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Bridging the Divide: Autonomous Vehicles and the Automobile Industry

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Executive Summary

The automobile industry is in the midst of a technology-driven revolution. The industry transition to autonomous, connected, electrified, and shared (ACES) vehicles has the potential to boost technological development and economic activity in the traditional manufacturing cities of the United States, bridging the divide between high-tech innovation hubs and regions historically known for industrial economies.

With the right policy environment, important investments, and effective retooling of existing advantages and relationships, traditional automotive manufacturing clusters can be at the forefront of the technological revolution within the auto industry and seize the growth and employment opportunities that it brings. The Mahoning Valley in northeast Ohio offers a useful case study of economic revitalization through coordinated investment to transform an existing local infrastructure and workforce to the growing electric vehicle (EV) and autonomous vehicle (AV) sectors. Once a hub for steel production, the Mahoning Valley has rebranded itself as "Voltage Valley," now home to hundreds of new-energy tech startups and one of the largest electric vehicle battery plants in the country.

Due to the massive digitization of today's cars, vehicle manufacturing should be considered a process that takes place in the physical and digital world. Imaging, robotics, navigation, connectivity, data processing, and artificial intelligence broadly are the building blocks of AVs. The importance of software development, which is increasingly recognized by automakers transitioning to producing smarter vehicles, will lead to the formation of economic clusters in cities like Pittsburgh which focus on critical technology development. Pittsburgh is the home of multiple successful AV startups, many of which are well connected to Carnegie Mellon University, demonstrating the role that higher education can play as a pipeline for emerging industry talent outside of traditional manufacturing hubs.

The clustering effects evidenced by the Mahoning Valley and Pittsburgh case studies demonstrate how policymakers can incentivize the scaling of AV development to unlock social benefits. AVs would benefit the general population by improving road safety, ameliorating traffic congestion, and reducing the emission of greenhouse gases and other pollutants. For individuals, AVs offer significant efficiency benefits: increasing access to ridesharing and public transportation, as well as reducing costs and travel time due to the route optimization and traffic management functions of artificial intelligence (AI). While improvements in traffic management and road safety would be immediately tangible, some benefits, like the reduction in emissions and average vehicle miles traveled, would likely become apparent only after a longer period of time.

The benefits of ACES vehicles are broad, especially for cities not traditionally considered technology hubs. However, to fully realize these benefits, the auto industry must work with policymakers and the general public to establish a favorable regulatory environment and build consumer confidence in artificial intelligence and AVs. Full-scale deployment will facilitate the potential of ACES vehicles to bridge the gap between the high-tech hubs and the rest of the United States. Obstacles to broader AV deployment and how to overcome them will be addressed in a forthcoming paper.

Introduction

AVs are no longer a moonshot technology. Developers have significant capital backing, market potential, and interest from policy stakeholders. The AV revolution is tied to other sweeping changes to transit that will be disruptive opportunities for growth: electrification, connectivity, workforce modernization, and new technology-driven infrastructure requirements. The auto industry and other non-traditional players are serious about AVs; 30 of the largest AV companies had **invested** $16 billion in developing fully autonomous technology through February 2020. The AV market could **reach** $1 trillion in 2030 and $3 trillion in 2040 by some estimates.

Yet the benefits go beyond profit potential for automobile manufacturers, tech companies, and startups, as well as convenience for commuters and logistics companies. The ACES vehicle transition is driving transformation within the auto industry that will bridge the divide between high-tech innovation hubs and regions where manufacturing has—or had—traditionally dominated economic activity.

This report is divided into three sections that describe the domestic economic benefits of the ACES transition, if managed properly. The first section focuses on how the transition will impact the existing automobile industry manufacturing footprint, using the Mahoning Valley in Ohio as a case study. The second section examines the software and computer side of the ACES transition, using Pittsburgh's fledgling AV research and development industry as a case study. The third section lays out broad benefits made possible by ACES if deployed with scale and proper management.

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Benefits: Building the Vehicle

TWENTY-FIRST CENTURY AUTO MANUFACTURING CLUSTERS: BATTERIES, CHIPS, AND FACTORY UPGRADES

Motor vehicle production in the United States has created clusters of economic activity. Original equipment manufacturer (OEM) assembly plants and those that make core parts attract and support suppliers—from tier one suppliers that produce significant components like suspensions and chassis to tier two and tier three suppliers that produce less complex components. Local universities can play a pivotal role as talent pipelines, innovation centers, and testing locations for AV research and development of smart vehicles. Key examples of this include the Ohio State University's Center for Automotive Research and the University of Michigan's Mcity, which each collaborates with industry partners in Detroit and Columbus to target resources toward the exploration and testing of advanced automotive technologies and the cultivation of a highly skilled and engaged future workforce. These clusters have generated three benefits: intra-industry benefits like access to specialized workers and a pool of supporting goods and services; inter-industry spillovers stemming from the spread of knowledge across industries; and spinoffs, or new firms created by former employees from the industry.

Automakers expect that within five years, electric vehicles will cost the same amount to produce as internal combustion vehicles. Industry trends suggest that the vast majority of level four and five autonomous vehicles will be battery-powered electric vehicles.[1] Given the right regulatory environment, electrified AVs would likely quickly achieve scale. Widespread adoption of EVs is generally considered a natural step toward widespread AV deployment. The EV architecture provides the power, voltage, and energy storage required by AVs that internal combustion engine vehicles cannot. Estimates of the power requirements for AVs vary widely—from 200 watts to over 2,000 watts—based on variables like chip design, algorithm efficiency, and types and volume of sensors used. There is concern that the amount of power required for autonomous functions would reduce vehicle range. However, models suggest that power demand from autonomous functions can be mitigated and eventually offset by designing more aerodynamic vehicles, lighter vehicles, and improving route efficiency via automation.

Utilities will need to invest in improving grid capacity and the ability to meet higher energy demand to serve electric vehicles and ultimately AVs. Required investments to manage the EV transition will vary by region. In some states, overall capacity is less of a concern compared to the ability to meet rapid demand spikes—for instance, in the evening when commuters return home from work and charge their vehicles. Charging during off-peak hours for electricity use would ease the transition. Utilities could also incentivize customers to charge at certain hours or locations to smooth demand spikes. Further, energy demand in the United States has hardly grown over the past 10 years while capacity has grown by roughly 12 gigawatts (about 1 percent of the 1,100 gigawatts of total installed generation capacity in the United States in 2020) a year, roughly enough capacity to service six million new EVs, according to the Department of Energy. The EV transition will occur over decades, not years. This suggests that the current pace of energy production expansion is sufficient to meet demand required by the transition to EVs and ultimately AVs.

The impending shift to EVs and AVs has generated two primary concerns with regard to the U.S. workforce. First, EVs, being less mechanically complex than internal combustion vehicles and composed of more

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1 The National Highway Traffic Safety Administration uses the following scale when referring to vehicle automation: Level 0, zero autonomy, the driver performs all driving tasks; Level 1, driver assistance, the vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design; Level 2, partial automation, the vehicle has combined automated functions like acceleration and steering but the driver must remain engaged at all times; Level 3, conditional automation, the driver is a necessity, but not required to monitor the environment, the driver must remain ready to take control of the vehicle at any time; Level 4, high automation, the vehicle is capable of performing all driving tasks under certain conditions, the driver may have the option of taking control of the vehicle; Level 5, the vehicle is capable of performing all driving functions under all conditions.

modular parts, will require less labor and fewer workers to build, and core components will be imported. The long-term trajectory of automotive production clusters in the Midwest and Southeast is only starting to take shape amid the accelerating transition to EVs and AVs. Second, there is a risk that the technology required for large scale deployment of EVs and AVs will be manufactured outside the United States. Shortages of semiconductors owed to chokepoints in global supply chains slowed automobile production in early 2021. China now has the edge in lithium-ion battery manufacturing and maintains dominant positions throughout the supply chain, from raw material refining to component manufacturing.

However, the right policy environment and effective use of existing advantages and relationships within the U.S. automotive industry should, in turn, create an opportunity for a manufacturing renaissance in the United States that brings with it new jobs in the industry. Further, the transition to AVs composing the majority of the U.S. automotive fleet will take decades, particularly for level five autonomous vehicles. This gradual transition will smooth disruptions to the workforce and provide time for the labor pipeline to adjust to the new automotive supply chain.

Investment in domestic capacity to produce EVs, and eventually AVs, appears poised for a breakout, and early signs suggest that automakers will improve existing facilities to produce EVs and AVs, keeping the anchors of automotive production clusters in place. The United States is home to some of the top global early-stage battery research and research into the technology that underlies autonomous vehicles. However, the United States does not offer the same level of support to those industries as offered by other countries, such as China and, to a lesser extent, the European Union.

That is likely to change. The Biden administration has made clear it intends to use an array of government levers to juice battery production in the United States and catalyze major manufacturing revitalization. Political pressure is growing to employ measures that will encourage domestic production of semiconductors. Government policy will also likely encourage U.S. manufacturing and the use of U.S. labor in developing and producing EVs and AVs. While the current regulatory environment for AVs does not provide a path to large-scale manufacturing and deployment, the Trump administration laid the groundwork for AV development and manufacturing to create U.S. jobs. The United States-Mexico-Canada Agreement requires that 75 percent of a passenger vehicle's value originate in North America for it to receive duty-free treatment, and that 75 percent of "core parts," including advanced batteries, originate in North America.

The Biden administration is poised to take further steps to ensure key EV, and by extension AV, parts are made in the United States. The president's executive order will undertake a review of supply chains in key industries and focus on advanced batteries, semiconductors, and rare earth minerals, all building blocks of electric and autonomous vehicles. Additionally, Biden plans to replace the government's 600,000 vehicle fleet with EVs, generating significant predictable demand over the coming years. In 2019, the government owned less than 3,000 EVs.

If adopted, a combination of government incentives and regulatory changes to encourage EV and AV adoption—including through investments in underlying technologies and infrastructure such as critical minerals, semiconductors, and other next generation technology—is estimated to create over 220,000 U.S. jobs and support another 425,000 over one to five years, according to a study from Keybridge Public Policy Economics. The study assumes four sets of incentives are provided for the manufacturing and purchase of EVs along with the buildout of charging infrastructure; three programs to support the creation of critical mineral supply chains outside of China's control; a domestic semiconductor and telecommunications manufacturing package; and the modernization of federal regulations to support AV adoption.

While powertrain simplicity in EVs may result in fewer labor requirements for production, production will drive new employment opportunities in advanced manufacturing, including battery assembly, electric motors, advanced driving systems, and semiconductors. To that end, automakers have already announced billions of dollars' worth of upgrades to existing manufacturing facilities, and parts suppliers estimate thousands of dollars' worth of new opportunities around electrification and automation.

To maintain and improve the workforce, pipeline automakers, other industry actors, government stakeholders, and education and training institutions continue to cooperate on curriculum development, internship and apprenticeship opportunities, and other paths to reskilling and upskilling. New components and systems, including advanced driver assist systems below full level five automation, will require upskilling workers throughout the supply chain—from engineering and design to software development to those on the factory floor and in repair shops.

EVs and AVs will require infrastructure investment to meet their full potential. A massive buildout of charging stations and upgrades to the electrical grid will be necessary as EV sales continue to grow, creating thousands of jobs. Finally, cities and states will invest in smart infrastructure to improve vehicle connectivity, which will not only create jobs but create long-term economic and environmental benefits as a result of reduced congestion, travel time, and more efficient movement of goods and people. These factors will encourage industry to continue to tap into U.S. manufacturing and the U.S. workforce as the EV and AV transitions unfold.

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THE MAHONING VALLEY

Change occurring in eastern Ohio to support the EV and AV transition is early evidence that automotive clusters will continue to be sources of economic growth and further innovation in the United States. The Mahoning Valley, formerly known for its steel production but now known for its manufacturing prowess, has taken on a new name, "Voltage Valley." It is home to Lordstown Motors, an electric truck company that purchased and repurposed General Motors' old assembly plant in Lordstown. GM and South Korea's LG Chem have inked a 50-50 joint venture to create an Ultium Battery cell assembly plant on a greenfield manufacturing site in Lordstown, OH—roughly four hours from GM's automobile manufacturing facilities in Michigan. The Lordstown GM-LG Chem plant will mass produce battery cells for EVs, with annual capacity of over 30 gigawatt hours (GWh). This would annually supply 300,000 vehicles with 100 kilowatt hours (kWh) battery packs and create over 1,100 new jobs.

What is important about the Mahoning Valley's ecosystem is the role that the tech sector has played in serving as an interlocutor across different EV and AV industry segments. The facilitation and investment coordination have been driven in large part by Brite Energy Innovators, a local energy technology innovator that supports startups, provides testing facilities and labs to big and small firms, and provides a connective tissue between entrepreneurs, established firms, educational institutions, and federal and state actors. Brite has enabled investment of more than $135 million in 250 companies since 2011. The incubator has ties to nearly 300 new-energy tech startups through mentorship, funding, and investor connections. Brite was involved in early discussions with Lordstown Motors and GM to find a new use for the Lordstown plant.

The Mahoning Valley workforce's experience in the auto industry combined with existing infrastructure, new and old players interested in developing the next generation of automotive technology, and support from the Ohio government has created an environment conducive to upgrading the once faltering auto industry cluster there. Tom Gallagher, Ultium's plant director, cited those reasons when explaining the decision to embrace the Mahoning Valley. Rick Sockburger, the CEO of Brite, told local media that following the GM-LG Chem deal, he was approached by a range of companies and suppliers inquiring how to move operations into the Mahoning Valley. He also said that Carnegie Mellon and Case Western inquired about working on projects in the region. Brite and Carnegie Mellon are partners in the Wells Fargo Innovation Incubator program, which supports clean technology and agriculture companies' entry into the market. The Mahoning Valley's transition to Voltage Valley is an example of how a commitment to producing the next generation of automobiles can help revitalize an automotive cluster, draw in new investors, and accelerate a transition to new technologies.

Another set of stakeholders in northern Ohio is working together to prepare the current and incoming workforce for technological change in the industry. The University of Toledo has partnered with AAA, Delphi, Electude, Owens Community College, Penta Career Center, and DriveOhio—the Ohio Department of Transportation branch focused on the future of mobility—to develop training curriculum and credentials for auto technicians or those in training to work on advanced driver assistance systems (ADAS). On the factory floor, "versatility and adaptability" will be key for workers, according to GM's head of global manufacturing, Gerald Johnson. Johnson predicts that some factory jobs will change as EVs and AVs become more mainstream, but there will be more job opportunities in the future compared to today.

Separate from the ADAS training program, LG Chem has piggybacked on GM's existing partnership with Youngstown State University to work on workforce development and establish a pipeline from the university to the battery plant. GM will also provide $5 million to support a workforce development partnership between Youngstown State University and Eastern Gateway Community College to prepare workers to join Lordstown Motors, Ultium, and other companies in the region. Additionally, GM has committed funds for the development of Youngstown State University Energy Storage Innovation and Training Center, a Department of Energy project that features a partnership with the university and Oak Ridge National Laboratory also focused on workforce development for the battery manufacturing industry.

GM's push for electrification builds on and leverages the ecosystem developed in the Mahoning Valley. Alongside announcements of plans to end sales of internal combustion consumer vehicles by 2035, GM has committed to the retooling of its Hamtramck facility as Factory Zero—the bulwark of GM's new electric vehicle manufacturing—with the Hummer EV and Cruise Origin as flagship production lines. GM has also announced investments at its Spring Hill, Tennessee assembly plant, where the Cadillac Lyriq will be built, and currently manufactures the Chevrolet Bolt and Cruise Autonomous Vehicle at the Orion assembly plant. GM is also nearing an agreement with LG Chem to build a second battery plant in Tennessee, complementing its Spring Hill assembly plant.

The view that the future of the automobile will be electric and ultimately autonomous is widely held. Given that electrification is a necessary step toward autonomous vehicles, and a potentially parallel step for lower-level driver-assist vehicles, most of the benefits associated with manufacturing autonomous vehicles will materialize during the EV transition. For example, Ford announced a $22 billion investment in electrification and a $7 billion investment in autonomous vehicles in early 2021. Ford chief executive officer Jim Farley has said Ford "cannot afford" to experience a shortage of batteries similar to the shortage of semiconductors that slowed automobile production around the world in early 2021. Daimler intends to produce electric versions of all its passenger vehicles by 2022. Volkswagen has set a target of 2030 for full electrification of its offerings. Toyota expects 70 percent of its vehicle sales to be electric by 2030, while Volvo expects to be fully electric around the world by then.

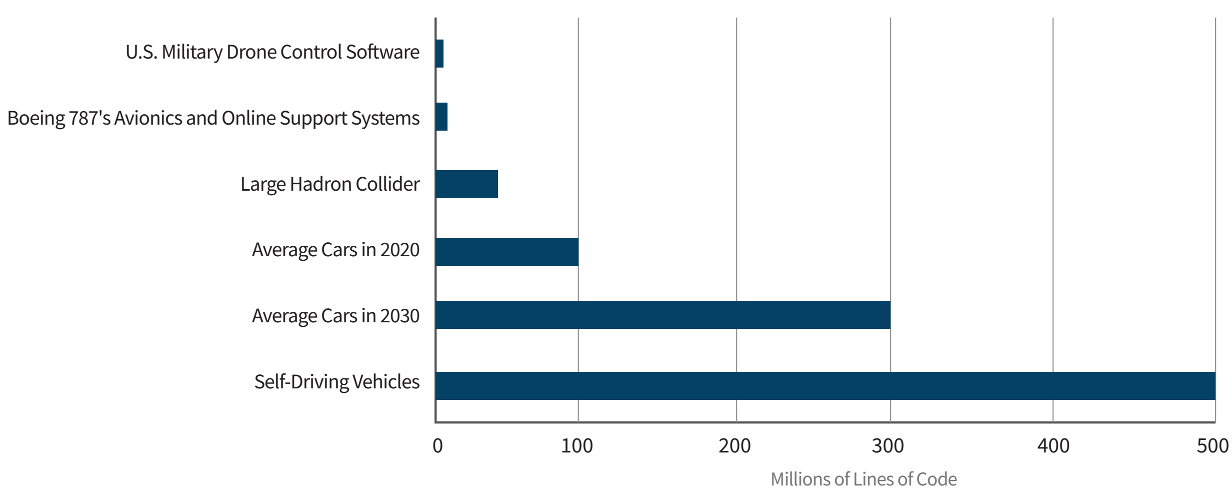
Other anchors of auto clusters are being upgraded to produce EVs and AVs. Ford is investing hundreds of millions of dollars to update assembly and transition plants in Kansas City, Sterling Heights, and Dearborn. Volkswagen has announced an $800 million investment in its Chattanooga plant to produce EVs, which it estimates will create one thousand new jobs. Daimler has announced a $1 billion investment in its Tuscaloosa plant for the production of electric SUVs and the construction of a new battery plant. These investments and others likely to follow will not only maintain economic opportunities in traditional manufacturing hubs but improve them by generating a more skilled workforce and creating opportunities for innovation and knowledge spillover.

Automakers are responding to projections that EV demand will grow, and costs will decline. Those projections are based on the rising demand for batteries as energy storage solutions, the growing recognition that battery production capacity is fundamental to the defense industrial base, and a more positive government role in the industry. Illustrated by the Lordstown Ultium plant, these assembly plants are likely to generate thousands of jobs and drive the next generation of manufacturing and innovation in the United States.

Software and Technology Clusters

Vehicles are no longer purely physical constructs; by 2030, the average car is expected to have around 300 million lines of code, and self-driving vehicles could have as many as 500 million lines of code. Given the massive digitization of today's automobiles, vehicle manufacturing should be thought of as something that takes place in both the physical and digital world. Imaging, robotics, navigation, connectivity, data processing, and AI broadly are the building blocks of autonomous vehicles. As autonomous vehicles improve, these systems—the foundation of advanced technology—will be as important, if not more important, than the physical vehicle itself.

How many millions of lines of code does it take?



Source adapted from: Jeff Desjardins, "How Many Millions of Lines of Code Does It Take?" February 8, 2017, Visual Capitalist, https://www.visualcapitalist.com/millions-lines-of-code/.

Automakers know the industry is changing. Take Microsoft's team-up with GM and Cruise, Google's partnership with Ford, Aptiv and Hyundai's partnership, and Argo and Volkswagen's partnership. These partnerships are emblematic of three shifts.

- First, companies recognize that to stay competitive, they must offer smarter, including autonomous, vehicles.
- Second, data collection and processing will be a critical part of automobile production, akin to engine production.
- Third, comparative advantage will have a crucial role to play in both hardware and software development for future AV development.

Most in the industry or those studying it believe automakers with years of experience are best suited to manufacture vehicles or be manufacturing partners; tier one suppliers are among the best suited to integrate advanced technology into existing systems and work on new systems; and companies geared toward software development, including AI, are best suited to develop critical software. That said, OEMs will still play a crucial role in technology integration. GM, for example, plans to hire 3,000 electrical system, infotainment software, and controls engineers, as well as developers for Java, Android, and iOS.

PITTSBURGH

Just as automobile manufacturing over the last century led to clusters of economic activity that drove innovation and growth, the transition to autonomous vehicles will lead to the establishment of economic clusters focused on technology integral to AVs. Pittsburgh is one such nascent cluster. The "Steel City" has more recently become known as the "**birthplace of AV technology**." Pittsburgh's embrace of the AV industry has contributed to its transformation from a manufacturing hub to a world leader in technology innovation. In **April 2019**, five entities—Aptiv, Argo AI, Aurora, Carnegie Mellon University (CMU), and Uber—were testing 55 self-driving vehicles in Pittsburgh. All five companies agreed to the "**Pittsburgh Principles**" under which companies must submit information about themselves, their fleets and employees, when and where they're testing and under what weather conditions; submit how many miles they test on city streets each year; submit safety plans to the city and define how the public benefits from testing; and submit a report every six months.

Pittsburgh's origins as an AV technology hub stems from CMU. CMU has been in the AV game for a long time. Its Navlab group built an autonomous box truck in 1986 and **ALVINN**, an AV retrofitted from an Army ambulance, in 1989. The Robotics Institute at CMU is a leader in robotics research, including autonomous systems, sensors, and cameras. The National Robotics Engineering Center, housed within the Robotics Institute, works with government and industry clients to develop technology from early stage to commercialization. The center developed an autonomous SUV that won first place at the 2007 DARPA Urban Challenge and other autonomous vehicles that saw success at subsequent iterations of the challenge. CMU partners with Uber, GM, and Argo AI to support AV research. Its expertise and partnerships have helped cement a pipeline of talent in Pittsburgh that has produced AV research, spin-off companies, and alumni that have founded cutting-edge AV technology companies in the city.

Aptiv, which develops algorithms, software, and hardware systems for AVs, operates a technical center in Pittsburgh. It acquired CMU spin-off Ottomatika in 2015, which provides software and systems development for AVs. Aptiv and Hyundai Motor Group formed a **joint venture**, Motional, in August 2020. The joint venture combines Aptiv's technological expertise with Hyundai's leadership in manufacturing to work on AV development. Motional intends to commercialize driverless vehicles as well as driverless systems for robo-taxi services in partnership with ridesharing company Via. In December 2020, Lyft and Motional announced their partnership to launch fully driverless vehicles on the Lyft network beginning in 2023. Headquartered in Boston, Motional also has operations in Pittsburgh, Las Vegas, Santa Monica, Singapore, and Seoul.

Argo AI, which builds software, hardware, maps, and cloud-support infrastructure for AVs, has its global headquarters, engineering and development operations, and fleet testing operations in Pittsburgh. Bryan Salesky, the company's founder and CEO, comes from the Carnegie Mellon pipeline. He managed commercial programs while at the National Robotics Engineering Center (NREC) and led software engineering for CMU's winning AV in the 2007 DARPA Urban Challenge. It received a $1 billion investment over five years from Ford in 2017 and a $2.6 billion investment from Volkswagen in 2020, giving each company a 40 percent stake in Argo AI. Argo AI tests AVs on public roads in Washington, D.C., Miami, Detroit, Palo Alto, and Austin. It has described Pittsburgh as "one of the most challenging environments in America" because its "steep and narrow streets snake over hills, under railroad tracks, through tunnels and across bridges" in addition to the snow and other inclement weather. Argo AI teamed up with CMU in June 2019 for a five-year $15 million sponsored research partnership that established the Carnegie Mellon University Argo AI Center for Autonomous Vehicle Research. The center will research autonomous vehicle operations in real-world conditions, including winter weather and construction zones. Deva Ramanan, an associate professor at the CMU Robotics Institute who is also the machine learning lead at Argo AI, will lead research at the center.

Two of the three cofounders of Aurora hail from CMU. The company has backing from Amazon and Sequoia, is expanding its footprint in Pittsburgh, and was the first startup authorized by the Pennsylvania Department of Transportation to operate AVs on public roads. The company is developing two products, Aurora Driver, which offers sensors, software, and compute that can fit into any vehicle type, and Aurora Ecosystem, which integrates autonomous systems with vehicle platforms, logistics services, mobility services, and fleet management services. The company has partnerships with Uber, Fiat Chrysler, and Hyundai. Aurora acquired Uber Advanced Technologies Group in December 2020, which had cited Pittsburgh as the ideal testing ground for AVs due to its workforce and environment. Uber ATG's CEO is a former CMU professor, Eric Meyhofer. After the acquisition was announced, Aurora sent offers to over 75 percent of Uber ATG employees, including the vast majority in Pittsburgh.

Pittsburgh is also home to firms that support AV testing and deployment. Edge Case Research, founded by two CMU alumni and supported by three lead engineers from CMU, advises companies on AV testing and safety validation. Edge Case has partnered with Uber ATG, AAA, LG, and the U.S. Army, among others. The CEO of Aurora sits on its board. SAE International, a global association of more than 128,000 engineers and related technical experts in the aerospace, automotive, and commercial-vehicle industries that develop voluntary consensus standards, is headquartered in Warrendale, a suburb of Pittsburgh. Its taxonomy and definitions for AV terms became a "de facto global standard" adopted by stakeholders in the automated vehicle technology industry. The U.S. Department of Transportation uses SAE's six levels of automation framework in its AV policy.

Benefits: Deployment

The clustering effect seen in the case studies above clearly demonstrates how policymakers can incentivize the scaling of autonomous vehicle—and broader AI—development to unlock broader social benefits. The section below outlines what the initial impacts of AV deployment could look like should this technology scale.

From the perspective of the population as a whole, AVs would significantly improve road safety, ameliorate traffic congestion, and reduce the emission of greenhouse gases and other pollutants. On an individual level, AVs offer large efficiency benefits—increasing access to ridesharing and public transportation as well as reducing travel time. Many benefits, such as improved traffic management and road safety, would provide immediate, tangible benefits to both individuals and society as a whole. Others, such as reductions in emissions and average vehicle miles traveled, may only become apparent over a longer period of time.

Economic analysis from research commissioned by Securing America's Future Energy suggests that the cost-per-mile of an ACES vehicle could be 50 cents by 2030 compared to the $1.31 cost-per-mile for a traditional bus today. Cheaper, more widespread transportation options would help connect overlooked communities with employment opportunities previously inaccessible due to lack of public transportation and the expense associated with private transportation options. The societal benefits of AVs can be divided into four categories: efficiency, safety, the environment, and cost & accessibility.

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Efficiency

Route optimization: AI allows for route optimization and optimized matching of drivers and riders, which is already being explored by Uber and Lyft. This technology includes predictions of upcoming delays and instantaneous rerouting. Jacksonville's planned AV-based 10-mile urban transit network would embrace this technology to allow transit vehicles to be automatically rerouted to less busy areas to reduce wait time.

Traffic management: Many AVs will instantaneously communicate with transportation infrastructure, including "smart" traffic lights, which has already shown promise in reducing stoppages and wait times. Pittsburgh's "SurTrac" pilot program, which installed intelligent traffic signals at 50 intersections in Pittsburgh, reduced travel times by 25 percent due to less stopping (30 percent decrease), and when stopped, less waiting time (40 percent decrease). Less advanced systems have also been proven to improve traffic management. The utilization of adaptive cruise control and AI-based monitoring of traffic flow increased traffic speed by 8–13 percent. Uptake of vehicles with automated assistance in navigation, parking, and crash aversion (adaptive cruise control) could increase the effective capacities of roadway lanes by up to 80 percent, depending on how widespread AVs are adopted. A single shared AV could replace about 10 privately owned vehicles, significantly reducing congestion and parking requirements.

Incident management: Traffic congestion on busy roads and highways is often exacerbated by improper incident management. AVs would be able to reduce the duration of incident-caused congestion by instantaneously alerting ambulances and emergency services, and the volume of congestion by immediately alerting oncoming traffic of the incident and optimally rerouting.

Safety

Road safety: AVs would drastically reduce the potential for road accidents. Automobile crashes were estimated to have a societal cost of $836 billion in 2010 alone. Ninety-four percent of crashes are attributable to human error, which autonomous systems even below level five would guard against. Sensors and computers cannot fall asleep, drive under the influence, or become distracted. Real-world data backs the safety theory. A 2017 trial showed that Tesla's crash rate fell almost 40 percent after the cars were equipped with autopilot.

Traffic management: Improved traffic management, especially in conjunction with artificially intelligent transport system (ITS) infrastructure, such as "smart" traffic lights, could significantly improve road safety by avoiding congestion. Some argue, however, that automation could increase the number of vehicles on the road and worsen congestion, especially if consumers opt not to embrace ridesharing and if skepticism toward autonomous vehicle technology persists. Research from the University of Adelaide, for example, found that traffic congestion could increase over the next 30 years if commuters switch to AVs but are averse to ridesharing. A drop in both vehicles on the roads and vehicle trips eventually occurs in scenarios where commuters remain skeptical of AVs, but commuter aversion delays the transition.

Environment

Reduction of greenhouse gas and air particulate emissions: Route optimization decreases travel time and therefore decreases emissions from internal combustion vehicles or required energy production to charge EVs. Improved traffic management decreases stoppages and idling time which would further reduce emissions and energy needs. Truck platooning (coupling of several heavy goods vehicles led by one human driver, simultaneously accelerating or braking) increases fuel efficiency by operating closer, reducing stops and air resistance.

Sustainability: AV-based public transport systems were found to be the most sustainable strategy in dense urban areas to shift the heavy trip load from private vehicles. Ridesharing in urban areas could allow for a "greenification" of cities, introducing green spaces and improving inner-city safety by reallocating space for bike lanes and safer pedestrian zones. More immediately, self-parking AVs are able to occupy parking spaces 15 percent tighter than normal cars, allowing for a significant reduction in parking infrastructure in urban areas. On average, U.S. vehicles sit idle for 95 percent of their lifetime. Autonomous ridesharing and public transportation solutions would allow for 24/7 use of vehicles, further reducing parking needs and opening up space for pedestrians and green micromobility options, like bicycles and scooters.

Cost & Accessibility

Personal costs: Implementing AVs in ridesharing applications and taxis will likely lower the cost of these services, especially in more remote areas. Reduced costs for ridesharing services could incentivize their substitution for personal vehicles, decreasing individuals' average vehicle miles traveled (VMT) and gasoline costs. In the medium-to-long run, improved public transport systems could incentivize a reduction of private vehicle ownership for people living in urban and suburban areas. Autonomous ridesharing and public transportation solutions would improve transportation options for individuals in areas previously overlooked. More affordable, accessible, and efficient transportation options would unlock economic opportunities for individuals by expanding their ability to commute farther, faster, and cheaper.

For example, Jacksonville's Ultimate Urban Circulator (U2C) program, which is an expansion of the city's Skyway automated people mover (APM) system, is expected to significantly increase access to public transportation for people living in Jacksonville's suburbs. Including AVs in public transport systems could drastically improve access for the roughly 50 million people in the United States with a disability and the 50 million who are over 65 years old. Jacksonville's U2C program will allow greater access to public transportation for disabled individuals, including those living in neighboring suburbs. Autonomous taxis in Tokyo, which employ AI for route optimization and driver-rider matching, also cut costs and increased access to ridesharing in remote areas.

Societal costs: The aggregate cost to society from traffic congestion in the United States was around $100 billion per year in 2010, with car crashes amounting to nearly $300 billion. In 2010, motor crashes in the United States cost $242 billion in economic activity and $594 billion in loss of life and decreased quality of life due to injuries. Even semi-autonomous systems in AVs, such as adaptive cruise control and parking assistance, can significantly reduce the difficulty of driving for the driver. AVs can also assist drivers with difficult driving passages to avoid crashes, reducing stress and increasing comfort. Annual social benefits from using AVs—including improvements in parking costs, fuel efficiency, travel time, and crash aversion—were estimated to total $4,000 per year per AV.

Conclusion: Deployment and Scale

The benefits of ACES vehicles are broad and deep, particularly for cities not traditionally considered technology hubs. However, to realize those benefits, deployment at scale must be achieved. Federal regulation and public sentiment are the primary barriers to widespread production and deployment of ACES vehicles. Federal Motor Vehicle Safety Standards, which mandate that vehicles have standard features like a steering wheel, mirrors, and pedals, are ill-suited to autonomous vehicles. Automakers can apply for an exemption from those standards but are capped at producing only 2,500 non-compliant vehicles annually—not enough vehicles to achieve economies of scale or familiarize consumers with the technology. As of March 2021, only one company, Nuro, had received an exemption. A review of data on consumer acceptance of autonomous vehicles found that direct experience with AVs is key to shifting sentiment in a favorable direction. Polls from the past two years suggest that at least half of people in the United States, if not more, do not trust AVs and would not purchase one. The current regulatory environment is not favorable for large-scale production of autonomous vehicles. That will limit public interaction with advanced autonomous vehicles. As a result, public skepticism will persist, and acceptance will be difficult to achieve. Absent consumer acceptance, the potential for ACES to bridge the gap between high-tech hubs and the rest of the United States will remain unfulfilled. Obstacles to a clear path to AV deployment and how to overcome them will be addressed in a forthcoming paper. ■

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