Initial Assessment and Modeling Framework Development for Automated Mobility Districts

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Initial assessment and modeling framework development for automated mobility districts

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Abstract
Automated vehicles are increasingly being discussed as the basis for on-demand mobility services, introducing a new paradigm in which a fleet of automated vehicles displaces private automobiles for day-to-day travel in dense activity districts. This paper examines such a concept to displace privately owned automobiles within a region containing dense activity generators (jobs, retail, entertainment, etc.), referred to as an automated mobility district (AMD) with the purpose of establishing an appropriate framework to continue with travel modeling activities. The paper reviews several such potential districts including airports, college campuses, business parks, downtown urban cores, and military bases, with examples of previous attempts to meet the mobility needs apart from private automobiles, some with automated technology and others with more traditional transit-based solutions. The issues and benefits of AMDs are framed within the perspective of intra-district, inter-district, and border issues, and the requirements for a modeling framework are identified to adequately reflect the breadth of mobility, energy, and emissions impacts anticipated with AMDs. This paper includes a review of previous relevant literature, and lays the groundwork for subsequent AMD modeling and simulation efforts to assess their mobility and energy impacts.

KEYWORDS:
Automated mobility district, connected and automated vehicles, energy impacts

Introduction and concept definition
The term “automated mobility district (AMD)” was introduced in 2016 to describe a campus-size implementation of automated/connected vehicle technology to realize the full benefits of an automated vehicle (AV) mobility service within a confined region or district. As Silicon Valley and Detroit race to field fully automated vehicles, two approaches are taken. One approach is to incrementally introduce technology into the consumer fleet until fully automated (and likely connected) operation is realized. This is the “something everywhere” approach in which ever-increasing control is given to the vehicle in successive model years. In the other approach, referred to as “everything somewhere,” fully capable automated mobility is deployed, but in a confined region. This latter approach allows developers greater control of the environment and less variance in implementation, thus minimizing risk.

The AMD concept falls in this latter “everything somewhere” approach and is being realized in demonstration projects and some deployments across the United States and the world. AMDs interconnect all activities within a district, such as commercial (retail), entertainment and dining, and employment. Districts with sufficient concentrations of activity are candidates for such AV deployments. Activity centers may include jobs within a corporate campus, residences within a retirement community, classes and housing within an academic campus, or the many activities within a military installation. The common theme in these districts is connectivity among a group of buildings that encompass intense trip attractions—jobs, housing, commercial activities, etc.

The concept of an AMD is not new. High-value districts such as airports, amusement parks, and some campuses already restrict access by automobiles providing access to the property and interconnecting buildings with both non-automated (traditional buses, shuttles, and pedestrian walkways) and automated means (automated people movers [APMs], moving walkways, escalators, and elevators). However, the ability to implement an AMD using AV technology is a potential transformational element with today’s emerging AV technology. The use of AVs within a confined geographic area lowers the thresholds in terms of technology requirements and cost. Reuse of existing road infrastructure without the need for dedicated guideways significantly reduces required infrastructure investment when compared to automated transit solutions which typically require dedicated guideway. The control system can leverage ever-growing vehicle and car ride-sharing logistics software, reducing risk to deliver a robust but sufficiently complex system to provide the required coordination. In all, the ability to field a dedicated automated mobility system restricting or eliminating vehicle access within a district will become feasible for a large number of activity center enclaves wishing to improve mobility and the user environment.

Restricting vehicle access and minimizing the parking reserves that accompany vehicle access provides several benefits within a district. Examples of AMDs using APMs can be observed at most major airports, some amusement parks, and other large complexes throughout the world. Automotive access is restricted to the perimeter, forcing passengers to use the AV system to access the amenities within the district. Such areas, similar in concept to traditional transit-oriented developments, see an increase in car/ride sharing (be it transit or for-profit service providers), which in turn provides benefits to the surrounding region. An AMD based on AV technology can provide similar interconnectivity within a district, greatly lowering the cost threshold, and thus increasing the likelihood of multiple AMDs throughout an urban area, which when networked provide improved mobility without the need for personally owned vehicles.

A modern AMD system can be realized through a fleet of vehicles, envisioned as an automated taxi fleet controlled and dispatched within a limited geographic area. The system can use existing roadway infrastructure and provide personalized customer interaction through digital connectivity with the end user's smart phone. A typical AMD system may have the following basic features:

1) *Fully automated and driverless vehicles*. SAE level 5 vehicles capable of all safety-critical driving functions and able to monitor roadway conditions and to drive itself for an entire trip [1, 2]. Such a design anticipates that the passenger will provide destination input, but is not expected to be available for vehicle control at any time during the trip.
2) *Service is confined to within a geographic boundary that encompasses a relatively dense area of trip attractions, such as a campus area.* This may be a medical, academic, or business park, or any other type of district. Such areas are typified by jobs, attractions, or other activities that draw people on a daily basis. The geographic extent of the mobility system is limited, typically to 4 to 10 square miles.
3) *Mobility within the district is restricted to or dominated by the AMD*. Within the district, access to end destinations is provided primarily by AV service or pedestrian access. Personal vehicles may or may not be strictly prohibited, but at a minimum they are highly discouraged, such as through policies controlling the availability and cost of parking. The district is designed to be most efficiently accessed by the AMD, although other forms may be permitted.
4) *Multi-modal access at the perimeter of the district.* The AMD provides efficient opportunities for modal interface to the AMD, be it bus, light-rail, shuttles, car-sharing, bike-sharing, or other modes. This may include parking reserves for people to transfer from personal vehicles to the AMD to reach their final destinations [3].

On a functional basis, AMDs are closely related to the past concepts of personal rapid transit (PRT) and group rapid transit studied and implemented only a few times beginning in the 1970s. These concepts now go by the name of automated transit networks (ATNs). An ATN is characterized by driverless, on-demand transit that provides direct origin-to-destination service to either individuals or small groups, very similar in concept to AMDs envisioned with AVs. The primary technological difference between traditional ATNs and AV-based AMDs is the need for an exclusive guideway. Note that modern ATN development is moving toward operations that include portions on a dedicated guideway as well as shared roadway infrastructure based on integration of AV technology [4]. The most important aspect of ATNs is that the history of ATN research and modeling provides a basis and lessons learned to explore AMDs and their anticipated impact moving forward.

Examples of AMDs, past and present

Examples of districts that restrict automobile access and provide alternative means (either automated or non-automated) abound, providing insights to AMD operations, modeling, and benefits.

The most prolific example of districts in which private vehicles are completely restricted is at major airports. People who access the airport by private vehicles are required to park at the periphery and access the terminal via parking shuttles. Others use a variety of public or private pooled access to the airport, such as light-rail, buses, hotel shuttles, and for-profit shuttles from various parts of the surrounding metropolitan area. Many major airports incorporate APMs on either the air side (secure side, most prevalent) or the land side (non-secure side). APMs are fully automated and driverless transit systems that operate on fixed guideways in exclusive rights-of-way. As such they are not subject to congestion or interference from other types of traffic [5]. Airport APMs were initially introduced in 1971 at Tampa International Airport as an air-side connector, i.e., a system that operates on the secure side of an airport, typically connecting aircraft gates with airport processing functions (ticketing, bag claims, etc.) or with other aircraft gates. Land-side APMs broaden their functionality to capture more aspects of the AMD concept. Land-side APMs typically connect the airport processing functions with other landside facilities such as parking, car rental, or regional transit [5]. The most representative example of land-side APMs at airports is the 2009 installation of the SkyTrain at Atlanta's Hartsfield-Jackson International Airport that interconnects the terminal, car rental, and the Georgia International Convention Center with two hotel options. This land-side APM provides the traveler with options to access a variety of services without having to use traditional road transportation. Although airport districts provide many examples, activity associated with air travel (such as multi-day stays) is not indicative of other dense activity districts in urban areas that are candidates for AV-based AMDs. However, the tools and processes used to model airport transportation have significant value to analyze proposed AV-based AMDs.

University campuses provide another significant basis for study of AMD-suitable locations. The student and faculty population who must traverse the campus daily (frequently changing locations for classes and other activities during the day) provide a case study in the needs for intra-campus mobility. Often, a significant portion of student housing is on campus. The Morgantown PRT system deployed on the campus of Western Virginia University in the 1970s (and still functional today) is the most significant deployment of the group rapid transit concept internationally. Although the technology used to deploy the system has long since been eclipsed, the benefits and use case remain valid. A system of completely automated vehicles interconnects various sub-campuses, minimizing the need for road-based transportation and allows students to live a "car-free" or "car-lite" lifestyle. The CityMobil2 demonstration of automated electric shuttles in Europe included a campus demonstration in Lausanne, Switzerland, in which students were able to summon a vehicle through a smart phone application. Indeed, many research studies of advanced transportation concepts have been first analyzed with respect to university campuses, likely because they were a familiar environment to researchers with known needs. An initial analysis of AMD energy impacts built upon modeling originally intended to study vehicle–parking–pedestrian congestion issues on the campus of Kansas State University in Manhattan, Kansas, and to relieve congestion through enabling more efficient access to both on-campus and off-campus attractions via a proposed PRT system [3]. Some university campuses physically restrict automobile access, though policy restriction is even more prevalent (such as using pricing or status to limit the number of parking permits available to students and faculty/staff). The desire to promote a high-quality pedestrian environment within the campus core leads to significant experimentation with methods for restricting vehicle access to the perimeter.

Urban centers, sometimes referred to as traditional urban cores, provide additional case studies in which various solutions have been attempted to enhance accessibility to a dense range of activities and to discourage access by private automobiles. Historically, the Urban Mass Transit Act of 1964 resulted in three demonstrations of APMs in urban areas, the Detroit People Mover, the Jacksonville Skyway, and the Miami Metromover. These systems were envisioned to provide alternative mobility in dense downtown areas plagued by accessibility issues brought on by the over-reliance on vehicles. Although these three are examples of automated solutions, many cities have used other methods to encourage quality mobility, while discouraging vehicle use and circulation. A recent example is the Free Metro Ride in downtown Denver. Constantly circulating buses between Union Station and Civic Center Station along 18th and 19th streets (on which vehicle access is restricted) provide options for commuters to conveniently access the core of Denver. This encourages non-automotive access to downtown using transit or ride-sharing services, as well as encouraging people to park at the perimeter and not create undue congestion while circulating for parking near a particular attraction.

Business Campuses are less represented in literature, although they are still targets for mobility districts. Google and Apple in Silicon Valley have both studied automated systems for campus circulation, although none has been implemented. Amusement parks and entertainment districts are likely to have AMDs second only to airports in the implementation of custom (and some automated) systems to provide access to attendees while restricting vehicles to the perimeter.

Military bases provide the final example of districts for consideration of AMDs. Newell [6] investigated the potential use of automated driving, car sharing, and ride sharing in military installations, envisioning that car sharing and ride sharing with automated driving could not only replace government-owned fleets and personally owned vehicles, but also could serve the everyday commute of government employees residing off base. Automated car sharing and ride sharing could provide users with a more optimized mobility service and enable parking lots/charging stations to be remotely located. Newell's analysis estimated that car sharing and ride sharing can reduce personal vehicle ownership by 42% to 78%. Military bases provide key advantages for early AMD implementation: they 1) are controlled environments with clear boundaries; 2) have controlled environments with low speed limits under a single jurisdiction; and 3) have a known user pool including service members, their families, and government employees.

Movement challenges and technologies of activity centers

Providing high-quality mobility to and within districts containing dense activity centers shares a number of common challenges. Though the type of district may determine the priority or relative importance of each, the general issues facing activity centers include:

- *Amount and proximity of parking:* Many campus settings (either academic or corporate) are primarily accessed by private automobile even when other traditional transit options are present. The quantity, quality, and proximity of parking become primary issues in determining the overall quality of mobility. This is also true of urban centers and other districts. In both these types of districts, inadequate parking space manifests itself in excess vehicle circulation in search of parking, which in turn increases vehicle–pedestrian congestion, creating additional safety concerns as well as deteriorating the attractiveness of the pedestrian environment.
- *Effective intra-campus circulation:* When the geographic expanse of districts exceeds common walking distances (or in extreme environmental conditions such as heat, humidity, or cold) intra-district circulation becomes a concern. Although many campuses have traditional shuttle service, its frequency and quality often prompt users to use personal vehicles to relocate within the campus (if parking is available).
- *Pedestrian–vehicle conflict and congestion:* Some districts may limit or fully prohibit vehicle circulation within the campus boundaries to maintain an attractive pedestrian environment. As campuses grow, the demands of efficient access via automobile conflict with intra-campus pedestrian movement, creating undesirable conflicts for both modes and introducing safety concerns, primarily for pedestrians and cyclists.
- *Efficient multi-modal access:* Medical, academic, recreation, and other campuses typically encourage their clientele to access campus facilities using non-personal vehicle methods. Public buses, private shuttles, line-haul systems (rail and light rail), ride-hailing (e.g., Uber, Lyft), all provide options, but without an efficient intra-campus mobility system, such systems fail to provide full and efficient service to patrons for all campus destinations and for intra-campus trips.

In some circumstances, security issues created by private automobile (or even rental vehicle) access may also be a motivating factor to restrict vehicle access within a district. The extent to which this may be a driving factor for adopting technologies to enable an AMD is beyond the scope of this paper.

Proposed benefits of an AMD

An AV-based mobility district is postulated to address the challenges of dense activity districts, and even reduce their transportation energy impact. The impact of AMDs on mobility and energy use can be analyzed from intra-district, inter-district, and border issue perspectives. “Intra-district” is the extent to which quality of mobility and minimization of energy use is impacted for trips within the district. An “inter-district” or “inter-regional” perspective analyzes internal-to-external and external-to-internal mobility and associated energy use consequences, as well as possible trips between distinct AMDs. As the prevalence of AMDs within a metropolitan area increases, the opportunity to inter-connect the AMDs with shared and/or automated services further increase. Boundary issues/impacts result at the perimeter of the district and encompass modal transfer facilities, parking, and curb-side drop-off opportunities. The intra-district, inter-district, and boundary impacts are illustrated in Figure 1.

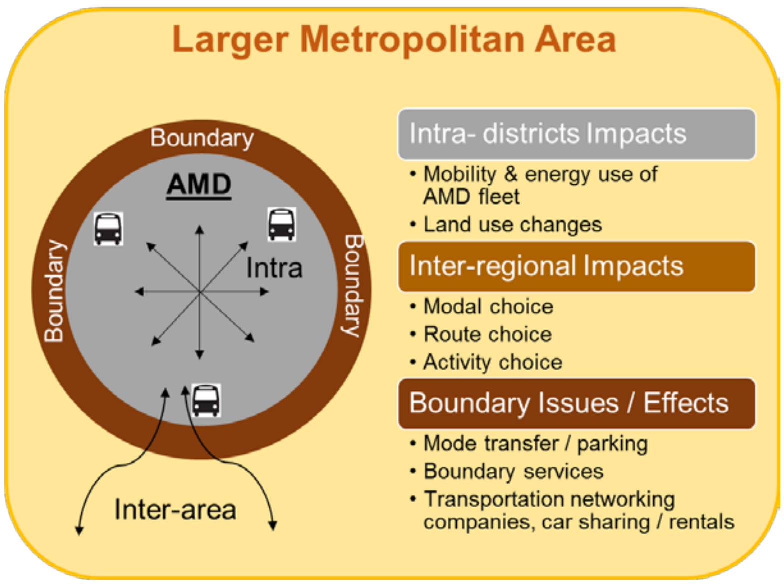

Figure 1 Analysis perspectives of AMD impacts within an urban area.

Intra-district impacts and effects are largely the result of eliminating vehicular trips and replacing them with AMD services. Mobility and energy impacts are internal to the district and include:

- Reduction (or possible full elimination) of personal automobile trips within the district and replacement by alternative modes including electric vehicle-based AV mobility
- Reduction in parking lots and structures internal to the district, freeing land for re-development and possible densification
- Reduction in vehicle–pedestrian congestion and conflicts, and associated safety benefits
- More efficient intra-campus mobility, enabling more flexible use of capital assets such as classroom, labs, etc.
- Land use and infrastructure changes that favor pedestrian activity, minimize road infrastructure and parking, and maximize curb-side drop-off/pickup.

Intra-district energy impacts can be directly observed and measured in deployed systems. Travel using personal automobiles is directly replaced by AVs, typically electric, on the roadways.

Inter-district impacts are those that affect the methods and patterns for accessing the district. Mobility and energy impacts arise from such issues as:

- Modal choice for accessing the AMD may change. A public transit or shared ride system (car-pool, transportation network company (TNC), etc.) may more efficiently aggregate riders to access the services across the AMD. Passengers traveling to any point in the district can disembark at the closest point of approach, allowing for greater opportunity of ride sharing or

more efficient transit. Without the AMD, travelers to two different destinations within the district may not be able to effectively use the same shared mode.
- Drivers' route selection may be altered and shortened. Rather than vie for parking close to the end destination, drivers only need to reach the boundary at the closest point of approach.
- Activity choices may be altered to favor the well-connected services within a district. Analogous to transit-oriented-design in which services are concentrated on a well-serviced corridor, attracting greater patronage for businesses, an AMD likewise will provide access to multiple-services in a region (rather than corridor for transit-oriented-design), providing a single point at the perimeter to access a variety of services.
- More activity clustering may be enabled. Trips that had been separated could be chained together using the AV mobility system within an AMD.
- Inter-AMD (that is mobility between adjacent AMDs) trips can better aggregate travelers to provide more efficient shared ride options, be it transit, automated taxi, or casual carpooling. This latter affect is greatly unknown as no such paradigm currently exists (to the authors knowledge). Multiple AMDs within an urban region may create a dynamic in which interlinkages between AMDs can be served with efficient, automated, shared, electric conveyance due to the high demand.

Inter-district mobility and energy impacts are primarily driven by changes in trip-making behavior. Understanding these impacts requires broader geographic data collection to assess changes in trip patterns resulting from AMD implementation. Though the impacts are observable, data collection for changes in route, mode, and activity clustering have traditionally been more difficult (and more costly) than for simply assessing intra-district impacts.

Boundary issues and effects encompass inter-modal transfer opportunities, as well as other commercial activity at the boundary due to convenient access. These include such aspects as:
- Locating car-share and bike-share assets at the boundary/perimeter to maximize usage potential for inter-district mobility.
- Appropriate siting and capacity of parking reserves. Adequate parking available at all major points of approach will limit traffic due to drivers searching for parking, encouraging access to the AMD from the closest point of approach.
- Inter-modal transfer facilities for transit. The AMD could substantially increase the catchment area for a regional transit facility or a shuttle system.

Note that these three perspectives may overlap in some respects. For example, well-planned parking reserves at the perimeter of the district will encourage better route selection and increase opportunities for car-pooling.

Literature review

Literature addressing the energy impacts of AMDs is taken from related applications involving AVs and/or mobility within dense activity districts.

Automated transit and PRT

Lowson [7] evaluated a new transport system, ULTra (Urban Light Transport), centered on fully automated electric vehicles in terms of efficiency and sustainability benefits. The ULTra system is an ATN system. Because the ULTra system is electrically powered, there is zero source emission in the city. Furthermore, energy use and emissions are substantially less than for other forms of motorized transport. With average system energy consumption of 0.55 megajoule per passenger-kilometer traveled, its benefit compared with conventional gasoline-powered cars is over 75% and could be as high as 90% under peak traffic periods during severe congestion. Lowson also conducted a detailed study for an application of ULTra system in Cardiff, Wales, and concluded that about 1 million gallons of fuel could be saved in Cardiff for 2006.

The ULTra vehicle, as deployed at Heathrow airport, is illustrated in Figure 2. It is based on conventional automotive technologies, but is powered by electricity with four rubber wheels. The prototype vehicle from which the Ultra system at Heathrow was developed, is 3.7 meters long, 1.45 meters wide and 1.6 meters high. The gross weight is 800 kilograms. It can accommodate four passengers at a time, and the maximum traveling speed is 40 kilometers per hour. In addition, because the vehicle is light and only travels at low speeds, the power requirements are low and the battery could be charged quickly. As an ATN, the ULTra system does require a dedicated, though small, guideway.

Figure 2 ULTra in service at Heathrow Terminal 5. Photo by Stan Young, NREL

Young et al. [8] evaluated the proposed implementation of an ATN in Manhattan, Kansas, on the campus of Kansas State University. The Manhattan community encompasses approximately 11 square miles and had a population of 44,800 in 2001. The ATN system adopted a set of guidelines common to ATN systems (Table 1).

Table 1 Essential characteristics of a PRT system

Category	Characteristics
Vehicles	1. Fully automated—no human drivers. 2. Captive to the guideway. 3. Available for exclusive use by an individual or small groups traveling together. 4. All vehicles are able to use all guideways and stations on a connected network.
Guideways	1. Exclusive use only by PRT vehicles. 2. Small in size and weight. 3. Can be elevated, on the ground, or underground.
Service	1. 24 hours a day. 2. Direct origin-to-destination, no transfers or stopping at intervening stations. 3. Available on demand rather than on fixed schedules.

A network model simulated changes in travelers' behavior, e.g., deciding between driving directly to campus or walking to a station on the edge of campus and riding the ATN. Their results show that, depending on service frequency of the PRT system, various numbers of travelers will choose to use the ATN system. Average wait time for a vehicle was the primary parameter that determined system usage. Wait times of less than three minutes significantly increase ATN usage over the nominal case. The results of the mobility impact of the ATN are summarized in Table 2, showing the shift of person-miles traveled and person-hours traveled as a function of ATN responsiveness.

Table 2. Mobility impact of the ATN

		Base Scenario	Service Frequency		
		No PRT	6 Min.	3 Min.	2 Min.
Person Miles Traveled per Day	Driving Personal Veh.	40,131	38,352	36,621	35,807
	Walking	20,216	18,814	16,770	15,681
	Riding the PRT	0	3,604	8,169	10,279
	Total	60,347	60,770	61,560	61,767
Person Hours Traveled per Day	Driving Personal Veh.	2,014	1,927	1,842	1,805
	Walking	5,037	4,688	4,186	3,923
	In the Parking Lot	1,877	1,686	1,532	1,497
	Riding the PRT	0	458.2	842.6	1,035
	Total	8,928	8,759.2	8,403	8,260

The analysis indicates an increase in person-miles traveled with increasing system responsiveness over the base scenario. A follow-up study by Chen et al. [3] showed that total system energy use decreased even under conservative assumptions with respect to ride sharing and empty vehicle recirculation, with energy reduction varying from 3% to 5% with a three-minute service frequency, noting that person-miles traveled within the AMD accounted for only 10% of the vehicle mileage. This analysis assumed that travel within the AMD was based on internal combustion engine vehicles, not electric vehicles. Further energy reduction could be gained from an electric vehicle-based system.

Automated shuttles

CityMobil2 is a European Union 7th Framework Programme for research and technological development. As a follow-up to the CityMobil Project (2006–2011), CityMobil2 started in September 2012 and finished in August 2016 and was coordinated and led by the University of Roma in Florence. It is building a pilot platform for automated road transport systems (ARTSs), which were implemented in several cities across Europe [9]. The project considered the technical, financial, cultural, and behavioral aspects and effects of land-use policies and the compatibility of new systems with the existing infrastructure in different cities [9]. CityMobil2 is designed to supplement existing public transit systems, offering collective, semi-collective and personal on-demand shuttle services [10]. The project provided the autonomous shuttles, called Cybercars, which provide a ride-to-the-ride for low-demand and far away pick-up points, to get the travelers to transfer to the next leg of the journey [10]. Cybercars operated autonomously using obstacle-avoidance technology on the existing roadways among vehicles, bikes, and pedestrians. The manufacturers of automated shuttles have been discussed in literature and include EasyMile and NAVYA [11].

In July of 2014, the first demonstration began in the small Sardinian village of Torre Grande with two automated vehicles from EasyMile. The town of Oristano offered infrastructure and logistic support, and the regional public transport operator Azienda Regionale Sarda Trasporti (ARST) managed the operation of the service in this demonstration. A larger CityMobil2 demonstration began operating in La Rochelle, a French town, in the fall of 2014. Another on-road demonstration took place in May 2015 at the 2015 Expo in Milan, Italy [10]. The CityMobil2 demonstration in Donostia–San Sebastián was conducted at the Gipuzkoa Science and Technology Park from March 2016 through June 2016. Other similar demonstrations were conducted in other European cities such as Lausanne, Switzerland, and Trikala, Greece [12].

Benefit and outcomes [11]:

- Automated road transport system (ARTS) ran for at least six months at five sites across Europe.
- An ARTS was demonstrated in the real world.

- Understanding of the interaction between automated shuttles and other road users was increased,
- A legal framework for certifying automated road transport systems in Europe was tentatively proposed.
- Technical specifications for interoperable ARTSs were developed, including a communications architecture.

Lessons learned from the CityMobil2 demonstrations [13]:

- The reality is very often more demanding and complicated in practice. Random vehicle malfunctions occurred.
- An ARTS interacts with pedestrians and cyclists, making it possible for road users to get used to the situation that a part of the road will be restricted for use by the ARTS only or that the ARTS has priority in a given part of the road.
- The legal issues for certifying automated transport systems have to be addressed [9].

A project similar to CityMobil2, the WEpod project (www.wepods.com), was launched in January 2016 in the province of Gelderland in the Netherlands. It used EasyMile's EZ10 shuttles and was operated on the campus of Wageningen University, with the test route limited to a circular loop around the campus [11].

A two-year demonstration project in the Swiss city of Sion has used automated shuttles, the CarPostal ARMA shuttle, on public roads. In this project, the interest is not only to test automated vehicle technology but also to determine if these vehicles can provide mobility in regions that currently are not serviced by public transportation. The project needs legal authorization to operate on public roads [11].

To address the challenge of first-mile, last-mile transport using AVs, Contra Costa Transportation Authority (CCTA) signed an agreement with EasyMile in October 2015 for a two-year test of two EZ10 automated shuttles to determine the potential of automated shuttles filling in the gaps of traditional public transportation [10]. The CCTA project included a fleet management component. Like other projects, CCTA has to have legal authorization to operate the automated vehicles on public roads.

Minnesota Valley Transit Authority (MVTA) used a global positioning system-based driver assist system (DAS) for bus-on-shoulder (BOS) operations. The DAS is a lane-keep assist and collision warning system that the operators use when on the shoulder. The Twin Cities metropolitan area has an extensive network (approximately 250 miles) of BOS operations. In 2015, the Federal Transit Authority awarded MVTA $1.79M to equip 11 more buses with the DAS. This second iteration of the DAS (Gen2 DAS) developed by MTS Systems Corporation is an updated and commercialized version [11].

Although significant interest has been generated in electric automated shuttles as a result of CityMobil2 and similar projects, little if any energy impact analysis is available.

Shared AVs, automated Uber/Taxi

Kornhauser et al. [14] explored the applicability of a fleet of automated taxis (aTaxis) with ride-sharing in New Jersey. In the model, aTaxis wait a given time before departing from designated stations. Passengers board at these stations and share a ride if they have similar destinations. Kornhauser et al. [14] developed a system that can identify ride-sharing opportunities based on traffic demand data. The analysis method aggregated travel demand into spatial grids, analyzing the propensity of ride sharing with respect to space (using rules about adjacency of grid origins and destinations) as well as time (proximity of time departures.) The aTaxis work did not extend to the impact of AMDs, but provides an extensible framework to analyze AMD impacts (ability to pool trips from or to a district with larger spatial catchments.)

Burns et al. [15] developed both analytical and simulation models to estimate the cost and performance of a shared fleet of driverless vehicles—a combination of the "mobility Internet," driverless vehicles, shared vehicles, specific-purpose designs, and advanced propulsion. The models are developed based on some key factors including area of the region, mean trip length, mean trip rate, mean vehicle speed, average fixed time needed per trip, fleet size, and vehicle cost. The model is then applied to three case studies: Ann Arbor, Michigan; Babcock Ranch, Florida; and Manhattan, New York. The study concludes that a shared fleet of driverless vehicles is able to offer better mobility experiences at a very low cost. These transformational mobility systems also provide benefits such as roadway safety enhancement, traffic congestion mitigation, increasing energy efficiency, emission reduction, and land use improvement.

Fagnant and Kockelman [16] assessed the mobility and environmental benefits of shared autonomous vehicles (SAVs), also known as automated taxis or aTaxis, by modeling the movement of travelers throughout a grid-based urban area by using an agent-based simulation. The results imply that each SAV can provide as much service as approximately 12 conventional vehicles, but incur about 10% additional travel distance. SAVs are expected to produce tremendous energy and emission savings with older and more polluting vehicles replaced by newer and cleaner ones.

Fagnant et al. [17] investigated SAVs, a new transportation mode combining short-term, on-demand rental vehicles with self-driving capability. Traffic simulation was performed in a 12-mile by 24-mile region in downtown Austin, Texas, by using MATSim’s dynamic traffic assignment simulation software. The results showed that each SAV is able to offer service that replaces nine conventional vehicles within the study area. Although 8% more trips were generated because of unoccupied vehicle travel, the number falls within the increase of demand density. In addition, SAVs may reduce vehicle emissions by replacing many existing heavy vehicles with higher emission rates and reducing cold-start emissions.

Fagnant and Kockelman [18] examined the potential benefit of introducing dynamic ride-sharing, a transportation mode that pools multiple travelers with similar origins, destinations, and departure times in the same vehicle, to existing agent-based SAVs simulation models with an adoption level less than 10% of all travelers in the study region. With the adoption of dynamic ride-sharing, total service times and travel costs for SAV users fall. The average waiting time at the heaviest peak hour falls from 9.0 minutes to 4.5 minutes. Dynamic ride-sharing may reduce excess vehicle miles traveled from 8% to 4.5%. The investigation of the profitability of SAVs demonstrates that a private fleet operator could earn 19% annual return on SAV investment by assuming a SAV purchase price of $70,000 and a travel fare of $1 per trip-mile.

Challenges of AMD study

While AMDs are expected to achieve benefits with respect to reducing vehicle ownership, congestion, energy use and emissions from personal travel, rigorous AMD impact analysis is challenging as it must consider many modes of travel, intra- and inter-district impacts, and models of both the travel network and of consumer travel choices. Most previous AMD-related studies (in the vein of ATNs or automated taxis) were simulated based on hypothetical scenarios or assumed traffic parameters, such as traveler adoption rate, trip request rate, ride-sharing occupancy, fleet size, and vehicle operating speed. These critical parameters significantly affect the traffic simulation results of mobility, cost, energy use, and emissions impact of AMDs. Furthermore, most previous studies concentrate on only a single domain of impacts, be it simulating operations of the system to determine the number of AVs required, anticipated wait time, or consumer reaction in terms of anticipated ridership. Holistic approaches that capture the full scope of mobility shifts are rare in literature. Obtaining objective and defensible traffic and ridership projections based on real field data remains one of the largest challenges of AMD studies because of limited field deployments of AVs. Generalized knowledge about traveler behavior within the AV domain is extremely sparse from previous limited automated vehicle deployments.

The other major challenge identified from previous studies is the development of modeling and analysis frameworks to assess the various contributing components to AMD impacts. The AMD concept of AVs serving as the basis for a public mobility, on-demand traveler request is relatively new (apart from older ATN studies) and is different and distinct from modeling frameworks for traditional transit modes which are highly reliant on captive ridership. Thus, there are no well-established simulation or widely accepted modeling tools or methodologies for impact analysis. Conducting AMD research requires transportation researchers to have strong programming capabilities to customize existing simulation tools for AMDs or build a simulation model from scratch.

The impact of AMDs on travel behavior of individuals is still unexplored territory. Will AMDs pave the way to more sustainable travel patterns? Will there be an increase in travel demand as people enjoy affordable transportation on-demand while increasing their productivity during travel? What is the impact of AMDs on short-term (mode choice) and long-term travel behavior such as vehicle ownership and use)? These questions need to be answered to accurately quantify the impacts of AMDs.

Directions for future research

Based on a literature review of AMDs, the following critical gaps were identified. Almost all of the existing AMD-related studies are simulation based and rely on numerous hypotheses and assumptions. While the results from existing studies provide a general idea of the impacts of AMDs on travel, none of the studies have been validated with actual field data. Future research should focus on models and frameworks informed from a full-scale field implementation of an AMD. Such an implementation is necessary to address the challenges identified above, and validate the assumptions made by previous studies. Questions pertaining to adoption rates; increase of vehicle miles traveled; operational attributes (frequency, fleet, and ridership); and energy/emission impacts of AMDs can be answered with certainty only after the users experience AMDs first-hand. This may be through deployments currently in engineering (as there are several throughout the world) or deployed AMDs based on more traditional automated transit technology.

Future research efforts should focus on developing a standard set of tools and metrics that will serve as benchmarks to design and deploy AMD systems across the United States and provide a basis for future research and development as AMDs are increasingly adopted. Such tools may include survey templates regarding traveler adoption and preference, travel behavior models, mobility and energy impact analysis frameworks, and traffic simulation models for AMD studies, as well as performance criteria that span quality of mobility as well as energy and emissions impacts of the system. Investigating AMD return on investment is another critical area for future research. Anticipated outputs from AMD studies include insights on parking needs and pricing, fleet size, frequency of service and accessibility through smart phone applications. Optimization techniques should be explored to minimize operational cost and maximize the mobility service and energy savings. Stakeholders interested in these insights include cities, transportation departments, federal agencies, fleet managers and policymakers desiring to maximally leverage potential AMD benefits.

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