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August 2026

Final Report

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16. Abstract As airports increasingly explore autonomous ground vehicle system technology (AGVS) to enhance operational efficiency and safety, the integration, validation, and regulatory compliance of those systems pose challenges. The adoption of AGVSs within airport environments—both nationally and internationally—has accelerated due to growing demands for efficiency and automation. Airports have begun testing AGVSs across various functions, including self-driving jet bridges, aircraft tugs, baggage carts, deicing vehicles, employee shuttles, mowers, foreign object debris collection, and perimeter inspections. While non-movement areas provide controlled conditions for AGVS experimentation, the movement area presents greater challenges due to high-speed aircraft operations and strict regulatory oversight. This state-of-technology assessment includes a literature review and outreach effort that were conducted to provide insights from industry stakeholders into the current state of AGVS technology in areas that may be beneficial for airport use. The literature review and outreach efforts aided in identifying existing standards, test approaches, and risk mitigations from currently implemented AGVS solutions. This report summarizes and synthesizes the key facts of these efforts. The research team conducted virtual discussions with representatives from airports and other entities involved with AGVS use at airports to document their experiences and perspectives on AGVS integration at airports. These research findings identified key challenges associated with navigating complex airfield environments, interoperability with existing airport systems, and the impact of radio frequency interference with AGVS operations. Despite these challenges, the findings demonstrate that AGVS testing within airport environments can be successfully conducted, highlighting the technology's potential to significantly enhance operational efficiency and safety.					
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 - Renu Robotics
- The xBridge Program at the Pittsburgh International Airport (PIT)
- Aurigo
- TractEasy
- Ghost Robotics
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LIST OF ACRONYMS

3D	Three-dimensional
4G LTE-A	Fourth-generation LTE
AC	Advisory Circular
ACI	Airports Council International
ACRP	Airport Cooperative Research Program
ADO	Airports District Office
ADS-B	Automatic dependent surveillance-broadcast
AES	Advanced encryption standard
AGVS	Autonomous ground vehicle systems
AGVT	Advanced ground vehicle technologies
AI	Artificial intelligence
AOA	Airport operations area
API	Application programming interface
ARP	Aerospace recommended practice
ASD	Aircraft Safe Docking
ASDE-X	Airport surface detection equipment – model x
ASDE	Authorized self-driving entity
ASV	Autonomous surface vehicle
ATC	Air traffic control
ATCT	Air traffic control tower
AWV	Autonomous Work Vehicle
AV	Autonomous vehicle
BVLOS	Beyond visual line of sight
C2	Command and control
CENTCOM	Central command
CFR	Code of Federal Regulations
CV	Connected vehicle
CVG	Cincinnati/Northern Kentucky International Airport
DFW	Dallas/Fort Worth International Airport
DoD	Department of Defense
DPS	Department of Public Safety
DSRC	Dedicated short-range communications
EOD	Explosive ordnance disposal
EUCOM	European command
EV	Electric vehicle
FAA	Federal Aviation Administration
FIPS	Federal Information Processing Standard
FLITE	Ford Launchpad for Innovative Technologies and Entrepreneurship
FOD	Foreign object debris
GA	General aviation
GNSS	Global navigation satellite system
GPS	Global positioning system
GRR	Gerald R. Ford International Airport
GSE	Ground service equipment

GUI	Graphical user interface
HMI	Human machine interface
HND	Haneda Airport
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
JB-MDL	Joint Base McGuire-Dix-Lakehurst
JFK	John F. Kennedy International Airport
LAF	Purdue University Airport
LiDAR	Light detection and ranging
LSAV	Low-speed automated vehicle
LTE-V	LTE-based V2X
MAC	Media access control
mph	Miles per hour
MTBFs	Mean time between failures
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NHTSA	National Highway Transportation Safety Administration
NIST	National Institute of Standards and Technology
NLR	National Laboratory of the Rockies
NUiC	No-user-in-charge
ODD	Operational design domain
OEM	Original equipment manufacturer
OSHA	Occupational Safety and Health Administration
OXD	Miami University Airport
PIT	Pittsburgh International Airport
QFD	Quality function deployment
Q-UGV	Quadru-pedal unmanned ground vehicle
R&D	Research and Development
RADAR	Radio detection and ranging
RF	Radio frequency
RFID	Radio-frequency identification
RSA	Runway safety area
SAE	Society of Automotive Engineers
SFO	San Francisco International Airport
SOP	Standard Operating Procedure
SSID	Service set identifier
TRB	Transportation Research Board
TSA	Taxiway safety area
UAS	Unmanned aircraft system
UGV	Unmanned ground vehicle
UIC	User-in-charge
UK	United Kingdom
ULD	Unit load device

USAF	U.S. Air Force
UWB	Ultra-wideband
V2I	Vehicle-to-infrastructure
V2N	Vehicle-to-network
V2P	Vehicle-to-pedestrian
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
WPA2	Wi-Fi protected access 2
XAI	Explainable artificial intelligence
ZTA	Zero trust architecture

EXECUTIVE SUMMARY

As airports increasingly explore autonomous ground vehicle system technology (AGVS) to enhance operational efficiency and safety, the integration, validation, and regulatory compliance of those systems pose challenges. The adoption of AGVSs within airport environments—both nationally and internationally—has accelerated due to growing demands for efficiency and automation. Airports have begun testing AGVSs across various functions, including self-driving jet bridges, aircraft tugs, baggage carts, deicing vehicles, employee shuttles, mowers, foreign object debris collection, and perimeter inspections. While non-movement areas provide controlled conditions for AGVS experimentation, the movement area presents greater challenges due to high-speed aircraft operations and strict regulatory oversight.

The Federal Aviation Administration (FAA) provides the regulatory requirements, standards, and guidance (e.g., Advisory Circulars [AC]) that govern vehicle operations within airports. Presently, certificated airports are required to establish protocols for managing pedestrian and ground vehicle traffic in movement areas and safety areas under Title 14 Code of Federal Regulation (CFR) 139.329, [*Pedestrians and Ground Vehicles*](#). Additionally, certificated airports must implement measures to prevent inadvertent entry to the movement area by individuals or vehicles (per 14 CFR 139.335, [*Public Protection*](#)). Personnel operating within this environment are trained in airport ground vehicle procedures per AC 150/5210-20, [*Ground Vehicle Operations*](#). Noncertificated airport operators are ultimately responsible for establishing procedures and policies for vehicle access and operation on the movement and safety areas of the airport. The FAA issued two documents to help airports with testing and demonstrating Autonomous Ground Vehicle Systems at airports:

1. Part 139 CertAlert 24-02: [*Autonomous Ground Vehicle Systems \(AGVS\) Technology on Airports*](#)
2. Emerging Entrants Bulletin 25-05: [*Testing and Demonstrating Autonomous Ground Vehicle Systems \(AGVS\) at Federally Obligated Airports*](#)

Airports that receive federal airport improvement program grants are statutorily obligated to comply with grant assurances under 49 U.S.C. § 47107, [*Project Grant Application Approval Conditioned on Assurances About Airport Operations*](#).

This state-of-technology assessment includes a literature review and outreach effort that were conducted to provide insights from industry stakeholders into the current state of AGVS technology in areas that may be beneficial for airport use. The literature review and outreach efforts aided in identifying existing standards, test approaches, and risk mitigations from currently implemented AGVS solutions. This report summarizes and synthesizes the key facts of these efforts. The research team conducted virtual discussions with representatives from airports and other entities involved with AGVS use at airports to document their experiences and perspectives on AGVS integration at airports.

These research findings identified key challenges associated with navigating complex airfield environments, interoperability with existing airport systems, and the impact of radio frequency interference with AGVS operations. Despite these challenges, the findings demonstrate that AGVS testing within airport environments can be successfully conducted, highlighting the technology's potential to significantly enhance operational efficiency and safety.

1. INTRODUCTION

This report presents the key findings of a research effort to address the challenges of integration, validation, and regulatory compliance for autonomous ground vehicle systems (AGVSs) in an airport environment. The research effort included a literature review of existing standards related to operational needs and safety/security risks associated with autonomous vehicles in airport environments. Additionally, outreach to industry stakeholders and airports was conducted to gather further insights into the state of autonomous technology.

1.1 Background

The testing and use of AGVSs in and around airports have recently become more prevalent, both domestically and internationally. Increased demand for more efficient airport operations has resulted in increased testing of driverless technology for various airport-related use cases, including self-driving jet bridges, aircraft tugs, baggage carts, deicing and snow removal, employee buses, maintenance vehicles, and passenger shuttles. Non-movement and remote areas of airports are viewed as safer environments for exploring this technology because they offer a more controlled, less busy, low-speed environment for testing and operation. The movement area, which includes runways, taxiways, and safety areas, however, poses a significantly greater complexity and hazards where high-speed aircraft operations are a factor.

Vehicle operations activity on an airport is addressed in airport regulatory requirements, standards, and guidance published by the Federal Aviation Administration (FAA). Current regulatory language requires certificated airports to establish procedures for controlling pedestrians and ground vehicles in movement areas and safety areas. Certificated airports are also required to provide safeguards to prevent inadvertent entry into the movement area and safety areas by unauthorized people or vehicles. Airport ground vehicle procedures and training are provided for all personnel operating within these areas. Standards and guidance are contained in Advisory Circular (AC) 150/5210-20, *Ground Vehicle Operations to include Taxiing or Towing an Aircraft on Airports* (FAA, 2015) and Title 14 Code of Federal Regulations (CFR) Part 139.329 (Pedestrians and Ground Vehicles, 2013). Noncertificated airport operators are ultimately responsible for establishing procedures and policies for vehicle access and operation on the movement and safety areas of the airport

The FAA issued two documents to help airports with testing and demonstrating AGVSs at airports:

1. Part 139 CertAlert 24-02: *Autonomous Ground Vehicle Systems (AGVS) Technology on Airports* (FAA, 2024b)
2. Emerging Entrants Bulletin 25-05: *Testing and Demonstrating Autonomous Ground Vehicle Systems (AGVS) at Federally Obligated Airports* (FAA, 2025)

1.2 Purpose

The purpose of this research is to assess the state of AGVS technology that is either currently operating at an airport or is a candidate for future operational usage in an airport environment.

During this effort, the research team evaluated the operational needs and the safety and security risks associated with the use of AGVSs on the movement areas and non-movement areas of an airport. This research concentrated on equipment for mowing operations, airport maintenance, aircraft towing, foreign object debris (FOD) detection and removal, and airport perimeter security. This research also explores control methodologies, integration with existing airport technologies, and the impact of wireless spectrum interference. Risk considerations, including fail-safe measures and the effects of signal disruptions on AVs, were assessed. Additionally, the research team evaluated the feasibility of centralized control systems, interoperability between AGVS technologies, and safety protocols for disabling AGVS operations from various airport locations.

1.3 Objectives

The primary objectives of this report are listed below:

1. Conduct a literature review to catalog existing standards and codes related to AGVSs and associated sensors, drawing from organizations including but not limited to:
 - a. European Union Aviation Safety Agency (EASA)
 - b. International Civil Aviation Organization (ICAO)
 - c. American Society for Testing and Materials International (ASTM)
 - d. Society of Automotive Engineers International (SAE)
 - e. Institute of Electrical and Electronics Engineers (IEEE)
 - f. Federal Aviation Administration (FAA)
2. Inventory AGVS testing and operation sites.
3. Gather lessons learned and best practices from both the automotive industry and airports with existing AGVS programs, including those under U.S. Department of Defense agencies.

1.3.1 Literature Review

Literature and stakeholders were identified by various means including web searches, leads from the FAA and their support contractors, conferences, and government publications. Several keywords and phrases were used as the focus for the Internet search and included but were not limited to the following: autonomous vehicle; airport operations; autonomous airport; integration of AGVS into airport facilities; automated airport operations; automated, FOD, mowing, perimeter, inspections; AGVS/airport design and standards; and AGVS Infrastructure. The research team critically evaluated each source to determine if the research objectives were addressed.

As part of this literature review, researchers condensed and integrated the primary points from each source, amalgamating them into a cohesive overview. The literature review included a review and summary of publications from the following entities: industry, academic, and government. Thirty-nine publications are discussed in detail in subsequent sections of this report.

1.3.2 Direct Outreach

The research team conducted virtual discussions/interviews with industry stakeholders, including civil airports and AGVS industry vendors, to document their experiences integrating or operating AGVSs in the airport environment. Stakeholders were selected among industry leaders with a focus on including various AGVS platform types and their applicability to airport operations. The research team's industry contacts, Internet searches, and leads from the FAA and their support contractors facilitated the outreach effort. The purpose of these discussions/interviews was to catalog and inventory AGVS operations at airports, as well as to gather key real-world insights from these operators.

Prior to stakeholder outreach, the research team reviewed and analyzed all publicly available information to understand the AGVS concept of operation and to use stakeholder engagement sessions to gather non-public information. To ensure consistency between outreach efforts, the research team developed a stakeholder engagement question bank, which is presented in Appendix A.

The question bank was developed to facilitate discussions and meet the objectives in Section 1.3 of this document. Its purpose was to catalog existing autonomous vehicle (AV) infrastructure and airports where AGVSs are currently operating or plan to operate, including concepts of use and support facilities and equipment, including but not limited to:

- Existing standards and codes
- Lessons learned and best practices
- AGVS validation approaches
- Control, communication, and integration of AGVS systems
- Risk identification and mitigation
- Obstacle/anomaly detection

At the conclusion of each discussion/interview, the research team summarized each of the respective discussions, which are included in this document. Eight total industry stakeholders participated in the outreach portion of this research effort.

2. LITERATURE REVIEW

The literature review method consisted of the review and annotation of industry, academic, and government published documents relating to AGVS operations in an airport environment. Additionally, the research team used these publications to supplement the information gathered during the outreach interviews. The research team also used these publications to learn about additional AGVS activities being conducted by other organizations that were unavailable for interviews.

2.1 INDUSTRY PUBLICATIONS

The team reviewed several publications that were relevant to understanding the current state of the technology and the industry being examined in this report. These publications below have

been reviewed and summarized by the research team to display the most relevant information in relation to AGVS research and enhance the findings in further sections of this document.

2.1.1 Airport Cooperative Research Program

2.1.1.1 Airport Cooperative Research Program Report 219

The Airport Cooperative Research Program (ACRP) Research Report 219, *Advanced Ground Vehicle Technologies for Airside Operations*, published by The National Academies Press, identifies the prospective advanced ground vehicle technologies (AGVT) for use on the airside of the airport environment. While there was no direct test as part of this report, the purpose of ACRP 219 is to help airport stakeholders and airport operators understand, implement, and integrate advanced ground vehicle technologies in airport environments (Hubbard et al., 2020).

ACRP Research Report 219 provides a comprehensive overview of the advanced technologies that are pushing innovation in AGVS operations. A few of the discussed technology categories are autonomous systems, sensors and perception technology, navigation tools, and communication/connectivity systems. Below is a list of the top sectors of the enabling technologies in the AGVS industry identified by the ACRP research team:

- RADAR (radio detection and ranging) for navigation and obstacle avoidance.
- Cameras, combined with machine vision (image-based inspection), allow lane lines, road signs, and traffic lights to be recognized and interpreted.
- LiDAR (light detection and ranging) is used to create a three-dimensional (3D) image or map of the surroundings.
- Machine learning (ML), a subset of artificial intelligence (AI), allows computers to discern vehicles, signs, pedestrians, and cyclists in the roadway environment. Machine learning allows cars to learn from experience to build their own database from which to draw.
- Maps provide a reference for autonomous vehicles (AGVSs) and are typically developed based on LiDAR and RADAR. The reference map provides a baseline for sensor data.
- Communications are important and necessary for connected vehicle (CV) applications, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X). Communication options include dedicated short-range communication (DSRC), which provides one or two-way radio communication, and 5G, which provides cellular-based communication. (Hubbard et al., 2020)

Each of these technologies allows the vehicles to assess their environment, recognize objects/obstacles, and respond appropriately. Since 2016, the National Highway Traffic Safety Administration (NHTSA) and much of the autonomy industry refer to the levels of automation as defined by SAE in Table 1. (Hubbard et al., 2020)

Table 1. Society of Automotive Engineers International Definitions for Levels of Autonomy (Hubbard et al., 2020)

Responsible for monitoring environment	Level	Description
Human operator	0	No automation: human driver does everything
	1	Driver assistance: ADAS provides limited assistance with some functions (e.g., backup warning beep, automatic headlights)
	2	Partial automation: ADAS can conduct some parts of driving task, human monitors and controls other tasks (e.g., cruise control)
Automation	3	Conditional automation: vehicle ADS can conduct some parts of task and monitor driving environment, but human ready to take back control
	4	High automation: vehicle ADS can conduct driving task and monitor driving environment but only in certain environments and under certain conditions
	5	Full automation: vehicle ADS performs all tasks under all conditions

ADAS = Advanced driver-assistance systems

ADS = Autonomous driving system

ACRP 219 highlights the lessons learned about AVs from many sectors of the autonomous industry, such as the roadway sector, agriculture, mining, and unmanned aircraft systems (UAS) at airports. The success with UAS integration at airports has proven that regulatory challenges are not an insurmountable hurdle. Overreliance on automation by operators has been another lesson learned from the automotive industry, as AVs do not always behave as expected or be able to perfectly analyze environmental information. Last, a lesson learned in technology advancement at airports is the importance of staging technology deployments. Fully understanding and planning for new technology at an airport takes proper planning, time, and confirmation that the readiness level is consistent with the project. (Hubbard et al., 2020)

The ACRP research team broke down their process of prioritizing and evaluating AGVS applications and technologies that would be used in an airport environment. The applications were split into two groups: ramp and aircraft activities, and airport operations. From there, the applications were sent to airport stakeholders for their review and evaluation. After evaluation and inputs from stakeholders, assessing demonstrations of the AGVSs and a review of published literature, the following table was created for further evaluation by the research team, Table 2 (Hubbard et al., 2020).

Table 2. Airside Applications Prioritized for Further Evaluation (Hubbard et al., 2020)

Airside Applications	Proposed Technology
Ramp Activities	
Baggage carts	Safety assist
Aircraft pushback	Remote from ramp, Automated with driver
Aircraft tow or tug to and from runway	Remote from cockpit, Automated with driver
Airport Operations	
FOD detection and removal	Safety assist*, Automated with driver
Mowing	Centralized, Automated with no driver
Snow and ice control	Platoon with driver in lead, Remote operation
Perimeter security	Automated with no driver

*Safety assist for FOD detection and removal will include evaluation of Automatic Dependent Surveillance-Broadcast (ADS-B) transponders for the airport ground ops vehicle.

To understand and effectively evaluate the selected AGVS technologies, ACRP 219 provides a basic overview of the evaluation process, as shown in Figure 1 (Hubbard et al., 2020).

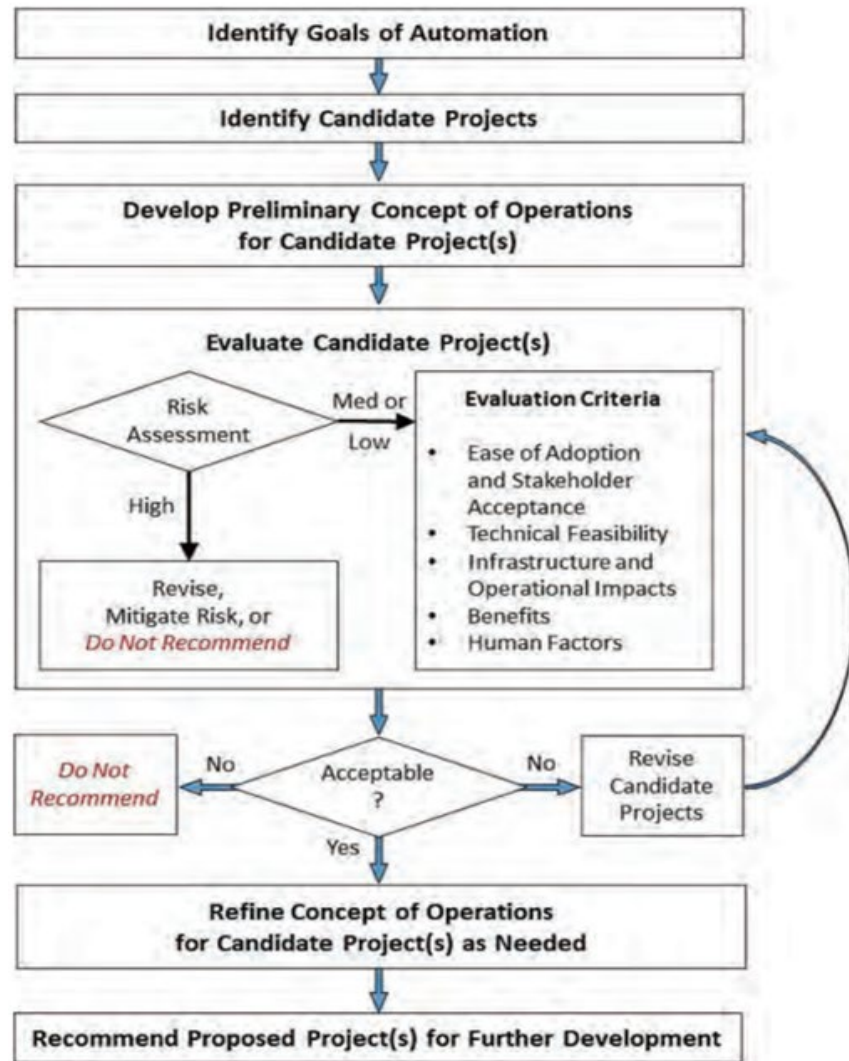


Figure 1. Overview of ACRP Evaluation Process (Hubbard et al., 2020)

During the project refinement stage of the process, details of the AGVS project start to form and change due to understanding of technical feasibility, ease of implementation, and stakeholder acceptance. Next, illustrating the evaluation and refinement of the project can be done using the quality function deployment (QFD) method to expand the details of the project into a concept of operations. Below, Figure 2, is an example provided by the ACRP research team for a specific airport with a goal of automating perimeter security for a demonstration or for full deployment (Hubbard et al., 2020).

Candidate Technology and Application: An automated vehicle without a safety driver will be used for perimeter security. Project Goals: The project goal is to provide automated surveillance of the perimeter fence and gates; this will reduce the reliance on personnel in a tight job market and will potentially increase the amount of surveillance that can be provided. A secondary goal is to learn more about the potential for airside automation. Operational Objectives: The first operational objective is to demonstrate the viability of automated perimeter security so the airport can reduce the reliance on personnel to conduct this task, which would allow increased airport security. A secondary operational objective is to collect data using an automated system to learn more about the benefits and limitations of automation. These operational goals align with the mission of the airport: to provide the highest quality of service for the community and for aviation customers (including safety and security), to be an employer of choice and to be a leader in innovation. The candidate project would enhance safety by removing personnel from perimeter security in harsh environmental conditions (e.g., heat and cold) and would enhance airport security by providing the potential for continuous surveillance during the day and night. Operational Scenario: The AV will patrol the perimeter of the airport inside the perimeter fence and check for holes in the fences, locked gates, and people along the perimeter of the airport outside the fence who may be trying to enter the airfield. When any of the above conditions exist and are recognized, or when an unrecognized situation exists, the AV will send an alert to a human supervisor who can view the situation remotely and provide a course of action for the AV, typically it would be one of two actions: stay at the location and provide video recording and a live feed until an airport operations vehicle arrives, or continue the perimeter check. Humans will be required to respond to alerts, charge the AV, and download any data or video the airport wishes to keep for documentation. Domain: The AV will operate in remote areas of the airfield, and is not expected to operate in the movement area. In terms of security designations, the AV will operate or not operate in the secure area or the air operations area. Potential Problems: Minor problems may include unrecognized situations and false alarms for unlocked gates or holes in the fence. No major problems are expected, but a problem such as a cybersecurity threat would represent a major problem. The fail-safe condition for the AV is to stop operation, send an alert, and stay in place until directed to do otherwise. Implementation Scenario: Candidate projects include full deployment (implementation on a permanent basis) and implementation as a demonstration project (implementation for 6 weeks on a trial basis under close supervision).

Figure 2. Concept of Operations for Automated Vehicles (Hubbard et al., 2020)

To quantify the evaluation of this project, the ACRP research team created a scoring system to provide a weighted comparison between the varying factors and information. Scoring was based on benefits, ease of adoption, and stakeholder acceptance. The combined overall score aided in the airport stakeholders' decision-making process for an AGVS project. Table 3 showcases sample scores for ease of adoption and stakeholder acceptance based on the perimeter scenario discussed above. A score of 0 indicates that there is no difference or preference, a score of 1 indicates a marginal or weak preference, a score of 3 indicates a measurable or medium preference, and a score of 9 indicates clear superiority or a strong preference (Hubbard et al., 2020).

Table 3. Sample Score Calculation for Ease of Adoption and Stakeholder Acceptance (Hubbard et al., 2020)

Do nothing	Automated perimeter security demonstration	Automated perimeter security deployment	Ease of adoption and stakeholder acceptance
0	0	0	Compatible with existing culture
0	3	1	Considers previous organizational experience with technology or other related initiatives
0	1	1	Compatible with existing workforce constraints and considerations (e.g., union rules) • Individuals are likely to use the technology as intended
0	1	1	Appropriate allocation of function
1	3	0	Considers funding and financial implications • Considers capital costs and eligibility of potential funding sources • Operating costs can be recovered with appropriate revenue stream
3	1	0	Considers need for regulatory compliance and approval (including airport certification, etc.) • Requires approval from FAA, TSA, OSHA, CPB, etc.
0	3	3	Project provides expected cost savings (positive B/C, benefits outweigh cost) • Benefits accrue to entities that incur a cost (in U.S. dollars or inconvenience)
3	1	0	Technology is reliable and trusted by users • Human or technical backup can takeover if needed
0	0	0	Technology can be implemented incrementally • Human or technical backup can take over if needed
7	13	6	Score
0.54	1.00	0.46	Normalized Score

B/C = Benefit/cost ratio

CPB = Customs and Border Protection

OSHA = Occupational Safety and Health Administration

TSA = Transportation Security Administration

Table 4 tallies all scoring for a normalized overall score to help in the selection of an airport's AGVS project.

Table 4. Sample Score Calculation for Candidate Projects (Hubbard et al., 2020)

Evaluation Criteria	Do Nothing	Automated Perimeter Security		Weight
		Demonstration	Deployment	
Ease of Adoption and Stakeholder Acceptance	0.54	1.00	Does not pass Risk Assessment because of Uncertainties	0.20
Technical Feasibility	1	0.14		0.20
Infrastructure Impacts	N/A	N/A		N/A
Operational Impacts	0	0		0.20
Benefits	0	1	1	0.20
Human Factors	0.67	1	1	0.20
Overall Score	0.44	0.63		1.0

ACRP Report 219 outlines the importance of having a comprehensive evaluation process to fully understand the objectives, challenges, and intent of using AGVSs in an airport environment. The evaluation procedures for the airside applications can be flexible to meet an airport's specific needs and the AGVS technology capability, allowing stakeholders to make informed, safety-driven decisions in fast-evolving industry (Hubbard et al., 2020).

ACRP Report 219 highlights airside applications that can support airport operations, ramp, and aircraft activities. Using the evaluation process outlined in Figure 1, the ACRP research team used the criteria of ease of adoption and stakeholder acceptance, benefits, technical feasibility, infrastructure impacts, operational impacts, and human factors on the following applications:

1. Airport Operations
 - a. FOD detection and removal: safety assist (including automatic dependent surveillance-broadcast (ADS-B) for fleet management and to prevent runway incursions) and automated with driver
 - b. Mowing: automated with no driver and central control
 - c. Snow and ice control: platoon with driver in lead and remote operation (general aviation (GA) airport)
 - d. Perimeter inspection: automated with no driver
2. Ramp and Aircraft Activities
 - a. Aircraft pushback and aircraft tug/taxi to runway
 - i. Aircraft pushback: remote from ramp and automated with driver
 - ii. Aircraft tow or tug to and from runway: remote from cockpit and automated with driver
 - b. Baggage carts: safety assist (ACRP, 2020)

With the extensive opportunities of AGVSs to increase capacity, efficiency, and safety at airports, ACRP Report 219 expresses the need for more research on the benefits and limitations of the use of automation in the airside environment. The ACRP team expressed their research priorities to address enabling technologies and infrastructure to support airside AGVS operations. In addition, these priority areas are supporting research in the application and advancement of the airside environment, listed below. (Hubbard et al., 2020).

1. AGVT Research Priorities

- a. AGVT sensor capacities in airside environments
- b. AGVT communications
- c. Geographic information systems (GIS) airside maps
- d. Vehicle transponders

2. Supporting Research Priorities

- a. Data
- b. Regulations
- c. Simulation tools
- d. Aircraft databases
- e. Centralized AGVT operations centers
- f. Airport primer for AGVT
- g. AGVT information sharing (Hubbard et al., 2020)

ACRP Report 219 emphasizes the significance of AGVSs within the airport environment and the broader transportation ecosystem. It underscores the need for collaborative efforts among stakeholders to address the challenges and capitalize on the opportunities presented by AGVS technologies for improving efficiency, safety, and sustainability in airport operations, while displaying a detailed evaluation process that can be adjusted to meet any airport's needs. Overall, the ACRP 219 Report, *Advanced Ground Vehicle Technologies for Airside Operations*, serves as a comprehensive resource for researchers, practitioners, policymakers, and industry stakeholders interested in understanding, implementing, and leveraging AGTVs in airport environments. (Hubbard et al., 2020)

2.1.1.2 Airport Cooperative Research Program Synthesis 29

The ACRP Research Synthesis 29, *Ramp Safety Practices—A Synthesis of Airport Practice*, addresses the development of innovative near-term solutions to support airports in meeting increased National Airspace System (NAS) demands. The primary participants in the ACRP include the FAA and other government agencies, the Transportation Research Board, academia, and the airport/airline industry. ACRP Synthesis 29 focuses on the challenges experienced by airports, airlines, and ground service providers (GSPs) in ensuring safe and efficient operations on ramps. Airports and airlines have shared responsibility for the safe and efficient operation of ramps and gates. The separation of responsibility between these organizations varies between airports. The Synthesis 29 study was conducted to assess the current state of airport ground handling practices in airport non-movement areas (i.e., ramps and gates). The target audiences for the study were airport operators, airlines, and GSPs. The FAA does not directly regulate apron management services at airports. FAA oversight of ramp areas is provided indirectly

through certification of airports and airlines primarily through Title 14 Code of Federal Regulations (14 CFR) Parts 119 (Certification of Air Carriers and Commercial Operators, 2018), 121 (Operating Requirements: Domestic, Flag, and Supplemental Operations, 2017), 135 (Operating Requirements: Commuter and On Demand Operating Rules Governing Persons on Board Such Aircraft, 2017), and 139 (Certification of Airports, 2004) (Landry & Ingolia, 2011).

ACRP Synthesis 29 consists of an academic review and a survey of the airport and airline industries. The academic review identified and referenced many technical documents related to safety in ground handling operations on airport ramps. These documents were generated by academia, industry associations, and government agencies, including the International Civil Aviation Organization (ICAO), Airports Council International (ACI), Flight Safety Foundation, TRB, and the FAA. Survey questions were forwarded to airports, airlines, and GSPs to obtain their input relating to current ground handling operations and practices on ramps. Large-, medium-, and small-hub airports and GA airports were contacted for the survey. The survey was designed to gather information on ramp safety operations, staff roles and responsibilities, safety training, audit and inspection programs, safety violation programs, and collaborative safety initiatives. The survey questions included the following topics: airport oversight of ramp areas, safety inspections of ramps and baggage make-up areas, conducting ramp safety meetings, airline and GSPs collaboration with addressing FOD, and ramp training requirements. The survey produced the following conclusions:

1. Ramp areas are complex regardless of airport size.
2. Comprehensive U.S. standards do not exist for non-movement area ramp markings, ground operations, and safety training.
3. Data repositories for accidents and incidents on ramps are needed to identify trends,
4. Airports, airlines, and GSPs have varying roles and responsibilities depending on airport contractual and operational agreements.
5. FAA and airport/airline industry safety initiatives are underway relating to ramp ground handling operations. (Landry & Ingolia, 2011)

ACRP Synthesis 29 also addresses future trends in technology and practices, which can benefit operations on airport ramps. These advancements include ADS-B, which is a global positioning system (GPS) for transmitting aircraft locations to ground receivers. These locations are then transmitted to controller screens and cockpit displays. This technology can also be used on ground vehicles. Airport Surface Detection Equipment—Model X (ASDE-X) is a surface RADAR system that can operate in conjunction with the ADS-B system to provide surveillance of aircraft and ground vehicles. In 2009, John F. Kennedy Airport (JFK) and the Port Authority of New York and New Jersey extended ASDE-X coverage into JFK ramp areas to generate surface surveillance data. Ramp towers are now being introduced and constructed at some airports and are typically responsible for aircraft movements conducted in the non-movement or ramp areas. Ramp tower controllers assist with traffic sequencing, separation, pushback, gate arrivals and departures, and coordination with the Air Traffic Control Tower (ATCT) (Landry & Ingolia, 2011).

The ACRP Synthesis 29, *Ramp Safety Practices— A Synthesis of Airport Practice*, provides an overview of current ground handling operations and practices on airport ramps. The synthesis study does not contain any technical information or include any feedback from airports and airlines pertaining to the introduction of AGVS technology in airport ground vehicles (Landry & Ingolia, 2011).

2.1.2 Society of Automotive Engineers

2.1.2.1 Aerospace Recommended Practice 1247E

The SAE Aerospace Recommended Practice (ARP) 1247E, *Aircraft Ground Support Equipment—General Requirements*, prescribes general design requirements that should be applied to ground support equipment used in the civil air transport industry (e.g., airports and commercial airlines). ARP 1247E is intended to standardize design requirements for various configurations of ground support equipment. It is recommended that the civil air transport industry extract sections of the document for incorporation into their procurement specifications. Additionally, the SAE defines the levels of driver automation from Level 0 (no driving automation) to Level 5 (full driving automation) in the context of motor vehicles and their operation on the roadways. ARP 1247E includes requirements for performance, operability, reliability, maintenance, total life, environment, transportability, safety, design and construction, and aircraft docking protection. (SAE International, 2018)

Each of these requirements will be addressed separately as follows:

1. Performance: Equipment, properly maintained, shall be designed to function for the prescribed “total life” period.
2. Operability: Equipment shall be capable of continuous operation at a rated load for a prescribed period and operate satisfactorily at an angle up to 5 degrees.
3. Reliability: Equipment shall operate reliably for 200 to 400 hours between periodic preventive maintenance periods, as required by application.
4. Maintenance: Maintainability/accessibility should be built into the design, allowing personnel safe and adequate access to all points on ground support equipment requiring service.
5. Total Life: Procuring agency shall identify total life requirement for ground support equipment from time of delivery until when equipment is no longer functional and classified as salvage.
6. Environment: Design of equipment shall be based on a normal ambient temperature range of -20 °F to 123 °F with 100% relative humidity. Temperature range can be extended for extreme climatic conditions, as required.
7. Transportability: Designs must accommodate over-the-road unrestricted transportation to the greatest extent possible.

8. Safety: Safety features of equipment must comply with AIR1375, Minimum Safety Requirements for Special Purpose Airline Ground Support Equipment, and Title 29 CFR Part 1910 - Occupational Safety and Health Administration (OSHA).
9. Design and Construction: Design and construction requirements are prescribed for the following equipment/systems: mechanical design, electrical design and equipment, hydraulic/pneumatic design, engines and related equipment, fuel systems, exhaust systems, self-propelled vehicles, and instruments/controls.
10. Aircraft Docking Protection: Self-propelled ground support vehicles, required to interface with aircraft, must have positive controlled (non-jerking) slow speeds allowing a safe approach to aircraft and contact where necessary (SAE International, 2018).

The SAE document ARP 1247E, *Aircraft ground support equipment—General requirements*, does not envision the use of ground support equipment using AGVS technology operating in airport environments. Existing requirements would need further evaluation and modification based on the expected use of driverless vehicles interfacing with personnel-driven vehicles and pedestrians in airport environments. (SAE International, 2018)

2.1.2.2 Report on Unmanned Ground Vehicle Reliability, SAE J2958_201111

The SAE Standard J2958_201111, *Report on Unmanned Ground Vehicle Reliability*, focuses on the reliability of unmanned ground vehicles (UGVs) used in U.S. military operations. The reliability of the UGVs has become very important as their use has increased substantially in U.S. foreign theaters of war. The number of UGVs deployed by the U.S. military in foreign theaters of war grew from 150 in 2004 to 4,000 by the end of 2006 to 12,000 by 2008. These UGVs perform high-risk missions (e.g., explosive ordinance disposal (EOD)), while being deployed in the European Command (EUCOM), Iraq, Afghanistan, and other Central Command (CENTCOM) locations. (SAE International, 2020)

SAE Standard J2958_201111 addresses reliability engineering as applied to these UGVs and is separated into four levels of analysis: component, unit, team, and system. Component-level reliability analysis focuses on individual UGV components such as gears, shafts, and bearings. Unit-level reliability analysis of UGVs combines the reliability of individual components, either in series with no redundancy (i.e., all components must function for the unit to remain operational) or in parallel with redundancy (i.e., multiple components are redundant and can be swapped in as spares). Team-level reliability analysis involves multiple UGVs operating together with the possibility of reassignment in the event of component failure to one UGV. System-level reliability analysis includes components difficult or impossible to analyze using the following techniques: human-machine interaction, communications, controls, and software. (SAE International, 2020)

The SAE J2958 report concludes that the most difficult challenge for accurately assessing the reliability of UGVs relates to systems reliability. While system reliability is very important in assessing overall UGV reliability, there has been very limited technological work done in this area. As a result, there are very few methods available for assessing system reliability of UGVs. Meantime between failures (MTBFs) for UGVs in military applications are reported to be

between 4 hours and 24 hours, clearly reflecting a low level of reliability. (SAE International, 2020)

The SAE Standard J2958 Report, *Report on Unmanned Ground Vehicle Reliability*, relates to the past, present, and future reliability of UGVs used in military operations and methods of analysis. Due to the nature of AGVS use by the military, it is difficult to draw any parallels between the reliability of UGVs in military operations with AVs used in airport environments. (SAE International, 2020)

2.1.3 National Renewable Energy Laboratory and Automated Mobility Services

The National Laboratory of the Rockies (NLR) report NREL/TP-5400-82470, *Roadmap to Automated Mobility Systems: Informing the Planning of a Sustainable, Resilient Transportation Ecosystem for Dallas/Fort Worth International Airport (DFW)*, was funded by DFW and provides a vision to enable the airport to integrate technologies to support positive traveler and employee experience while leveraging technology to support sustainability (Duvall et al., 2022).

Figure 3 provides a context for activities, including five automation pathways that support traveler access, employee mobility, and freight/service access to the DFW terminals. The integration of technologies is expected to reduce risk for the airport and support operational resilience. Technologies will be leveraged at all levels, from the consumer level to the airport infrastructure level and beyond, as the airport integrates with technologies in the greater DFW metropolitan area to support a smart city concept (Duvall, et al., 2022).

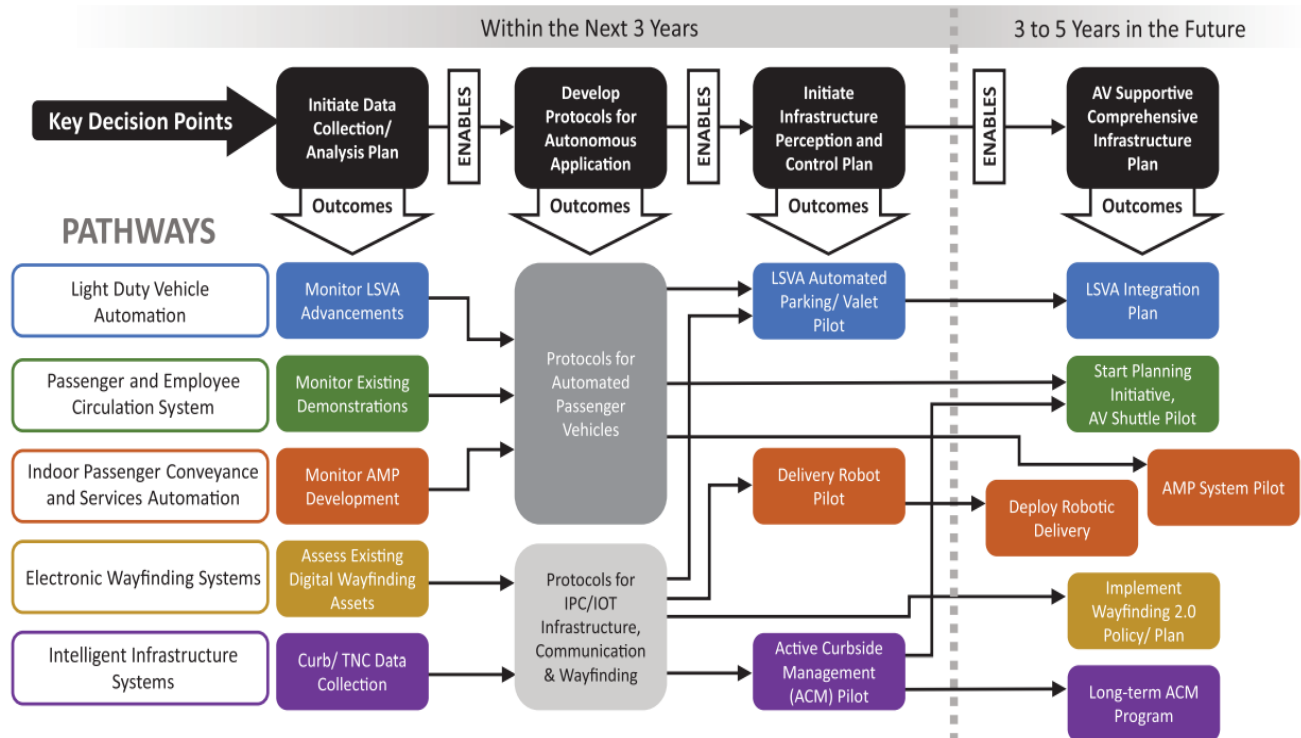


Figure 3. Roadmap Toward Mobility Automation at DFW (Duvall et al., 2022)

The NLR report defines four decision points that support the validation of technology:

1. Develop plans for data collection and analysis
2. Identify protocols for autonomous applications
3. Deploy pilot-scale projects
4. Develop a comprehensive infrastructure plan to support AGVSs in the future (Duvall et al., 2022)

These steps could be used to support airside AGVS deployments, although the DFW applications are primarily focused on landside and terminal applications and include the following:

1. Vehicle automation (light-duty vehicles only)
2. Passenger and employee circulation systems for service in public areas (non-secure, systems will not use fixed guideways)
3. Indoor passenger movement and services (to replace moving walkways and golf carts)
4. Electronic wayfinding to connect users, vehicles, and infrastructure
5. Intelligent infrastructure management systems (Duvall et al., 2022)

Integration of these technologies will result in additional infrastructure for electric vehicle (EV) charging (including quantity, location, and type of equipment), which is a separate planning activity. (Duvall et al., 2022)

Infrastructure requirements were acknowledged, but they would depend on the specific application. For example, low-speed automated vehicles (LSAVs) may have specific signal-related technology requirements depending on the vendor and routes (Duvall et al., 2022). Fundamental concepts related to infrastructure planning include:

- Global navigation satellite system (GNSS), which may not be sufficient for AGVS positioning in an airport.
- Detailed 3D mapping may be required for indoor applications (LiDAR-equipped vehicles/robots may provide this function prior to deployment or on an ongoing basis).
- Magnetic markers have been used to assist with transit vehicle positioning on fixed routes.
- Lane markings, signals, and signs to assist AVs and support interactions with people, although modern AVs do not require predetermined paths and can navigate within zones (Fragapane et al., 2021). Connected signal technology has been implemented in many low-speed shuttle AGVS deployments.
- Management and control, which may include centralized and decentralized control, and smart dispatch based on demand pattern.
- Communication, which needs to be reliable and may use cellular networks and/or Wi-Fi for two-way data transmission. 5G will be helpful but is not required for AGVS deployment. Related cybersecurity issues must be addressed. (Duvall et al., 2022)

Coordination with peer airports was recommended, and Haneda Airport (HND) and Pittsburgh International Airport (PIT) (in partnership with Carnegie Robotics) were specifically identified as candidates for peer exchange. (Duvall et al., 2022)

Figure 4 provides a diagram of the control systems. This may be relevant for airside deployment. The report also noted the need for coordination of technology applications, and presented a roadmap for selected activities, as shown in Appendix B. (Duvall et al., 2022)

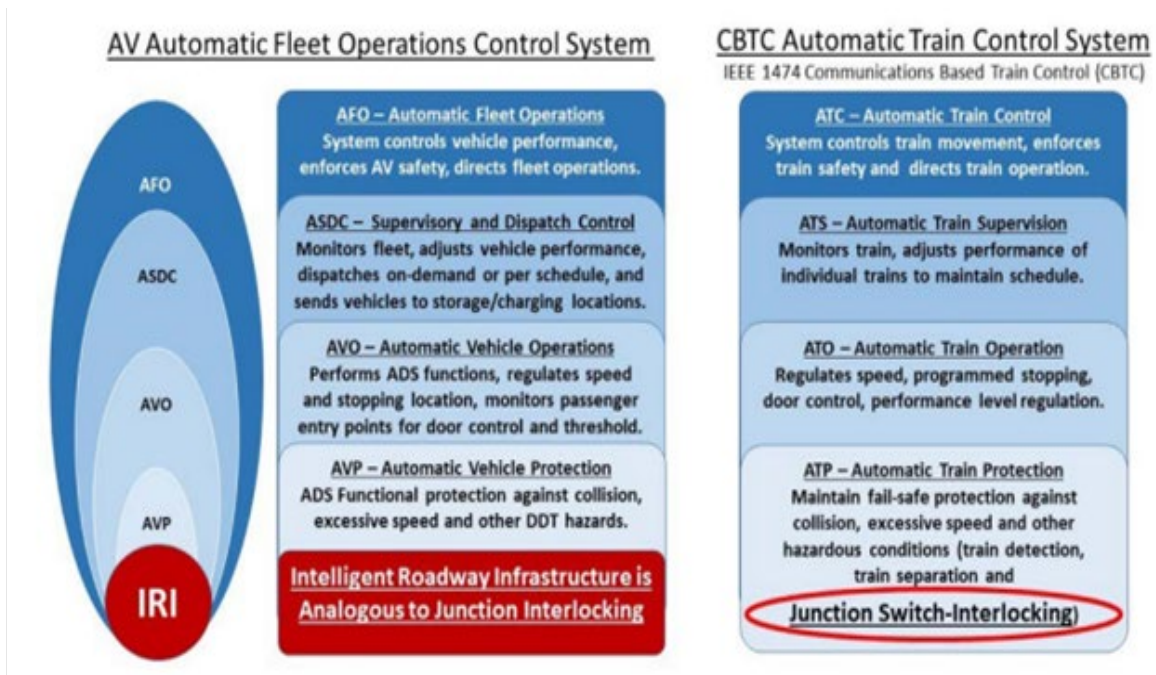


Figure 4. Control Systems for AGVSs and the Automatic Train (Duvall et al., 2022)

2.1.4 Dallas Fort Worth International Airport

In the *Journal of Airport Management*, Jodie Brinkerhoff (2022) from DFW published an article, “De-Risking the Future—A Case Study: DFW Airport Driving Innovation and Reducing Risk on the Road to Autonomy.” The journal article discusses how DFW plans to incorporate autonomous technologies, including AGVSs, and how they have translated innovation into a process that spans a variety of airport activities. One impetus for innovation at DFW is to support resiliency; other drivers include recognition that DFW’s Innovation Division is focused on taking new solutions to market to improve customer experience, reduce costs, identify new revenue sources, and foster a culture that supports innovation. (Brinkerhoff, 2022)

The process for innovation at DFW is shown in Figure 5. This process ensures that metrics are used, future risks are identified, and key stakeholders are included (“CP” represents a checkpoint and means that an executive stakeholder must sign off on the project). (Brinkerhoff, 2022)

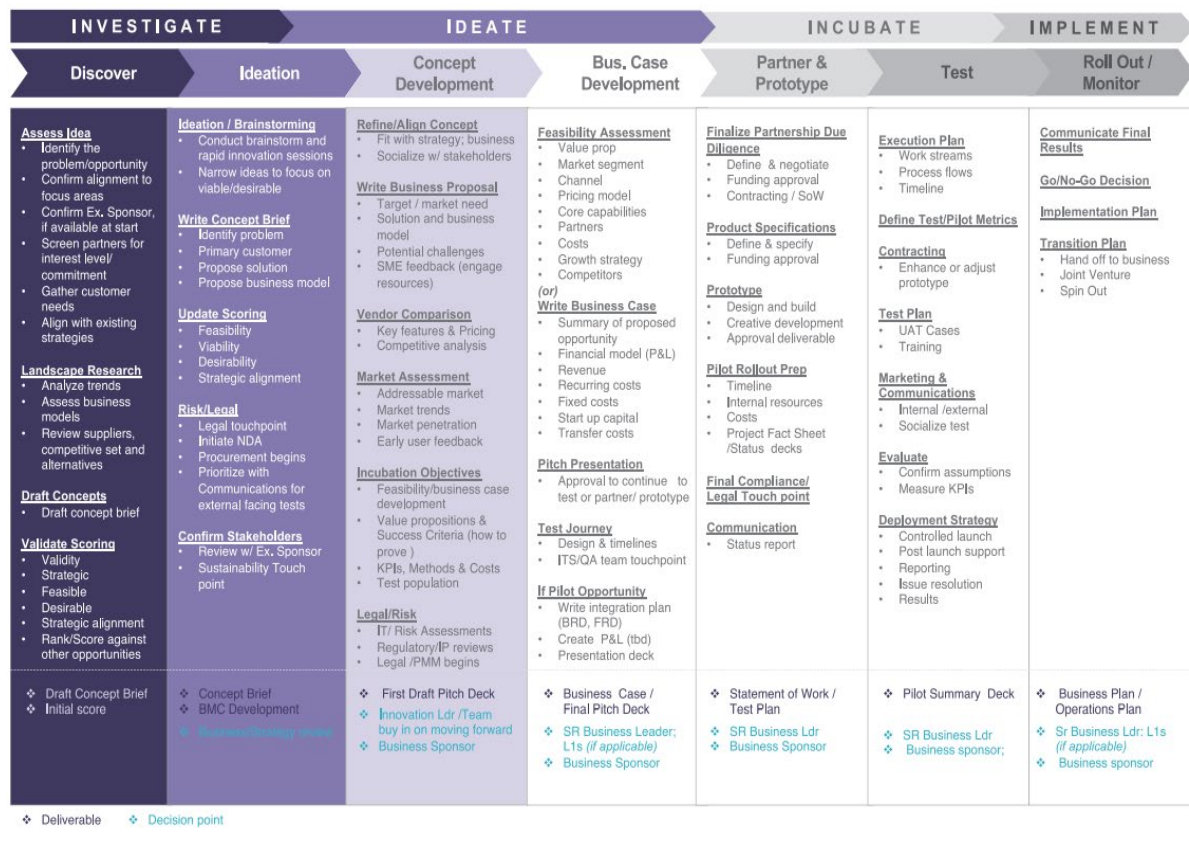


Figure 5. Dallas Fort Worth Airport Innovation Process (Brinkerhoff, 2022)

One of the trial projects deployed using this process was a 15-person AGVS shuttle; preparation included 9 months of planning, 7 planning stages, and 100 validation steps. One lesson learned was that the AGVS shuttle (15 to 30 miles per hour (mph)) technology is not mature enough for the DFW international parkway, due to the traffic characteristics (many left turns and cross-traffic intersections), and the speed difference between the low-speed shuttle and the speed of traditional vehicles (the posted speed limit is 55 mph, but many vehicles travel faster). Figure 6 shows a photograph of the shuttle. (Brinkerhoff, 2022)



Figure 6. The DFW AGVS Shuttle (Brinkerhoff, 2022)

This shuttle project began with tests in a remote parking lot to gather data before expanding to a wider operating zone. Interviews with numerous stakeholders, such as the Department of Public Safety (DPS), were conducted to ensure safety. Additional issues identified included the availability of power (and resiliency of power supply), passenger safety, insurance, and cybersecurity. (Brinkerhoff, 2022)

The primary focus of DFW's current plan is landside and terminal AGVSs. The article also provides information about how the airport fosters an innovative culture that encourages the implementation of new technologies, collaboration, and cooperation. (Brinkerhoff, 2022)

2.2 ACADEMIA PUBLICATIONS

This section examines the scholarly research conducted within the AGVS industry. The contents of this section identify methodologies and emerging trends within the AGVS industry based on the relevant peer-reviewed publications. The following publications have been reviewed and summarized to display the most relevant information in relation to autonomous research and enhance the findings in further sections of this final report.

2.2.1 Purdue University

Purdue published a journal article, *Case Study of an Automated Mower to Support Airport Sustainability*. This paper documented the airside deployment of an electric, automated mower at the Purdue University Airport (LAF), Indiana, a Part 139-certificated airport. The results of the study were generally positive; important considerations included safety and operational integrity. During the 2-year deployment, the automated mower did not interfere with aeronautical activities and was not a threat to people (Hubbard, Hubbard, & Baxmeyer, 2021).

Several safety elements were in place that supported risk mitigation. These elements included a hard-wire induction loop with current around the perimeter of the mowing area, mower software that ensured the mower would stop if it crossed the induction loop or if the loop lost power, a software geofence that uses the real-time mower location (the geofence capability also ensures that the mower does not operate if it is lost or stolen), a physical barrier, mower sensors for collision avoidance (sonar), and remote monitoring and control capabilities via a cell-phone application or the Internet. Remote monitoring allows the mower to be stopped or sent to the home station for a charge, in addition to other commands. This project was deployed in close collaboration with the mower vendor, ECHO Robotics. The mower used a standard cell phone signal for communication, and its location and status were available in real time. Diagrams of mower sites are shown in Figure 7, Figure 8, and Figure 9. Site A is the initial testing location in an uncontrolled area of the airport. Site A is inside the fence line of the airport adjacent to the fuel farm; power was readily available for mower charging and for power for the perimeter induction loop. Site B is a site closer to the taxiway that is proposed for operation with solar power. Site B is outside the taxiway safety area/object free area (Hubbard, Hubbard, & Baxmeyer, 2021).



Figure 7. Mower Sites (a) and (b) at LAF (not to scale) (Hubbard, Hubbard, & Baxmeyer, 2021)



Figure 8. Initial Site (a) near Fuel Farm with Existing Power (Hubbard, Hubbard, & Baxmeyer, 2021)

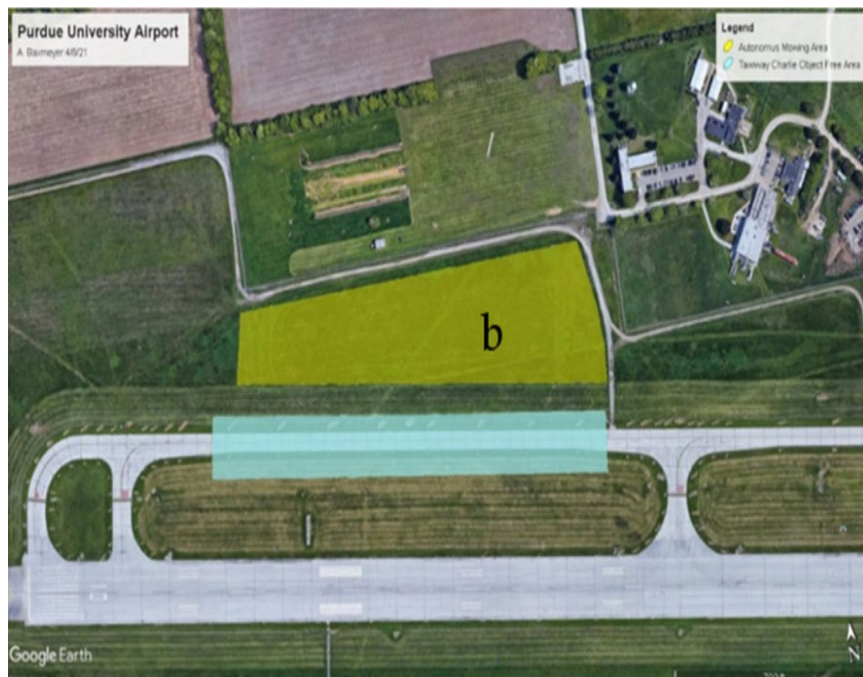


Figure 9. Site (b) Closer to Taxiway Proposed for Operation with Solar Mower (Hubbard, Hubbard, & Baxmeyer, 2021)

The results of this study illustrate that with proper planning and coordination with airport stakeholders, an automated mower can be successfully deployed in remote and controlled areas

at an airport with limited passenger service and a Part 139 certificate. At LAF, coordination and concurrence were obtained from the appropriate FAA Airports Certification & Safety and Airport Compliance offices. In addition to coordination and approval with the FAA, ensuring safety, developing an appropriate inspection protocol, and matching the capabilities of the mower to the field were all important implementation considerations (Hubbard, Hubbard, & Baxmeyer, 2021).

Future deployment in protected areas, such as the runway safety area (RSA), would probably require demonstration of frangibility, which would necessitate additional testing and approval. Automated electric mowers may replace or augment conventional mowers. Benefits include reduced emissions and reduced personnel for mowing. Automated mowers may be especially helpful in remote areas of the airfield (Hubbard, Hubbard, & Baxmeyer, 2021).

2.2.2 Seoul National University

The Seoul National University published an article, *Results and Lessons Learned from Autonomous Driving Transportation Services in Airfield, Crowded Indoor, and Urban Environments*, sponsored by ThorDrive and Seoul National University, that discussed the results of airfield driverless tug testing conducted at Cincinnati/Northern Kentucky International Airport (CVG), a large-hub Part 139 airport¹. ThorDrive, a spin-off from the research center at Seoul National University, Korea, benefits from its strong connection to the university, which contributed significantly to the development of the company's autonomous driving technology (Baek, Kim, Seo, & Lee, 2024).

The autonomous driving system architecture of ThorDrive vehicles consists of two main components: the general-purpose system and the mission-purpose system (Baek, Kim, Seo, & Lee, 2024). The general-purpose system is divided into four modules: localization, perception, planning, and control. The localization module determines the vehicle's current location. The perception module identifies surrounding objects and predicts their behavior. The planning module generates the best path based on the inputs from localization and perception. Finally, the control module calculates the necessary control inputs to follow the planned trajectory (Baek, Kim, Seo, & Lee, 2024).

The mission-purpose system includes new algorithms tested in this study. These algorithms were designed to address specific challenges in different environments. Mission algorithms for airfield driving include aircraft detection, aircraft intention prediction, and occlusion-aware risk assessment. A flowchart of the system architecture is shown in Figure 10 (Baek, Kim, Seo, & Lee, 2024).

¹ Note that the AGVS testing done at CVG was conducted in 2020, prior to the release of CertAlert 24-02.

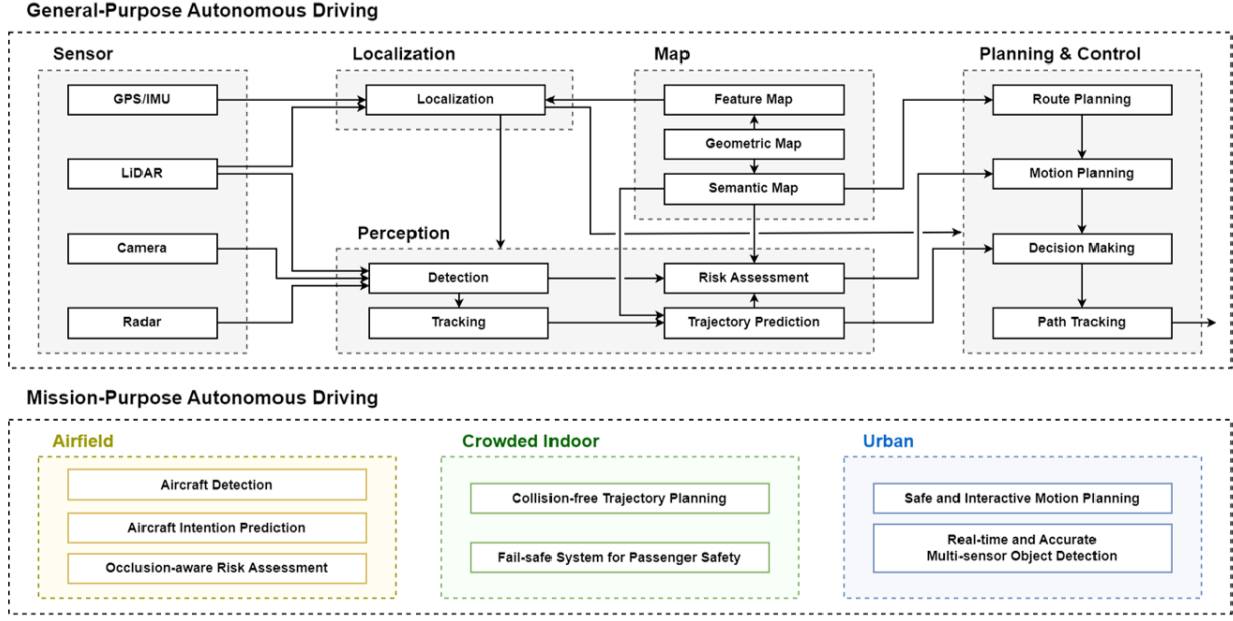


Figure 10. Overall Architecture of the General- and Mission-Purpose Autonomous Driving Systems (Baek, Kim, Seo, & Lee, 2024)

The testing at CVG was done with an AGVS tug transporting baggage and cargo for 3 weeks, with a total driving distance of 2,163.2 km over a 106.7-hour test time. The AGVS had 11 safety, 51 non-safety, and 1 emergency disengagement during testing. The AGVS had zero disengagements 81.3% of the time. The article notes how different airfield driving practices are from standard highway driving, and how algorithms predicting human driving behavior vary considerably from aircraft operations (Baek, Kim, Seo, & Lee, 2024).

Some aircraft can be much larger than the objects an AGVS might encounter in urban environments, and, therefore, the research team needed to overcome limitations in previous models to fit the airport environment. An algorithm using conditional random field optimization merges segments in LiDAR perception detection with an image-based detection algorithm. The new aircraft detection method was less affected by aircraft size and achieved higher tracking and classification accuracy than other algorithms (Baek, Kim, Seo, & Lee, 2024).

Because ground service equipment (GSE) in an airport environment has different requirements than traffic movements in urban driving environments, an aircraft intention prediction mission algorithm was applied. The aircraft's pose and intention are the linchpins to successful movement predictions. The algorithm used a Bayesian network with the following variables: aircraft pose and beacon signal (A), GSE and ramp agent information (O), and the aircraft's intention (k). The article claims 2.3% improvements in cloudy weather, 1.6% improvements in rainy weather, and 9.3% improvements in different airport environments compared to the baseline (Baek, Kim, Seo, & Lee, 2024).

Finally, a simplified reachability quantification algorithm was claimed to improve an occlusion-aware risk assessment. This improved the AGVS's ability to quantify the risk of occlusions

constantly in operation at a diversion environment where workers or equipment can occlude the path of the AGVS abruptly at any time (Baek, Kim, Seo, & Lee, 2024).

The Seoul research team identified the need to solve the problem of detecting and mitigating aircraft jet blast as a potential gap. Overall, the authors reported that testing at CVG saw some improvements, but there is still work to be done to continue to improve the safety of AGVSs in a diverse and quickly changing airport apron environment (Baek, Kim, Seo, & Lee, 2024).

2.2.3 Colorado State University Journal Article

Colorado State University authors published an article, “Multiple-Scenario Unmanned System Control: A Systems Engineering Approach and Review of Existing Control Methods,” in the journal *Aerospace*. In this article, the authors offer insight into what an autonomous system data infrastructure looks like from a programming viewpoint (Eaton, Chong, & Maciejewski, 2016). The architecture proposed is modular and can be modified across vehicle types and sensor abilities. There are five primary functions within the proposed architecture that provide the framework: Mission Management, Vehicle Management, Sensors Management, Communications Management, and Safety Management. Each area has a controller that receives the information of its subprocesses and manages the overall function. Figure 11 demonstrates the framework from a top level, and Figure 12 highlights a detailed system architecture (Eaton, Chong, & Maciejewski, 2016).

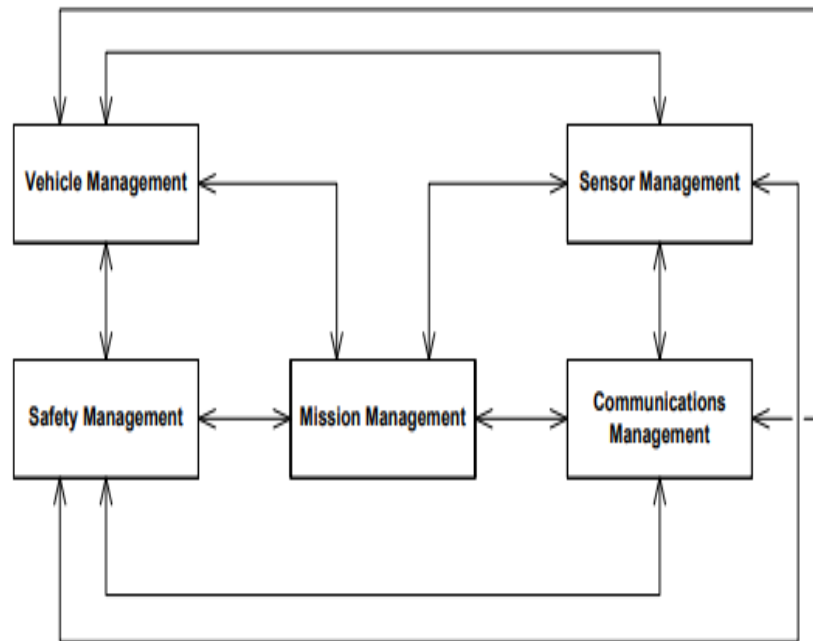


Figure 11. Top-Level System Architecture (Eaton, Chong, & Maciejewski, 2016)

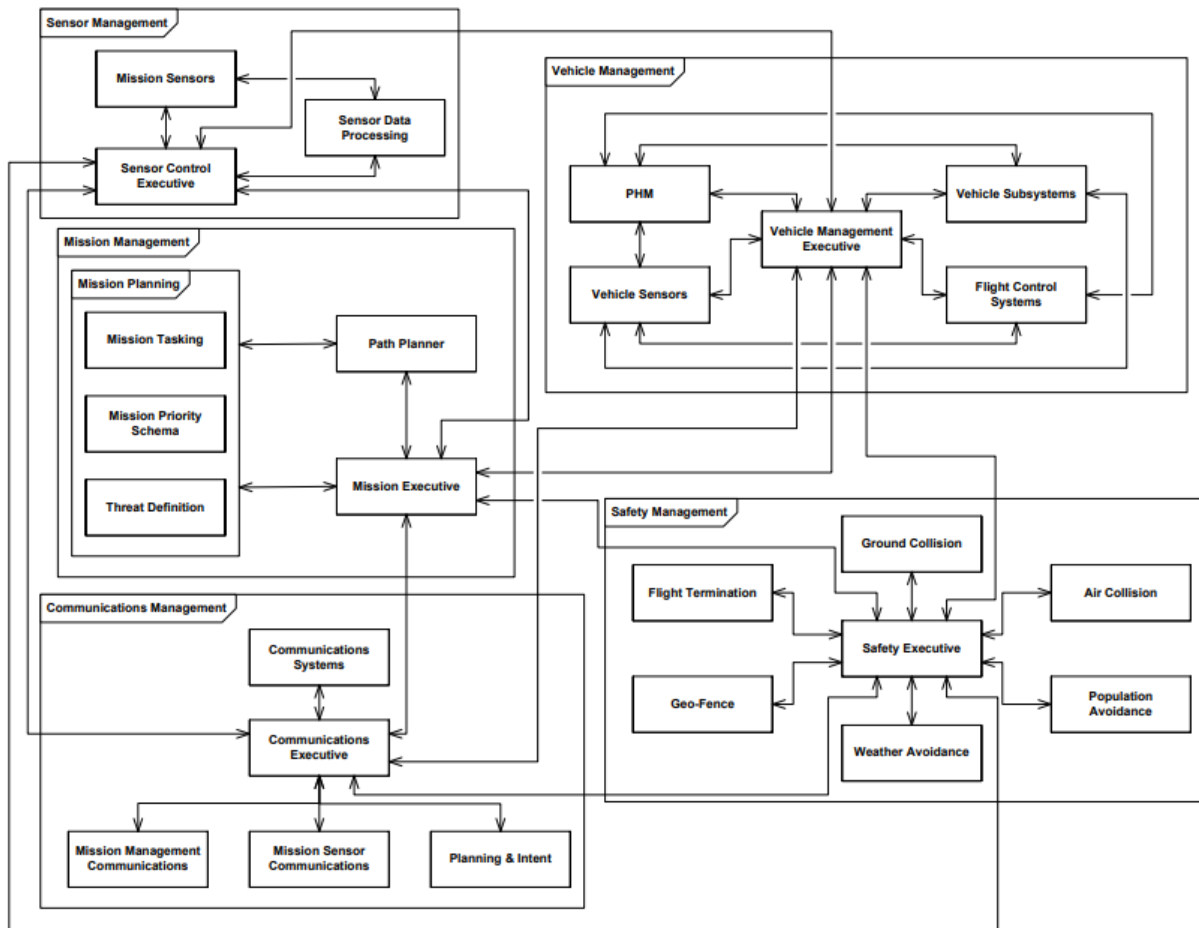


Figure 12. Detailed System Architecture (Eaton, Chong, & Maciejewski, 2016)

When evaluating AVs for airports, this architecture may be useful in understanding how the autonomous surface vehicle (ASV) works and, subsequently, how best to mitigate operational risk (Eaton, Chong, & Maciejewski, 2016).

2.2.4 American University of Sharjah

The American University of Sharjah published an article, “Smart Airport Foreign Object Debris Detection Rover using LiDAR Technology” in the journal *Internet of Things* that describes a simple prototype FOD detection robot that has only been shown as proof of concept in an indoor laboratory and an outdoor parking lot. No actual fielding of the robot has been performed, nor has it been significantly tested on examples of FOD that match the kinds of items listed in AC 150/5210-24A, *Airport Foreign Object Debris (FOD) Management* (FAA, 2024a). (Elrayes, Hag Ali, Zakaria, & Ismail, 2019)

The proposed prototype rover is intended to operate on a track that runs alongside and parallel to a runway. No specific construction requirements are given, but it is assumed that this infrastructure would be needed for every runway at every airport where this technology would be employed. Instead, if the rover were to be deployed directly on the runway and use the existing

painted lines on each side of the runway as a guide, no additional infrastructure would be needed so long as the paint on the runway was not chipped/cracked/degraded causing the rover to lose its ability to track it and, thus, wander off and get lost. This issue would be more likely in inclement weather where snow, ice, or moisture might affect the sensor's ability to track the paint line (Elrayes, Hag Ali, Zakaria, & Ismail, 2019).

Other issues and concerns with deploying such a rover were documented in the paper:

1. The small rover would need to be manually placed at the start of the runway by an operator. This would mean that the runway would need to be shut down for the duration of the rover's run.
2. The rover is very small and, therefore, could take a long time to traverse the length of a runway. Assuming a ground speed of 0.5 m/s, it would take more than 2 hours to traverse the length of a 4.2-km runway.
3. The LiDAR's ability to detect FOD will be affected by any roll/pitch of the vehicle on uneven pavement or the presence of FOD on the painted line, causing it to be less accurate.
4. The position of the robot along the runway is computed by integrated wheel odometry. Over time, the odometry estimate will drift and become more inaccurate. A study would need to be performed to determine just how much error accumulates along a 4.2-km runway. One way to alleviate this issue would be to have additional painted infrastructure that the robot could detect and use to reset its odometrical uncertainty. (Elrayes, Hag Ali, Zakaria, & Ismail, 2019)

Even when FOD is found, the location of the FOD needs to be communicated back to a person who will then have to drive out to the location indicated by the robot and manually search for the FOD in question (Elrayes, Hag Ali, Zakaria, & Ismail, 2019).

2.2.5 Jadavpur University

The Jadavpur University and National Ilan University published a journal article, *Autonomous Vehicles Enabled by the Integration of IoT, Edge Intelligence, 5G, and Blockchain* that examines four core enabling technologies for AGVSs: Internet of Things (IoT), Edge intelligence, 5G, and Blockchain. The article explains how each technology helps fulfill AGVS requirements and is integrated into AGVS architectures while highlighting remaining challenges and gaps (Biswas & Wang, 2023).

The AGVS domain is relatively new and, therefore, there are no international standards developed specifically for AGVS safety and security. The International Organization for Standardization (ISO) 26262 standard for automotive safety (ISO, 2018) is the most applicable for AGVS safety analysis. However, ISO 26262 was published without considering deep learning; therefore, it lacks adequate ways to incorporate safety issues when linking AI with AGVSs. Additionally, the article notes the lack of a universally defined standard for sensor failure or a comprehensive study on sensor failure detection. This is problematic since the all-

around safety of AVs heavily depends on the multiple sensors present. AI systems in self-driving cars must not only make real-time and safe decisions but also explain how those decisions are reached to comply with the law in many jurisdictions. There are four principles of explainable artificial intelligence (XAI), which outline the essential criteria that an AI system must meet to qualify as XAI. These four principles are:

1. Explanation—the system delivers accompanying evidence, reasoning, or context for all outputs and decisions it generates;
2. Meaning—the system is understandable to the stakeholder;
3. Explanation accuracy—system explanations must be accurate and truthful; and
4. Knowledge limits—the system recognizes its own boundaries. (Biswas & Wang, 2023)

The use of edge computing to process high-bandwidth sensor data close to where it is produced (i.e., on the vehicle itself) rather than offloading it to the cloud is considered best practice for AGVSs. This brings the computing and storing of data to the same level where it is produced (at the network edge) and dramatically improves the latency and bandwidth use, enabling critical decision-making in real-time. (Biswas & Wang, 2023)

The article does not include AGVS validation approaches, aside from noting that AI-based algorithms are difficult to test thoroughly. Testing in the real world is not yet widely conducted. This leaves significant gaps because nothing can simulate the performance of the vehicle in real-world circumstances riddled with uncertainties and variance. (Biswas & Wang, 2023)

V2X communication allows wireless connectivity among vehicles, roadside units, pedestrians, passengers, and base stations. The four types of V2X communications are V2I, vehicle-to-network (V2N), vehicle-to-pedestrian (V2P), and V2V. Cooperative autonomous driving leverages V2X communications for improved efficiency and performance. It has two categories. The first is cooperative sensing that shares information among AVs through V2V and V2I communication. It increases the sensing range of an AGVS and makes the system more robust. The reliance on roadside sensing infrastructure will also reduce the need and the cost of many expensive onboard sensors, making this approach highly cost-effective. The second category is cooperative decision-making, in which a group of AVs cooperate among themselves and make decisions based on the information shared with each other. (Biswas & Wang, 2023)

The article also covers the underlying wireless technologies in detail. Mainstream vehicular communications have two categories: dedicated short-range communications (DSRC) and LTE-based V2X technology (LTE-based V2X, or simply LTE-V). DSRC is bound by the Institute of Electrical and Electronics Engineers (IEEE) 802.11p and IEEE 1609 standards. LTE-V is based on cellular network technologies such as 4G/5G. DSRC faces bandwidth constraints to deliver a high data-rate link and is also prone to malicious attacks. The 6 GHz bandwidths used by fourth-generation LTE advanced (4G LTE-A) are highly congested, leaving minimal space for use by AVs. This has spurred the 5G communication to exploit the under-used millimeter wave bands (10–300 GHz). These bands are indispensable for 5G V2X communications because recent studies have shown the necessity of multi-Gbps links to enable such communications. Autonomous or semi-autonomous vehicles connected by 5G technology are predicted to be

better supporters of the various AI algorithms required for environment sensing, perception, and decision-making. (Biswas & Wang, 2023)

Risk mitigation is performed in SAE Level 3 AVs via an alert human driver who can take over control during any unexpected situation when the system may fail. Automated emergency braking, driver monitoring, and traffic jam assistance are some extra functionalities other than those already present in Level 2 vehicles. Geo-fencing could be used to confine AGVS operation to controlled areas in an airport environment. The paper also discusses risk mitigation approaches applicable to cooperative driving, in which AVs will drive in platoon formation, while communicating with each other through 5G or 6G. One such approach helps the host vehicle authenticate messages from a target vehicle by sanity-checking its reported trajectory. Another prevents a forged event, such as an accident on the highway, from propagating through the vehicle network (Biswas & Wang, 2023).

Obstacle detection in AVs is performed via sensor fusion, which combines data from various sensor types to accumulate the advantages of each type and achieve better overall accuracy. For instance, the fusion of LiDAR and camera data leads to better performance under poor light conditions. Moreover, different layers of sensors with overlapped sensing areas contribute to redundancy, which ensures high reliability (Biswas & Wang, 2023).

2.2.6 Royal Melbourne Institute of Technology

Researchers for the Royal Melbourne Institute of Technology (RMIT) published an article, *A Novel Vehicle-Based GNSS Integrity Augmentation System for Autonomous Airport Surface Operations*, in which they discuss the problem of GNSS quality in the presence of large objects (buildings), which can cause the GNSS position solution to degrade due to multipath reflections. This article describes an approach to modeling situations where multipath reflections caused by nearby terminals could affect a simulated aircraft. This approach is then used to flag areas where GNSS signal quality is expected to diminish. This system could be used by AVs operating outdoors at airports that normally make use of GNSS signals to navigate. By knowing where GNSS accuracy is likely to drop, the AVs could switch to a perception-based localization system based on landmarks, painted lines on the road, or other features that can be detected by sensors to maintain a good pose estimate while the GNSS quality is low. The results of this paper identify important factors that must be considered by any autonomous system that will operate at airports while using GNSS as a primary navigation modality. (Bijjahalli, Ramasamy, & Sabatini, 2017)

2.2.7 Delft University of Technology

The Delft University of Technology published a journal article, *Multi-agent planning and coordination for automated aircraft ground handling*, that addresses the problem of how an aircraft at a gate can be serviced by a group of autonomous ground vehicles and how the activities of those vehicles could be controlled and managed by a centralized controller. This article only presents a simulation of this situation and details how a team of AVs (or agents) could be scheduled and coordinated. The algorithms described in this article would form the core foundations for a centralized system that manages the activities of teams of AVs that could be applied to a wide range of different airport activities. This work has only been performed in

simulation in a proof-of-concept demonstration and has not yet been deployed to manage AVs at an actual airport. (Chen, Ermiş, & Sharpanskykh, 2023)

2.2.8 Seoul National University

Researchers from the Seoul National University published a journal paper, *Probabilistic Context Integration-Based Aircraft Behavior Intention Classification at Airport Ramps*, which presents the challenge of how an AGVS might use sensors, such as cameras and LiDAR, to detect the presence of and infer the motion of nearby aircraft. Algorithms that process the video and point clouds generated by these sensors are implemented and tested against data from these sensors that were manually captured at an airport. The paper shows that these algorithms have success in detecting, classifying, and inferring the behavioral intention of aircraft. AVs that operate in the movement area and gate of an airport would benefit from these algorithms, as they provide real-time situation awareness of the position, heading, and velocity of all aircraft moving around them. The work in this paper was performed offline with images captured at an airport and has not yet been deployed on an autonomous system. (Lee & Seo, 2022)

2.2.9 Austrian Institute of Technology

The Austrian Institute of Technology published a paper, *Towards Scene Understanding for Autonomous Operations on Airport Aprons*, which describes an algorithm for processing camera images taken from the vantage point of an AGVS operating on an airport apron, where all nearby objects of interest are detected and classified. A deep learning algorithm is trained on images captured from a camera placed in different locations at the apron area of an airport. For each image captured by the camera, all nearby objects on the apron are detected and their category recognized. This algorithm would be of significant use to an AGVS because it would allow the AGVS to differentiate between personnel, service vehicles, cones, airplanes, jet bridges, and other airport infrastructure. This ability to recognize different categories of objects would allow the robot to interact with specific objects (e.g., a cone-placement and removal robot) while ensuring safe operation around others (e.g., giving people and service vehicles the right of way). (Steininger et al., 2022)

2.2.10 Guangdong University of Technology

Researchers from the Guangdong University of Technology published a journal paper, *A Systematic Evaluation of Different Indoor Localization Methods in Robotic Autonomous Luggage Trolley Collection at Airports*, which approaches the problem of how an indoor robot tasked with collecting luggage trolleys inside the airport terminal can know its location given that GNSS signals are blocked by the roof of the building. During this research, several indoor localization technologies were tested and evaluated in this paper, including wireless sensor networks (radio-frequency identification [RFID], ultra-wideband [UWB]), camera-based localization, and LiDAR-based localization. Of the different technologies tested, UWB, camera, and LiDAR-based localization were reported to have sufficient accuracy to meet the localization accuracy requirements. The results of this component technology study may be useful to inform the design of any future mobile robotic system that would be deployed in airport terminals. (Sun et al., 2023)

2.2.11 The Chinese University of Hong Kong

The Chinese University of Hong Kong published a paper titled *Socially Compliant Path Planning for Robotic Autonomous Luggage Trolley Collection at Airports* that addresses how an autonomous trolley collection robot will plan a path that safely and efficiently navigates a busy and crowded airport terminal. Path planning and trajectory-following algorithms used by mobile robots normally assume that the rest of the environment is stationary (such as off-road navigation) or that the local moving objects are moving in a relatively controlled and uniform fashion (such as for street navigation). Robots that must navigate in crowds of moving people require algorithms that also consider social norms, not only to avoid collisions with people, but also to avoid the appearance of being hazardous while they operate. This paper's findings may help inform the design of any future mobile robotic system to be deployed within airport terminals, but this has not yet been done (Wang & Meng, 2019).

2.2.12 Uppsala University

In a student thesis published for Uppsala University, *Automated vehicles on airports—A case study of process challenges and opportunities in developing employee acceptance*, Säter (2021) describes a study where airport employees were interviewed to assess their reactions to the introduction of AVs at airports and under what circumstances they would accept or reject such technologies. Introducing AVs in airports may be appealing from the standpoint of safety improvements, cost savings, and efficiency gains. However, without properly engaging the existing employees to obtain their support, consent, and trust, introducing automated systems can lead to a range of problems that could reduce the anticipated gains. This paper underscores the importance of “taking process into account” when introducing these sorts of systems. In addition, “inclusive communication practice, excessive test phases, and altered processes and protocols” were also found to have high importance. Finally, keeping the employees engaged and accountable to the technology, and given a sense of control over the technology is important to nurture a sense of trust in that technology and the new processes that it enables. Any commercial product offering must be accompanied by appropriate market research to ensure that the intended customers will accept and use the product. Because products that exhibit autonomous capabilities are often rare, consumer acceptance research is critical, because there is comparatively limited existing information available. (Säter, 2021)

2.2.13 Department of the Air Force Air University

2.2.13.1 Autonomous Rovers: Flight Line Delivery of Maintenance Tools and Parts

In a research paper for the Department of the Air Force Air University, Stanton (2020) submitted a paper, *Autonomous Rovers: Flight Line Delivery of Maintenance Tools and Parts*. This paper describes a study of the maintenance activities and processes of workers at a specific military airbase and how they could be improved by introducing an AGVS to provide on-demand transportation of people, parts, and tools. The paper describes a methodology by which the maintenance activities are modeled, and a simulation of these activities to study the effect of introducing autonomous transport vehicles. In this study, the role of an expeditor, a person whose job is to drive people, parts, and tools around the airbase, is augmented with a rover that handles the actual transportation. The primary cost savings occur by moving the expeditor to a

supervisory role, where more meaningful tasks can be performed, such as interacting with personnel and verifying the status and progress of various jobs. This work describes a purely simulated study and not a physical robotic deployment, so there were no specific lessons to be learned, no specific best practices to document, and no specific risks identified. (Stanton, 2020)

This paper's primary contribution is a method that can be used to model repetitive transportation tasks normally handled by a human and to demonstrate how a rover can manage them instead. This method can be used to justify the use of autonomous transport vehicles by providing models for a simulation where various metrics, such as time spent and distance traveled (both of which can be used to generate cost), can be calculated. This cost can then be used to justify the expense of the purchase, configuration, and deployment of such autonomous vehicles in related situations. It is worth noting that this study was exclusively performed at the Air Mobility Command Base, Joint Base McGuire-Dix-Lakehurst (JB-MDL), New Jersey, where all models were based solely on the maintenance processes and schedules at that airbase. The paper did not attempt to generalize its findings to state how transferable the results may be to a commercial airport. The methodology employed, however, did not seem to be specifically limited to this airbase or military air bases in general. The approach to modeling the activities performed by the maintenance crews may be transferable to modeling similar activities at commercial airports. (Stanton, 2020)

2.2.13.2 Autonomous Vehicles for Flight Line Use

In a graduate research paper for the Department of the Air Force Air University, *Autonomous Vehicles for Flight Line Use*, Sollee (2021) details a study where an AGVS was deployed at JB-MDL in New Jersey to perform various labor-saving tasks. Sollee (2021) evaluated the AGVS's safety and effectiveness on the flight line as an expediter and measured cost-savings benefits when the AGVS was used for FOD collection.

The primary task for the AGVS was to assist maintenance personnel by carrying tools and parts to them when needed (a task known as an expediter). The specific vehicle used in this study was able to successfully complete 53% of its task without requiring any human intervention. A secondary task was to collect FOD removal by dragging a specialized FOD collection trailer. Pulling a trailer in this way greatly improved the FOD collection rate compared to manual FOD walks performed by maintenance personnel. The AGVS was also equipped with a small aerospace ground equipment trailer (an oil dispensing cart). (Sollee, 2021)

Specific lessons learned from this study include:

- The ability for a human to intervene and remotely control an AGVS if it encounters difficulties is important to ensure smooth operations.
- Real time location awareness of the AGVS is useful to schedule maintenance personnel .
- The primary failure mode for the AGVS occurred when the AGVS drifted off its designated route due to accumulated navigation error. This emphasizes the need for robust and accurate navigation and localization.

- Manually defining the GNSS waypoints for the AGVS to follow was time-consuming and sometimes prone to human error.
- The paper reports an astounding rate increase in pounds of FOD collected per hour as compared to “traditional” FOD walks. The AGVS, however, used a commercially available dragged FOD collection trailer, which could just as easily be pulled by a crewed vehicle. The lesson learned is that a mechanized FOD pickup device dragged behind a motorized vehicle will increase the rate of FOD collected per hour. Whether the motorized vehicle is autonomous or crewed is not relevant to this metric. (Sollee, 2021)

This paper identified specific risks including the following:

- Inclement weather can adversely affect the AGVS’s sensors causing it to be unable to successfully self-navigate or self-localize.
- Issues with GNSS signal caused by being too near buildings or other obstructions can reduce the ability of the AGVS to be able to identify its position and destination.
- An AGVS must be able to detect and navigate around personnel and other moving vehicles safely and successfully.
- The study did not specify how much FOD was left behind. The AGVS blindly dragged the trailer but could not determine whether any FOD was left behind. (Sollee, 2021)

Other topics that were not covered by this research paper but were referenced in future work include:

- No wireless frequency or spectrum analysis was performed in this study. This must be done before an AGVS can be successfully integrated at an airport.
- Cybersecurity must also be explicitly addressed to determine the risk of malicious takeover of an AGVS by a remote attacker.
- Centralized command and control stations were used to monitor the status of the AGVS and allowed for remote operator override as needed.
- How to update existing policies to allow AGVSs to be used on airbases is still to be determined. (Sollee, 2021)

In summary, Sollee (2021) described a limited deployment of an experimental AGVS to support maintenance operations at a U.S. Air Force (USAF) airport. The paper primarily focused on measuring the performance of an AGVS in terms of its reliability as an expeditor to carry tools and parts to maintenance crews. The actual technical maturity of the AGVS under test seemed quite limited compared to the available hardware and software of more modern autonomous research vehicles, so the specific numbers do not seem to be as relevant. This paper’s primary contribution is the description of the lessons learned, risks, issues, and challenges observed when the physical AGVS was in use at the airport. This study highlights the types of challenges that an

AGVS will encounter when operating at any airport and validates their significance, providing insight into the complexity of addressing them (Sollee, 2021)

2.3 GOVERNMENT PUBLICATIONS

In this section of the literature review, the research team reviewed publicly available government publications pertaining to AGVS. The following publications have been reviewed and summarized to display the most relevant information in relation to autonomous research and enhance the findings in further sections of this document.

2.3.1 National Safe Skies Alliance

In the National Safe Skies Alliance (Safe Skies) paper titled *Utilization of Autonomous Vehicles for Security at Airports*, Pellerin, Cusson, Goldsmith, and Zoufal (2020) assess the use of AGVSs for airport security with airport operators and security managers as the intended audience. Sponsored by the FAA, Safe Skies provides frameworks for the aviation industry to explore emerging technologies and their applications. This paper concludes that while AGVSs are not a plug-and-play solution, the technology provides value under certain conditions. The best-suited airport security applications include deterrence of criminal and disruptive behavior through random and planned vehicle patrolling; security surveillance, communication, and situational awareness; and reducing risks to human safety from hazardous activities. The paper also provides frameworks for assessing specific autonomous vehicle solutions and cost-benefit analysis of AGVS deployment. (Pellerin, Cusson, Goldsmith & Zoufal, 2020)

As a general notice, the opinions and conclusions expressed or implied in this report are those of the individuals or organizations who performed the research and are not necessarily those of Safe Skies or the FAA.

Existing standards from the FAA (2015) on the safety of ground vehicles and from National Institute of Standards and Technology (NIST) (n.d.) on cybersecurity and encryption are mentioned in this paper. This paper asserts that although FAA regulations do not prohibit AGVS operations in an airport's movement area, they require airport operators to ensure the safe movement of ground vehicles and pedestrians in the non-movement area. According to 14 CFR § 139.329, airport operators must limit movement, implement safety procedures for ground vehicles and pedestrians, have vehicle and tower communication rules, and require initial and recurrent training for vehicle operators (Pedestrians and Ground Vehicles, 2004). This regulation does not specifically address AGVSs, but an airport may want AGVSs to comply with communications requirements. The NIST (n.d.) cybersecurity standard that was adopted by the U.S. Department of Transportation National Highway Transportation Safety Administration (NHTSA) for AGVSs is also recommended for airport operators. The NIST Advanced Encryption Standard (AES), published as Federal Information Processing Standard (FIPS) 197 (NIST, 2023), is recommended for the safe transmission of wireless data to airport AGVSs (Pellerin, Cusson, Goldsmith, & Zoufal, 2020).

Pellerin, Cusson, and Goldsmith (2020) cite several lessons learned and best practices. With the current technology, an AGVS's likelihood of operating successfully is tied to the level of predictability in how it is expected to move. Because airport environments can be unpredictable,

however, AGVSs must demonstrate the ability to safely maneuver through a changing environment with airplanes, tugs, people, and other obstacles. All successful industrial applications of AGVSs are built on having a functional IT support infrastructure. Without the appropriate level of connectivity, AGVSs cannot perform the requested functions or will shut down altogether. San Francisco International Airport (SFO) studied potential efficiency gains of an autonomous aircraft-towing vehicle to improve airfield and gate use. The exercise resulted in two key findings: (1) it was easier and less costly to tow aircraft to remote parking positions, and (2) airports could reduce pushback maneuvering time by eliminating engine run-up and tug disconnect time. (Pellerin, Cusson, Goldsmith & Zoufal, 2020)

The paper presents a validation framework based on NIST's robotics and AGVS testing standards as well as the U.S. Army Developmental Test Command test standards. It starts with establishing a clear objective that defines the operating scenario and considers the logistics of use. Next, the airport defines the capability requirements providing a complete description of desired system behavior, along with metrics to quantitatively evaluate the extent to which each requirement is met. The initial evaluation should test the system at a high level to see if it can meet the basic requirements of the operation. This evaluation can focus on the overall logistics of the operations and whether the vehicle under analysis can meet the standard. If the system meets the initial thresholds, additional subtests can analyze whether the vehicle can meet other specific functional requirements. (Pellerin, Cusson, Goldsmith & Zoufal, 2020)

V2V communications involve AGVSs sharing data and sending messages to each other via a wireless network. The information being shared can include vehicle speed, location, direction of travel, braking, and loss of stability. V2V communications can operate as a mesh network, meaning that every node (AGVS) can send, receive, and retransmit data to every other network node. There are potential applications for V2V and V2I communications in an airport environment. For example, V2V could be used to ensure that AGVSs do not interfere with the activities of traditional airport vehicles or with other AGVSs. V2I-enabled AGVSs could enhance other airport security features and capabilities, such as perimeter security. An airport perimeter security system could notify an AGVS of an alarm and direct the vehicle to investigate a potential intrusion. (Pellerin, Cusson, Goldsmith, & Zoufal 2020)

Risk mitigation with AGVSs at airports is discussed on various fronts. In most cases, the autonomous system will discontinue movement as a default if the GNSS signal is lost. The failure to move, however, may itself pose a safety hazard in areas of aircraft or other operations. Backup communication capability, particularly linked to human controllers, is critical to sustaining safe operations. The airport will have areas appropriate and safe for AGVS use and areas that are not. Appropriate geofencing boundaries provide an AGVS with guidance to operate in specific areas and avoid others. From a security standpoint, when computation is done onboard the vehicle, wireless communication becomes less of a risk for hacking and jamming. If the AGVS does not require V2V capability to operate, attempts to disable a single vehicle are not easily spread to the entire fleet of vehicles due to the isolated nature of each vehicle. Data that must be transmitted over a wireless network should be encrypted. Encryption scrambles the data so that even if intercepted, the data are unreadable by unauthorized personnel. AGVS companies interviewed by Pellerin, Cusson, Goldsmith, and Zoufal (2020) consistently said encryption is their system's best cyber-defense. Wireless network security is enhanced by using a strong

security protocol (such as Wi-Fi Protected Access 2 (WPA2)) on access points, using a non-default service set identifier (SSID), and using media access control (MAC) filtering to restrict access to authorized devices. (Pellerin, Cusson, Goldsmith & Zoufal, 2020)

Anomaly detection can be performed by AVs as a secondary function and simultaneously to their primary task. For example, an autonomous system mowing a remote area of the airport perimeter or cleaning a part of the terminal can also collect data and potentially report anomalous behavior or identify unattended baggage. (Pellerin, Cusson, Goldsmith & Zoufal, 2020)

2.3.2 National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) published a paper, *SafeTug Semi-Autonomous Aircraft Towing Vehicles*, which introduces the concept of an autonomous tug robot capable of taxiing an aircraft from the runway to the gate and from the gate to the runway. This would improve aircraft fuel efficiency because aircraft would not need to run their engines while taxiing (Morris et al., 2015). This paper analyzes this concept in three major areas:

1. A simulation of “tug dispatching and scheduling” plus accompanying analysis explore how different sizes of autonomous tug fleets affect airport efficiency. These studies suggest that a tug fleet that is one-third the size of the aircraft fleet is the optimal size that balances the overhead of dispatching a tug to each aircraft to achieve the optimal dynamic scheduling output.
2. A human factors study of a graphical user interface (GUI) concept that is needed to enable a human operator to control and monitor the fleet of autonomous tug robots.
3. A preliminary design of the hardware, sensors, and software architecture that is required to implement an autonomous tug robot. (Morris, et al., 2015)

Tug robot systems have yet to be implemented or fielded at an airport. As such, the benefit of this paper is in the conceptual analysis and hardware feasibility for such a system (Morris et al., 2015).

Some challenges involved with implementing and deploying a fully autonomous tug fleet include:

- The up-front cost of buying many tug robots may be prohibitive. No analysis was performed on the return on investment for such a purchase, because that calculation is a function of the size and resources of each individual airport, as well as the cost of the tug robots themselves (which the paper does not provide, given the preliminary nature of the design).
- The paper acknowledges that some airport infrastructure enhancements may be needed to support the use of these autonomous tug robots. These enhancements may include special lanes that keep the tugs separated from crewed vehicles. They may also involve artificial landmarks to support localization when GNSS is unavailable or unreliable. Additional improvements could include a wireless communication infrastructure that supports the

robots in their required operating area without interfering with the communication requirements for crewed aircraft systems. A system of tug depots and a tug battery charging infrastructure may also be a helpful improvement.

- The introduction of tug robots also requires hiring trained supervisory personnel and mechanics who can perform maintenance and repair for the robots' wear and tear through regular use. (Morris et al., 2015)

Some challenges involved with designing a human machine interface (HMI) to manage a fleet of autonomous tug robots include:

- Obtaining the correct level of operator trust. If the operators do not trust the autonomous tugs to operate correctly or efficiently, then the tug fleet will be underused, and the airport will not obtain its return on investment. If the operators trust the tugs too much, then they may not be diligent in monitoring the tugs and may not be able to quickly identify if a situation arises that requires direct operator intervention. The latter statement illustrates a notable issue that Morris et al. (2015) did not sufficiently explore—namely that they expect the autonomy system to periodically fail and require human intervention to apply manual corrective action to the robots.
- Maintaining sufficient situational awareness. An operator must have enough information streams available to keep them informed on what the tug is doing and what it intends to do, and to understand the environment directly around the tug. Without this information, a supervisor may not be able to properly identify situations where the tug may require intervention, or, if an issue has already occurred that requires intervention, the supervisor may not be able to adequately troubleshoot the situation.
- Avoiding operator overload. The autonomous tug system is intended to reduce the demands of humans operating at airports by reducing the required workforce of available human drivers. The autonomous tugs must be capable enough, however, to operate for extended periods without operator intervention AND not require constant monitoring of information by airport operations personnel, as that would simply shift the focus of the existing labor force. If the tugs require high monitoring, then the labor demands would shift to the remote operators and require many employees to manage the fleet.
- Coordination with ground crews while at the gate. Turning an aircraft at the gate involves coordination with the pilots and the ground crew. Some communication occurs via radios, while other methods use hand signals. Morris et al. (2015) suggest that the tugs would not only need to be controlled by the pilots during pushback, but they would also need to coordinate with the personnel on the ground next to the wings (the wing walkers). It is even suggested in this paper that the tug robots may need to understand the hand signals used by the wing walkers, which is a significant technical challenge for any perception system. Instead, work may need to go into a distributed series of wireless control units that would be carried by all personnel working around the aircraft. (Morris et al., 2015)

The final part of the paper describes the challenges involved with designing an automated tug by retrofitting an existing manually driven towbar-less tug system. This section describes some

high-level issues involving the development of a fully autonomous control system without much detail about the implementation, as that was not part of this paper's scope. One major gap in the technology description for this paper is the discussion about the available technology for perception systems. While a high-level study of the use of LiDAR and electro-optical cameras was provided, no actual detailed analysis of the performance of these systems operating on in situ data was provided. Each sensor system and the algorithms used to process their data will have challenging failure modes and edge cases that can be situation and environment specific. For instance, poor weather conditions may reduce the effective range and capability of these sensors. (Morris et al., 2015)

This paper gives a preliminary analysis of the issues involved with employing a fleet of autonomous tug robots to remove the need for aircraft to expend fuel when taxiing from the runway to the gate and from the gate to the runway. A simulation was run that, assuming the simulation parameters accurately reflect the real world, showed the utility of different sizes of autonomous tug fleets. An extensive HMI study was run in which potential operators and users of the autonomous tug fleet were interviewed and allowed to evaluate a prototype GUI to control these tugs. Finally, a preliminary design concept was provided to describe how such a tug robot might be implemented, although more analysis would need to be done to demonstrate the effectiveness and robustness of that design. (Morris et al., 2015)

2.3.3 United Kingdom's Automated Vehicles Act 2024

The United Kingdom's (UK) *Automated Vehicles Act 2024*, referred to herein as the AV Act, establishes a comprehensive regulatory framework intended to facilitate the safe deployment and operation of AVs on public roads in Great Britain. The AV Act is part of the UK's broader strategy to advance connected and automated mobility (United Kingdom, 2024).

The AV Act provides clear definitions for AVs, distinguishing them from traditional driver-assistance technologies. Specifically, it defines AVs as vehicles capable of traveling autonomously without human input for some or all of a journey. This categorization is critical, as it clarifies the distinction between fully autonomous systems and those that still require human oversight. (United Kingdom, 2024)

The AV Act establishes two operational modes for AVs: the User-in-Charge (UIC) mode and the No-User-in-Charge (NUiC) mode. In UIC mode, a human operator is present in the vehicle and can take control when necessary, responding to transition demands issued by the system. In contrast, the NUiC mode allows the vehicle to operate entirely autonomously, without the need for a human to be present or ready to intervene. In this mode, a licensed NUiC operator remotely monitors the vehicle's journey and addresses any issues that arise, ensuring that the vehicle operates safely. (United Kingdom, 2024)

The regulatory framework established by the AV Act also introduces new legal entities responsible for the oversight and operation of AVs. Authorized self-driving entities (ASDEs), typically the vehicle manufacturers, are tasked with ensuring that AVs comply with regulatory standards and remain safe throughout their operational life. Additionally, licensed NUiC operators oversee vehicles operating in NUiC mode, bearing responsibility for the safe management of these vehicles during their autonomous journeys. (United Kingdom, 2024)

Safety and compliance are central to the AV Act, with a “Statement of Safety Principles” serving as the foundation for assessing the safety of AVs. Vehicles must pass a self-driving test based on these principles before being granted operational authorization. The authorization process is dynamic, allowing for revocation or modification if a vehicle no longer meets the required safety standards. (United Kingdom, 2024)

The AV Act also addresses liability and insurance, extending the single-insurer model introduced in the *Automated and Electric Vehicles Act 2018* (United Kingdom, 2018). This model ensures that insurance covers both the operator and any third parties affected by AGVS-related incidents. In cases where a vehicle operates in NUIC mode, the licensed operator assumes liability, shifting responsibility away from the vehicle owner. (United Kingdom, 2024)

Furthermore, the AV Act establishes a framework for data collection and sharing, which is essential for ensuring transparency and regulatory compliance. This framework allows data to be shared with public authorities and international organizations, facilitating the monitoring and investigation of AGVS operations. The AV Act also includes provisions to prevent the misrepresentation of vehicles as fully autonomous, protecting consumers from misleading marketing practices. (United Kingdom, 2024)

While the 2024 UK AV Act marks a significant step forward in the regulation of AVs, it acknowledges the need for further refinement through secondary legislation. Future developments will address remaining regulatory gaps and ensure that the UK’s approach to AGVS technology remains robust and adaptable as the industry evolves. (United Kingdom, 2024)

While this legislation is intended for the automotive industry, its framework could potentially also be adapted to the aviation industry. This framework provides guidelines and best practices for AGVSs in the aviation industry within the United States. (United Kingdom, 2024)

3. INVENTORY OF AGVS TESTING AND OPERATION SITES

This section summarizes information gathered from the stakeholder outreach conducted by the research team. All airport operators and private entities conducting AGVS testing who were identified during this research conducted their operations within existing FAA regulations at the time of testing. The outreach was collected in the form of virtual discussions/interviews, with representatives from civil airport operators and AGVS industry vendors to document their experiences integrating or operating AGVS in an airport environment. The purpose of these discussions/interviews was to catalog an inventory of current and prospective AGVS usage in an airport environment and gather key insights from these operators.

3.1 CIVIL AIRPORT OPERATORS

3.1.1 Dallas Fort Worth International Airport

DFW is located between Dallas and Fort Worth, Texas. In 2018, DFW unveiled a strategic plan with a vision for the future that included AGVSs (Duvall et al., 2022). This led to the pilot of an AGVS shuttle trial in the landside area at DFW Airport. Named the EZ10 shuttle (from TractEasy, formerly EasyMile), the initial goal was to test it in mixed traffic, see Figure 13. The

DFW environment, however, proved challenging, prompting a shift to testing in a more controllable parking lot. The trial ran for four months and focused on understanding mapping, charging, and operations, and was operated by a safety driver.



Figure 13. Dallas Fort Worth International Airport TractEasy Shuttle (Arnold, 2019)

During the trial period, the DFW team aimed to grasp the technology rather than focusing on its immediate application. The transportation team, first responders, airport planners, customer experience leaders, and risk managers were educated about the technology, but, ultimately, the trial was disrupted due to the COVID-19 pandemic. Lessons learned from the trial were that the AGVS generally performed as intended and became a foundation for many conversations about DFW's roadmap to an autonomous future.

Following the AGVS shuttle trial, surplus funds were used to test an AGVS cargo tug named TractEasy (now called the EZ-Tow). This trial took place in a controlled airside environment and operated as expected over a half-mile loop. The primary challenges encountered were external factors, such as ground handlers not staging the cargo correctly, other equipment being staged within the defined route, and manual processes for the overall movement and staging of cargo. Despite these challenges, the tug successfully navigated two ramp areas and crossed an active taxi lane.

Parallel to these initiatives, DFW conducted a comprehensive research study in collaboration with the NLR, outlining the phases and pathways to achieve fully integrated autonomy, culminating in a "Phase 4" SAE level of autonomy status (SAE International, 2020). This roadmap was detailed in an article published in the Journal of Airport Management (Brinkerhoff, 2022).

The development of the AGVS ecosystem within the airport environment has been progressing at an intentionally slow pace. DFW has been adapting their goals, accordingly, ensuring they do not force AGVS technology into an unprepared environment.

In summer 2023, DFW initiated an investigation into charging infrastructure, including mobile charging units (DFW, 2023). Additionally, from 2021 to 2023, trials were conducted on autonomous lawn mowers, specifically testing Graze AGVS² mowers to improve mowing efficiency, see Figure 14. Despite facing challenges due to startups being acquired by larger companies and undergoing research and development (R&D) periods, the trials proved successful. Special attention was given to risky areas, such as steep banks.



Figure 14. Graze AGVS Mower Operations at DFW (Fort Worth Inc., 2023)

The AGVS mowers faced minimal communication issues and no path deviations, although battery life occasionally posed challenges. The team prioritized introducing these mowers to test technology and products outside of the airport's airport operations area (AOA), to prioritize safety. The mowers demonstrated minimal friction and risk on four sites, providing confidence to all stakeholders that a future expansion into the AOA could be possible.

DFW's objective is to be prepared for the moment that regulations, technology, and stakeholders align to introduce AGVS technology into the airfield. The focus has shifted from the technology itself, which is adaptable, to thoughtfully considering the ecosystem, looking at how to integrate autonomy well, in the context of the highly complex DFW environment where human factors remain present.

² Note that trials of the Graze AV at DFW were conducted from 2021–2023, prior to the publication of CertAlert 24-02.

The integration of electric vehicles into the airport's electrical infrastructure will also create a critical dependency on the grid. DFW has developed a blueprint to manage the airport's grid for electric vehicles and other electrical uses, assessing the demand curve for electric consumption.

3.1.2 Cincinnati/Northern Kentucky International Airport

CVG, located in Hebron, Kentucky, is a large-hub Part 139-certificated airport that is actively involved in the research and testing of AVs for airport improvement. In 2018, CVG began its autonomous testing with indoor autonomous floor scrubbers and sweepers using QR-code-based navigation. Due to a few malfunctions with QR-code-based navigation, however, CVG found that this navigation method also required the most maintenance. Since then, CVG has mandated that all AGVSs must use LiDAR technology for sense-and-avoid capabilities, ensuring the safety and efficiency of AGVS operations within the airport's confines. CVG currently employs two Avidbot floor sweepers in their terminal (see Figure 15).



Figure 15. Avidbot Floor Sweeper at CVG (Avidbots, 2022)

The CVG research team decided to start their AGVS testing indoors within the airport terminal to develop best practices from early lessons learned, which could then be applied to outdoor/airside AGVS research. Indoor testing of autonomous equipment created a lower-risk and controlled space to understand the technology and evaluation processes before moving to a higher-risk environment like the airport ramp.

While indoor testing continued, research and testing of AVs on the ramp was motivated by an incident with a distracted fuel truck driver colliding with an aircraft's wingtip. This incident highlighted the AGVSs safety features that can mitigate human error, gaining approval from CVG stakeholders.

CVG began testing on the ramp with a Korean company called Thordrive that specialized in AGVS tugs. CVG tested Thordrive's tugs for 3 years, even working with airport tenants Amazon and DHL, who were interested in automating more of their ramp operations. See Figure 16. Thordrive was recently sold and is no longer working with CVG. A startup named Airtreck, with many former Thordrive employees, is working to develop an autonomous wing walker for aiding in aircraft pushbacks.



Figure 16. Thordrive AGVS Tug at CVG (Engel, 2021)

Aurigo, a robotics company specializing in cargo and baggage AVs, partnered with CVG and British Airways for future testing (see Figure 17). Additionally, DHL and Amazon have begun using AVs on their ramp areas, with operations taking place only within their leased property boundaries.



Figure 17. Aurrigo and British Airways Cargo AGVS at Heathrow (Aurrigo, 2019)

Graze Robotics was the next autonomous company to partner with CVG. Graze specializes in autonomous mowing applications; their testing takes place at CVG mowing fields outside of the airport fence line. A critical lesson learned involving Graze was an incident in which sun glare caused the LiDAR navigation system to miscalculate, resulting in the AGVS mower crashing into a fence. Minimal damage was incurred by the crash. The solution was a software patch applied to all systems that has prevented any similar incidents from occurring. Ghost Robotics has recently partnered with CVG to test their quadrupedal unmanned ground vehicle (Q-UGV) for perimeter inspections (see Figure 18). The latest addition to CVG's autonomous testing is Easy Aerial's drone in a box, to be used for perimeter inspections and quick response for emergency situations.



Figure 18. Ghost Robotics AGVS “Dog” Used for Perimeter Inspection at CVG
(Almendarez, 2023)

Throughout their testing over the past six years, CVG has used their experience to improve each technology they bring to the airport. CVG has maintained a requirement of LiDAR and electro-optical-based navigation systems for all AGVSs, as they are reliable for tracking aircraft and other AGVSs. Navigation systems requiring fixed infrastructure, such as the installation of visually observable QR codes or other fiducials, are brittle and subject to failure if the view of those visual landmarks is blocked or if the landmarks degrade over time. Similarly, GPS-based navigation systems require their antennas to have unimpeded views of the skies and are also subject to being overpowered by strong localized radio frequency (RF) sources. The CVG research team is working towards developing a centralized command and control system to manage all AGVS systems on CVG’s property. CVG strongly prefers systems that support open application programming interface (API) standards due to the ease of interoperability and integration. This conversation on command and control led to plans between the research team and the airport operations team who seek to be involved with AVs on the airfield to monitor all AGVS systems. In an emergency, airport operations have requested an emergency stop “button” to halt all AGVS operations on the airfield.

As of spring 2024, all AGVS operations at CVG have occurred on the ramp or outside the non-movement area and in accordance with FAA Part 139 CertAlert 24-02 requirements (FAA, 2024b). Many of the systems being tested by CVG operate via 5G cellular service, which has been mostly reliable, with a few isolated areas where there is a lack of service. While such service interruptions are minor now, they could be more problematic if the root cause is not addressed before testing in more critical areas of operations. RF interferences have not been a concern, as all systems operate far from all runways and navigational aids (NAVAIDs). Before deploying AVs to scale on the airfield, a thorough spectrum analysis and RF testing of systems

would be performed either by the airport or a contracted specialist. Recently, CVG began work with Miami University at Miami University Airport (OXD), a non-towered airport located in Oxford, Ohio. The goal of this work is to create a test bed for AGVS operations in effort to increase efficiency in GA airports using AGVS systems.

3.1.3 The Ford Launchpad for Innovative Technologies and Entrepreneurship

In January 2022, The Gerald R. Ford International Airport Authority (GRR), in collaboration with the Michigan Economic Development Corporation, Seamless Ventures, and Southwest Airlines, created The Ford Launchpad for Innovative Technologies and Entrepreneurship (FLITE) program. FLITE has completed 22 projects with a total of \$750,000 in grants. FLITE operates on a structured approach: recruit innovators, award and execute projects, and continuously learn and scale.

FLITE's goal is to create opportunities for companies to pilot-test in a live airport environment. An airport official is assigned to each project to guide the technology through the aviation industry. GRR has contracted Seamless Ventures to manage and operate the FLITE program. Many of the technology companies in the FLITE program seek to build momentum and create connections with other partners both inside and outside the industry. The FLITE program is designed to engage AGVSs that are near commercial readiness level and want to showcase their capabilities in an airport environment. The FLITE team thoroughly evaluates each applicant before approval, ensuring that its technology provides value for aviation and is the best fit for its use.

FLITE's most recent demonstration is with Cybernet and their automated Fortbrand tow tractor. Cybernet's goal is to help human operators with anti-collision sensors to prevent accidents in manned operations, showcasing that technology still has value for human operations. Cybernet uses this semi-autonomous approach to integrate AGVSs within the current regulations and to address airport stakeholders' concerns. By keeping a human operator behind the wheel, Cybernet can prove that AGVS technology can prevent crashes and incidents in an airport environment. On May 2, 2024, FLITE hosted a Cybernet demonstration where the AGVS tow tractor autonomously moved from a storage local to a staging point where a human took control and operated their task. Afterward, the human operator returned the AGVS to its staging area, where the AGVS autonomously returned to the storage area for charging (see Figure 19). The goal of this phase demonstration was to allow for a human operator to take control in more high-risk areas and for the vehicle to operate autonomously in low-risk areas, ultimately reducing labor costs and freeing the operator to perform different tasks.



Figure 19. Cybernet AGVS Tug at GRR (Travel PR News Editor, 2024)

3.1.4 The xBridge Program at Pittsburgh International Airport

PIT's xBridge program is a tech proving ground for technologies and startups. The airport is a proof-of-concept site for technologies in a real-world operating environment. xBridge partners with technology companies to allow them to test and demonstrate their technologies at the airport. By offering the use of the airport for real-world testing opportunities to companies, the airport benefits from the exposure of seeing advanced technologies in operation there. At the time of this interview, companies whose autonomous robotic vehicle technologies have been tested at PIT have been limited to operating outside the security perimeter, though they are interested in expanding this scope soon.

Ottonomy is one of the companies that has deployed robots inside the terminal. Ottonomy makes small autonomous food delivery robots, as shown in Figure 20. Travelers used an app to order food from the various restaurants and concession stands in the airport, and the robot navigates through the terminals to the customer's location.



Figure 20. Ottobot Delivery Robot at PIT (Neinstein, 2022, November 21)

Another company that deployed robots inside the terminal is Carnegie Robotics, which developed a retrofit kit for existing Nilfisk-brand floor scrubbers that integrated their AI and robotic technologies to allow the scrubber to operate without human control. The scrubbers were also outfitted with ultraviolet cleaning lamps to assist in the sterilization of the floors (see Figure 21).



Figure 21. Ultraviolet Scrubber at PIT (Neistein, 2020)

Outside of the terminal, Mapless AI tested a remote control retrofit kit that converts cars into remotely piloted vehicles to move travelers from the parking lots to the terminal entrances, as shown in Figure 22. When travelers park their cars at the airport, instead of waiting for a shuttle bus to take them to the terminal entrance, they use an app to request that a remotely piloted car be sent to their location. A remote human operator drives the car to the traveler's location, and the traveler then manually drives the car to their destination. Once the traveler exits the car, the remote operator again takes control and pilots the empty car back to a staging area to wait for a new customer request.



Figure 22. Mapless AI Remotely Operated Car at PIT (Neistein, 2022, October 17)

Other non-AGVS “smart” technologies being tested at PIT for automatically monitoring gate operations include Assaia and Synaptic Aviation. These companies do not offer AGVS solutions but instead rely on a set of fixed cameras that view aircraft when they are parked at gates. Intelligent machine vision algorithms analyze video streams to detect and classify the people and vehicles that approach and interact with the aircraft. The vision system observes the operations and notifies the supervising controllers of the status of the various activities being performed. Should an operation be skipped, the supervising operator is notified immediately so that they can take appropriate corrective action.

The xBridge program is looking to expand the kinds of AGVS technologies tested at PIT. Some of the AGVS technologies being considered for future testing include robotic wheelchairs, autonomous people movers, uncrewed airplane tugs, and FOD sweeping robots. They have considered using AGVS technologies for perimeter security but were unable to find a solution that fits their needs. Instead, they will assess non-AGVS offerings. Like many technologies deployed at other airports, wireless communication to/from the AGVS platforms is typically accomplished using cellular networks, but PIT is interested in researching alternative communications technologies such as long-range wide area network (LoRaWAN).

While the xBridge program has successfully allowed multiple companies to work at PIT, other airports that do not have a program face additional hurdles. For example, one challenge facing companies who want to deploy and test their technologies at airports is insurance. The PIT xBridge program has found that insurance coverage and liability is a concern of airports and may cause additional financial hurdles for tech companies (Future Travel Experience, 2020).

3.2 AUTONOMOUS GROUND VEHICLE SYSTEM INDUSTRY VENDORS

3.2.1 Aurrigo

Founded in 1993, Aurrigo operates in the automotive industry, specializing in wiring and safety systems, primarily in the UK. The company entered the AGVS sector in 2015 and expanded to aviation in 2018. Aurrigo first developed the Auto-Dolly, with the ability to carry 1.7 tonnes, designed to enhance efficiency with an auto-lock system (see Figure 23). Additionally, they created the Auto-DollyTug for baggage and cargo transportation with an added cab for manual drive capabilities. It features robotic arms for automated loading and unloading of unit load devices (ULDs), 360-degree turning capabilities, and the capacity to carry one unit load device (ULD) and tow four more (see Figure 24). Initial deployments have occurred at Amsterdam Airport Schiphol, Stuttgart Airport, and with the International Airlines Group at London Gatwick Airport and the first U.S. deployment at CVG, leveraging CVG's previous AGVS experience. Current operations are small-scale, such as managing one gate at a time, with plans to expand.



Figure 23. Aurrigo's Auto Dolly (Aurrigo, 2024)



Figure 24. Aurriego's Auto-DollyTug at Amsterdam Airport Schiphol (Aurriego, 2024)

Aurriego's vehicles operate within specific weather constraints like manned ramp vehicles, capable of functioning in temperatures from -10 °C to 45 °C and handling various weather conditions, including heavy rain and snow. The company uses an open API for current deployments, aiming to integrate into airport fleet management systems, and employs 5G technology without relying on a specific communication system. In baggage halls, they avoid GNSS dependency, using cameras, LiDAR, and wheel odometry instead, achieving Level 4 autonomy with a focus on widebody cargo and ULD operations.

The company employs a digital twin of the operational domain for initial setup, allowing flexibility and adjustments in their operational plans. Their detect-and-avoid capabilities are customizable based on the surrounding environment and airport standard operating procedure. Vehicles are equipped with e-stops, sensor and communication health monitoring, and multiple kill switches, stopping automatically if a sensor link is lost. Safety measures include manual intervention options and customer-specific requirements. Aurriego uses internal validation approaches and client-requested validation testing during any launch of a new system. Aurriego provides onsite training, manuals, and company presence for proof of concepts ranging from 2 months to 1 year. They offer a 1-week, hands-on driver training program, with recurrent training depending on regional needs, and they engage with local authorities and unions, such as the regional aviation authorities, for support.

Aurriego acknowledged the controlled nature of the aviation sector compared to public transport, despite the lack of specific airport regulations. They dealt with challenges like insurance variations and the necessity for adaptable safety standards. They also addressed the absence of a formal certification process for autonomous airport ground vehicles, using FAA waivers when applicable. Concerns about job displacement by potential clients were addressed by emphasizing the supervisory roles still required, and the openings for additional tasking to manned ground

crews. The company highlighted the benefits of AVs in improving efficiency and safety without interfering with existing infrastructure.

3.2.2 TractEasy

TractEasy was formed by the merger of TractEasy and TLD to support airports and industrial AGVS solutions. TractEasy provides software with a strong industrial background, while TLD is known for airport equipment and created the EzTow and EzDolly. TractEasy's current operations include the EZTow, shown in Figure 25, which has a 20-ton towing capacity and features automatic hook and unhook for towing; and the EZDolly, which handles full ULDs and heavy cargo. The company has developed Aircraft Safe Docking (ASD) and ASD+ systems, which reduce speed near aircraft for safer operations. TractEasy claims they have achieved Level 4 autonomy and are operational in six countries. In Europe, ASD and ASD+ are used at two airports for passenger aircraft, and upcoming U.S. cargo operations are set to start soon.



Figure 25. TractEasy EZTow (BMW Group, 2021)

The AVs can operate 24/7 with an average of less than one manual intervention per week and have adaptive driving paths to mimic human variability for better efficiency. Their self-contained AVs use a cloud-based fleet management system and rely on LiDAR, GPS, and wheel odometry with a fusion algorithm for localization. Typically, 4G and wireless capabilities are used in the U.S. Safety features include cameras, RADAR, LiDAR, and redundant sensors and control systems. TractEasy has completed RF spectrum testing with potential military applications to be able to operate within their sensitive RF infrastructure. Although obstacle circumvention has been deployed at one site, it is not currently in use. Overall, client acceptance of AVs is higher in the automotive industry than in the aviation industry. Several challenges were identified, including economic challenges as AVs replace multiple human shifts, making it economically challenging for some airports' current schedules. TractEasy found that airports with busier

around-the-clock needs are more cost-effective than less busy airports. Successful models like those in Hong Kong and Singapore, where ground handling equipment is owned by airports and rented by airlines, have had the smoothest integration of AGVS into their infrastructure. An AGVS use case has been to address union complaints at airports regarding long or strenuous routes, freeing up ramp crews to perform other tasks. Additional challenges faced by TractEasy include data management gaps in current airport operations, as many airports are unable to provide accurate information on the daily number of tugs and baggage operations. Many airports have put in place a requirement for safety drivers, which can possibly delay deployment, but are necessary for maneuvering around improperly parked vehicles and other unexpected obstacles. Ghost stops, caused by unidentifiable objects like bags, emphasize the need for cleanliness on ramps. Localization deviations are addressed with safety tests for every software update.

3.2.3 Ghost Robotics

Ghost Robotics, founded in 2015, specializes in quadruped AGVSs inspired by animal movement in the wild. Initially serving the Department of Defense (DoD) and allied governments for inspection work, Ghost Robotics has expanded into the commercial sector, particularly the oil and gas industry. Their AVs, including the Vision 60, shown in Figure 26, are designed for rough terrain and have operated autonomously in many airbases. They are also exploring applications for flat FOD surfaces and cold factory environments in collaboration with Purdue University. Their AVs have a battery life of 3.25 hours, can cover 6 miles, weigh 110 lb, and are designed to navigate stairs. A new 50-lb range AGVS is expected to be released in 2025. The AVs are equipped with a Doghouse Conex charging box and have an IP67 rating for all-weather operation. Ghost Robotics maintains a modular design for easy part replacements and provides in-house maintenance, unlike many other AGVS companies. Each purchase includes engineering training to ensure proper operation and maintenance. Ghost Robotics recently deployed a crossing sign at one of their military deployment sites where their AGVS “Dog” frequently crosses a roadway, as shown in Figure 27.



Figure 26. Ghost Robotics Quadruped "Dog" (Ghost Robotics, 2024)

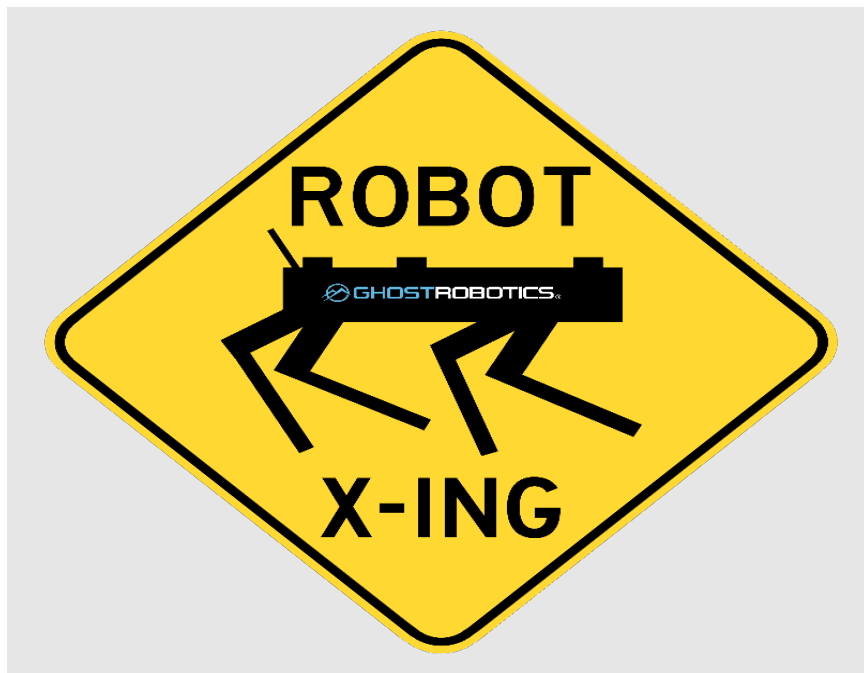


Figure 27. Ghost Robotics X-ing Sign (Ghost Robotics, 2024)

In terms of communications, Ghost Robotics uses LTE-AT&T FirstNet Quad and Wi-Fi for their operations. Their cellular use, however, is restricted near runway surfaces, and communication

performance has been reported to decline during fog at CVG Airport. The AGVSs' durability is ensured by their IP67 rating, allowing them to operate in rain and snow and withstand immersion in water. If a communication link is lost, the AVs can continue to the next waypoint, and the intuitive and durable controls are designed to withstand drops.

CVG Airport is the first U.S. civilian airport to purchase a Ghost Robotics AGVS dog, following an internal review committee's evaluation of new technologies. The AVs are programmed via tablet or joystick and have received DoD funding for research and updates. They are equipped with onboard cameras and sensors and have potential applications for beyond visual line of sight (BVLOS) and human-in-the-loop UAS operations. Ghost Robotics robots are being used at CVG for supplemental perimeter inspections inside the airport fence, with increased inspection coverage after a perimeter fence-jumping incident. The airport purchased these AGVSs with forfeiture funds through their airport police department and is still proving the business case for airport operations. The biggest issue remains access to funds for purchasing AGVSs. Safety risk assessments are tailored to the entire airport, with specific protocols for AGVS operation off the autonomous path.

Several challenges highlighted by Ghost Robotics include the need for communication improvements to enhance safety, especially during foggy conditions at CVG. The airport sponsor should notify their Regional Airport Certification and Safety Inspector (Part 139 Airports) or Airports District Office (ADO) (non-part 139 airports) of all AGVS testing conducted in movement or non-movement areas. However, landside or terminal areas are excluded from this notification requirement. Additionally, future FAA regulations that mandate placing identifiers, such as QR codes, within the airfield are desired. Operational limitations include challenges with FOD detection, as different tenants are responsible for FOD walks and collection, and the "Dog" struggles with smaller items like screws. Airport clients often have unique cyber requirements that could complicate central command and control (C2) systems. Concerns raised by ethics committees have been alleviated through education outreach, and positive public perception is being fostered through community engagement.

3.2.4 Honda

The R&D division of Honda's North America branch, located in North Carolina, focuses on electric-powered vehicles, mowers, and AGVSs. Their approach to the autonomous industry leverages their advanced sensing as they aim to enhance AGVS capabilities. Honda's current AGVS lineup consists of two vehicles: an open-cab Autonomous Work Vehicle (AWV), see Figure 28, and an autonomous mower, see Figure 29.



Figure 28. Honda AWW (Petrie, 2023)



Figure 29. Honda AGVS Mower (Honda News, 2023)

The current use cases under consideration for Honda's team are for mowing, perimeter security, hauling aircraft equipment, and baggage cart towing. The Honda team expressed challenges such as GNSS-denied environments for baggage handling and operational constraints for night

operations that would need to be addressed. Snowplowing/blowing was another use case presented, but the cold temperatures pose limitations on battery effectiveness. However, Honda North America R&D remains committed to electric vehicles.

Currently, Honda is operating both AGVSs throughout North America. The AWV open cab is being tested at Toronto International Airport, and there are plans for Miami Executive Airport as part of its proof-of-concept phase. During this phase, Honda is learning about the Operational Design Domain (ODD) and gaining insights into the airport environment and its specific needs. The AWV can carry items or sensors with a two-pallet capacity. This modularity enables it to be used for many tasks such as mowing, hauling FOD removal tools, towing baggage carts, and conducting perimeter fence inspections. It can navigate complex construction environments and handle slopes up to 10 degrees. Key safety features include a blue serin light for visibility, a 94 dB horn for obstacle announcements, 5 LiDAR, 5 RADAR, and a 4-disc brake system for emergency stops. The AGVS Mower-operates at 10 mph, handles a slope up to 15 degrees with slope control, and features multiple RADAR/LiDAR sensors for object detection and environmental awareness. Both vehicles can operate in moderate rain, on par with current weather minimums of manned airport ground vehicles.

Operationally, AVs rely on GNSS and cell service, making consistent connectivity crucial, especially in airports with complex terrains. The validation process for airport use involves assessing camera usage, data storage, and security standards, with cameras currently off until security agreements are met. Detailed operation manuals and a 3-hour training session, including a written and a driving test, are required for AGVS operators.

To ensure compliance and safety in airport operations, Honda seeks additional guidance from the FAA regarding specific restrictions inside the fence for AGVSs. Despite challenges related to connectivity, terrain, and regulatory compliance, Honda's commitment to integrating advanced AGVSs in airport environments highlights their potential for enhancing operational efficiency and safety.

3.2.5 Ford Launchpad for Innovative Technologies and Entrepreneurship-Hosted State of Autonomy at Airports and Relevant Regulation Round Table

The FLITE has identified a gap between the technical capabilities of autonomous technology and the current regulatory environment. Many proof points for autonomy are consistent across different applications, such as autonomous ground handling, mowing, and security vehicles. This discussion had two objectives: to assist startups in navigating these proof points and to support FLITE's efforts in fostering innovation in autonomy.

FLITE facilitated a conversation involving five companies (i.e., Cybernet, Dataspeed, Aurigo, Snowbotix, and Renu) that have participated in the FLITE program over the past two years. Representatives from the GRR Airport Operations team also joined. The discussion highlighted various challenges related to technology, regulation, and business.

The companies highlighted the challenge of not having a clear roadmap for autonomous ground operations. This lack of clarity complicates the development and demonstration processes and creates uncertainty for investors. One company mentioned discussions with venture capital and

private equity investors, describing it as a “chicken and egg” problem due to the inability to confirm commercial revenue timelines. A potential opportunity lies in the integration of these technologies into airport operations through safety management policies and risk assessments.

Several companies discussed the potential for military projects to serve as proof points for commercial airports, as the military is generally more open to funded trials. As one of the key economic drivers of automation is accomplishing tasks with less labor, companies talked about reducing the regulation for one-to-one escorting. Current regulations requiring an escort in the AOA undermine the value proposition of automation. Suggestions included considering remote monitoring and studying human factors to ensure remote monitoring success.

Companies are choosing to pursue applications that are less technically and regulatorily complex. For example, one company chose perimeter patrol deeming it more feasible because they are outside the movement area. Another company focused on landside applications for commercial viability. Non-U.S. companies face challenges with project awards due to “Buy America” requirements in many contracts. Liability and insurance issues also need resolution. Despite these challenges, several companies noted positive responses from staff, who see job shifts and upskilling opportunities rather than job losses.

4. FINDINGS

The findings from this report provide an analysis of the key factors affecting the deployment of AVs at airports. This section outlines critical elements such as lessons learned from early AGVS implementations, a summary of AGVS use cases, approaches to validating AGVSs, the role of communication technologies, and the impacts of wireless frequencies on airport operations. It also explores various risk mitigation strategies to ensure the safe and efficient integration of AGVSs.

4.1 USE CASES FOR AGVS

Throughout this research, multiple use cases for AGVS operations in an airport environment have been identified. Following are findings from use cases identified in the stakeholder outreach.

4.1.1 Mowing

Mowing operations at airports require prior planning and can occupy maintenance personnel for extended periods of the day, typically taking place weekly during the summer months. Airports frequently encompass thousands of acres that must be regularly mowed to mitigate wildlife hazards, adhering to strict schedules to manage vegetation growth. The autonomous mowers identified in this research are designed to operate independently in remote areas of airfields and landside sections of airports. Many of the AGVS mowers are designed to be low profile and have many to one control. Given the demanding timelines for completing mowing operations, the primary objective of these AGVS mowers is to autonomously maintain expansive, low-risk sections of airports. This enables human operators to concentrate on higher-risk zones, such as RSAs and movement areas. Further testing is necessary to explore the feasibility of deploying AGVS mowers and other AVs in RSAs and taxiway/taxi lane safety areas (TSAs), where they

must meet specific function and frangibility standards at certificated and federally obligated airports, as stated in AC 150/5300-13 (FAA, 2022) and 14 CFR Part 139.309(b)4 (Safety Areas, 2004).

4.1.2 Inspections

Airport operations must complete regular inspections across various areas, including perimeter security, 14 CFR Part 139 airfield inspections and compliance, FOD detection, and wildlife management. The inspection AGVSs identified in this research primarily focus on perimeter inspections but can be used for a broader range of inspection tasks. Unlike the specialized function of mowing AVs, inspection AVs vary in design, ranging from standard four-wheeled vehicles to more advanced Q-UGVs like those developed by Ghost Robotics. These AVs can enhance coverage of remote perimeter areas and document critical findings, such as fallen trees or breaches in fencing. While there are goals to extend their capabilities to perform more advanced inspections, further testing is needed to ensure they can operate effectively in challenging conditions, including steep or uneven terrain.

4.1.3 Ramp Operations

Ramp operations at airports can vary by the type and scale of operation. During this research, there were a variety of ramp-focused AGVS operations, such as baggage carts, aircraft tugs/towers, and aircraft pushback vehicles. Some of the primary objectives of integrating AGVSs into ramp operations include reduced aircraft turn times, enhanced safety, and increased efficiency, all aimed at optimizing a dynamic environment. However, it was discovered that certain ramp infrastructure preparation and enhancements are necessary for improved integration. Examples cited by the outreach participants include the addition of dedicated AGVS lanes, artificial landmarks, upgrades to wireless communication, and the creation of specially trained personnel to manage operations. Challenges such as coordination with pilots and ground crew, human error during cargo loading, and preparing for unpredictable human driving must be addressed before full implementation. Industry vendors are actively working with airports and airlines to test their AVs, working towards solutions to these challenges.

4.1.4 Foreign Object Debris

The research and literature review indicated that while there are currently few AGVSs specifically designed for FOD collection or removal, the potential for integrating AGVS technology into existing FOD management systems is significant. Currently, FOD management largely depends on human visual inspections, sometimes augmented by commercially available technologies like stationary RADAR, electro-optical cameras, hybrid systems, and mobile detection platforms. These technologies can identify FOD under different environmental conditions and offer real-time alerts. While these systems are advanced, they still require manual intervention for FOD removal, either by picking up FOD by oneself, using mechanical systems like power sweepers and vacuum systems, or non-mechanical methods like magnetic bars and rumble strips. Recent developments, particularly in military settings like JB-MDL in New Jersey, show the promise of AGVS use in FOD collection and related tasks. These applications demonstrate the potential for AGVSs to be integrated into FOD detection and removal systems at airports, with mobile FOD detection systems using RADAR, LiDAR, and high-resolution

cameras to automate detection and improve operational efficiency. AGVSs could reduce the need for runway closures, minimize delays, and enhance airfield safety. Companies like Ghost Robotics are already exploring AVs, such as their Q-UGV “Dog,” for FOD detection and collection in rugged terrains, and developing wheeled AVs for flat surfaces. However, effective FOD management also involves documenting and reporting incidents, investigating sources, and maintaining a database of retrieved debris. The successful integration of AGVSs into these processes will require advanced navigation and localization capabilities, particularly in environments shared by both AVs and human-operated vehicles. While the potential for AGVSs in FOD management is clear, further research and field trials will be necessary to validate their effectiveness and reduce risks.

4.2 LESSONS LEARNED

In reviewing the implementation and integration of AGVSs within airport environments, several key lessons have emerged. These insights are crucial for understanding both the opportunities and challenges presented by AGVS technology in a complex, high-security, and safety-focused setting. By reflecting on these lessons, airports and the FAA can better prepare for future advancements, mitigate potential risks, and ensure smoother transitions in the adoption of autonomous systems.

4.2.1 Scaling AGVS Operations

The scaling of AGVS operations at airports presents several challenges that require careful planning and robust infrastructure. In the landside AGVS shuttle trial at DFW, the primary objective was to understand the technology, ensuring they do not force AGVS technology into an unprepared environment. Key lessons learned included the importance of speed and sensor sensitivity, as AGVS performance depends heavily on accurately detecting and responding to environmental changes. Additionally, a reliable and accessible charging infrastructure is crucial, as inadequate facilities can hinder AGVS efficiency and scalability.

Investing in a strong IT and communications network is also critical. AGVSs rely on continuous, reliable connectivity for optimal performance, with technologies such as DSRC or cellular service (4G/5G). During the deployment of an automated mower at LAF, uninterrupted cell phone signals were essential for real-time monitoring and control. Reliable connectivity across the airport environment ensures safe and consistent AGVS operations.

4.2.2 Safety and Risk Mitigation

Safety was a consistent theme across all AGVS use cases. For example, in mowing operations, safety measures such as geofencing, collision avoidance sensors, and a hard-wire induction loop were vital to ensuring that AGVSs operated within designated areas. Remote monitoring via mobile apps provided additional safety by allowing human intervention when necessary. Similar safety measures were implemented in other AGVS applications, including emergency stops, sensor health monitoring, and automatic shutdown mechanisms if sensor links were lost.

In some trials, “ghost stops” were observed, where AGVSs stopped unexpectedly due to unidentifiable objects such as bags on ramps. This highlighted the importance of maintaining

cleanliness in these areas to prevent operational disruptions. Additionally, localization deviations caused by environmental factors required safety tests after each software update to ensure the system's reliability and to mitigate potential risks.

Nighttime operations, as observed during trials, also reduced the risks of interference from human drivers. These lower-risk periods provided valuable opportunities to test AGVS performance in controlled environments while minimizing potential hazards.

4.2.3 Connectivity and Navigation Challenges

The reliability of connectivity is crucial for AGVS operations. Without consistent wireless connections, AGVSs may be unable to perform their functions or may even shut down entirely. In trials where 5G cellular service was used, connectivity was generally reliable, though some areas lacked coverage. This emphasizes the need for robust wireless infrastructure to support continuous AGVS operations.

Navigation accuracy also emerged as a significant challenge. AGVSs experienced issues, such as GNSS signal interference near buildings or obstructions, leading to navigation errors and route deviations. Ensuring precise and reliable navigation systems is essential for AGVSs to operate safely in complex airport environments.

4.2.4 Technological Limitations and Incidents

Several technological limitations were identified during testing. For instance, sun glare caused a LiDAR malfunction in an AGVS mower, resulting in a minor collision with a fence. The issue was resolved with a software patch that prevented further incidents, illustrating the importance of continuous software updates to address unforeseen challenges.

Additionally, human intervention remains necessary when AGVSs encounter difficulties, such as navigation errors or unexpected “ghost stops” due to environmental factors. This highlights the importance of integrating manual override capabilities into AGVS systems to ensure smooth operations, especially when the AGVSs face unexpected obstacles or operational failures.

4.2.5 Operational Efficiency and Improvements

AGVSs have demonstrated significant potential to improve operational efficiency. For example, mechanized FOD collection using AGVSs greatly increased the amount of debris collected per hour compared to traditional methods. However, the efficiency gains were largely attributed to the mechanized collection process rather than the autonomy of the vehicle itself. This suggests that optimizing AGVS operations requires pairing the vehicles with advanced equipment and well-structured processes.

Moreover, real-time location tracking of AGVSs has improved the scheduling and management of maintenance tasks, allowing operators to better coordinate operations and ensure smoother workflows.

4.2.6 Phased Implementation

A phased approach to AGVS deployment has proved to be an effective strategy for managing the complexities of AGVS integration. Conducting pilot programs in controlled environments, such as remote areas of the airport or landside locations, allows airports to gather data, identify potential challenges, and make necessary adjustments before broader deployment. This methodical approach ensures that the technology is thoroughly tested and reliable before full-scale implementation.

By evaluating each phase of deployment, airports can address any operational or technical challenges, ensuring that the infrastructure and operational frameworks are in place to support the expanded use of AGVSs, thereby minimizing risks and optimizing the integration process.

4.2.7 Stakeholder and Employee Engagement

Effective communication among stakeholders—such as airport operators, air traffic control (ATC), regulatory bodies, and local governments—is essential for the successful integration of AVs. Collaboration and open dialogue ensure that regulatory requirements are met and that safety and operational standards are maintained. Lessons learned from UAS integration at airports demonstrate that regulatory challenges can be overcome through coordinated efforts.

Employee engagement is equally critical. Involving airport personnel in AGVS education and testing fosters ownership and accountability, leading to smoother integration and operation. Engaging employees early in the process builds trust and acceptance, ensuring that the workforce is prepared to support the transition to autonomous systems. Without proper employee engagement, the introduction of AGVSs may face resistance, potentially undermining the anticipated gains in safety, cost savings, and efficiency.

This version seamlessly incorporates the new findings related to “ghost stops” and localization deviations, ensuring that the information is presented cohesively within the broader lessons learned.

4.3 VALIDATION APPROACHES FOR AGVS

This research identified a broad spectrum of validation approaches for integrating AGVSs into airport environments. These approaches demonstrate significant variability, tailored to the unique requirements of each integration effort. The diversity in these approaches is influenced by various factors, including the unique needs of each airport, the technological limitations of AGVS systems, existing infrastructure, environmental conditions, the level of autonomy, regulatory frameworks, and the specific application and deployment location of the AGVSs (e.g., movement vs. non-movement areas). Much of the data and insights have been derived from deployments in non-movement areas such as terminals, ramps, and roadways.

The literature review and stakeholder outreach consistently emphasized the importance of defining specific operational scenarios and airport performance metrics. These rigorous tests are essential to confirm that AGVS systems can manage diverse operational challenges and consistently meet performance standards across different scenarios. Original equipment

manufacturers (OEMs) have reported that customers, both in aviation and other industries, frequently request comprehensive operational validation testing without a clear understanding of their validation requirements. To address this, OEMs typically provide documentation based on prior testing to guide customers through the validation process. On the other hand, some airports have developed their own validation processes tailored to their specific operational needs and most often collaborate with OEMs based on the capabilities of the technology.

Military projects have often served as valuable proofs of concept for AGVS testing in controlled commercial airport environments. For instance, the use of AGVSs in military operations—such as those used for EOD—illustrates their capabilities and reliability in controlled settings. Additionally, testing at JB-MDL in New Jersey, where AGVSs were deployed for flight line delivery of maintenance tools and FOD collection, provides critical insights that can inform broader commercial adoption. These projects underscore both the strengths and limitations of AGVS technology, offering a controlled environment to test AGVSs and mitigate operational failures when these systems are introduced into more complex commercial settings.

One notable approach observed during this research is Cybernet’s semi-autonomous strategy at GRR. This approach integrates AGVSs within existing regulatory frameworks while addressing stakeholders’ concerns. In this strategy, a remote operator provides oversight, supported by additional safety systems. Cybernet’s approach successfully demonstrates AGVS technology’s potential to prevent crashes and incidents in an airport environment.

In the context of the UK’s 2024 Automated Vehicles Act (United Kingdom, 2024), significant efforts have been made to develop standardized metrics for AGVS validation. The AV Act has driven the industry toward creating a more consistent framework for evaluating AGVS performance. While these standards are beginning to emerge, they have not yet been fully established or universally adopted.

Detailed functional testing has also proved beneficial in assessing AGVS capabilities. For instance, at CVG, initial indoor testing of AGVS floor sweepers provided a safe and controlled environment. This method enabled the CVG team to learn and understand the best practices for validating and integrating AGVS systems before transitioning to more complex environments and technologies. The process highlighted the level of awareness required by airport operators to fully comprehend their operational environment and determine how AGVSs can best fit their needs.

Effective communication and robust control systems are critical for the operation and coordination of AVs within airport environments. Various communication technologies and sensor systems were identified during this research, each serving a distinct purpose.

4.4 COMMUNICATION TECHNOLOGIES

V2X communication, which includes V2I, V2N, V2P, and V2V communications, facilitates cooperative autonomous driving by enabling AGVSs to share information, thereby enhancing their efficiency and performance. While this framework is well-established for roadway environments, it may need to be adapted for airport environments to account for unique operational considerations, such as coordination with ATC and airport operations personnel.

These adaptations will be crucial to ensure that V2X communication can support the safe and efficient integration of AVs within the dynamic and complex environment of an airport. The primary categories of wireless technologies used in AGVS systems are DSRC, Wi-Fi, and LTE-based V2X (LTE-V). DSRC operates under IEEE 802.11p and IEEE 1609 standards, while LTE-V uses 4G/5G cellular networks. Despite the bandwidth constraints of LTE-V, 5G technology overcomes these limitations by means of underused millimeter wave bands, which are crucial for high-speed V2X communications. The advent of 5G technology is key for supporting advanced AI algorithms required for environmental sensing, perception, and decision-making, as it delivers the high upload speeds needed for real-time data processing. This research, however, has shown that many AGVS operations are still capable of effectively operating on 4G and even 3G coverage due to limited 5G coverage in many airport environments. The following communication technologies are components of AVs identified in this research.

4.4.1 Control Systems

Robust control systems are needed to manage the dynamic operations of AGVSs in complex airport environments. Both centralized and decentralized control architectures were found throughout this research and play distinct roles. Centralized systems provide a unified command and control structure, while decentralized systems allow for more dynamic, localized decision-making. Effective implementation of these systems requires reliable two-way data transmission, often operated by DSRC, cellular networks, or Wi-Fi. AGVSs can also operate as a mesh network, where each vehicle acts as a node that can send, receive, and retransmit data. This setup ensures continuous communication, even if some nodes fail, and may prevent interference with traditional airport operations. By dynamically repositioning AGVSs, the communication range can be extended to cover larger areas.

4.4.2 Sensor Technologies

Sensors are crucial for AGVSs to make informed decisions based on accurate depictions of their environments. Different sensor types serve different roles within the system. The following are sensor types highlighted by the research team:

- *LiDAR*: LiDAR uses pulses of infrared light to measure distances between the sensor and surrounding objects, creating detailed 3D maps. This capability is vital for obstacle detection and navigation in complex environments.
- *Cameras and Machine Vision*: Cameras paired with machine vision technology enable AGVSs to recognize and interpret visual information, such as lane markings, road signs, traffic lights, pedestrians, aircraft, and other vehicles. Visual data are essential for perception and decision-making in AGVS navigation.
- *RADAR*: RADAR systems provide reliable distance measurements and are particularly useful in low-visibility conditions like fog or heavy rain, where LiDAR and cameras may be less effective.

- *Ultrasonic Sensors*: These sensors are used for close-range detection and collision avoidance, especially in parking scenarios. They are cost-effective but limited to very short-range applications due to their imprecision.
- *GNSS*: GNSS provides location data for AGVSs, enabling navigation in large outdoor spaces. GNSS signals can, however, be obstructed indoors, under aircraft wings, or by large structures, requiring supplemental localization methods.
- *Inertial Measurement Units (IMUs)*: IMUs measure velocity and orientation by detecting forces, including gravitational forces. They help maintain stability and control, particularly during turns or abrupt maneuvers.
- *Infrared Sensors*: Infrared sensors enhance safety by providing night vision in the form of heat detection. By detecting heat signatures from people and vehicles, AGVSs can detect objects that may not be visible to standard cameras in low-light conditions.

4.5 Wireless Frequency Potential Impact

The integration of AGVSs into airport operations raises concerns regarding the impact of RF transmissions from AGVS sensor or communication systems on existing airport navigational and communication equipment. In this study, participants reported no observed interference or impact from AGVS systems on the critical navigation equipment and communication systems at the airport, nor any interference from airport equipment to AGVS systems. While these initial observations are promising, they do not provide a comprehensive guarantee of safety as no testing was completed airside. The importance of RF spectrum testing underscores the necessity for ongoing vigilance by operators as AGVS technology advances.

4.6 Risk Mitigation

Effective risk mitigation strategies are essential to ensuring that AGVSs can operate safely, efficiently, and without disruption to airport operations. This section outlines key risk mitigation measures that enhance the reliability, resilience, and overall safety of AGVS operations. These strategies include the implementation of backup communication systems, geofencing, human operator intervention capabilities, V2V and V2I communication, robust cybersecurity protocols, and advanced obstacle detection and avoidance technologies.

4.6.1 Backup Communication Systems

The research team found that in the short term, it is a viable framework for AGVSs to stop operating if they do not interfere with other operations. In the long term, a backup communication system would be integral for ensuring continuous operation in the event of primary system failures. These systems act as a safety net, allowing AGVSs to operate reliably or perform emergency procedures even when the main communication channels are disrupted. The presence of backup communication systems ensures that AGVSs maintain connectivity and control, thereby reducing the likelihood of incidents caused by communication failures. This redundancy is vital for risk mitigation, as it allows AGVSs to receive critical updates and instructions, ensuring that they can respond promptly to any changes in their environment.

Backup systems also enhance AGVS operations' resilience by enabling quick recovery from disruptions.

4.6.2 Geofencing

Geofencing has been identified as a vital risk mitigation strategy, effectively enhancing the safety and security of AGVS operations. By defining and enforcing virtual boundaries, geofencing restricts AGVS movements to designated, authorized zones, preventing them from entering sensitive areas such as active runways or restricted zones. This technology plays a crucial role in maintaining operational safety by ensuring that AGVSs navigate precisely within their designated operational area, avoiding areas where they could pose a risk to aircraft or personnel.

Geofencing can be dynamically updated to accommodate temporary changes, such as construction zones or emergency closures, enhancing operational flexibility and responsiveness. Furthermore, geofences can be scheduled. Scheduling different zones for AGVSs based on the time of day, active runway, or other airport activities allows the operator to optimize operations during peak and off-peak times.

4.6.3 Human Operator Intervention

Despite the advanced capabilities of autonomous systems, maintaining the ability for human operators to intervene at the vehicle and/or remotely to control AGVSs remains a significant risk mitigator. Human oversight is essential for resolving issues that AGVSs may not be able to handle autonomously, ensuring operational continuity and safety. For instance, during trials at CVG, the Thordrive autonomous driving system was designed to allow human operators to step in when the AGVS encountered unexpected situations, thus preventing possible accidents. Additionally, the use of a safety driver for AGVSs is a common starting point for many airports as part of a phased integration of AGVSs into their environment. Many OEMs offer options such as remote monitors for emergency interventions and "stop buttons," which can be placed in varying locations or assigned to different responsible parties in case of emergencies.

4.6.4 Vehicle-to-Vehicle and Vehicle-to-Infrastructure Communications

V2V and V2I communications are other methods of improving the risk mitigation of AGVSs. These communication systems allow autonomous systems to share information with each other and potentially be integrated into traditional airport vehicles, facilitating coordinated movements and preventing collisions. Such coordination is especially vital in complex airport environments where various operations, such as snow removal and aircraft towing, require multiple vehicles and systems to work seamlessly together.

ACRP Report 219 (Hubbard et al., 2020) stresses the importance of V2V and V2I communications as pivotal elements in advancing ground vehicle technologies for airside operations. According to Report 219, these technologies enable AGVSs to exchange real-time data about their positions, speeds, and intentions, aiding in the creation of a cohesive network of vehicles that can anticipate and respond to each other's actions. This interconnected system

reduces the likelihood of accidents by providing vehicles with the situational awareness needed to make informed decisions (Hubbard et al., 2020).

Simultaneous V2V and V2I communications enhance the operational efficiency of airport tasks. By optimizing vehicle interactions and movements, these technologies can streamline both manned and unmanned ground operations. The ability to manage and adjust operations based on real-time data allows airports to maintain high levels of safety. This approach also maximizes the efficiency of their maintenance and operational tasks, ensuring that AGVSs enhance rather than disrupt existing workflows.

4.6.5 Cybersecurity Measures

Cybersecurity is a foundational element of safe autonomous operations, particularly in complex and sensitive environments like airports. Strong wireless data encryption is crucial to protect against cyber threats and ensure that critical operations are not disrupted by malicious activities. These measures, such as the adoption of zero-trust architectures (ZTAs), maintain the integrity and confidentiality of communication channels, ensuring that AGVSs operate securely and support the overall security of airport operations. ZTAs operate on the principle of “never trust, always verify,” meaning that all users, devices, and network components must be continuously authenticated, authorized, and validated before access is granted to any resources. This approach significantly reduces the risk of unauthorized access and helps safeguard the critical systems that underpin AGVS operations at airports.

In addition to robust encryption, airport operators are encouraged to adopt the NIST cybersecurity standards, which have been embraced by the U.S. Department of Transportation’s NHTSA for AVs. The NIST AES, published as FIPS 197 (NIST, 2023), is recommended for the safe transmission of wireless data to airport AVs, providing a robust framework to safeguard data against unauthorized access and tampering. These standards provide a comprehensive set of guidelines for securing AGVSs against potential threats. Airport clients, however, often have unique cybersecurity requirements that could complicate the implementation of centralized C2 systems. Airports are encouraged to be aware of their existing cybersecurity and IT infrastructure when considering the integration of AGVSs, as this awareness is critical for identifying potential vulnerabilities and ensuring seamless system compatibility.

4.6.6 Detect and Avoid

Effective obstacle detection and avoidance is critical as most tasks require AGVSs to navigate complex terrains that may include various stationary and moving obstacles. Sensor fusion technology plays a pivotal role by combining data from multiple sensors, such as LiDAR, cameras, RADAR, and ultrasonic sensors, to create a comprehensive understanding of the surrounding environment. This multi-sensor approach was very common in this research and enhanced the reliability and accuracy of obstacle detection, allowing AGVSs to navigate safely and efficiently even under challenging conditions, such as poor lighting or adverse weather.

Each AGVS system employs its unique approach to obstacle avoidance, where the level of autonomy dictates the sophistication of obstacle avoidance capabilities. Some OEMs program AGVSs to stop immediately upon detecting an object, triggering push notifications or audible

alerts, such as horns, to prompt human intervention for object removal. Other systems can autonomously navigate obstacles within a certain range of their original path, enhancing operational flexibility and efficiency. In contrast, some AVs may require direct human intervention to adjust their path or resume operations after encountering an obstacle.

Intelligent machine vision algorithms, such as those displayed in the XBridge program at PIT, play a crucial role in enhancing the detect-and-avoid capabilities of AGVSs. These algorithms analyze live video streams to detect and classify people and vehicles as they approach and interact with aircraft, providing AVs with a detailed understanding of their surroundings. By integrating these advanced machine vision techniques, AGVSs can improve their obstacle detection and classification accuracy, enabling more precise navigation and avoidance strategies.

5. CONCLUSIONS

This research has evaluated the operational needs, safety, and security risks associated with the deployment of AVs within airport environments. Key insights have been gathered through the literature review and stakeholder outreach, revealing that while AGVS testing is actively underway, work is needed to address operational challenges and define policy for the safe integration of AGVS at airports.

The findings indicate that non-movement areas offer a more controlled environment suitable for AGVS testing and deployment. Movement areas, however, present considerable challenges due to the dynamic and high-risk nature of aircraft operations. This research highlights the need for safety protocols, reliable communication systems, and advanced sensor technologies to ensure the safe operation of AGVSs in these complex areas.

Despite the progress made, the integration of AGVSs into airport environments is still in its early stages of understanding the impacts of a full-scale integration of AGVSs.

Collecting and analyzing data from current and future AGVS deployments will be crucial to understand the full-scaled effect of AGVS integration on airport operations, safety, and security. These data will also inform the development of industry-wide standards and best practices.

The findings in this report highlight key considerations for the strategic implementation of AGVSs in airport environments. As the industry continues to evolve, addressing operational challenges, safety concerns, and technological advancements will be essential. If additional research is conducted, there should be an emphasis on refining integration strategies, leveraging data-driven insights, and adapting regulatory frameworks. By building upon this foundational work, stakeholders can drive meaningful progress in airport automation and innovation.

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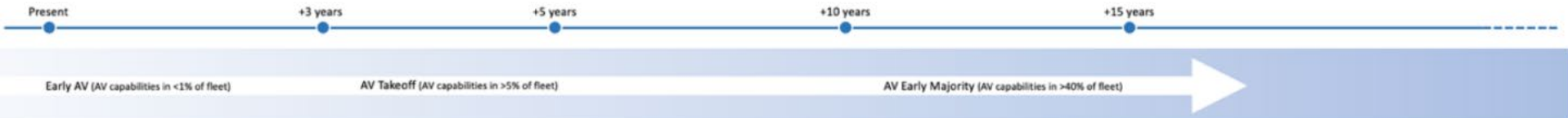
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APPENDIX A—STAKEHOLDER QUESTIONS

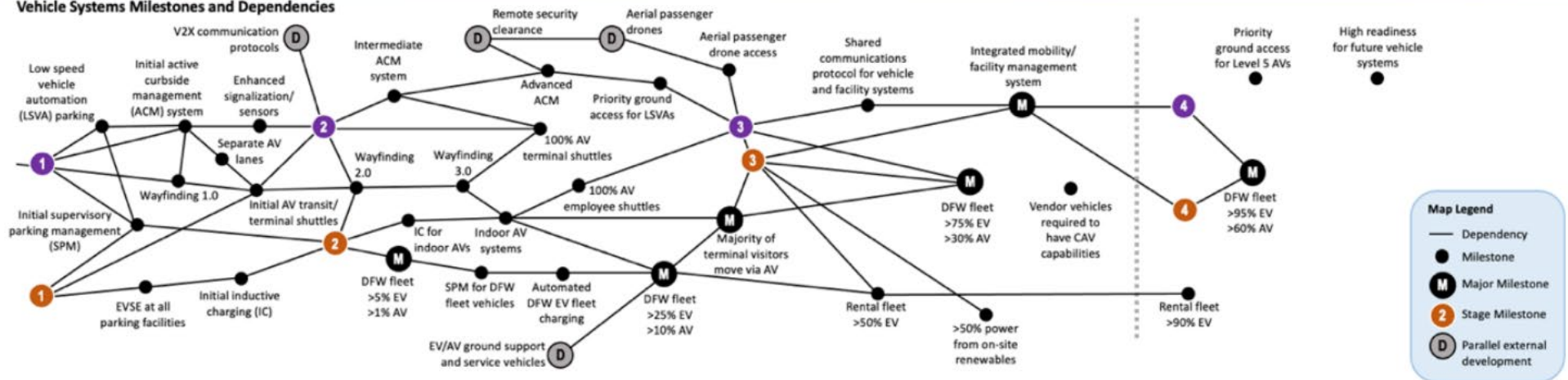
Question Bank
<i>Lessons Learned</i> What does or does not seem to work when it comes to AGVS systems or applications of them?
<i>Best Practices</i> A. Are there specifics on what actions resulted in improvements to AGVS systems after initial testing/integration?
Are there any validation approaches and/or risk mitigations utilized?
What applications av systems are being used / tested / investigated by the airport?
What is the operational (and planned) domain of AGVS equipment? A. Geographic location on airfield, designation of operational area, weather limitations, etc. B. What is the operating proximity to other vehicles, aircraft, personnel?
<i>Control and/or Communication of Systems</i> A. Are the AGVS systems being controlled by a central hub? Or are you looking into doing so? B. Generally, are the systems utilized being controlled more through radio links or over internet/WIFI? C. Have there been any issues with controlling the AGVS systems? a. If yes, has the cause been identified? And how were they controlled/stopped?
What are the enabling technologies? A. RADAR, lidar, cameras, communications, etc.
What are the safety features? A. Safety oversight? Remote and/or in-vehicle? Who provides oversight? B. Obstacle detection and avoidance? C. Other safety features? D. Any special risk mitigations established specifically to utilize them on the airport/airfield?
Have you seen common or similar trends with their different AGVS systems? A. For example: Have the AVs had difficulties in losing connection / command link / doing unintentional actions? a. Have there been apparent specific aspects of AGVS solutions that just simply work?
How interest and experience in AGVS landside translates to AGVS activities airside now and in the future

APPENDIX B—DALLAS FORT WORTH INTERNATIONAL AIRPORT ROADMAP TO AUTONOMY

Dallas – Fort Worth Airport Roadmap to Autonomy



Vehicle Systems Milestones and Dependencies



Infrastructure Perception and Control Systems

- 1**
 - Pilot scale for specific projects
 - Planning for integration in new construction
 - Data coordination and management plan
- 2**
 - Sensors integrated in key locations
 - Intersection and roadway management
 - V2X, I2X communication
- 3**
 - Full sensor integration in all facilities
 - Active management for all mobility on DFW property
 - Area restrictions of legacy vehicles
- 4**
 - Automated 'air traffic control' for ground vehicles
 - Ground access priority for AV-equipped vehicles
 - Legacy vehicles restricted

Power Generation and Vehicle Charging Systems

- 1**
 - Expanded EVSE in parking facilities
 - Pilot scale photovoltaic (PV) power generation
 - Planning for integration in new construction
- 2**
 - V2G initial deployment
 - Inductive charging at key locations
 - Expanded PV, EVSE at all facilities
- 3**
 - Automated inductive charging (IC) in all facilities
 - V2G at scale supports resilience, emergency response
 - Optimal PV/renewable generation can sustain operations
- 4**
 - Standard off-grid function for all operations
 - Automated inductive charging in all facilities
 - Mature V2G supports resilience, emergency response

(Duvall et al., 2022)