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Synergies of four emerging technologies for accelerated adoption of electric vehicles: Shared mobility, wireless charging, vehicle-to-grid, and vehicle automation

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ABSTRACT

This technical note discusses the synergetic attributes of four emerging technologies that have significant potentials to enhance smart and sustainable urban mobility, and ultimately improve urban sustainability. Shared mobility, wireless charging, vehicle-to-grid (V2G) integration, and vehicle automation have complementary features that rectify the practical barriers and implementation restrictions of each other. We attempt to bridge between transportation research studies and the environmental sustainability community, discuss the recent findings, and identify critical knowledge gaps to better understand the synergies and mutual benefits of these emerging technologies and avoid unintended environmental consequences.

1. Introduction

Urban transportation is the backbone of economic thrive in developed and emerging societies, but a major factor in energy consumption, air pollution, human health, and traffic congestion. Electric vehicles (EVs) can help address some of the sustainability challenges facing urban transportation. First, they can directly reduce tailpipe emissions. Second, EVs displace major urban emissions by concentrating emissions from tailpipes to centralized power plant stacks. Although the life cycle emissions might not be reduced due to fossil fuel-fired power generation concentrated emissions can be treated more efficiently and effectively (Cai and Xu, 2013). Third, the overall life cycle energy efficiency of EVs (from fossil fuel to power) is higher than that of internal combustion engine vehicles. Last but not least, EVs help accommodate renewable energy in power generation. From 1990 to 2017, EVs and hybrids have grown from zero to nearly 1.2% of the U.S. market share for new vehicles, lagging behind Norway (39%), Iceland (11.7%), Sweden (6.3%), China (2.2%), and Germany (1.6%) (International Energy Agency (IEA), 2018). Despite significant exogenous effects of local, state, and federal policies and regulations for adoption of EVs, the sales of these alternative fuel vehicles have been relatively slow due to low gasoline prices and high purchase cost of EVs. Meanwhile, sales of pickup trucks and SUVs have overwhelmingly increased primarily due to low gas prices.

EVs also face significant challenges for large-scale deployment, including traveler range anxiety, access to charging infrastructure, and charging time management. Shared mobility, wireless charging, vehicle-to-grid (V2G) integration, and vehicle automation are emerging systems and technologies in the transportation sector. They each can help address some of the challenges facing EV adoption and the combination of all can offer even greater benefits for EVs. Shared mobility improves the efficiency of transportation systems by downsizing the fleet. Wireless charging and V2G facilitate the automation of charging process for EVs and enhance road electrification at large scale by improving the economics of EVs. This could remove range restrictions and strengthen public interest in EVs. Vehicle automation provides wide-ranging socio-technical transformations with potential benefits for mobility, safety, environment, infrastructure, urban planning (Taiebat et al., 2018).

The transportation research community has started exploring

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the synergies of these technologies on operations and systems issues of mobility supply-side. The economic and environmental impacts of each individual technology are also examined in various studies. The *synergetic* environmental effects and mutual economic benefits, however, have received less attention in the environmental sustainability research community. Thus, those impacts for smart and sustainable urban mobility are still relatively nascent. This technical note attempts to bridge between transportation and environmental research communities, foster the discussion of recent findings, and identify research gaps in environmental literature for understanding the synergies between these emerging technologies for speeding up the EV adoption.

2. Emerging Technologies in Mobility Sector

The impacts of individual emerging technologies on EV adoption are discussed below:

2.1. Shared Mobility

Users of a shared electric vehicle (SEV) fleet rent SEVs by hours or pool their ride with others instead of owning one. SEVs have electric drivetrain, entailing zero-tailpipe emissions. The required energy to power the transportation is supplied with power grid. Displacing transportation emissions from urban areas by promoting de-carbonized mobility leads to better air quality. A large body of literature has shown that SEVs satisfy the same level of service, travel time, and wait time compared to conventional shared fleets, or even facilitate it, in term of operational and maintenance costs. Shared mobility can effectively shrink vehicle-miles-traveled (VMT) by combining trips and also provide the basis for fleet downsizing, congestion mitigation, and potentially reduction in energy and emissions (Lu et al., 2018; Shaheen and Cohen, 2013; Meyer and Shaheen, 2017; Cai et al., 2019).

As of 2018, the share of electrified rides among the service provided by major ride-sourcing platforms and transportation network companies (TNCs) remained below 1% (Slowik et al., 2019). Using EVs for shared mobility could lead to significantly larger per-vehicle and per-passenger reductions in GHG emissions and criteria air pollutants compared to privately owned EVs. Furthermore, higher utilization rate, faster fleet turnover, and better economics of SEVs could promote battery innovation cycles and more rapid adoption of efficient vehicles at the fleet level.

In spite of benefits, SEVs are highly dependent on charging infrastructure and utilizing most of charging opportunities to keep the functional status. After the completion of trip, it is likely that SEVs are not plugged-in in a vast majority of times, thus losing the charging opportunity. To insure continuous utility, current shared electric mobility systems, consider two mechanisms for charging: (1) Incentivize users to drive the car to a parking depot and plug-in, or (2) Fleet concierge personnel (station attendants) relocate the cars from the city and physically plug-in to the charging stations. In both scenarios, the additional costs can be significant for fleets, due to high costs of human-in-loop service (Chen et al., 2016).

2.2. Wireless Charging

Wireless power transfer (WTP), also known as wireless electric vehicle charging (WEVC), is an alternative to conventional plug-in (conductive) charging, which may influence the charging process in a host of negative and positive ways. WPT can be implemented through:

1. Stationary transmission pad, embedded in dedicated parking slots,
2. Semi-dynamic charging for congested areas in intersection and taxi waiting lanes, or
3. Dynamic charging for highway dedicated lanes.

WPT offers several benefits comparing to manual plug-in charging, such as convenience, safety, improved user experience. Despite higher capital cost, WPT is expected to decrease fleet operational costs by automation of charging process and reducing human-in-loop (operational) expenses (Jang, 2018). WPT can avoid lost charging opportunities when users forget to plug in, thus eliminating personnel dispatch cost for recharging or financial incentives to encourage users to recharge. In particular, recovered lost charging opportunities or created new ones by WPT can improve the efficiency of charging infrastructure utilization, thus reducing the infrastructure requirements for serving unitary charging demand. Additionally, WPT saves infrastructure space through ground-based or below ground wireless charging with no above ground clutter, thus serving more vehicles in charging depots/lots. Dynamic or semi-dynamic charging can create additional charging opportunities when vehicles are moving.

Given the current technical maturity, WPT has comparable performance with plug-in charging in terms of energy and life cycle greenhouse gas (GHG) emissions (Bi et al., 2016). The National Transportation Research Center at Oak Ridge National Laboratory recently tested a 120-kW wireless fast charging system, which has achieved 6 times the rate of the commercially available WPT systems, while maintained over 90 percent charging efficiency of convectional plug-in systems (Foote and Onar, 2017; Oak Ridge National Laboratory, 2018). The major sustainability benefit of WPT is due to the requirement of a downsized battery that significantly reduces vehicle weight and helps increase the fuel economy. However, there is significant uncertainty and even conflict between the results of cost analysis and life cycle energy burdens between studies. For instance, Chen et al. (2016) stated that automation of charging process radically decreases the operational costs, and consequently travel cost of SEVs. Bi et al. (2019) argued that while WPT can reduce life-cycle GHG and energy burdens by approximately 8%, the life-cycle costs break even beyond 20 years.

2.3. Vehicle-to-Grid

Another well-studied emerging technology is vehicle-to-grid (V2G) integration, also known as bidirectional charging in which EV discharges to the grid when needed. In this case, the vehicle works as a distributed but mobile energy storage unit performing grid demand side management services such as frequency regulation, spinning reserve, and peak shaving. This intelligent, two-way communication between the power grid (operators and markets) and the vehicle therefore supports utilities to better manage electricity resources. V2G can significantly improve the economics of EVs and reduces the life cycle costs of EV ownership by providing revenue for owners as they sell power back to the grid.

However, there are several obstacles in practical implementation. Among those, the major barrier is the participation in V2G program and acceptance of individual consumers to allow utilities drain their EV batteries. Research shows that concerns over battery degradation, inconvenience, distrust, and further range anxiety are among major challenges of V2G (Sovacool et al., 2017). Shared mobility fleet provides an alternative solution to individual ownership, and as such rectify a part of aforementioned challenges. Furthermore, bidirectional wireless charging captures all benefits of V2G and enables a higher level of energy management by eliminating the need for human intervention.

2.4. *Vehicle Automation and Connectivity*

The emergence of connected and automated vehicles (CAVs) is a radical innovation in the transportation system that challenges incumbent business practices, and may require entirely new business strategies. CAV technology improves the economics of EVs given their complementary attributes. Robotaxis replace conventional vehicles operated by human drivers with CAVs for ride-sourcig and ride-sharing services, aiming at reduce vehicle costs, labor costs, and traffic congestion (Taiebat et al., 2018). Electric robotaxis or on-demand shared automated electric vehicles (SAEVs) have the potential to address environmental concerns by reducing transportation oil consumption by nearly 100% and optimistically mitigating 87–94% of U.S. per-mile GHG emissions (Greenblatt and Saxena, 2015). Commercial fleets are the likely *early adopters* of CAV technology (Heard et al., 2018). Given the ultra-high utilization rates, commercial fleets tend to favor powertrains with lower operations and maintenance costs such as EVs (Arbib and Seba, 2017), specially to comply with potential future regulatory mandates for operating in core urban zones. For a comprehensive review of the environmental impacts of CAVs and their effect on vehicle electrification and urban sustainability, reader are refer to (Taiebat et al., 2018).

3. Synergetic Effects for Smart and Sustainable Urban Mobility

Shared mobility, WPT, V2G, and CAV technologies are complementary and mutually reinforcing the EV adoption for smart and sustainable urban mobility. Automated parking features or full automation allows optimized charging scheduling to improve the efficiency of wireless charging infrastructure utilization. In this case, the process of replacing vehicles on transmitter pads is automated and the charging lots can be built in tighter spaces. When a fully automated vehicle needs to charge, it parks itself over a WPT pad and automatically tops up the battery. Vehicle automation also improves dynamic charging process by precise charging alignment via lane-following technologies to keep proper orientation between the vehicle and the grid power supply units.

Moreover, through connectivity and communication of vehicles with the power grid, it is possible to optimally manage bidirectional power transfer. Hence, SAEVs batteries can serve as distributed energy storage devices for uptake of electricity generated from intermittent renewable sources via V2G mechanisms. Thus, charging scheduling can be optimized to take advantage of the lowest rates and return electricity back to grid at when it is needed the most, providing extra revenue margin for fleet management. Integration of CAVs, WPT, and V2G network along with large-scale depolyment can offer a solution for leveling out electricity consumption and ensuring that auxiliary capacity is always available by efficiently circulating electricity to where it is needed, bringing the highest environmental benefits of renewable energy for both the power grid and electric mobility.

Despite rapid technologic advancements, these synergetic effects are largely unquantified. Existing studies include assumptions on some of these technologies but not all while mostly missing environmental analysis (see Table 1). For instance, Chen et al. (2016) considered SAEVs with automated charging infrastructure (implicitly WPT) reporting dramatic reduction in fleet-level per-mile travel cost. Weiss et al. (2017) qualitatively discussed the disruptive impact of SAEVs on electric utilities, and argued the readiness of traditional utility infrastructure for commercial introduction of SAEVs. Iacobucci et al. (2018) modeled a fleet of SAEVs with the size of 10–14% of a fleet of private cars showed that it provides significant grid-scale storage and spinning reserves while offering a comparable level of transportation service with conventional private cars. Marletto (2019) discussed the potential changes in utility investments and new business models for energy sector to embrace SAEVs in smart grids. Iacobucci et al. (2019) argued that using SAEVs for V2G is only financially attractive when electricity price variability is high.

4. Research Needs

The recent findings show lack of scientific consensus and large uncertainties in the synergetic impacts of four emerging technologies for EV adoption. In particular, the environmental impact analysis is largely missing from existing literature, as the focus is still on operation and system optimization. It is clear that the integration of WPT with vehicle automation and dynamic charging can further improve the efficiency of charging and reduce cost, especially for shared EV fleets. However, to the best of our

Table 1
The scope and findings of recent studies on synergetic impacts of emerging technologies.

Study	Scope					Approach	Region	Impacts	Economic Analysis	Environmental Analysis
	Vehicle Electrification	Vehicle Automation	Shared Mobility	V2G	Wireless Charging					
Chen et al. (2016)	✓	✓	✓	–	Indirectly	Agent-based modeling	Austin, TX	Aggregate fleet size, electricity demand, and infrastructure requirement	$0.41–0.47 per occupied VMT	–
Weiss et al. (2017)	✓	✓	✓	–	–	Demand response and scenario analysis	NA	Marginal and peak electricity requirement	EV charging cost of 3–22 cents/kWh	–
Iacobucci et al. (2018)	✓	✓	✓	✓	–	Transport network optimization and operating reserve request model	Tokyo, Japan	Fleet size requirement, Time of day reserve capacity quantification	40% reduction in system cost due to V2G	–
Iacobucci et al. (2019)	✓	✓	✓	✓	–	Optimization with electricity price-based charge scheduling	Tokyo, Japan	Grid impacts and time of day capacity/charging power requirement	10% reduction in charging cost with V2G, more saving with dynamic pricing	–
Bi et al. (2019)	✓	Indirectly	–	–	✓	Life cycle assessment and optimization	Washtenaw County, MI	Aggregate electricity demand, infrastructure requirement, environmental life cycle performance	Breakeven analysis of infrastructure life cycle	Decline in life cycle GHG (9%) and energy burden (7%)

knowledge, there is no quantitative study using real-world travel demand data to evaluate the cost and benefits of WPT for shared and automated EV fleets. Similarly, existing studies retain only qualitative analysis of V2G and vehicle automation on shared electric mobility. Furthermore, the required changes by utilities and electricity grid (to accommodate demand increase) have received less attention. Therefore, the true costs/benefit and environmental performance of combined WPT, V2G, and SAEVs remain unknown.

The convenience and economics of wireless charging along with benefits from vehicle automation result in travel cost reduction. This along with better accessibility of shared electric mobility may bring an undesired rebound effect and offset the environmental benefits (Taiebat et al., 2019). It encourages public to travel more frequently or longer distances, resulting in induced travel demand. Furthermore, SAEVs generate significant unoccupied trips between passenger-trips (12% of total VMT on average) and from driving to charging stations (6.5% of total VMT on average) (Loeb et al., 2018). The induced travel and unoccupied VMT could adversely affect the relative reduction of environmental impacts.

The charging patterns of SAEVs operated by TNCs are very different and likely more frequent compared to regular EVs. The frequent connectivity of vehicles for charging might be a burden on power grid, especially during peak load, and exacerbate battery degradation (Taiebat et al., 2018). In conventional plug-in scheme, vehicles are charged mainly overnight when the power demand is low and grid utilizes base load. In WPT scenario, a large number of vehicles could be charging at the same time during the daytime peak load. Depending on power generation specifics, it may result in more pollution from higher emission power plants, leading to higher life cycle emissions of transportation. Finally, the emerging mobility technologies could aggravate some other adverse effects on society, including congestion, inequality, and mobility access issues, by competing with public transit.

Policymakers should embrace comprehensive policy frameworks to avoid such unintended consequences. Defining standardized and unified data sharing and communication schemes among these technologies are a priority to balance charging infrastructure needs and grid operations as well as mobility service fleet operations. The environmental research community should start quantifying the overlooked trade-offs of the aforementioned synergetic effects. Addressing the following questions with analytical rigor is urgently needed:

- What are the long-term and short-term economic benefits and environmental trade-offs of SAEVs with wireless bidirectional charging relative to existing transportation systems?
- How can it affect existing traffic measures?
- How should the utility infrastructure be prepared to maximize the economic benefit of these emerging transportation systems?
- What operational policies and regulations are needed for controlling the externalities of these emerging technologies?

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