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Editorial

Drone to recharge electric vehicles: Operations, benefits, and challenges



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ABSTRACT

Electric vehicles (EVs) are a promising solution to reduce greenhouse gas emissions and foster sustainable urban transportation. However, the widespread adoption of EVs is hindered by range anxiety and the fear of running outnqt of battery before reaching a charging station. To address this challenge, we propose a novel drone-to-vehicle (D2V) charging system, which leverages drones as mobile charging units to provide on-the-go recharging services for EVs. This study explores the operational and technical aspects of the D2V system, including drone charging docks, order-dispatching strategies, and dynamic drone reallocation mechanisms. A key contribution is to introduce a concept of the adaptive route meetup location selection (ARMLS), which optimizes drone dispatch and pricing models based on real-time parameters such as distance, battery levels, and traffic conditions. Our analysis highlights the potential of D2V systems to alleviate range anxiety, enhance road network efficiency through dynamic traffic redistribution, and reduce carbon emissions by integrating renewable energy sources. The study suggests that implementing D2V services can significantly improve the reliability of EVs in critical situations while fostering broader EV adoption. Future work will focus on reinforcement learning-based optimization algorithms to further improve drone operations and address scalability challenges. The proposed D2V system represents a crucial step toward a sustainable and efficient urban mobility future.

1. Introduction

In numerous cities and metropolitan areas, the road transport sector is a significant source of greenhouse gas emissions, greatly contributing to air pollution (Bag et al., 2022). Recently, electric vehicles (EVs) have reemerged as a promising solution due to their environmental benefits, energy efficiency, and compatibility with renewable energy sources. In response, governments worldwide have implemented various supportive policies, including subsidies for EV purchasing and investments in charging infrastructure, to promote the adoption and utilization of EVs (Liu et al., 2022).

However, a key challenge to widespread EV adoption remains the "chicken-and-egg" dilemma between electric vehicles and charging infrastructure (Majhi et al., 2022). A prominent issue arising from this dilemma is "range anxiety", where drivers are concerned about the distance their vehicles can travel with a limited battery charge. According to Franke et al. (2012), overcoming range anxiety requires careful planning of recharging stops, but this is complicated when EVs in operation face the uncertainty of traffic conditions (Xie et al., 2017). Research (Neubuer et al., 2013) in Nordic countries indicated that the travel range of EVs can fluctuate by as much as 60% due to various uncertain factors, including weather conditions, temperature, heater usage, and average speed. Such uncertainties can lead to emergency situations when an EV unexpectedly runs out of battery, causing traffic congestion even worse if the vehicle is stranded on the road during peak hours.

Current charging modes for EVs include charging stations (Kchaou--Boujelben, 2021), battery swapping (Qi et al., 2023), dynamic wireless charging (Liu et al., 2024), and mobile charging (Yan et al., 2024; Yang et al., 2024). For the first three charging modes, EV drivers must adjust their routes to include charging locations, leading to additional travel time. The mobile charging mode, however, is less feasible if an EV is stranded in traffic congestion. These charging limitations make drivers experience stress, fearing their vehicle will run out of charge unexpectedly. A recent patent filed by Amazon (McClintock et al., 2017) proposed the use of drones carrying batteries to recharge EVs on the move. Karagianni et al. (2022) developed a greedy algorithm to study the problem of scheduling drones to recharge EVs offline. This innovation has prompted the development of a new charging mode—drone charging vehicles—that aims to alleviate range anxiety, particularly in emergency situations where EVs are stranded on the road during peak hours.

The concept of a D2V service, which uses charging drones to deliver electricity directly to EVs, has emerged as a potential solution to mitigate range anxiety.[1] As illustrated in Fig. 1, an EV driver can request a charging service through a mobile app, specifying his origin, destination, battery level, and planned route. The app will then dispatch the nearest charging drone, which will follow the optimal route and charging schedule to meet the vehicle's needs. Each drone is equipped with electromagnetic and ultrasonic sensors to accurately locate and attach to

[1] https://www.yankodesign.com/2021/07/13/this-ev-charging-solution-uses-a-network-of-charging-drones-to-charge-your-car-anytime-anywhere/.

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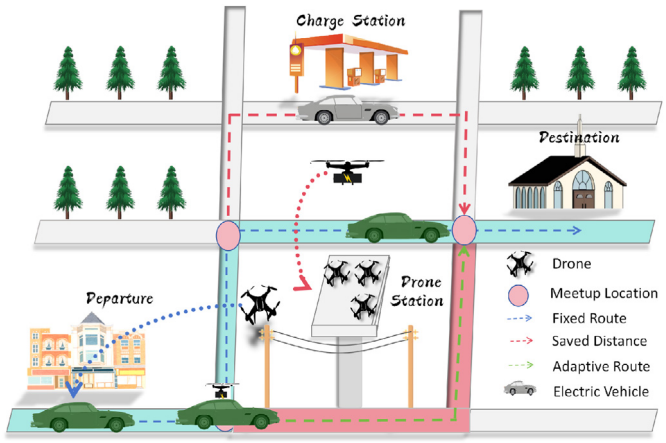


Fig. 1. Framework of the drone-to-vehicle (D2V) service.

the roofs of EVs. Unlike the charging station model, EV drivers using D2V do not need to alter their routes to incorporate charging locations, thereby saving time and reducing travel distance (depicted as the dashed red line in Fig. 1). The charging drones will utilize wireless coils to transfer power while securely stationed on top of the EV in motion, allowing EV drivers to receive a charge anytime and anywhere.

This study explores the key components of the D2V system, including drone charging docks and the platform design problem. It also examines the competitive advantages of D2V as an EV charging mode and addresses the operational challenges associated with its implementation. The ultimate goal is to contribute to solutions for alleviating range anxiety, thereby supporting the broader adoption of EVs and fostering a sustainable future.

2. Operational problems

2.1. Drone charging docks

Efficient and reliable charging solutions are crucial for a variety of drone applications. Drone charging docks are specialized stations where drones can land to recharge, undergo maintenance, or be inspected as needed. These stations are equipped with navigation systems that enable drones to connect, either physically or wirelessly, to the charging infrastructure. This process is both convenient and efficient, as it eliminates the need for human intervention. Additionally, it increases flight time and productivity by allowing drones to operate for longer periods without the need for battery swapping. Drone charging docks can also incorporate renewable energy sources, such as solar power, to enhance sustainability by reducing the carbon footprint of drone operations. These docks include standard charging stations, wireless charging stations, solar-powered charging docks, and mobile charging platforms.[2] These innovations make drone services more eco-friendly, sustainable, flexible, and convenient. However, when deployed in outdoor environments, drone charging docks may be affected by weather conditions, which can impact the safe landing and recharging of drones.

2.2. Platform design

2.2.1. Order-dispatching

In the D2V service, when an EV driver experiences low battery, they can submit a service request while on the road through the platform. The request includes details such as the origin, destination, real-time global position system (GPS) position, and route plan. In response, the platform provides a quote based on factors such as the distance, battery level, and other relevant parameters. The driver can then choose to accept or cancel the order. Order matching is generated considering various factors, including the service request's current GPS position, destination, and remaining route, the position and battery level of available drones, the battery status of the electric vehicle, etc. One of the main objectives is to optimize drone scheduling to maximize the number of completed EV charging requests.

2.2.2. Drone charging replenishment

The efficient operation of the D2V service relies heavily on the reliable replenishment of drone batteries. Since drones in the D2V system serve as mobile charging units for EVs, they must maintain an adequate battery level to effectively deliver power to EVs in need. This introduces a critical challenge of drone charging replenishment, which must be addressed to ensure the continuous and optimal operation of the service. The primary issue arises from the fact that drones are themselves electric vehicles, dependent on their own battery power for flight and operation. This creates a complex interplay between the drone's energy requirements for mobility and its ability to supply charging power to EVs.

2.2.3. Drone reallocation

In the D2V service, the problem of drone reallocation is critical to maintaining operational efficiency, ensuring timely service, and maximizing the effectiveness of the drone fleet. Drone reallocation refers to dynamically adjusting the positions and assignments of drones to meet real-time demands for electric vehicle (EV) charging. Drones must be reallocated not only based on immediate charging requests but also considering long-term operational constraints such as battery life, flight distance, and environmental factors. This creates a complex decision-making problem that involves real-time scheduling, dynamic fleet management, and efficient route planning.

2.2.4. Meetup location

In the D2V service, the selection of meetup locations is a crucial factor in determining the efficiency and flexibility of the service. The meetup location selections can be categorized into two types: fixed route meetup location selection (FRMLS) and adaptive route meetup location selection (ARMLS). FRMLS refers to a scenario where a request with the planned route is submitted to the platform. A drone with a sufficient battery level is then scheduled to meet the electric vehicle at an optimal location without altering the vehicle's initial route. In contrast, ARMLS involves submitting a request with the planned route to the platform, where a drone with an adequate battery is assigned to meet the EV at a location within a coordinated route, incentivized by a reasonable charging price. FRMLS and ARMLS aim to eliminate the additional travel and waiting times typically associated with charging stations. Furthermore, ARMLS has the potential to redistribute traffic flow within the network by implementing a strategic charging pricing scheme.

2.2.5. Charging pricing

Charging pricing is a critical component of the D2V service, as it significantly impacts the system's efficiency, accessibility, and adoption. The pricing model in D2V must balance the operational costs of drones with the need to offer affordable and competitive services to electric vehicle users. Given the dynamic nature of where drones are dispatched in real-time to meet EVs for on-the-go recharging, the pricing scheme should be flexible and transparent, adapting to various factors such as travel distance, battery level, and traffic conditions. One of the key elements in D2V pricing is under the ARMLS model. In this model, the pricing scheme can be adjusted based on several variables, such as the distance to the meetup location, the time of day, and the expected energy consumption of both the drone and the EV. For instance, users could be incentivized with lower charging fees for agreeing to meet at more optimal locations, such as areas with less traffic congestion or those that minimize energy consumption for the drone. This incentive system not only ensures fair pricing for users but also encourages more efficient use

[2] https://www.strixdrones.com/drone-charging-docks/.

of the D2V service.

2.2.6. Key regulatory considerations for D2V

Deploying drones in urban areas requires careful attention to regulatory concerns. Urban environments pose challenges such as airspace management, safety standards, public safety and privacy, and noise pollution. Regulatory frameworks must address restrictions on drone flights, particularly near airports, densely populated areas, and other sensitive locations. Regulators are considering the development of "drone airspaces", which are dedicated corridors for drone traffic. However, implementing these routes in dense urban areas remains a significant challenge. Drones for D2V services must include safety features, such as collision avoidance systems and real-time monitoring, to ensure safe operations. Moreover, developers of D2V technology and regulators need to address concerns regarding potential drone malfunctions or the possibility of injuries to pedestrians. Privacy issues related to GPS tracking and personal data from EV drivers must be managed through secure and transparent data handling practices. Additionally, the widespread use of drones in urban areas could lead to considerable noise pollution, especially if drone fleets operate simultaneously. Therefore, some regulatory frameworks may impose noise limits on drones, requiring manufacturers to design quieter systems. Governments and regulatory bodies must collaborate with industry stakeholders to establish guidelines and standards that ensure drones operate safely and efficiently in urban spaces while minimizing risks to people and property.

2.3. Social benefits and challenges

One of the primary barriers to the widespread adoption of EVs is the issue of range anxiety. The D2V service offers an immediate, on-the-spot solution by quickly meeting the EV at a predetermined location and providing enough power to reach the nearest charging station or final destination. This emergency charging capability could significantly enhance the reliability of EVs in critical situations, fostering greater confidence among drivers and encouraging the adoption of electric mobility.

Drone charging services can also play a role in redistributing traffic flows through dynamic pricing mechanisms. By offering preferential pricing or discounted rates, drone charging systems can encourage drivers to select meeting points that avoid congested areas. This can help alleviate traffic congestion on specific roads, thereby improving the overall efficiency of the road network. Furthermore, reducing congestion time decreases vehicle idling, which in turn lowers carbon emissions and helps mitigate air pollution. Additionally, drones can be powered by renewable energy sources, further enhancing the service's sustainability. The expansion of drone charging services not only improves social welfare by providing reliable and eco-friendly solutions but also generates direct economic benefits. Drones can offer instant charging in high-demand areas, while service providers can charge fees based on the amount of power delivered. This model creates a new revenue stream, benefiting both service providers and consumers.

Interoperability poses a challenge in the field of drone charging docks. Compatibility issues can arise between different drones and charging systems produced by various manufacturers. Since drones are essentially electric vehicles that depend on their own batteries for flight, using them to transport battery power for recharging EVs introduces a complex scheduling problem. Efficient communication and task coordination are essential for dispatching and reallocating drones dynamically. This involves addressing how requests are transmitted and handled within the system to maximize responsiveness and reliability. In particular, contacting a central coordination server might not always be possible. Therefore, decentralized solutions need to be deployed (Loisel et al., 2024). In addition, the support edge nodes require ingenuity to adapt to varying demands and to embed information about the drones' and vehicles' trajectories (Sedlak et al., 2024). This complexity is further heightened by the need for drones to balance their own power consumption while efficiently delivering power to the vehicles they are servicing. As drones are deployed to meet EVs in real time, it is essential to monitor and manage their battery levels carefully. Running out of power mid-flight could disrupt the charging service and compromise the system's reliability. Due to the unpredictable nature of service requests, quickly deploying and reassigning drones becomes a significant challenge in the D2V service model. The primary issue lies in balancing drone availability, battery levels, and geographical location to optimize the delivery of charging services to EVs. Additionally, identifying optimal meetup points within road networks presents a major challenge, as both the vehicle and drone are dynamic entities constrained by space and time. This problem involves defining systematic approaches to optimize tradeoffs between energy efficiency, quality of service, and operational costs that can enhance the scalability and sustainability of the D2V system. The solution requires defining tools and algorithms to dynamically optimize this multi-objective problem, autonomically adapting (Morichetta et al., 2024) to varying scenarios where failures or demands can change and to specific intents and objectives from the stakeholders (Morichetta et al., 2023).

3. Conclusions

In this study, we have explored a novel and innovative approach to alleviating the persistent issue of range anxiety in EVs through the use of D2V charging technology. By leveraging the flexibility and efficiency of drones, we propose a dynamic, on-the-go charging framework that offers EV users the convenience of recharging their vehicles without the need to deviate from their planned routes. This solution addresses the challenges of traditional station-based charging, which often requires additional travel time. We have discussed the operational aspects of the D2V system, including drone charging docks and platform design principles to ensure efficient service delivery. Additionally, the concept of ARMLS is presented as a promising strategy for optimizing service routes, reducing travel time, and alleviating congestion during peak periods. The incentive-based pricing model for the D2V service provides a framework for balancing operational costs with affordability, ensuring the sustainability of the system while encouraging widespread adoption of EVs. For future research, reinforcement learning can be utilized to decide how drones should be reassigned to different charging requests depending on real-time information. For instance, drones that have recently finished charging can be redirected to charge other electric vehicles if their own battery levels are adequate. Furthermore, when drone charging docks are designed with renewable energy sources such as solar power, it is challenging to design large-scale, efficient algorithms for rebalancing drone charging replenishment with solar power and scheduling charging tasks for EVs. Finally, the emerging D2V charging mode should be integrated into future urban transport management system (Gao et al., 2023), and more environmentally friendly and advanced technologies for next-generation smart transportation systems (Qu et al., 2024) should be incorporated into the D2V platform. In conclusion, the D2V charging system represents a promising step toward solving range anxiety and fostering the widespread adoption of electric vehicles, contributing to a more sustainable and efficient future for urban transportation.

CRediT authorship contribution statement

Dongdong He: Writing – original draft, Methodology, Investigation, Conceptualization. **Ying Yang:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Andrea Morichetta:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Jianjun Wu:** Writing – review & editing, Investigation, Conceptualization.

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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