ARTICLE

INNOVATION AND EMERGING TECHNOLOGIES

Emerging transportation innovations: Promises and pitfalls

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Rapid growth in information and communication technologies has spawned a number of major innovations in transportation area, including automation and connectivity. At the same time, the advancement in battery technology has accelerated the electrification of transportation vehicle propulsion. This paper, focusing on highway-oriented surface transportation, examines the current development of these innovations, along with their synergies, benefits, pitfalls, trends, possible barriers to deployment, and wider impacts.

***Keywords*: Transportation; Automation; Connectivity; Electrification.**

INTRODUCTION

Innovation in transportation has been taking place since time immemorial. The consistent motivation has been to go longer distances, carry heavier loads, and to move faster. As technologies advance, innovations follow. From the invention of wheels to paved roads to the discovery of oil and mass production of automobiles, technology and attendant innovation have continually enhanced human mobility. The past century witnessed an unprecedented growth in motorization around the world accompanied by dramatic increases in economic prosperity. On the other hand, motorization and the use of fossil fuels also brought in massive adverse impacts in the form of road crashes and attendant social adversities and economic loss, and climate change with frequent occurrence of extreme natural disasters.

In recent years, the rapid development of information, communication, and related technologies has led to a host of transportation innovations. These developments have provided opportunities to mitigate or at least, reduce some of the adverse effects of automotive transportation on socioeconomic and natural environments, whereas enhancing the effectiveness and efficiency of transportation systems and eventually improving the quality of life. While these innovations are mostly technological, their implementation has significant social, economic, and legal implications.

Automation of some of the driving functions has been appearing over several decades with such features as the cruise control or automated braking system. However, the notion of automation often leads to connotations of fully self-driving vehicles. The levels of autonomy range from zero automation where the human driver is responsible for all driving tasks to full automation where the driver is entirely kept out of driving. Connectivity pertains to communication and information sharing between vehicles, infrastructures, and other entities such as pedestrians and bicyclists. Internet enabled ride-hailing and ride-sharing have transformed the for-hire transportation industry. Micromobility using e-scooters has also provided an appealing innovation in university campuses and other areas. Although electrification was common in the early days of automobiles, limitations of the batteries had practically eliminated the use of electric vehicles (EVs) over the past century. Recent advances in the battery technology are making electrification of automotive transportation economically feasible as well as acceptable to consumers. Batteries are having longer charge depletion times and taking shorter times to recharge through plug-in charging or guideway charging.

Automation responds to safety and congestion, connectivity addresses travel efficiency and fuel use, electrification is motivated by the need for a cleaner environment and the reduction of greenhouse gas emissions, and shared mobility and the use of remote communication promote efficient utilization of societal resources. The combined effect of these innovations, in the context of the profound changes that are taking place in retailing and the postpandemic employment sectors, can be expected to radically change the way we live, go to work, shop, and entertain ourselves, and some of these effects have already started to become manifest, particularly through the use of telecommunications as a substitute for transportation[1]. Consequently, we are on the cusp of potentially massive reconfigurations of the land use of our metropolitan areas.

AUTOMATION, CONNECTIVITY, AND ELECTRIFICATION

A fully autonomous vehicle (AV) can navigate the roadway without human driver input. The AV uses three basic technologies (radar, lidar, and sonar) for sensing artificial intelligence (AI) techniques that use the sensed information to characterize the roadway environment (guideway, other vehicles, traffic signs, lane markings, and obstacles), and an AI-based control system to chart paths for its navigation. The sensed information may be complemented with information received via connectivity from other vehicles and entities. The Society of Automotive Engineers[2] classifies

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Received 23 December 2021; accepted 27 March 2022; published online 7 May 2022; doi:10.1142/S2737599422400011

autonomy in levels from 0 to 5. At Level 0 (No Driving Automation), the driver is entirely in charge of operating the vehicle, including the primary driving tasks (braking, accelerating, and steering). However, the vehicle has driver support systems that may intervene momentarily during driving, for example, lane -keeping assistance, forward-collision warning, automatic emergency braking, and blind-spot warning. With these technologies, the vehicle is still considered Level 0 because the technologies do not drive the vehicle, but offer brief action or warning in specific situations. Most vehicles on current roadways are Level 0. At Level 1 (Driver Assistance), the vehicle has at least one driver support system that aids in braking, steering, or acceleration, but not more than one simultaneously. At Level 2 (Partial Driving Automation), the vehicle possesses advanced driving assistance systems (ADAS) that can take over the primary driving tasks in specific situations. The driver is responsible for driving the vehicle, supervising the technology closely, and remaining alert and ready to take control at any time. Level 3 (conditional driving automation) uses a variety of driver assistance systems and AI to make driving decisions based on the prevailing driving environment conditions. When the system encounters a situation it cannot navigate, it requests the driver to take over. Therefore, even though the human driver may have their hands off the wheel, they are always alert and able to take control at any time. Level 4 (High Driving Automation), often used in driverless taxis and public, typically operates in geofenced areas and does not require human participation in the driving task except in specific unusual conditions such as inclement weather or off-road terrain. At Level 5 (Full Driving Automation), the vehicle has no steering wheel or pedals, and can drive itself everywhere in all conditions without any human interaction. A Level 5 vehicle operates in all weather and terrain conditions and is not bound by geofencing, and the only role of the human occupant or user is to specify the destination(s). Levels 1–5 are automated, 3 is partially autonomous, and 4 and 5 are fully autonomous.

Connectivity refers to the ability to transmit/receive data for facilitating safe and efficient driving operations between the vehicle and other entities (such as vehicles, pedestrians, and infrastructure). Connectivity is considered a valuable supplement to the sensors borne by an AV, as the latter may not be unable to fully characterize the roadway environment due to weather, occlusion due to other vehicles or infrastructure, and possible sensor malfunction. In such cases, information on the driving environment can be provided through connectivity. Vehicle connectivity can be categorized as follows: traditional, conventional, or "isolated" vehicles (nonconnected human-driven vehicles [HDVs]), which do not possess any automation or connectivity; connected human-driven vehicles (CHDVs), which are HDVs with connectivity; and automated or AVs, which are automated driving systems that may or may not possess connectivity (i.e., CAVs or nonconnected AVs, respectively). In any case, connectivity, which may be uni- or bidirectional, is enabled by technologies including global positioning systems and radio, DSRC, cellular, Wi-Fi, Near Field Communication, and Bluetooth. Connectivity source-receptor pairs include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-cloud (V2C), and can be facilitated using connected roadside units (RSUs) that perform heavy computational tasks. Connectivity enables vehicles to be aware of things happening in a specified radius (often 300 meters) around them; communicate with nearby vehicles, data centers, or other entities; be aware of the intentions of other vehicles in its immediate vicinity in the traffic stream and undertake crash-avoidance maneuvers if needed; receive broadcast alerts and real-time information on downstream or network-wide road conditions (e.g., congestion, accidents, weather); carryout vehicle diagnostics; and facilitate ride-sharing. Connectivity can be enabled in a vehicle by installing a device such as a transponder at a relatively low cost. Connectivity technology continues to evolve and communication protocols are being debated and modified to identify the best approaches for specific applications. With regard to benefits, certain specific benefits pertain to individual connected vehicles (CVs); however, there can exist significant systemic and systemwide benefits to the transportation system, and these are expected be manifest particularly when CV market adoption is high.

EVs use electric motors rather than internal combustion for propulsion. Electric propulsion of roadway vehicles started in Europe in the early 19th century[3]. In 1902, its mass production was pioneered by the Studebaker Automobile Company in the United States. Several electric companies followed suit, and soon thereafter, approximately 30% of the cars on the road in the United States were electric[4]. However, over the decades, the popularity of EVs waned due to a confluence of factors including inadequacy of charging infrastructure, limited charging range, and expansion of roadways that led to trip lengths that were beyond the existing EV range. Other factors were related to increased attractiveness of rival sources of energy: first, the wide availability of inexpensive alternative energy sources (mostly fossil based); second, the invention of a starter for the internal combustion engine (ICE) eliminated the need for laborious hand cranking; and third, the invention of the muffler significantly reduced noise emitted from the ICE[5]. The new millennium has seen a resurgence of EVs, due to various factors including the awareness of potential role of transportation in climate change and air pollution, advancements in charging technology, and the need for reduced reliance on foreign sources of energy. The electric motor's power sources are batteries (which need periodic recharging or swapping) or electricity from an extravehicular source such as overhead pantographs, or in-pavement or other guideway chargers. EV charging stations receive AC power from the grid. However, as batteries can be charged only with DC power, EVs typically possess an onboard AC-to-DC converter, or the charging station is fitted with AC-to-DC converters.

Figure 1 presents a broad view of the key impacts of the three technologies (and some interrelationships between the impacts). Subsequent sections discuss the trends of the new technologies, their impacts in terms of the opportunities and challenges, and the prospective synergies between the technologies.

TRENDS

Automated vehicles

Predictions of the anticipated market penetrations of the various SAE levels of CAVs have been made using interviews and market research surveys[6]. Generally, it may be estimated roughly that by the year 2030, AV Level 0 (currently the dominant share) may likely gradually decrease to 50–70%, whereas Levels 1 and 2 will increase to 20–35%, and Levels 3 and 4 will increase to 10–15% and 2–5%, respectively. Other researchers have addressed the AV market growth from the perspectives of vehicle sales, on-road fleet share, and amount of travel, and have suggested that it may probably be year 2045 before 50% of all new vehicles are autonomous and year 2060 before 50% of the vehicle fleet is autonomous, or possibly longer due to technological challenges or consumer preferences[7].

Connected vehicles

Market intelligence analysts have predicted that the demand for connectivity devices in vehicles will grow due to increases in traffic safety concerns, but may be hindered by the timeliness of communication-related policy and regulation. Also, it is predicted (**Fig. 2**) that the US connected car market will exhibit a threefold increase between 2020 and 2023[8], spurred by technological developments including 5G networks, cloud computing, and AI, supportive government policy on communication bandwidths, and increasing customer demand for smart features in vehicles[9,10]. As a result, it has been forecast that by 2025, approximately 70% of licensed drivers in the United States will be driving a connected car[8]. The shortage in semiconductor chip logistics challenges associated

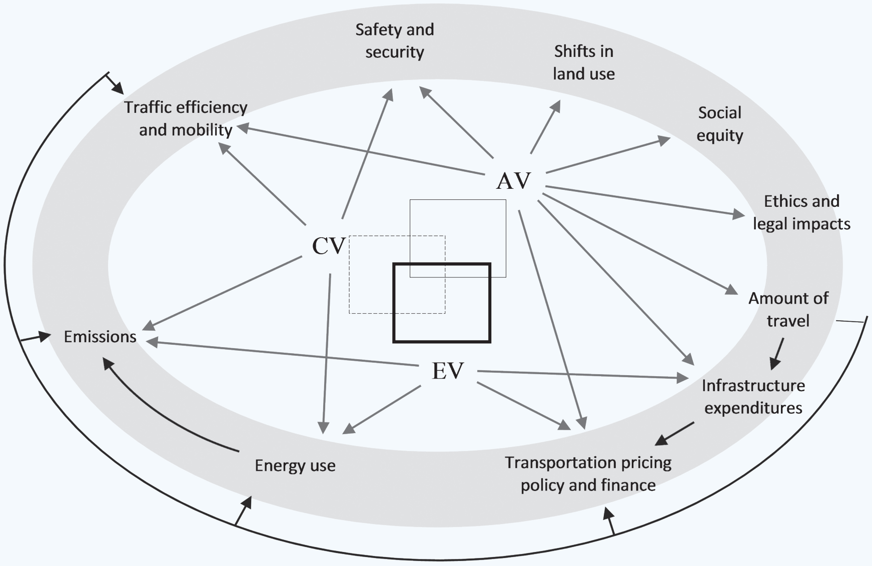

Figure 1 A broad view of impacts of the three technologies.

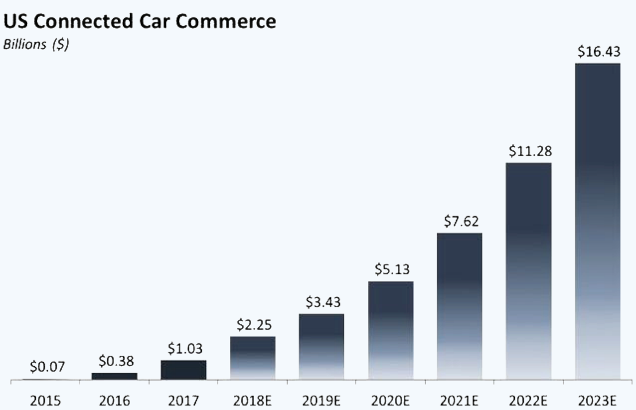

Figure 2 Anticipated growth in CV commerce in the United States[8].

with the COVID-19 pandemic, may reduce such predicted growth of CV market share, at least in the short term. At the current time, of all passenger car sales in the United States in 2020, 91% (i.e., over 13 million vehicles) were connected[11].

Electric vehicles

After about a century of decline and dormancy, EV demand has surged in the last decade, fueled by the need for diversification of transportation energy sources from gasoline to other sources[12]. This trend is driven by forces associated with environmental protection, climate change, and national energy security. EV annual sales in the United States have grown from a few thousands in 2010 to more than 315,000 in 2020 (and a similar pattern worldwide). Although the sales are much larger in the Europe and parts of Asia, the US EV market is expected to show strong growth in the next decade. In 2021, about 9.7% of all automotive sales in the United States were EVs, as the EV sales increased by 89% over the previous year, and EVs currently constitute approximately 3% of the current stock. **Figure 3** presents the global trend in the EV market: the total stock of electric cars on the world's roads exceeded 10 million in 2020, a 43% increase over 2019, with most of the growth attributed to battery electric models (BEVs). The Energy Information Administration (EIA)[14] predicts that light duty vehicles (LDVs) will witness the strongest growth in electrification.

THE PROMISES

The most anticipated benefit of AVs is safety. Worldwide, motor vehicle crashes continue to be a leading cause of fatalities, particularly of young persons. Annually, one million people worldwide lost their lives due to traffic accidents, and tens of millions more sustain injuries[15]. More than half of those killed are pedestrians, motorcyclists, and cyclists. Globally, the economic loss due to road crashes is close to $2 trillion each year, in addition to pain and suffering of families. As human error remains by far the most dominant cause of these crashes, the goal of "zero-death" can be achieved only by eliminating humans from driving. Substantial safety benefits can be achieved even at lower levels of driving autonomy. Another prospective impact of AVs is the value of travel time: because in-vehicle travel time can be devoted to other possibly gainful purposes, the travel time may no longer be as great a burden as it is now; therefore, residential locations that are currently considered remote may become more attractive, causing long-term land use shifts[16]. A significant land use impact can also take place due to the reduced need for parking particularly at downtown locations[17], assuming AVs can drop off their passengers directly at their destinations, proceed empty to their residences or to a parking garage located further away from downtown where land space (and parking) is cheaper, and then return (when summoned) to pick up the passengers at the drop off location[18]. Thus, AVs can also be expected to reduce first-mile last-mile (FMLM) distances and out-of-vehicle travel time (OVTT). In addition, recognizing that 20% of Americans have a disability and 16% are 65 or older[19], AVs may promote transportation equity through increased travel opportunities for the infirm, handicapped, and elderly[20].

Vehicle connectivity can significantly improve transportation systems in terms of safety, mobility, capacity improvement, energy use, and emission reductions[21]. Connectivity facilitates real-time transfer, from/to vehicles in a road network, information on road hazards, inclement weather, crashes, and other congestion-related events and, therefore, could improve routing efficiency and departure time optimization[22]. Other potential benefits of connectivity include speed harmonization, traffic signal control and optimization[23], fuel efficiency improvement[24], and traffic flow stabilization[25].

One of the key promises of EVs is that they will help limit the carbon footprint and pollution caused by ICE vehicles. About 63% of fossil fuel consumption in the United States is currently associated with highway transportation including trucks, buses, and automobiles. As plug-in charging will require electricity from the grid, and because much of the electricity is currently generated using fossil fuel, EVs will still be

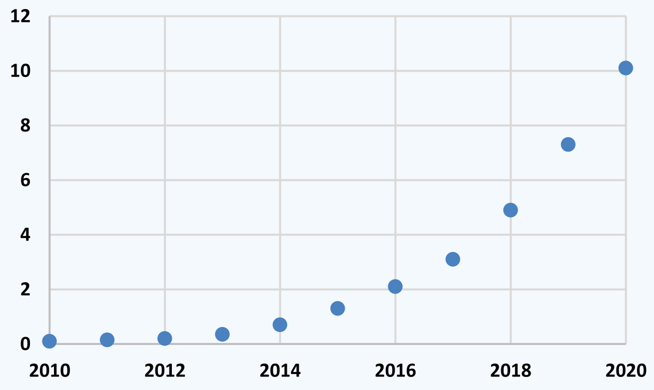

Figure 3 Growth in global EV market (millions), plotted using data from IEA[13].

associated with emissions, although at a lesser extent compared with conventional vehicles. Another potential benefit is that the road user costs of repair and maintenance associated with hybrid and plug-in EVs are generally lower compared with conventional vehicles (EVs have fewer moving parts compared to conventional vehicles, and servicing is relatively easy, less frequent, and overall, less costly). In addition, EV initial costs can be expected to reduce, in the short term, directly through government tax credits and incentives, and in the long term, through the economy of scale as productions increase. EVs are also quieter compared to conventional vehicles, which means lower noise pollution.

THE PITFALLS

A possible pitfall with AVs is the need for providing new or high-quality infrastructure requiring large capital investments and subsequent maintenance and operational expenses. Other pitfalls include the ethics of AV driving control system choices, possible degradation of pedestrian safety (at least in the short term) due to the elimination of informal and nonverbal communication between the AV and pedestrians, and reduced employment of for-hire drivers. In addition, the perception of increased safety offered by AVs may encourage their passengers to exhibit driving behavior that may be unsafe. Further, AVs may represent an attractive tool for malicious individuals who might view these vehicles as a nontraceable opportunity for carrying out criminal or terrorist activities including anonymous delivery of harmful devices or materials. Also, the mélange of computers aboard an AV makes it an attractive target for persons who seek to abuse information contained in the vehicle. Other potential pitfalls include damage liability when a crash occurs, possibility of in-vehicle software or sensor failure, possible inability or ineligibility of passengers to take over the driving task from the automated system, and possible lack of high-quality and updated digital maps in the vehicle's computer for reliable navigation. There is also the transport agency's potential public relations problem of prevalent "ghost" (or, zero occupancy) vehicles cruising in congested areas taking up valuable space in the traffic stream.

Vehicle connectivity faces problems associated with public–private sharing of communication channels. Inconsistent government policies on communication protocols will likely impair the efficacy of connectivity. In addition, lack of standardized communication protocols across manufacturers causes nonuniformity in the types and extents of data sharing across entities (vehicles, pedestrians, infrastructure, etc.). As such, these challenges could jeopardize market penetration of CVs. Also, Internet connected systems may render the vehicle vulnerable to hacking.

Challenges that impair EV adoption, at the current time, include the battery weight, lengthy time-to-charge, range anxiety, and inadequacy (or poor accessibility) of charging infrastructure. Another potential strategic problem is the electric grid destabilization that could be addressed using market-based initiatives. For example, charging rate incentives or disincentives could be imposed to encourage EV owners to charge their vehicles mostly during nonpeak hours when overall demand for electricity is low or to feed electricity back into the grid during peak periods of electricity use. As charging stations are established around the country with funds made available through the newly enacted infrastructure bill[26], there is a concern that the rural areas may be left underserved because of their possible low priorities in terms of population densities. Also, the issue of disposal of used batteries can be a major environmental concern in the long term.

SYNERGIES AMONG THE INNOVATIONS

It can be assumed that there will exist synergies in concurrent deployment of the innovations (not necessarily the same start times but overlaps in their deployment). The sibling relationship between vehicle autonomy and connectivity was discussed by Anderson *et al.*[27] Connectivity can catalyze the advancement of AVs[28]—the spatial ranges of traditional sensors have relatively limited range, and communication with other vehicles and infrastructure via connectivity, can help the AV gain a more comprehensive awareness of its driving environment and thereby allow it to make informed driving decisions at strategic (route planning) or operational (lane changing) levels[29]. Several researchers corroborated the notion that connectivity capabilities can significantly enhance the operational performance of AVs[30]. With regard to AV–EV synergy, it has been argued that the convergence of the electric propulsion systems and AVs is inevitable because it is easier for computer-driven vehicles to be powered by electricity. Offer[31] stated that automation capabilities can improve the economics (and therefore, market share) of EVs. Also, AV technology with electric propulsion is expected to not only facilitate more productive use of travel time, but also lead to novel business models in the mobility market. Adler *et al.*[32] stated that vehicle automation, connectivity, electrification, and shared ownership will collectively disrupt transport market and public finance, and that the introduction of road tolls in line with "user pays" and "polluter pays" principles will become more attractive. Researchers[33] have also stated that electric and shared-use AVs will be most cost-effective in the context of short, intracity trips where vehicle occupancy is often high and where vehicles are unlikely to be left bereft of power without access to nearby EV charging stations.

The effect of the sum of multiple innovations is potentially superior to the sum of their individual effects. Ha *et al.*[34] suggested that the strength of the synergy (and hence, its benefits) between the emerging innovations will likely be a function of the prevailing levels of advancement of the innovations, and the gap between their prevailing levels. In other words, the benefits may be more achievable when the advancements are at a mature, rather than nascent, stage.

ANTICIPATED BARRIERS TO DEPLOYMENT

In spite of the advancements in vehicle communication and automation technology and their prospective impacts, there are significant challenges that must be addressed for safe and successful integration of the technology-driven innovations in road transportation. Although no reliable estimates have yet been attempted, both capital and operational costs can be expected to be rather high depending on the scale of deployment, and may not be justified on the basis of financing through traditional users' pay. Even if we assume that the difficulty of financing all or some of the innovations can be resolved as we go through the transition phase of delivering them over several decades, enormous challenges remain for the deployment. With regard to AVs, these challenges include trust in automation, consumer concerns about vehicle safety; hardware and software reliability particularly in highly dynamic and complex roadway environments. With regard to CVs, implementation barriers currently include cellular coverage limitations, lack of consistent, reliable, and standardized communication protocols, concerns about privacy and data security, and the inconsistency of governments' communications-related policy and regulation, and difficulty of fusing and transmitting complex information on the driving environment. EVs face formidable deployment barriers including lack (or slow placement) of charging infrastructure, insufficient standardization of charging infrastructure, charging range limitations, and initial cost of vehicle purchase. Other obstacles to deployment include the large battery weight, short charge depletion time, long time-to-charge, and grid capacity limitations. These challenges continue to be addressed through research and development efforts supported and funded by the government and the private sector. However, as the automobile industry gears up for the production of EVs, labor unions have serious concern about possible loss of jobs because EVs, compared with traditional vehicles, require significantly less labor.

In order to address the innovative technology-vehicle adoption barriers, governments can continue to offer incentives such as tax credits and easing of vehicle import restrictions. The transportation innovations, when they are introduced in the market, will be competing against their traditional counterparts. The latter has benefited from many decades of technology development and learning, and therefore, has technology that is mature, an established or even captive market, supporting infrastructure woven into the anthropogenic landscape, and consumer loyalty, awareness, and experience.

For all the key transportation innovations—automation, connectivity, and electrification—the most formidable of the deployment barriers, probably, is the inadequacy of the current infrastructure to support the new technologies. Although initiatives included in the recently passed Infrastructure Investment and Jobs Act can be expected to address this issue, the levels of funding provided may be unable to make a significant difference. Other potential barriers include public distrust and uncertainty of demand. Promises offered by emerging transportation innovations cannot be realized unless appropriate legislative initiatives and policies are established to address public concerns and perceptions regarding their implementation. Further, there is the issue of driver training; it is expected that there will be a transition period having a mix of traditional and the emerging vehicles with new technological capabilities (with the latter having increasing shares over time), prospective users of the latter will need to be trained to operate safely in the mixed traffic streams or at dedicated guideways limited to vehicles bearing one or more of the transportation innovations.

CONCLUSION

Advancements in basic technologies are spurring key transportation innovations, namely, automated driving, connected entities, electric propulsion, and sharing and micromobility as well. These innovations promise significant benefits in terms of transportation safety, travel efficiency and economic productivity, and the environment. The realization of these benefits will depend upon when and to what extent the innovations gain market access along the transition phase that can stretch several decades, in the face of potential problems and likely barriers of their implementation.

Although fully automated and CVs may not entirely replace human-driven fleet in the near future, we can well expect the gradual introduction of increasing number of vehicles with higher levels of autonomy and connectivity in coming years. Fully automated and connected trucks and automobiles are likely to appear first along specific freeway corridors with dedicated lanes for such vehicles. At the same time, as our electricity production moves gradually away from the use of fossil fuels and charging opportunities increase, the benefit from electrification with increasing market penetration of EVs will start to become substantial.

For transportation agencies to make significant investments in infrastructure realignment to accommodate connected and automated vehicles, the societal benefit must be substantially higher than the agency cost. In the meantime, these agencies will continue to deploy these innovations on test tracks or on limited-access in-service roads and at the same time, engage in investigations using computer microsimulation and driving simulator experiments. These field experiments and carefully conducted simulations will provide treasure troves of data for further insight in the individual and synergistic effects of these sibling innovations, and to address knowledge gaps in vehicle automation, connectivity, electrification, as well as other attendant innovations like sharing and micromobility.

Finally, it may be worthwhile to comment on a number of issues that lie at the heart of the emerging transportation technologies. First, is the long-term viability of EVs in the context of battery production capacity and the issue of sustainable mining. As the transportation terrain evolves gradually from traditional fuel to EVs, stakeholders are keeping a close eye on both opportunities and risks to the supply chain that emanate from consumer preferences, government regulations, and the availability of the base material (Lithium). For example, EV market growth could be stymied by the uncertainty in battery production capacity. As most EV batteries come from very few suppliers as such, automakers could in future be left at the mercy of battery suppliers. In addition, alloys used in batteries constitute 9% of mining outputs of rare earth elements and other elements including nickel, and the vulnerability of their supply is underscored by the dearth of countries that produce these elements; political unrest and other unfavorable conditions could lead to disruptions in the EV supply chain. Studies by the Lawrence Berkeley National Laboratory and the University of California, Berkeley, have determined that there exist adequate lithium reserves to support large-scale battery production for EVs. However, lithium extraction processes present significant environmental and health hazards, including contamination of surface waters and drinking water, respiratory problems, ecosystem damage, and landscape degradation[35,36].

The second issue is the wider effects of the emerging transportation technologies on the cityscape, commuting, and the quality of life of city residents. The transportation innovations are taking place not in isolation with innovations in other aspects of our daily life. For example, technology for conferencing has advanced greatly in recent years, particularly in response to remote workplace requirements during the pandemic. We can very well envision in a not-so-distant future where a significant proportion of our service and related sector employees will work from home or from neighborhood workstations to which they will travel by walking or biking, or using autonomous public transit. This will cause a revival of the neighborhood concept of urban living and cities will regain the human scale such that we will not waste enormous amounts of time commuting to work and instead, will be able to devote time to creative and intellectual pursuits. Thus, cities will get reengineered into thriving communities with innovation and culture contributing to greater and greater human progress.

ACKNOWLEDGMENTS

This work was supported by Purdue University's Center for Connected and Automated Transportation (CCAT), a part of the larger CCAT consortium, a USDOT Region 5 University Transportation Center funded by the USDOT Award #69A3551747105. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organization.

CONFLICT OF INTEREST

The authors declare no conflict of interest associated with this paper.

COMMENTS AND QUESTIONS FROM REVIEW PANEL

The authors in this paper discuss synergistic emergence of three trends: Electrical vehicle (EV), connected vehicle (CV), and autonomous vehicle (AV), and how these trends can transform the urban landscape, social interaction, and government policy. The paper is well organized and easy to read: we have heard about many of these issues before, but as outsiders have not seen them discussed in one place. We believe this holistic perspective can be useful to a broad audience. Following are a few questions for the authors that should help connect more with readers:

QUESTION 1 You say that SAE defines several levels of automation and some partial automation is already available. What has been the public acceptance and impact of this partial automation so far?

AUTHORS' RESPONSE: So far, it appears that public acceptance of vehicle automation Levels 1 and 2 automations have been very high. A report released in 2019, "Worldwide Autonomous Vehicle Forecast, 2020–2024" from the International Data Corporation (IDC) finds that vehicles with Level 1 autonomy will jump from 31.4 million in 2019 to 54.2 million in 2024[a]. The driver support systems they offer, support appropriate braking, steering, and acceleration, and therefore, seem to be very popular as they have led to significant increases in safety and increases in travel mobility. Even in the pandemic, Level 2 autonomous cars witnessed a sharp rise in sales, 11.2 million Level 2 cars were sold in 2020, representing an increase of 78% from 2019[b]. With regard to Level 3, the high price of Level 3 AVs seems to be an inhibiting factor. Generally, it seems that beyond Level 3, higher levels of automation, are associated with greater user distrust of automation and anxiety, and reduced likelihood of public acceptance. However, with increasing deployment of partial automation Level 3, public trust in automation is expected to grow, and the acceptance and adoption of full automation (Level 4 and subsequently, Level 5), can be expected to follow.

QUESTION 2 Battery electric vehicles are generally unfamiliar to emergency responders and to mechanics. What is needed to ensure that these essential providers are effective?

AUTHORS' RESPONSE: CAV stakeholders and researchers seem to agree that the new technology will usher in disruptive shifts in the driving-related job market[c] and duly recognize the need to train the transportation-related workforce to prepare for the future world of connected, automated, and electric vehicles. In Michigan, Gov. Snyder's 2017 State of the State address emphasized the need for "technicians to understand how to work with cutting edge technology that will be in future vehicles." Such government support and public awareness are critical. Several universities and community colleges in the United States have established courses related to workforce development in a bid to support future careers that address these issues.

The efficacy of essential service providers, in the emerging era of new transportation technologies, will hinge on (a) the robustness of the technologies so they can work well under all weather and traffic conditions, (b) synergistic functioning of autonomy, connectivity, and electric propulsion, and (c) availability of qualified technicians to repair faults in the technologies.

QUESTION 3 How can connectivity be used to make traffic flow better on urban arterials?

AUTHORS' RESPONSE: Connectivity enhances the performance of traffic signals at urban arterials[d]. A 60% penetration of CVs in the traffic stream can result in significant reductions in average delay at a given intersection[e]. For example, through connectivity, drivers at or approaching an intersection could receive information regarding the time-to-green or the remaining green time at an intersection, thereby adjusting their driving behavior to smoothen their movement along the signalized arterial.

Another anticipated systemwide benefit of connectivity is the improvement to routing efficiency and departure time optimization[f,g]. Connectivity allows drivers to receive real-time information from other vehicles already in the road network regarding road hazards, weather effects, crashes, and other congestion-related events[h]. Network routing and urban roads navigation software provides this information, albeit with some delay. Such delay could be considered a significant shortcoming because sharing of the newly calculated route with all drivers potentially creates new areas of congestion, and in some cases, such translocation of congestion from one area to another worsens overall congestion[i]. With vehicle connectivity, it is possible to reroute collaboratively from a central controller so that congestion translocation is avoided[j,k]. Alternatively, for less urgent trips, connectivity capabilities can make the driver aware of the optimal (as well as alternative) times for starting a trip, thereby enhancing driver convenience, and possibly, reduced fuel consumption and improved safety.

QUESTION 4 Some readers may have followed the work of Geoffrey West (https://en.wikipedia.org/wiki/Geoffrey_West) regarding the scaling theories of cities. The emergence of EV, CV, and AV would break some of the fundamental assumptions of the scaling derivation. Could the authors comment on whether that also would predict a more homogenous distribution of city sizes?

AUTHORS' RESPONSE: In their 2007 article in the *Proceedings of the National Academy of Sciences* titled "Growth, innovation, scaling, and the pace of life in cities," Geoffrey West and his coauthors argue that properties of cities (such as patent production, personal income, length of electrical cables, etc.) are power functions of population size with scaling exponents, β, that fall into distinct universality classes. Quantities reflecting wealth creation and innovation have $\beta \approx 1.2 > 1$ (increasing returns), whereas those accounting for infrastructure display $\beta \approx 0.8 < 1$ (decreasing returns, or economies of scale). The authors of the 2007 article also explored possible consequences of these scaling relations by deriving growth equations[1], which quantify the dramatic difference between growth fueled by innovation versus growth driven by economies of scale. According to the authors, this difference suggests that, as population grows, major innovation cycles must be generated at a continually accelerating rate to sustain growth and avoid stagnation or collapse.

In the opinion of the authors of the current manuscript, the observations in the present manuscript are generally consistent with the West paper. In the context of emerging transportation technologies, the properties of a city could include the number of connected vehicles (CVs), the number of automated vehicles (AVs), the number of electric vehicles (EVs), and the amount of infrastructure provided to accommodate these new technologies. Increase in population (and hence traffic volumes) will be expected to be associated with increased adoption of the emerging technologies at an increasing pace, because they represent technological innovations. Therefore, the first three properties are likely to exhibit $\beta \approx 1.2$ (increasing returns), consistent with what the West study prescribes for technological innovations. Also, as population (and traffic volumes) increase, EV-, AV- and CV-infrastructure would be expected to increase (albeit at a reducing rate of increase), due to right-of-way limitations; this seems to be consistent with the prognosis of the West study regarding infrastructure.

Regarding the homogeneity of city size distributions, it is not certain which direction the effect of the new technologies will take. One thing for certain is the reduction of the value of travel time because AVs will free up during trip time to be used for other purposes (resting, recreation, etc.). As such, it is expected that travelers may not object to residing in areas far from downtown, therefore, cities can generally be expected to grow larger.

Overall, the combined impact of transportation and technological innovations can spawn other innovations, for example, neighborhood-generic workstations, allowing workers to stay in or near central cities that provide urban amenities. People will thus be able to walk or bike or use public transit for short distances and thus will have more time for creativity, and artistic and cultural pursuit. The ultimate result can be the enhancement of the quality of life and the resurgence of urban livability.

QUESTION 5 The current paper provides an important snapshot of the current state of affairs: we were wondering whether the authors would feel comfortable drawing on their vast experience to speculate on the long-term implications of the transportation innovation?

AUTHORS' RESPONSE: As is the case of any innovation, there exists the prospect of both beneficial and adverse long-term effects of these transportation innovations, and stakeholders to be impacted include the road users, road agencies, and governments.

Electrification of vehicle propulsion, in the long term, will lead to overall reduced use of fossil-based fuels with attendant lowered emissions and increased air quality, but at the same time creating environmental and social problems associated with the mining of materials for battery production. In addition, there will be changes in the urban landscape following the gradual decommissioning of existing gasoline stations in favor of electric charging stations. Also, in the long term, the traditional structure for road pricing at most countries, which is tied to consumption of gasoline and diesel, will be severely impacted as revenues will plummet. Therefore, in the medium term, agencies will have to consider electricity-usage based fees, such as $/Kw-hr of charging, and in the long term, transition to energy neutral forms of road user fees, such as a vehicle-mile fee or weight-distance fee.

We anticipate that in the long term, vehicle automation will be characterized by not only a high market penetration of AVs but also high levels of autonomy of vehicles in the traffic stream. This will drastically increase traffic safety (in the current traditional vehicle environment, 95% of crashes are partly or fully caused by human error). Also, reductions in the value of travel time may cause shifts in urban land use. Increases in traffic efficiency and mobility at freeways and arterials due to vehicle automation will increase the productivity of travel-related businesses. On the other hand, in the long term, it can be expected that there will be massive loss of driving jobs, and governments and other employers will need to develop retraining programs for the millions of drivers who will be laid off. AVs are expected to cause a reduction in first-mile last-mile (FMLM) distances, lower out-of-vehicle travel time (OVTT) and reduce the need for parking particularly at downtown locations. Therefore, automation will render obsolete, certain infrastructure associated with traditional human-driven vehicles, such as parking lots in airports and downtown areas.

Vehicle connectivity, in the long term, will facilitate truck platooning at freeways (that will reduce travel time, enhance trucking productivity, and reduce energy consumption and emissions). Also, V2P, V2V, and V2I connectivity will drastically reduce vehicle crashes and pedestrian fatalities and injuries, and reduce the need for traffic signals as traditionally used.

Overall, we speculate that the spread and magnitude of these implications will be a function of time, location (urban vs. rural), level of existing development, and economic and social conditions in the future, and the extent of synergies among the three sibling technologies.

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