies that

lacked sufficient relevance or did not meet the inclusion criteria. A total of 21 articles were then reviewed in full text, of which 6 were excluded due to a lack of substantive focus on the operational use, challenges, or risks of AGVs in airport settings as shown in [Table 1](#). This systematic and structured approach ensured the inclusion of studies that were both methodologically sound and directly relevant to the objectives of the review.

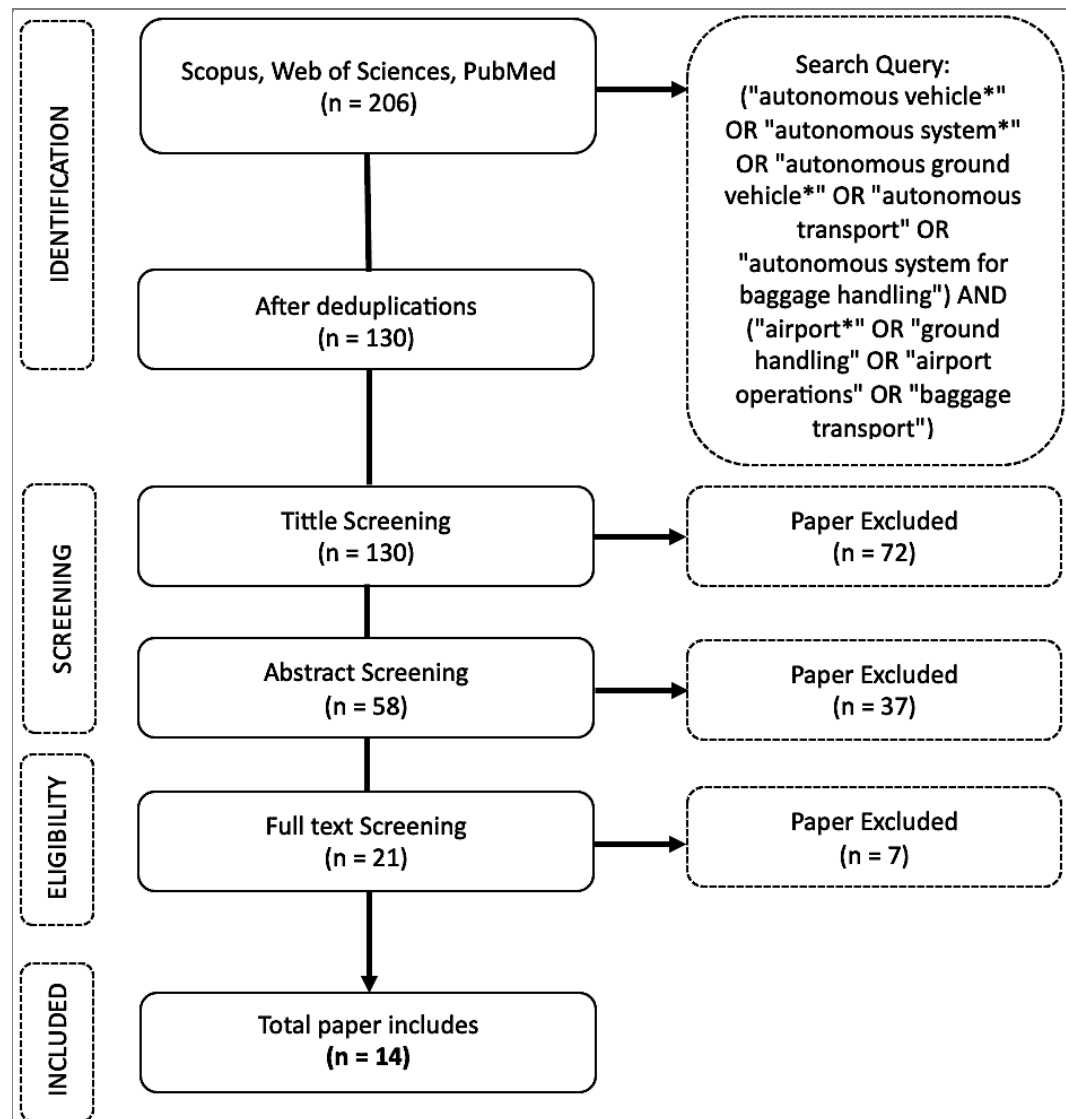


Figure 1.
PRISMA flowchart
illustrating the study
selection process for
the systematic
review

4. Results and Discussion

4.1. Results

In analyzing the word cloud as shown in [Figure 2](#), it is evident that the most frequently occurring terms, such as “autonomous vehicles”, “systems”, “algorithms”, and “airport”, reflect the primary focus of the research on the technological frameworks and computational models used to support AGVs deployment. The prominence of terms like “optimization”, “impacts”, and “navigation” indicates a significant emphasis on improving operational efficiency and addressing the challenges posed by AGVs deployment in complex airport environments. Additionally, the frequent appearance of terms such as “object detection”, “collision avoidance”, and “sensor” highlights the critical role of perception systems in ensuring operational safety. The presence of “ground vehicles”, “aircraft”, and “traffic” further emphasizes the ongoing research into integrating AGVs with existing airport infrastructures. This word cloud analysis reinforces the findings from the literature that technological innovation, risk mitigation, and optimization of AGVs functionalities are central to the development of AGVs for airport operations.

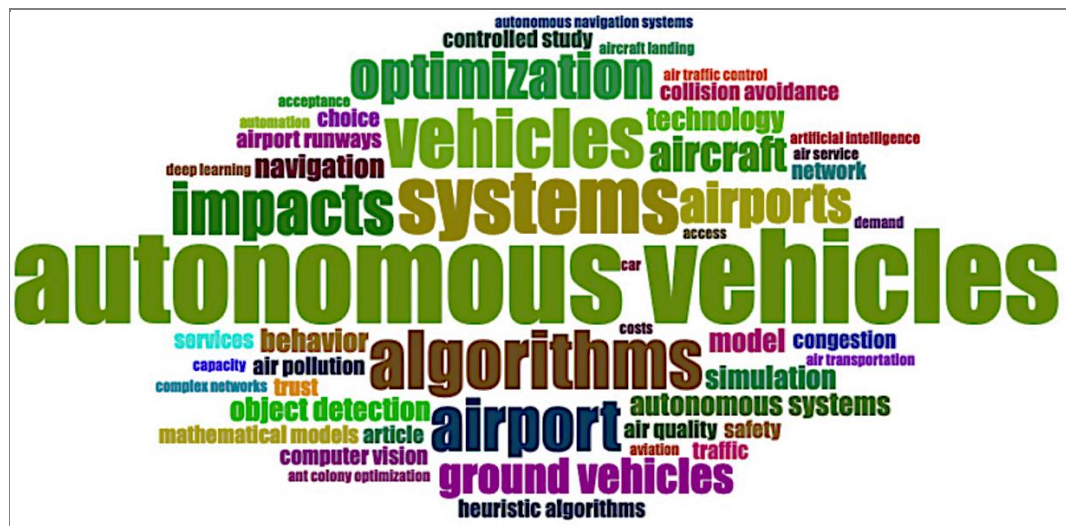


Figure 2.
Word cloud of the
most frequent terms
in the literature on
AGVs in airport
operations

Figure 3 illustrates the thematic evolution in the literature on autonomous vehicles for airport operations over four time periods: 1975-2015, 2016-2020, 2021-2023, and 2024-2025. This thematic shift demonstrates the maturation of autonomous vehicles research, moving from foundational theories to practical, efficiency-driven innovations in airport operations and environments. In the early period (1975-2015), research primarily focused on the broader impacts and systems of autonomous vehicles, with an emphasis on developing mathematical models. From 2016 to 2020, the focus shifted towards vehicles and algorithms, indicating a growing interest in the technical aspects of autonomous systems, especially related to vehicle design and algorithmic optimization. The term impacts remained central, reflecting the ongoing concern with the operational consequences of autonomous vehicles deployment. Between 2021 and 2023, the literature increasingly centered on autonomous vehicles and airport, highlighting a transition towards practical applications of AGVs within airport environments. The focus on optimization and autonomous vehicles in the 2024-2025 period suggests a trend toward improving efficiency and performance, while impacts continues to dominate, indicating that evaluating the outcomes of AGVs integration remains a critical research focus.

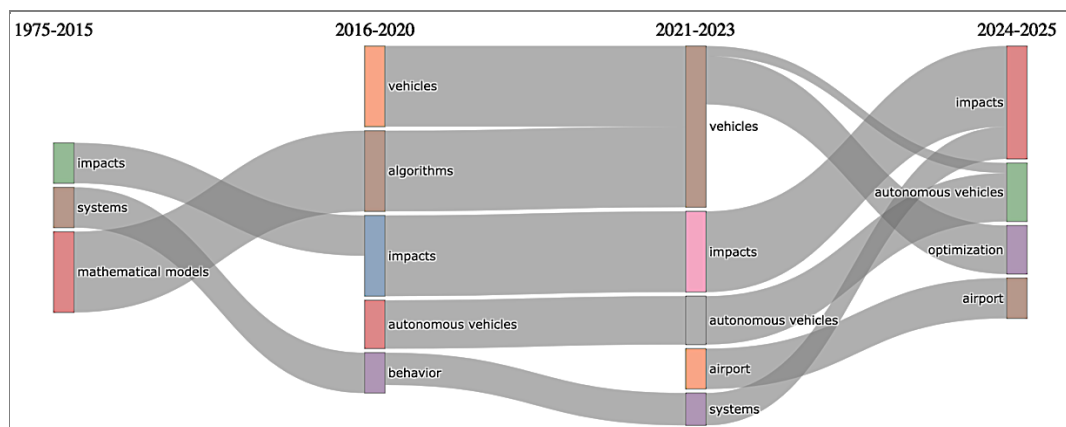


Figure 3.
Thematic evolution
over four time
periods

Based on the analysis of thematic evolution in the previous section, [Figure 4](#) presents a Three-Field Plot that maps the relationships between countries, authors, and keywords within the field of autonomous vehicles in airport operations. This plot provides a comprehensive view of the global landscape of autonomous vehicles research, highlighting the prominent countries such as Germany, Korea, and the United Kingdom, which are leading the advancements in this area. Authors such as Zhang H, Dimitropoulos K, and Koenig F are central to the literature, contributing significantly to themes like autonomous vehicles, airport operations, and automated detection systems. The visualization underscores the growing international focus on autonomous vehicles and their integration into airport settings, while also revealing the interconnectedness of research efforts across various regions. This representation further emphasizes the collaborative and interdisciplinary nature of autonomous vehicles research.

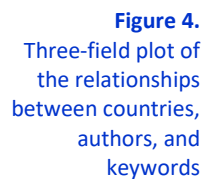
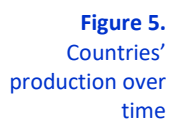


Figure 5 illustrates the production of articles on autonomous vehicles in airport operations across five major countries—China, Germany, Spain, the United Kingdom, and the United States—over time. The graph demonstrates a notable increase in the number of publications beginning around the mid-2000s, with a significant surge in recent years, particularly after 2019. China, represented by the red line, shows the most rapid and consistent growth in research output, surpassing the other countries by a considerable margin around 2019. The United States (represented in purple) also exhibits a steep rise, following a slower initial growth compared to China. Germany, depicted in green, shows a more gradual increase, with a noticeable uptick starting in the 2010s. Meanwhile, Spain (yellow) and the United Kingdom (blue) show relatively slower growth in comparison, though both countries demonstrate steady increases in publication output in recent years. This trend indicates a growing global interest and investment in autonomous vehicles research, with China and the USA emerging as the leading contributors to the field in recent years. The data highlights the shifting dynamics in autonomous vehicles research, with certain countries like China experiencing an exponential rise in activity as the field gains prominence.



The increasing volume of autonomous vehicles research across countries highlights the growing international interest and collaboration in this field. To further examine these global dynamics, **Figure 6** illustrates the Co-occurrence Network, which visualizes the relationships between countries based on co-authorship and shared research themes in autonomous vehicles

studies for airport operations. This network highlights the central countries, such as the USA and China, and the collaborative ties between them and other nations in advancing AGV research.

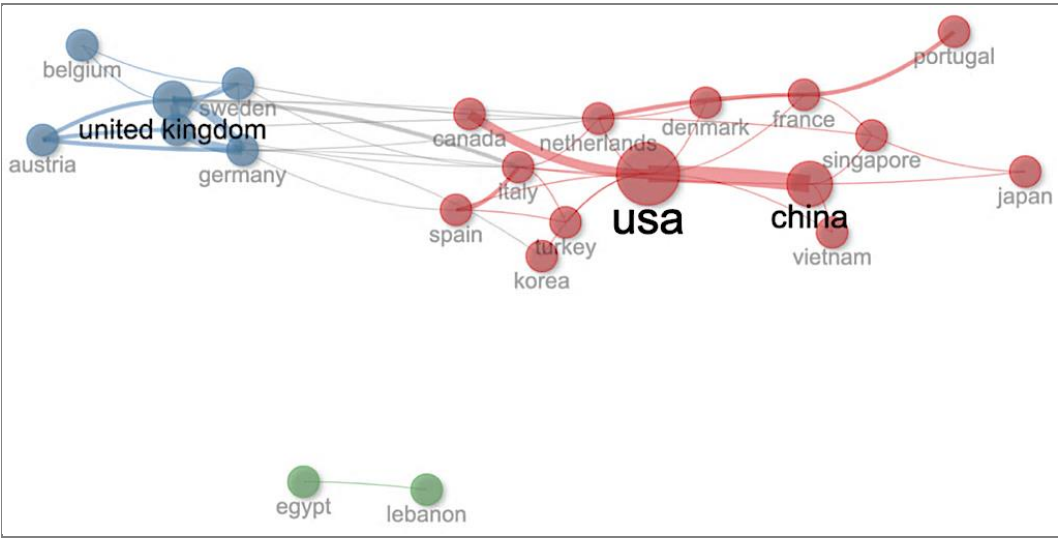


Figure 6.
Co-occurrence
network

Table 1.
Results of screening papers
based on those relevant to
the research

No	Author; Year; County	Problem	Risk	Technologies innovation	Discussion
1	de Frutos Carro et al.; (2024); Spain [24]	The main problem this paper is: a. Dynamic airport environment is to requires adaptive perception in a changing and complicated context. b. Visual perception uncertainty is Struggles with lighting, occlusion, and clutter. c. Safety and risk is high risk if perception or navigation fails.	The use of autonomous vehicles in airports, especially for baggage handling and ground transport operations, brings significant potential benefits but also several critical risks that must be addressed.	Autonomous vehicles and their technologies is impact to efficiency and faster training using synthetic data, reduced need for real work annotation, improved perception systems for detecting relevant objects on the apron.	The main discussions in this paper are: a. The effectiveness of data synthesis is proven to be used for training visual perception models in the context of autonomous navigation at airports. b. Simulators such as MSFS2020 are assumed to be a feasible and efficient environment for developing and validating perception systems in autonomous vehicles, as they can replicate various complex scenarios that are difficult to achieve in the real world. c. This study provides a strong basis that synthetic data can speed up and save the development process of perception systems for AGVs at airports, as long as it is accompanied by proper validation using real data.
2	Grosset et al.; 2024; France [41]	The main challenge with implementation of AGVs in airport is Requires fuzzy multi-agent coordination for energy-aware task allocation, decentralized decision-making, and charging station planning.	The risks associated with the use of AGVs in airports, particularly in baggage handling and ground transport operations is battery contention, task abandonment, congestion, and misallocations may disrupt operations.	The technologies innovation is related impact to efficiency. It reduces delays, lowers energy cost, adapts to dynamic environment, and increases throughput compared to baseline strategies.	This paper presents a multi-agent simulation implemented in Python, using fuzzy logic to explore collective battery recharge management for autonomous industrial vehicles in an airport environment. Simulation results show that the system can improve the overall energy efficiency of the fleet, reduce idle time, and balance the energy load between vehicles. This contributes to operational

No	Author; Year; County	Problem	Risk	Technologies innovation	Discussion
					cost savings and extended vehicle battery life.
3	Ozturk & Kuzucuoglu; 2016; Turkey [30]	The main problem with implementation of AGVs in airport is Auction-based multi-robot coordination over large areas, debris detection accuracy, and real-world deployment robustness.	The risks associated with the use of AGVs in airports, particularly in baggage handling and ground transport operations is Coordination breakdowns, collision hazards, communication failures, and debris detection gaps.	AGVs and their technologies is impact to efficiency Faster runway clearance, reduced closure time, dynamic adaptability, and validated performance in simulation environments.	This paper proposed decreasing the duration of airport closure in order to prevent delays, ensuring safety by shortening the traveling distance robots, and decreasing costs by hiring fewer people for handling and maintenance of the FOD removal process. The system consists of multiple autonomous robots that collaborate to detect, classify, and clean FOD. Coordination between robots is done to divide the task area, avoid collisions, and maximize area coverage in a short time.
4	Bijjahalli <i>et al.</i> ; 2017; Australia [38]	The challenge from this paper is modelling multipath masking; real time integrity; RNP compliance; and simulation complexity.	The risks associated with the use of autonomous vehicles in airports, particularly in baggage handling and ground transport operations is GNSS inaccuracies collisions, operational disruptions, regulatory violations.	Technologies innovation is impact to reliable navigation reduces delays, enables autonomy, and smoothness operations.	The model predictive behavior of these systems supports a timely detection of any deviations from the Required Navigation Performance (RNP), producing useful alerts for onboard mission management. This research utilizes additional sensors and verification algorithms to detect GNSS signal anomalies, make corrections, and provide warnings when there is a potential position error that can jeopardize autonomous vehicle navigation.
5	Zein <i>et al.</i> ; 2018; Egypt [40]	Based on this paper, the problem is route memory replaces map reliance, sensor fusion needed for obstacle handling, and scalable feasibility.	The risks associated with the use of autonomous vehicles in airports, particularly in baggage handling and ground transport operations is GPS drift, collisions, environmental sensitivity, scalability issues.	Technologies innovation is impact to fast deployment, low infrastructure, autonomous routing, reduced manual intervention.	This paper presents a proposed design of a mechatronics system for autonomous vehicles. The proposed design is able to memorize a route based on Global Positioning System (GPS) rather than using pre-saved maps that are infrequently updated and do not include all roads of all countries. This research explains how GPS is a vital component of autonomous vehicles navigation in the context of location determination, route following, and distraction avoidance. The discussion explains that it is possible to integrate GPS with additional sensors and correction algorithms to minimize signal distraction.
6	Sheng <i>et al.</i> ; 2022; China [45]	The main challenge with implementation of AGVs is handling loop traffic dynamics; maintaining adaptive, safe inter vehicle distances.	The risks associated TTC below 4 s increases collision probability AGVs must monitor and avoid unsafe regimes.	The impact to efficiency is throughput improves with shorter gaps but safety depends on keeping $TTC \geq 4$.	The purpose of this research is analyse autonomous vehicles safety under varied traffic environment interference, especially for airport closed loop conditions. The simulations used allow testing of various traffic scenarios and interactions

No	Author; Year; County	Problem	Risk	Technologies innovation	Discussion
					between autonomous and manual vehicles, including critical and emergency situations that are difficult to replicate in the real world. Risk analysis was conducted to understand the factors that cause crashes and test the effectiveness of risk mitigation strategies. The results show that the simulation is effective in mapping accident hotspots and assisting decision-making related to airport traffic management. This approach can be used to improve safety, operational efficiency, and airport infrastructure planning.
7	Wen <i>et al.</i> ; 2023; China [46]	The challenge is handling multiple autonomous vehicle types; complex evaluation integration; linguistic expert input.	The risks associated with the use of autonomous vehicles in airports, particularly in baggage handling and ground transport operations is safety, operational disruption, social acceptance, compliance challenges.	Combined task deployments and data-driven prioritization is one of their technologies related impact to efficiency.	This research aims to evaluate different types of autonomous vehicle operations at smart airports, focusing on the transition from conventional to autonomous vehicle operations to improve the sustainability and efficiency of airport operations. Five types of autonomous vehicles operations were evaluated based on ten criteria, including energy efficiency, safety, operating costs, and environmental impact. The results show that the application of autonomous vehicles for functional activities and scheduled people deliveries is the best alternative for building a smart and sustainable airport.
8	Li <i>et al.</i> ; 2021; China [37]	The main challenges and problem this paper is models pre-trained on clear airport scenes must be fine-tuned using low-visibility imagery, while simulated weather conditions need to closely mimic real airport environments.	The highest risk is missed detections, delayed response, false alarms due to image artifacts.	Based on impact of technologies innovation detection success >60% post-processing, fewer sensor redundancies, and cost-effective upgrade.	Transfer learning was shown to improve target recognition performance compared to models trained from scratch with limited datasets. The model is able to recognize important objects such as aircraft, vehicles, and signs more accurately despite low visibility. This research shows that transfer learning is an effective solution to the challenge of object recognition at airports under low visibility conditions, which can improve the safety and efficiency of airport operations.
9	Ugirimurera <i>et al.</i> ; 2021; USA [32]	The main problem this paper is autonomous vehicles in airport environments is requires detailed forecasting, simulation calibration, and multi-mode behavior modelling.	Risk associated with uncontrolled autonomous vehicles adoption is increased congestion or delays, fuel use, and infrastructure strains.	Related to efficiency by technologies innovation is coordinated autonomous vehicles & electrification reduce emissions and shared	This research emphasizes the importance of strategic planning and adaptive traffic management policies at airports to meet future mobility challenges. Policies that encourage the use of public transportation, vehicle sharing, and the adoption

No	Author; Year; County	Problem	Risk	Technologies innovation	Discussion
				mobility yields major delay cutbacks.	of green technologies can help reduce congestion, emissions, and the need for costly infrastructure expansion.
10	Wang <i>et al.</i> ; 2021; China [34]	The main implementation challenges and problem is system uses a multi-step processing pipeline: coarse detection via object detection networks, followed by fine alignment using geometric/computer-vision refinement. Managing latency while maintaining accuracy in real time is a challenge.	The risk in baggage handling and ground transportation is misalignment and hook failures, collision with infrastructure or personnel, and failure under occlusion.	The efficiency and operational improvement with accurate catching across dynamic curb side conditions, fleets of AGVs can scale up to handle peak volumes more efficiently than reactive, manual systems.	Experiments show that the proposed framework can locate and retrieve trolleys reliably. The proposed object detection and pose estimation methods show higher accuracy, providing a credible perceptual approach for mobile manipulation. Moreover, the proposed framework can be easily extended to other mobile manipulation tasks for object search and retrieval.
11	Cai <i>et al.</i> ; 2023; China [31]	The main challenges is airport environments often lack sufficient landmarks for reliable positioning. Simultaneously, moving crowds (passengers & staff) introduce noise and occlusions that degrade localization accuracy.	Risk in airport AGVs operation is over optimization of path cost and collisions human discomfort.	Efficiency gains the framework enables AGVs to operate in real-world crowded spaces like airport terminals or apron areas, making automated service tasks.	a. Advantages of Curiosity Approach: By utilizing the internal motivation of curiosity, robots can avoid known or dangerous paths, and choose exploration paths that provide maximum information for subsequent decision making. b. Adaptation in Dense Environments: This model allows the robot to adjust its path in real-time to dynamic changes, such as crowd movement or unexpected obstacles, making it particularly suitable for operations in airports or shopping malls.
12	Zhang <i>et al.</i> ; 2024; China [28]	The main implementation challenges is Virtual-channel guidance & sensing. The framework relies on painted/marked virtual channels plus "turning-induction markers" to keep a GSE tug inside a safe corridor. Designing, maintaining, and re-marking these lanes across stands especially at legacy aprons can be costly and disruptive.	The principal risk is Collision & docking damage. Problem detected boundaries or doors can let the tug stray or dock off centre, risking wing-strike or fuselage-scratches. Sensor or comms failure. The architecture depends on uninterrupted camera and LiDAR data and wireless dispatch signals; packet loss or lens occlusion can freeze or misguide the vehicle.	The impact on efficiency and safety based on technologies innovation autonomous vehicles is fuzzy PID plus dynamic/static obstacle logic gives deterministic braking distances and steering envelopes, cutting human-error variability.	This research shows that the integration of advanced technologies such as sensor fusion and object detection algorithms can significantly improve the performance of autonomous GSEs at airports. By reducing human involvement, the risk of operational errors can be minimized, and the efficiency of the ground handling process can be improved. However, the implementation of this system requires supporting infrastructure, such as the installation of turn induction markers and virtual channel maintenance.
13	Martini <i>et al.</i> ; 2015; Italy [47]	The key problem discussed is ensuring reliability and trustworthiness in a fully decentralized autonomous system. Without a central controller, each Unmanned Aerial Vehicles (UAVs) must rely on local	The paper identifies several risks: Undetected faults or malicious agents can compromise team behavior; Incorrect detection (false positives) could result in unnecessary isolation of	The detection system successfully prevented error propagation and enhanced operational stability, which in turn led to improved mission completion rates	The main results of this study: a. The proposed system can accurately detect motion miss behavior with low false positives b. It operates in real-time and is scalable to large robotic teams c. Validated with both simulated and real

No	Author; Year; County	Problem	Risk	Technologies innovation	Discussion
		observations to assess whether a neighboring robot is behaving abnormally.	functional UAVs; and In critical missions (e.g., search & rescue), a misclassification may reduce operational effectiveness or increase safety hazards.	and lower response times in coordinated tasks.	aerial robots, showing robustness to noise and heterogeneity
14	Eitrheim <i>et al.</i> ; 2024; Norway [48]	The lack of understanding and trust from ground handling employees toward autonomous vehicles can hinder the acceptance and implementation of this technology in the airport operational environment.	These risks affect not just operational safety but also the social acceptance of autonomous vehicles in the workplace.	The integration of autonomous vehicles in airport ground operations represents a significant technological advancement, particularly through the development of advanced perception systems, autonomous navigation, and human-machine interaction tools. These innovations aim to enhance operational efficiency and safety.	This research purpose to understand what factors influence ground crew trust in autonomous vehicles and how this affects their risk perception. The main results of this study higher familiarity and experience with autonomous vehicles leads to lower perceived risk and higher trust; Perceived lack of control and low transparency increase risk perception; and Trust and perceived usefulness are key predictors of autonomous vehicles acceptance among ground handling staff.

The analysis of the selected studies highlights several key challenges, risks, and technological innovations associated with the deployment of AGVs in airport operations. Key challenges include the need for adaptive perception systems capable of handling dynamic and complex airport environments, such as issues with visual perception under varying lighting conditions, environmental clutter, and navigation in crowded spaces. These challenges are discussed in studies by de Frutos Carro *et al.* [24] and Zein *et al.* [40], which focus on the difficulties in perception accuracy and environmental complexities. Additionally, the coordination of multiple AGVs in tasks like baggage handling and ground transport presents significant difficulties, including risks of misallocation and coordination breakdowns that can lead to operational disruptions, as noted in Grosset *et al.* [41] and Öztürk and Kuzucuoğlu [30].

The risks highlighted across the studies primarily focus on safety concerns such as the potential for collisions, sensor inaccuracies, and communication failures. These risks are compounded by the need for real-time decision-making in an environment with constant change. Several studies, including those by Bijjahalli *et al.* [38], Sheng *et al.* [45], and Wen *et al.* [46], emphasize the critical importance of managing these risks through technological innovations, such as advanced perception systems, sensor fusion, and real-time decision-making algorithms. These innovations aim to enhance the safety, efficiency, and overall performance of AGVs in airport operations, particularly in tasks like baggage handling and aircraft servicing.

The following section reports the key findings derived from the reviewed literature, which emphasize the technological advancements and operational strategies needed to overcome the identified challenges. Notably, improvements in perception systems, such as the use of synthetic data for training and the integration of GPS-based memory systems, have been shown to reduce the dependency on pre-stored maps and enhance the real-time decision-making capability of AGVs [40]. Furthermore, innovations in multi-agent coordination are expected to optimize task allocation and energy management, as demonstrated in studies by Grosset *et al.* [41], Martini *et al.* [47], and Wen *et al.* [46]. These advancements contribute to more efficient AGVs operations in airports, addressing key challenges and enhancing operational efficiency.

Moreover, human factors play a crucial role in the acceptance of AGVs within airport environments, as discussed by Eitrheim *et al.* [48]. This research highlights that the trust of ground handling personnel in AGVs significantly influences the risk perception and the overall acceptance of these technologies. Increased familiarity and experience with autonomous systems tend to reduce perceived risks and enhance trust, thereby facilitating smoother integration of such

technologies into airport operations. Therefore, in addition to technological advancements, it is vital to address the social and psychological aspects of implementing AGVs in airports to ensure the successful adoption of these systems.

To address the research questions, the following analysis examines: 1) the primary challenges associated with the implementation of AGVs in airport operations, with a detailed exploration of the technological, infrastructural, and human factors that influence their integration; 2) the risks related to the deployment of AGVs within airports, particularly in baggage handling and ground transport operations, evaluating how these risks are identified, managed, and mitigated; 3) the impact of AGVs and their underlying technologies on the efficiency and safety of airport operations, assessing both the potential benefits and limitations in enhancing operational performance and minimizing safety hazards, while providing recommendations for improving the development and implementation of safety standards for their use in airport environments.

4.1.1. Challenges on the Autonomous Ground Vehicles in Airports

The implementation of AGVs in airports faces major challenges, particularly in visual perception and navigation within complex environments. Airports are dynamic spaces with mixed traffic, varying weather, and non-standardized surfaces [24]. Another challenge is managing the collective energy of AGVs fleets, which becomes more difficult in high-demand operational settings such as airports [41]. In the context of FOD, the main challenges are coordination between robots, FOD detection, and operational security [30]. A crucial challenge is the accuracy and integrity of the navigation system. In airport areas, GNSS signals can be disrupted by various factors [38]. Another challenge involves selecting appropriate AGVs application scenarios, given the wide range of possible uses such as baggage handling, logistics, and FOD clearance. Decision-making becomes complex because it must balance multiple evaluation criteria and involve various stakeholders, including airport management, regulators, technicians, and end users [46]. Other challenges include: long-term strategic uncertainty: Airports like DFW will have to plan infrastructure for years before full adoption of AGVs, risk of revenue erosion: the presence of AGVs could disrupt non-aeronautical revenues such as parking and car rental, requiring new business plans, and inter-stakeholder synergies: Cross-team program management across technology, operations, finance, and corporate culture is required - for AGVs implementation to be successful. Human factors also play a key role. The level of trust and acceptance among ground handling staff greatly influences the successful integration of AGVs. Therefore, addressing social and psychological factors is essential to ensure smooth deployment [48]. Navigation in aircraft areas is very complicated, which can cause vehicles to be able to walk in narrow areas, full of signs, and sometimes many other vehicles or people as well [28]. So it can be concluded that the implementation of autonomous vehicles at airports faces major challenges ranging from visual navigation, GNSS signal interference, to operational coordination and multi-stakeholder decision making. The successful implementation of this technology relies heavily on accurate system integration, a well-thought-out long-term strategy, and adaptation to the complexity of the airport environment.

4.1.2. Risk Area

De Frutos Carro *et al.* [24] identified several key risks of using AGVs at airports, particularly in baggage handling. These include misperception, system failure, operational disruption, and cybersecurity threats [24]. Another risk is poor energy management, which can cause vehicles to lose power during critical operations [41]. Vulnerability to environmental disturbances, such as strong wind gusts, heavy rain, or lost communication signals, which can disrupt cooperation between robots [30]. Based on the research of overcoming these risks by improving GNSS integrity through vehicle-based augmentation, so as to provide more reliable and timely positioning [38]. Operational efficiency increases, as AGVs can work continuously without fatigue or human error due to fatigue.

Under low-visibility conditions, AGVs face several risks. These include collisions caused by object misidentification, delays due to uncertainty in navigation, and reduced operational efficiency during extreme weather or night operations. Transfer learning techniques can help mitigate these issues by allowing AI models to adapt to new and rare environmental conditions [37].

When it comes to curbside management, the risks include Traffic congestion due to autonomous vehicle behavior that is too defensive or too slow, especially in areas with high mobility, conflicts between AGVs and conventional vehicles, for example when fighting for drop-off spaces or fast parking, lack of specific policies or regulations for AGVs, so they do not have safe

operating zones or priority lanes, and errors in autonomous decision-making due to the complexity of curbside scenarios, for example sudden road crossings or vehicles stopping at random [32]. Unexpected behavior of AGVs, such as moving out of lane, not responding to commands, or trajectory conflicts with other vehicles is also one of the risks that need to be investigated [47]. The use of AGVs at airports carries various risks ranging from misperceptions, system failures, to environmental and cybersecurity disruptions that can hinder critical operations such as baggage handling and navigation in low visibility areas. To mitigate these risks, technical approaches such as GNSS augmentation, transfer learning, as well as policy support and operational management adaptive to the dynamics of the airport environment are required.

4.1.3. Impact of Autonomous Ground Vehicles on Airport Efficiency and Safety

AGVs enhance airport operations by improving logistics efficiency, minimizing human error, and strengthening safety measures [24]. Technologies such as fuzzy logic and multi-agent simulation have demonstrated great potential in achieving these improvements [41]. Likewise, multi-robot coordination for FOD clearance can further enhance operational safety and reduce runway downtime [30]. Accurate risk models and better understanding of traffic dynamics at airports, AGVs can positively contribute to: improved traffic efficiency, reduction of potential accidents, utilization of traffic management systems, and design of data-driven operations [45].

If the target recognition system can be optimized even in low visibility conditions, then: Efficiency is increased as AGVs can continue to operate, uninterrupted by weather or night time, Operational safety is increased, as the ability to recognize important objects (aircraft, other vehicles, workers) is maintained, Adaptability to the dynamic airport environment is increased, with the use of transfer learning that allows AI models to continuously learn from new data, and Potential to reduce dependency on humans in navigation and decision-making tasks in limited situations [37]. Another situation also explains that it reduces the need for human labor for routine and repetitive tasks, thereby reducing the risk of injury and improving the allocation of human resources as well as improving operational safety by avoiding manual errors and accidents that may occur during manual collection of trolleys [34]. Successful integration of AGVs depends on building trust among airport personnel, particularly ground handling staff. Addressing human factors and promoting confidence in AGV systems are critical to enhancing both efficiency and safety [48]. AGVs have great potential to improve operational efficiency and safety at airports through automation of logistics tasks, reduction of human errors, and adaptation to dynamic environmental conditions. With the support of technologies such as fuzzy logic, multi-robot coordination, transfer learning, and traffic risk modeling, AGVs are able to perform operations more reliably, even in complex situations such as low visibility or high activity areas.

4.2. Discussion

The word cloud analysis highlights a strong focus on the technological, operational, and safety aspects of AGV deployment in airports. Frequent keywords such as “autonomous vehicles”, “systems,” “algorithms,” and “optimization” indicate that research has shifted from general discussions on AGVs’ potential impacts to more technical, performance-oriented studies. This evolution demonstrates growing research maturity and a practical move toward improving AGV efficiency and reliability through technological innovation.

The Three-Field Plot illustrates that the USA and China are leading contributors to global AGV research, reflecting substantial investment and rapid growth in this field, especially after 2019. This trend, supported by the Co-occurrence Network, highlights active international collaboration among major research hubs. These patterns suggest that AGVs research is evolving into a globally coordinated effort, where cross-country cooperation can accelerate the development of airport-ready autonomous systems.

The challenges identified in the results, particularly related to perception systems, navigation accuracy, and coordination of multi-agent systems, are consistent with the findings in existing literature. Research by de Frutos Carro *et al.* [24] and Zein *et al.* [40] emphasize that the dynamic and complex nature of airport environments presents significant difficulties for AGVs. Moreover, the integration of AGVs within existing airport infrastructures, as highlighted by terms such as ground vehicles and aircraft, continues to be a focal point in recent research. The challenges around adapting AGVs to work alongside human-operated vehicles, particularly in environments with high traffic and congestion, are echoed in studies by Öztürk and Kuzucuoğlu [30], which focus on the coordination of multiple AGVs for tasks such as FOD clearance.

In addition to these technological and operational challenges, social factors such as the trust and acceptance of autonomous systems by airport personnel play a critical role. Eitrheim *et al.* [48] emphasize that fostering trust among ground handling staff is essential for the successful adoption of AGVs, as their confidence in the technology directly influences its integration and operational success.

In terms of risks, the findings suggest that while AGVs can improve efficiency, their deployment introduces safety concerns, especially regarding collision avoidance and perception under low-visibility conditions. Studies by Bijjahalli *et al.* [38] and Li *et al.* [37] underscore the importance of addressing these risks through enhanced sensor technologies and AI-driven models, such as transfer learning, to adapt AGVs systems to challenging operational conditions. These technologies are essential to ensuring the safe operation of AGVs, especially in environments where real-time decisions are critical for preventing accidents.

Regarding the impact of AGVs on airport operations, the findings align with the literature's suggestion that AGVs offer significant benefits in terms of efficiency and safety. For instance, fuzzy logic and multi-agent simulation, as noted by Grosset *et al.* [41], provide a means of improving operational efficiency by optimizing the allocation of tasks among AGVs. The ability of AGVs to operate in environments with limited human intervention, particularly for routine tasks like baggage handling, has the potential to reduce human errors, improve the allocation of human resources, and enhance overall safety by avoiding manual accidents, as suggested by Wang *et al.* [34].

Long-term AGVs integration requires more than technical readiness; it depends on adaptive policies, infrastructure investment, and cross-agency coordination. Ugirumurera *et al.* [32] emphasize that flexible regulatory frameworks are needed to accommodate evolving technologies. Similarly, de Frutos Carro *et al.* [24] stress that cybersecurity and navigation reliability must be prioritized, as system failures could disrupt critical airport operations. A strategic roadmap aligning technology, regulation, and workforce training will be essential for sustainable AGV implementation.

5. Conclusion

This study provides valuable insights into the practical applications of AGVs in airport operations, highlighting the challenges, risks, and technological innovations that shape their deployment, following the PRISMA guidelines. A comprehensive search of Scopus, Web of Science, and PubMed yielded 206 records, which were distilled down to 15 peer-reviewed studies focusing on the role, risks, challenges, and innovations of AGVs. This review highlights the potential of AGVs to improve airport efficiency and safety, while also identifying key gaps in risk management, system integration, and real-world applications. The findings of this study provide significant insights into the thematic evolution of AGVs research in airport operations. Over time, the focus has shifted from broader discussions on the impacts and mathematical models in the early years (1975-2015) to a growing emphasis on technical aspects, such as vehicle design and algorithmic optimization (2016-2020). The literature has progressively moved towards practical applications from 2021 to 2023, and the period from 2024-2025 indicates a continued focus on improving operational efficiency and performance. This progression reflects the maturing of AGVs research, from theoretical foundations to innovations centered on enhancing the operational capabilities of AGVs in complex airport environments.

Technological innovations have played a key role in this evolution, particularly in areas like perception systems, which use synthetic data for training and GPS-based memory systems to enhance real-time decision-making. Additionally, advancements in multi-agent coordination have optimized task allocation and energy management, making significant contributions to both risk mitigation and operational efficiency. These innovations offer a solid theoretical foundation for improving AGVs integration into existing airport infrastructures, while also addressing the broader operational challenges associated with AGVs deployment. However, alongside technological advancements, human factors, particularly the trust and acceptance of AGVs by airport personnel, are critical to the successful deployment and integration of these systems. Effective integration of AGVs relies not only on technological proficiency but also on overcoming human-centric challenges, which include addressing concerns related to system reliability, safety, and interaction with human operators.

Despite these advancements, several key research gaps remain, particularly concerning the broader impacts of AGVs implementation, including operational consequences and social

acceptance. While technological and risk-related challenges are being addressed, the successful integration of AGVs into human-centric airport operations requires continued attention. Furthermore, while safety and risk management remain important, there is a need for further exploration of policies and regulations, especially in complex curbside scenarios where AGVs interact with conventional vehicles. Future research should focus on longitudinal studies to assess long-term impacts, the development of adaptive regulatory frameworks, and the exploration of advanced solutions for energy management, environmental resilience, and robust navigation under challenging conditions. The insights provided in this review offer a valuable foundation for further advancing AGVs technologies and optimizing their implementation in airport operations.

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