Roadmap to Automated Mobility Systems: Informing the Planning of a Sustainable, Resilient Transportation Ecosystem for Dallas/Fort Worth International Airport

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NREL is a national laboratory of the U.S. Department of Energy
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List of Acronyms

ACM	active curb management
APM	automated people mover
ATN	automated transit network
AV	automated vehicle
DART	Dallas Area Rapid Transit
DFW	Dallas/Fort Worth International Airport
EV	electric vehicle
eVTOL	electric vertical takeoff and landing
IIS	intelligent infrastructure systems
IoT	Internet of Things
IPC	infrastructure perception and control
LSAV	low-speed automated vehicle
NCTCOG	North Central Texas Council of Governments
NREL	National Renewable Energy Laboratory
SPM	supervisory parking management
TNC	transportation network company
VMT	vehicle miles traveled

Executive Summary

Roadmap in Brief

The National Renewable Energy Laboratory (NREL) developed this report to provide Dallas/Fort Worth International Airport (DFW) assistance toward a vision that considers the maturation and proliferation of mobility automation, electrification, and infrastructure integrated with Internet of Things (IoT) technologies as they present themselves on the path to 2035. In planning ongoing infrastructure investments, DFW has goals to accommodate and leverage these enabling technologies toward greater sustainability and enhanced traveler and employee experiences, ensuring that infrastructure investments are fully utilized into the future. The objective of this document is to assist DFW to anticipate and envision future airport access by travelers, employees, and goods by examining existing needs and exploring opportunities enabled by technology that informs longer-term infrastructure planning. The vast infrastructure of DFW, which includes buildings, roadways, and other physical structures, as well as growing digital and energy network infrastructures, requires long-term planning and strategy to fully leverage technology advancement and avoid abandoning assets due to functional obsolescence.

Key Decision Points

This planning report anticipates shifts in airport mobility access as enabled by technology adoption in the consumer, infrastructure, and smart city market to enable DFW to minimize risk and maintain operational resiliency to the greatest degree. Risk minimization and resiliency are underscored in light of global impacts, including increased frequency and magnitude of extreme weather events due to climate change, unpredictable social phenomena such as the recent pandemic, and associated volatility in the labor market accompanying such disruptions. To assist infrastructure planning, key decision points on the roadmap to mobility automation are identified (Figure ES-1), and information to support their importance is detailed within this report.

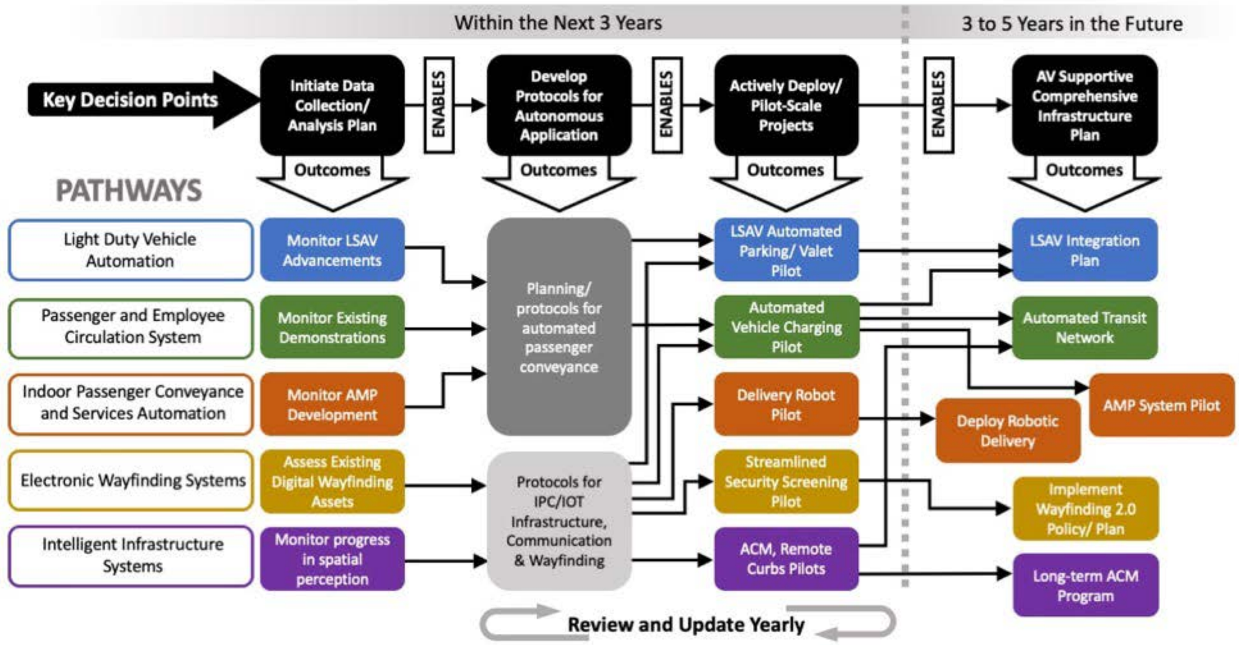

Figure ES-1. Key decision points on the roadmap toward mobility automation

Summaries of these key decision points are as follows:

- **Initiate Data Collection/Analysis Plan:** This plan entails strategic research objectives for initial and ongoing data collection, compilation, and analysis of automated mobility technologies as crucial to inform subsequent decision points. In the present era of rapid innovation, keeping apprised of the development of relevant policies and practices is crucial to enable the implementation of automation technologies.
- **Develop Protocols for Autonomous Application:** As it is common for mobility technology advancements to outpace policies, the absence of policies ready to quickly act upon the emergence of new technologies will delay progress toward automated mobility goals. Proactively establishing policies in anticipation of emerging or anticipated technologies as being prepared and in place will facilitate pilot-scale deployments and enable long-term goals.
- **Actively Deploy Pilot-Scale Projects:** Pilot projects are vital to better understand practical application of new technologies, and, through iteration of practice, will facilitate derivation of refined plans to inform eventual broader deployment. Pilot projects serve as foundational building blocks toward longer-term automated vehicle (AV) goals and will be instrumental in developing an AV-supportive comprehensive infrastructure plan.
- **AV-Supportive Comprehensive Infrastructure Plan:** The initial decision points culminate toward a key decision point targeted for the 3- to 5-year time frame. It is important to revisit each of the decision points and related milestones/outcomes annually, so as to incorporate anticipated developments in technology as they emerge, as part of an iterative process.

Recommended DFW Roadmap Pathways

Specific topical pathways on the roadmap to automated mobility are identified in this report. They are informed by needs to accommodate mobility services from three perspectives: (1) traveler access, (2) employee mobility, and (3) service and freight access to DFW terminals. These topical pathways include:

- **Light-Duty Vehicle Automation:** Accommodation for the emergence of light-duty vehicles for private and shared use that incorporate automated capabilities, including passenger and service applications.
- **Passenger and Employee Circulation Systems:** Non-fixed-guideway automated transit network systems serving nonsecure-side mobility needs for travelers and employees.
- **Indoor Passenger Conveyance and Services Automation:** Emerging systems for the movement of people within large facilities, replacing legacy systems such as moving walkways or golf carts.
- **Electronic Wayfinding Systems:** Networked communication between users, vehicles, and infrastructure, facilitating greater ease of movement and multidirectional information exchange.
- **Intelligent Infrastructure Systems:** A framework of supervisory management across mobility, infrastructure, buildings, and energy systems, enabling optimal and resilient operations.

Other facets of emerging mobility technologies are in active pursuit in parallel to mobility automation efforts. Perhaps the effort most closely associated with mobility automation is the effort to estimate electric vehicle (EV) charging infrastructure needs, quantity, location, and type. The mobility electrification report is in progress, and will be cross-informative with this roadmap report. As these efforts continue to mature, it is important to frequently update progress and emergence of relevant research and technologies to maintain alignment.

Roadmap Extended Summary

In preparation of this document, the NREL team focused on key ground transportation airport access needs and activities from three perspectives: (1) traveler access, (2) employee mobility, and (3) service and freight access to DFW terminals. The team conducted a review of future transportation forecasts and anticipated technology landscapes in the near-term 5- to 20-year time frame and investigated and documented both general trends of mobility automation and electrification, as well as any specific application within the airport domain. This planning activity is concurrent with other directed studies and pilot projects at DFW with respect to overall energy, electrification, and EV planning and early demonstrations of AVs and other automated systems at the airport.

Specific areas of emphasis for this study include:

- Automation and electrification of mobility that will enhance on-airport access and circulation within the airport.
- Personal versus shared mobility services, as witnessed pre-pandemic by ride-hailing adoption, and the corresponding impacts on airport operations.
- Consumer adoption of EVs and AVs of various levels, notably the need to provide EV charging for customer, employee, and rental vehicles.
- Enhanced demand for additional curb space to accommodate increased mobility-as-a-service, as well as emerging low-speed auto-parking and auto-valet.
- Low-speed automation enabling automated parking, valet services, and EV charging, as well as long-term impacts and benefits for the airport.
- Inter-terminal and intra-airport circulation services and traveler wayfinding.

This summary highlights the issues and proposed paths forward for critically identified concerns that will have significant impact on quality of service and sustainability of DFW landside access. Although there are no “silver bullets” with respect to novel technologies, this summary presents expected impacts of technology and recommendations to employ them to meet currently identified needs, as well as strategic directions with respect to the intersection of these technologies with infrastructure planning, always with emphasis on paths to maintain DFW’s international leadership in customer service and sustainability. Ordered topically, these summary vignettes provide snapshots capturing current status, future stress, and recommended pathways associated with policy, methodology, or technology interventions and their associated timelines.

- **Intra-Terminal/Inter-Airport Circulation:** Access and circulation once visitors are on airport grounds is of primary concern as DFW grows, and these are areas in which the airport has complete jurisdictional control and responsibility. With respect to secure inter-terminal circulation, the Skylink people mover system is a significant asset connecting the five terminals once a traveler or employee has cleared security. Put into service in 2005 and replacing the older Airtrans system that had served the airport since the 1970s, the Skylink system provides high-quality, Americans with Disabilities Act (ADA)-accessible, inter-terminal connection, but only on the secure side. A recognized need is better and more resilient circulation services between terminals on the nonsecure side of the airport, as well as linkages to other airport mobility hubs (intra-airport circulation) such as connecting with the consolidated rental car facility, Dallas Area Rapid Transit (DART) and TEXRail transit, and various other business centers throughout the DFW campus. Nonsecure airport mobility is currently served by fleets of inter-terminal buses and intra-airport shuttles. In some cases, particularly with respect to airport business centers, these facilities are served only by personal or corporate fleet vehicles. A frequently cited traveler scenario that illustrates the importance of this issue is the large percentage (>50%) of travelers that return to DFW at a different terminal from which they departed, requiring nonsecure groundside conveyance if the traveler exits at the arriving terminal to retrieve luggage. This common situation, combined with other factors such as escalating curbside and inter-terminal congestion and difficulty recruiting and retaining a driver workforce, expose needs for both tactical short-term and strategic longer-term objectives for more accessible, reliable, and resilient nonsecure-side circulation systems for the airport.

  - **Recommended Pathway:** An integrated, automated system to facilitate landside access can provide for systematic, predictable, manageable, and energy-efficient nonsecure circulation. Fixed-guideway automated people mover (APM) technology, such as that used in the Skylink system, however, is cost-prohibitive, space-prohibitive, proprietary, not easily scalable, and does not adjust easily to shifting demand patterns in the operations landscape. The next generation of dedicated mobility systems (which can be thought of as modern APMs) appropriate for inter-terminal and intra-airport mobility will be based on emerging automated and connected vehicle technologies and electrified drivetrains. Such an integrated mobility service requires a systems-engineering approach as opposed to a more passive evolutionary development, as is currently prevalent. Investing in these emerging systems works toward ensuring long-term operational performance with respect to moving passengers, employees, and freight in a timely, cost-efficient, and energy-efficient manner, while maintaining high degrees of performance and safety. The systems architecture of the older DFW Airtrans system exhibited some qualities of such a system but was based on 1970s and 1980s aerospace technology requiring exclusive guideway for navigation (typically electromechanical guidance), propulsion (hot-shoe power pickup), and safety. Recent AV technology has eliminated the need for strictly exclusive guideway for navigation and power, but some form of protected guideway (maintaining separation from the open roadway) may still be needed to guarantee performance (eliminating effects of congestion prevalent in manually operated traffic streams) and avoid crashes with manually operative vehicles. This report recommends a systems-level approach directed toward enabling DFW to advance toward such a landside, nonsecure mobility system that would serve travelers, employees, and freight. A planning, visioning, and specifications initiative would posture DFW to leverage emerging automation, communications, and vehicle electrification technology within a nearer time frame, perhaps 5 years—laying the groundwork for a resilient, automated, and extensible high-performance landside automated mobility system.

- **Airport Wayfinding and Traveler Communication:** Communications with the traveling public have a direct impact on quality of experience. Airport and terminal wayfinding are of immediate concern and relatively low-hanging fruit compared to other aspects of mobility infrastructure. Independent of whether travelers are served by automated mobility systems or simple, traditional bus circulation systems, an information system to communicate services in an effective manner and receive information back from travelers on the quality of communication and services is a critical asset. Whereas traditional roadway traveler information has evolved to be served by prominent navigation apps such as Google Maps, Waze, Apple Maps and a few others, wayfinding within airports remains in the domain of the airport at present, though several mapping companies are actively developing indoor navigation. DFW has several existing assets ranging from traditional signing, airport ambassadors, information kiosks, and their own airport app. Several existing assets appear well supported (automated kiosks and human ambassadors); however, as a whole, wayfinding through the airport appears non-integrated. The on-site, fact-finding visit by NREL personnel exposed and amplified this issue, particularly when attempting to identify inter-terminal circulation buses and transit stations. Frequent business travelers and employees likely are not in need of such information assets, but casual travelers, or even business travelers for which DFW is not a primary hub, are challenged to find pickup and drop-off zones, inter-terminal circulation shuttles, transit connections, and parking options. The literature review revealed a litany of new IoT wayfinding technology to create digital (rather than physical) customer information system infrastructure. Everything from automated roving robot-based systems to extensive online presence is being employed to provide increasing multilingual information services to travelers. The digital information infrastructure enables two-way communication, in essence a channel for ongoing behavioral feedback from travelers on ease of wayfinding. Using these communication pathways enables an airport to quickly identify and remediate issues. A digital information system could also provide real-time information to the airport operations centers on the number, location, and movement of in-airport travelers and employees, a critical informational asset to optimize daily operations and assist in emergency situations.

  - **Recommended Pathway:** Systematically review existing traveler wayfinding (physical signs as well as electronic means such as smartphone airport apps), discover best practices including appropriate effectiveness metrics, and solicit industry partners or even industry consortia (perhaps toward a unified airport digital app), all toward formulating and implementing a long-term, systematic wayfinding and travel information system. Feedback from DFW personnel reflected an apprehension that navigation app giants such as Google may grow to be the primary information interface for airport travelers just as they have become the primary conduit for roadway information, thus ceding possible access and control of information and data streams. Developing standards for coordinating with Google and similar companies for information release through an advanced airport information portal could preempt such concerns.

- **Curbside Congestion and Management:** A critical area for initial traveler impressions of the airport is curbside pickup and drop-off. This will soon expand to include auto-valet services offered through enabling low-speed automated vehicle (LSAV) technology. Curbside pickup and drop-off has always been a bit chaotic with family members and friends arranging to meet or depart, as well as taxi queues. Before the pandemic, ride-hailing giants Uber and Lyft contributed stress to airport curbside operations nationwide. Significant and measurable shifts away from parking toward ride-hailing services escalated curbside congestion. DFW curbside access, like in many modern airports, was designed to optimize automobile access with efficient proximity to premium parking. The ride-hailing phenomenon (along with consistent air travel growth) placed additional stress on the curbside by substituting a substantial number of "drive and park" trips with curbside drop-off trips. Curbside congestion at DFW during peak periods has led to backed-up congestion all the way to International Boulevard. Future LSAV technology enabling auto-valet service will further enable travelers with a personal vehicle to disembark at the curbside, leaving their unoccupied car to park itself, adding even more stress to the curb. Systematic active curb management with digital detection, tracking, and coordination will allow the airport to extract maximum capacity from existing curb space while giving time to construct future infrastructure capacity. Current curb management at DFW is manual and largely passive, requiring attendants to observe traffic flow and direct vehicles and drivers that do not respect signed directives to move along. Even during the site visit, unattended vehicles were observed at the curbside without any cognizance by airport curb management personnel. Digital curb management is an emerging technology and discipline, not only at airports, but also at any high-demand attraction where congestion is likely.

  - **Recommended Pathway:** DFW should develop a curb management master plan for future operations that is automated, includes technology to continually monitor and actively manage curb congestion, tracks all vehicles and their dwell times, and monitors passengers for safety once they exit the vehicle and enter the terminal. Enabling technologies, including byproducts of AV development, are beginning to appear on the market. Lidar, radar, and camera/video solutions are being customized for infrastructure (roadside and curbside) deployment. Active curb management can report status of curb activity (and any subsequent queuing) to operations management; allow for appropriate control strategies such as pricing, metering, and policy enforcement; and direct personnel to priority locations and issues. Such a system can inform and carry out policy deployment (dedicated pickup/drop-off zones) and integrate with communications and wayfinding to guide travelers accordingly. The science and practice of active curb management (and its associated metrics, methods, and technology) are quickly evolving and maturing within the smart city IoT space. At the airport, curb management science will provide both near- and long-term benefits.

- **Sustainable, Efficient, and Equitable Employee Access:** Employee access to and from the airport is vital to the airport's functionality and its ability to attract and retain a high-quality workforce both for its professional positions, but even more so for the thousands of labor positions critical to airport operations. A recent severe weather event caused widespread power outages to the Dallas region. Although DFW retained power, many of the residential locations of the workforce were negatively affected. This severe weather event, along with the impacts of the pandemic, exposed resiliency concerns related to workforce access to the airport. Although there is token evidence of increased use of alternative modes, all evidence at DFW points toward a primarily unimodal workforce, relying on personally owned and operated vehicles to get to work. Even though DFW is served by public transit routes with relatively recent transit improvements to the airport (DART and TEXRail), transit serves a minority of employee commute trips, estimated at less than 1%. The overwhelming majority of employees (whether direct airport employees or employees of the airlines, concessionaires, or contractors) access the terminals through dedicated employee parking. A single parking facility is paired with each terminal, located in remote areas of the larger DFW grounds. At each parking facility, dedicated shuttles convey employees to the corresponding terminal. The time burden imposed due to remote parking and shuttles, estimated to be as great as an extra hour to the daily commute, was a noted concern by DFW. During the site visit, the NREL team experienced employee shuttle operations and noted that although it added a time penalty, the employee shuttles appeared well orchestrated with minimal wait times (perhaps 10 minutes maximum during peak period). A landside, nonsecure automated mobility system as well as auto-valet and parking vehicle technology could provide solution paths toward improving connectivity and convenience for transit commutes, and potentially minimizing or eliminating the need for employee shuttles.

- **Recommended Pathways:** This report recommends a series of actions toward more effective (sustainable and time-efficient) employee commutes:
    - Full monitoring of employee shuttles (as well as all other shuttle and bus services) such that on-time performance, wait times, and other associated issues with shuttle efficiency are fully monitored and assessed. A replacement system for existing shuttles is possible, as described in the first section, along with a systematic approach to landside nonsecure mobility. Additionally, an airport wayfinding app could feature information to inform employees specifically to optimize commute experiences.
    - AV functionality (such as auto-parking and auto-valet) may also impact employee parking concerns and efficiency, allowing employees to be dropped off curbside (avoiding a last-mile shuttle delay) while their unoccupied vehicle navigates to remote employ parking. Such technology and policies should be explored both with simulations (the DFW digital twin) and through demonstrations.
    - Developing and encouraging use of efficient employee access to the airport apart from personally owned and operated vehicles is both a policy and technology pathway. Many companies provide expanded employee commute options for both knowledge workers and labor positions. This includes everything from policy-based approaches for public transit (paying for transit passes) to sponsored zero-emission van pools, ride-hailing car pools, and other chauffeured pooled ride options. These latter options allow for direct curbside drop-off at terminals, avoiding shuttle delays. Methods appropriate to the airport and extensible to the many work locations and job types of airport employees need to be investigated. The best experience for an employee is a time-efficient commute, “chauffeured” to the entry of their work location, and done so in an energy-efficient, low-emissions environment.

The preceding issues are brought forward as significant strategic and tactical concerns based on the findings of the study that are not currently the focus of other known initiatives. Several other issues and recommendations are complementary, but many of these are already in progress or being addressed by parallel initiatives. Among these issues are:

- **Traveler EV Accommodation:** As the general public adopts more EVs, the airport likewise needs to accommodate EVs, their charging needs, and other aspects of consumer EV adoption. This also includes rental car fleets. Hertz recently announced a purchase of 100,000 Tesla vehicles as part of their rental car fleet, which resulted in a request to DFW to expand EV charging capacity in the consolidated rent-a-car facility. Similarly, travelers with private EVs will expect charging services for their vehicles in much the same way as traditional petroleum refueling stations are available on airport premises. Although there are many unknowns concerning EV adoption, mass consumer adoption of EVs is no longer debated from either a technological or policy viewpoint. Preparing DFW for the electrification of the consumer fleet is already under study in partnership with NREL, and this report defers to its findings and recommendations with respect to EV service equipment for both travelers and rental car fleets. Such studies also include airport-owned fleets.
- **Employee EV Accommodation:** Access to EV service equipment by the workforce is a critical equity factor. Whereas higher socioeconomic populations, correlated with higher air travel, typically have capability of access to convenient home-based charging, those on the lower economic spectrum are more apt to reside in multifamily dwellings with less access to dedicated charging facilities at their residence. As such, access to workplace EV service equipment is more critical to enable a larger percentage of the workforce a practical path to EV ownership. As with traveler-owned EVs, employee EV ownership and associated access to workplace-based EV service equipment is under study in parallel activities between DFW and NREL, and a summary of the direction and pathways is provided in the body of this report.
- **On-Site Renewable Energy and Grid Integration:** Adoption of photovoltaic power generation infrastructure on DFW grounds could positively affect energy resiliency and the ability for DFW to lead the nation, if not the world, in exhibiting a fully sustainable airport. Facilitation and integration of renewable power sources and associated analysis, policy, and economics are under intensive study with regard to the airport, with future direction being provided by parallel initiatives. The body of this report offers a summary of these activities.

NREL is pleased to be in partnership with DFW in preparing for the future of efficient mobility and autonomy. The body of this report contains examples of other major airports undergoing similar preparation for likely future scenarios with which DFW can partner and learn. Although airports are often described as a city in a microcosm, airports themselves are a vital and unique “front door” to the world for any major metropolitan area, with unique needs and stress points. DFW, with its history of environmental leadership, is positioned to be a leader with respect to planning for and implementing effective infrastructure systems spanning physical, energy, and information topics. This focus on fostering mobility automation across the spectrum of emerging technologies will allow DFW to build its status as a model of operational optimization for the nation and the world, and to continue to provide exceptional customer experiences while maintaining an effective and resilient workforce.

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Introduction

Project Origin and Objectives

This report aims to anticipate and envision an integrated and actionable roadmap for sustainable mobility futures at Dallas/Fort Worth International Airport (DFW) by identifying actions for new infrastructure and institutional coordination opportunities around automation and efficient mobility. Investments in infrastructure supportive of mobility systems automation will benefit DFW transportation operational assets, such as the bus fleet. Such investments will also expand to the identification of opportunities and key levers for beneficial forms of infrastructure to adapt to disruptions—via automation, connectivity, efficiencies or electrification, or shared mobility—in a broader context of airport access. With the airport as a critical hub and enabler for a future of net-zero emissions, this roadmap and the corresponding actions taken will aspire towards serving as a "lighthouse" for future airport landside access. An aim is to address future technology trends and associated infrastructure needs, inclusive of inter-regional long-distance travel, commuter travel, and freight activity.

The goal of this roadmap is to inform planning on infrastructure, with stakeholder engagement and mapping to better inform institutional coordination for such planning across four key actors: service designers, operators, users, and cross-scale policy actors. The effort aims to be mindful of DFW's unique history (e.g., opening in 1974 and now standing as the fourth-busiest airport in the world by passenger traffic), ecology, economics, sociodemographic changes, and governance. Understanding DFW's roles and authorities as it aims to shape future sustainable infrastructure systems is key, especially as the transitions ahead will need to be inclusive of mobility, energy, buildings, and other systems, considering supply, demand, and distribution of infrastructure to equitable service benefits.

Sustainability and Resilience

Emerging technologies and practices that may affect airport operation are identified in Figure 1 such as automation, and an evaluation framework including concepts of in-boundary versus transboundary to clarify the scope in Figure 2. This roadmap is organized into three focused dimensions of ground transportation activities that are all considered to be key Scope 3 transboundary greenhouse gas emission activities for transportation, based on global protocols for greenhouse gas accounting at the community scale (World Resources Institute, 2021):

- (1) traveler access,
- (2) employee mobility, and
- (3) other transportation services or needs (across DFW to the broader region).

Figure 1. Overview of aspects and features of a sustainable airport.

Source: NREL Capabilities Supporting the Sustainable Airport (from S. Cary, NREL). Scope includes in-boundary sustainability, greenhouse gas, and resilience impacts.

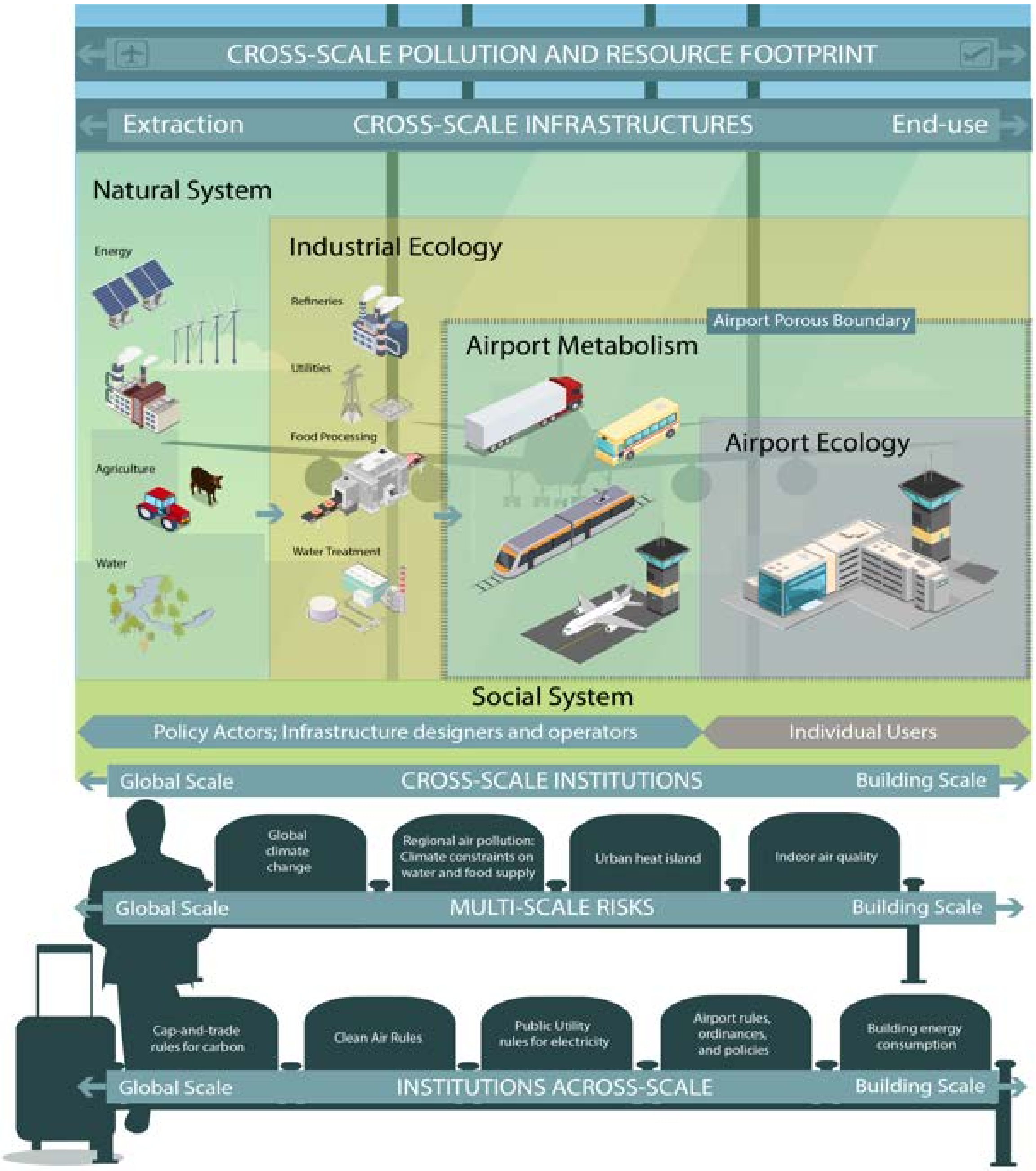


Figure 2. Evaluation framework across scales.

Source: NREL/DFW Airport as a Socio-Ecological- Infrastructure System (from E. Hotchkiss/R. Horton, NREL/DFW). Scope includes transboundary impacts and scales considered for automated mobility systems that meet user needs and goals for decarbonization, electrification, etc.

Customer Experience Orientation

In pursuit of developing this roadmap, DFW has expressed priorities to improve and maintain customer experiences, a guiding foundation in the development of this document. With advances in mobility automation, it is anticipated that customer experiences will benefit through greater ease of access, improved connectivity from the surrounding region and within the airport, and improved convenience through reduced stress, costs, and time commitments. Throughout the roadmap, potential benefits to customer experiences are highlighted.

Relationship to Prior Work at DFW

Information has been drawn from the National Renewable Energy Laboratory's (NREL's) internal expertise, including from the Athena and bus fleet electrification projects, published material, currently ongoing research, targeted peer institution engagement, and directed DFW key personnel feedback, among other sources.

Key Stakeholders/Partners

As a major mobility hub for the region, DFW is closely connected with a range of planning and transportation entities and organizations. As such, representatives of these interests serve as key stakeholders and/or partners, including the North Central Texas Council of Governments (NCTCOG), the Texas Department of Transportation, and public transit operators Dallas Area Rapid Transit (DART) and Trinity Metro.

DFW is served by both rail and bus and has noted a keen interest in extending their sustainability goals to incorporate efficient and resilient infrastructure investments that consider airport mobility and access within the context of a broader region and transboundary ecosystem for meeting net-zero emissions goals by 2030. A systems approach to airport infrastructure and operations planning can help identify levers of opportunity while accommodating new demographic, infrastructure, and technology changes in the region. Framing out the key components of the system and roadmap will enable new markets and opportunities for the region. This may also minimize risk and add resilience by having less impact on the environment, and enable more agile responses to elevated frequency and magnitude of extreme weather events and unpredictable social phenomena, such as public health concerns. The long-term mobility roadmap and vision is intended to be a phased approach to meet the needs of DFW management and planning, for which a strategic future mobility roadmap will be developed. The initial phase is described in the following section, focused on landside ground transportation objectives.

Perspective and Approach to Planning Exercise

As much as possible, this roadmap sticks to the employee, traveler, and service provider perspective with respect to each of the topics identified in characterizing existing practice and future mobility needs, as well as mapping these to emerging technologies to serve needs within a strategic future mobility roadmap.

Specifically, landside ground access considering broader regional mobility includes the following facets:

- Traveler (as "individual user"):
    - Access to/from DFW with a focus on the individual user, and the infrastructure services, technology, environment conditions, and policy that all play a role in shaping consumer journeys, low-emissions travel behaviors (e.g., if car-alternative options are time-/cost-efficient), increases in energy efficiency, mobility energy productivity (http://www.nrel.gov/mep/), and/or asset productivity.
    - Options to prioritize electric and carbon-neutral modes for mobility within and between DFW facilities; infrastructure design influenced by fleet size, procurement policy, public and private fleets, environmental sustainability, and climate action goals and priorities.
    - Quality of travel experience to reduce travel time, provide cost savings, and improve energy productivity for moving travelers and goods, enabled by upgrades to airport landside planning, management, and operations.
    - Lessons learned from ride-hailing pre-pandemic, and the need for high-quality and efficient curb operations.
    - Lessons from other airports.
- Employee (as "individual user" and/or DFW "infrastructure designer/operator"):
    - Access to DFW from residential locations via private vehicles, transit, or other combinations of modes.
    - Delivery of workers to specific employment locations within DFW facilities (once they have arrived at the DFW facility).
    - Work-related transportation patterns while on duty within DFW facilities.
    - Opportunities to reduce employee travel time and improve overall mobility energy productivity for employees and airport operations.
- Service needs/other transportation considerations:
    - Access by delivery, vendor, emergency services, and other operational needs.

Literature Review

Approach

The literature review was conducted with the intent to identify how the ongoing evolution of the transportation system (particularly mobility automation) is expected to influence traveler, employee, and service aspects of airports. Considerations range from impacts on regional mobility to terminal-level opportunities. The summary below outlines high-level mobility automation trends, airport-specific automated mobility applications, and considerations for implementing automated vehicle (AV) pilots. Relevant examples from the United States and abroad are also documented.

Key Trends and Findings (Macro/Regional Level)

The Dallas-Fort Worth metropolitan area is among the fastest-growing regions in the country (Moore et al. 2019). Along with this growth, commute times have increased, and it is expected that AVs may exacerbate this trend. For example, researchers at the University of Texas have predicted vehicle miles traveled (VMT) could increase by 30% to 50% on Texas roadways due to automation (Huang, Kockelman, and Quarles 2020). AVs are expected to induce additional travel beyond current levels (e.g., higher rates of travel for people who cannot currently drive) and to circulate without passengers. They may also entice travelers away from transit or air, further contributing to higher VMT and associated impacts.

Increased VMT and congestion could negatively impact DFW's customers and employees by increasing travel time to/from the airport. In turn, this may cause potential customers to pursue alternatives to air travel or seek other ways of reducing their travel time (such as direct drop-off at the curb). Longer commute times could impact the willingness of potential employees to pursue jobs at DFW.

On the other hand, VMT increases may be offset by increasing telecommuting opportunities, and at high levels of AV penetration, automation may improve the efficiency of the system, reducing travel times and congestion. Additionally, state or regional policies could dramatically influence how AVs impact the transportation system. Policy effects are hard to predict, as there are no clear roadmaps in place.

Wider availability of AVs for personal transport will likely have differing implications for different subsets of the population. A study from the DFW region found that AVs will offer greater benefit to technologically-savvy workers who can utilize time spent in an AV for work-related purposes (Moore et al. 2019). Conversely, part-time employees and those in lower-wage professions are less likely to view time in an AV as productive since their work functions cannot be performed during travel. Such workers may still benefit from enhanced mobility opportunities afforded by AVs, such as filling gaps in transit schedules or providing flexibility for routine household trips such as child pickup and drop-off.

Similar to the system-level effects of AVs on the transportation system, there is a strong case to be made that AVs will increase VMT and congestion within the airport network (Gurumurthy and Kockelman 2021). This impact will be most noticeable at the curb, where limited space exists to accommodate the level of pickup and drop-off activity that could be experienced.

Efforts to incentivize ride pooling or public transit use may be less effective at reducing airport trips among passengers than in other domains, due to the time sensitivity and price inelasticity of airport trips. Nevertheless, policy interventions such as time-based pricing should be considered as part of a comprehensive management strategy. Repurposing parking facilities to serve as remote curbs is another strategy that holds promise for managing increased demand anticipated to result from AVs.

Mobility Automation at Airports

Low-Speed Automated Vehicles

Limited customer- or employee-focused AV applications have been implemented at airports to date, though many are in the planning stages. Low-speed automated vehicles (LSAVs), particularly shuttles, are among the most common examples, with pilots completed or ongoing in the United States (including at DFW) and throughout the world. A sample of airports that have implemented or are in the planning stages for implementing automated shuttles includes (Airports Council International 2019; Coyner et al. 2021; Gittens n.d.; Hájnik, Harantová, and Kalašová 2021):

- DFW: EasyMile shuttle connecting remote parking lot to main parking lot.
- Austin-Bergstrom International Airport: EasyMile shuttle between terminal and passenger pickup areas (taxis, ride-hailing, rental cars).
- Denver International Airport: EasyMile shuttle connecting Peña Boulevard commuter rail to Panasonic’s Denver office.

Several shuttle projects in the planning stage include:

- Daniel K. Inouye International Airport (Honolulu, Hawaii): Replacing “Wiki” shuttle with autonomous shuttle, supporting terminal-to-terminal transfers (people and baggage).
- Paris Charles de Gaulle Airport (Paris, France): Driverless Navya 15-seater shuttles connect train station to Groupe ADP headquarters.
- Christchurch Airport (New Zealand): Driverless 15-seater electric shuttle produced by Ohmio is undergoing testing on airport roads.

These shuttles provide connections between airport terminals, parking facilities, other transportation services, or nearby employers. They sometimes include onboard personnel, which has been identified as an important factor in building trust among passengers (Ashkrof et al. 2019). LSAV demonstrations may require infrastructure modifications, such as implementing new connected signal technology and roadside units or adding markings and signage. One study found that the use of shuttles or other automated mobility options are most successful when they replace or enhance an existing mobility service, rather than create an entirely new offering (Nordhoff et al. 2021). Additionally, passengers with higher socioeconomic status and/or familiarity with existing services are more likely to approve of driverless vehicles.

While LSAVs are likely to continue to generate significant interest, some challenges exist related to their accessibility, speed, and other operating constraints (Cregger, Machek, and Cahill 2019). For instance, LSAVs typically do not meet accessibility requirements for transit vehicles, as defined in the Americans with Disabilities Act (ADA), and their low speeds preclude some use cases. The long-term viability and scalability of automated transit applications may hinge on advancements in transit bus automation technology. To date, public transit bus automation has not been the subject of much industry focus, due to limited market size and customization requirements. However, a few examples of airport-based transit bus automation were found in the literature and are described in subsequent sections.

Parking Valet

Automated parking valet is an innovative application of AV technology that has been effectively demonstrated at airports in Europe. The approach saves passengers time and can reduce the amount of parking space by half (Airports Council International 2019). Customers using the automated valet system reported high levels of satisfaction. Automated parking valet has been implemented at Lyon–Saint Exupéry Airport (Lyon, France), with additional trials underway at Charles De Gaulle Airport (Paris, France), Dusseldorf International Airport (Dusseldorf, Germany), and London Gatwick Airport (London, UK). The system was designed by Stanley Robotics and consists of robots that park vehicles dropped off by customers and return them to the pickup location based on flight information. Over 95% of customers at Lyon's airport reported they would use the system again (Hájnik, Harantová, and Kalašová 2021).

Automated Wheelchairs

Wheelchairs are another strong candidate for passenger-focused automation at airports. The automated wheelchair concept has been trialed at a few airports (including DFW) and has been more extensively studied in hospital settings (Scudellari 2017). They may be particularly well suited for early implementation, as the technology is relatively mature, meets a growing need (aging population), and addresses a well-defined problem. Some automated wheelchair systems can operate in tandem to serve the needs of groups. Cincinnati/Northern Kentucky International Airport trialed semiautonomous wheelchairs developed by Whill Inc. that can be controlled from a smartphone (Airports Council International 2019). A fully autonomous version of the system has since been deployed at Tokyo International Airport (Scudellari 2017).

Related Efforts at Airports

Most of the early applications of vehicle automation at airports have dealt with operations, rather than passenger or employee travel (with some notable exceptions, discussed above). These operations are important to the overall customer experience and may help offset pain points experienced in accessing the airport. Operational improvements may also change how employees perform their job duties. Moreover, positive experiences with automation in other domains could pave the way to greater acceptance for mobility-focused automation.

Related examples of automation efforts and other uses of advanced technology at airports include:

- **Customer assistance:** Airports, particularly in Asia, have begun to deploy mobile customer assistance robots that can respond to passenger inquiries in multiple languages, providing timely information such as departure details or baggage claim information (Pellerin et al. 2020). In some cases, they also perform surveillance, incident detection, wayfinding, and/or data collection functions.

    - South Korea, Incheon Airport: Customer service robot, Troika, assists travelers in multiple languages.
    - China, Shenzhen Airport: Anbot conducts security, incident detection, and customer service functions.
    - Japan, Tokyo International Airport: Haneda Robotics Lab is planning to trial robots for various tasks (luggage transport, security, etc.). The Reborg-X (also deployed at Mt. Fuji Shizuoka Airport) guides visitors, while also conducting surveillance and detecting incidents such as fire or other hazards.
- **Baggage transfer and delivery:** Many airports are experimenting with the use of AVs for baggage transfer and delivery. These systems may reduce the time to transfer bags and improve baggage tracking.
    - DFW trialed the Vanderlande FLEET autonomous checked baggage system in 2019 for international-to-domestic transfers (Future Travel Experience 2018).
    - Cincinnati/Northern Kentucky International Airport is using ThorDrive to transport luggage between terminals and aircraft (Airport Technology 2021).
    - Rotterdam, Netherlands: The FLEET baggage system optimizes baggage delivery and provides tracking (Airports Council International 2019).
- **Security screening:** Airports are deploying advanced technologies to expedite and improve the security screening process.
    - Detroit Metropolitan Airport is using an autonomous cart system (DAIFUKU) to support security operations (Pellerin et al. 2020).
    - Cincinnati/Northern Kentucky International Airport is using the Internet of Things (IoT) to monitor passenger (and baggage) flows through security (Future Travel Experience 2021b).
    - Amsterdam Airport Schiphol: Computed tomography scanning technology streamlines baggage screening processes (Airport Technology 2021).
- **Cleaning:** Autonomous robots have been deployed at airports in recent years to clean and sterilize airports (e.g., Pittsburgh International Airport) (Lyons 2020).
- **Contactless services:** A variety of transactions historically involving human interactions such as ticketing, payment, and baggage drop are increasingly being replaced by contactless, automated solutions (Future Travel Experience 2021a).
- **Airside operations:** Although not the focus of this effort, a few examples of automation pertaining to airside operations were found in the literature and are noted below (Airports Council International 2019):
    - London, UK, Heathrow Airport "CargoPods": Autonomous cargo vehicles (airside).
    - London, UK, Gatwick Airport: Electric AVs to shuttle employees between airfield locations.

Airport Mobility Electrification

Vehicle electrification often occurs in tandem with automation, as demonstrated by the LSAV demonstrations noted previously. However, airports and other regulatory agencies are also beginning to implement or require more ambitious electrification efforts (Hájnik, Harantová, and Kalašová 2021). For example, the California Air Resources Board approved a rule in 2019 that requires airport shuttle operators at the state's 13 largest airports to exclusively use zero-emission buses by 2035. In the Atlanta region, the GreeningATL project is installing 300 chargers in an effort to convert all airport shuttles to electric.

An innovative demonstration project underway in Visby, Sweden—Smartroad Gotland—involves implementation of wireless electric road charging to charge shuttles between the airport and Visby town center (Hájnik, Harantová, and Kalašová 2021). The embedded charging system powers an electric bus and an electric heavy-duty truck over the course of 1.6 kilometers.

Automation Infrastructure Requirements

Infrastructure requirements to support mobility automation are generally tailored to the use case and implementation details. For example, LSAVs may have specific signal-related technology requirements depending on the vendor and routes (Stantec and ARA 2020). As a result, it is hard to generalize about what may be required. That said, certain fundamental concepts may help with infrastructure planning:

- Although GPS is improving and has a role to play, it is unlikely to be sufficient to support automated vehicle positioning in an airport context (Kim et al. 2017). Detailed 3D mapping may be required for indoor applications (lidar-equipped vehicles/robots may provide this function prior to deployment or an ongoing basis), and magnetic markers have been used to assist with transit vehicle positioning on fixed routes (Cregger, Machek, and Cahill 2019).
- As compared to earlier systems, modern AVs do not require predetermined paths and can navigate within zones (Fragapane et al. 2021). However, lane markings can assist AVs and help establish expectations for interactions with people.
- A variety of deployment scenarios are viable, including centralized and decentralized control, smart dispatching based on predetermined demand patterns, dynamic relocation, etc. (Fragapane et al. 2021).
- Connected signal technology has been implemented in many low-speed shuttle AV deployments (Stantec and ARA 2020). Additional markings, signage, and signals are also commonly included.
- Reliable and comprehensive cellular networks and/or Wi-Fi are needed to support two-way data transmission (Airports Council International 2019). 5G will be helpful but is not required for AV deployment.

Literature-Derived Recommendations

- Convene technology scan/peer exchange with Haneda Airport and/or Pittsburgh Airport (partnership with Carnegie Robotics).
- Conduct a thorough assessment of Wi-Fi/cellular infrastructure (including cybersecurity aspects) and upgrade system as needed.

- Identify opportunities for embedded roadway systems, such as charging or localization assistance (magnetic markers).
- Identify priority routes for LSAVs based on key passenger and employee movements.
- Consider non-infrastructure solutions to mobility challenges based on identified customer and employee pain points. These could include informational robots, software-/app-based solutions, collaboration with airline partners (e.g., to provide shuttle schedules, and terminal transfer information en route), and application programming interfaces to facilitate data exchange among partners.
- Identify business cases for automation technologies.
- Develop pilot project implementation guidelines that address measures of effectiveness, partners, data collection needs, and potential pathways to deployment.
- Conduct technology trials for automated parking valet and automated wheelchairs.

Site Visit and Observations

In November 2021, Stan Young and Andy Duvall of the NREL team conducted a site visit to DFW, and were hosted by Sean McIntyre, Shaniqua Epps, and other DFW staff. The site visit enabled engagement with key DFW leadership and relevant stakeholders, helping to inform understanding of the unique history, geography, and possible directions for decision-making ahead. A central purpose of the site visit was to gain experiential insight into mobility operations at the airport and the surrounding area. Through an in-depth tour of the DFW facilities and grounds conducted over 2 days, the NREL team collected observations and photos, met with key stakeholders, and learned background information to support development of the roadmap.

Overview of Observations

The site visit served to inform a vision of the specific context of DFW, including geographic and situational aspects of DFW operations. Primary elements of the observations included:

- **Passenger access:** All traveler and employee access routes were observed, including parking facilities, transit access, curb space activity, access and security operations, and variability in design and perspectives among the terminals.
    - The NREL project team attempted to anticipate the impact of current and planned facilities on passenger flow, behavior, and experiences.
- **Employee commutes:** The NREL project team observed the employee access process, including remote parking facilities, transit access, employee shuttle system operations, and estimated commute time burden.
    - The observation noted a low volume of transit commuting, even with proximate transit options.
- **Identification of DFW mobility challenges:**
    - It appears that nonsecure-side mobility was challenging, with intermittent and/or non-scheduled bus-based circulation between terminals, and curb activity in drop-off and pickup zones that included unattended cars parked in locations marked as no parking or standing zones.
    - In conversation with personnel, the NREL team noted some key passenger and employee access challenges.
    - It is estimated that more than 50% of the time, local passengers return to a different terminal than was used for their original departing flight, resulting in a need to carry baggage from the return terminal to a car parked at a potentially distant departure terminal.
    - Employees noted that a need to take a shuttle bus from a remote parking location to a place of work added 30 or more minutes onto daily commute times.
- **Current/prior automation and electrification efforts:** Historic perspective of Airtrans system.
    - The NREL team noted remnants of Airtrans guideways, which were in operation as an automated non-secure side people and cargo moving system between 1973

and 2005. The Airtrans system was among the earliest and at the time most advanced automated people movers in the world.

- With long distances to traverse between and within terminals, the team noted within-facility potential for AV/electric vehicle (EV) application using existing infrastructure. Such as system could be designed to scale and adapt to service needs within the facility.
- The NREL team also noted the use of EVs in airside application, specifically luggage and aircraft tugs.
- The DFW team provided information on an EasyMile-based TractEasy airside automated tug pilot project for near future deployment.

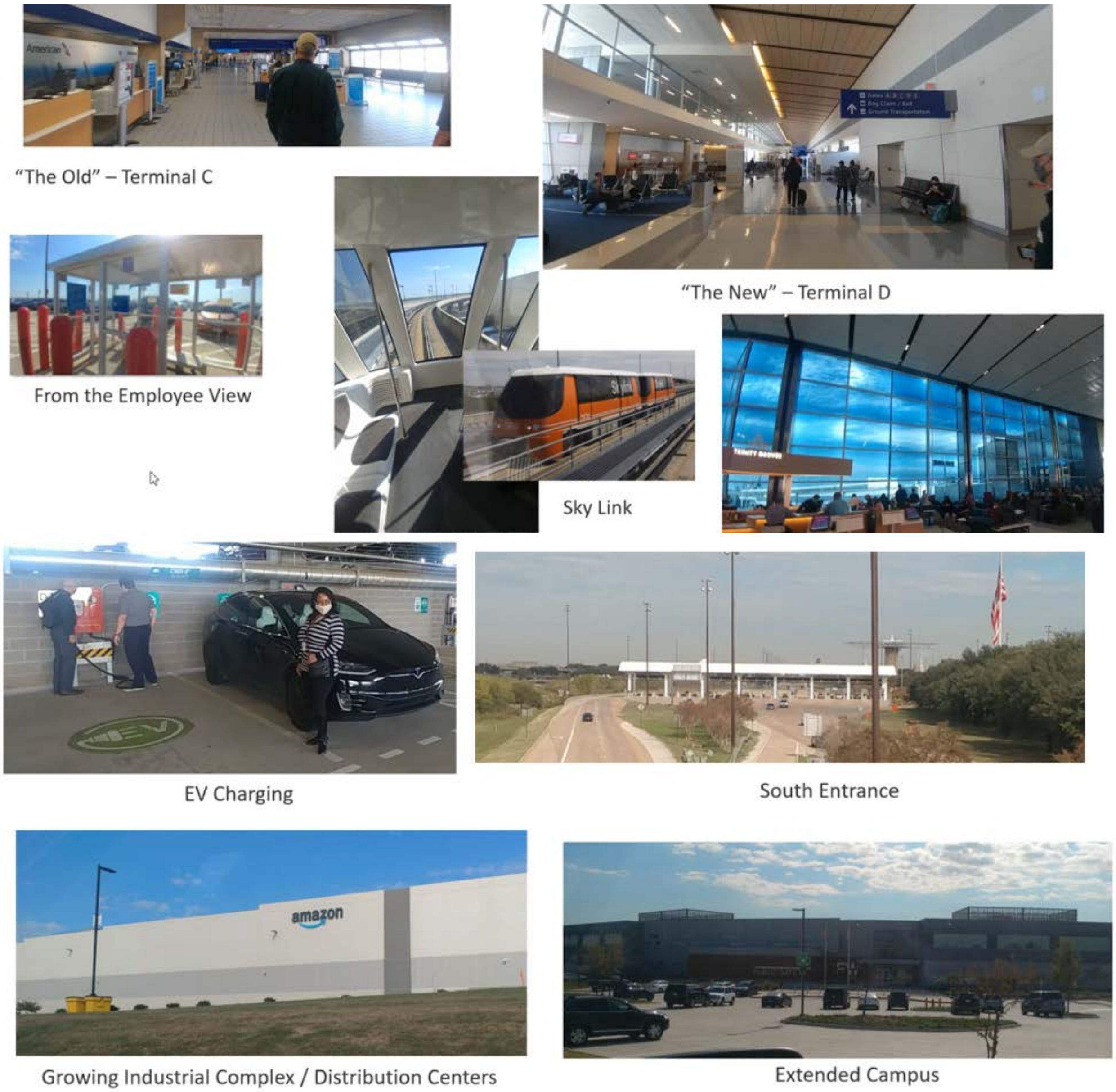


Figure 3. Collage of site visit photos

The photos in Figure 3 showcase some examples of travel experiences and customer needs. Subsequent discussions identified pain points such as nonsecure-side mobility options ("Where do I catch this bus?") to inform approaches for analysis and data-driven discovery that offer insights to planning and decision-making.

Additional observations:

- Different Department of Homeland Security checkpoint configurations exist for each terminal—contributing to a sense that terminals function like five separate mini-airports, each connected by Skylink.
- Tolling at the South Entrance may enable tracking and monitoring of transactions, and function as a logical entrance, or "welcome gate" to the traveler. This capability may enable additional functions, such as active curb space monitoring and parking coordination.
- Amazon has multiple large buildings at a warehouse and distribution center, constructed less than 3 years ago and which continues to grow.
- The DFW extended campus includes police, fire, and related training facilities, and the operations centers that all support airport functions.
- The Integrated Operations Center is highly connected with all aspects of the airport and could readily serve as a central management hub for automated mobility systems.
- Transit access: Regional rail to the south. At the peak of rush hour, six people were observed waiting for rail; thus, there does not appear to be a significant contribution to airport access for either passengers or employee commuters.
- Light rail stations at the north end of the airport have been added in recent years: DART to the east of International Parkway, and TEXRail on west side of International Parkway near Terminals A and B. At 6 p.m. on a Tuesday, a trip made via DART was estimated to take twice the travel time as driving between the station at DFW and downtown Dallas.

Figure 4. Examples of transit access. The far right photo shows a lone sidewalk—the only hint of pedestrian or bicycle access around the airport complex, and the sidewalk didn't continue beyond the intersection around the corner.

Concepts To Consider for Automation and Further Demonstrations

- **Auto-parking capability: Auto-valet**
    - To enable disabled access, save time, address curb impacts, and to potentially reduce commute time for employees with low-speed self-parking capable cars.
    - Couple with inductive charging for more efficient use of EV charging equipment, balance supply-demand, and explore vehicle-to-grid capabilities.
    - Demo/proof-of-concept pilot project funded by NCTCOG.
- **Automated mobility platforms**:
    - Infrastructure perception and control (protected guideway; needs lightweight barrier, lightweight infrastructure): perception via lidar, radar, video processing, connected and autonomous vehicles, connected vehicle (CV) data; control: eco-approach, signal optimization, curb optimization, safety-affirmative signaling, red-light running-dilemma zone.
        - Relevant to curbs, pain point observations of cars parked unattended (a system to monitor and observe curbside behavior); site that backs up onto International Boulevard.
    - Equity, technology, and system control considerations.
    - Potential to leverage data to inform movement between and within DFW facilities, augmenting management capabilities and operational control.
    - Public-private partnerships (e.g., Labyrinth: inside airport automated shuttles, Steer, Econolite, Renu Robotics, Luci: automated wheelchairs).
    - Potential for automation more broadly with development of integration across systems.

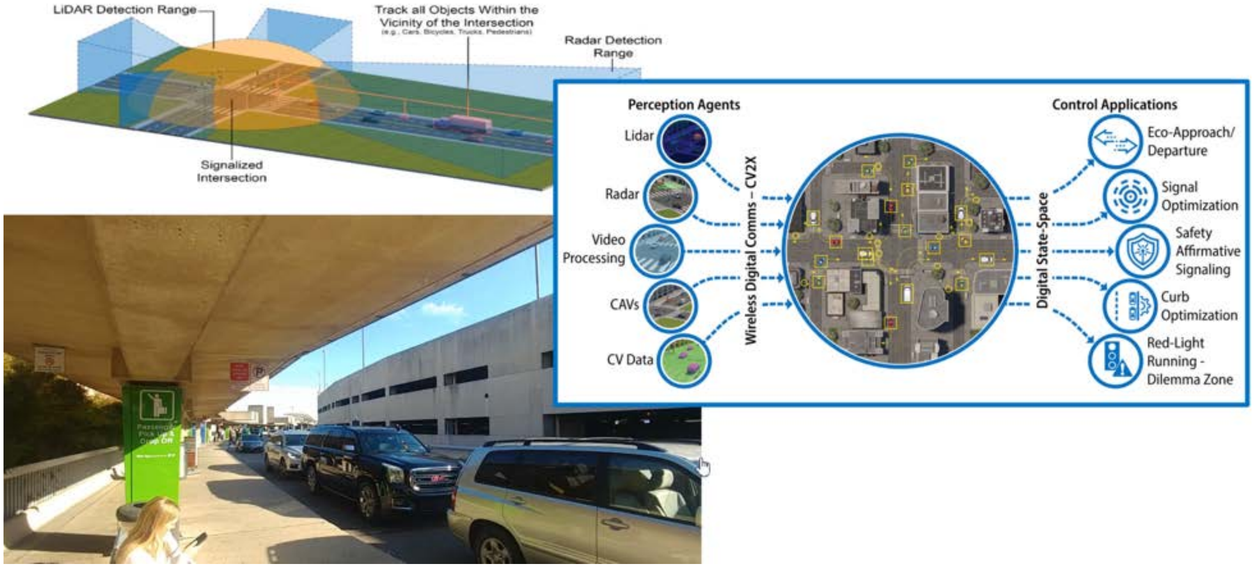


Figure 5. Curbside observations and opportunities for increasing perception and control applications

Other concepts emerging from site visits and early-stage brainstorms among NREL and DFW teams include:

- Airport app for comprehensive, personalized, automated wayfinding and information (to address inadequate existing wayfinding supports and always changing dynamics).
- Framing the airport as a destination.
  - The facility has excess capacity, and a number of attractive destinations on the secure side.
  - An objective could be to move people to the secure side as soon as possible—facilitated by multiple entry points through security.
- North transit access—is a "best kept secret", with voluminous capacity and currently low use, while the south transit area is challenging to access and could benefit from better integration.
  - Adjacent to the north transit access point some large stretches of underutilized curb space was observed, that could likely serve as an ideal location for Uber/Lyft ride-hail zones.
- Potential capability to leverage Skylink at Terminal F for expansion utilizing modern Transportation Security Administration (TSA) security technologies.

In summary, some of the key factors affecting sustainability and resilience outcomes associated with automated, connected, efficient (ACE) mobility are noted in the following sections. These are used to develop initial estimates of the range of potential outcomes for DFW, and which factors or opportunities may exist toward more optimal operation.

Future of Mobility/Autonomy to Inform Infrastructure Investments

Automated Mobility Systems for DFW Landside Access

Autonomy—specifically AV technology that allows for fleets of vehicles to provide dedicated service to circulate passengers, staff, and cargo between terminals—is within sight of reality. Currently, such services are provided on the nonsecure landside by fleets of manually driven buses and shuttles to ferry people between terminals and to various services and facilities such as the consolidated rental car facility and employee and passenger remote parking. This section discusses the evolution of AV technology as an enabler to provide better, more responsive, resilient, and energy-efficient service. To understand current needs and possible solutions, a historical understanding of the evolution of automated people movers (APMs) in airport settings, specifically DFW, provides perspective on the possible advantages that AV-enabled mobility systems may offer.

DFW's Legacy of Automated Transit Systems

Automated mobility systems in airport applications have typically been classified as APMs over the past 50 years, and have been based on automated train technology. DFW was one of the first pioneers of airport APM systems that have shaped many other airport designs. When DFW was first designed and constructed, a nonsecure landside APM system was competitively procured and installed to transport air passengers between the terminals and provide a connection to the remote parking lots.

Between 1974 and 2005, this APM system not only carried air passengers, but also served employees who parked at employee lots and traveled on the APM to their terminal work locations. The system also carried containerized cargo in special vehicles configured for this service, with the special stations designed to load and unload the cargo containers located "off-line" from the main guideway through each terminal, allowing other train cars to bypass the station, a unique function for APMs of the day.

This original APM system, called Airtrans, was one of the largest airports APM systems ever built, with the scale of its progressive expansions reaching 15 miles of guideway and 33 stations at the end of its service life. The Airtrans system concept was formulated as an integral part of the DFW terminal complex facilities and roadway design, tying together the airport landside facilities and functional parts as a nonsecure system (Vought Heritage n.d.). The alignment followed the configuration of the spine roadway and the adjacent curved terminal footprints, with most terminal stations underneath the terminal buildings. The Airtrans system operated for over 30 years along the exclusive transitways spanning the length of the north/south spine roadway system.

The nonsecure Airtrans system was replaced by the secure Skylink APM system, which began operations in 2005. The Skylink guideway is located on an aerial alignment that follows the secure airside of the terminal buildings above the edge of the apron. Its functional purpose is to transport air passengers and employees between the terminals without requiring them to exit the secure area into the nonsecure parts of the terminals—in contrast to its predecessor's (Airtrans) functional purpose. This begs the question of whether the role of the previous Airtrans system could be satisfied by new 21st-century automated systems for transporting passengers, employees, and potentially cargo throughout the nonsecure airport landside. Replacing the current landside busing operations by an automated transport system can possibly provide improved passenger service levels, reduced energy use and emissions, higher reliability and resilience, and extensibility to grow with airport demand.

A key attribute of the original Airtrans system design was the ability to dynamically configure unique, special operating routes to serve specific origin/destination trip ends as the trip demand patterns change throughout the day. This operating concept, referred to within the APM industry as an automated transit network (ATN) system, allows smaller individual vehicles (i.e., only one-car trains) to carry passengers between specific origin and destination stations without any intervening stops. Modern ATNs call for off-line stations so as not to impede vehicle movement on the mainline transitway. The ability to bypass intervening stations substantially lowers trip time for essentially all passengers. This ATN operation paradigm can improve customer experiences with more tailored routing and is a primary benefit of modern automated mobility system concepts. The term "ATNs" is used herein to refer to automated mobility systems of this nature.

AV Technology Enabling the Next Generation of Automated Mobility Systems

The advent of AV technology has provided a wholly new perspective on the way the APM systems can be configured and operated in the future (Lott and Gettman 2016). As AV technology matures to the point that it can be integrated into airport automated mobility system applications, it will become possible to achieve greater flexibility of routes and higher levels of passenger service, combined with lower infrastructure, system optimization, and operating costs.

Replacing train-centric systems with their automotive counterparts, and specifically AV capabilities (SAE Level 4 automation), has inherent advantages:

- Robotic steering controls on board each vehicle perform navigation and steering functions, eliminating the need for fixed tracks or guideways.
- No switches are necessary along the transitway.
- Rubber-tired vehicles replace rail vehicles, allowing flexibility to operate in some aspect on conventional "roadway" infrastructure.

The maturation and increased deployment of AV technology in airport ATN applications bring key functional advantages and attributes, including off-line stations and virtual coupling of vehicles.

Off-Line Stations

The ability to provide off-line stations is a distinguishing feature of the ATN system definition. This feature of ATN systems will be relevant to the future application of AV technology in operating concepts that provide a direct service between the passenger's origin and destination stations, while bypassing other intermediate stations to which the passengers are not bound. The ability to capture this feature in AV operation was a component in an early AV technology that Toyota advanced as one element of their prototype AV bus. They called the operational system concept the Intelligent Multimodal Transit System (IMTS), with the off-line station concept shown in Figure 6.

Figure 6. Toyota first demonstrated platooning of AV technology in the Aichi Expo (left), with the off-line station concept shown on the right.

Source: Wikimedia (left), Toyota (right)

The strategic conclusion on the benefit of off-line station configurations is that while conventional APM uses exclusively on-line (or in-line) stations, the future with AV applications will allow off-line stations to be possible, reliable, and cost-effective. Off-line stations allow a practical configuration of the transit network, allowing for both fixed-route and demand-response (or on-demand) service while retaining overall system capacity. It also makes the system more extensible over time, allowing it to grow and respond to the changing demand patterns of a growing airport.

Not only will AV technology efficiently enable off-line stations, but station berths (particularly for high-demand/high-capacity stations) can be configured in parallel rather than serial, allowing vehicles to bypass others in the process of loading/unloading. Figure 7 shows an operating ATN system at Masdar City in Abu Dhabi, United Arab Emirates, using parallel vehicle berths in stations. Such station configurations are also possible for larger AV systems, such as buses and shuttles. Off-line stations and parallel berths, though advanced for automated mobility systems, are inherent in vehicle-based technology, where the manual analogies are curbs and driveways that enable vehicles to pull off the roadway for boarding and deboarding without obstructing mainstream traffic.

Figure 7. Masdar City personal rapid transit system, Abu Dhabi, United Arab Emirates.

Source: 2getthere

Virtual Coupling of AVs

Another operational first for Toyota was at the 2005 Japanese World Expo held in Aichi Prefecture, in which they carried several million passengers via virtual coupling. Virtual coupling of vehicles into a bus platoon, also shown in Figure 6, was accomplished while the vehicles were in motion—a feature of AV technology that is currently in development for large semi-truck applications operating cross-country on interstate freeways and referred to as "cooperative adaptive cruise control." This feature is being developed for transit vehicle applications more recently through the Federal Transit Administration's bus automation programs (Cregger, Machek, and Cahill 2019). This technology has been of interest to the NCTCOG for potential application to semi-truck tractor-trailer caravans in the I-30 corridor through the Dallas-Fort Worth region.

Supervisory Control for ATN Systems

Whereas many of the AV technology functions and abilities that enable AV-based automated mobility systems have been demonstrated, supervisory control systems for fleets of AVs providing public mobility have yet to reach a demonstratable degree of maturity. The required supervisory control subsystems for AV fleet operations can be compared and contrasted to those defined in the *IEEE 1474 Standard on Communications-Based Train Control (CBTC)*. The control system similarities to an APM automated train control system are illustrated in Figure 8.

These concepts were presented at the 2021 Business of Automated Mobility Forum, which was sponsored by SAE International and the Association of Unmanned Vehicle Systems International. The associated technical paper was included in the conference proceedings and subsequently selected by SAE as one of the best papers in the forum proceedings and published as a journal article (Lott, Young, and Zhu 2021).

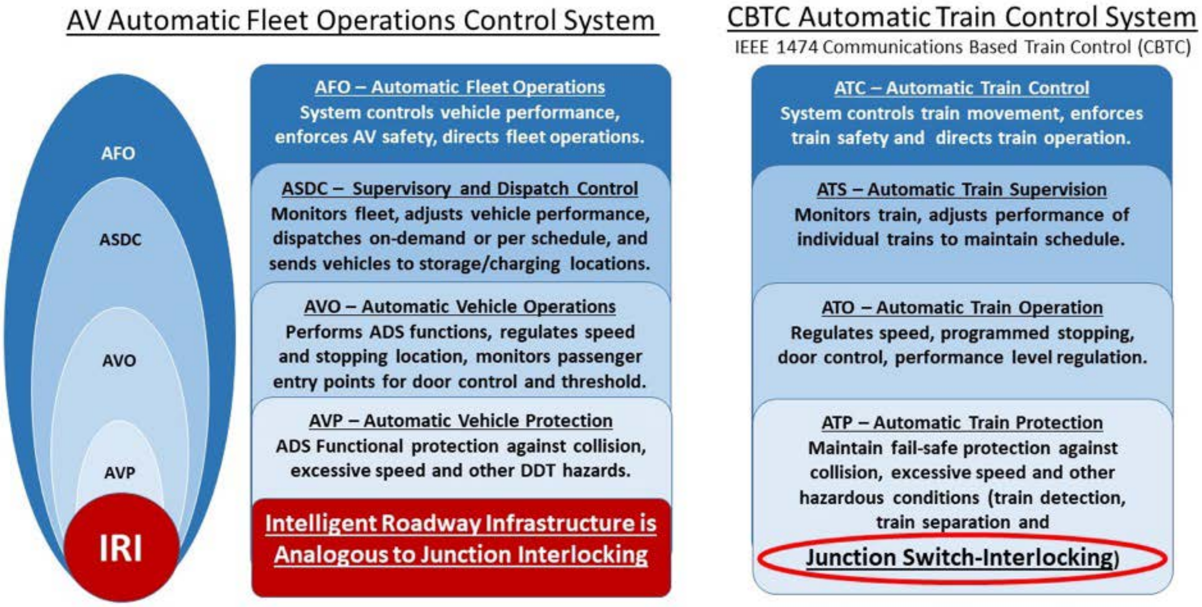


Figure 8. Correlation of an AV system's autonomous vehicle and fleet operational control with automatic train control functional subsystems for APM systems

Whereas most AV technology has been demonstrated as autonomous vehicles independently navigating existing roadways, supervisory control of a system of vehicles delivering a mobility service is much less mature. Such functions include dispatch of vehicles, recirculation of vehicles, cleaning, charging (refueling of vehicles), and overriding safety controls. Many of these areas have ongoing research (some of which is cited above).

The evolution of automated transit into more efficient operations using smaller vehicles operating point-to-point will create a demand-responsive configuration that is notably different from traditional APMs, with the ability to adapt to heterogeneous demand patterns. Analytical studies have shown that it is common, especially within airport landside environments, to have a subset of stations produce a large component of the overall passenger demand. Figure 9 shows the findings of analytical studies for a conceptual ATN system using on-demand four-passenger vehicles in a fully automated fleet deployment at Newark Liberty International Airport (Cronin and Lott 2011). This study compared small vehicle ATN-type operations with conventional, fixed-route large APM vehicle operations. The findings, as illustrated in the figure, reflect that three stations have substantially higher origin-destination demand among them than the other stations in the system. Similar results of other airport studies suggest that the optimum automated transit solution could be to serve the high-demand pairs with larger vehicles operating on fixed routes, and then the rest of the network stations would be effectively served by small vehicles dispatched in a demand-response mode.

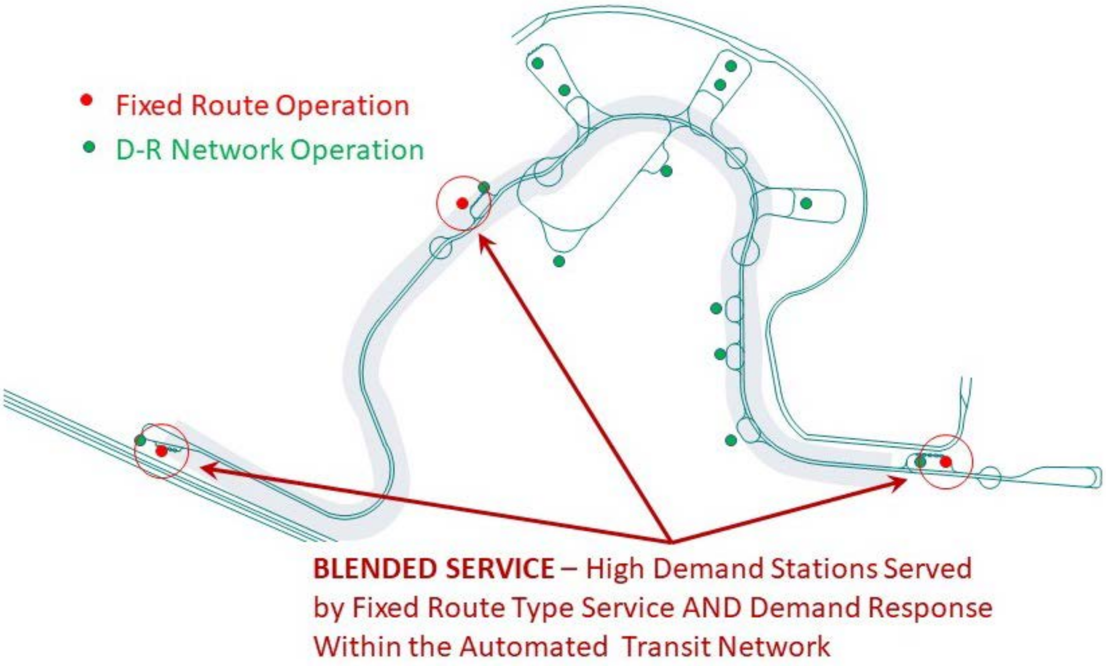


Figure 9. Concentrated high-demand patterns are typically found between a few trip production stations internal to the complete transit network.

Closely coupled with demand management is the management of empty vehicles to adequately serve remote portions of the network, especially when those locations have passenger surge flow conditions. In the analysis of Newark Airport referenced above, this condition of periodic surge flow was the case at the Northeast Corridor rail station, where commuter rail and inter-regional high-speed trains brought air passengers to the airport. As these vehicles will likely be battery-electric, empty vehicle management must also address vehicle charging. The combination of all the features described above provides rich new operational capabilities from which AV transit services (ATN systems) can be deployed and optimized in the performance of the functions necessary for airport automated mobility systems.

Physical Infrastructure for AV-Enabled Automated Mobility Systems

The flexibility of transitways and stations enabled by AV technology is comparable to the flexibility in the roadway system for regular vehicles. Grades and elevation of the transitway, dependent on the built environment of each station's surroundings, offer the opportunity to reduce capital costs by locating stations at grade, or adjacent to (or integrated into) the facilities being served. If based on battery-electric vehicle technology, the power requirements (relative to conventional APMs) and safety concerns (relative to both APMs and internal combustion engines) offer more opportunity for architectural and functional integration into the building envelope. As smaller, lighter AV technology matures, it will become possible not only to achieve greater flexibility of routes and higher levels of passenger service, but also to build transitway structures with lower capital costs. Even aerial structures could be built at substantially lower capital cost. Figure 10 shows an example of a lightweight structure that supports the ULTra four-passenger personal rapid transit vehicle technology that is now operating at Heathrow Airport.

Figure 10. Lightweight infrastructure for the London Heathrow International Airport small four-passenger vehicle system.

Source: ULTra PRT

Examples of Landside Nonsecure Airport Automated Mobility Systems

Although no comprehensive airport landside AV-based automated mobility system has been deployed (noting that the Heathrow Terminal 5 system only connects a single parking facility to the terminal), nonsecure APMs are prevalent in airport systems. In 2012, a study sponsored by the Texas Department of Transportation investigated linking high-speed rail to several key mobility hubs, including a station that would service DFW. The study assumed that a connector automated transit system would be built to provide connections for passengers traveling from the high-speed rail station to DFW, as well as interconnects to the terminals and the consolidated rental car facility. This concept for a DFW nonsecure landside APM system that provides a connection to the high-speed rail station site is shown in Figure 11 (Lott 2013). Although never proceeding past the study phase, the concept of a system to interconnect DFW facilities and extend to existing or planned developments and improvement is consistent with objectives of other landside nonsecure automated mobility systems in the United States.

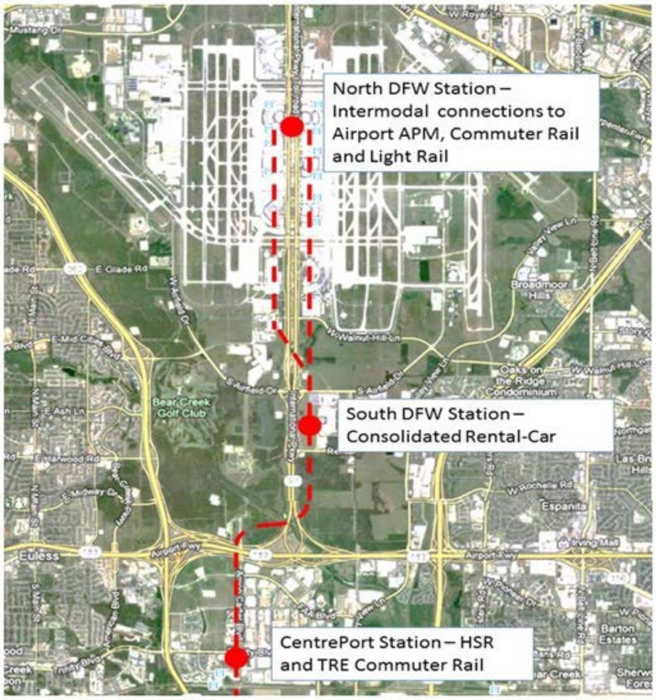


Figure 11. Conceptual nonsecure APM connector system connecting to a high-speed rail system at the Trinity CentrePort station.

Source: DFW Airport

Two relevant case studies cited below exhibit a combination of an on-airport circulation automated transport system with an extension to reach other major mobility hubs or remote locations. Though both employ traditional APM technology, they represent functional parallels of the objectives at DFW for a sustainable, efficient, high-performance landside mobility system.

Case Study 1: New York John F. Kennedy Airport (JFK) Connector System

Known as the "AirTrain" at JFK, this automated rail transit system has been in operation for over 15 years, and it can be classified as a nonsecure airport landside APM system. With a length of 8.1 miles, it connects all the JFK unit terminals that are built and dedicated to specific airlines with the airport rental car facility and hotels located at Federal Circle, as well as an airport long-term parking facility and several different public mass transit systems. At Jamaica Station in Queens, New York, the AirTrain station provides access to Long Island Railroad and the New York City Transit Authority subway lines to Queens and midtown Manhattan. The AirTrain station at Howard Beach provides access to the subway lines to Brooklyn and lower Manhattan. These strategic functional purposes of the AirTrain APM system are illustrated in Figure 12.

The alignment as it was built allows multiple routes to be operated within the terminal complex. The three operating routes include one that is a dedicated terminal circulation route, connecting all terminals together as a nonsecure system. A second route operates between all the terminals, the Federal Circle facilities serving the rental car facilities and a remote landside curb front for airport shuttles, and extends to remote parking on the east side of the airport, as well as adjacent public transit lines. The third operating route is the line that connects all the terminals and the

Federal Circle landside facilities with Jamaica Station. Note that as a traditional APM, the AirTrain operates with on-line stations, requiring trains to stop at every station.

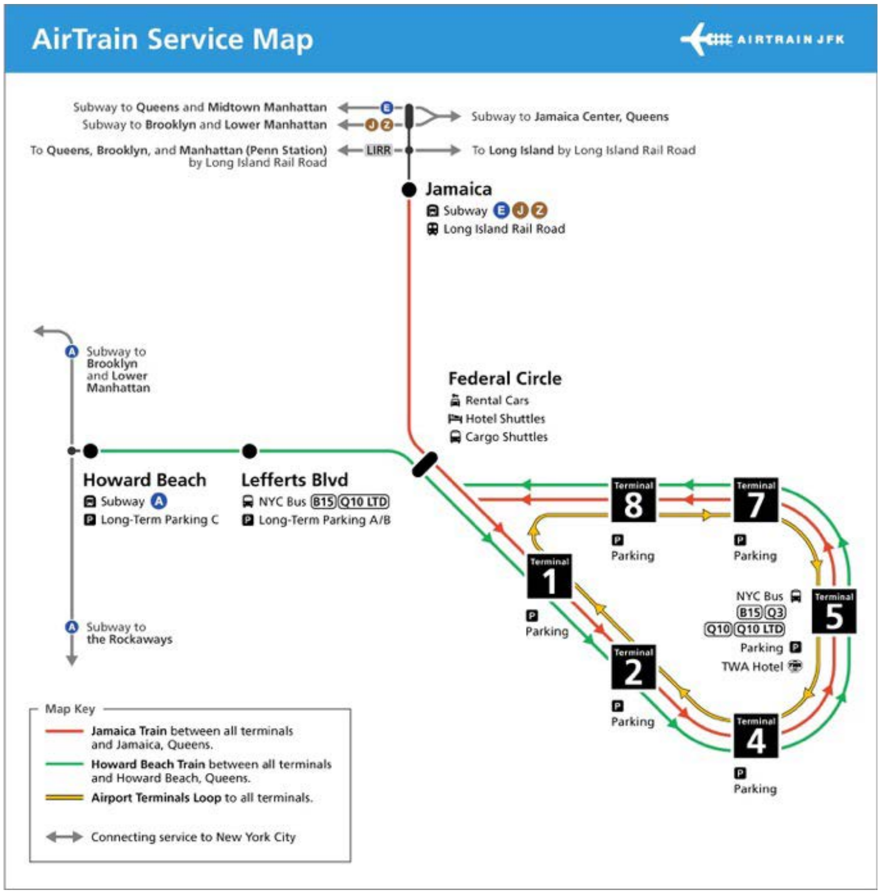


Figure 12. The JFK AirTrain system alignment's functional elements that connect the airport terminal complex with the remote landside facilities.

Source: *John F. Kennedy International Airport. https://jfkairport.com/to-from-airport/air-train*

Case Study 2: Los Angeles International Airport (LAX)

Known as the "Automated People Mover," the LAX APM system started construction in 2019 and will enter passenger service in 2023. The APM system connects three stations in the airport terminal complex that are accessible from all airline terminals with the major landside facilities, all of which are part of the $5.5-billion Landside Access Modernization Program projects (Los Angeles World Airports 2021).

As illustrated in Figure 13, the APM system extends to several major airport landside facilities, including a station at the new intermodal transfer facility. Extending further to the east, the APM connects to the LA Metro LRT system, and then with the remote consolidated rental car facility located adjacent to the I-405 freeway.

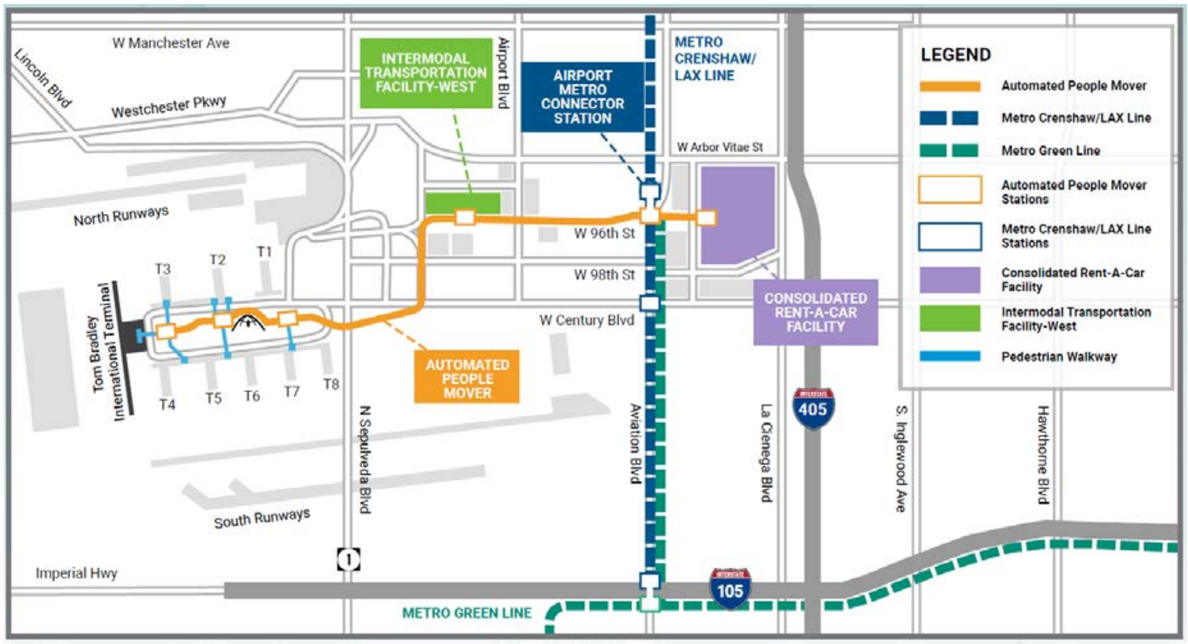


Figure 13. The LAX APM connects the central terminal complex with the remote landside transportation facilities.

Source: LAX. 2021. "Automated People Mover: LAX Quick Facts." https://www.lawa.org/-/media/lawa-web/connecting-lax/lamp-business/lawa_factsheet.ashx.

A major feature of the remote "Intermodal Transportation Facility–West" location is the curb fronts for ride-hailing car services of transportation network companies (TNCs), as well as private automobile drop-off and pickup of air passengers and employees. The Intermodal Transportation Facility curb fronts allow for accessible terminal access without vehicles entering the Central Terminal Complex, substantially reducing the heavy traffic congestion that currently hinders efficient traffic circulation and terminal access throughout most hours of the day.

Both case studies reflect parallel functional aspirations of the DFW objectives for landside nonsecure mobility. As AV technology matures, equivalent functionality based on vehicle-based ATN systems (as opposed to train-based traditional APM systems) will allow DFW to implement a scalable, cost-effective, automated mobility system to address its unique challenges, as well as extend the system as appropriate to remote parking, transportation hubs, consolidated rent-a-car, and other facilities.

Airport Access

Ground transportation access to DFW is accomplished through a range of different modes. The primary access mode at present is via private automobile, which is unsurprising as ground transportation systems both within the airport and in the surrounding region have been designed and built over much of the last century to support private automobiles as a preferred mode in most settings. However, with the advent of automated mobility technologies, shifting practices and social perceptions of mobility will necessitate changes in approaches, which will manifest in many ways and affect the shape of future infrastructure. Separate systems exist to accommodate the ground transportation access needs for different categories as identified previously, including traveler, employee, and service user types. Each of these user types will be affected differently with the emergence of automated mobility technologies. In addition, all user types are increasingly dependent on *wayfinding* technologies—that is, systems to assist users to navigate to destinations and to provide useful information along the way to improve their experiences.

Wayfinding

Though not in itself an automation technology, the conglomeration of technologies embodied within current wayfinding represents parallel endeavors that are integral to the future of automated mobility. Wayfinding technologies initially emerged as tools to facilitate vehicle movement from point to point; they are increasingly being leveraged to assist individual users in a broader spectrum of tasks. The evolution of wayfinding is visible in the increasingly strong connection between informational resources, such as search engines, and the physical world. Wayfinding relates to mobility automation in that it comprises critical components to exchange information between travelers and information systems. As such, wayfinding encapsulates more than just routing tools; it is the networked system of communication linking users, vehicles, and systems at large. Communication of timely, accurate, and useful information is critical in shaping AV options as more convenient and desirable in order to foster behavioral adoption and shifts away from legacy technologies.

Wayfinding Technologies

Airport wayfinding has incorporated new technologies over time. Airports began with simple tools such as static signage and staffed information desks. The digital era ushered in electronic displays appropriate for ever-changing information (such as flight status), interactive maps and kiosks for self-check-in and navigation, and mobile applications. Digital technologies will likely dominate the future of wayfinding. This section focuses on recent influential digital solutions—mobile applications (and the associated problem of indoor positioning) and non-app digital navigation tools such as robot guides.

Mobile Applications

Interest in smartphone apps with airport navigation features has increased in recent years. A mobile app is an attractive option to airports, airlines, and other businesses alike due to the ability to push new updates and utilize a technology that is already in the pockets of most travelers. However, during the stress of navigating an airport and balancing heavy luggage and family members, having to pull out a phone may not always be an attractive option. Despite this, an overwhelming number of mobile applications with wayfinding features exist. Some of these apps integrate multiple aspects of the traveling experience, although few are truly a "one-stop shop." There may be opportunity for applications to extend their services or combine with one another to become an all-in-one app for the full airport travel experience. Existing apps can be divided into three main categories: large private companies (such as Google and Apple), airlines and airports, and other third parties.

Large companies such as Google and Apple have moved beyond exterior navigation and are piloting interior building navigation. Indoor Google Maps launched in March 2021, with airports being one of its primary applications (Google, 2022). To determine which direction the traveler is facing, Google compares the mobile phone's camera image to a database of facility images. The app displays directions superimposed on the camera image (referred to as augmented reality). In April 2021, Zurich Airport partnered with Google Maps and became the first airport to offer indoor live view (Business Traveler India, 2021). Apple Maps is rumored to be working on indoor map navigation as well, but they have not yet launched.

Many airlines and airports have their own apps, with varying wayfinding features. Airlines such as Delta, United, and American Airlines have apps with terminal maps for the airports that they operate in. Airport apps vary between outdated and rarely used, and they utilize Bluetooth low energy (BLE) beacon technology to identify a user's location for targeted content. Some airports and airlines work in partnership with other private companies to develop smartphone apps and deploy indoor positioning technology. The need for travelers to download these individual apps remains a barrier; travelers may be more likely to use an app they have already downloaded, such as Google or Apple Maps.

Indoor Positioning Technology

Electronic location referencing remains a major barrier indoors, and its advancement is crucially linked to the development of smartphone navigation apps. Whereas GPS technology has revolutionized outdoor navigation, no parallel technology has emerged to aid indoor navigation. It remains a challenge for smart phones to know the precise location and trajectory of an indoor user.

Two example approaches to this issue include Google's strategy of scene matching smartphone digital camera images against a database of existing building photos and BLE beacons. The former process requires large resources, and its adoption remains to be seen. Beacons are a more prevalent solution, but must be deployed strategically throughout the environment, cataloged, and the information made available to smart phone applications. Indoor positioning technology has multiple uses beyond wayfinding such as marketing (*i.e.,* pushing coupons to the cell phone of a person walking by a shop).

Until a standards-based method provides ubiquitous indoor positioning (similar to GPS outdoor), indoor wayfinding will likely lag outdoor wayfinding applications in terms of ease of use and full functionality.

Non-App Digital Navigation Tools

There are many digital wayfinding solutions beyond mobile applications such as robot guides, smart carts, and advanced digital signs. Robot guides have been piloted in places such as Japan, South Korea, and Turkey. These robots will use artificial intelligence and profiling capabilities to provide passengers with personalized information such as directions, even accompanying travelers to their gate. They can serve multiple purposes beyond wayfinding, such as security. San Diego's free smart carts work as traditional luggage-carrying carts, but include a screen that show directions to a gate, restaurants, shops, etc. in addition to personalized flight status information and advertisements (Rozario, 2022). Combining wayfinding needs with other passenger experiences such as carrying luggage could be an impactful pairing. The smart carts also address the inconvenience of using a smartphone for indoor navigation. Lastly, Delta Air Line's "Parallel Reality" technology aims to display personalized information on a digital screen to multiple passengers at the same time, and could address the need for signs to be in multiple languages (Delta, 2020). A beta experience is planned for Detroit Metropolitan Airport.

Flexible digital solutions that accommodate changing information and are more convenient to use than a smart phone application may become more prominent. Such solutions may be paired with other technologies such as biometric identification and could involve powerful partnerships. However, clear signage and other simple and traditional technologies remain the backbone to allow for a traveler to seamlessly navigate.

Traveler Access

The majority of DFW groundside access is via light-duty vehicles. For travelers, this is primarily through private automobiles using surface parking lots. As with many airports, TNCs such as Uber and Lyft have been serving an increasing share of traveler groundside mobility needs. An analysis of this behavior and resultant impacts is discussed in the Curb Activities and Management section. Additional access modes include public transit, hotel shuttles, and other options.

Looking toward a future with more automated mobility options, the spectrum of options for traveler movement entails numerous technologies and practices. Initially, the integration of automation will emerge with automated parking valet services. Automated parking valet technology enables a traveler to exit their vehicle at a curb, after which the vehicle will then leave unoccupied to park itself within the facility. Whether this is through built-in proprietary technology in current development among multiple automakers or through third-party offerings, it will be necessary to develop procedures in which a supervisory system is able to communicate with and organize individual vehicles to maintain their parking and charging most efficiently. An overview of anticipated autonomy impacts on traveler access is shown in Figure 14.

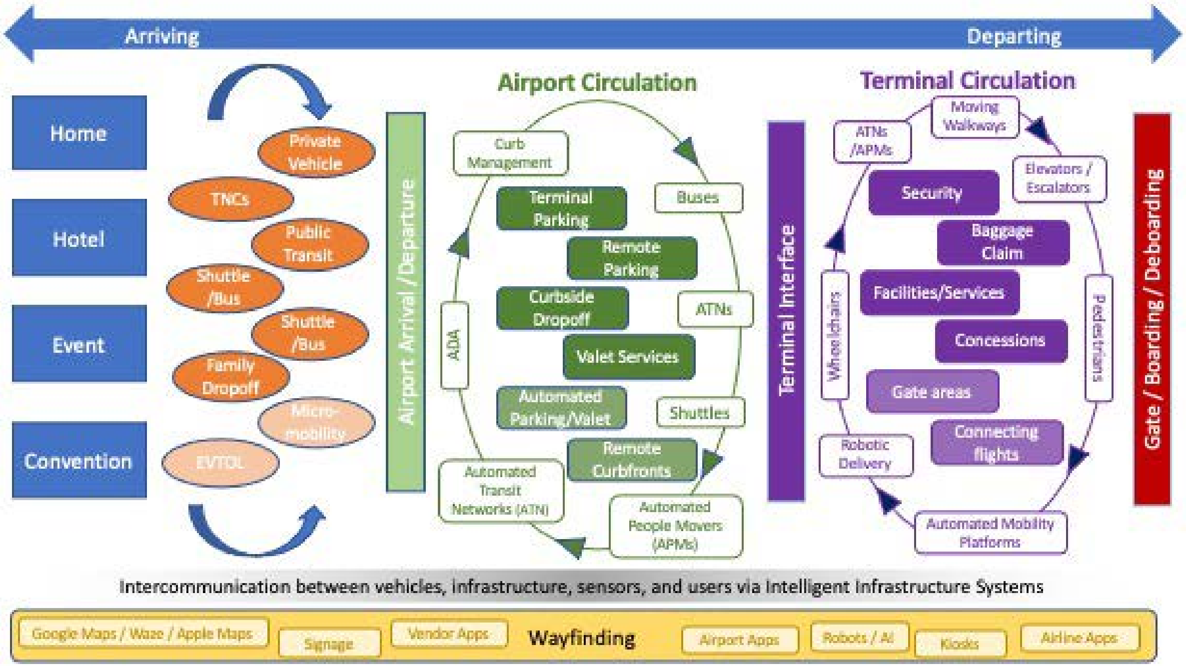


Figure 14. Impact of autonomy on airport groundside access

Additional anticipated future traveler access technologies may include micromobility and electric vertical takeoff and landing (eVTOL) vehicles. Micromobility is relatively low-cost and requires little infrastructure but may afford alternatives to automobiles for traveling short distances or in conjunction with transit. On the other hand, eVTOL service would require air and ground space accommodations, but could reduce ground traffic volume and offer reduced time of access and improved convenience to travelers. While the purpose of this report is focused on groundside access, eVTOL technologies are rapidly advancing, with some iterations being automated to improve efficiency and lower cost by not needing a pilot on board. Therefore, at some level, eVTOL technologies will need to be considered within the context of overall automated mobility.

After arrival on DFW property, travelers move through airport circulation and terminal circulation areas, for which mobility automation is anticipated to play increasing roles. As automated technologies emerge, the mobility options in these areas are likely to adopt automation to improve system efficiency, reduce costs, and enhance the customer experience. These technologies are expected to appear as automated bus, shuttle, and other people mover circulator services on the nonsecure side, and automated mobility platforms, robotic delivery systems, and other autonomous functioning services in the terminal area.

As discussed in the Wayfinding section of this report, providing information and location services to travelers is already a rapidly growing and evolving segment within the overall transportation system. This multidirectional flow of information is expected to improve user experiences for ever-increasing purposes and will become even more vital in airport operations.

Employee Access

Employee commuting accounts for substantial energy and emissions impacts for large organizations as is likely the case for DFW. The primary commute mode for most DFW employees is private automobile, though public transit and pooled rides are available. DFW employees commute from a wide range of ZIP codes located in counties and municipalities within over a 1-hour travel radius around the airport, as shown in Figure 15. However, the densest concentrations of employee residence ZIP codes are proximal to the airport site. Concentrating on the top 20 employee residence ZIP codes (Figure 16) reveals that 43% of employees live in these areas, which may frame strategies to improve the energy efficiency of commutes for these employees.

Many employees park their vehicles at outlying surface parking lots, which are served by employee-only shuttle buses to take employees to their work locations, primarily at the terminals. The shuttle buses run frequently, but the process adds 15 to 20 minutes or more each way to employee commute times. This added time cost of commuting is of concern for employees, who, like most people, have little extra time to spare.

This observation suggests that viable alternative commuting options may be designed, specifically for those ZIP codes proximate to DFW with high concentrations of employee residences. As technology becomes available to provide electric or automated shuttle services between strategic residential locations and DFW, it may be possible to reduce overall commute time for some employees while reducing energy use and emissions toward DFW operational goals.

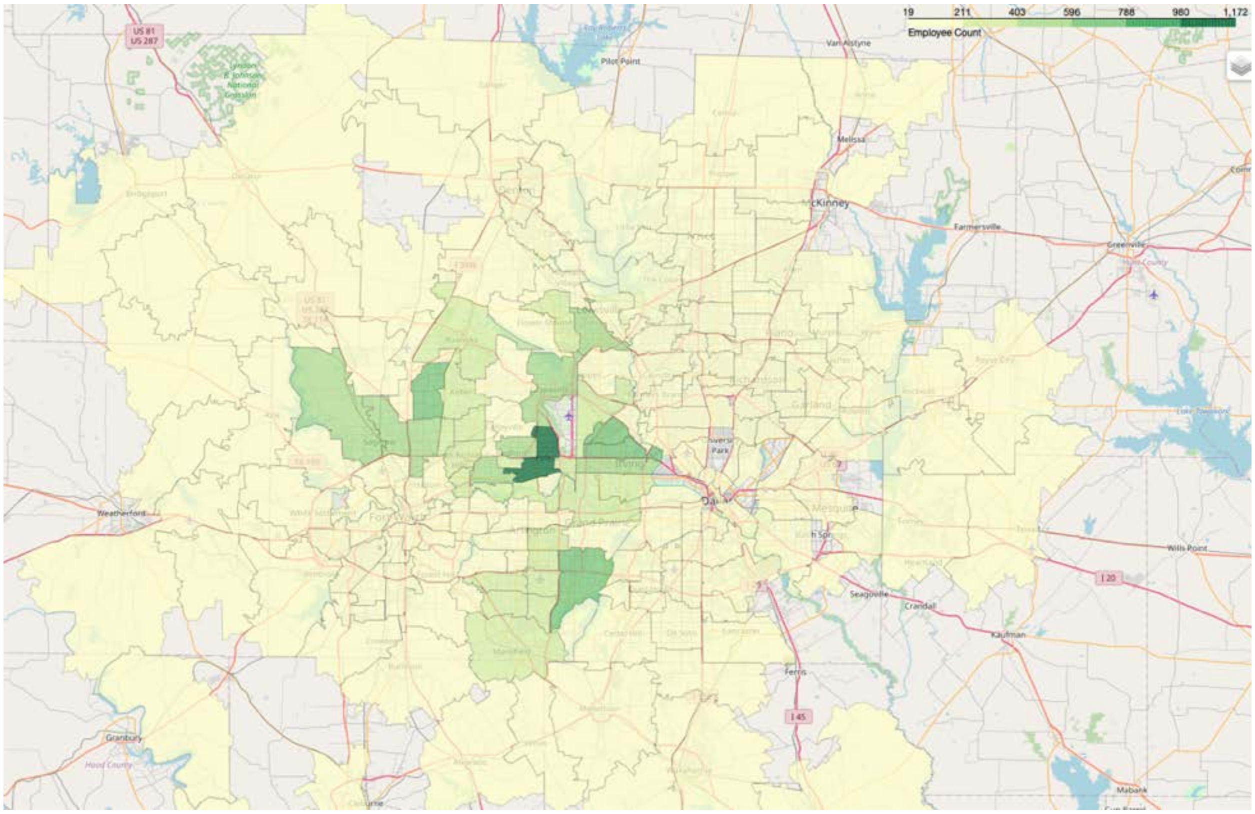


Figure 15. Distribution of residence location of DFW employees aggregated by ZIP code

Figure 16. Top 20 ZIP codes for DFW employee residence locations

Quantifying Airport Employee Commuting and Related Energy Use: A Comparison of Six U.S. Airports

As compared to other large airports for which employee commute data were available, DFW has potential to identify energy-efficient commuting options. Each of the six airports analyzed in Figure 17 was found to have unique spatial distribution; some airports like DFW and JFK (New York) saw a large share of employees within 8 km (5 miles) of the airport, while other airports like ATL (Atlanta) and LAX (Los Angeles) saw the largest share of employees residing more than 32 km (20 miles) from the airport. DEN (Denver) and LGA (LaGuardia) saw a more even distribution of employees living closer to and farther from the airports.

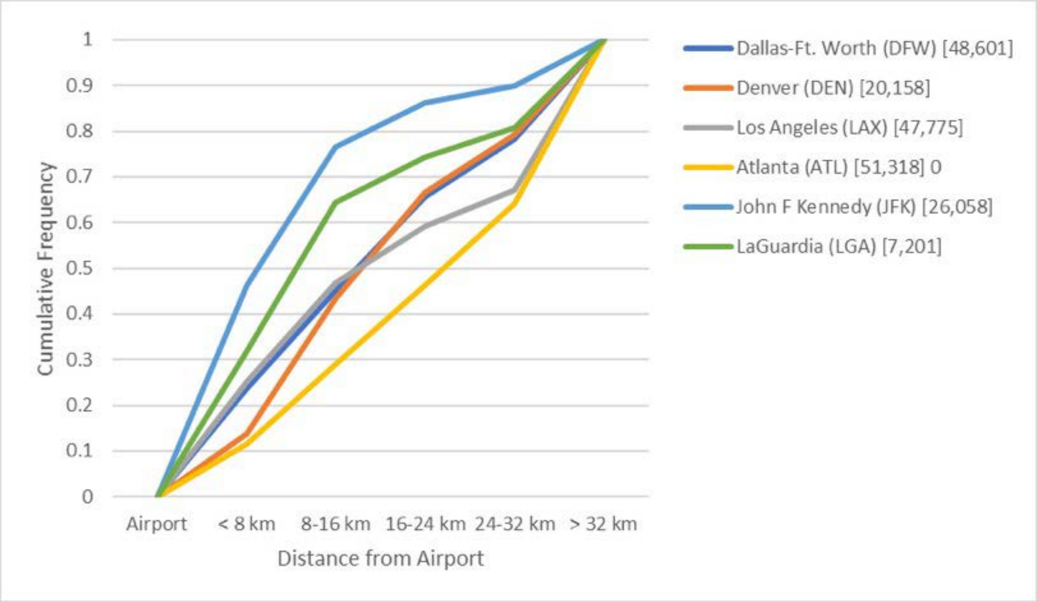
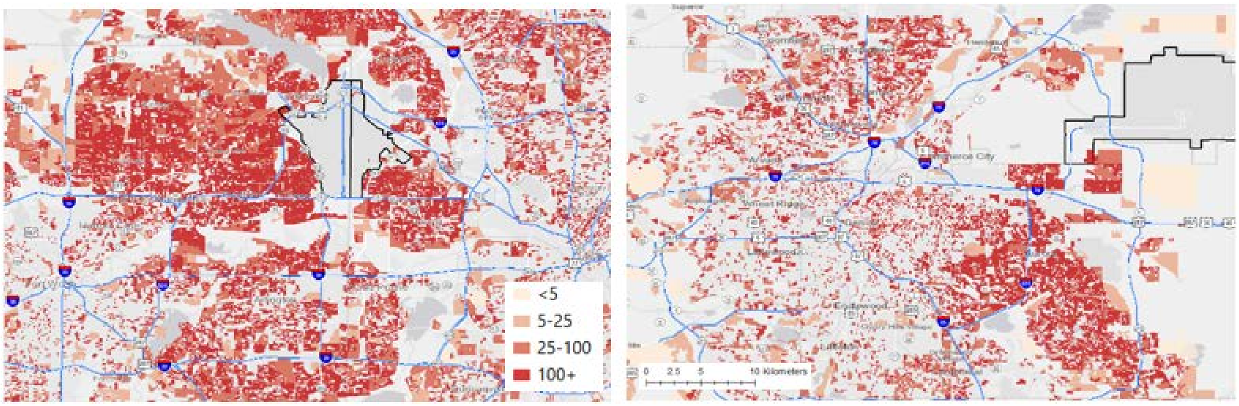


Figure 17. Cumulative frequency distribution of airport employees, with total number of employees in brackets in the legend.

Note: The city median commute distances (in kilometers) are from *The growing distance between people and jobs in metropolitan America*, Kneebone and Holmes (2015) https://www.brookings.edu/wp-content/uploads/2016/07/Srvy_JobsProximity.pdf.

In Figure 18, data collected by the U.S. Census Bureau were used to estimate employee commuting VMT to generate origin-destination maps for analysis (US Census Bureau Center for Economic Studies n.d.). The analysis revealed that DFW, as compared to Denver International Airport as a comparable large facility, has a higher concentration of employees who live nearer to the airport, further supporting the idea that offering sufficiently favorable commute options to targeted locations could result in net energy savings and potentially reduced commute times.



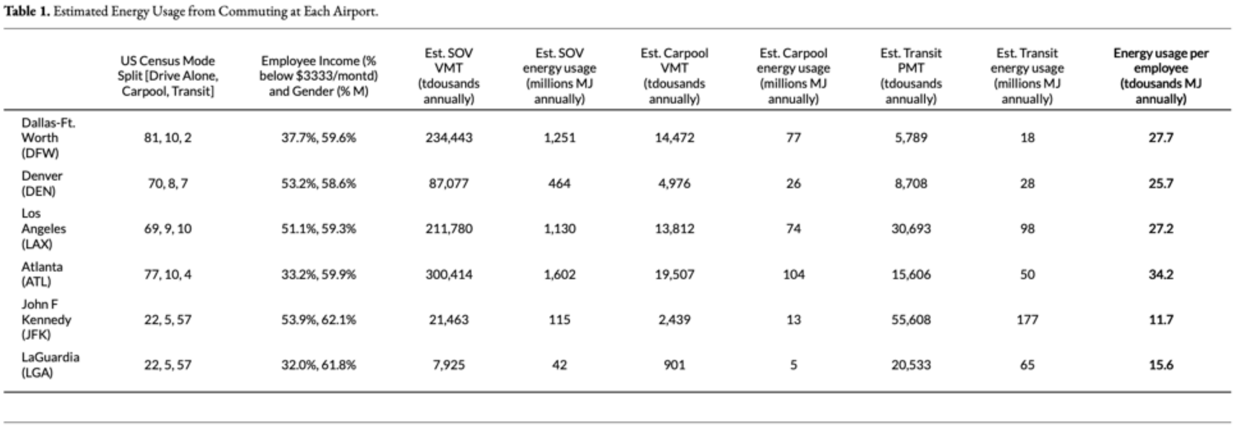


Table 1. Estimated Energy Usage from Commuting at Each Airport.

	US Census Mode Split [Drive Alone, Carpool, Transit]	Employee Income (% below $3333/montd) and Gender (% M)	Est. SOV VMT (tdousands annually)	Est. SOV energy usage (millions MJ annually)	Est. Carpool VMT (tdousands annually)	Est. Carpool energy usage (millions MJ annually)	Est. Transit PMT (tdousands annually)	Est. Transit energy usage (millions MJ annually)	**Energy usage per employee (tdousands MJ annually)**
Dallas-Ft. Worth (DFW)	81, 10, 2	37.7%, 59.6%	234,443	1,251	14,472	77	5,789	18	**27.7**
Denver (DEN)	70, 8, 7	53.2%, 58.6%	87,077	464	4,976	26	8,708	28	**25.7**
Los Angeles (LAX)	69, 9, 10	51.1%, 59.3%	211,780	1,130	13,812	74	30,693	98	**27.2**
Atlanta (ATL)	77, 10, 4	33.2%, 59.9%	300,414	1,602	19,507	104	15,606	50	**34.2**
John F Kennedy (JFK)	22, 5, 57	53.9%, 62.1%	21,463	115	2,439	13	55,608	177	**11.7**
LaGuardia (LGA)	22, 5, 57	32.0%, 61.8%	7,925	42	901	5	20,533	65	**15.6**

Figure 18. Density of employee origins (employees per square kilometer) by census block for DFW and DEN (Denver)

Note that assumptions for mode split based on each region were applied, including estimates for carpooling and transit. Using these baselines, scenarios could be modeled to identify impacts of a potential 15% increase in transit use or carpooling. For example, with mobility automation advances, new choices for transit, including right-sized, on-demand, or express to local options, public mobility variations may be devised to leverage emerging technologies to provide better, cheaper, and more desirable service.

Future considerations, with inputs from DFW, may include delivery of workers to specific employment locations within DFW facilities or work-related transportation patterns while on duty. Overall, the aim for this analysis is to identify potential opportunities for energy and emissions savings via telework potential, reducing employee travel time and adding comfort and convenience for the increased use of sustainable alternative modes to single-occupancy driving. In addition, metrics can be used that show how various scenarios might improve mobility energy productivity, as well as improved equity of access to mobility options and destinations.

Service and Goods Delivery at the Airport

In addition to the movement of people, whether as travelers going through the airport facility or as employees commuting to work locations, the movement of vehicles for the purpose of providing services or delivery of goods is a facet of groundside transportation at DFW. In the context of automated mobility, current advancements in technology may find earliest application in roles where human passengers are not involved, as concerns for passenger safety are reduced.

On the ground support for air operations side, DFW is host to a pilot demonstration project using an automated tug supplied by TractEasy/EasyMile as initial exploration. This pilot project has the capacity to inform service and goods delivery at DFW, in that automated movement and distribution of materials may have similar use cases.

Many of the same technologies identified for moving people are relevant to the movement of services and goods. However, logistics for goods delivery is simplified as compared to moving people. The movement of goods greatly benefits from a supervisory system to ensure delivery when and where needed, necessitating development of intelligent infrastructure systems (IIS) to more seamlessly manage the flow of goods (such as food, beverages, parts, equipment, and other service items) where and when they are needed. An automated supervisory management and control system can help schedule delivery shipments within DFW facilities to take advantage of off-peak times, increasing system efficiency through reduced congestion. Sensors embedded in infrastructural elements can generate data to identify the stock status of goods supplies, generate orders, and move products from warehouse locations to where they are most needed.

Some of the most advanced examples of automated goods movement operations at present are at large order fulfillment centers, operated by such companies such as Amazon and FedEx. Many of these systems have achieved a high degree of automation, and though the parameters of these operations differ from the airport setting, much can be learned by exploring the efficiencies built into these systems, where unnecessary movements are eliminated, and just-in-time delivery keeps stock levels consistent.

Curb Activities and Management

Curb space activity at airports is highly complex, and with limited physical space, active management of curb resources is critical as technologies and practices dependent on access to curb space rapidly evolve. Before the pandemic, cities across the United States and globally were experiencing substantial transformations in urban mobility, catalyzed by communications technology enabling shared use. Among the largest changes in urban mobility is ride-hailing—services managing ride requests and available vehicles operated by TNCs such as Uber and Lyft—which quickly gained market share and generated operational and behavioral responses.

Airports, generally sub-jurisdictions to cities and primary mobility hubs, were also seeing impacts on curb space activities resulting from increases in air travel demand and changes in ground transportation for travelers arriving and leaving airports in the years leading up to 2019. Several dynamics occur when it comes to managing the curb, especially given the limited curbside space at the terminal and additional ground transportation infrastructure (e.g., parking and car rental facilities). The main two factors impacting ground transportation are the number of people arriving/leaving the airport (e.g., air travelers and airport personnel) and the ground transportation mode used to travel to/from the airport.

Airports have traditionally been proactive when it comes to managing the infrastructure for ground transportation such as parking, the curb front, and charging fees for using this infrastructure. For example, airports typically charge fees to commercial services accessing the airport curb front. Initially, ride-hailing did not have to pay for accessing the airport curb front since they were mixed with private vehicles, but once the increase was noticeable, airports started implementing a TNC fee. The generated revenue from the ground transportation fees in conjunction with other data sets provided a data trail and the ability to quantify initial key changes of new mobility options.

Studies conducted using data resources outside of DFW evaluated the following research questions:

- What is the trend for airport passengers for the years prior to the pandemic?
- How is revenue from ground transportation trips to and from airports affected after the introduction of ride-hailing?
- How is the uptake of ride-hailing associated with new distributions in mode share and mode choices for ground transportation trips to and from airports?

All these questions are explored with the intention to inform additional plausible changes with the introduction of future AVs.

The emerging impacts of ride-hailing and AVs is an area of increased attention for airports. This analysis presents observability of ride-hailing trends and new service adoption in city airports, impacts on revenue change, and travel mode shifts (e.g., impacting parking and car rentals) to inform future travel demand and curb management strategies.

Comparative assessment of the benefits and losses resulting from new mobility patterns helps airports and cities better understand needs with data, technology upgrades, and infrastructure modernization (e.g., of curb management and parking) to continue data collection, monitoring, analysis, experimentation, and evaluation, all of which can result in best practices as a transportation management authority.

Data and Approach

This study analyzes the changes in airport passengers and revenue from ground transportation at six U.S. airports around the introduction of ride-hailing. The study first analyzes baseline annual air travel, then examine the revenues from parking. The data are primarily from each of six regional airports: Austin, Dallas, Denver, Kansas City, Portland, and San Francisco.

The data analyzed in this section were collected outside of the primary activities supporting this report, and it is proposed that similar methods be used on a regular basis using internally available DFW data for ongoing perspective and increased accuracy specific to DFW. Data for this initial comparison were sourced from the Seattle-Tacoma and Denver airports from January 2013 to December 2018 and include:

- Airport passengers (enplaned and deplaned) collected from the airports.
- Transactions for parking, car rental, taxis, and ride-hailing collected from the airports.
- Transit transactions collected via the local public transportation authority (Sound Transit for Seattle-Tacoma and the Regional Transportation District for Denver).

Uber and Lyft started operations of their most popular services (UberX and regular Lyft) in the Seattle metropolitan area in April 2013. The Seattle-Tacoma (SEA) airport began implementing a TNC fee for pickups and drop-offs (collecting revenue from ride-hailing transactions) in April 2016. Uber and Lyft started operating in the Denver metropolitan area in October 2013, and Denver International Airport (DEN) started collecting ride-hailing fees in November 2014. To account for the gap in data on TNC use prior to initiating the airport fee transactions, we estimated the initial airport TNC use by regressing the data collected assuming a fitted TNC exponential growth per month.

Since airport travel has a lot of seasonal variability, a 12-month moving average is used for each month by combining passenger data with five ground transportation modes where the transaction rate per airport passenger for each mode can be obtained.

While the data and analyses are consistent across all five modes for both airports, limitations remain, including the lack of data to exactly calculate the mode share at each airport (e.g., number of air passengers per transaction or vehicle occupancy; number of employees and contractors at each airport; number of air passengers connecting flights; parking in the vicinity of the airport; other ground transportation modes such as pickup/drop-off by a private vehicle, and special shuttles services).

Findings

Airport Passengers and Parking Revenue Trends

For U.S. cities with large regional airports—such as Austin, Dallas, Denver, Kansas City, Portland, and San Francisco—the number of recorded airport passengers raised steadily (Figure 19), from approximately 181 million in 2011 (total annual passengers for all six airports) to approximately 226 million in 2017. This represents an annualized growth rate of 3.4% for these six airports, with a doubling time of approximately 2 decades (even faster than global air travel demand projections). In 2019, air travel represented over 9% of total U.S. transportation energy use (Energy Information Administration, 2021), with a 567% increase (from 309 to 1,752 petajoules) in jet fuel and aviation-related gasoline consumption from 1960 to 2015 (Henao, et al. 2018).

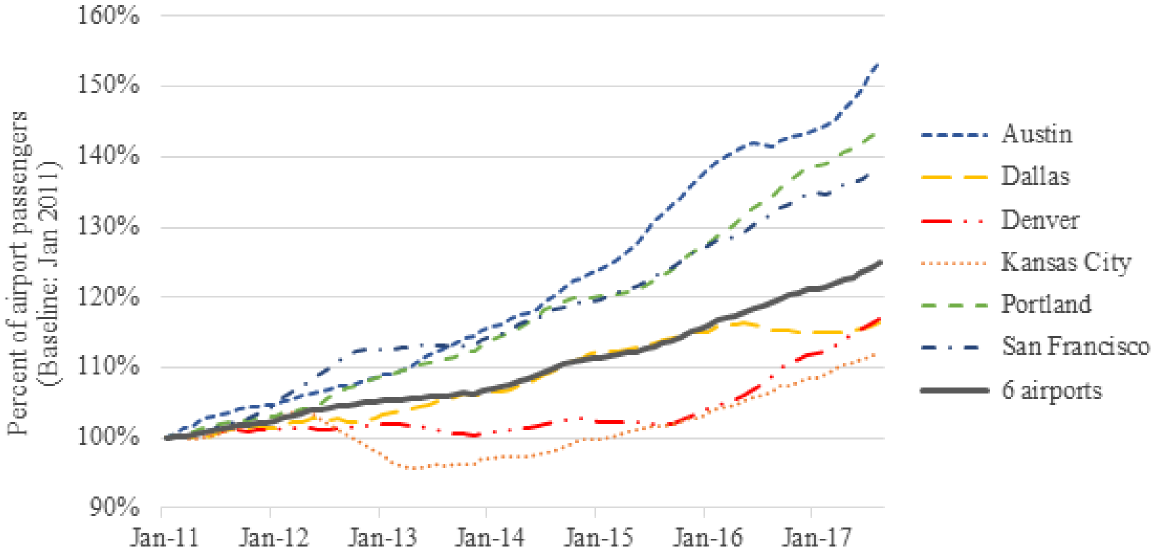


Figure 19. Airport passengers.

Total airport passengers = enplaned + deplaned. All airports are indexed to January 2011 as a baseline (100%). Each month is a 12-month running average. All airports except for Kansas City have mass transit service.

Revenues in airport parking no longer follow the same trend as airport passengers (Figure 20). Rather, parking revenues per passenger peaked approximately 12 to 24 months after introduction of ride-hailing, and steadily declined thereafter. Findings from the six airports show an annualized declining rate range of 3% to 7%; continuing this trend would mean that parking demand rates at airports could be cut in half in about 14 years. This rate of decline is on par with the increase in ride-hailing use and growth in the number of airline passengers. On one hand, this can be viewed as a declining revenue base, yet on the other, it may allow airports to continue to grow without investing in additional parking infrastructure or to consider repurposing existing land for other uses.

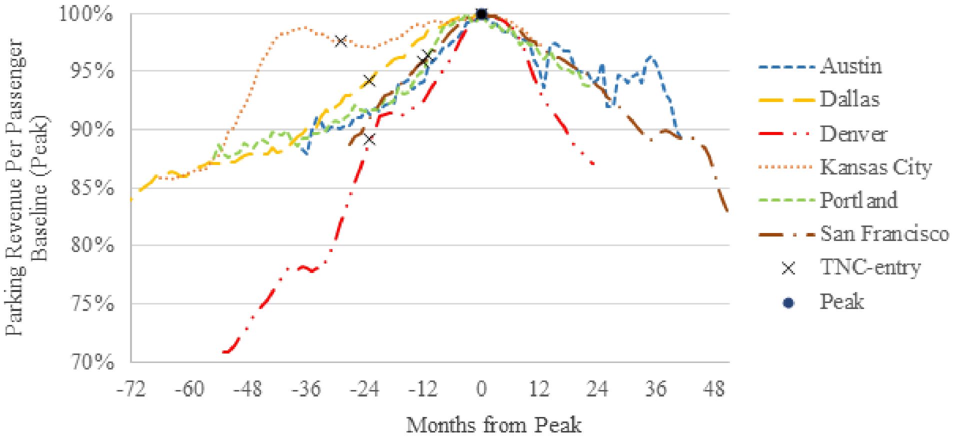


Figure 20. Parking revenue per passenger.

Data are indexed to peak (100%); each month is a 12-month running average.

Ride-Hailing Uptake and New Distributions in Mode Share

Further exploration with more detailed ground transport data for the Seattle-Tacoma and Denver airports from January 2013 to December 2018 shows a significant uptake on ride-hailing while all other modes declined (Figure 21).

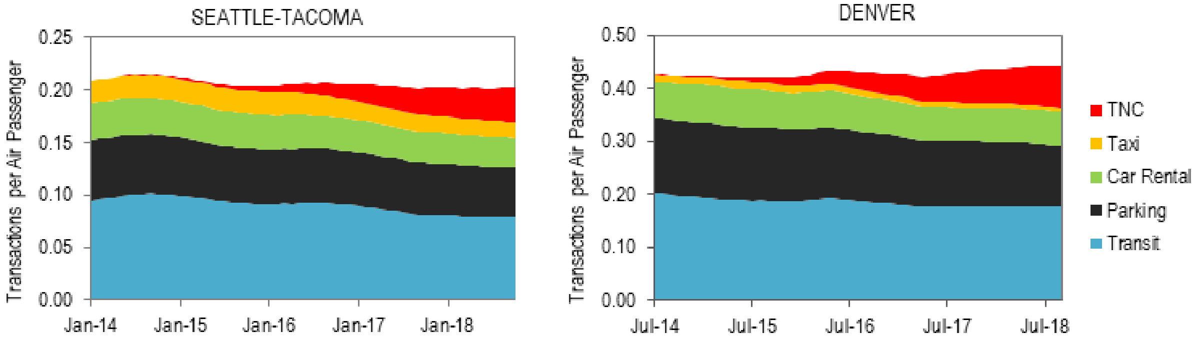


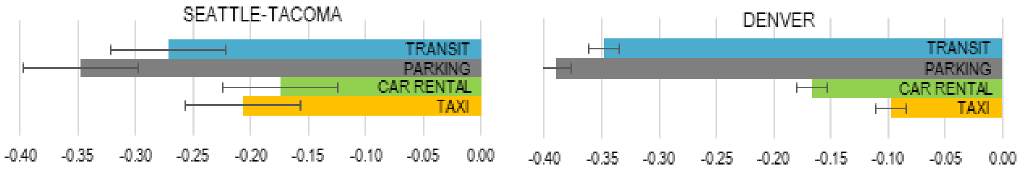
Figure 21: Distribution of ground transportation transactions per mode at Seattle-Tacoma and Denver airports

In Table 1, the results from analysis of mode replacement are shown as the number of transactions per mode after ride-hailing introduction. The results indicate that during the study period, for every 100 new TNC transactions for ground transportation to and from the Seattle-Tacoma airport, approximately 27% replaced transit trips, around 35% replaced parking trips, 17% replaced car rental trips, and 21% replaced taxi trips. Similarly, at the Denver airport, ride-hailing transactions replaced transit trips, parking trips, car rental trips, and taxi trips at 34.7%, 39.0%, 16.6%, and 9.7%, respectively. These first statistical regressions aim to help predict the change in the number of transactions for four existing modes (transit, driving/parking, car rental, and taxis) after ride-hailing uptake. For example, for every three ride-hailing trips, roughly one parking space may no longer be needed at airports.

Table 1: Change in Mode Share (Transit, Parking, Car Rental, and Taxi) per TNC Addition

Mode (SEA)	Estimate	Pr (>|t|)		95% Confidence Interval	
Transit	−0.2714	<2e−16	***	(−0.3226	−0.2201)
Parking	−0.3483	<2e−16	***	(−0.3995	−0.2970)
Car rental	−0.1739	9.35e−11	***	(−0.2251	−0.1226)
Taxi	−0.2065	2.75e−14	***	(−0.2578	−0.1553)

Mode (DEN)	Estimate	Pr (>|t|)		95% Confidence Interval	
Transit	−0.3475	<2e−16	***	(−0.3610	−0.3340)
Parking	−0.3896	<2e−16	***	(−0.4031	−0.3761)
Car rental	−0.1658	<2e−16	***	(−0.1793	−0.1523)
Taxi	−0.0971	<2e−16	***	(−0.1106	−0.0836)



Discussion and Conclusions

Before the pandemic, there were clear signals on the following fronts for several airports: (1) increase in air travel passengers, (2) changes in ground transportation revenues (i.e., peak and reduction of parking revenues on a per-passenger basis), and (3) shifts on the distribution of ground transportation transactions per mode, especially with the introduction of ride-hailing.

Since ride-hailing uptake has unique, context-specific impacts on mode share for ground transportation trips to and from airports, as well as potential shifts in other modes, there needs to be caution with replicating the city- or airport-specific factors identified in the results. For example, Seattle and Denver both may have a higher quality of airport transit service compared to most U.S. airports. In addition, a new rail line to the Denver airport opened in April 2016, which may also have confounding effects.

A future hypothesis could explore that any additional proportional (negative) change in mode for transit, in terms of impacts from ride-hailing, could be confounded by relative existing transit quality and/or ease of ground access for transit and TNC at airports. For example, an area with “good/healthy” transit may lose less share (proportionally) compared to an area with “bad” or lower-quality transit. Additional data at an airport like DFW with a different quality of transit service and different connectivity at the terminal (e.g., curb front vs. garage) may help to test this hypothesis.

While travel demand models typically use travel cost and travel times in the utility function, most lack a full range of characteristics and real-world data even within these two variables (e.g., parking cost, parking time). Airports are unique since the access and egress to airports and their terminals as multimodal connections include individual mode characteristics for additional monetary cost and time.

Real-world data are therefore critical to evaluate specific context and inform modeling methods and assumptions. The utility value of monetary cost, travel time, and terminal access/egress time through travel surveys at the individual level (across different demographics) may all be key predictive factors to further explore mode share changes, utility function, and mode choice modeling methods at airports. At the high level, replicating this analysis at an airport such as DFW requires the following specific data (both pre-pandemic and currently):

- Air travel passengers (including enplaned, deplaned, and connecting) and employees.
- Transactions and revenue for ground transportation modes including but not limited to parking, car rental, taxis, TNCs, shuttles, buses, and public transportation.
- Additional policies, infrastructure, and design changes in ground transportation.

A similar analysis conducted at DFW will help plan the next steps for decision makers when it comes to curb management. The anticipated growth in air travel passengers and the shifts to new modes such as ride-hailing and AVs need to be coupled with policies aiming at giving a higher value to the ground transportation modes that are more efficient in moving people with a limited curb space. This includes improving the quality of service for public transportation at the terminal (e.g., frequency of transit and location of station at DFW) given curb space priority and capacity for vehicles with multiple passengers (i.e., high-occupancy vehicles), new terminal design and configuration at the curb, and additional monetary (i.e., discounted cost for high-occupancy vehicles using the curb) and non-monetary incentives (i.e., priority with security screening).

Roadmap Decision Points and Potential Outcomes

Integration and Alignment: Building Upon Other DFW/NREL Studies

The progression toward mobility automation at DFW requires specific decisions to be made and actions to be taken along the way to ensure that automation processes are supported. Past analysis methods were tailored to DFW for determining the relative importance of different factors. Data/inputs for more quantitative bounding analysis, with assumptions where needed, were based on stakeholder engagement using Delphi survey methods of local expert opinion. The decisions and actions intersect with other processes in progress, including efforts supporting increased sustainability and resilience in operations at the airport, some of which are also focal points of NREL research work. These include:

- Athena digital twin effort, building upon data sets/analyses already available.
- Coordination with the DFW Innovation, Planning, and Environmental Affairs teams.
- Conceptualization of a larger EV blueprint for DFW.
- Terminal C Deep Retrofit team.
- Pilot automated parking valet project recently awarded through an NCTCOG opportunity.

Relationship Between Mobility Autonomy and Electrification

A key connection between the roadmap to autonomy effort and other aligned work includes vehicle electrification and charging systems. Automated vehicles are not necessarily electric, but a coevolution between AV and EV technologies is strengthening, in part because of opportunities to simplify automated management of EVs through AV and connected technologies.

Resilience, Flexibility, Adaptability, and Innovation

The ability of DFW to maintain operations in changing environments and in the face of challenges—like the increased frequency of extreme weather events and health/social disruptions as part of the global pandemic—is of vital importance to integrate into planning and practices. Mobility automation supports improved resilience by reducing dependence on human drivers and labor-intensive systems, and by adding flexibility to maintain and scale mobility functions as needed. Automated mobility, including the automation of system management, reduces energy expenditure through improved efficiency, and subsequently reduces costs while continuing assurance of customer reliability. Parallel efforts jointly coordinated between DFW and NREL will focus on key social, ecological/climate, and infrastructural components for which automated mobility systems are integral components.

DFW is integral to the function of the metropolitan area and the highest-profile gateway into the community. As such, transportation entities in the region look to DFW as a guide in the advancement and adoption of emerging mobility technologies and practices. It is in this function that DFW serves as a regional mobility innovation hub for sustainability and acceleration of decarbonization. This stature as an innovation leader requires DFW planning to consider a range of potential outcomes, including the future of long-distance travel, the possible impact of intercity AV trips on air travel, and factors to promote low-greenhouse-gas travel, whether through technology or behavior.

It is within this environment of interconnections between technological advancement and behavioral response that DFW must take an iterative planning approach to navigate the emerging landscape. Figure 22 illustrates the complexity of relationships and dependencies with considering milestones of advancement from the present to possible future outcomes.

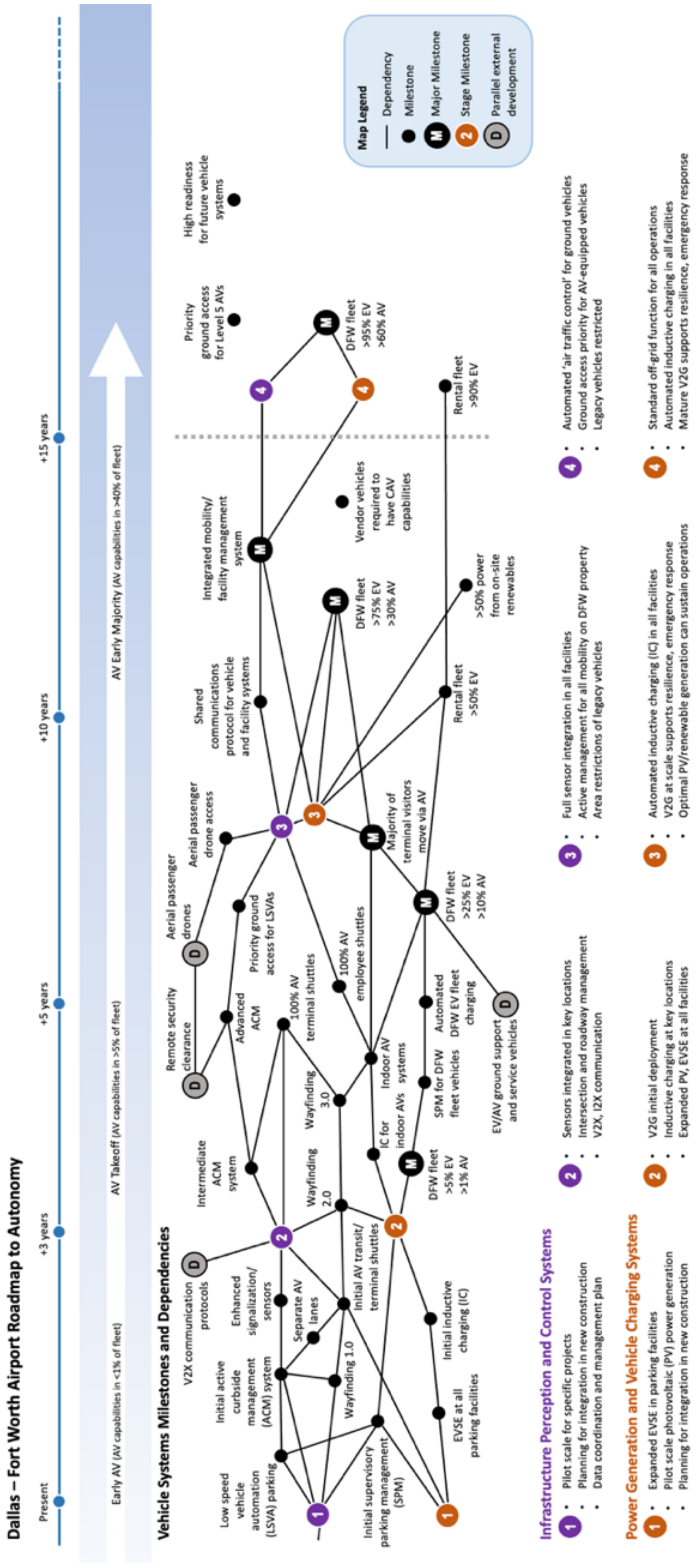


Figure 22. Dependencies and relationships of mobility automation advancements

Key Decision Points

Though anticipating pathways to mobility automation in precise order over the course of the next couple of decades is a daunting task, some key decisions made early in the process can set the process on a favorable track. These key decision points are crucial to supporting long-term planning with empirical data and information derived from research and practice. An overview of recommended key decision points within the first 3 years is highlighted in Figure 23 and outlined in the following subsections.

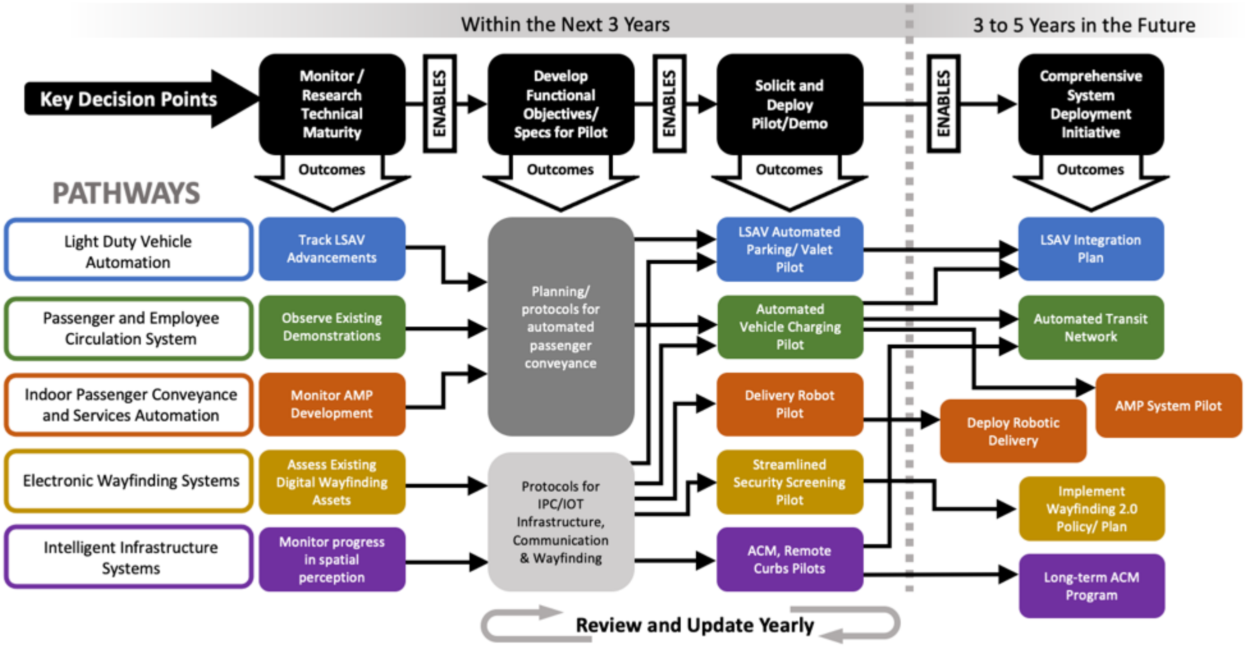


Figure 23. Key decision points on the roadmap toward mobility automation

Initiate Data Collection/Analysis Plan

A first step in the roadmap toward automated mobility future outcomes is to identify and compile data resources to support potential applications. This requires developing plans to collect and analyze relevant data for informing policies and practices that enable automation. Supporting this decision point is key for meeting initial milestones along the recommended pathways, as outlined in the next section of this report. Specific data collection items of focus include but are not limited to:

- Data regarding curbside activities, including TNCs, parking revenue, and other opportunities.
- Tracking advancements in automated passenger demonstration projects, such as LSAVs and automated mobility platforms.
- Monitoring wayfinding systems advancements.

Develop Protocols for Autonomous Application

In conjunction with tracking relevant projects, and informed by data analyses, the development of policy protocols for autonomous applications is a second key decision point. It is common for mobility technology advancements to outpace policies, in which case timely application of these advancements can be delayed when policies fail to adequately accommodate for their emergence. With comprehensive protocols in place governing potential AV application in many contexts, progress toward long-term goals may be ensured rather than delayed. This requires proactive formation of policies before they are needed, using available data and analysis for AV application to form the basis of AV policies, in anticipation of emerging technologies. Conversely, dependence on developing one-off approaches to approve AV pilot projects will also result in slow progress. Instead, AV protocols and policies should be envisioned to encapsulate new technologies as they come online.

Along with policies to support core AV technologies is the need to develop policy protocols for the communication architecture integral to automated vehicle movement and automated systems management. This is a first step toward a supervisory management system as part of an overall intelligent infrastructure system.

Major groupings within AV-supportive policies may include:

- Protocols for automated passenger vehicle systems.
- Protocols for infrastructure perception and control (IPC)/IoT infrastructure, communication, and wayfinding.

Actively Deploy Pilot-Scale Projects

Following the first two key decision points is a decision point to support active deployment of pilot-scale projects. Pilot projects are vital to understanding practical application of new technologies and, through iteration, derive more refined plans to inform eventual broader deployment. Much can be gleaned by observing deployments at other locations, but it is only through local practice at DFW that specific contextual parameters of pilot projects in application may be learned. Pilot projects serve as foundational building blocks toward longer-term AV goals and will be instrumental in developing an AV-supportive comprehensive infrastructure plan. Anticipated pilot-scale projects include:

- LSAV automated parking/valet pilot.
- Automated vehicle charging pilot.
- Delivery robot pilot.
- Streamlined security screening pilot.
- Active curb management (ACM), remote curb pilots.

AV-Supportive Comprehensive Infrastructure Plan

Each of the preceding key decision points is framed at being of focus within the first 3 years. These initial decision points culminate toward a key decision point targeted for the 3- to 5-year time frame, described as an AV-supportive comprehensive infrastructure plan. Note that it is important to revisit each of the decision points and related milestones/outcomes frequently, suggested on an annual schedule, so as to incorporate anticipated developments in technology as they emerge. It cannot be understated that this is a time of rapid evolution for automated technologies, and much can occur in a short time frame, necessitating course corrections.

Creating an AV-supportive comprehensive infrastructure plan is an iterative process, and the plan should be thought of as a living document that will receive ongoing revision and refinement. Facets of the overall plan include topical areas encapsulating but not limited to the following:

- LSAV integration.
- Automated transit networks.
- Automated mobility platform system.
- Robotic delivery system.
- Advanced wayfinding plan/strategies.
- Long-term ACM plan.
- Intelligent infrastructure system.

Recommended Roadmap Pathways

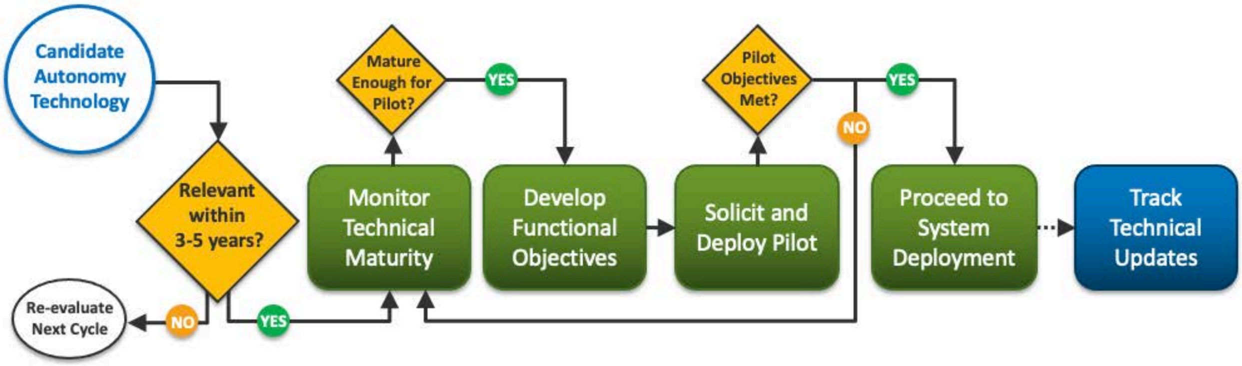
The mobility space is changing rapidly with the confluence of automated and electric vehicle technology and the interconnectivity enabled by connected devices and the Internet of Things, combined with ever-increasing communication channels between travelers, commuters, and systems. The conclusions in this report are laid out in pathways that follow the main technological themes from the report. Emphasis is placed on near-term activities, framed as 0–3 years and 3–5 years into the future, that will prepare and/or posture DFW to plan for and leverage advancements, technology, and autonomy in ground access mobility to the advantage of the airport and its customers. This top-level planning report for the impact of autonomy on DFW landside access and circulation should be revisited on a periodic basis, perhaps once every 1–3 years, as the underlying technology advancement and societal adoption of such technologies is constantly in flux.

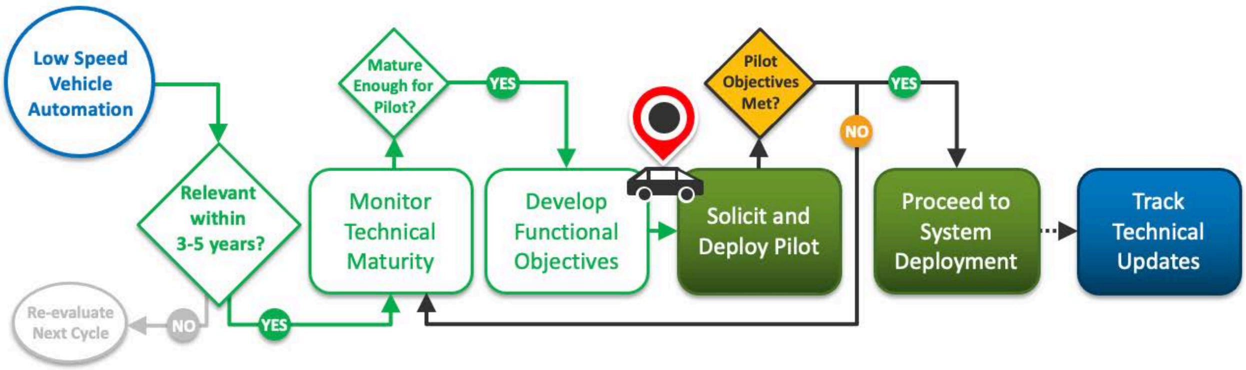
DFW Roadmap Pathways

Below are topical pathways identifying milestones, capabilities, and interconnections, as is illustrated via anticipated timelines. For each pathway, steps along the way are enumerated in logical time sequence, with emphasis on near-term (0–5-year) milestones and suggested actions. Although presented as distinct, these pathways may intersect, share milestones/dependencies, or be interdependent with other pathways. Evaluation of the progression along pathways is assessed using the following characterizations with respect to societal and/or behavioral adoption of technologies, whether electrification, automation, or other aspects, as an indication of state of technology penetration.

1. Innovators and early adopters (<5% market penetration).
2. Takeoff stage (eclipsing >5% and up to 10% market penetration).
3. Rapid uptake (≈10% to 40% market penetration).
4. Early majority (>40% market penetration).
5. Late majority (>60% market penetration).
6. New paradigm (sustained >75% market penetration).

Each of the candidate technologies is evaluated as progressing along the roadmap pathway:





Pathway: Light-Duty Vehicle Automation

This pathway refers to the availability and adoption of various levels of vehicle automation technology and associated services for light-duty vehicles to be in common use by the general public. This includes both the traveling public (customers of DFW) accessing the airport and employees as regular commuting practices. Vehicle automation in the near term includes ever-advancing capabilities for vehicles to automatically navigate, park, and be summoned by owners, as well as services that incorporate such advances. Vehicle automation is in the "innovators" stage, meaning less than 5% adoption (indexed to Level 3 autonomy as measured by SAE). Manufacturers have fledgling products on the market with varying degrees of automation, but such features are largely luxury or specialty options and represent only a very small portion of the overall market at present. Near-term automation features, specifically those associated with low-speed operations such as automated parking, automated valet, and charging (for electric vehicles), have the potential to substantially change traveler or employee expectations for accessing the airport.

Within the next 3 years

Advancement of LSAVs will enable automated parking and automated valet to rapidly evolve. Vehicles will have initial capability for automated parking (pulling into and out of a parking stall) and auto-valet maneuvers (allowing the driver/owner to exit at the curb front, and the vehicle subsequently navigates to a parking stall). Auto-valet may interface with a supervisory parking management (SPM) system for assigned parking location or associated services such as vehicle charging, cleaning, etc. Several industry suppliers are already building and licensing such technical capability for simple auto-parking capacity, as well as the capability to interface with an SPM system; however, all is in embryonic stage, and no industry standards or common interfaces have yet emerged. Advances in LSAVs that allow vehicles to self-park, provide electronic valet, enable automated charging, and even reposition vehicles for convenient reconnection with passengers have strong potential for significant impacts and opportunities at DFW, specifically leveraging vast parking reserves and dominant use of private vehicles for airport access.

LSAV technologies are expected to progress from a nascent level toward the innovator and early-adopter stage. Combined with EV adoption and standardization of inductive charging, automated charging is anticipated to appear, though likely in a very early market stage.

Recommended Actions

Monitor LSAV maturity through periodic assessment of industry capability and product capability, beginning immediately, to both determine the technology capability and refine the anticipated time frame for auto manufacturers to deliver LSAVs at scale.

Sponsor a pilot study (currently under consideration with NCTCOG) to demonstrate LSAV functionality and services integrated with SPM and ACM—see the intelligent infrastructure pathway. This will lead to a functional understanding of impacts and a deployment framework to leverage LSAV capabilities for DFW.

Years 3–5

LSAVs for fleet operations (such as rental cars) are anticipated to enter innovator adoption phase, perhaps reaching takeoff stage by year 5 for new rental acquisitions. Systems will be integrated with inductive EV charging. Consumer pace of adoption of LSAVs is uncertain.

ACM emerges for high-capacity curb fronts such as airports. SPM systems for fleet management emerge, facilitating automated fleet management and vehicle charging and initial consumer services.

Recommended Action

Plan LSAV integration into DFW through continued monitoring of LSAV technology maturity and adoption. Begin planning, modeling, and simulation of DFW to accommodate auto-parking and auto-valet functionality on DFW operations (parking and curb front) at various scales and scenarios.

Years 5+

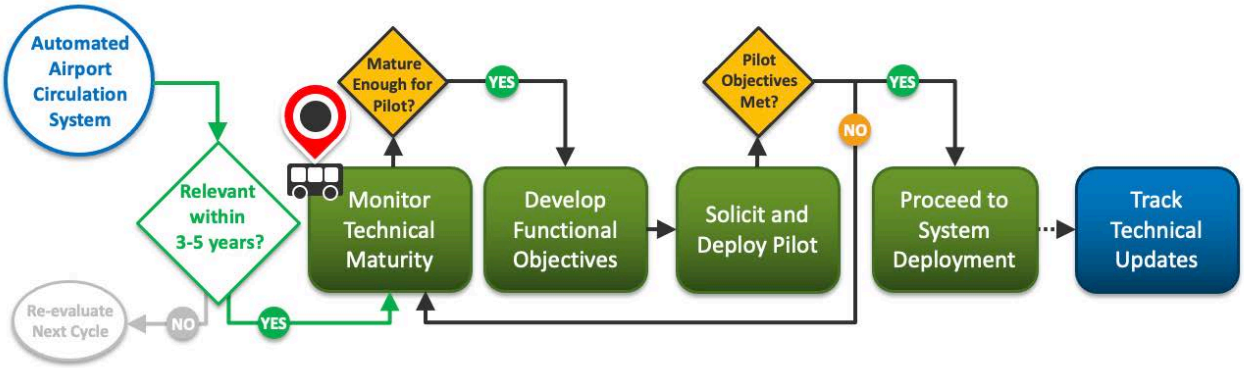
Rapid uptake of LSAV for fleet operations and early adopters of consumer technology.

Consumer adoption may advance to the *takeoff stage*, but this is dependent on supporting intelligent infrastructure systems and corresponding services (SPM, ACM, and automated inductive charging).

Separate curb space/lanes for LSAVs emerge. Dedicated infrastructure emerges for Level 3 automated vehicles (automated parking, valet, and associated services).

Interdependencies

- IIS.
- Pace of LSAV and other vehicle automation maturity.
- Availability of automated inductive charging standards and services.



Pathway: Automated Airport (Nonsecure) Passenger and Employee Circulation System

Passenger and employee movement between terminals and other airport campus buildings and services such as the consolidated rental car facility, parking areas, and transit interconnection (as examples) are currently facilitated primarily by bus and shuttle fleets that are manually driven, operate on unclear schedules, and supplemented by private or corporate vehicles. The pandemic and severe weather events revealed resilience issues associated with labor shortages. Passenger inconvenience of arriving at a terminal different from departure complicates vehicle access, especially for travelers with luggage that cannot use the Skylink upon exit from the secure side. The Airtrans system (decommissioned in 2006) once provided this linkage. Security protocol limits the use of the newer Skylink to secure-side conveyance only. The need to plan and address landside, nonsecure mobility in a resilient, automated, and convenient manner continues to escalate in priority. Although vehicle technology is rapidly maturing, systems comprising technologies that are fully mature and vetted in the ability to address this airport circulation issue remain 5+ years distant.

Within the next 3 years

Recommended Action

Actively monitor initial demonstrations of AV-based shuttle and people mover systems. Many initial demonstrations of AV-based shuttle technology have already occurred, with more moving forward to deployment, each with incremental capability improvements. Systems to watch carefully include the anticipated ribbon cutting of the LAX landside people mover to connect terminals with a multimodal transportation hub (using traditional automated people mover technology), San Jose airport's procurement of an AV-based people mover system to provide connectivity to the airport, the UTC effort in Jacksonville, Florida, and various other demonstrations of AV-based mobility systems. The Automated Bus Consortium, with initial deployment in Houston, is of particular interest as a pathway to automate existing shuttle bus services. Automated TNC demonstrations such as Waymo in Chandler, Arizona, and sites in New York, as well as various others in deployment stages provide another approach for eventual consideration at DFW. These demonstrations will directly inform DFW planning on the maturity of the technology, as well as frameworks of operation for possible application at the airport.

Years 3–5

Initial AV-based public mobility systems (not traditional automated people mover technology) that are not dependent on fixed guideways will emerge from demonstration to initial productive deployed people mover systems at major activity centers such as campuses, airports, and downtowns. Likely limited in scale, but with ability for expansion, initial systems will have mature AV technology, but perhaps less mature system elements (size and configurations for station boarding/deboarding, management and information systems etc.)—elements that will improve as operational experience is gained.

Recommended Action

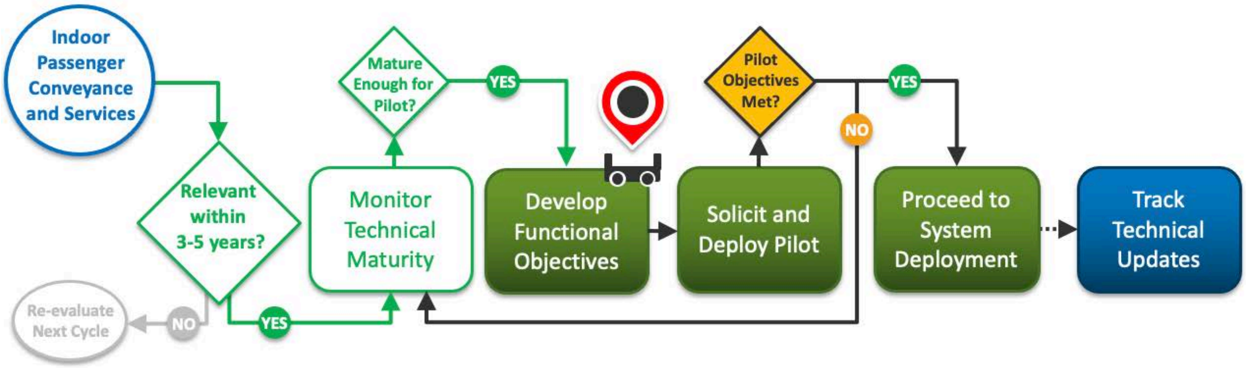
Begin detailed planning, evaluation, and comparison of competing automated systems. Even when AV technology matures, DFW will need to design a system specific to the needs and constraints of the DFW environment. A viable system may resemble automated buses, or perhaps a more dedicated system of smaller AV-based shuttles, vans, or single-party vehicles. The layout, operation, and technology components can be tested and vetted in digital models (expanding the existing DFW digital twins), and viable AV mobility system architectures will be explored to prepare DFW to specify an appropriate AV system to meet nonsecure circulation needs.

Years 5+

The pace of fundamental AV technology advancement, though rapid and encouraging of late, remains difficult to predict. Realignment of timelines with actual progress will be required at regular intervals. This will lead ultimately to a robust connectivity system that reduces (or at least softens) the need to park in close proximity to the terminal of service. A circulation system that is on-demand, convenient, and easily navigable will increase attractiveness of more distant parking, make remote curb drop-off viable for travelers, and generally change the traditional spatial constraints of airport design. Some of this can be seen at existing airports in which traditional people mover technology has allowed for decentralized airport configuration, such as at Orlando International. Increased maturity of AV technology will enable similar design flexibility using more extensible and cost-effective technologies.

Interdependencies

- Pace of fundamental AV technology development and maturity.
- Development of AV mobility systems, including supervisory control and human interfaces.
- Managed inductive charging.
- Integration with IIS.
- Integration with established and electronic wayfinding.



Pathway: Indoor Passenger Conveyance and Services Automation

Inter- and intra-terminal passenger movement is currently served by either the Skylink (for secure-side inter-terminal movement) or by pedestrian movement for intra-terminal and some inter-terminal movement for adjoining terminals. In many respects, DFW functions as five independent airports with respect to access and operations. The Skylink is designed to serve as a critical high-performance, automated, inter-terminal linkage for many years to come. However, the DFW large complex of five terminals presents opportunities to improve traveler experience using indoor automated systems of various types for movement of people and merchandise. Near-term technologies already in deployment include robotic systems that convey food and beverages directly to the travelers rather than visiting the restaurant or food stand. Systems, again based on fundamental AV technology, are envisioned to provide human conveyance to replace moving walkways and wheelchair services with *automated mobility platforms* capable of providing equivalent services in an automated and extensible fashion. In many ways the pandemic accelerated the use of robotics in airport operations. Robotic disinfecting machines have been deployed to provide automatic sanitization services, reducing the need to put employees at risk while maintaining a higher degree of passenger safety. Although robots have been used previously, the rapid adoption for such services as sanitation established precedence for broader use of robotic automation for customer service.

Within the next 3 years

Recommended Actions

Pilot and deploy robotic merchandise delivery. Already in early adopter stage, robotic delivery of food and merchandise has progressed from demonstrations to operational deployments on many campuses, and even airports (Seattle and Philadelphia). Likely first-generation but rapidly maturing technology, pilots leading to understating of key system attributes and interaction with infrastructure will allow DFW (or its vending partners) to invest wisely for operational systems in the near future.

Monitor and pilot human conveyance systems. Referred to as *automated mobility platforms*, various demonstrations and early market entries are available. Many evolve from powered wheelchair platforms (such as Whill) and present a system of "intelligent powered chairs." As indoor movement platforms, the vehicles can be fundamentally extremely lightweight and power efficient as weather protection, heating, ventilating, and air-conditioning are provided inherently by the building envelope. A system of automated mobility platforms can better link interior spaces, replacing non-scalable traditional methods, such as moving walkways or golf carts, and provide alternatives to lengthy pedestrian walks to distant gates, such as those extended from Terminal D to the south.

Years 3–5

At the current pace of technology maturation, robotic delivery of merchandise should reach rapid uptake for most major complexes, necessitating updated policy and refined system frameworks for DFW deployment.

The first generation of indoor automated mobility platform systems for human conveyance will emerge, with initial demonstrations, pilots, and deployments.

Recommended Actions

Plan and deploy robotic merchandise delivery systems. Informed by DFW pilot studies, as well as by significant industry experience in other locations, large-scale deployment at DFW should be viable.

Pilot automated mobility platforms. Early-market entries of automated mobility platforms are anticipated in this time frame, enabling a pilot at DFW to vet the technology and gain knowledge of key implementation issues.

Years 5+

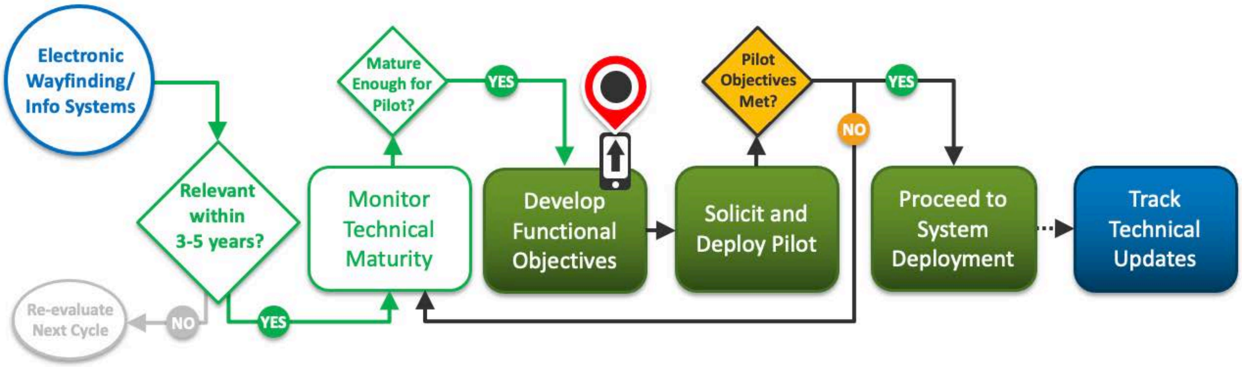
Indoor automation systems are anticipated to mature quickly and be available to influence new building design. As DFW is in a continuous cycle of terminal redevelopment, within 5 years the technology for indoor conveyance should begin to intersect with architecture design and layout options, providing additional standard tools for mobility appliances to service travelers. With time, these technologies will become as commonplace as escalators and elevators with respect to building design.

Recommended Action

Begin new terminal design exploration that leverages new indoor automation technologies.

Interdependencies

- Although indoor automation is dependent on fundamental AV technology maturity, the inherent lower-speed domain will make it less dependent on continued rapid advancement as compared to higher-speed applications, resulting in faster deployment.
- Integration with IIS, including IPC systems, which will be required for supervisory safety monitoring
- Integration with established and electronic wayfinding. This is more critical for indoor applications, as GPS location guidance is not available in many indoor settings.



Pathway: Electronic Wayfinding Systems

Wayfinding encompasses the means of communication to customers for navigating the airport and accessing its many services. As a parallel analogy, wayfinding applications for roadways have undergone a transformation in the past 15 years, with paper maps and traditional navigation aids replaced to a large degree by online navigation applications powered by GPS to orient travelers, and by internet data stores to guide travelers using a dynamic, intuitive map interface to attractions and commerce. Although static roadway signage remains, reliance on it has diminished. Older methods of navigating (paper maps, 511 systems, and AAA Trip Tickets) have all but disappeared. Within the airport context, most airline transactions (ticketing, check-in, and boarding passes) have likewise transitioned to smartphone interfaces. Unlike roadways, static and traditional airport signage remains the dominant wayfinding method to locate gates, connecting flights and baggage claim. However, a growing and significant digital presence is emerging through various airport, airline, and third-party smartphone applications, as well as interactive displays and robotic and holographic interactive information kiosks. Note that electronic indoor navigation continues to be held back by a lack of a common "local navigation system" analogous to GPS to automatically orient the traveler indoors, though several technical approaches are competing for market viability. Conversion to a primarily electronic wayfinding interface is critical to cost-effectively provide myriad information channels (in multiple languages) needed to direct travelers and link them to services, and to keep such a system up to date and accurate within an ever-changing dynamic environment.

Within the next 3 years

Information provided to the traveler will continue to migrate to smartphone applications. Already there is an application to reserve a time for security screening that is being demonstrated at airports. Google is actively demonstrating indoor navigation capabilities in early pilots using digital scene mapping and augmented reality technologies.

Recommended Actions

Full assessment of existing electronic wayfinding technology. DFW has a long-term plan and policy for static (physical sign-based) wayfinding. Similar longer-term cognizance of the many possible electronic wayfinding options will enable DFW to be responsive to market pressures. A thorough review of existing DFW and major airline apps in comparison to industry leaders is recommended. This includes various initiatives such as those underway by Google and other players to determine "best of breed" approaches. The outcome of this study will lead to initial implementation of electronic wayfinding policy and direction, and initial implementation of such a system (or enhanced system).

Development of electronic wayfinding policy and direction (Wayfinding 1.0). An airport consortium collaborative approach with emphasis on standardized data interfaces would likely provide the best broad-based, fair, and cost-effective path toward implementation. Several of the same issues that are faced by road authorities have parallels within airports. The airport owner must maintain authoritative messaging with respect to safety-critical functions and events such as severe weather, pandemic policies, and so on. However, partners such as airlines and navigation applications (Google, Apple Maps, Waze, and others) are needed to cost-effectively disseminate and customize information to all travelers.

Years 3–5

Within the 3- to 5-year time frame, indoor electronic wayfinding is expected to technically overcome the "local positioning problem" with a common standards-based solution (or solution set). Major smartphone application players will begin to aggregate airport and airline travel information into common interfaces. More airport operations and commerce functions (parking, curb, food and beverage, and other activities) will migrate to smartphone-based digital interfaces. Travelers will become more dependent on electronic wayfinding, although static wayfinding standards will remain of utility. The traveling public will expect critical information to be served in a more user-friendly, intuitive, and custom-tailored interface.

Recommended Action

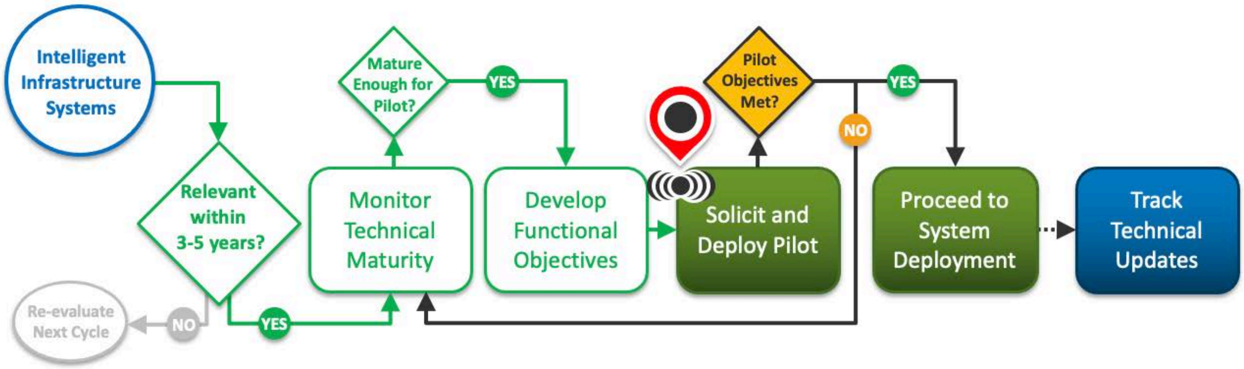
Implement electronic wayfinding policy/plan (Wayfinding 2.0). Although the interface will likely migrate to a smartphone, the role of the airport as the authoritative source of critical information will remain. Standardized data interfaces that allow the airport to provide critical information for consumption by numerous consumer-facing applications will allow the airport to continue to orchestrate operational control without having to own the information conveyance software—much like is done for roadways.

Years 5+

Fully mature indoor electronic wayfinding (Wayfinding 3.0) will move to early majority acceptance or beyond, dependent on the pace of advancement. Electronic wayfinding will not only provide navigation aid throughout the airport but also begin to link and integrate the many airport services both internal to the terminals as well as landside access.

Interdependencies

- Technical progress in indoor electronic wayfinding will largely depend on a technically viable and industry-scalable solution for a "local positioning system."
- Electronic wayfinding progress is largely influenced by policy for information standardization and dissemination, for which the airport is a major stakeholder and in a leadership position to influence and guide.



Pathway: Intelligent Infrastructure Systems

Just as the airport closely monitors and controls air operations, so also will landside airport access operations become increasingly intelligent and connected. Sometimes termed as IPC, this area refers to the greater application of IoT technology to coordinate and orchestrate airport mobility access, which is appliable both externally (parking and curbside) and internally (traveler movement within terminals). In the near term, technology that was developed primarily for AV application will migrate to roadside use. Active curb management systems are one example for which pilots and demonstrations are underway in pickup and drop-off hot spots in major cities. IPC technology, like its AV-based cousin, is capable of sensing, tracking, and classifying moving objects, including vehicles and pedestrians, to a high degree of accuracy. This foundational technology will enable many critical IIS within an airport. To fully leverage improvements afforded by vehicle autonomy, infrastructure systems need to evolve in parallel to provide the supervisory, management, and safety layers, and to integrate landside mobility data into the DFW operations center to expand and complete the active operating picture (real-time digital twin) of DFW.

Curb management is a critical and near-term IIS enabled by IPC technology. Curb congestion was escalating rapidly prior to the pandemic, fueled primarily by increased use of TNCs such as Uber and Lyft. Data from multiple airports revealed that on a per-passenger basis, revenue from parking and rental cars peaked 2 years after TNC market entry and began to decline as TNC service adoption increased. TNC transferred a significant portion of private vehicle parking demand to demand for curbside space for pickup and drop-off. Although pandemic-era data are available, the disruption of air travel demand has likely masked TNC trends since 2020.

Within the next 3 years

Recommended Actions

Close monitoring and data collection of TNC and curb usage. The need for curb monitoring and control was exposed by the rapid adoption of TNCs at airports. DFW currently collects various data associated with requisite access fees and surcharges that will reveal market share impacts of TNCs and subsequent escalation of curb demand.

Implement active curb management pilot study. The pilot would provide proof of concept for the ability to perceive, track, and identify moving objects, serving as the basis for enhanced safety, management, and control. Such a pilot was recently approved for funding through an NCTCOG grant opportunity in combination with LSAV auto-valet demonstration, though not yet contracted. The objective of the ACM pilot implementation would be to monitor occupancy, inflow, outflow, and various other aspects that determine curbside operation performance and convey such information to the airport's operations center.

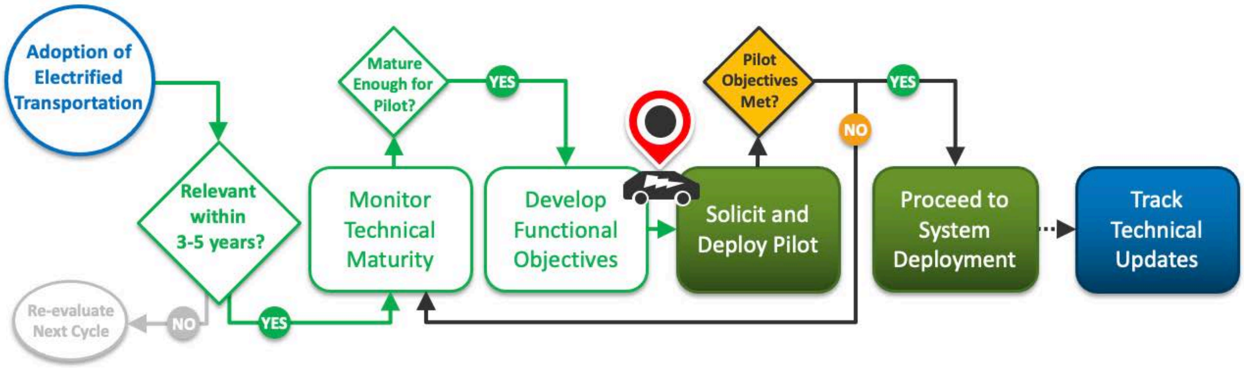
Years 3–5

Recommended Action

Develop long-term policy/program for active curb management. Concurrently, IIS are anticipated to address many monitoring and management applications such as security queue management, safety aspects of automated mobility platforms, and the basis for supervisory parking management systems. Initial application of IPC technology for security queuing monitoring is already at pilot stage. Video image processing identifies waiting passengers, assesses queue length, and estimates queue processing time. Further application of such capability for safety management of mobility systems (both indoor and outdoor) is a logical extension of the technology.

Years 5+

Applications of IIS are anticipated to achieve *takeoff*, providing robust infrastructure-based perception to integrate landside mobility systems for efficient management, ensure safety, and provide enhanced customer experience.



Pathway: Societal Adoption of Vehicle and Mobility Electrification

While most automation technologies remain at best in the innovator and early-adopter stage, vehicle electrification has surpassed the innovator state of technology, having eclipsed 5% of new car sales in the past 12 to 18 months. EV adoption among new vehicle sales is staged for *takeoff* in the coming 12 to 24 months, anticipated to reach 10% of new vehicle sales in some markets within 3 years. Already, DFW has received communication from the consolidated rental car facility of the need to accommodate electric vehicle charging as the rental car fleet adapts to societal expectation of EV rental availability. Accommodating EVs and requisite charging infrastructure is the topic of concurrent studies at DFW by NREL and is brought forth here as a significant influencer and interdependency in several aspects. Many of the most modern EVs also include advanced automation features, as EVs have penetrated premium markets associated with enhanced driver conveniences. Of particular note is the need to accommodate vehicle charging, and to do so seamlessly, while also providing premium services such as auto-parking, valet, and recall.

Also of note is the ability of EVs to integrate into buildings and structures more seamlessly. Having no onboard petroleum fuels, and not emitting CO_2 or other emissions, EV-powered vehicles can enter and exit a building envelope with significantly less hazard concerns, opening integration possibilities inherently prohibited by internal combustion engine vehicles. These unique characteristics of EVs underscore the importance of continued technical advancement and consumer adoption of EVs, as well as progress toward sufficient vehicle charging infrastructure, automated inductive EV charging, associated charging management, and managing interdependencies with mobility automation within airports.

Beyond ground vehicle electrification, electrification of small aircraft as well as novel drone service referred to as eVTOL, when mature, has significant potential to induce more medium-distance air travel and provide better access to major airports. Although rapidly advancing, technical maturity and market readiness is likely 5 or more years distant, and so no initial near-term action is recommended.

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