nature energy

ARTICLES
https://doi.org/10.1038/s41560-020-0632-7

Check for updates

Emissions benefits of electric vehicles in Uber and Lyft ride-hailing services

Alan Jenn ✉

The use of plug-in electric vehicles in ride-hailing services is expected to have substantial emission reduction benefits. However, these benefits depend on the energy fuel mix in the grid and vehicle usage. Here we employ high-resolution data from Uber and Lyft in California to provide insights into the use of electric vehicles in ride-hailing. The growth in electric vehicle use has been rapid in the past two years and a proportionally small number of electric vehicles are already using a large share of electricity provided by the public charging infrastructure. Concerns about the ability of electric vehicles to provide the same level of service as gasoline vehicles has been overstated: we found no statistical difference between the two technologies for services provided to ride-hailing companies. Lastly, the potential environmental and emission reduction benefits are approximately three times higher for electric vehicles being used in ride-hailing compared with those of regular vehicle usage in California.

Transportation network companies (TNCs) are a relatively new transportation service provider and include rapidly growing companies, such as Uber and Lyft. Generally, the business model of these companies is to leverage existing vehicle owners to provide rides through a peer-to-peer 'sharing economy'. The drivers for TNCs earn money by providing rides for users who pay for the service, a portion of which goes to the parent companies. The growth of these companies has been tremendous: Uber and Lyft have provided a combined 5.5 billion rides with over 50 million users of the services, a remarkable growth, especially considering the services have been around for less than a decade. As these services continue to expand, there are several unique opportunities for disruptive changes in the transportation sector. This study focused specifically on ride-hailing from Uber and Lyft, which is an automotive transportation unlicensed taxi service (and, in this context, primarily app based). We adopt the term ride-hailing instead of ride-sharing, which can be misleading as single-fare rides are not necessarily shared.

One transition that TNCs may help enable is a cleaner vehicle fleet through the electrification of vehicles that operate in their service. The benefits of the emissions reduction from plug-in electric vehicles (PEVs) in TNCs is larger because vehicles driven for these services are driven substantially more than the average vehicle. Additionally, electric vehicles can be particularly compelling for drivers of TNCs due to the lower use-phase costs of the vehicles[1], but may face other difficulties in the form of higher upfront costs to purchase and possible range imitations. However, there are also alternatives to the traditional driver-owned service model, which include programmes that allow participants in ride-hailing service economies to use a fleet or car-share vehicle rather than their own (this is common if the driver cannot afford their own vehicle). For example, in January 2016, General Motors announced a new programme called Maven after their acquisition of Sidecar, a TNC founded in 2011. Maven is a car-sharing company that allows its users to rent vehicles within their fleets.

The benefits of electrifying new mobility services are discussed in the literature in terms of theory, but there are no examples of empirical work that examines the real-world impacts. As early as 2011, Kley et al. identified electric vehicles in the context of products that could be leveraged in different types of mobility services, such as car-sharing (membership-based service that provides qualified drivers access to a network of shared short-term rental vehicles), despite the relative dearth of these services at the time[2]. The authors identified critical issues of charging infrastructure and electric drive-train technological restrictions on the value proposition, value chain configuration and revenue model of the new technology vehicles within the new service ecosystem[2]. This study laid the groundwork for important considerations of two rapidly growing fields and difficulties in integrating the two together in a successful business operation. In 2012, the Polytechnic University of Milan launched Green Move, an electric-vehicle-sharing system, the details and design of which were documented in a peer-reviewed article[3]. The ambitious project featured a peer-to-peer approach using an integrated device that bridged the user, vehicle and a control centre with keyless mobility (using smartphones). Unfortunately, the project was not a commercial service and limited in size to only four electric vehicles. It ended in 2013, but was one of the earliest conceptions of electric vehicles in use within new mobility services.

As both car-sharing and ride-hailing services increase in popularity and size, there is also a corresponding increase in research on the topic. However, regarding the electrification of vehicles in TNCs, the vast majority of studies focused on car-share services rather than ride-hailing. A large number of studies focus on optimizing the operational aspects of various car-sharing services[4–8]. Other studies provide insight into specific case studies of how electric vehicles are being used in programmes and the lessons learned in regions such as Chicago[9], and how they are being adopted by users in Germany[10]. An analogous concept of electrification has been studied in taxi fleets. The literature includes detailed considerations of operation and charging behaviour[11–14]. However, two studies examined environmental and emissions benefits, such as an estimated 48% reduction in exhaust emissions by integrating electric taxis into the Nanjing fleet[15] and a tenfold reduction of emissions in Brazil[16]. These studies provide valuable points of reference to compare the emissions benefits derived from this work, although there are several distinct differences between taxis and ride-hailing vehicles, which includes deadheading (movement of service

Institute of Transportation Studies, University of California, Davis, CA, USA. ✉e-mail: ajenn@ucdavis.edu

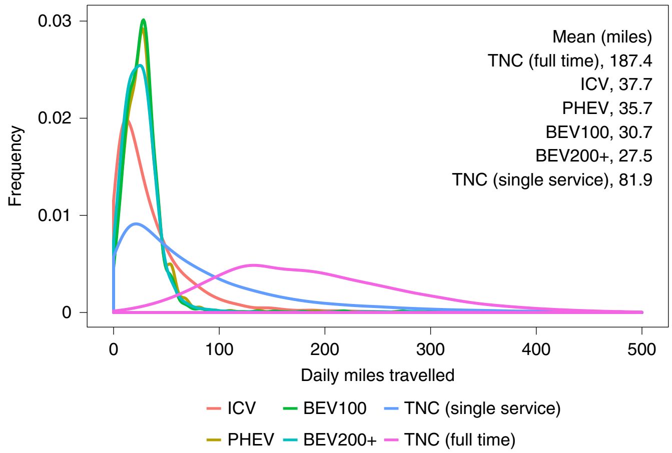

Fig. 1 | A comparison of average daily travel behaviour in California. Gasoline vehicles (California Household Transportation Survey), plug-in hybrids, short and long-range BEVs (UC Davis PH&EV Center survey) compared with TNC electric vehicles. The TNC (single service) data are compiled from a set of over 400,000 BEV trips from a single TNC, so this distribution is probably an underestimate of the daily distance because the BEVs probably drive for more than one service. TNC (full time) consists of a subset of over 1,000 BEVs that are known to be full-time drivers and contain trips for both Uber and Lyft services. Sample size for each group: TNC (full-time), 118,668; ICV, 11,585; PHEV, 4,798; 100-mile BEV (BEV100), 4,026; BEV200+, 1,953; TNC (single service), 427,624).

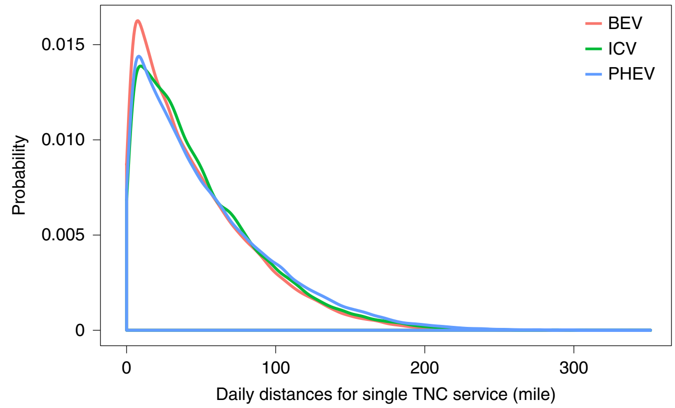

Fig. 2 | Comparison of daily distribution of travel behaviour. Values by Lyft ICVs ($n = 928$ vehicles and 395,212 trips), PHEVs ($n = 1,664$ vehicles and 600,193 trips), and BEVs ($n = 1,736$ vehicles and 427,624 trips). A Kolmogorov–Smirnov test provides statistical evidence that the distributions are the same. ICV to PHEV, $D = 0.0264$, $P < 0.0001$; ICV to BEV: $D = 0.0431$, $P < 0.0001$).

vehicles in non-revenue mode) when picking up travellers, sharing rides and fleet ownership and/or operation differences).

The discussion of electric vehicles in a ride-hailing context is rare, but the body of literature on the topic is growing[17–24]. These studies have begun to provide important insights on impacts of ride-hailing services. For example, Clewlow and Mishra found that the services led to a decrease in public transit usage, but did not substantially alter vehicle ownership rates[17]. Jenn et al. showed that use of TNCs correlates with a greater acceptance of electric vehicles[18], and similarly Cassetta et al. demonstrated an upward trajectory in both new mobility services (both ride-hailing and car-sharing modes) simultaneously with electric mobility[19]. Other studies showed that electric vehicles can be a favourable mode in ride-hailing services due to their relative cleanliness[20,21], lower total cost of use[22] and ability to link technology and demand-management strategies through shared use[23]; however, regulation would be required to ensure the sustainability of the transportation system[24].

It is clear from the existing literature that there is a gap in empirical evidence that measures the impact of combining shared mobility services, particularly ride-hailing services, with vehicle electrification. The work presented in this study provides a real-world insight into the implications of electric vehicle use in services such as Uber and Lyft. These insights include an overview of the travel intensity and energy demand from PEVs being used in these services within California. We also measured the comparative emissions savings from electric vehicle use as well as the associated charging infrastructure implications from a higher-intensity usage.

In this study, we examined empirical data on the use of electric vehicles associated with TNC services in Uber and Lyft fleets (which constituted over 98% of ride-hailing trips at the end of 2019[25]), employing data from several electric-vehicle-charging network providers and TNCs. Our work provides insight into the use of electric vehicles in ride-hailing services and quantifies the associated emissions benefits. However, the higher travel intensity also requires much more charging, the implications of which we also attempted to identify in this study.

Characterizing the use of electric vehicles in TNCs

Our analysis of PEVs first compared the travel behaviour between conventional gasoline and electric vehicles in California with that of electric vehicles employed in TNC services. Figure 1 displays the distribution of daily miles travelled for several groups of vehicles in California. For the average driver (non-TNC), gasoline vehicles tend to be driven slightly more than their electric vehicle counterparts. For a comparison against conventional gasoline vehicles, we employed the California Household Travel Survey (CHTS) (which provides 118,668 trips) and for ordinary electric vehicles we employed the multiyear panel survey Plug-in Hybrid & Electric Vehicle (PH&EV) with 15,275 respondents to derive a generalized profile of electric vehicle travel patterns (see Methods for additional details of the surveys). Although the difference between internal combustion engine vehicles (ICVs) and plug-in hybrid electric vehicles (PHEVs) is relatively small, both outpace short-range and long-range battery electric vehicles (BEVs). However, we found that PEV TNC travel behaviour was substantially higher than that of typical vehicles in California by at least a factor of two. We observed a drastically different distribution of mileage travelled by everyday vehicles (whether gasoline or electric) and that within the TNC fleet.

There are two TNC distributions in Fig. 1. The TNC (single service) distribution is derived from over 400,000 trips provided by BEVs for one TNC service. It is highly likely that this distribution underrepresents the total daily miles travelled because most vehicles drive for more than one TNC service. The TNC (full-time) distribution can alternatively be considered an upper bound of TNC travel: the distribution is constructed from a set of over 1,000 vehicles that are known to be driving full-time (as their primary occupation) and contain the comprehensive travel for both Uber and Lyft services.

One of the primary concerns of BEV use in TNC services is that the limited range of the electric vehicle will prevent the vehicles from being used in the same manner as gasoline vehicles. In addition, travelling to charging stations and the length of time required to charge BEVs being used for ride-hailing may also detract from drivers' ability to provide the same length of service as a gasoline vehicle. Surprisingly, we found that electric vehicles actually provided the same level of service in terms of number of rides and distances of trips every day. The distributions of daily distances in Fig. 2 were compared using a Kolmogorov–Smirnoff test and revealed to

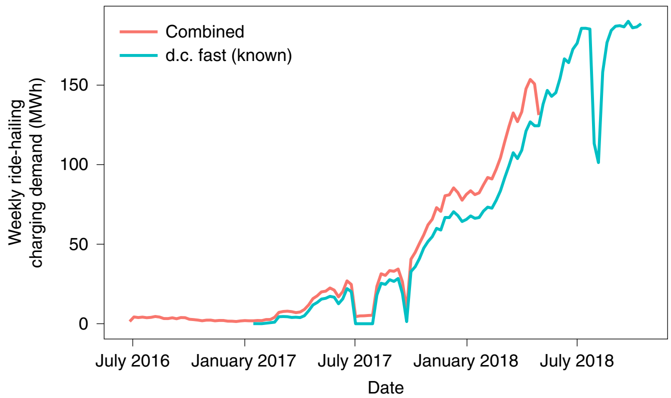

Fig. 3 | Weekly charging demand of electric vehicles driving for TNCs from August 2016 to October 2018 in San Diego, Los Angeles and San Francisco. The combined group is an underestimate of total charging as PHEV charging demand is not included, nor does this ride-hailing services are included. The d.c. fast (known) group represents known full-time drivers of the service. By October 2018, the charging demand for d.c. fast represents nearly 35% of non-Tesla fast-charging demand. Represented are 1,240 charging locations of the 1,413 non-Tesla d.c. fast-charging locations in California over several charging network providers (predominantly EVGo and Chargepoint). There is currently no explanation for the dips in demand observed in the data.

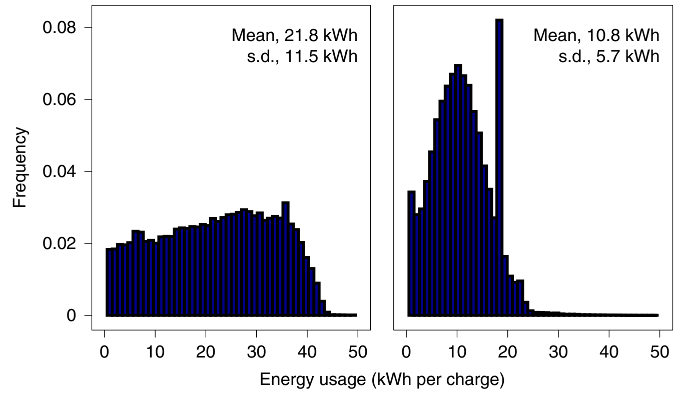

Fig. 4 | The amount of energy used per charging event at d.c. fast chargers for a subset of known full-time TNC drivers compared with that of all other electric vehicles in California. Full-time TNC vehicles (left) have a significantly higher charge requirement with a relatively uniform distribution that tails off near 40 kWh (average of 22 kWh), whereas ordinary electric vehicles (right) have a truncated normal distribution centred around 11 kWh. Note that the large peak for other vehicles is a result of specific membership policies with certain service providers that restrict users to 30 min of charging. Sample sizes: full-time TNC (left), 118,668; other electric vehicles (right), 1,971,055).

be statistically identical. Although we are confident in the similarity of service by amount, we do not rule out possible differences in where the services were provided. We found that the majority of trips (over 90%) occurred within five miles of where the charging of TNC vehicles occurs.

The growth and utilization of electric vehicles in TNC services has been explosive, especially as the introduction of the Maven programme in early 2017 (whose entire electric vehicle platform consisted of Chevrolet Bolts). We were able to track approximately 105,000 unique vehicles charging at non-Tesla d.c. fast-charging stations (representing a little less than half the total number of full electric vehicles in California) and just over 1,000 unique TNC electric vehicles from 2014 to the end of May 2018. Although these TNC vehicles represent less than 0.5% of the electric vehicles in California, the charging demand from this service was 35% of the total energy demand at non-Tesla d.c. fast-charging stations for the remaining electric vehicles (Fig. 3).

From the beginning of 2017, the charging demand grew by approximately tenfold in size over a span of nine months followed by another fivefold growth over the next six months. The continuous rapid growth speaks to a critical challenge for both the TNC services and charging service providers to enable electrification. Also, note that the location of the chargers corresponds relatively closely with the dense urban areas with a high demand for ride-hailing services, but not all the stations are necessarily being employed to charge TNC service vehicles. Careful consideration should be made for the location-based demand of ride-hailing services and to find corresponding charging locations to minimize deadheading related to charging the vehicles.

In Fig. 4, we display the amount of energy charging requirements for TNC vehicles compared with that of regular electric vehicles in California. We observe a very different distribution of charging patterns between the two types of vehicles. The charging demand from TNC vehicles was relatively uniform from 0 to 40 kWh. Although the average charging event for these vehicles was around 20 kWh (approximately 60–70 miles in range), these vehicles visited charging stations on average 2.5 times a day, whereas other unique electric vehicles visited d.c. fast-charging stations on average once every 2 weeks. This means that, despite the range 'limitation' of electric vehicles, we observe that these TNC service vehicles regularly travel to and exceed this mileage on a daily basis. This stands in comparison with ordinary electric vehicles that charge, on average, 11 kWh during a fast-charging session. There is a unique spike in the ordinary vehicle distributions that is the result of certain restrictions on the length of charging to 30 minutes.

The charging patterns of TNC vehicles are also noticeably different to the d.c. fast-charging patterns of other electric vehicles (Fig. 5). As the d.c. fast chargers are all public infrastructures (as opposed to being available at home locations), we observe negligible charging events for regular PEVs that occur between the hours of around 3.00 and 8.00. However, for the TNC PEVs, we still observe a relatively high proportion of charging events that happened over this same time period. TNC vehicles also have a dip in charging between the hours of 18:00 and 20:00, probably due to an increased demand for ride-hailing services in that period, whereas this time period is actually the highest peak for observed charging behaviour among regular PEVs. Interestingly enough, there is a slight difference in the distributions of charging times by region. San Diego has two peaks during the early morning hours for TNC vehicles (at 5:00 and 8:00), which are not observed in the other regions. Additionally, for ordinary electric vehicles in San Diego there is a continued upwards trend in charging that starts from 7:00 and finishes at 15:00, with a noticeable flattening in both Los Angeles and San Francisco after 10:00. On closer inspection, we found that some of these abnormalities are due to a relatively small volume of vehicles with a distinct impact on the load shape. Although the number of events is still high (in the thousands), the charging pattern observed in San Diego can be attributed to a handful of vehicles. In the latter months, once more vehicles are observed in the charging dataset, the load shape pattern is much closer to those of Los Angeles and San Francisco.

The overview from the charging event data provides a number of interesting insights into the differences between electric vehicles that provide services for ride-hailing programmes (such as the Chevrolet Bolts) and regular electric vehicles. The travel intensity of TNC PEVs is striking and points to a need for a larger charging infrastructure to help manage the energy demand from these vehicles.

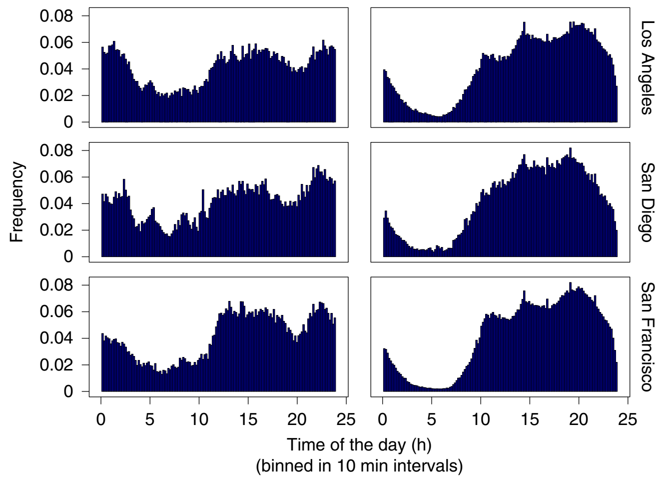

Fig. 5 | Histograms of the time of day that charging begins at d.c. fast chargers for TNC vehicles (left) and for other electric vehicles (right) in Los Angeles, San Diego and San Francisco. In comparison with regular electric vehicles, there is a substantially higher frequency of charging events that begins between 0:00 and 8:00. Additionally, there is a dip in charging for TNC drivers at around 18:00–20:00, probably due to the higher demand for ride-hailing services at that time, whereas for regular PEVs this period is the highest for charging events. Sample sizes: TNC Los Angeles, 40,834; TNC San Diego, 23,482; TNC San Francisco, 54,352; other electric vehicles Los Angeles, 708,107; other electric vehicles San Diego, 178,329; other electric vehicles San Francisco, 1,084,619).

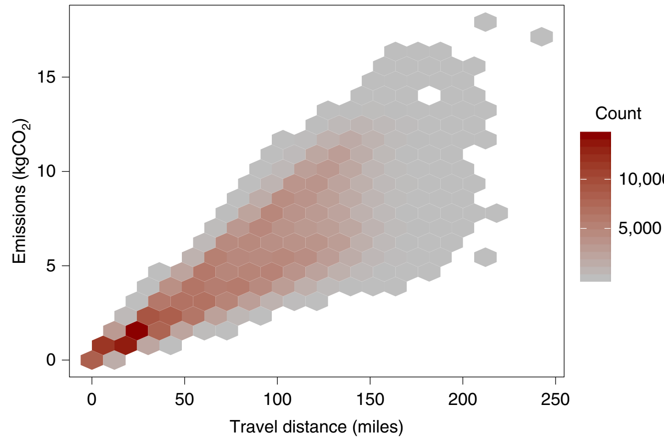

Fig. 6 | The emissions associated with every observable TNC charging event from January 2017 to May 2018. The emissions are a function of the average hourly marginal emissions in California at the time associated with the charging event as well as of the total charging amount. The two relatively distinct bands result from the bimodal daytime and night-time emissions factors in California ($n = 118{,}668$).

Emissions implications of PEVs driving for Uber and Lyft

We can calculate the associated emissions for each charging event based on the amount of energy demand and the time of the event. The upstream emissions that result from plugging in an electric vehicle depend on the time of charging because different power plants respond to increase in charging demand at different times of the day. We calculated the average hourly emissions in California from the California Independent System Operator (ISO) Greenhouse Gas Emission Tracking Reports (see Methods for emissions calculations), which allows us to understand how clean or dirty the electric grid is at different times of the day. Owing to the high availability of solar power, the emissions during the day are lower than the night-time emissions, although California as a whole has a relatively cleaner grid compared to that of the remainder of the United States.

In Fig. 6, we provide a complete display of the emissions associated with every charging event for TNC PEVs from January 2017 to May 2018. The vertical variation is a result of differences in grid emissions at different times of the day. Thee two distinct bands for the points are a result of the relatively different emission rates of the electric grid at daytime and night-time. The horizontal variation is a result of longer travel distances from the electric vehicles that lead to a larger energy demand.

How much emission has been saved by the use of PEVs in ride-hailing services? If we assume that the PEVs were all relatively fuel-efficient gasoline vehicles (29.4 MPG, the average efficiency of the Lyft conventional gasoline fleet), we can calculate the difference in emissions across all miles travelled as captured by the charging infrastructure (left panel, Fig. 7). The daily emission savings averages at 38.7 kg of CO_2 to electrify the ride-hailing service. Across all 1,000 BEVs from the beginning of 2017 to May 2018, this resulted in a total savings of 1,142 tons of CO_2, the equivalent of removing approximately 260 gasoline vehicles off the road (note that this is true unless the electric vehicles themselves change the demand for ride-hailing services). When we compare these savings against replacing average gasoline vehicles (not in ride-hailing services) with electric vehicles, the emissions reductions are nearly three times lower (right panel, Fig. 7). Our analysis does not include upstream emissions from fuels production, which introduce substantially more uncertainty. However, including these results would probably lead to a larger difference in emissions savings as the relative emissions increase with life-cycle analysis for gasoline are larger than the electricity grid in California.

Discussion and policy implications

Electric vehicle use in new mobility ride-hailing services has grown rapidly over the past 18 months and there is still tremendous potential for further expansion. In November 2016, electric vehicles provided about 16,000 rides and by February 2018 the number of rides had increased fivefold to over 85,000 rides. Nevertheless, the approximately 5,000 vehicles that provide services on Uber and Lyft platforms constitute less than 1% of the 700,000 electric vehicles in California at the beginning of 2018. Understanding the ramifications of this new vehicle technology coupled with new mobility options, such as Lyft and Uber, is critical to ensuring these two revolutions in transportation can maximize social welfare. These benefits come in the form of electrification, which reduces transportation emissions, and the potential of TNCs to provide shared mobility, which reduces congestion and the costs of travel. In this study, we observe both large benefits in the form of emissions reductions and challenges that must be overcome for charging infrastructure development and use. These infrastructure issues are apparent in the rapid growth of charging demand of TNC electric vehicles (Fig. 3), the relative difference in charging demand per vehicle (Fig. 4) and the difference in the timing of charging (Fig. 5).

The emissions benefits are immediately apparent: due to the higher travel intensity of vehicles that participate in ride-hailing programmes, using electric vehicles extends the per-mile benefits of this technology over a greater number of miles. One of the concerns for electric vehicles in these services is their ability to provide comparable services due to potential issues with electric range. Although we did not perform a direct comparison with ride-hailing service vehicle travel, we did observe that the PEVs in the TNC service are able to drive upwards of 190 miles a day on average (compared with 20–30 miles a day for a typical driver) and can top 300 miles a day in several instances.

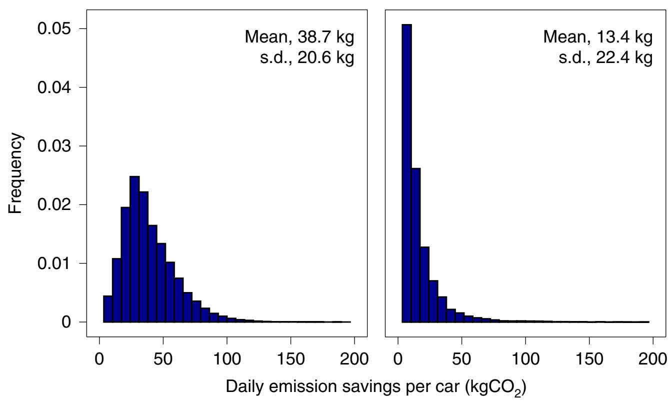

Fig. 7 | Histogram of the comparative emission savings. The left histogram is for switching a ride-hailing vehicle from a gasoline vehicle (29.4 MPG average in ride-hailing fleet from Lyft data) to an electric vehicle (28 kWh per 100 mile average in the ride-hailing fleet). The right histogram is for switching an average gasoline vehicle in California (27 MPG average from CHTS data) to a comparable electric vehicle in the TNC fleet. We found the emissions savings to be nearly three times higher for electrifying ride-hail versus electrifying the average California driver.

The travel often exceeds the range of the battery and at least demonstrates with a battery in the range of 200+ miles (BEV200+) a technical capability with the availability of d.c. fast chargers (although not necessarily an economic feasibility). From a purely emissions standpoint, we found that even in the most pessimistic scenario, replacing a full-time ride-hailing service vehicle with a BEV yields an emissions reduction three times higher than replacing an average gasoline vehicle in California. If policy to promote the adoption of electric vehicles begins to move away from a number-of-vehicles focus to a more electric-miles focus, strong consideration should be placed on the large potential in electrifying the growing ride-hailing services.

It is simultaneously necessary to consider other impacts of electrification. A high travel intensity leads to larger emissions benefits, but also means a greater requirement for the charging and associated infrastructure. Our analysis indicates that regular PEV users tend to have a lower average utilization of chargers during the hours of the day with a greater TNC utilization. However, one of the key drawbacks of the analysis is that many of the observed charging events are often based on behaviour that stems from free charging opportunities provided by specific network providers. From an economic feasibility perspective, it is unclear whether this programme is sustainable. The potential success of adopting electric vehicles requires a balance between the higher upfront cost of the vehicle and the marginal cost with use, which is free in this case study, but has the potential to be more expensive than gasoline—particularly with d.c. fast charging.

Our work is an empirical study of electric vehicles being used in ride-hailing services and we hope to highlight the need for future research topics in this area. Other considerations for future studies include a direct comparison of gasoline and electric vehicles in ride-hailing services (for example, utilization, spatial coverage, costs and so on), travel demand patterns to determine the optimal siting of chargers, projections of growth in electrification within this sector and the necessary charging infrastructure requirements, plans for viable adoption and usage strategies and policy support mechanisms to ensure beneficial outcomes, to name a few.

Methods

Survey data. Our work employs data from two surveys: the CHTS and the PH&EV panel survey.

The CHTS was administered by the California Department of Transportation from 2010 to 2012[26]. The survey collected travel behaviour information from over 42,500 households and 109,113 total participants using a variety of methods (telephone interviews, online and mail surveys, wearable and in-vehicle global positioning system devices and on-board vehicle sensors. The CHTS was used to display the daily travel behaviour of conventional gasoline vehicles in Fig. 1 and to obtain the average fuel efficiency of conventional gasoline vehicles in equations (1) and (2) necessary for Fig. 7.

The PH&EV Center, part of the Institute of Transportation Studies at the University of California, Davis, conducted a cohort survey of electric vehicle purchasers in California every year from 2015 to 2018[27]. The respondents of the survey were selected from the California Clean Vehicle Rebate Project, a rebate program for purchasers and leasers of electric vehicles within California. The California Clean Vehicle Rebate Project is administered by the Center for Sustainable Energy, which has an agreement with the University of California, Davis, to provide contacts (e-mail) for solicitation to disseminate and gather respondents for the survey. Altogether, the survey includes 15,275 respondents, all of whom have applied for the California Clean Vehicle Rebate Project rebate after the purchase or lease of a PEV.

The survey itself supports many projects that investigate a broad array of topics at the PH&EV Center, which range from (but are not limited to) consumer purchase behaviour and attitudes, driving behaviour and charging behaviour[28,29]. For the purposes of this project, we employed the survey to display the daily travel behaviour of PHEV and BEV drivers shown in Fig. 1.

Charging data. We employ charging data from a combination of charging network provider data and a small subset of vehicles logged with on-board diagnostic devices. The data contain a comprehensive set of charging events from EVGo (~3.8 million events) and Chargepoint (~9.2 million events) that span 2014 to 2018 in California. Each charge event provides information on the location, individual plug identification (as locations may have multiple plugs), start and end time of the charging event, energy dispensed and a subset of identifiers for TNC charging events

Ride-hailing data. Ride-hailing data were provided by TNCs such as Uber and Lyft. Data from Lyft contain a comprehensive set of 1.4 million trips in San Francisco, Los Angeles and San Diego. The data span 2017 to 2018 for every electric vehicle and for a random sample of 5,000 conventional gasoline vehicles (all specified by vehicle make and model). Each trip record contains information on time and census tract of pickup as well as the distance of the ride.

Emissions calculations. We calculated the emissions associated with each of the charging events from the charging data, which enabled us to understand the contribution of electrifying ride-hailing services to reducing emissions. The total emissions, E, were calculated as follows:

$$E = \sum_i \sum_t X_{it}^{G_t} \tag{1}$$

where i is an index for each individual observation, t represents an hourly time index and each i has a corresponding element in t. The G parameter values represent the grid emissions at each hour of the day and are derived from the California ISO using historical hourly load data and corresponding hourly emissions data from 2014 to 2018. This provides the average hourly emissions for the grid across the full span of charging and TNC trip data. The emissions rates range between 270 and 350 $gCO_2\,kWh^{-1}$ during night-time hours and drop to 150–200 $gCO_2\,kWh^{-1}$ during daytime hours. X represents the kWh demand from the new mobility vehicles in each time period and was obtained directly from the data.

We also estimated the counterfactual emission savings from electrifying the ride-hailing vehicles by comparing with a scenario in which all these vehicles were gasoline. As drivers can actually use gasoline vehicles in the TNC service, it is not unreasonable to assume that the service they would have provided and the travel intensity of those vehicles would not be drastically different from the electric vehicles now being used in TNCs. In fact, we observe in our data that the service provisions between electric vehicles and gasoline vehicles in TNCs are identical in terms of miles travelled and number of trips provided in a given day. However, it is important to note that some of the travel behaviour would probably differ because gasoline vehicles would not have to travel to charge their vehicles (although they would need to drive to gasoline stations), this is not something we observe in our data. The emission savings from these vehicles can be calculated by taking the difference between the emissions calculated in equation (1) with the corresponding gasoline vehicle emissions, together represented as:

$$S = \sum_i \sum_t \left(\frac{\delta}{\beta_{\mathrm{BEV}} \beta_{\mathrm{gas}}} - G_t \right) \tag{2}$$

The electric vehicles in our analysis are assumed to have an efficiency, β_{BEV}, of 28 kWh per 100 miles. The substitute ride-hailing gasoline vehicle data were calculated based on the distance-weighted fuel efficiency, β_{gas}, of a representative sample of TNC gasoline vehicles at 29.4 MPG (ride-hailing vehicles are generally more fuel efficient than the average vehicle).

We also considered a comparison of TNC emissions savings to the savings from switching an ordinary gasoline vehicle (not involved in ride-hailing services) to understand the relative emission savings for a targeted PEV adoption policy. The process used to calculate the emissions is:

$$E'_{\mathrm{gas}} = \sum_j \frac{\nu_j \delta}{\beta_{\mathrm{gas}}} \quad (3)$$

$$E'_{\mathrm{BEV}} = \sum_j \nu_j \beta_{\mathrm{BEV}} G \quad (4)$$

$$S' = \sum_j \left(E_{j\mathrm{gas}} - E_{j\mathrm{BEV}}\right) \quad (5)$$

The set j describes the index for individual observations of travel behaviour from a separate dataset, the CHTS. The vehicle miles travelled associated with these vehicles is provided from the CHTS as parameter ν. We focused primarily on estimating the emissions savings as a bounding exercise, particularly related to the emission savings from the TNC electrification, and therefore estimated an optimistic scenario for the emission savings from switching a regular (non-ride hailing service) vehicle to an electric vehicle (S_0). Therefore, the β_{Gas} parameter was assumed to be 27 MPG (approximately the average in California) and the G parameter was assumed to be 186 $\mathrm{gCO_2\,kWh^{-1}}$, the lowest average emissions rate. The emissions conversion from gasoline to CO_2 is represented as δ and its value is based on EPA measurements of 8,887 $\mathrm{gCO_2\,mile^{-1}}$.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from EVGo, Chargepoint, Uber and Lyft, but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. The data from the CHTS are available from the Transportation Secure Data Center, National Renewable Energy Laboratory, at www.nrel.gov/tsdc. California grid load and emissions data are available from the California ISO Historical EMS Hourly Load Data (http://caiso.com/planning/pages/reliabilityrequirements/default.aspx#Historical) and Today's Outlook (http://www.caiso.com/TodaysOutlook/Pages/emissions.aspx). Source data are provided with this paper.

Code availability

The code can be obtained by contacting the author directly at ajenn@ucdavis.edu.

Received: 1 October 2019; Accepted: 16 April 2020;
Published online: 29 June 2020

References

1. Pavlenko, N., Slowik, P. & Lutsey, N. *When Does Electrifying Shared Mobility Make Economic Sense?* Working Paper 2019-01 (International Council on Clean Transportation, 2019).
2. Kley, F., Lerch, C. & Dallinger, D. New business models for electric cars—a holistic approach. *Energy Policy* **39**, 3392–3403 (2011).
3. Luè, A., Colorni, A., Nocerino, R. & Paruscio, V. Green move: an innovative electric vehicle-sharing system. *Procd Soc. Behav. Sci.* **48**, 2978–2987 (2012).
4. Becker, H., Ciari, F. & Axhausen, K. W. Measuring the car ownership impact of free-floating car-sharing—a case study in Basel, Switzerland. *Transp. Res. D* **65**, 51–62 (2018).
5. Jacquillat, A. & Zoepf, S. Deployment and utilization of plug-in electric vehicles in round-trip carsharing systems. *Int. J. Sustain. Transp.* **12**, 75–91 (2018).
6. Mounce, R. & Nelson, J. D. On the potential for one-way electric vehicle car-sharing in future mobility systems. *Transp. Res. A* **120**, 17–30 (2019).
7. Xu, M., Meng, Q. & Liu, Z. Electric vehicle fleet size and trip pricing for one-way carsharing services considering vehicle relocation and personnel assignment. *Transp. Res. B* **111**, 60–82 (2018).
8. Brendel, A. B., Lichtenberg, S., Brauer, B., Nastjuk, I. & Kolbe, L. M. Improving electric vehicle utilization in carsharing: a framework and simulation of an e-carsharing vehicle utilization management system. *Transp. Res. D* **64**, 230–245 (2018).
9. Ai, N., Zheng, J. & Chen, X. Electric vehicle park-charge-ride programs: a planning framework and case study in Chicago. *Transp. Res. D* **59**, 433–450 (2018).
10. Burghard, U. & Dütschke, E. Who wants shared mobility? Lessons from early adopters and mainstream drivers on electric carsharing in Germany. *Transp. Res. D* **71**, 96–109 (2019).
11. Yang, Y., Zhang, W., Niu, L. & Jiang, J. Coordinated charging strategy for electric taxis in temporal and spatial scale. *Energies* **8**, 1256–1272 (2015).
12. Rao, R., Cai, H. & Xu, M. Modeling electric taxis' charging behavior using real-world data. *Int. J. Sustain. Transp.* **12**, 452–460 (2018).
13. Tian, Z. et al. Understanding operational and charging patterns of electric vehicle taxis using GPS records. In *17th International IEEE Conference on Intelligent Transportation Systems* 2472–2479 (IEEE, 2014).
14. Zou, Y., Wei, S., Sun, F., Hu, X. & Shiao, Y. Large-scale deployment of electric taxis in Beijing: a real-world analysis. *Energy* **100**, 25–39 (2016).
15. Yang, J., Dong, J., Lin, Z. & Hu, L. Predicting market potential and environmental benefits of deploying electric taxis in Nanjing, China. *Transp. Res. D* **49**, 68–81 (2016).
16. Teixeira, A. C. R. & Sodré, J. R. Simulation of the impacts on carbon dioxide emissions from replacement of a conventional Brazilian taxi fleet by electric vehicles. *Energy* **115**, 1617–1622 (2016).
17. Clewlow, R. R. & Mishra, G. S. *Disruptive Transportation: The Adoption, Utilization, and Impacts of Ride-hailing in the United States* Research Report UCD-ITS-RR-17-07 (Institute of Transportation Studies, 2017).
18. Jenn, A., Laberteaux, K. & Clewlow, R. New mobility service users' perceptions on electric vehicle adoption. *Int. J. Sustain. Transp.* **12**, 526–540 (2018).
19. Cassetta, E., Marra, A., Pozzi, C. & Antonelli, P. Emerging technological trajectories and new mobility solutions. A largescale investigation on transport-related innovative start-ups and implications for policy. *Transp. Res. A* **106**, 1–11 (2017).
20. Jittrapirom, P. et al. Mobility as a service: a critical review of definitions, assessments of schemes, and key challenges. *Urban Plan.* **2**, 13–25 (2017).
21. Jalali, R., Koohi-Fayegh, S., El-Khatib, K., Hoornweg, D. & Li, H. Investigating the potential of ridesharing to reduce vehicle emissions. *Urban Plann.* **2**, 26–40 (2017).
22. Sarasini, S. & Linder, M. Integrating a business model perspective into transition theory: the example of new mobility services. *Environ. Innov. Societal Transit.* **27**, 16–31 (2018).
23. Barth, M. & Shaheen, S. A. Shared-use vehicle systems: framework for classifying carsharing, station cars, and combined approaches. *Transp. Res. Rec.* **1791**, 105–112 (2002).
24. Sprei, F. Disrupting mobility. *Energy Res. Soc. Sci.* **37**, 238–242 (2018).
25. Gessner, K. *Uber vs. Lyft: Who's Tops in the Battle of U.S. Rideshare Companies* (Second Measures, accessed 1 January 2020); https://secondmeasure.com/datapoints/rideshare-industry-overview/
26. NuStats *2010–2012 California Household Travel Survey Final Report* (California Department of Transportation, 2013).
27. Jenn, A., Lee, J. H., Hardman, S. & Tal, G. An in-depth examination of electric vehicle incentives: consumer heterogeneity and changing response over time. *Transp. Res. A* **132**, 97–109 (2020).
28. Tal, G. & Nicholas, M. A. Studying the PEV market in California: comparing the PEV, PHEV and hybrid markets. In *2013 World Electric Vehicle Symposium and Exhibition* 1–10 (IEEE, 2013).
29. Tal, G., Nicholas, M. A., Davies, J. & Woodjack, J. Charging behavior impacts on electric vehicle miles traveled: who is not plugging in? *Transp. Res. Rec.* **2454**, 53–60 (2014).

Acknowledgements

This study was funded entirely by a grant from the National Center for Sustainable Transportation (NCST), supported by USDOT through the University Transportation Centers programme. The authors thank the NCST and USDOT for their support of university-based research in transportation, and especially for the funding provided in support of this project.

Author contributions

A.J. conducted all the analysis and manuscript writing and editing.

Competing interests

The author declares no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41560-020-0632-7.

Correspondence and requests for materials should be addressed to A.J.

Reprints and permissions information is available at www.nature.com/reprints.

nature research

Corresponding author(s): *Double-blind peer review submissions: write DBPR and your manuscript number here instead of author names.*

Last updated by author(s): *YYYY-MM-DD*

Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see Authors & Referees and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used in the data collection effort, data was provided from various providers
Data analysis	The software used for the analysis in this study was R, version 3.6.0 ("Planting of a Tree")

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The only dataset used within this study that is publicly available is the California Household Transportation Survey (https://www.nrel.gov/transportation/secure-transportation-data/tsdc-california-travel-survey.html). All other datasets are strictly confidential and are unable to be shared publicly (Plug-in Hybrid & Electric Vehicle Center annual surveys, Chargepoint and EVGo charging session data, and Uber and Lyft trip data. All figures in the report are generated from the aforementioned raw datasets.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Quantitative study based on a combination of survey respondents, population data (electric vehicles in Uber/Lyft), and sample data (gas cars in Uber/Lyft).
Research sample	Several research samples/populations were used in this study: -California Household Travel Survey (CHTS): random selection of households in California. Provided with weights to make the data representative on the basis of demographic characteristics including age, gender, education, and race. -Plug-in Hybrid & Electric Vehicle panel survey: convenience sample of plug-in electric vehicle owners in California, these respondents were recipients of the California Clean Vehicle Rebate after purchasing an electric vehicle. The dataset is assumed to represent characteristics of electric vehicle owners in California though there are likely some bias due to the convenience sampling (though this reflects a minute portion of the study). -Charging data: Population data (all non-Tesla, public DC fast charging events) which will be representative of the charging behavior of non-Tesla EV owners in California. Also provides a the population data of charging events for users of the electric vehicles under the Maven program (rental of EVs for Lyft and Uber services). -Trip data: Population data for EVs (all EV trips for Lyft) and sample data (5000 vehicles) for gasoline vehicles. The gasoline vehicles were provided by Lyft such that they represented their fleet fuel efficiency and travel behavior (number of trips and daily distance traveled).
Sampling strategy	See note above
Data collection	We did not collect our own data, all data was obtained from third-parties.
Timing	-CHTS: 2010-2012 -PH&EV Survey: 2010-2017 -Charging data (EVGo and Chargepoint): 2014-2018 -Trip data (Lyft and Uber): 2017-2018
Data exclusions	No data were excluded
Non-participation	N/A
Randomization	N/A

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging