Analysis of Automated Transit Network Systems with Battery-Electric Vehicles in Automated Mobility Districts

Preprint

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1 Automated Mobility Services, LLC
2 National Renewable Energy Laboratory

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Analysis of Automated Transit Network Systems with Battery-Electric Vehicles in Automated Mobility Districts

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ABSTRACT

The paper provides an overview of the insights and findings of the National Renewable Energy Laboratory's (NREL) ongoing research on the implementation of automated mobility districts (AMDs). AMD is a term coined by NREL to describe a geographically defined district or major activity center located in a dense urban setting with mobility applications provided by automated/autonomous vehicle (AV) systems spanning internal circulation and first-mile/last-mile connections to regional transportation hubs. Research over the past five years has focused on understanding the evolution of AMDs, beginning with demonstrations of automated shuttles prior to the pandemic, to more integrated on-demand mobility systems currently in initial stages of deployment. Initial insights and findings from earlier studies include the need for designation of a "jurisdiction having authority," a clear vision of a complete system to provide end-to-end mobility services, and the requisite intelligent infrastructure to complement AV technology. NREL's most recent Phase III research investigates station boarding/alighting (curb) issues, the full electrification of fleets, and the need for a systems engineering methodology (SEM) to properly analyze the complexities resulting from the convergence of automation, on-demand mobility, and electrification of the transit systems within the AMD. The paper reviews the findings of AMD research conducted during Phase I, II, and III, with special emphasis on Phase III results with respect to a descriptive example of the proposed SEM when a "digital twin" analytical model is used to simulate the transport fleet's battery-electric vehicle miles of travel and associated duty cycles through a rigorous analytical assessment with a comprehensive modeling process.

INTRODUCTION—FOUNDATIONAL EARLY RESEARCH

The National Renewable Energy Laboratory (NREL) has researched automated mobility districts (AMDs) for more than five years, with findings presented in three phases of work on the conceptual development and deployment of fully automated transport systems in AMDs. The associated documentation of Phase I research (Young and Lott 2020) and Phase II research (Young and Lott 2022), as well as multiple published technical papers documenting Phase III research on AMD implementation, describe the observations and assessments of what has been learned from the emerging automated/autonomous vehicle (AV) technology industry applied to systems of movement within areas of dense development. This body of work has evaluated the implementation challenges and synergies of automated/autonomous and electric vehicle (A/EV) deployment in managed fleets and the associated practical findings of the necessary infrastructure that will facilitate early deployment in large-scale AMDs.

The results of the recently completed Phase III of this AMD implementation research is being published by NREL in 2024 as the 3rd edition of *The Automated Mobility District Implementation Catalog*. The Phase III research findings were initially published in 2023 through multiple papers featuring lessons learned from prior studies of fully automated, on-demand transport systems over the past two decades (Lott and Young 2023a). These earlier studies addressed AV systems operating on dedicated transitways, thereby limiting the operational complexities of the AV fleets interacting with pedestrians, micromobility roadway users, or other human-operated vehicles in mixed traffic—operating conditions that tend to mask more fundamental operational factors. These studies of earlier small-vehicle automated mobility systems—which historically were referred to as "personal rapid transit" from the 1970s to the 2000s, and more recently as "automated transit networks" (ATNs) from the 2000s forward—provide valuable insight into the future of large-scale AMD operations.

The research to this point has focused on mobility systems, or rather a system of systems, within a geographically defined district or major activity center located in a dense urban setting, referred to an AMD, with mobility applications spanning internal circulation and first-mile/last-mile connections to regional transportation hubs provided by fully automated fleets (Young and Lott 2023).

Multiple AV Fleets. The functional purpose of AV fleet operations within an AMD is to provide essential mobility for internal district circulation, as well as external access/egress through first-mile/last-mile connections to intraregional transit and perimeter parking facilities. Multiple AV fleets with different vehicle types, sizes, and operations, each characterized by different routes and dispatching methods, will be the norm within large-scale AMDs, just as manual fleets of traditional fixed-route transit, taxi, and ride-hail companies, paratransit, and other services are today. The various operating modes may include fixed-route and fixed-schedule transit, combined with on-demand microtransit providing direct origin-to-destination passenger service. Although these different transit operating modes typically use different size vehicles, with each vehicle type comprising a unique AV technology, the different vehicle fleets would all have fully automated management of dispatching, station (or curb) dwell times, and service levels provided throughout the day.

Automated Transit Network Operational Mode. The term automated transit network system was adapted from the automated guideway transit industry[1]. Small-vehicle ATN systems typically utilize dedicated transitways with "off-line" stations that allow vehicles to pass by each station on the mainline transitway without requiring a station stop. This off-line station capability contrasts with traditional train, metro, and light-rail that typically stop at all stations. The off-line station configuration allows a small ATN vehicle to be uniquely dispatched to serve a given passenger's personal origin-to-destination transport request. This ATN mode of operations is comparable to on-demand ride-hailing services provided by transportation network companies like Uber or Lyft, but with a dedicated fleet of small- to medium-size automated transit vehicles that are dispatched to provide personal and/or shared-ride services. Off-line stations are comparable to dedicated curbside and/or pickup/drop-off zones, apart from the main travel way. The fleet management supervisory software of an ATN system determines each vehicle's dispatch assignments to and from pickup and drop-off locations/stations, temporary storage areas, and maintenance locations, along with the vehicle's associated dwell periods at each of those locations. As such, previous studies and methods of analysis of ATN systems provide extremely valuable insight into AV fleet operations within an AMD. Note that although dedicated guideways may no longer be needed to facilitate full vehicle automation (as is demonstrated by Waymo operations in Arizona and

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[1] The basic definition of what characterizes an ATN system has been codified in the ANSI/ASCE-21 Automated People Mover Standards (ASCE 2021).

California today), the operational complexities of on-demand, electrified, and off-line stations provide a close paradigm to envisioned AMD systems.

NREL's PHASE I–III TOP-LEVEL RESEARCH FINDINGS AND CONCLUSIONS

Through the process of documenting the early pilot deployments of AV technology for public mobility and performing related assessment of similar advanced transit technology applications, the authors have gained insight into the complexity of fully automated operations of an AMD's mobility systems. To this research on AV operational complexity has been added, in Phase III, assessments of the convergence of vehicle fleet electrification, along with off-line (curb) station operations. These aspects significantly complicate the fleet management challenges for a large-scale AMD implementation requiring a systems engineering methodology (SEM) approach. The following findings from Phase I through III are of major significance as they relate to operational complexity, fleet size implications, and necessary infrastructure investments.

- Systems-Level Vision for AMD – Early demonstrations of automated shuttle technology shared a common vision of fully automated public mobility, though early demos were significantly limited in size and scope. These demos shared a larger vision, what NREL defines as an AMD, acknowledging that the early work was laying the groundwork for a more effective, equitable, and sustainable public mobility system. This vision is critical, as is the need for a jurisdiction having authority—i.e., the need for an appropriate public entity capable of setting standards, policy, financing, and other governing aspects of AMDs for the sustained, consistent, coordinated, and safe operation of multiple AV fleets providing mobility service within an AMD.
- Intelligent Infrastructure – The importance of intelligent roadway infrastructure has been realized to facilitate cooperative automation functions between multiple fleets and traffic management infrastructure. This concept was specifically identified as being important for providing greater safety, operational efficiency, and environmental/sustainability results of multi-fleet operations. Intelligent infrastructure is believed to be essential when AMDs reach a scale where multiple AV fleets, each with hundreds of vehicles in operation during peak periods, service our urban districts. Applications have been studied for key roadway intersections (Lott et al. 2021) where individual vehicle-based perception technology is insufficient to provide an operating picture to safety maintain speed with the traffic stream (AVs compensated by slowing operations, becoming an impediment to normal travel flow). Intelligent infrastructure is also being studied for application in station operations in the boarding and alighting areas in transit stations (Young et al. 2022)[2].
- Off-Line Stations with Parallel Berth Configuration – Stations have significant (and often dominant) impact on the operational efficiency and system throughput capacity of AV fleets, and the placement of stations off the main travel lanes, combined with various configurations that provide parallel boarding berths, drives major design considerations. This addresses a critical aspect of automated, on-demand systems with respect to energy use and fleet management since a parallel station berth configuration allows for flexible boarding—i.e., allows one party more time (if needed) than a subsequent party without disruption (or only minimal disruption) to station efficiency or throughput capacity (Lott

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[2] An accessible version of this paper is available as a preprint: https://www.nrel.gov/docs/fy22osti/81978.pdf.

et al. 2022)[3]. This also has bearing on system resiliency, allowing for single vehicle failures without significant impact to system operations.

- Vehicle Fleet Electrification – AV technology is a natural fit with electric-propulsion vehicle fleets for energy reduction and greenhouse gas mitigation. But the vehicular design with battery-electric propulsion systems has major implications as it converges with AV operations (Lott and Young 2023b). Other aspects identified in the research are:
    - Fully automated fleets will be best served by fully automated battery charging capability for optimal energy and service management.
    - Off-line stations with parallel berth configuration allow vehicles to dwell for an extended time until they are dispatched into service.
    - Battery charging in station berths is a vital option for "opportunity charging" during off-peak periods without disrupting station capacity and performance levels.
    - "Deep charging" of vehicle batteries at high-power, DC fast-charge stations with nominal dwell times can also be accomplished in fully automated mode in the depot or in storage areas specifically designed for this purpose.

Conclusions on Resilient and Sustainable AMD Implementation Elements. The operational impacts of battery-electric vehicles and the need for periodic recharging, combined with the complexities of mixed transit mode routes and on-demand operations with station off-line (curb) boarding and alighting, have been a particular focus of the latest Phase III AMD research. The following points summarize the high-level seminal conclusions drawn from the composite of the Phase I–III research completed to date:

1. Maximizing safety and throughput capacity of AV systems will require the application of "intelligent infrastructure" to roadways and potentially to AV stations/curbfronts specifically identified as passenger pickup and drop-off zones.
2. System-of-systems view and approach are required to achieve the full vision of effective, safe, and efficient public mobility using AV fleets, including appropriate jurisdiction authority for management and monitoring of the AMD system.
3. Electrifying AV fleets will require trade-off analyses of vehicle type, fleet configurations, and service mode operation, combined with battery-electric vehicle charging strategies and vehicle characteristics of operating range, charging time, charging facility size, and infrastructure power supply requirements.
4. Demand-responsive operations of small- to medium-size vehicles allow energy consumption and fleet operations to be optimized when vehicles are only moving (and sized) in direct proportion to ridership activity.
5. A systems engineering design and analysis methodology that simulates all modes, vehicles, and travelers is needed to analyze the fleet size, station and battery charging infrastructure, operating plan, and energy use based on the numerous variables of the combined fleet automation, electrification, and multiple fleet transit services. In modern times, this is referred to as a "digital twin."

The research findings and conclusions summarized above frame the premise that there is a need for new tools and methodologies for application in large-scale AMD implementation projects. The following sections present the proposed SEM, with the concepts discussed in terms of the nature and benefit of the associated analytical approach.

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[3] An accessible version of this paper is available as a preprint: https://www.nrel.gov/docs/fy22osti/81976.pdf.

SYSTEMS ENGINEERING METHODOLOGY FOR AMD SITE IMPLEMENTATION

NREL's ongoing research is transitioning to assessing the analysis process necessary to perform the conceptual and preliminary engineering studies of AMD sites. Working from the foundation of the first three phases of research of prototypical AMD implementations, ongoing research is addressing the SEM necessary for progressing beyond planning-level studies. The methodology needed must encompass the automated operations (and capabilities) of AV fleets with blended fixed-route and on-demand point-to-point service modes. Fleet operations must be analyzed in the context of vehicle battery recharging parameters and constraints, as well as associated operational provisions at charging stations (vehicle servicing capacity and power limitations). Because of this interdependent complexity, the remainder of this paper will refer to A/EV deployments as the basis for AMD implementation.

Past studies of ATN system applications provide valuable insights for applying the proposed methodology to early engineering studies of large-scale AMD site deployments in the near- to medium-term future. In particular, previous ATN studies provide insights on the operational management required for dispatching fleets of small vehicles (4–20-passenger capacity) into operation for on-demand, direct origin–destination service. Previously studied ATN applications provide internal district circulation and connections to regional and interregional transit at major intermodal stations (Lott and Young 2023a), as envisioned for AMDs comprising A/EVs utilizing public roadways. Although these studies encompass a single system, they form the basis of understanding the SEM approach for an AMD at scale.

On-Demand Dispatch Operational Complexity. A representative ATN study of a conceptual connector to the Bay Area Rapid Transit (BART) system on Alameda Island from the 2000s provides as an example of the proposed analytical SEM approach. This study illustrates key aspects of the proposed SEM needed for modern AMD analysis. This study is simple in its level of detail, but it illustrates key analysis capability necessary for AMD system modeling.

Figure 1 shows a location where a conceptual ATN system was studied for the BART system in San Francisco, California, approximately 20 years ago. The ATN concept was identified by BART as a "group rapid transit" technology that had an 18-passenger vehicle capacity with off-line stations configured with parallel berths. Figures 2 and 3 illustrate the complexity of vehicle operations that must be analyzed in a manner that allows the use of energy drawn from the onboard battery storage for on-demand service. The system modeling simulation's ability to emulate the dispatching of vehicles into service in response to a passenger's demand call is critical, including the aspects of "empty vehicle management" to position vehicles where needed in anticipation of high service demand, while allowing vehicles to remain dormant during times when demand is low.

Not only is a simulation framework that tracks each rider and vehicle (more recently referred to as agent-based simulation) critical, iterating the simulation over a range of realistic and representative demand and operational scenarios, measured in the hundreds or perhaps thousands, is also necessary to expose and address system-level operations concerns. In the BART representative study, the iteration of various scenarios revealed that a mixed fleet of vehicle sizes, with large vehicles servicing high-demand stations on a fixed schedule, complemented by a smaller fleet of on-demand vehicles servicing lower-demand stations, provided improved performance compared to an on-demand system with 18-passenger vehicles.

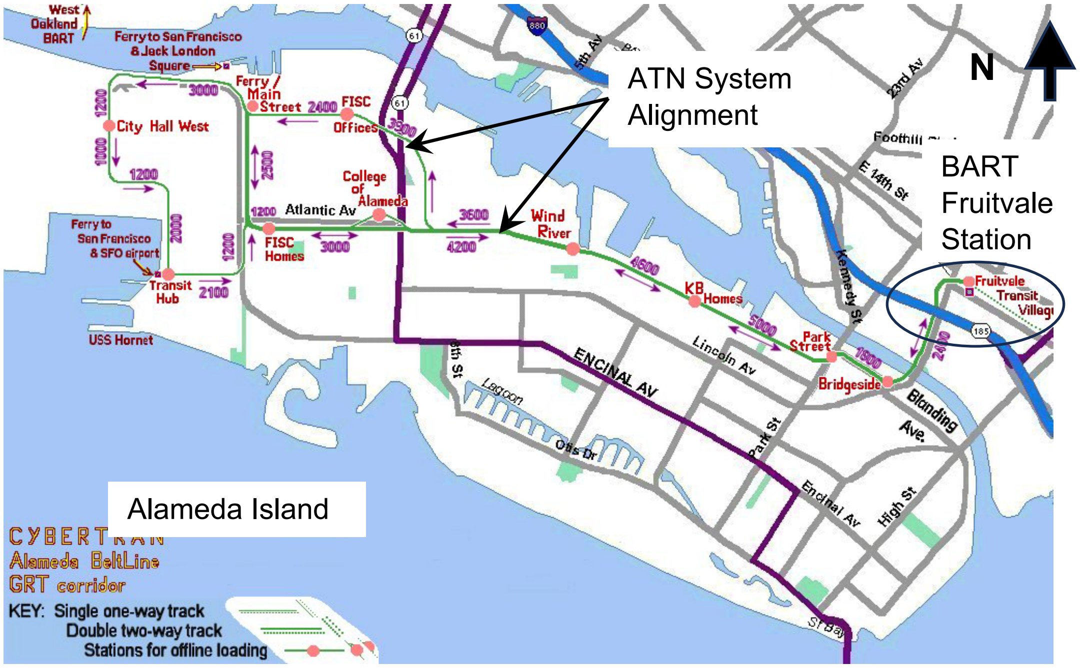
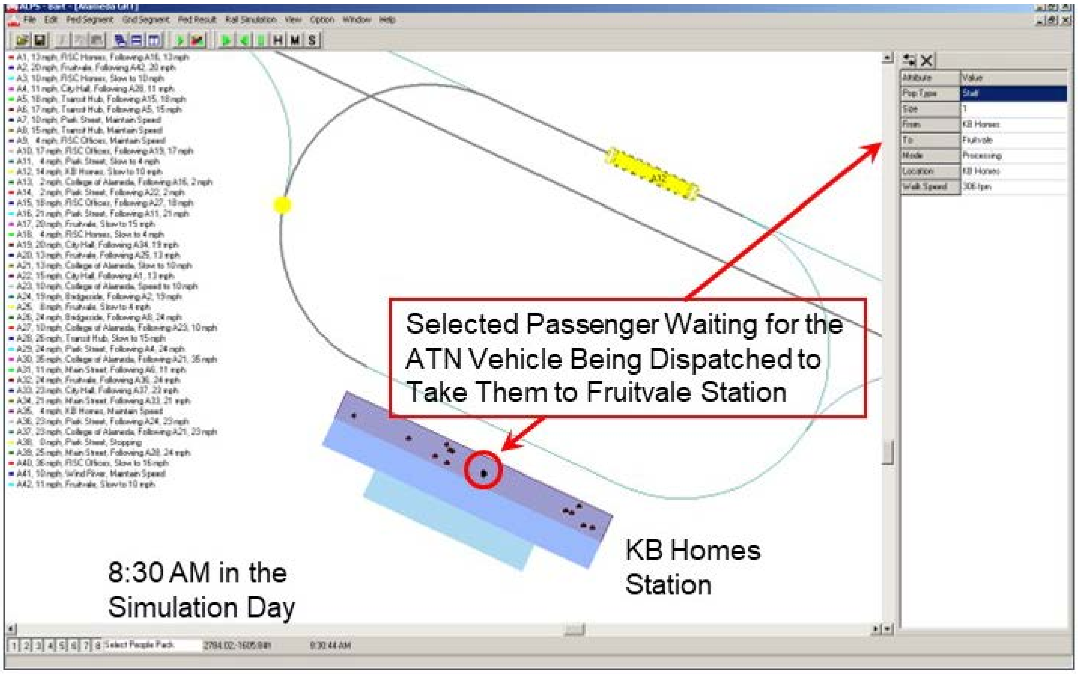


Figure 1. BART study of a conceptual ATN system that would create an AMD on Alameda Island.



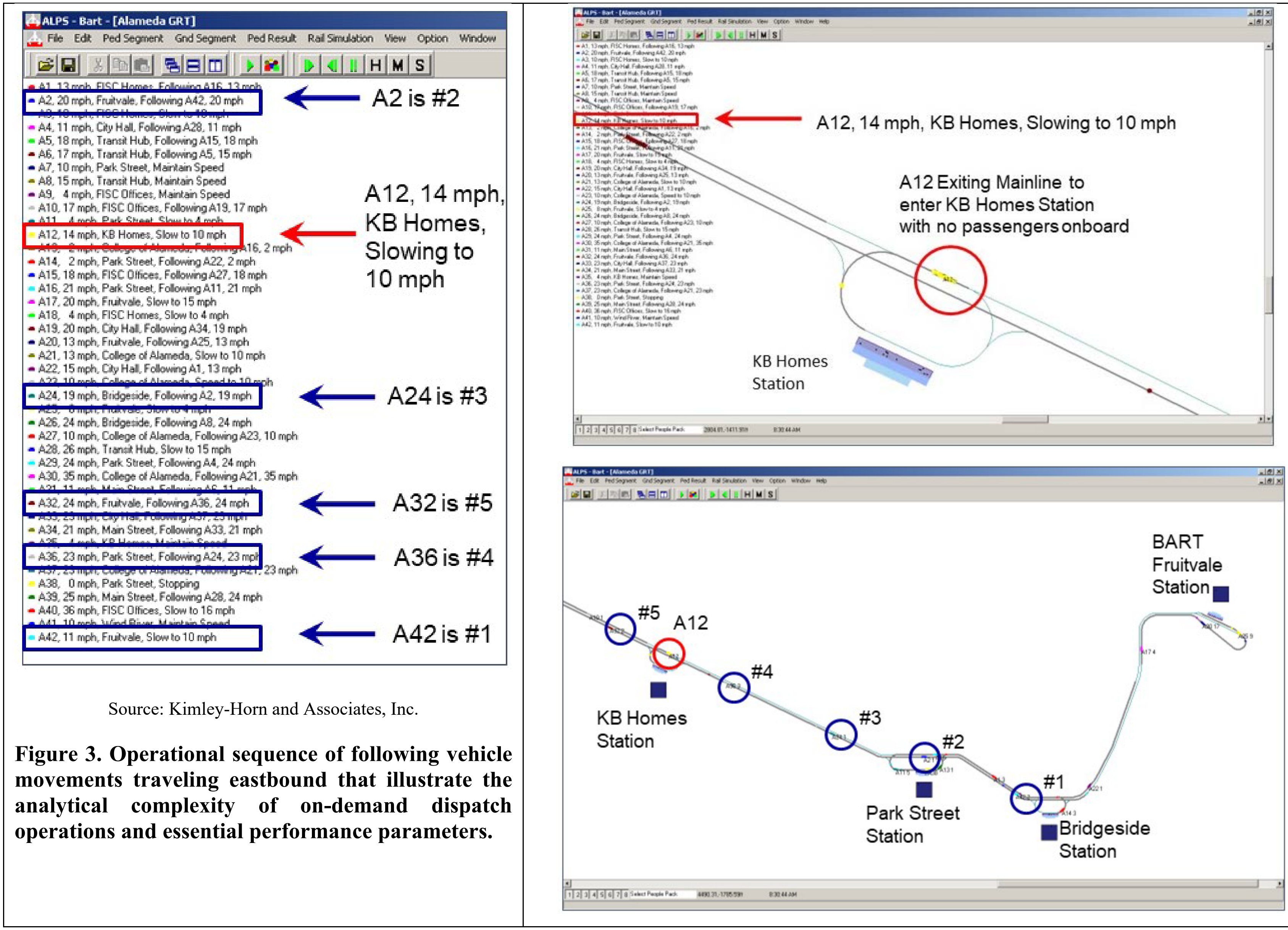
Selected Passenger Waiting for the ATN Vehicle Being Dispatched to Take Them to Fruitvale Station

KB Homes Station

8:30 AM in the Simulation Day

Figure 2. ATN vehicle on-demand dispatch is driven by specific passenger person-trip flows through the AMD simulation.

Source: Kimley-Horn and Associates, Inc.



A1, 13 mph, FISC Homes, Following A16, 13 mph
A2, 20 mph, Fruitvale, Following A42, 20 mph
A3, 10 mph, FISC Homes, Slow to 10 mph
A4, 11 mph, City Hall, Following A28, 11 mph
A5, 18 mph, Transit Hub, Following A15, 18 mph
A6, 17 mph, Transit Hub, Following A5, 15 mph
A7, 10 mph, Park Street, Maintain Speed
A8, 15 mph, Transit Hub, Maintain Speed
A9, 4 mph, FISC Offices, Maintain Speed
A10, 17 mph, FISC Offices, Following A19, 17 mph
A11, 4 mph, Park Street, Slow to 4 mph
A12, 14 mph, KB Homes, Slow to 10 mph
A13, 2 mph, College of Alameda, Following A16, 2 mph
A14, 2 mph, Park Street, Following A22, 2 mph
A15, 18 mph, FISC Offices, Following A27, 18 mph
A16, 21 mph, Park Street, Following A11, 21 mph
A17, 20 mph, Fruitvale, Slow to 15 mph
A18, 4 mph, FISC Homes, Slow to 4 mph
A19, 20 mph, City Hall, Following A34, 19 mph
A20, 13 mph, Fruitvale, Following A25, 13 mph
A21, 13 mph, College of Alameda, Slow to 10 mph
A22, 15 mph, City Hall, Following A1, 13 mph
A23, 10 mph, College of Alameda, Speed to 10 mph
A24, 19 mph, Bridgeside, Following A2, 19 mph
A25, 0 mph, Fruitvale, Slow to 4 mph
A26, 24 mph, Bridgeside, Following A8, 24 mph
A27, 10 mph, College of Alameda, Following A23, 10 mph
A28, 26 mph, Transit Hub, Slow to 15 mph
A29, 24 mph, Park Street, Following A4, 24 mph
A30, 35 mph, College of Alameda, Following A21, 35 mph
A31, 11 mph, Main Street, Following A6, 11 mph
A32, 24 mph, Fruitvale, Following A36, 24 mph
A33, 23 mph, City Hall, Following A37, 23 mph
A34, 21 mph, Main Street, Following A33, 21 mph
A35, 4 mph, KB Homes, Maintain Speed
A36, 23 mph, Park Street, Following A24, 23 mph
A37, 23 mph, College of Alameda, Following A21, 23 mph
A38, 0 mph, Park Street, Stopping
A39, 25 mph, Main Street, Following A28, 24 mph
A40, 36 mph, FISC Offices, Slow to 16 mph
A41, 10 mph, Wind River, Maintain Speed
A42, 11 mph, Fruitvale, Slow to 10 mph

Source: Kimley-Horn and Associates, Inc.

Figure 3. Operational sequence of following vehicle movements traveling eastbound that illustrate the analytical complexity of on-demand dispatch operations and essential performance parameters.

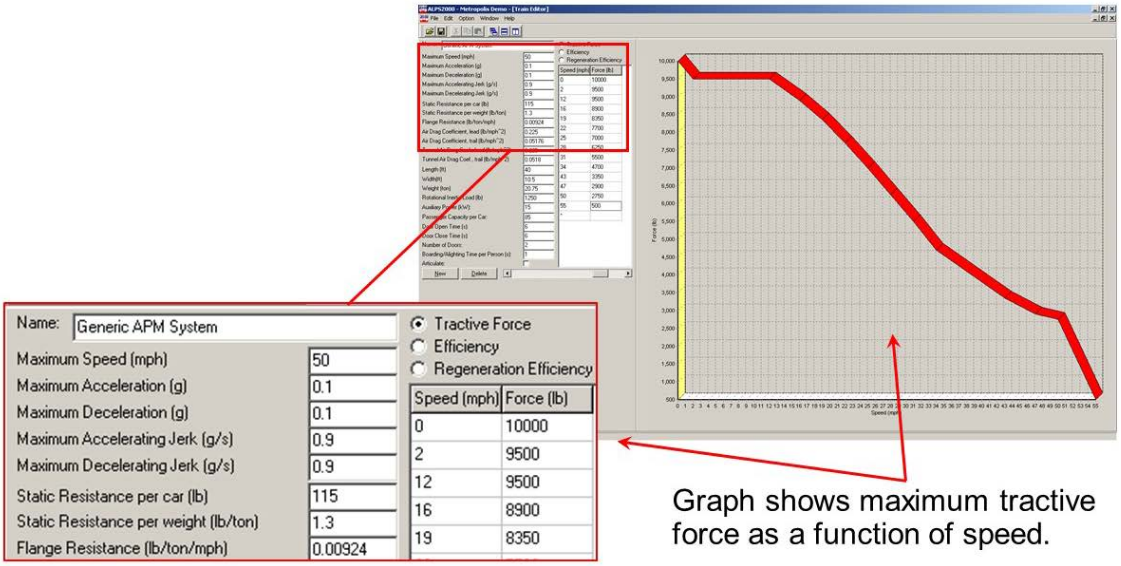
Figure 3 identifies the sequence of five ATN vehicles operating eastbound (left to right) through the transitway network. The following lists the status of each vehicle that the simulation model was reporting at approximately 8:30 a.m.:

1. A42, 11 mph current speed, bound for Fruitvale Station, and slowing to 10 mph.
2. A2, 20 mph current speed, bound for Fruitvale Station, and following A42.
3. A24, 19 mph current speed, bound for Bridgeside Station, and following A2.
4. A36, 23 mph current speed, bound for Park Street Station, and following A24.
5. A32, 24 mph current speed, bound for Fruitvale Station, and following A36.

Although a relatively simple simulation example, the methodology exhibits an essential requirement of the system simulation in that vehicles are constrained to the operating conditions of other vehicles—i.e., the vehicle immediately ahead—or, in other words, network congestion of other vehicles on the transitway as well as congestion within stations from boarding and alighting. This particular simulation modeling study for the BART ATN included only a single mode. A robust system simulation methodology would be capable of simulating mixed-mode travel paths that may have components of walking, driving/parking, and other travel mode uses (e.g., commuter bus, rail transit, or vertical takeoff and landing regional access modes). The application of this modeling technique to roadway-based A/EV operations in mixed traffic will have many more human-driven vehicles and other pedestrians and roadway users with which the fleet vehicles interact. Multimodal simulations are necessary to apply the SEM analysis approach for many AMD conceptual and preliminary engineering studies, assessing not only the vehicle-to-vehicle interactions within the same fleet, but also queuing issues within the stations, vehicle boarding and alighting, and micromobility interactions. The fundamental principle of tracking each individual person moving through the AMD, as well as each vehicle's unique performance and operations, is the basis for modeling larger and more extensive AMDs with multiple A/EV transit fleets.

Vehicle Battery Charging Operations. Detailed analysis of battery-electric vehicle performance and power consumption is based on including propulsion system characteristics in the simulation. Figure 4 shows the net force required to propel an electric motor-driven rubber-tired vehicle of a typical bus size after all losses are included—classically defined as the "tractive effort" curve. Some of the key parameters and the energy required to accelerate a vehicle are enlarged in the inset. Each type of electric propulsion vehicle being studied in the analysis would have its characteristic data input to the model to represent its performance and energy use during the simulated operations.

A similar analysis is needed and would be defined for each battery-electric vehicle in each operating A/EV fleet as part of the analysis process for a conceptual AMD implementation site. As the operational simulation of multiple fleets is modeled, the associated propulsion power and energy consumption of each vehicle would also be continuously calculated to account for the changes in passenger load, vehicle speed and associated acceleration/braking, and grade variations as the vehicle maneuvers along its travel path. A simple illustration of these simulation-based derivations of these parameters from a previous ATN study is shown in Figure 5 for one of the station-to-station links of the BART ATN system described above. The changes to speed shown in the figure are representative of an A/EV's operations in a modern AMD as the vehicle progresses through traffic signals and maneuvers through other vehicular traffic along its route when dispatched between a passenger's origin and destination station.



Name: Generic APM System

● Tractive Force
○ Efficiency
○ Regeneration Efficiency

Maximum Speed (mph)	50
Maximum Acceleration (g)	0.1
Maximum Deceleration (g)	0.1
Maximum Accelerating Jerk (g/s)	0.9
Maximum Decelerating Jerk (g/s)	0.9
Static Resistance per car (lb)	115
Static Resistance per weight (lb/ton)	1.3
Flange Resistance (lb/ton/mph)	0.00924
Air Drag Coefficient, lead (lb/mph^2)	0.225
Air Drag Coefficient, trail (lb/mph^2)	0.05176
Tunnel Air Drag Coef., trail (lb/mph^2)	0.0518
Length (ft)	40
Width(ft)	10.5
Weight (ton)	20.75
Rotational Inertia Load (lb)	1250
Auxiliary Power (kW)	15
Passenger Capacity per Car	85
Door Open Time (s)	6
Door Close Time (s)	6
Number of Doors	2
Boarding/Alighting Time per Person (s)	1
Articulate	☐

Speed (mph)	Force (lb)
0	10000
2	9500
12	9500
16	8900
19	8350
22	7700
25	7000
28	6250
31	5500
34	4700
43	3350
47	2900
50	2750
55	500

Graph shows maximum tractive force as a function of speed.

Figure 4. Electric propulsion system's tractive effort curve used for power and energy analysis. The parameters shown represent the propulsion equipment's characteristic values for a large A/EV technology.

Source: Kimley-Horn and Associates, Inc.

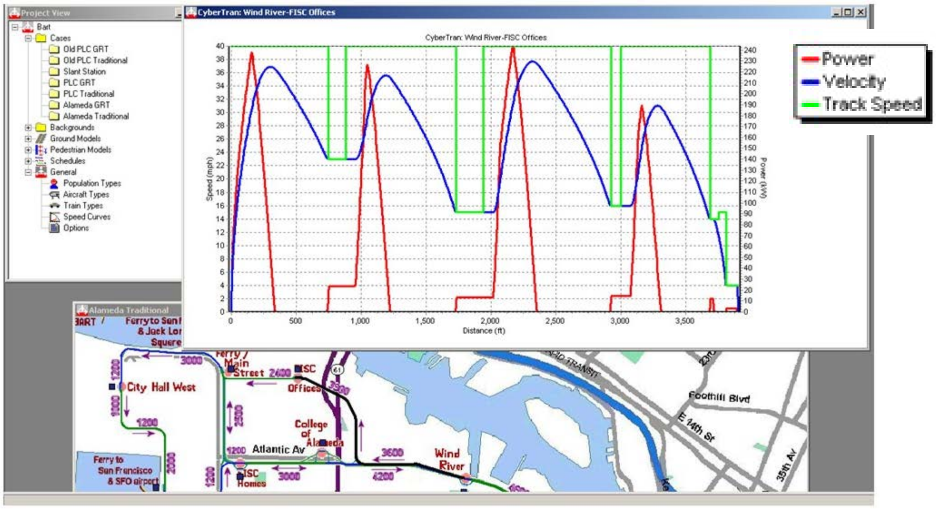


Figure 5. Electric propulsion system's power consumption during travel speed variations for a unique route determined by its dispatching to carry an on-demand passenger from the associated origin and destination station.

Source: Kimley-Horn and Associates, Inc.

The continuous calculation of each vehicle's propulsion energy consumption, as well as its regenerative braking power generation, is essential for assessing battery-electric vehicle deployment during on-demand fleet operations. Additionally, with respect to opportunity charging of vehicles, the simulation must accurately reflect each vehicle's dwell times when stopped in station berths or in temporary storage areas, since these times contribute to the accurate calculations of energy use and the vehicle battery's state of charge throughout the day. Furthermore, the SEM simulation will provide output to the district's energy distribution digital twin, which monitors the overall energy demand across all sectors, renewable energy generation, and the status of local energy storage as well as the electrical grid.

CONCEPTUAL AND PRELIMINARY ENGINEERING OF AMD DEPLOYMENT SITES

The methodology summarized above is considered essential to conceptual and preliminary engineering of a prospective AMD's mobility systems in terms of the implementation costs and associated operating costs for a given pattern of person-trips that drive the mobility systems' ridership demand. As previously emphasized, the SEM assessment/analysis process must thoroughly address the battery charging requirements of each fleet vehicle during the operating day and the associated fleet operational impacts for various battery-electric vehicle charging strategies.

From the combined analysis of passenger demand, fleet operations, and associated battery-electric vehicle charging operations, a method is developed to establish the vehicle fleet size, anticipated passenger service levels, and battery charging infrastructure requirements for the AMD and its identified stations/curbfronts for mobility system access. The types of engineering-level analytical studies envisioned for the proposed methodology include the following:

> **Planning and Conceptual Engineering Phase:** Starting from the conceptual initial deployment phase, the system scope (route coverage area, network configuration, and necessary fleet size) and implementation cost is developed. Then the work advances to the definition of an initial systems and facilities procurement plan. From this initial work, a conceptual definition of the ultimate implementation phase is developed in terms of the systems and facilities plan.
>
> **Preliminary Engineering Phase of Initial Deployment:** Early engineering studies advance the initial deployment of multiple AMD mobility systems in terms of the scope of the final design, procurement, and installation, including the associated cost estimates for the systems, facilities, and components of the A/EV fleets and mobility functions. This engineering work includes the procurement plan and technical specifications for the systems, facilities, and component parts and services.
>
> **Real-Time Digital Twin Application:** Integration of the simulation model into the deployed system for a real-time digital twin that resides within the operation control center and allows future time analysis based on existing conditions in system operations. Additionally, the real-time SEM interfaces with other district systems, such as an energy digital twin to co-optimize for energy efficiency and resiliency across multiple sectors within the district.

Early conceptual studies, followed by increasingly more detailed preliminary engineering studies, are necessary to optimize aspects of the planning and design of a multi-fleet AMD implementation. Figure 6 illustrates the flow of information within the proposed SEM by which the battery-electric vehicle fleets operating in mixed-mode service—some with fixed-route and fixed-schedule dispatching and some with dynamic on-demand dispatching—can be studied as a composite of each vehicle's individual, moment-by-moment performance and operations within a simulation model.

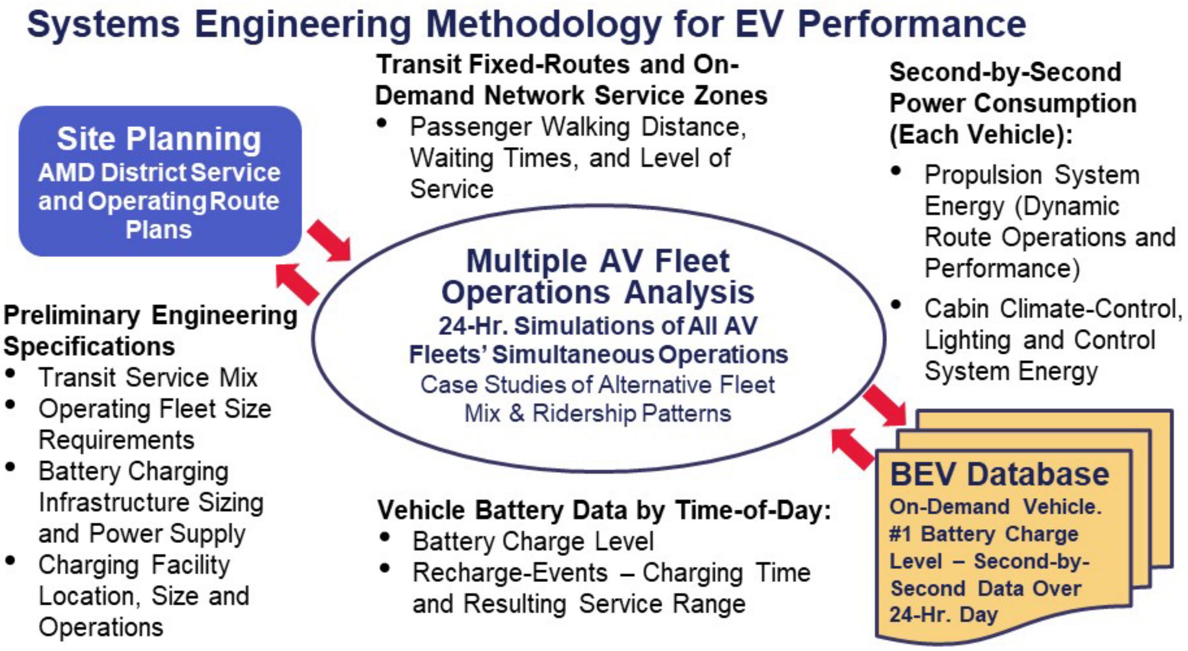


Figure 6. A systems engineering methodology that provides an analytical approach and key performance indicator derivations suitable for AMD planning and design.

CONCLUSIONS ON SYSTEMS ENGINEERING METHODOLOGY FOR AMDS

This paper reviews the top-level insights and finding from NREL's automated mobility district research over the past five years and presents a proposed system engineering analysis approach for AMDs comprising multiple fleets of A/EVs operating in a geographically constrained environment to provide circulation within the district as well as first-mile/last-mile services to regional transit, interregional transit, and parking facilities. The method draws on previous work to simulate ATNs for conceptual and pre-engineering analysis of A/EV systems constrained to a guideway network. System simulations of ATNs over the past two decades are relevant for A/EVs within an AMD (providing public mobility but not confined to a guideway network) in that they characterize the importance of parallel berth stations (pickup and drop-off zones) to efficiently manage a system with heterogeneous demand in terms of both time and energy. Furthermore, these simulations that track the power draw of individual vehicles point to the need for a simulation that tracks each individual traveler and each vehicle across multiple fleets for performance as well as planning, engineering, and operations.

For travelers, key performance parameters include wait time, travel, queueing, and accessibility while for vehicles they include traditional measures such as speed, dwell time, tractive force, and energy, as well as parameters critical to newer battery-electric propulsion systems such as the state of charge of the battery pack. More critically, the proposed systems engineering simulation methodology will allow for evaluating mobility in conjunction with fleet energy management that will determine fleet size, charging strategy (both deep and opportunity charging), and overall system energy performance and traveler experience. The level of detail in each phase of the SEM for an AMD site application is anticipated to be progressively more detailed—advancing from concept evaluation to pre-engineering and a real-time, digital-twin-embedded operations management tool.

The modeled parameters from the simulation methodology (i.e., the digital twin) will span systems, traveler mobility, and energy, as detailed below:

Mobility:

- A/EV system access walking time and distance from district trip origins.
- Access point (stations/curbfronts) comfort and convenience.
- Walking distance/time between AMD A/EV circulation systems and other transportation mode access points (e.g., regional transit).

Passenger Service Level:

- Average and maximum station waiting time.
- Total trip time = waiting time + in-transit travel time.

Fleet Size:

- Peak period operating fleet: Number of vehicles.
- Off-peak period operating fleet: Number of vehicles.
- A/EV battery-related duty cycle.
- Empty vehicle management operational strategy.
- Percent spare vehicles.

Infrastructure:

- Station/curbfront locations, size, and configurations.
- Intelligent roadway infrastructure: Locations and perception/control features.
- Vehicle battery charging facilities/provisions: Number of charging positions, charging power levels (Level 1, 2, or 3 [DC fast charge]), and charging facility total power supply requirements.

The systems engineering approach described herein applied in the early design phases will allow trade-off analysis of cost and complexity to identify an optimal solution for the most critical elements of an AMD's implementation. The resulting digital twin provides an effective planning and engineering tool as well as the input and output needed to link to energy and other digital twins for further overall district-level system benefits.

Looking forward, the SEM can be used not only in the capacity described above, but also to investigate new forms of mobility that have the potential to augment and improve the systems of systems. In Phase IV of NREL's AMD research, the introduction of A/EV-only roadways (or guideways) will be investigated as a means to leverage the benefits of automated control, while allowing full reuse of the existing roadway system (in that A/EVs can navigate both traditional roadways and special-use guideways/roadways) much in the same way that high-speed freeways and interstates allowed for the benefits of modern automobiles through restricting access to lower speed modes of travel.

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