Automated Mobility Platforms: A Framework for Versatile, Energy-Efficient Urban Transportation for the 21st Century

Preprint

Stanley E. Young,[1] Kevin L. Moore,[2] Stanley A. Young,[1] Andrew L. Duvall,[1] Mark Orrs,[2] Colin Endsley,[2] Arianna Castro,[2] Israel Olivas,[2] Jee Hoon Bae,[2] and Logan Cummings[2]

1 National Renewable Energy Laboratory
2 Colorado School of Mines

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
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Automated Mobility Platforms: A Framework for Versatile, Energy-Efficient Urban Transportation for the 21st Century

Stanley E. Young, P.E.,[1] Kevin L. Moore, Ph. D.,[2] Stanley A. Young,[3] Andrew L. Duvall, Ph.D.,[4] Mark Orrs, Ph.D.,[5] Colin Endsley,[6] Arianna Castro,[7] Israel Olivas,[8] Jee Hoon Bae,[9] Logan Cummings[10]

[1]National Renewable Energy Laboratory, Golden, CO 80401; e-mail: stanley.young@nrel.gov
[2]Colorado School of Mines, Department of Electrical Engineering, Golden, CO 80401; e-mail: kmoore@mines.edu
[3]National Renewable Energy Laboratory, Golden, CO 80401; e-mail: stanley.a.young@nrel.gov
[4]National Renewable Energy Laboratory, Golden, CO 80401; e-mail: andrew.duvall@nrel.gov
[5]Colorado School of Mines, Golden, CO 80401; e-mail: orrs@mines.edu
[6]Colorado School of Mines, Golden, CO 80401; e-mail: cendsley@mines.edu
[7]Colorado School of Mines, Golden, CO 80401; e-mail: ariannacastro@mines.edu
[8]Colorado School of Mines, Golden, CO 80401; e-mail: iolivas@mines.edu
[9]Colorado School of Mines, Golden, CO 80401; e-mail: jbae@mines.edu
[10]Colorado School of Mines, Golden, CO 80401; e-mail: lcummings@mines.edu

Abstract

This paper presents automated mobility platforms (AMPs) as a framework to deliver high-quality urban mobility. AMPs leverage advances in sensing technology developed from automated roadway vehicles to provide opportunities for efficient movement of people and goods in dense urban environments, campuses, and large facilities like airports. In this paper, we layout the concept of AMPs and how they can serve the mobility needs of the population by providing service at the intersection of micromobility (services such as electric scooters or bikes), personal rapid transit, and moving walkways. Several key attributes and justification for the AMPs concept are described, including improvements to accessibility (inherent in design) covering both socioeconomic and disability equity, safety, energy efficiency, cost-effectiveness, urban land and space management, and scalability. We summarize the results from an ongoing national laboratory-sponsored, faculty-supported, student-led investigation into AMPs that includes stakeholder engagement and technical feasibility assessment.

Introduction

Automated mobility platforms (AMPs) can fill a service gap in short-distance or district-scale transportation at the intersection of micromobility (an umbrella term to capture manual and electric scooters and bikes) and automated people movers such as moving walkways. AMPs incorporate automated vehicle operation to deliver on-demand service for various locales, based on a use of lightweight platforms as an embedded service in the infrastructure fabric, in the same fashion as elevators and escalators serve vertical movement in a multistory building and moving walkways within a large facility like an airport. Accordingly, AMPs are envisioned as an integral part of infrastructure design of a development. An AMP system is automated in that it requires minimal passenger and operator input, and on-demand so that it can be summoned through a wireless communications device, such as a cell phone, or from a kiosk. The design subsumes the Americans with Disabilities Act (ADA) accessibility principles from the start, and equitable access through a focus on providing mobility to serve everyone, without regard to socioeconomic status. Current transportation systems centered on private automobiles are among the greatest impediments to mobility equity. An AMP system incorporates aims for energy efficiency through lightweight design, electric propulsion with inductive charging, and efficient supervisory dispatch algorithms. The system also enables space efficiency through shared operation of small vehicles, automated storage, and relocation of vehicles to serve as needed. AMP vehicles can function without the need for a fixed guideway, but more optimal operation necessitates separation from larger vehicles to maintain safety, and from pedestrians to avoid interaction. A conceptual rendering of an AMP vehicle is presented in Figure 1, and a rendering of an AMP system in an airport setting is shown in Figure 2.

Figure 1. Conceptual rendering of an AMP vehicle.

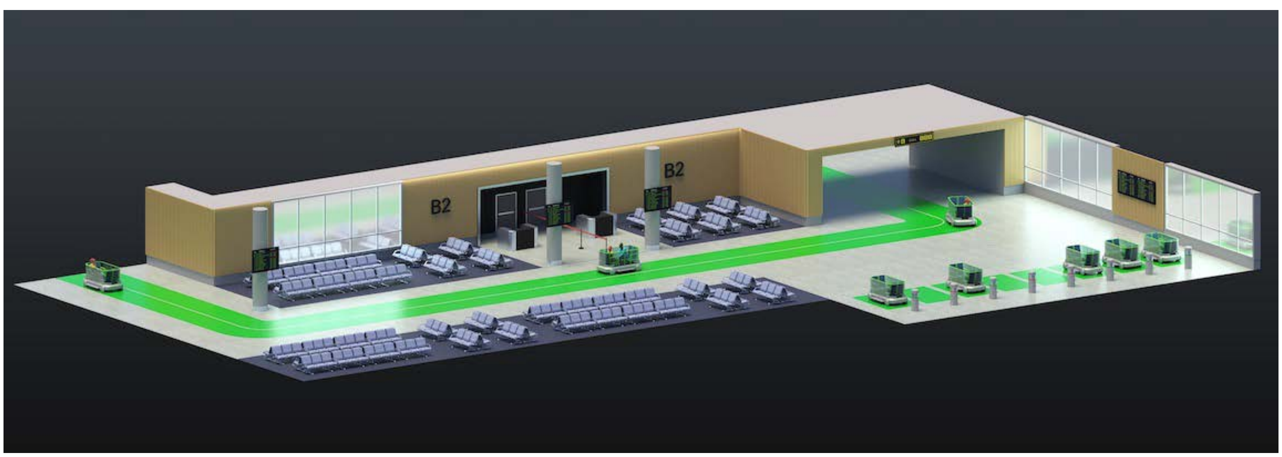

Figure 2. AMP system in an airport setting.

History

Visions for a new, high-tech urban mobility date back to the late 1960s. The most notable demonstration project was the automated people mover constructed in Morgantown, West Virginia in the 1970s as a demonstration of the personal rapid transit (PRT) concept. PRT was defined as an automated, demand-responsive, direct origin-to-destination transit service using a fleet of small vehicles. Morgantown succeeded in demonstrating most of the tenets of PRT, but their vehicles could hold up to 21 people (bordering on "automated group transit," or AGT) (Raney et al. 2005). Although technically successful, PRT did not achieve wide market acceptance, though demonstrations of PRT continued. In addition to the Morgantown PRT system—which remains functional on the campus of the University of West Virginia—systems at Heathrow airport terminal five (Bly 2013), Rivium, and Masdar (Gustafsson 2013), all of which remain operational to this day, captured the PRT or AGT technical concepts in physical systems using proprietary technologies. Indeed, some airport systems, most notably the Dallas Fort Worth AirTrans system that served the airport from 1974 to 2005, captured some of the PRT concepts with the technology of the day. However, none of the systems that embraced PRT concepts achieved widespread commercial success.

Emerging automated vehicle technology combines advanced sensors, robotics, control systems, artificial intelligence, and battery electric propulsion. Simultaneously, inductive power transfer technology has made significant progress and achieved a level of standardization in recent years (SAE 2020). Such technological advancement spurred the investigation and experimentation into a transformational framework for mobility in dense developments. Concerns of energy efficiency, equitable access, safety, and human-scale urban design call for a renewed investigation toward a practical, efficient mobility system that serves all.

Current Transportation and Mobility Challenges

Safety

The U.S. Department of Transportation cites safety as one of its top priorities (DOT n.d.). In their effort "to protect America from health, safety, and security threats," the Centers for Disease Control and Prevention (CDC) reports "Road traffic crashes […] are the leading cause of nonnatural death for U.S. citizens residing or traveling abroad" (CDC 2020). The National Highway Traffic Safety Administration states that "35,000 people die in motor vehicle related crashes in the United States each year" (NHTSA n.d.). A report by McKinsey & Company explains, "For every person killed in a motor-vehicle accident, 8 are hospitalized, and 100 are treated and released from emergency rooms. The overall annual cost of roadway crashes to the U.S. economy was $212 billion in 2012" (Bertoncello et al. 2015). The CDC shares, "every day, almost 3,700 people are killed globally in crashes involving cars, buses, motorcycles, bicycles, trucks, or pedestrians" (CDC 2020).

Figure 3 illustrates the number of fatal and injury crashes for several age groups. The shape of the graphs, often referred to as the "bathtub curve," reflect greater hazard exposure for the young (ages 16–17) and the old (80+). This is most pronounced for fatal crashes.

Figure 3. Bathtub curves for auto accidents (Tefft 2017).

Energy Efficiency

Progress has been made in recent decades regarding the expansion of transportation modes available to Americans, particularly in urban areas. Ride-hailing services like Uber and Lyft have provided additional access and flexibility in the way the general population accesses goods and services within a city. The rise of online shopping and other online conveniences has resulted in a lesser need to travel, and subsequently overall travel has decreased slightly and spans more modes of transportation compared to 2001 (Spring et al. 2018). Micromobility services have appeared in cities providing additional options for district-scale mobility, as well as first/last mile connections. Despite this progress, nearly 70% of travel done by Americans is in a private vehicle (Spring et al. 2018), and 86% of commuters travel to work in their own car (Richter 2019). There are hundreds of millions of cars in the United States; the National Household Travel Survey of 2017 counted 222.5 million vehicles out of 256 million people surveyed (National Household Travel Survey 2017). The average American in 2017 traveled 36 miles per day, and the average vehicle fuel economy was approximately 24.9 miles per gallon, meaning the national fuel consumption rate was roughly 470 million gallons per day (Spring et al. 2018; EPA n.d.). Transportation eclipsed power generation in recent years as the number one overall sector for greenhouse gas emissions.

Spatial Constraints

Traditionally, the solution to reducing urban traffic congestion has been to add roadway capacity with additional lanes or routes. However, such solutions pose unintended consequences of induced demand, meaning more roadway infrastructure or capacity encourages more travel, but not necessarily improved mobility (Schneider 2018). Freeways that spawned the suburbs and longer commutes, when widened, also encourage development even further to less expensive real estate. This creates even longer commutes, but still the same trips—with no increase in fundamental mobility; that is, connecting people with a wide variety of goods, services, and employment opportunities. Roadway capacity can even decrease access to goods and services and create social isolation when used as an instrument to further decrease density of development, lengthening trips to access opportunities.

Transportation in the U.S. is dominated by personally owned and operated vehicles as opposed to public transportation. Time efficiency and convenience resulting from vehicle ownership (which has resulted in great productivity advances) have driven this cycle for decades. However, vehicle operation becomes challenged in higher density urban areas where parking requirements, congestion, and other spatial constraints for roads and parking structures work against the efficiency of the vehicle-highway system.

Equity of Mobility Access

Many Americans take personal transportation for granted, not realizing the independence and freedom that comes with owning a personal vehicle. In many places, ownership or access to a personal vehicle is a prerequisite to employment. *No car, no job; no job, no car* is the paradox of employment access in America (Fund for Our Economic Future 2021). Having a personal vehicle equates to freedom from adhering to public transportation schedules, and to be self-reliant and independent. Owning a personal vehicle is more convenient, saves time, and allows individuals to take unplanned trips and to travel farther faster than alternate modes in most cities. Having a personal vehicle can undoubtedly improve one's quality of life, but for a substantial portion of the U.S. population, owning and/or operating a personal vehicle is not a feasible option. Many Americans are limited by the cost of owning a personal vehicle, the cost of learning to drive, and difficulties with licensing, health issues, disabilities, and age.

Obtaining a car is among the biggest purchases a person will make in their lives. The cost to own and operate a vehicle includes fuel, insurance, license, registration, maintenance, and car depreciation. The American Automobile Association has broken down these costs and estimates that the average overall cost to own and operate a vehicle in 2021 is $9,666 (AAA 2021). Car expenses equate to approximately 20% of the U.S. median annual household income of $49,725. For lower-income households, cost of ownership is proportionally larger. The difficulty in accessing reliable transportation contributes to socioeconomic disadvantage.

In addition to economic limitations to mobility access, those who are not physically able to drive a car (whether because of disability, age, or other factors), are limited as well. For this large and growing segment of the population, current transportation options are often inadequate.

Discussion

Many of the challenges in our current mobility systems offer opportunities for improvement if clean slate approaches are considered. The core of the AMP concept sets aside entrenched ideas about vehicles and infrastructure to focus on meeting mobility needs. In each area of challenge, AMPs are well suited to leverage emerging mobility technologies and expand mobility options to improve outcomes. This section discusses facets for which AMPs offer solutions.

Safety

A 2007 publication in the *American Journal of Epidemiology* investigating motor vehicle crash rates by travel mode discovered that fatal injury rates were highest for motorcyclists, pedestrians, and bicyclists (Beck 2007). A research article from *Consumer Reports* on safety benefits of automated vehicles states that in 2012, pedestrian deaths from motor vehicles accidents accounted for 14% of all crash fatalities (Consumer Reports 2014). These findings suggest that smaller vehicles and non-motorized modes are at risk in mixed traffic situations, and that physical separation from large vehicles, a key aspect of the AMP concept, could return safety benefits. The current transportation system poses risks to users, confirmed by the NHTSA findings that road traffic crashes are a leading cause of death in the United States for people aged 1–54, and that more than half those killed are pedestrians, motorcyclists, or cyclists. Additionally, NHTSA reports that 94% of serious crashes are due to human error (NHTSA n.d.).

By removing the prospects of human operator error, an AMP system can contribute to improved safety outcomes. Although automated systems are not immune from failures, they do have inherent protection against human-caused crashes. Automated systems do not drive while impaired, do not drive while texting, do not get tired, and eliminate human sensing and perception limitations that can tragically result in fatalities and injuries. This will ultimately decrease the number of fatalities and injuries within our surface transportation system.

While the automotive industry must overcome the technical challenges of "corner cases"—that is, handling the numerous unexpected situations that arise when driving on public roads—a public AMP mobility system using established spatial perception technology, constrained to a network of protected travel lanes in a manner analogous to protected bicycle paths, AND limited in speed to 25 to 30 mph can greatly reduce the hazard potential of personal mobility. Indeed, the Morgantown PRT, which operates separately from other vehicles, was crash free from its inaugural service until 2016 when two vehicles collided with only minor injuries due to system control software failure, and another incident in 2020 due to a rockslide. Neither crash resulted in serious injury.

Energy Efficiency

The AMP concept can result in vast efficiency gains for our transportation habits. Fifty-six percent of trips taken by Americans are to either work or home (Spring et al. 2018), and most trips are short, under 3 miles in length. Most travelers drive alone rather than carpool, and usually do not bring enough cargo to their destination to justify the size and power of their vehicle. AMP systems could reduce such inefficiencies in much the same way as carpooling in that one vehicle, smaller in size than a typical car, could serve multiple passengers, contributing to a substantial reduction in energy use.

From a physics perspective, energy consumption is roughly proportional to mass due to laws of dynamics and friction losses. Current vehicle weight averages 4,156 pounds according to the Environmental Protection Agency, whereas an AMP vehicle at a nominal curb weight of 500 pounds would lower the vehicle mass to passenger mass ratio from an order of magnitude different to within the same magnitude. Although no formal study on AMP system energy efficiency has been conducted to date, experience from micromobility (Sun et al. 2021) and other modes with closer to 1:1 vehicle to occupant mass ratios suggest greater fuel efficiency—from two to five times that of large vehicles.

Additionally, the sheer number of resources required to produce and maintain a functional fleet of hundreds of millions of vehicles is staggering. Vehicles are complicated and expensive. The production of a vehicle, on average, requires 62 Gigajoules of energy, which is enough to power a typical home for 1.7 years (Sato et al. 2020). Vast quantities of materials are required, as the average vehicle requires 700 kg of steel alone (Sato et al. 2020). A well-implemented AMP concept would reduce overall embodied energy, as one AMP vehicle could service many people and replace one or more automobiles, reducing the energy footprint of the transportation sector.

Spatial Constraints

Increases in population and land-use density require efficient use of available space. Land to support private automobiles (roadways, parking, pickup/drop-off) is a burden in densely developed communities. The most desirable spaces for humans evoke images of parks, resorts, gardens, and beaches, all of which are absent of vehicles and parking, except perhaps on the periphery. To create attractive human-scale spaces, taming dependence on automobiles through superior mobility options is needed. Cohesive infrastructure is paramount for spaces to be conducive to a higher quality of life. AMPs enables these emerging design philosophies.

It is in these higher density developments that alternatives to vehicle ownership models—and high-performance public mobility options—are needed. Several cities are attempting to reclaim space once dedicated to automobiles using incentives to shift people from their own cars into shared mobility, make mobility services more affordable, and transition to electric vehicles. However, can this be done without a parallel advancement in mobility that delivers, or rather out-delivers, the mobility of an automobile? Clean, space-efficient cities are needed for continued human development and growth, for which we will need clean and highly responsive automated mobility services—for which AMPs have been conceptualized to address.

Equity of Access

It is well established that private vehicle ownership is expensive and constitutes a substantial portion of household income for those in low-income populations. In addition, many Americans with disabilities are at a mobility disadvantage due to the lack of accessibility for diverse individual needs. Medical conditions can make driving difficult, dangerous, and even impossible for a portion of the population. According to the Bureau of Transportation Statistics, there are 25.5 million Americans over the age of 5 that have self-reported travel-limiting disabilities. Of these citizens, 13.4 million are age 18 to 64, and 11.2 million are age 65 and older. These disabilities limit the forms of transportation available to this portion of the population. Such disabilities and the related impact on mobility can limit an individual's opportunities, particularly for employment. In most states, a person cannot legally drive until the age of 16, limiting educational and work opportunities for many young adults. At the other end of the spectrum, according to the Department of Economic and Social Affairs, more than 46% of older persons aged 60+ years have experienced moderate to severe disabilities that often impacts their ability to drive (Ageing and Disability, n.d.). As a form of shared public mobility, AMPs could allow individuals to increase their access to economic opportunities, improve social mobility, and achieve improved quality of life. AMP vehicles equipped to accommodate people of any age and with a variety of disabilities to allow for seamless boarding and deboarding extends this equity to the mobility impaired.

Lessons Learned from Micromobility and Ride-Hailing

With the advancement of communications technology, ride-hailing applications such as Uber and Lyft (generically referred to as transportation network companies or TNCs) emerged and quickly increased in mode share. With ride-hailing, the number of vehicles on the road has not been reduced, though a reduction in parking has been documented, particularly at airports. Moreover, due to the nature of Uber and Lyft, the amount of carbon emissions in the air or traffic congestion has increased or remained on par with single occupancy vehicles based on a number of studies and assessments.

Another issue with ride-hailing is that it is inaccessible to people without smartphone access, though this is being addressed in some markets with traditional telephone voice services. While smartphones may seem to be an essential part of our lives, there are still more than 75 million Americans that do not own a smartphone (Mobile Fact Sheet 2021). So, while TNCs have become a viable technical alternative for some who cannot or should not be driving, many people lack the technology to use such services. Older Americans are typically the demographic without ready access to a smartphone, and combined with mobility issues, are some who might most benefit from AMPs.

Micromobility, which includes services such as electric scooters or bikes, has also recently emerged as an entirely new transportation concept and has contributed to the overall decline in reliance on private vehicles—particularly in denser urban areas, campuses, and similar environments (Spring et al. 2018). The small vehicles encapsulated under the term micromobility are convenient in areas they operate, are communally shared (at low cost to users), and take advantage of wireless digital connections to streamline use.

Even with improved efficiency over automobiles, micromobility faces several challenges. Shared micromobility systems cannot reach all Americans. System operation depends on a high density of users in a small enough area that the range limitations of the scooter or bike are sufficient for travel to and from where they are going. A typical micromobility device can travel a maximum of approximately 10–20 miles, though most trips are much shorter (Sun et al. 2021). Personally owned micromobility vehicles may be an effective transportation method but require upfront costs to the user. Micromobility can also be hazardous to users. The Austin Public Health department found that out of every 100,000 trips taken, 20 individuals were injured, compared to less than one for automobiles (Governors Highway Safety Association 2020; Beck et al. 2007). The exposure of the user to their environment inherent in this style of transportation, the relative lack of traffic laws and regulation, and infrastructure that is dangerous and poorly suited to micromobility all contribute to risks. Additionally, the maintenance of micromobility devices can be challenging. The scooters need to be manually charged and organized each night for the network to be operational. Some companies are attempting to address this with autonomous scooters that can move where needed without user input, which could potentially reduce the labor required to keep a micromobility network operational, but this is not yet in wide deployment. Lastly, the physical requirements to operate micromobility devices are inherently exclusionary to those with disabilities or are not capable of physically operating the device. This can be seen in age distribution trends of micromobility users; 86% of riders in one survey taken in Zurich were between 18 and 50 years old (Reck et al. 2021).

AMPs can address these issues while still providing similar and complementary services to TNC and micromobility solutions. AMPs may pick up multiple riders along a path, and are capable of automated charging and autonomous relocation to meet passenger demand. AMPs may be more feasible for operation in areas of lower density than the typical use case for TNCs or micromobility due to auto-repositioning. An AMP system also features improved safety due to automated operation, protected travel lanes, four-wheel stability, and the existence of a physical structure around passengers that keeps them inside of the vehicle when moving, an added benefit to riders during inclement weather, which can be problematic for micromobility.

A network of AMPs could better serve members of the community for which TNCs are too large or expensive, or for which standard micromobility is not suited. An e-scooter simply cannot be used by someone with a broken leg, missing limb, vision impairment, balance challenges with age, or many other conditions. Additionally, AMPs could be integrated with accommodations for the visually or audially impaired with intelligent modes of interaction, further extending the user base to groups of the population and enabling greater freedom of mobility.

Conclusion

The current transportation status quo, particularly the reliance on private automobiles, presents challenges in safety, efficiency, and equity. To mitigate these factors, a flexible, efficient, accessible, and integrated transportation concept must be developed. To date, most transportation infrastructure has been designed to prioritize privately owned automobiles at the expense of other modes. Reliance on automobiles for mobility limits access for some population subgroups, and the expense of committed land use and infrastructure maintenance is a resource burden to communities. Alarming statistics abound that illustrate the energy inefficiency of, and the American commuters' dependence on, private automobiles. Approximately 470 million gallons of gasoline are burned daily through private automobile operation, while production of a private automobile regularly consumes enough energy to power an average American home for 1.7 years. The AMP concept has the potential to improve the energy efficiency for many short-distance trips common in daily transportation.

In addition, AMP systems offer other key benefits to complement emerging shared modes. AMPs can be accessed without a smartphone, and at lower cost than TNC services. Micromobility has demonstrated significant energy efficiency gains and convenience over private automobiles, yet is not perfect. The injury rates of micromobility modes can be more than 20 times higher than private automobiles, and the labor-intensive maintenance and distribution of micromobility limit its scalability. AMP vehicles do not require significant rider fitness or agility; boarding and deboarding are primarily roll-on and roll-off for wheelchairs. The AMP concept incorporates separated pathways from larger vehicles to prevent errant automobiles from presenting a safety hazard, and an improved mobility alternative for many trip parameters.

Inherent accessibility is at the heart of the AMP concept. If integrated and deployed at facility and district scales, AMP systems have the potential to positively transform urban mobility in the coming century in much the same way that elevators enabled upward development of buildings in the last century. Such systems may also address many of the largest challenges of legacy transportation systems.

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References

Ageing and disability. (n.d.). *United Nations*. https://www.un.org/development/desa/disabilities/disability-and-ageing.html.

American Automobile Association (AAA). (2021). *Your Driving Costs*. https://newsroom.aaa.com/wp-content/uploads/2021/08/2021-YDC-Brochure-Live.pdf.

Beck, L.F., Dellinger, A. M., & O'Neil, M. E. (2007, April 21). *American Journal of Epidemiology,* Volume 166, Issue 2, 15 July 2007, Pages 212–218, https://doi.org/10.1093/aje/kwm064.

Bertoncello, M., & Wee, D. (2015). "Ten ways autonomous driving could redefine the automotive world." *McKinsey & Company*. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/ten-ways-autonomous-driving-could-redefine-the-automotive-world.

Bly, P. H., Hammersley, J. C., & Lowson, M. V. (2013). Evaluation of Passenger Satisfaction with the Heathrow PRT system. In Automated People Movers and Transit Systems 2013: Half a Century of Automated Transit—Past, Present, and Future (pp. 127-142). https://doi.org/10.1061/9780784412862.010

CDC. "Road traffic injuries and deaths—A global problem." (2020, December 14). *Center for Disease Control*. https://www.cdc.gov/injury/features/global-road-safety/index.html.

Consumer Reports. (2014). "Avoiding crashes with self-driving cars." https://www.consumerreports.org/cro/magazine/2014/04/the-road-to-self-driving-cars/index.htm.

Fund for Our Economic Future. (2021, August 29). No car, no job, no job, no car: Solving the ultimate paradox in NEO. *Crain's Cleveland Business*. https://www.crainscleveland.com/custom-content-twotomorrows/no-car-no-job-no-job-no-car-solving-ultimate-paradox-neo.

Governors Highway Safety Association. (2020, August 31). *GHSA Strategic Business Plan*. https://www.ghsa.org/sites/default/files/2020-09/GHSA_SBP_2020-2022_complete.pdf.

Gustafsson, J., Lohmann, R., & Lowson, M. (2013). Personal Rapid Transit Live Applications Challenges. In Urban Public Transportation Systems 2013 (pp. 347-356). https://doi.org/10.1061/9780784413210.031

Mobile Fact Sheet. (2021, April 7). *Pew Research Center*. https://www.pewresearch.org/internet/fact-sheet/mobile/.

National Household Travel Survey. (2017). https://nhts.ornl.gov/.

NHTSA. "Automated vehicles for safety." (n.d.). National Highway Traffic Safety Administration. https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety.

Raney, S., & Young, S.E. (2005, January). "Morgantown people mover – Updated description." *Transportation Research Board*. https://rosap.ntl.bts.gov/view/dot/17792.

Reck, D.J., & Axhausen, K.W. (2021, May). "Who uses shared micromobility services? Empirical evidence from Zurich, Switzerland." *Transportation Research Part D: Transport and Environment*, 94(1361-9209), 102803, https://doi.org/10.1016/j.trd.2021.102803.

Richter F. (2019, May 29). Cars still dominate the American commute. *Statista*. https://www.statista.com/chart/18208/means-of-transportation-used-by-us-commuters/.

SAE. *Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology*. (2020, October 20). https://www.sae.org/standards/content/j2954_202010/.

Safety. (n.d.). *Federal Highway Administration*. https://safety.fhwa.dot.gov/.

Sato, F.E.K., & Nakata, T. (2020, May 11). Energy consumption analysis for vehicle production through a material flow approach. *Energies*, 13 (9), 2396, https://doi.org/10.3390/en13092396.

Schneider, B. (2018, September 6). CityLab university: induced demand. *Bloomberg CityLab*. https://www.bloomberg.com/news/articles/2018-09-06/traffic-jam-blame-induced-demand.

Spring, M. J., Chambers, M., & Smith-Pickel, S. (2018, December). *Transportation Statistics Annual Report 2018*. https://doi.org/10.21949

Sun, B., Garikapati, V., Wilson, A., & Duvall, A. (2021, November). Estimating energy bounds for adoption of shared micromobility. *Transportation Research Part D: Transport and Environment*, Volume 100 (1361-9209), 103012, https://doi.org/10.1016/j.trd.2021.103012

Tefft, B.C. (2017, June). Rates of motor vehicle crashes, injuries and deaths in relation to driver age, United States, 2014-2015 [Research Brief]. *AAA Foundation for Traffic Safety*. https://aaafoundation.org/rates-motor-vehicle-crashes-injuries-deaths-relation-driver-age-united-states-2014-2015/.

U.S. Department of Transportation (DOT). (n.d.) "Safety: Keeping traveling Americans safe." https://www.transportation.gov/safety.

U.S. Department of Transportation (DOT). (2019). "Highway Statistics 2019." https://www.fhwa.dot.gov/policyinformation/statistics/2019/.

U.S. Environmental Protection Agency (EPA). (2021). *The 2020 EPA Automotive Trends Report*. https://www.epa.gov/automotive-trends/download-2020-automotive-trends-report-previous-year.

U.S. Environmental Protection Agency (EPA). (n.d.)."Highlights of the automotive trends report." https://www.epa.gov/automotive-trends/highlights-automotive-trends-report.