Electrifying Urban Ridesourcing Fleets at No Added Cost through Efficient Use of Charging Infrastructure

Authors:

Gordon S. Bauer
University of California, Berkeley
Energy & Resources Group

Amol Phadke
Lawrence Berkeley National Laboratory
Energy Analysis and Environmental Impacts Division
International Energy Studies Group

Jeffery B. Greenblatt
Emerging Futures, LLC, Berkeley, CA

Deepak Rajagopal*
Lawrence Berkeley National Laboratory
Energy Analysis and Environmental Impacts Division
International Energy Studies Group
University of California, Los Angeles
*Corresponding author

December 2018
DISCLAIMER

This is a working paper, therefore intended to facilitate discussion on research in progress. This paper represents the opinions of the authors, and not meant to represent the position or opinions of the authors’ institutions. Any errors are the fault of the authors. Working papers published under this Series may subsequently be published elsewhere.

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory is an equal opportunity employer.

Acknowledgements

This research was conducted with funding from the Macarthur Foundation and the National Science Foundation. Data were provided by San Francisco County Transit Authority, New York City Taxi & Limousine Commission, StreetLight Data, and Google. Jarett Zuboy provided important feedback to improve narrative structure and clarity.

Author contributions

Gordon S. Bauer: gathered data, conducted analysis, wrote manuscript
Deepak Rajagopal: provided guidance and conceptual insight, assisted with writing manuscript
Jeffery B. Greenblatt: provided guidance and conceptual insight, reviewed manuscript
Amol Phadke: provided guidance and conceptual insight, reviewed manuscript
Electrifying Urban Ridesourcing Fleets at No Added Cost through Efficient Use of Charging Infrastructure

Gordon S. Bauer\textsuperscript{a}, Amol Phadke\textsuperscript{b}, Jeffery B. Greenblatt\textsuperscript{c}, and Deepak Rajagopal\textsuperscript{*}

Abstract

Ridesourcing fleets present an opportunity for rapid uptake of battery electric vehicles (BEVs) but adoption has largely been limited to small pilot projects. Lack of charging infrastructure presents a major barrier to scaling up, but little public information exists on the infrastructure needed to support ridesourcing electrification. With data on ridesourcing trips for New York City and San Francisco, and using agent-based simulations of BEV fleets, we show that given a sparse network of three to four 50kW chargers per square mile, BEVs can provide the same level of service as internal combustion engine vehicles (ICEVs) at lower cost. This suggests that the cost of charging infrastructure is not a significant barrier to ridesourcing electrification. With coordinated use of charging infrastructure across vehicles, we also find that fleet performance becomes robust to variation in battery range and placement of chargers, suggesting that such capability may help enable electrification. Our results suggest that mandates for ridesourcing electrification could encourage efficient utilization of fast-charging infrastructure, bringing down costs for all BEV users without significantly increasing the cost of ridesourcing services.

Meeting the Paris Climate Agreement’s 2 °C and 1.5 °C targets will likely require massive deployment of electrified transportation.\textsuperscript{1} Transportation represents the fastest-growing source of the world’s greenhouse gas (GHG) emissions, with passenger cars accounting for close to a sixth of carbon dioxide emissions,\textsuperscript{1} and car sales set to more than double by 2050.\textsuperscript{2} In the U.S., transportation emissions have grown by over 20% since 1990, while emissions from almost all other sectors have decreased or remained constant.\textsuperscript{3} Battery electric vehicles (BEVs) could reduce transportation-related carbon emissions and urban air pollution,\textsuperscript{4,5} but despite years of strong public support, several barriers have slowed adoption of BEVs.\textsuperscript{6,7} BEVs typically cost more than similar conventional and hybrid vehicles, and they provide a shorter driving range.\textsuperscript{8} Charging infrastructure incurs additional cost, and the vast majority of public charging infrastructure consists of Level 2 chargers,\textsuperscript{9} which take hours to provide a full charge. Public DC fast charging requires much less time (providing 60–80 miles of range in 20 minutes),\textsuperscript{10} but relatively few fast-charging stations are available, and low utilization increases charging costs.

Ridesourcing—a taxi-like service that uses smartphone apps (from Uber, Lyft, etc.) to connect riders with self-employed drivers\textsuperscript{11}—holds potential to overcome these barriers and drive a step-change in transportation electrification. Vehicles used for ridesourcing accumulate mileage more quickly than vehicles used for personal purposes only, such that BEVs used for ridesourcing can provide greater benefits to vehicle owners due to lower costs per mile,\textsuperscript{12,13} and they provide

\textsuperscript{a} University of California, Berkeley
\textsuperscript{b} Lawrence Berkeley National Laboratory, Berkeley, CA
\textsuperscript{c} Emerging Futures, LLC, Berkeley, CA
\textsuperscript{*} Institute of the Environment and Sustainability, University of California, Los Angeles,
Email: rdeepak@ioes.ucla.edu, Corresponding author
better returns on public electrification investments in terms of reduced carbon emissions and air pollution per vehicle.\textsuperscript{14} In addition, because ridesourcing vehicles are typically driven in urban cores, ridesourcing BEVs could increase public health benefits while exposing many consumers to the technology, which might increase private BEV sales.\textsuperscript{15} Although ridesourcing currently represents a relatively small share of all vehicle miles traveled, the sector has experienced explosive growth that shows no sign of slowing, with some forecasts expecting the global market to increase almost three-fold by 2030,\textsuperscript{16,17} and others predicting that, with the advent of vehicle automation, ridesourcing will soon dominate the transportation market.\textsuperscript{18}

Meanwhile, local governments are increasingly concerned by ridesourcing’s adverse emissions impacts,\textsuperscript{19} and BEVs offer a solution. In California, the public utility commission has been directed to assign ridesourcing companies targets for electrification.\textsuperscript{20} Uber has announced that all its vehicles in London will be electric or hybrid by 2025,\textsuperscript{21} and Lyft has set a goal of 1 billion autonomous electric rides per year by 2025.\textsuperscript{22}

Despite such ambitious plans, early efforts at ridesourcing electrification have experienced mixed results. In a London pilot project, Uber found that over 80\% of BEV drivers lacked access to home charging, and insufficient public infrastructure prevented drivers from serving as many rides as they could with internal combustion engine vehicles (ICEVs).\textsuperscript{15} Elsewhere, ridesourcing BEV drivers have reported declining rides because their vehicles lacked sufficient charge as well as losing revenue owing to time spent charging and looking for charging stations.\textsuperscript{23,24} In a South Korean pilot project, BEV taxis provided a much lower benefit-to-cost ratio compared with natural-gas-powered taxis because of limited charging infrastructure and battery range.\textsuperscript{25} Ridesourcing electrification will require additional public fast-charging charging infrastructure, but there is a lack of information regarding optimal infrastructure design and BEV fleet operation (see literature review in supplementary information).

In this study, we show that (1) modest additions of public fast-charging infrastructure make urban ridesourcing electrification practical under a range of vehicle operating strategies, and (2) the current economics of urban ridesourcing can support vehicle electrification and the required charging infrastructure at total costs lower than the costs of the ICEV-based ridesourcing system. In addition, the increased utilization of charging infrastructure due to ridesourcing BEVs could reduce public charging costs for all BEV users and further support large-scale transportation electrification. Therefore, electrifying the urban ridesourcing sector is a cost-effective approach to reducing transportation-related greenhouse gas emissions and urban air pollution, and properly designed policies could realize these benefits with no cost burdens to governments, transportation network companies, or ridesourcing drivers.

**Paying off fast-charging infrastructure via high utilization**

Contrary to common perception, simple economic reasoning suggests that ridesourcing drivers have adequate time to charge during their shifts, and that—with sufficient utilization—fast-charging infrastructure will pay for itself. As previous studies have noted,\textsuperscript{26} the short rider wait times that are key to ridesourcing’s value proposition are predicated on having a significant number of drivers idling at any given time. This idle time represents time when drivers could charge BEVs without losing revenue. As shown in Equation 1, the amount of time drivers spend
idling \((t_{idle})\) can be expressed as a relation between driver wage rate \((w)\), the ratio of empty miles to passenger miles (deadheading ratio, \(r\)) and the rate that could be earned by serving trips continuously \((f)\) multiplied by the time period \((t_{tot})\), minus average refueling time \((t_{fuel})\).

\[
t_{idle} = t_{tot} * (1 - w/f * (1+r)) - t_{fuel}
\]

For instance, in New York City (NYC), Uber fares are calculated by adding $1.75 per mile and $0.35 per minute to a $2.55 per trip base charge, of which Uber takes a 25% cut.\(^{27}\) Given an average speed of roughly 12 miles per hour and an average trip distance of 3 miles,\(^{28}\) a driver carrying passengers for a full hour would serve 4 trips, earning $39.15 \((f)\). Assuming gross driver earnings \((w)\) average $24 per hour,\(^{26,29}\) and a deadheading ratio (empty miles divided by passenger miles) of 0.25,\(^{30}\) we can estimate that drivers in NYC are moving for roughly 46 minutes out of the hour, and have roughly 14 minutes in which to recharge the 9.2 miles they traveled. As shown in Figure 1, a 50-kW charger can provide this amount of charge in roughly 3 minutes, suggesting that drivers have more than enough time to charge during their shift. Based on these assumptions, the average driver would have to charge less than once per shift, such that time spent relocating to charge is negligible.

The cost of charging infrastructure is highly sensitive to utilization. In the U.S., public charging infrastructure is utilized less than 10% of the time,\(^{31,32}\) which often makes DC fast charging more expensive than gasoline on a per-mile-driven basis. As shown in Figure 2, once utilization surpasses about 15\% (roughly 3.5 hours per day), the combined cost of infrastructure and electricity becomes less than the equivalent cost of gasoline in both NYC and San Francisco (SF), and operational savings start to accrue.

These calculations suggest that neither the cost of infrastructure nor the time required to charge should pose significant barriers to ridesourcing electrification. This conclusion is based on several major assumptions: that charging in between trips does not affect the ability to serve demand for rides, that time spent relocating to charge is not significant, and that charger utilization greater than 3.5 hours per day is feasible when accounting for relocation time and queuing at stations.

To test these assumptions, we develop an agent-based model that routes a fixed number of active vehicles to trips, rebalances idle vehicles to match demand, and determines the best times for vehicles to charge given a fixed number of charging points and locations. We repeat this analysis numerous times for different combinations of the fixed input parameters to determine the minimum charging infrastructure required for BEVs to generate at least as much revenue per shift-hour as ICEVs. We conduct this analysis with data for ridesourcing trips in both SF and NYC (summarized in Table 2 in the methods section).

As shown in Table 1, we conducted simulations for a variety of scenarios for vehicle range, charging infrastructure, and charging relocation strategy (i.e. the rules that determine when vehicles go to charge), for a total of 360 BEV fleet simulations (180 for each city). We also conducted an ICEV fleet simulation in each city for comparison. We then determined whether each BEV fleet provided equivalent service to the ICEV fleet, defined as earning at least 95% as
much revenue per hour, with no more than 5% additional empty miles and average wait times no more than 1 minute longer.

![Figure 1. Distribution of time spent by an average NYC ridesourcing driver, with time cost of charging for both DC fast charging (50 kW) and Level 2 charging (22 kW or 7 kW). We assume a vehicle energy consumption of 0.28 kWh/mile, equivalent to the performance of the 2018 Chevrolet Bolt. For relocating to charge, we assume one charging session per 8-hour shift and an average relocation distance of 2.5 miles at a speed of 10 miles/hour.]

![Figure 2. Relationship between the total cost of charging infrastructure (capital cost, electricity, and demand charges) and percent utilization by time. Cost assumptions are shown in Table 3 in the methods section.]

6
<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>Values simulated</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Battery range</strong></td>
<td>90 miles (based on 2019 Nissan LEAF with decreased range from winter driving or capacity fade), 238 miles (based on 2019 Chevy Bolt advertised range)</td>
</tr>
<tr>
<td><strong>Charger utilization</strong></td>
<td>25%, 50%, 75%, 100%</td>
</tr>
<tr>
<td><strong>Charging speed</strong></td>
<td>7.7 kW (present-day Level 2 charging), 22 kW (next-generation Level 2 charging), 50 kW (public DC fast charging)</td>
</tr>
<tr>
<td><strong>Number of chargers</strong></td>
<td>Total distance * 1.4 / (Charging rate per hour * 24 hours * charger utilization)</td>
</tr>
<tr>
<td><strong>Number of charging locations</strong></td>
<td>Unrestricted, 10 locations</td>
</tr>
<tr>
<td><strong>Charger distribution strategy</strong></td>
<td>k-means clustering (“optimal”), random point selection after k-means clustering to 5,000 points (“random”), random point selection from bottom 20% of points by total number of trips within a 1.5-mile radius (“perimeter”) (tested only with 50% charger utilization and 50-kW charging)</td>
</tr>
<tr>
<td><strong>Charging relocation strategy</strong></td>
<td>Optimal routing (“opportunity”), optimal when &lt; 20% state of charge (SOC) (“threshold”), move to closest charger when &lt; 20% SOC (“blind”)</td>
</tr>
</tbody>
</table>

**Table 1.** Description of simulation runs.

**Feasibility of ridesourcing electrification by scenario**

As shown in Figure 3, our simulation results suggest that BEVs with 238 miles of range (equivalent to the Chevrolet Bolt EV) can provide equivalent service to ICEVs in a range of different infrastructure scenarios in both cities (see supplementary information for full results). However, the ability of the fleet to serve demand is sensitive to both charging speed and charging relocation strategy. Using chargers rated at 7kW—the most common form of public infrastructure today—does not allow for equivalent service in any of our simulations, suggesting that such slow charging is not sufficient for ridesourcing electrification. This result is consistent with the analysis summarized in Figure 1. Using 22-kW charging works in some cases but not in others, while using 50-kW charging (DC fast charging) allows BEVs to provide equivalent service across a wide range of scenarios. This result suggests that DC fast charging infrastructure rated at 50kW is both necessary and sufficient for ridesourcing electrification.

In the “blind” scenario, in which drivers have no information on when they should charge or charger availability, only 50-kW charging allows for equivalent service in both cities. This scenario represents how BEVs currently operate, suggesting that 50kW charging will be necessary to initiate BEV penetration. In NYC, 22-kW charging can provide equivalent service if there is no restriction on the number of charging locations, but when BEV penetration is low, there will not be enough utilization to support more than a few locations. On the other hand, the fact that 22-kW charging works in many cases suggests that 50-kW charging may work even if our model is too optimistic, and effective charging speed is lower in practice when accounting for time spent parking and plugging in.
If fleet operators are able to direct vehicles to charge only when they have enough idle time to do so ("opportunity" and "threshold" scenarios), the number of 50-kW chargers required decreases to two per square mile in NYC (512 total chargers), and three per square mile in SF (175 total chargers). In the "threshold" scenario, vehicles are only available to charge once their battery range falls below 20%, whereas in the "opportunity" scenario, vehicles are available to charge whenever idle. The former scenario performs slightly better in NYC, while the latter performs better in SF, likely because the larger area of NYC induces a larger penalty for charging frequently.

In some ways, 238-mi. range represents an ideal case; to account for the impact of colder temperatures, more aggressive driving, using vehicles with less battery range, and capacity fade over time, we also ran each simulation with 90 miles of battery range. As shown in Figure 4, such vehicles can also provide equivalent service to ICEVs in both cities with 50-kW charging so long as timing of charging is managed efficiently ("opportunity" scenario). This result suggests that if a fleet is operated carefully, performance becomes insensitive to battery range. In turn, using vehicles with less range could decrease operating costs by reducing vehicles’ up-front costs and extending batteries’ functional lifetime.

As shown in Figure 5, fleet performance is also relatively robust to how the chargers are sited. Relative to clustering chargers by trip origins and destinations ("optimal" scenario), results remain largely unchanged when chargers are placed semi-randomly ("random" scenario, see methods section for details), suggesting that mildly perturbing placement does not affect fleet performance. Even if chargers are placed only on the periphery ("perimeter" scenario), revenue remains stable in both cities, and in NYC overall service with the "threshold" charging relocation strategy remains comparable to the ICEV fleet. If this scenario is modified such that charging at the beginning and end of shifts is incorporated into drivers’ commutes ("commute" scenarios), fleet performance in NYC becomes equivalent to the "optimal" charger placement scenario. Average wait time remains roughly 3 minutes longer in SF, but this may be because the trip data does not include trips entering or leaving city limits. This result suggests that in some cases, if many ridesourcing drivers come from outside the city (e.g. over half in SF), placing charging near popular commute routes may be sufficient. A map of each charging distribution is shown in Figure 6.
Figure 3. Results for all simulations, showing the performance of a fleet of BEVs with 238-mi. range relative to a fleet of ICEVs for each combination of charging infrastructure, battery range and charging relocation strategy. “Opportunity” represents simulations where vehicles are routed to charge whenever they have enough idle time to make it worthwhile, “threshold” represents simulations where vehicles are only allowed to charge when below 20% state of charge, and “blind” means that as soon as vehicles reach 20% state of charge, they move to the closest available charger whether or not they have enough time to gain a meaningful amount of charge, and whether or not there is another vehicle moving to the same charger.
Figure 4. Results for all simulations with 90-mi. battery range. Labels are the same as in Figure 3.
Figure 5. Results for simulation runs with different strategies for charging relocation and charger placement. In “optimal” simulations, chargers were clustered based on trip origins and destinations. In “random” simulations, charger locations were selected randomly after clustering trip origins and destinations to 5,000 points, and in “perimeter” and “commute” simulations, charger locations were selected randomly from points in the lowest 20% of trips per square mile. Each simulation was run with three and four 50-kW chargers per square mile for NYC and SF, respectively.
Figure 6. Maps of distributions of chargers in SF (left) and NYC (right) for each placement strategy and for both unlimited locations and placement restricted to 10 locations. The color and size both represent the number of chargers at each location.

**Total costs of ridesourcing electrification**

As hypothesized, the results presented above suggest that ridesourcing fleets can provide high levels of charger utilization. In both cities, fleets with average charger utilization of over 12 hours per day were feasible with both 22-kW and 50-kW charging. With 50-kW charging and some management of charging timing (“opportunity” and “threshold” scenarios), fleets in both cities achieved charging utilization of up to 20 hours per day while providing equivalent service to ICEVs. These results correspond to about 750 50-kW chargers in NYC, and 175 in SF, with densities of about three chargers per square mile in both cities (NYC covers an area roughly five times as large as SF). These quantities are roughly equivalent to the total number of gasoline pumps in each city.\(^{36}\) In comparison, NYC currently only has 16 public fast chargers, but it plans to build up to 1,000 more by 2020.\(^ {37}\) SF currently has 20 fast chargers spread across 13 locations,\(^ {38}\) but there is public funding for the installation of several thousand additional chargers (power ratings have not been publicly announced).\(^ {39,40}\) Based on our results, these existing plans are more than sufficient to fully electrify ridesourcing in these cities provided that chargers are rated to at least 50kW.
As a result of high utilization, we estimate that the cost of installing these fast chargers is quiet low: $0.07/shift-hour in SF and $0.17/shift-hour in NYC, including demand charges. In contrast, we estimate that all other ridesourcing BEV expenses fall in the range of $3.27–$3.40/shift-hour including both operating costs and amortized capital costs. The impact of BEVs on net revenue is either positive or close to zero in all scenarios (Figure 7). In other words, even if the charging infrastructure is significantly overbuilt, resulting in only 5-10 hours of utilization per day (11 and 5 chargers per square mile for SF and NYC, respectively), the cost still represents at most 2% of driver earnings and an even lower proportion of total revenue. This comparison assumes that fleets or their drivers pay for charging infrastructure; any public infrastructure funding will increase potential savings for ridesourcing fleets. It could be paid for with less than 1% of revenue from the rideshare tax in NYC,41 or less than 4% of the proposed rideshare tax in SF.42

![Figure 7](image-url)

**Figure 7.** Average expenses and net revenue of operating a ridesourcing BEV per shift-hour, broken down by component for each city. Dashed lines show comparison to total ICEV cost and net revenue, while red numbers show total expenses and black numbers show net revenue after expenses. Error bars show difference between BEV scenarios (only 50-kW scenarios that provide equivalent service to ICEVs are shown).

**Discussion & policy implications**

This analysis suggests that ridesourcing fleets can be electrified while maintaining or even increasing net revenues. The cost of charging infrastructure is a relatively small fraction of the total cost of an electric, ride-sourced trip, indicating that it may be prudent to slightly overbuild capacity to ensure high-quality service. In particular, 50-kW charging at a density of roughly
three to four chargers per square mile would allow the fleet to better serve demand while also increasing revenue slightly.

Efficiently routing vehicles to charge makes fleet performance insensitive to changes in battery range, which may enable batteries to be used much longer than currently expected, further lowering costs. Although short-range BEVs may not readily serve all of drivers’ personal trips, leasing or renting vehicles for ridesourcing is already common, and almost two-thirds of ridesourcing drivers in NYC report acquiring a new vehicle for the sole purpose of working in the ridesourcing industry.\(^{26}\) Regardless, if infrastructure is made accessible to multiple groups, it will be critical to enable reservation of charging slots, to minimize queuing.

Although we exclude certain costs such as parking at charging stations, and developing and operating routing software, our sensitivity analyses show that—in every case—differences in revenue between ICEV and BEV fleets fall within the range of -$0.80 to $0.80/shift-hour, or a few percent of total revenue (see supplementary information).

In short, our results suggest that given sufficient charger utilization, switching to BEVs with today’s technology will not impose a significant cost burden on the ridesourcing industry. Previous work has shown that the environmental benefits of ridesourcing electrification could be large,\(^{14}\) and positive experiences could also accelerate private adoption of BEVs, suggesting there is a strong justification for policy intervention. A combination of mandates on ridesourcing companies coupled with public investments in charging infrastructure can help ensure that ridesourcing companies invest in driver adoption of BEVs while freeing them of concerns related to availability and utilization of charging infrastructure. Mandates that require industry to obtain a certain percentage of miles from zero-emission vehicles would naturally spur the development of innovative financing and leasing strategies for ridesourcing BEVs and accelerate the development of efficient charging-routing algorithms. One of the first instances of such a mandate is the California Clean Miles Standard and Incentive program which sets targets for reduction in emissions per passenger-mile for ridesourcing companies beginning in 2023.\(^{20}\) Our work is the first to suggest that such policies are not only feasible but could deliver emissions reduction at low cost.

While our analysis is limited to two cities, there is nothing to suggest our conclusions do not apply to a wide variety of other cities as well. That said, our study has several important limitations. First, our model does not optimize each driver’s revenue when moving in between trips, so estimates of deadheading ratios must be validated, but this is difficult given the proprietary nature of this information. In any case, because we modeled the ICEV and BEV fleets consistently, we expect our comparisons to be robust. In addition, we do not examine how individual driver preferences and behaviors will impact BEV adoption, which is an important area of future research. Finally, neither dataset provides actual ridesourcing trip data for an entire metropolitan area. In each case, data from several sources are combined to extrapolate individual trips; this approach could be improved upon, but again this would rely on securing proprietary information. We hope this study shows the value of detailed ridesourcing data and thus encourages more data sharing in the future.
Methods

Fleet modeling: To route vehicles to trips and charging, we use an agent-based model originally described in Bauer et al. (2018). The model heuristically relocates vehicles between trips to better serve demand and charge opportunistically. Proceeding chronologically, the model assigns each trip to the closest available vehicle that would have at least enough range to serve the trip, make it to the closest charging station, and commute home. When more than one vehicle meets these criteria, the model assigns the one with the least earnings per hour. If no vehicle can serve a trip within 10 minutes, vehicles that have remained idle are allowed to relocate in anticipation of future demand to serve the trip with a 10-minute wait time. This “clairvoyant” approach was verified to be realistic in previous work through sensitivity analysis. We also ran simulations in which vehicles do not relocate in between trips, which support our main results (see supplementary information). If a trip request is not served within 15 minutes, it disappears and its revenue is lost. After trip assignment, idle vehicles are routed to charging stations using the following heuristic approach. Vehicles only relocate if they have been idle for enough time that they could have made it to the charging station, regained any charge lost in transit, and spent at least 10 additional minutes charging. Charging time is also limited by the amount of time chargers have been available, and occupied chargers are not available to accept vehicles. Assignments are made in order of the amount of energy gained. To test the impact of this routing algorithm, we conducted simulations with restrictions on charging (Table 1). The fixed charger locations are predetermined using k-means clustering of trip origins and destinations, which resulted in equivalent performance to the charger location algorithm described in Bauer et al. (2018). In simulations with a fixed number of charging locations, placement of both the locations and chargers were determined with k-means clustering, and then each charger was moved to the nearest location. Figure 9 shows a flow-chart of the model process; an animation visualizing the simulation can be viewed on Youtube.

The main difference between the model developed for this study and that reported previously is that, at each minute, vehicles in the present study were removed or added to the fleet to match the time-varying fleet size determined exogenously. Each vehicle was assigned a shift length and commute distance (to and from home) randomly selected from a distribution based on survey data (see below for details). At the end of the shift, after serving any active trip, vehicles were designated as inactive as soon as they had enough range for their commute. When starting a new shift, initial vehicle range was selected randomly from the ranges of vehicles already to have completed their shifts, and the simulation repeated on the same 24-hour period until the average range of all vehicles (both active and inactive) at the end of the day was within 5% of what it was at the beginning of the day. Model inputs and outputs can be summarized as follows (see Table 1 for details):

Inputs: battery range, charging speed, number of chargers, number of charging locations, number of active vehicles by minute, driver shift length, driver commute distance, vehicle routing algorithms

Outputs: wait time by trip, revenue per shift-hour by vehicle, utilization by charger, deadheading distance and time by vehicle
**Trip data:** We conducted fleet simulations in both SF and NYC. To estimate trip data for NYC, we obtained data from the NYC Taxi and Limousine Commission (TLC) on trips taken by Yellow Taxis, Green Taxis, and For-Hire Vehicles (FHVs), the latter of which includes all ridesourcing vehicles. The taxi datasets included geolocations and timestamps for trip pick-up and drop-off points, as well as trip distance, whereas the FHV dataset included only the number of trips by pickup zone and hour. To estimate individual trip records, we sampled trips from the combined taxi dataset to create a trip record with the same distribution by hour and pickup zone as the FHV data from February 2017, with 422,000 trips (the average for a weekday). Pick-up and drop-off coordinates were clustered into cells with radius 250 meters such that the maximum difference in travel time would be 1 minute assuming an average speed of 15 miles per hour. This clustering resulted in 6,500 total cells. Origin-destination matrices with times and distances between each of these cells were estimated using data downloaded from Google Maps API, as described in Bauer et al. (2018).14

The SF simulations are based on data obtained from the San Francisco County Transportation Authority (SFCTA) for Uber and Lyft trips starting and ending within city limits in November and December 2016. The data were aggregated by hour and traffic analysis zone (TAZ), and pickup minutes were estimated using LOESS regression, with the number of trips in each minute adjusted such that the total number of trips in each hour was equal to that in the original data. To estimate times and distances for each trip, we integrated the SFCTA data with data obtained from StreetLight Data Inc. based on GPS data from smartphone apps and in-vehicle devices. These data include the distribution of times and distances for vehicle trips taken between TAZ pairs by hour. StreetLight Data metrics were also used to create relocation matrices between each zone pair, similar to the data from Google described above. For each unique vehicle-trip and vehicle-charger pair, relocation times and distances are drawn randomly from the corresponding distribution provided by the data.

**Driver commutes and shift lengths:** In both cities, we used survey data of Uber drivers29 and NYC TLC data on ridesourcing driver working hours26 to estimate the distribution of shift lengths for drivers. To estimate commute distances, in SF we obtained data on the home cities of about 1,000 Uber/Lyft drivers within the Bay Area,35 and we used the Google Maps distance from each city to SF to create a sampling distribution. Drivers originating outside the Bay Area were excluded, because we assumed they would have to charge somewhere in the Bay Area on their way to and from home, such that these “super-commuters” would not affect charging infrastructure requirements. Based on the distribution for SF, in NYC we estimated commute distances by sampling from a gamma distribution with a scale factor of 2 miles and shape factor of 5 miles.

**Number of drivers active:** In SF, we obtained data from SFCTA on the average number of drivers active in each hour, then used LOESS regression to estimate the number active in each minute. In NYC, we calculated the total amount of revenue generated in each minute based on Uber fares,27 and we used this to determine the number of drivers that would be active if the average gross earnings were $23/hour, the average of values found in surveys.26,29 We then used LOESS regression to create a smooth curve for number of active drivers, adjusted such that the average earnings over the entire day were equal to $23/hour.
Table 2. Summary of city characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>San Francisco</th>
<th>New York City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (square miles)</td>
<td>47</td>
<td>303</td>
</tr>
<tr>
<td>Number of trips</td>
<td>162,707</td>
<td>422,652</td>
</tr>
<tr>
<td>Average trip distance (miles) and duration (minutes)</td>
<td>2.7 miles 14 minutes</td>
<td>3.1 miles 15 minutes</td>
</tr>
<tr>
<td>Total number of active drivers</td>
<td>14,735</td>
<td>27,275</td>
</tr>
<tr>
<td>Average commute distance (miles)</td>
<td>12.4</td>
<td>10.0</td>
</tr>
<tr>
<td>Average shift length (hours)</td>
<td>4.6</td>
<td>7.0</td>
</tr>
<tr>
<td>Average driver earnings ($/shift-hour)</td>
<td>18.55</td>
<td>24</td>
</tr>
</tbody>
</table>

Sources
San Francisco County Transit Authority; San Francisco Tax Collector’s Office
NYC Taxi & Limousine Commission; Hall & Kreuger (2018); Parrot & Reich (2018)26,29

Cost analysis: Each component used to estimate the cost of each fleet is described in Table 3.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
</table>
| Vehicle purchase        | BEV 238: $29,120 (2019 Chevrolet Bolt after federal tax credit; assumed that battery lasts at least as long as vehicle)  
                         | ICEV: $23,845 (2019 Toyota Camry)                                      | 44     |
| Vehicle lifetime        | 200,000 miles                                                         | 45     |
| Vehicle maintenance     | BEV: $0.04/mile  
                         | ICEV: $0.06/mile                                                      | 46     |
| Charger installation    | 7 kW: $5,000  
                         | 22 kW: $20,000  
                         | 50 kW: $50,000                                                      | 47,48  |
| Electrical connection   | Same cost as two additional chargers per location                     | 47,48  |
| Vehicle insurance       | $150/vehicle-month                                                   | 49     |
| Energy costs            | BEV  
                         | NYC: $0.061/kWh + $30.90/kW  
                         | SF: $0.151/kWh + $15.90/kW                                          | 50-53  |
|                         | ICEV  
                         | NYC: $0.09/mile ($2.68/gallon, 30 miles/gallon)  
                         | SF: $0.11/mile ($3.27/gallon, 30 miles/gallon)                       |        |

Table 3. Cost model components. All amortization calculations assume an annual discount rate of 5%.  
Gasoline prices reflect 5-year averages.
Figure 8. Flow chart depicting agent-based simulation for BEV fleet operations.
References


30. San Francisco County Transportation Authority. TNCs Today: A Profile of San Francisco Transportation Network Company Activity. (2017).


Supplementary information

Literature review
To our knowledge, the only other study to investigate the charging infrastructure needs of ridesourcing fleets is Wood et al. (2018),¹ who built an optimization model of a hypothetical ridesourcing fleet in Columbus, Ohio, based on GPS data from cell phones. However, these data did not distinguish ridesourcing trips from trips taken by other modes, and the authors assumed that all drivers have access to home charging, whereas ridesourcing electrification in major cities likely will depend on public charging as discussed above.

Several previous studies have employed agent-based modeling techniques to study taxi fleets, but most focus on self-driving cars, and few have modeled BEVs.²–⁴ Of those that do consider BEVs, the charging relocation strategy is typically absent or simplistic. Chen et al. (2016)⁵ only allowed vehicles to charge when they did not have enough range to serve a trip, while Bischoff et al. (2014)⁶ only allowed vehicles to charge when at taxi stands. Hu et al. (2018)⁷ studied the feasibility of electrifying Yellow Taxis in NYC, defining “feasibility” as able to serve 99% of the same trips as an ICEV. They found that only 7% of the fleet could be electrified with current charging infrastructure, and half of the fleet could be electrified by installing approximately 400 additional charging stations. However, the authors did not consider charging congestion or relocation times after charging. They also placed several restrictions on when the vehicles could charge, such as being within half a mile of the nearest station. Yang et al. (2017)⁸ simulated electrification of taxis in Beijing to determine optimal charging siting, but they assumed charging would only occur when the taxis currently had idle time, i.e., they did not allow for relocation to charging stations.

This study builds on previous work by incorporating flexibility in when drivers relocate to charge. Both Wood et al. (2018)¹ and Hu et al. (2018)⁷ determined charging and trip assignment separately, leading to much less flexibility in the timing of charging than if the two are determined simultaneously. Also, most previous studies have only allowed vehicles to charge when battery range falls below a threshold, and they have required vehicles to remain charging until at full capacity.⁷,⁹,¹⁰ We hypothesize that flexibility may be even more important for ridesourcing than for other BEV applications, because the vehicles return to the drivers’ homes at the end of shifts, where charging stations may not be available.

Vehicle activity results

Figure S1 and Figure S2 show more details related to vehicle activity: the first shows overall averages for the amount of time devoted to each activity, while the second shows vehicle counts disaggregated by activity and minute in SF.
Figure S1. Fraction of time devoted to each activity in each city for all simulations resulting in equivalent service to ICEV fleets.

Figure S2. Vehicle activity by time of day with 7kW charging in San Francisco.
Extended simulation results: NYC

Figure S3 to Figure S7 show results for each city for each measure of fleet performance: demand served (and correspondingly driver revenue), average wait times, and deadheading (the ratio of empty miles to passenger miles).

**Figure S3.** Percent passenger-miles served by BEV fleets in NYC under different charging and vehicle scenarios.
Figure S4. Average wait times in NYC by simulation scenario.

Figure S5. Ratio of empty miles to passenger miles in NYC by simulation scenario.
Extended simulation results: San Francisco

Figure S6. Percent passenger-miles served by BEV fleets in SF under different charging and vehicle scenarios.

Figure S7. Average wait times in SF by simulation scenario.
Figure S8. Ratio of empty miles to passenger miles in SF by simulation scenario.
**Sensitivity analysis**

Figure S9 shows the impact of changing cost assumptions on the difference in net revenue between BEV and ICEV fleets in each city, with each scenario described in Table S1. Figure S10 shows the impact of changing the assumption that idle vehicles rebalance in anticipation of future demand.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td>Base scenario, described in Error! Reference source not found.</td>
</tr>
<tr>
<td>low_gas</td>
<td>Gas prices decrease by $1/gallon</td>
</tr>
<tr>
<td>hi_gas</td>
<td>Gas prices increase by $1/gallon</td>
</tr>
<tr>
<td>low_eff</td>
<td>ICEV fuel economy = 25 miles/gallon</td>
</tr>
<tr>
<td>hi_eff</td>
<td>ICEV fuel economy = 50 miles/gallon</td>
</tr>
<tr>
<td>nofedsub</td>
<td>No federal tax subsidy for BEVs</td>
</tr>
<tr>
<td>parity</td>
<td>BEV 238 purchase price is the same as ICEV ($23,845), and BEV 90 price decreases accordingly</td>
</tr>
<tr>
<td>chgsub</td>
<td>Cost of charging installation is ignored, assuming it is paid for through public funding</td>
</tr>
<tr>
<td>hiutil</td>
<td>Vehicles are used by multiple drivers, increasing vehicle utilization to 20 hours per day</td>
</tr>
</tbody>
</table>

**Table S1.** Description of cost model sensitivity analysis scenarios.
Figure S9. Impact of changing cost assumptions on potential savings from switching to BEVs. For more details on each scenario, see Table S1.
Figure S10. Comparison of simulation results by vehicle routing strategy ("dumb" represents simulations in which vehicles never rebalance in between trips to match demand, while "smart" represents the base scenario with clairvoyant rebalancing). Results show that removing clairvoyance decreases vehicle revenue somewhat, but the impact of charging relocation strategy and battery range remain the same, with the exception of the "blind" scenario, where longer-range BEVs can no longer serve demand.
References