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Views & Comments

Carbon Trade-Offs of Autonomous Vehicles in Transportation Systems

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1. Introduction: advancements in autonomous driving technology

A growing number of autonomous vehicle (AV) companies are deploying their fully driverless vehicles into commercial services, with Waymo (USA) leading the charge by deploying over a thousand vehicles into commercial services in early 2025 [1]. The increasing number of partnerships between ride-hailing/automotive companies and AV companies signifies progress in AV safety and cost reduction.

In the first half of 2025, several major partnerships were announced. On April 29, 2025, Waymo and Toyota (Japan) announced a preliminary agreement to explore a strategic collaboration on the development and deployment of autonomous driving technologies. The partnership aims to co-develop a new AV platform by integrating Waymo's autonomous systems into Toyota's next-generation personally owned vehicles and to explore the incorporation of Toyota vehicles into Waymo's ride-hailing fleet [1]. On May 6, 2025, Pony.ai (USA) and Uber (USA) announced a strategic partnership to integrate Pony.ai's Robotaxis services into the Uber platform, beginning with a pilot launch in a key Middle Eastern market later this year [2]. Furthermore, on April 25, 2025, Pony.ai and Tencent Cloud (the cloud business division of Tencent; China) announced a strategic partnership aimed at jointly advancing autonomous driving technology and expediting the commercial deployment of Robotaxi services by leveraging Tencent's comprehensive technology ecosystem, including Weixin and Tencent Maps [3]. Such industry collaborations are indicative of the ongoing maturation of AV technology, which has progressed through five capability tiers, with level 5 representing the pinnacle of full autonomy under all conditions without the need for human intervention [4].

Automation at all levels enhances safety and reduces driver strain via the use of advanced sensors and rapid real-time decisions. These benefits have spurred major automaker investments in development, accelerating industry adoption of semi-autonomous systems. Some automotive companies have already commercialized Level 3 autonomy, which allows self-driving conditional on human intervention (Fig. 1).

2. Autonomous driving: a means for reducing vehicle emissions and improving energy efficiency

A key advantage of AVs is their potential to markedly reduce transport emissions, as road traffic accounts for 20% of global energy-related CO_2 emissions [5]. AVs can communicate with each other and traffic systems to enable smoother traffic flow, more accurate speed control, and optimized route planning. This coordination leads to fewer traffic disruptions, reduced vehicle idling, and a smoother, steadier driving experience. For example, by minimizing traffic congestion, AVs can reduce emissions from idling and stop-and-go traffic. The synchronized movement of AVs can smooth out traffic flow by dampening traffic shockwaves, reducing phantom jams, and improving merging and lane changing, ultimately increasing road capacity and network throughput. Furthermore, the energy efficiency of AVs can be maximized by programming them to accelerate and decelerate more gradually [6]. While some investigations have indicated that AVs could reduce energy consumption by 10%–20% under optimal traffic conditions [7,8], the implementation of autonomous driving technologies in early-stage AVs has shown limited energy-saving benefits [7].

Additionally, autonomous driving systems are better suited to electric vehicles (EVs), which have simpler powertrains, than to internal combustion engine (ICE) vehicles, which present greater mechanical integration challenges for advanced control systems [9]. Therefore, the broader implementation of autonomous driving accelerates the transition from ICE vehicles to EVs, which in turn improves energy efficiency and reduces emissions. The key environmental benefits of EVs compared with fossil fuel–powered cars are as follows: EVs are more energy-efficient, use less energy to travel the same distance, and can use electricity generated from renewable sources, reducing greenhouse gas emissions and air pollution. These attributes make EVs a critical element in reducing vehicle-related emissions.

The third way that AVs contribute to energy savings is through "platooning," whereby vehicles drive very closely together, thus reducing aerodynamic drag. This coordinated close-distance driving is particularly effective for heavy trucks where trailing vehicles

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Fig. 1. Illustrative example of AVs (highlighted in blue) operating in a platoon amidst conventional traffic on China's Donghai Bridge.

experience up to 10% fuel savings [10]. This automated platooning, which human drivers are not capable of, directly decreases freight transport emissions.

3. Shared autonomous mobility: system-level efficiency and environmental synergy

The maturation of autonomous driving technology will catalyze a major transformation in mobility service models, leading to a rise in shared AVs (SAVs) [11,12]. SAVs are predicted to boost vehicle utilization rates, potentially lowering the overall number of private vehicles, thereby increasing economic benefits and reducing environmental impacts. Unlike private cars that are parked for most of the day, SAVs can be shared among multiple users, continuously fulfilling travel demands.

The potential benefits of SAVs are as follows. First, the widespread adoption of SAVs could considerably decrease vehicle emissions by reducing the need for individual car ownership, leading to less vehicle production and more efficient utilization of existing vehicles by optimizing their routes, minimizing "deadhead" kilometers with better dispatching systems. Second, SAVs could reduce traffic congestion. Third, SAVs are expected to substantially reduce the demand for parking space, allowing large areas of urban land to be freed up for green spaces, public facilities, or other more valuable uses. Furthermore, shared autonomous mobility services are expected to provide more convenient and economical travel options for people unable or choosing not to drive, including the elderly, young people below driving age, and people with disabilities. Therefore, shared autonomous mobility services enhance the equity and inclusivity of the transportation system.

4. Infrastructure challenges: the other side of the coin

While autonomous driving technology demonstrates substantial emission reduction potential at the vehicle level, it is also important to consider its effect from a broader transportation system perspective, particularly the effects of AVs on road infrastructure. The interaction between vehicles and roads considerably affects the infrastructure's life-cycle performance and associated emissions.

For example, autonomous platooning—where vehicles travel in tightly coordinated formations—generates more frequent, high-intensity loading with shorter recovery intervals than conventional driving patterns. This altered loading behavior can accelerate damage accumulation in road pavements, potentially increasing the frequency of maintenance and, consequently, infrastructure-related emissions. Cheng et al. [13] developed a model to evaluate vehicular load effects on pavement damage, performance, and emissions. This model is universally applicable because it integrates various factors such as different vehicle types and environmental conditions, validated by combining laboratory and field data [14]. Furthermore, this model effectively analyzes and solves critical problems concerning how road infrastructure performs and how emissions change under complex loading conditions, including platooning mode. The authors applied this framework to 1457 road segments and found that autonomous platooning hastened pavement deterioration. This accelerated wear is primarily attributed to highly channelized loading, where vehicles in a platoon tend to follow nearly identical wheel paths, subjecting the same narrow pavement areas to concentrated and repeated stress. This in turn led to a 27.9% increase in infrastructure emissions due to more frequent maintenance operations. These findings provide valuable insights into how vehicle–road interactions can reshape the global road infrastructure's performance and emissions, offering a more realistic evaluation of the mechanical/physical impacts and environmental impacts associated with different vehicle driving and loading conditions on road infrastructure.

Additionally, the substantial mass of heavy-duty electric trucks, powered by heavy battery systems [15,16], increases pavement loading and stress on road surfaces, regardless of whether they are platooning or not. This intensification of stress accelerates pavement wear, which in turn may necessitate more frequent maintenance or even full rehabilitation efforts—leading to additional emissions from the infrastructure sector. Therefore, when considering the deployment of autonomous EVs—especially heavy-duty models—across large-scale road networks, the combined effects of both channelized loading from platooning and the increased pavement stress from the sheer mass of EVs warrant careful evaluation. This holistic approach is crucial for a more realistic assessment of the mechanical/physical impacts and environmental impacts associated with different vehicle driving and loading conditions on road infrastructure.

In addition to posing challenges to road infrastructure, the widespread adoption of EVs, particularly within high-use SAV fleets, markedly strains the energy infrastructure by demanding more electricity. The concurrent charging demand from a large number of EVs could strain local and national electricity grids, creating new peak load challenges and potentially requiring substantial upgrades to power generation and distribution networks. However, this also presents an opportunity. Advanced AVs and SAVs, with their sophisticated connectivity and management systems, are ideal candidates for smart charging and vehicle-to-grid (V2G) services. By intelligently scheduling their charging during off-peak hours and even feeding power back to the grid during periods of high demand, these fleets could act as a distributed energy resource, helping to stabilize the grid and facilitate the integration of intermittent renewable energy sources. A comprehensive assessment must therefore account for the carbon footprint of grid reinforcement versus the decarbonization potential offered by V2G services.

The net effect of AV use is further affected by how the vehicles are used and owned. If AVs are personally owned, they are likely to be driven much more than comparable human-driven vehicles, for the simple reason that occupants can sleep, work, or be entertained, and thus the inconvenience and time cost of using a vehicle would be greatly diminished. The result would be much greater usage of vehicles and thus more energy use and emissions. On the other hand, if the AVs are used in pooled mobility services with multiple riders, then there would be much less vehicle use (and cost per passenger) and thus much less energy use and emissions.

5. Integrated consideration: balancing vehicle and infrastructure emissions

In summary, AVs present a range of complex and sometimes conflicting effects on emissions from both vehicles and road infrastructure—the two primary components of land-based transportation systems. Studies have shown that when considering the integrated vehicle–road system holistically, autonomous driving can reduce cumulative emissions by an average of 5.1% [13], with even greater reductions possible when used for multi-passenger mobility services. However, this environmental benefit could be diminished by the increased weight of EVs, which negatively affects road infrastructure and leads to high emissions from maintenance and repairs. Furthermore, heavy-duty EVs can create potholes, uneven surfaces, and debris, which are particularly hazardous for cyclists and pedestrians, potentially leading to falls. Consequently, this increased danger could reduce public and institutional support for EVs, as authorities prioritize the safety and accessibility of vulnerable road users and the general public.

These tradeoffs underscore the urgent need for coordinated technical and policy strategies that balance the interests of multiple stakeholders—such as the vehicle manufacturing sector, transportation planners, and infrastructure managers. By proactively addressing these challenges, the deployment of autonomous and EV technologies can be guided toward a more sustainable, equitable, and efficient transportation future.

6. Conclusion and outlook

The rapid advancement of autonomous driving and EV technologies offers unparalleled opportunities for constructing a sustainable transportation system; however, it also introduces novel challenges. To fully harness their positive potential while mitigating adverse effects, cross-sectoral and interdisciplinary collaboration is imperative. Future research should deepen the understanding of the life-cycle environmental impacts of AVs and EVs, optimize the synergistic planning of vehicle design and road infrastructure, and formulate innovative policies to incentivize shared mobility and guide appropriate technology adoption. Only through such integrated efforts can we ensure that this technological revolution ultimately contributes to building a cleaner, more efficient, equitable, and resilient transportation ecosystem of the future.

Regarding vehicle design optimization, manufacturers should prioritize strategies to enhance EV sustainability, including the following. ① Advanced lightweighting: Use high-strength composites and aluminum alloys in an EV's chassis and body to reduce weight, counterbalancing heavy battery systems to minimize pavement stress and energy consumption. Integrate the battery pack into an EV's chassis or body to improve structural integrity, potentially eliminating the need for additional chassis reinforcement. ② Modular and durable design: Develop AV interiors with modular components and robust materials to withstand the high utilization rates of shared mobility fleets. Examples include standardized, replaceable sensor suites with rugged interfaces and wear-resistant, easily cleanable interior surfaces to reduce long-term operational costs and material waste. ③ Powertrain efficiency enhancement: In addition to optimizing the motor, refine regenerative braking systems tailored to autonomous driving patterns and upgrade battery thermal management systems to enhance longevity and performance under continuous operation in SAV fleets.

Regarding road infrastructure optimization, key priorities for infrastructure upgrades include:

(1) High-durability pavement materials: Invest in polymer-modified asphalt, high-strength concrete, and other advanced materials to withstand the concentrated loads from heavy EVs and frequent AV platooning.

(2) Smart sensing systems: Deploy embedded sensors (e.g., fiber optic, piezoelectric) in pavements to monitor real-time pavement health, strain, and temperature. This data enables predictive maintenance algorithms to proactively address issues, reducing disruptions, costs, and extending pavement service life.

(3) Dedicated lanes and charging integration: Design specialized lanes for AVs and heavy EVs in high-traffic corridors, constructed to higher durability standards and potentially integrated with inductive charging infrastructure for EVs.

(4) Self-healing pavement technologies: Explore self-repairing materials to address micro cracks and wear preemptively, preventing escalated damage and reducing maintenance burdens. By aligning vehicle innovation with infrastructure resilience and policy foresight, the transportation sector can leverage AV and EV technologies to drive sustainable development, balancing technological progress with environmental stewardship and social equity. Beyond physical upgrades, the true optimization of future road networks lies in the deep integration of vehicles, roads, and the cloud. This "vehicle–road-cloud" paradigm leverages cloud computing, big data analytics, and 5G communication to create a digital twin of the transportation system. By fusing real-time data from AV sensors, roadside units, and traffic management centers, the cloud platform can perform system-wide optimization, predict traffic flow, dynamically manage congestion, and provide vehicles with optimal routing and speed advisories that go far beyond individual vehicle capabilities. This holistic digital infrastructure is essential for maximizing the energy efficiency and safety of the entire system and enabling advanced functions like cooperative vehicle-infrastructure systems (CVIS).

In shaping new policies, a pivotal strategy is to actively guide the market toward shared autonomous mobility (SAM) over privately owned AVs, thereby maximizing social benefits while mitigating risks of increased congestion and energy consumption [17]. This can be achieved through a three-pronged approach: ① Incentivizing SAM fleets: Offer tax credits, priority access to urban zones, and subsidies for fleet-specific charging infrastructure development to lower operational costs for SAM operators. ② Discouraging low-occupancy AV use: Implement dynamic road pricing linked to passenger occupancy and travel time, alongside higher registration fees for privately owned AVs primarily used for solo travel, to disincentivize inefficient mobility patterns. ③ Urban planning reallocation: Repurpose road space and convert parking lots into public amenities or green spaces, prioritizing pedestrian, cycling, and public transport infrastructure over private vehicle parking.

Policy frameworks must also: ① Establish data and cybersecurity protocols: Mandate secure data-sharing mechanisms (between vehicles, infrastructure, and operators) under strict privacy safeguards to ensure safe and efficient AV operations. ② Revise funding mechanisms: Introduce road usage charging based on vehicle weight, axle configuration, travel distance, and road segment durability to equitably fund infrastructure maintenance and adaptation. ③ Promote inclusive mobility: Ensure AV benefits, such as improved accessibility for elderly and disabled populations, are distributed broadly. This may involve mandating SAM deployment in underserved areas or subsidizing SAM services for vulnerable demographics to avoid exacerbating social inequities. By aligning market incentives, urban design, and regulatory safeguards, these policies can foster a sustainable, inclusive AV ecosystem that balances technological innovation with collective societal welfare.

CRediT authorship contribution statement

Xiaobo Qu: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Daniel Sperling:** Writing – review & editing, Writing – original draft, Conceptualization. **Hui Li:** Writing – review & editing, Writing – original draft, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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