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Recharging Systems and Business Operations to Improve the Economics of Electrified Taxi Fleets

I-Yun Lisa Hsieh[a], Ashley Nunes[b], Menghsuan Sam Pan[c], and William H. Green[a†]

[a] Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[b] Harvard Law School, Harvard University, Cambridge, MA, 02142, USA

[c] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA

[†] whgreen@mit.edu

Abstract

While vehicle electrification offers great benefits to society, mass-market adoption of battery electric vehicles remains a challenge owing to the long recharging times and limited recharging infrastructure. High opportunity costs tied to long recharging times are particularly problematic for commercial fleet operators. With an aim to improve the economics of electrified taxi fleets, we present a framework for techno-economic analysis, examining the cost competitiveness of various recharging business models (i.e., combined ecosystems of recharging systems and taxi operations).

When considering the achievable throughput of the recharging systems, we find that—on a per-kilometer basis—1) battery swapping emerges as a cost-effective option although it requires higher upfront investments for the battery inventory requirement; 2) increasing vehicle fleet size enhances the economic viability of double-shift taxi electrification. We expect that an electrified taxi fleet relying on the *right* recharging systems/operations could achieve cost parity with a gasoline-powered taxis system by 2022. Between now and then, the electrification of high-use vehicles requires government support; policies discussed include purchase subsidies and revenue-neutral gas tax imposition. By using real-world financial data taken from an operating electrified taxi fleet in Beijing, this paper provides a theoretical and practical reference for cities moving toward electric taxi ecosystems and sustainability.

Keywords:

Fleet electrification/ Electric taxi/ Recharging infrastructure/ Battery swapping

1. Introduction

While internal combustion engine-powered vehicles (ICEVs) are the preeminent mover of goods and services, they also remain a major source of hazardous air pollutants (OECD, 2014). The ensuing public health outcomes are particularly worrisome for China, where motorization rates are soaring (Saikawa et al., 2011). Although battery electric vehicles (BEVs) offer an opportunity to reduce the impact of these negative externalities, widespread market penetration of this technology remains a challenge owing in large part to longer-than-average energy replenishment times (Merchant, 2017). Currently, most BEVs are recharged using Level 2 chargers, where a BEV is plugged into external energy supply and left for several hours (Guinn, 2018); this in comparison to the few minutes taken to refuel a gasoline-powered vehicle.

Long BEV charging times are particularly problematic for multi-shift taxis and similarly operated mobility-on-demand fleets. Because minimizing vehicle downtime is crucial to maximizing profit, fleet owners show preference for ICEVs over electric ones. The consequences of this preference are not insignificant. Compared to personal light-duty vehicles, taxis – owing to traveling greater distances – consume more fossil fuels making them disproportionally larger contributors to air pollution (Rosa and Abdalla, 2011). In Beijing, for example, an average taxi emits nearly 10 times as much as a private car (Beijing Transport Institute, 2011). As part of a drive to cut air pollution, the Beijing municipal government has announced its plan to replace all 67,000 conventional taxis in the city with BEVs (Hanley 2017). This changeover will take place over time with a mandate that all newly added and replaced taxis in the city must be battery-powered. While this plan shows the city's ambitions to improve air quality with BEVs, the proliferation of the technology still requires efficient recharging infrastructure.

Charging concerns remain an obstacle for fleets even with fast charging; current fast charging speeds cannot compete with gasoline refueling and are thought to reduce the battery's lifespan (Rezvanizaniani et al., 2014). Battery swapping, on the other hand, could be a viable option to solve the charging conundrum. This technique entails rapidly replacing – rather than slowly charging – depleted batteries with charge-ready substitutes. As the company Better Place demonstrated earlier (George, 2013), with specially designed BEVs and appropriate infrastructure, such 'swaps' can be achieved in a few minutes (Bullis, 2011), making this technology appealing to a dense closed system like the taxi industry where downtime minimization is crucial to business viability. In 2016, the world's largest network of battery swapping stations commenced operation in Beijing, China (BJEV, 2016). BAIC BJEV (a new energy subsidiary of Beijing Automotive Group) established the alliance, cooperating with Sinopec Beijing (an oil and gas company) to commercialize battery swapping services. BAIC BJEV started implementing the idea in a taxi fleet, building up a solid prototype in the close-collaboration network as the first step before trying to expand a capital-intensive battery swapping network. As the supporting infrastructure comes to maturity, BAIC BJEV plans to expand its swapping business to car-sharing, car-hailing, and ultimately to private vehicle markets (Li, 2016).

Published literature on battery swapping focuses on operation scheduling and infrastructure planning (Mak et al., 2013; Rao et al., 2015; Sarker et al., 2015; Y. Wang et al., 2015), while research on electric taxis centers more on aspects of charging stations optimization (Tu et al., 2016; Z. Tian et al., 2016), service pricing (Liang and Zhang, 2018; N. Wang et al., 2015), environmental benefit compared to gasoline taxis (Cai and Xu, 2013; Shi et al., 2016), and charging behaviors (Rao et al., 2018; Zou et al., 2016). However, few economic evaluations have been conducted that compare fleet operating costs across various energy replenishment modes—BEV fleet with charging or battery swapping and ICEV fleet with gasoline refueling. A BEV taxi system was claimed to have higher gross cost in the battery swapping mode than in the charging one owing to the higher fixed equipment/construction cost (Liu et al., 2018); but, this statement may not hold true if the achievable throughput of infrastructure is considered.

Consequently, our work examines - for the first time to our knowledge - the cost competitiveness of swappable battery technology against BEV charging activities, accounting for the throughput of the fleet network. With an aim to accelerate the urban transformation toward sustainability, this paper identifies cost-effective options for emission-free taxi service networks. We conduct a techno-economic analysis to investigate the extent to which battery swapping addresses the recharging time concerns surrounding the adoption of BEVs by fleet operators, using the real-world financial data in Beijing. We also propose an alternative business operation that double-shift electric taxis could run with to deliver the same number of passenger trips as gasoline taxis. We explore whether any of the proposed BEV recharging business models can achieve cost parity with existing ICEV based system, and how the outcomes change if improving battery technology and the government supports/interventions are considered. We conclude by stating some implications for policymakers seeking to facilitate the transition to electric mobility.

2. Method & Data

We begin this section by first defining the business models that are explored in this study. Secondly, we identify the cost components considered in the combined ecosystem of taxi operations and the recharging systems. Lastly, we present the framework for per-kilometer cost evaluation.

2.1 Business models

1) *BEV fleet with conventional Level 2 charging*

In this scenario, the taxi fleet relies on a network of Level 2 chargers. The Level 2 chargers have an assumed rate of 7 kW[1] and, as discussed below, this delivers about 44 km driving range per hour of charging. Unless otherwise stated, we assume that with this and other business models, the driver stays with the taxi during recharging, similar to how current taxi fleets using gasoline-powered vehicles operate. For taxis that run single 12-hour shift per day, although most of the Level 2 charging can be done while the driver is not working, they still need to temporarily halt operations for a few hours mid-day for partial energy replenishment to deliver the same number of passenger trips in their daily shift. For taxis with double shifts (i.e., two 12-hour shifts), a much larger taxi fleet is needed to meet customer demand since each taxi spends a lot of time off the road recharging.

2) *BEV fleet with Level 2 charging with extra vehicles*

In this scenario, the fleet avoids long idle time associated with Level 2 charging by having a sufficient number of charged and readily available vehicles. The driver can go to a charging depot and switch to a fully charged vehicle when the taxi runs low on charge. This strategy is important

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[1] In Beijing, 7 kW is the most common Level 2 charging rate in public charging stations (Wang, 2016).

for taxi drivers who operate in multiple shifts and always need to be on the road generating revenue. Currently, double-shift ICE-powered taxis in Beijing operate an average of 570 km per day to meet consumer demand[2]. If the double-shift taxi business is relying on Level 2 charging, the time needed to recharge for 570 km is 13.2 hours. In this business model, the taxi company purchases several extra vehicles, and always has a rotation of vehicles being charged. Therefore, the idle time (or opportunity costs) associated with Level 2 charging times is minimized. To keep the same number of double-shift taxis on the road generating revenue, the fleet needs to be 1.55 times as large as a conventional double-shift taxi fleet (0.55 = 13.2 hours/24 hours).

Note that we do not consider single-shift taxis with extra vehicles case for simplicity and also for the following reasons. Firstly, current Beijing single-shift taxis are always single driver with one vehicle; only that one driver is authorized to drive each taxi. It would be convenient for the driver to have a second taxi to avoid the need to stop mid-day to recharge, but the capital expense for the additional vehicle, which would have very low utilization[3] makes this option infeasible. Secondly, the extra vehicle would be shared among several drivers, but only be on the road for 12 hours/day. This is out of consideration because if vehicle sharing is already part of the fleet

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[2] From the fact that 60% of Beijing taxis run single shift and the rest 40% work double shifts (Lee, 2013), we infer that the average operating hours a day is 16.8 hours. Assuming a taxi travels 400 km daily (Lee, 2013), the distance driven per active hour of taxi time is estimated to be 23.8 km/hr (=400 km/16.8 hr). This suggests that the daily distance driven is about 285 km for single-shift taxis and 570 km for double-shift taxis.

[3] Assuming that a fully-charged taxi can go 208 km (=260 km×(100%-20%)) before it needs another charge (see footnote 4), an extra vehicle for single-shift taxis would only have to provide 77 km (=285-260 km) to satisfy the consumer travel demand (note that an average distance traveled per day for single-shift taxis is 285 km).

arrangement, this sub-optimal operation (as opposed to double-shift taxis with extra vehicles) is not economically justifiable.

3) *BEV fleet with conventional fast charging*

In this scenario, the fleet relies upon a network of fast chargers. The fast chargers are assumed to charge a BEV from 20% to 80% in 22.5 minutes; another 30 minutes is required to charge from 80% to 100%.

4) *BEV fleet with fast charging with extra vehicles*

Similar to the scenario of Level 2 charging with extra vehicles, we only consider double-shift taxis in this case. The fleet avoids idle time associated with fast charging by having a sufficient number of charged and readily available vehicles. The time that must be spent recharging each day, in order to travel 570 km/day, using a fast charger is about 2.4 hours. So to keep the same number of double-shift taxis on the road double-shift fleet needs to be 1.1 times larger than a conventional double-shift fleet (0.1 = 2.4 hours/24 hours).

5) *BEV fleet with battery swapping*

In this scenario, the fleet relies upon battery swapping stations to replace depleted batteries with fully-charged batteries within a few minutes (about the same time required to refuel a gasoline vehicle). Battery recharging rate and battery stock quantity determine the maximum number of fully charged batteries a swapping station can provide each day. Based on the commercialized battery swapping services in Beijing, battery swapping stations are assumed to have 28 swappable batteries in stock and host 28 chargers (BBTNews, 2017), each with 1/3 C rate (i.e., three hours for a full charge), used to charge the swapped-out batteries with remaining 20% state of charge[4]; this implies that each swapping station, ideally, can provide about 280 swaps per day, about one fully charged battery every five minutes.

6) *ICEV fleet with gasoline refueling*

This is a business-as-usual scenario in which the taxi fleet uses ICE-powered vehicles and replenishes the vehicle energy within a few minutes via gasoline refueling.

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[4] Zou et al. (2016) showed that the majority of the electric taxis drivers in Beijing charge their cars when the available driving range drops to about 55 km. Thus, we assume that battery's state of charge at the start of charging events is 20% (~55 km/260 km) and end up with 100% across all the business models in this study.

2.2 Cost components

We examine the value proposition of various business models through the lens of applicable expenditures. These include vehicle procurement, battery, extra battery, electricity, recharging system, land, maintenance, labor, opportunity, and gasoline refueling costs, each of which are fully described in this section. Table 1 shows a list of governing parameters applied in our investment appraisal for the taxi business; the exchange rate for USD/Yuan is set to be 6.32. BAIC BJEV EU260 is chosen as the representative BEV taxi due to its capability to be delivered either for battery swap mode or BEV charging modes (Autohome.com, 2018).

1) *Vehicle procurement cost* is the upfront cost to purchase a base car (i.e., BEV without battery). The battery cost is separately taken into account in its own category.
2) *Battery cost* accounts for battery usage for delivering kilometers and is determined by the battery's cycle life, degradation, production volume, and mechanical complexity. Cycle life is the number of complete charge/discharge cycles a battery can support before its capacity falls below 80% of the charge envisioned by the manufacturer. Today, a standard BEV battery warranty covers 150,000 km. Presumably, the warranty is quite conservative; most BEV batteries will actually last significantly longer. We assume that the warranty includes a factor of 2 safety factor, so an average battery is assumed to last about 300,000 km with Level 2 charging before it needs to be replaced (sensitivity analysis is performed to address the uncertainty in this safety factor assumption; see Section 3.1.3). For the business case using the swapping technique, we assumed its lifetime is the same as that of Level 2 charging; this is because, according to the swap station designers, swappable batteries are charged in the optimal condition (i.e., constant humidity and constant temperature), and thus the battery life can be maximized (Aulton.com 2019). However, if the battery is routinely charged using a fast

charger, its lifetime would be degraded by 20% to 30% (Rezvanizaniani et al., 2014). We assume that average battery with fast charging lasts for 225,000 km (i.e., degradation by 25%) before it needs to be replaced.

Due to the lower production volume and higher mechanical complexity, a swappable battery pack cost was reported to be $383/kWh in a BEV with the model year (MY) 2017 (BBTNews, 2017), being ~$95/kWh more expensive than more widely produced non-swappable batteries[5]. Battery prices are expected to drop significantly over the next decade as production volumes increase (Hsieh et al., 2019). This incremental cost of $95/kWh is also expected to decrease as the battery swapping scale increases in the future.

3) *Extra battery cost* is the capital investments for the batteries in the extra vehicles and for the battery inventory in the swapping stations.
4) *Electricity cost* quantifies the electrical expenditures associated with charging batteries. The current commercial electricity price during the normal time period (aka. non-peak and non-off peak) in Beijing is used in our analysis ($0.135/kWh) and charging efficiency is assumed to be the same across different BEV recharging options.
5) *Recharging system cost* monetizes the costs (excluding land) associated with building a recharging system. These costs include building construction, charging mechanism procurement and associated installation. The cost of running power lines to the charging station is not included; it is assumed this is covered by the electricity cost. The cost of a fast charger is about 20 times as much as a Level 2 charger (Wang 2016). The recharging system costs of battery swapping stations do not include the expensive battery inventory requirement (28

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[5] We use a lithium-ion battery pack price of $288/kWh in 2016 to represent the non-swappable battery cost in a BEV with MY 2017 (Hsieh et al., 2019).

swappable batteries are assumed in this study) (Zhou 2016), which is considered in the extra battery cost category.

6) *Land cost* quantifies expenditures for the land used for rechargers. For BEV charging alternatives (i.e., Level 2 and fast charging), the land/vehicle ratio is similar to that of a parking garage (d1ev.com, 2017). Battery swapping stations require larger space for higher swappable battery housing requirement – an inventory of 28 swappable batteries and 28 chargers (BBTNews, 2017). However, since each vehicle spends only a few minutes at the swapping station, the land requirement per vehicle in the fleet is much less than the other recharging options. A swapping station's land/vehicle supported ratio[6] is about half as much as a fast charger and only one-tenth as much as needed for a fleet using Level 2 chargers.

7) *Maintenance cost* is the cost associated with maintaining the charging/swapping station. The annual maintenance costs are assumed to be 10% of recharging system costs (Chang et al., 2012; Kearney, 2011).

8) *Labor cost* is the drivers' revenue when operating on the roads. In Beijing, taxi drivers pay taxi companies a monthly fee to "rent" the vehicles. The operating revenue (before deducting the costs) for a taxi in Beijing was shown to be 34.5 ¢/km, and about 62% of which is for taxi driver[7] while the rest 38% is for taxi companies (Lee, 2013). Therefore, this study uses 21.4 ¢/km as a per-km labor cost to taxi companies for operating taxis on the roads. Note that the labor cost while recharging is taken into account separately, in the opportunity cost category, as discussed below.

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[6] Land/vehicle supported ratio is defined as the land use per vehicle actively charging; parameters are shown in Table 1.

[7] Note that the taxi drivers *net* earnings in Beijing are the revenues minus the sum of the monthly rent fee to the taxi company, the operating fuel costs, and the vehicle maintenance costs.

9) *Opportunity cost* is the operating revenue lost by a taxi company owing to the idle time that taxis and drivers spent on recharging/refueling. These costs exclude fluctuations in consumer demand based on time of day and days of the week.

10) *Gasoline refueling cost* represents the business-as-usual gasoline taxi energy replenishment cost, which is computed using the retail gasoline price in Beijing.

Table 1. Governing parameters used in the study and the sources

Parameter	Value	Source
BEV Model (BAIC BJEV EU260)		
MSRP ($)	32,600	(Autohome.com, 2018)
Fuel Economy (kWh/100 km)	15.9	
Battery Capacity (kWh)	41.4	
Driving Range per Full Charge (km)	260	
ICEV Model (BAIC Senova D50)		
MSRP ($)	15,340	(Autohome.com, 2018)
Fuel Economy (on-road) (L/100 km)	7.5	
Driving Range per Full Refuel (km)	670	
Retail Gasoline Price ($/L)	1.14	(chemcp.com, 2018)
Refueling Time for 536 km (gas tank from 20% to 100%) (Minutes)	4	Assumption
Taxis in Beijing		
Fleet-Average Daily Distance Driven (km)	400	(Lee, 2013)
Distance Driven per Active Hour of Taxi Time (km/hours)	23.8	(Lee, 2013); footnote 2
Vehicle Lifespan (Year)	6	(MOT, 2015)
Annual Productivity (Days)	350	(Beijing Jiaotong University, 2016)
Operating Revenue (¢/km)	34.5	(Lee, 2013)
Labor Cost (¢/km)	21.4	
Discount Rate for Cost of Capital (%)	5	(PBC, 2018); Chinese central bank's interest rate for long-term (i.e., more than five years) loans.
Recharging Vehicle Attributes		
Changes in State of Charge (%)	20 - 100	(Zou et al., 2016); footnote 4
Range per charge (km)	208	Assumption

Recharging System Attributes[8]		
Level 2 Charging Rate (kW)	7	(Wang, 2016)
Fast Charging Rate (kW)	45	
Swap Station Battery Inventory (#)	28	(BBTNews, 2017)
Swap Station Battery Charging Rate (kW)	14	Assumption
Recharging Time with Level 2 for 208 km (Hours)	4.8	Estimation based on the parameters shown in Recharging Vehicle/System Attributes
Recharging Time with Fast Charge for 208 km (Minutes)	52.5	
Recharging Time with Swapping for 208 km (Minutes)	5.1	
BEV Charging Land Use (m^2/plug)	25 - 40	(d1ev.com, 2017; Wang, 2016)
Level 2 Charging System Cost ($/plug)	820 - 1,300	
Fast Charging System Cost ($/plug)	16,300 - 24,200	
Swap Station Land Use (m^2/station)	150 - 200	(BBTNews, 2017)
Swap Station Cost ($/station)	997,400	
Battery Inventory Cost ($/station)	443,970	
Recharging System Lifespan (Years)	8	Assumption
Unit Land Use Cost ($/$m^2$)	3,530	(Yang, 2017)
Land Use Lifespan (Years)	40	
Electricity Cost ($/kWh)	0.135	(Beijing Municipal CDR, 2018)
Battery Parameters		
Non-swappable Battery Cost (Car Model Year 2017) ($/kWh)	288	(Hsieh et al., 2019)
Swappable Battery Cost (Car Model Year 2017) ($/kWh)	383	(BBTNews, 2017)
Level 2 Battery Cycle Life (Cycles)	1,155	Assumption based on the battery warranty.
Fast Charge Battery Cycle Life (Cycles)	865	(Rezvanizaniani et al., 2014); 25% lower than that of Level 2 charging
Swappable Battery Cycle Life (Cycles)	1,155	(Aulton.com, 2019); swappable battery lifespan is maximized because being charged in an optimal condition.

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[8] Uncertainties in the recharging system attributes (i.e., land use and system cost) are assumed to be uniformly distributed over the range; a Monte Carlo cost model is run with 1,000 runs for each of the business cases and the resulting mean values are presented in Results & Discussion (section 3).

2.3 Conversion into per-kilometer costs

To assess the cost-effectiveness across the business models, each cost component is transformed to be on a per-kilometer (per-km) basis by applying conversion factors. Conversion factors vary depending on the cost component and the achievable throughput of the recharging systems. To combine upfront investments and operating costs into a single number, we distributed all costs over all kilometers by using a 5% discount rate to determine the cumulative costs per kilometer. The calculation framework is demonstrated in Table 2, and the governing equations are shown in Supplementary Information (SI.I). Each vehicle/trip served corresponds to a driving range of 208 km. For the cost components of recharging facility (including recharging system, land, maintenance, and battery inventory in swapping stations), an annual number of vehicles served is determined by 1) recharging times and 2) utilization factor that captures the real-world efficiency discounts related to infrastructure utilization. On the other hand, for the cost components of vehicle (including vehicle procurement and batteries in the extra vehicles), annual number of trips served is determined by 1) recharging time, 2) active hour of taxi time per charge (i.e., operating hours for 208 km), and 3) utilization factor that describes how intensively a vehicle is used. Recharging times with Level 2 charger, fast charger, and battery swapping for 208 km are indicated in Table 1. An active taxi drives 208 km in 8.74 hours on average (= 208 (km)/ distance driven per active hour of taxi time (km/hours) = 208/ 23.8). Utilization factors are different between single-shift and double-shift taxis, as explained below (see SI.I for more details):

- Vehicle: utilization factor for a vehicle is determined by the vehicle usage intensity; single-shift taxis would have lower vehicle utilization factor and so higher per-km vehicle procurement cost compared to double-shift taxis.

- Recharging facility: utilization would be very poor in single-shift BEV fleet relying on the conventional Level 2 charging. We expect that there would be one Level 2 charger for each single-shift taxi, but that charger would only be used for 4.8 hours at night (reaching full charge, 208 km of useful driving distance) plus another 1.8 hours mid-day (for 77 km), so the utilization factor would be only 27%.

  On the other hand, recharging behaviors of single-shift taxis working with fast chargers are uncertain; one would think that all the single-shift taxis would like to charge at the end of the day or early in the morning, but there will not be enough plugs at those peak hours. The ideal case would be fast chargers being uniformly used during the workday (i.e., 12 hours active hours plus recharging times for 285 km), and thus the utilization rate of fast chargers would be 55% at best. For single-shift BEV taxis relying on battery swapping, we expect that they will not use swap stations in the middle of the night. In the case that all BEV taxis use swap stations uniformly during the workday, the utilization would be about 50% at best. Because of real-world recharging scheduling problems and downtime for maintenance, the infrastructure utilization rate needs to be discounted further. Assuming there is an efficiency discount of 30% in reality even for an ideal recharging system, for single-shift taxis we estimate the utilization rate for recharging facilities could only achieve 39% and 35% in the conventional fast charging and battery swapping modes, respectively. In contrast, utilization factors (or utilization rates) for recharging facilities would be much higher for a double-shift BEV fleet: we assume 90% for conventional BEV charging modes, and 80% for BEV charging with extra vehicles and battery swapping modes[9].

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[9] The recharging facility would be more heavily utilized when the time duration for each charge is longer (and thus the required number of coordinated BEV charging activities is fewer per day per plug).

Table 2. A framework to transform cost components into per-kilometer (per-km) costs; labor cost data is provided on a per-km basis, so no conversion factor is needed. Equations for per-km cost evaluations are detailed in Supplementary Information I.

Cost Component	**Conversion Factor**
Recharging System, Maintenance, Land, Extra Battery (for swappable battery inventory)	Annual number of vehicles served $\sim f$(recharging time, utilization factor for recharging facility)
Vehicle Procurement, Extra Battery (for extra vehicles)	Annual number of trips served $\sim f$(recharging time, active hours of taxi time, utilization factor for vehicle usage)
Battery	$\sim f$(per-kWh battery cost, battery cycle life)
Electricity	$\sim f$(battery capacity, driving range)
Opportunity	$\sim f$(distance driven per active hour of taxi time, recharging time)
Gasoline Refueling	$\sim f$(fuel economy)

3. Results & Discussion

3.1 Cost competitiveness comparison

Figure 1 presents the costs on a per-km basis across various BEV recharging modes for taxis with single and double 12-hour shifts, and compares these with the existing gasoline taxi system. The aggregation represents the total costs per kilometer incurred by taxi operators to run a fleet. It is noted that we do not aim to include all cost components of the taxi business but rather, major expenditures. The key observations are highlighted as follows:

3.1.1 Cost breakdown

Firstly, labor cost is the most significant cost contributor, accounting for up to 68% of the total per-km costs in China’s taxi business; we expect that the cost contribution from labor would be even higher in other well-developed countries. Secondly, per-km battery costs for the fast charging business models are higher than the Level 2 charging cases due to the higher degradation rate and thus shorter battery cycle life. However, per-km battery costs are comparable between fast charging and battery swapping even though battery lifespan in the latter is longer than the former; this is because the swappable batteries are more expensive per-kWh than mass-market non-swappable batteries. Thirdly, electricity costs on a per-km basis are the same among all scenarios, results from the assumption that electricity costs per kWh and charging efficiency are homogeneous across all the BEV recharging modes. However in reality, the electricity costs for fast chargers may be higher than the others due to the lower charging efficiencies (i.e., higher losses) from fast charging and potential demand charges (Chlebis et al., 2014).

And fourthly, per-km vehicle procurement (i.e., BEV without battery) costs are the same across different recharging modes for single-shift taxis because those BEVs—regardless of recharging options—are all able to deliver 285 km per day. However, these costs are various depending on the recharging options for double-shift taxis; vehicles relying on battery swapping can deliver higher number of trips per year than those using fast/ Level 2 chargers, causing per-km vehicle procurement cost in the swapping option to be the least, followed by the fast charging cases and then the Level 2 charging cases. We observe that per-km vehicle procurement costs are the same between conventional BEV charging scenarios and BEV charging with extra vehicles scenarios; this is due to the fact that the increased vehicle fleet size would not only increase the upfront costs but also increase the vehicle usage utilization rate (see SI.I for more details). Finally, opportunity costs associated with the recharging times are nonnegligible when the taxis are relying upon conventional BEV charging (without extra vehicles), especially for those running double shifts per day. Note that the impacts of fluctuations in consumer demand on per-km opportunity cost are ignored due to data availability. But in reality, we can expect that the operating revenue lost due to the recharging time should be higher during periods of high demand in the day.

3.1.2 Total cost

For single 12-hour shift taxis (Figure 1(a)), most of the BEV recharging activities can be done when the drivers are not working. But since a taxi can only go 208 km for each charge, and single-shift taxis drive farther than that each day, the driver has to stop mid-day to get another (partial) charge. The idling time (or opportunity costs) for recharging[10] in the middle of a shift makes the conventional Level 2 charging mode at least 21% more expensive than the alternative BEV

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[10] Single-shift taxis are expected to spend shorter recharging times on partial (instead of full) charge for another 77 km (=285-208 km) in middle of their daily shift. The opportunity costs of charging that 77 km are amortized across 285 km when we calculate per-km opportunity cost for single-shift taxis.

business models, so it is not economically attractive. On the other hand, the conventional fast charging and battery swapping options are found to be cost comparable to each other at present (the difference is within 3%), but single-shift BEV fleet relying upon fast chargers is expected to reach cost parity with ICE sooner (as discussed below).

For double-shift taxis (Figure 1(b)), conventional Level 2 charging with drivers idling during the time it takes to fully recharge the BEVs would not work. To meet customer demand, the taxi company could increase the size of the vehicle fleet. Although imposing higher upfront capital costs for the extra vehicles than the conventional Level 2 case, the Level 2 with extra vehicles scenario dramatically improves the cost-effectiveness of double-shift BEV taxis by mitigating the idle time associated with slow charging, and even makes this business model a more attractive option than conventional fast charging, despite the latter boasting an 82% shorter charging time. However, these aforementioned scenarios (i.e., conventional Level 2, Level 2 with extra vehicles, and conventional fast) are all significantly more costly (by 11% - 64%) than the existing ICE-powered double-shift taxis. To make BEV taxi ecosystems more appealing to fleet owners running with multiple shifts, more efficient recharging alternatives are needed. Obtained results reveal that the fast charging with extra vehicles and the battery swapping scenarios are the two most economical business models among all the electrified energy replenishment options.

An important finding here is that battery swapping emerges as one of the least costly options on a per-km basis for both single-shift and double-shift taxis, although it imposes high aggregate upfront costs for its battery inventory requirement. Its fiscal attractiveness is mainly due to a swapping station's ability to serve 10 times as many BEVs as a fast charger and 56 times as many BEVs as a Level 2 charger. Despite the BEV taxis ecosystem still being more costly than the business-as-usual ICEV fleet at the moment, these incremental costs will be shrinking as the battery costs drop in the future. We assume that the cost difference between swappable battery and non-swappable battery (i.e., $95/kWh in 2017) would follow the same learning rate that was found in non-swappable battery production (Hsieh et al., 2019), decreasing over time when the scale of battery swapping increases. Based on BAIC BJEV's timeline for their swapping service deployment[11], we estimate that when the non-swappable battery cost for car MY 2022 is $176/kWh (Hsieh et al., 2019), the swappable battery cost will be around $220/kWh. These cost improvements in batteries will drive the BEV taxi ecosystem recharged by either battery swapping (for double-shift taxis) or fast chargers (conventional fast for single-shift and fast with extra vehicles for double-shift taxis) to achieve cost competitiveness with the existing ICE-powered system in Beijing in 2022.

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[11] There was about two-year time delay between BAIC BJEV's first stage—100 swapping stations and 4,000 vehicles being in operation—in Optimus Prime Plan and their actual battery swapping service implementation (bjev.com.cn, 2019; China Energy Storage Alliance, 2017). Hence, we expect and assume that the second stage—1,000 swapping stations and 100,000 vehicles—will not be completely fulfilled until 2022 (two years later from the planned schedule). This production expansion is estimated to reduce the cost difference between swappable batteries and non-swappable batteries to $44/kWh.

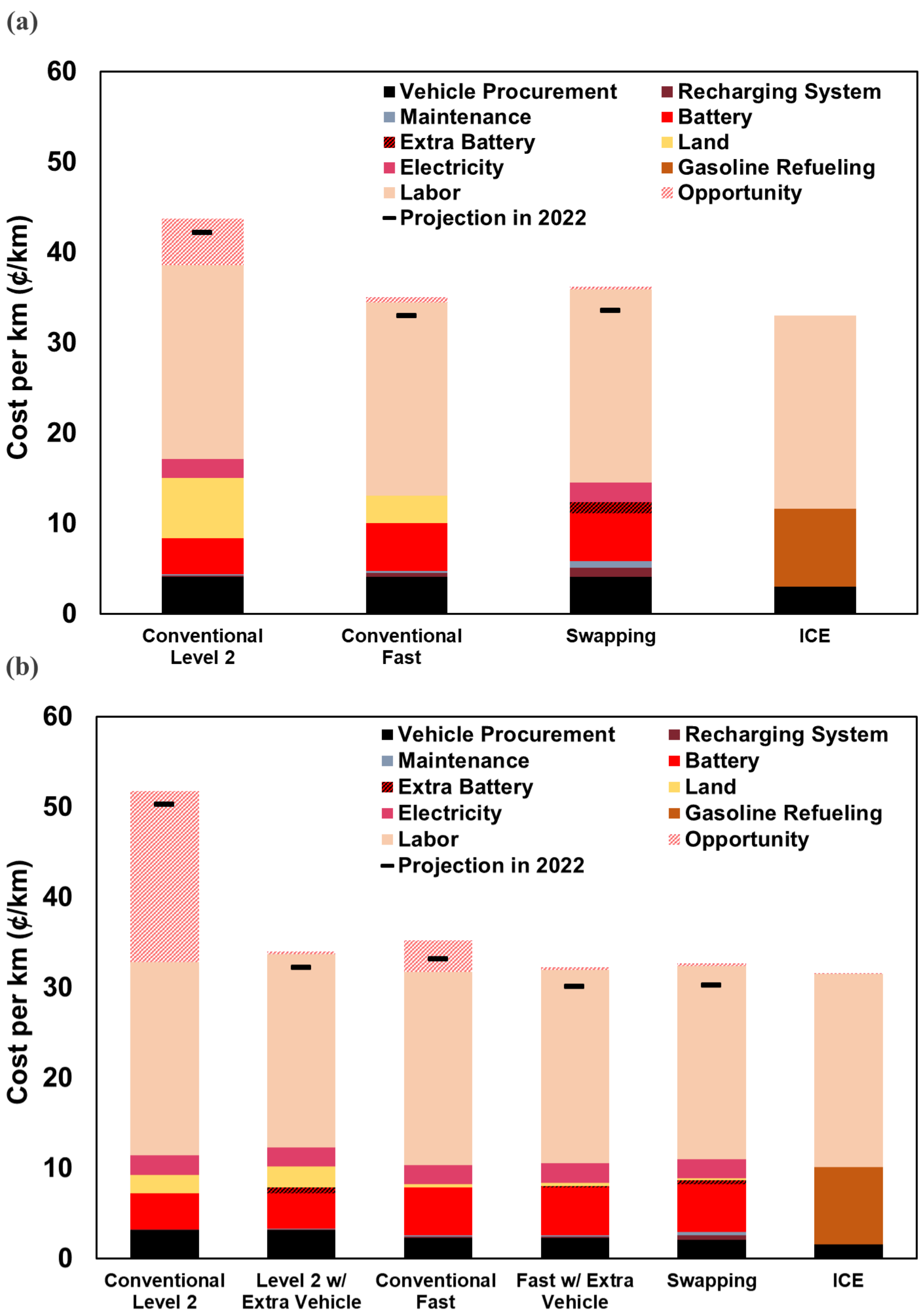

Figure 1. Cost breakdown per kilometer of different recharging/refueling options for (a) single-shift taxis and (b) double-shift taxis using the financial numbers in Beijing. For electric taxis with double shifts to meet consumer demand, a larger vehicle fleet is needed if

they rely on conventional BEV charging, since a significant fraction of the taxis will be out of service (recharging).

3.1.3 Sensitivity analysis

The total cost comparisons presented above (Figure 1) rely on a number of parameters (Table 1). We use a tornado diagram (Figure 2) to illustrate how the cost ratios (i.e., BEV taxi ecosystems relative to ICE-powered taxi system) are conditioned by the assumptions. The major parameters here are battery cost, battery cycle life, equipment life, electricity cost, gasoline price, annual maintenance cost, and discount rate. For brevity, we focus only on the sensitivity of per-km costs for double-shift taxis (excluding conventional Level 2 charging option that is not feasible) to the assumptions. The sensitivity range for each variable is based on the low and high values provided in SI.II. The governing parametric values from Table 1 are used to calculate the base of the tornado diagram (grey vertical lines in Figure 2).

Figure 2 shows that the three variables with the largest impact on the per-km cost ratios are gasoline price, battery cycle life, and battery cost. It is noted that higher gasoline prices and longer battery cycle life correspond to a lower cost ratio. The sensitivity analysis reveals several findings. Firstly, the cost competitiveness of per-km cost for ICEV and BEV taxis is highly dependent on location. This is because gasoline price varies widely across countries. Compared to the U.S. (with gasoline price of \$0.77/L), many countries levy substantially higher fuel taxes for multiple reasons—including energy security, local air pollution, climate change, and government revenue. BEV taxis are found to be already financially more attractive than ICEV taxis in countries with very high gasoline tax such as Norway (with gasoline price of \$2.28/L). Secondly, even doubling battery cycle life (i.e., doublling safety factor for battery warranty—from 2 to 4) or reducing battery cost by half, BEV taxi ecosystem could not achieve cost parity with ICEV taxi system unless with the business models of either battery swapping or fast with extra vehicles. Thirdly, electricity price is also an important factor even having less influence on the per-km cost ratio than the top three variables. Low electricity prices could make an electrified taxi fleet relying on the right recharging systems/operations on par with their gasoline-powered counterparts.

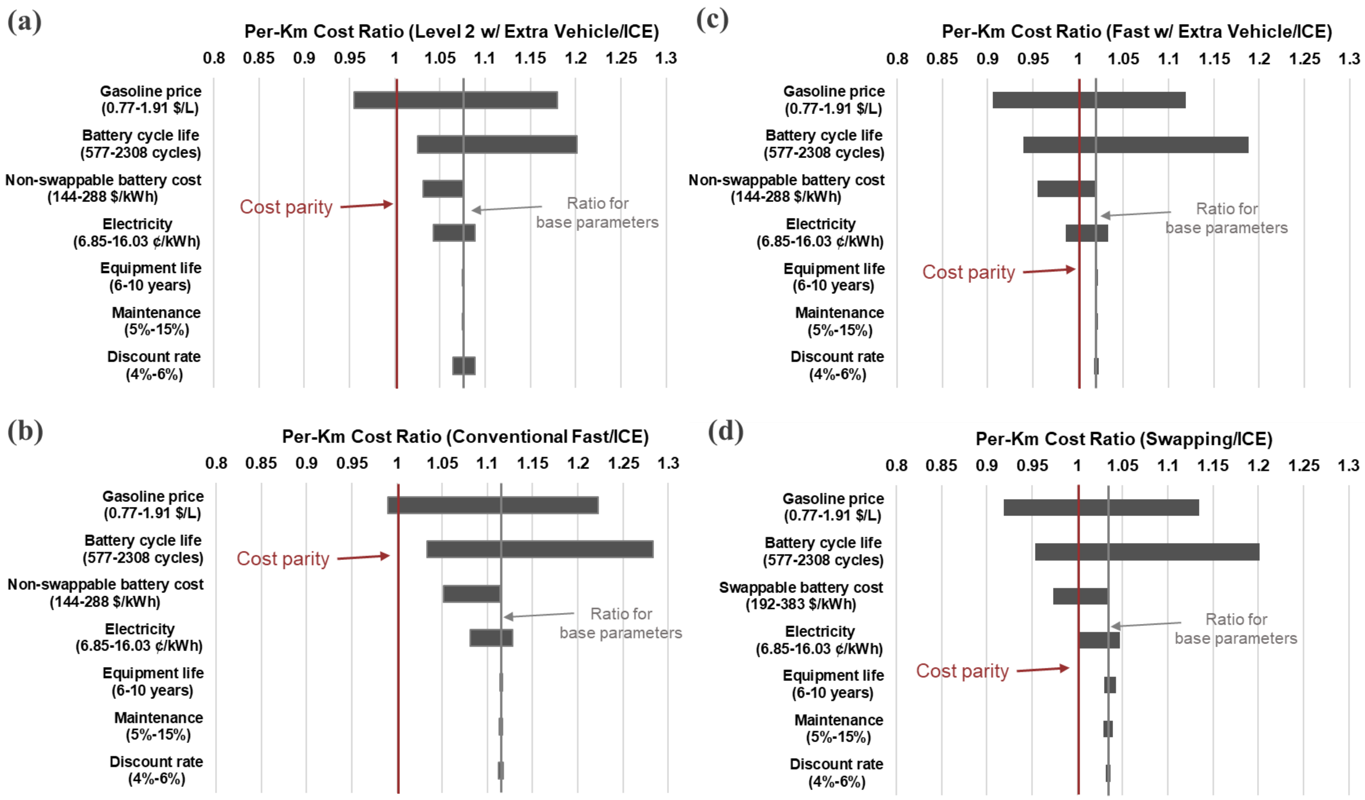

Figure 2. Sensitivity of per-kilometer cost ratios of double-shift BEV taxi ecosystem relying on (a) Level 2 charging with extra vehicle; (b) conventional fast charging; (c) fast charging with extra vehicle and (d) battery swapping relative to ICE-powered taxi system with respect to major parameters.

3.2 Policy analysis and implication

Currently, BEV taxi ecosystems – independent of recharging options – are more expensive than existing ICE-powered systems. Yet, gasoline consumption is associated with numerous negative externalities: reduced energy security, increased greenhouse gas emissions and diminished quality of life and public health due to local air pollution. To achieve environmentally sustainable ground transportation, local governments are taking a variety of actions to accelerate the adoption and use of electrified vehicles. In several cities all or a portion of the taxi fleet has been mandated to be electrified; this with present-day economics typically reduces net revenue by the taxi fleet or requires an increase in fares paid by passengers, though as shown above this economic impact is expected to become much smaller or vanish entirely in the next decade. In this section, we discuss some government policies that could be utilized to close the cost gaps between the proposed BEV fleet alternatives and the existing ICEV fleet system.

3.2.1 Purchase subsidy

Procurement subsidies are the most common policy employed by national governments – particularly in China – to incentivize widespread BEV adoption. In 2017, the central and Beijing municipal subsidies for electric taxi operators totaled up to about $18,370 per vehicle[12], the use of which puts BEV taxi purchase costs on par with their gasoline-powered counterparts (Beijing Municipal Government, 2015). Thanks to the government's financial assistance, a subsidized electrified fleet is already per-km cost comparable to ICEV fleet, if they rely upon fast chargers

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[12] The first-stage subsidy for general BEV purchase is linked to the driving range (e.g., about $10,450 for range greater than 250 km in Beijing, 2017). On top of that, there was a second stage of financial incentives for electric taxis in 2017 to cover the remaining cost gap between BEVs and counterpart ICEVs, which was up to $7,916 (=50,000 Yuan).

(conventional fast for single-shift and fast with extra vehicles for double-shift taxis) or battery swapping techniques (for double-shift taxis). Although Level 2 with extra vehicles business model particularly benefits from BEV purchase subsidies because of its largely increased size of the vehicle fleet, it still cannot become economically favorable. The magnitude of this benefit varies according to BEV recharging options, as summarized in SI.III. However, paying subsidies puts strains on government budgets and is not a sustainable expenditure policy for achieving the goal of high electrification of transportation.

3.2.2 Gas tax

Instead of paying subsidies, an alternative policy instrument that could be implemented to stimulate BEV adoption by fleet owners is raising a gas tax to fund BEV recharging infrastructure in a revenue-neutral manner. It was demonstrated that people would be more likely to accept a gas tax increase if they understood that the extra revenue would be used for energy efficiency (Kaplowitz and McCright, 2015). While raising a gas tax would affect the whole car market (not specific to the taxi industry), this will have a much more significant effect on taxis than private cars because taxis consume much more fuel. We estimate that a 10% increase in retail gasoline price or 22% increase in gasoline tax (i.e., \$0.11/L increase) would increase the cost/km of an ICEV taxi fleet by 3%; the gas tax needed to close the cost gap between ICEV and BEV fleet is discussed below (Figure 3). Raising a gas tax (which internalizes the negative externalities of gasoline consumption) diminishes the current cost advantage hold by ICEV fleet and also generates extra revenue that the government can direct toward promoting an electrified transportation system. Government support that scales up battery production volume, is key to driving the cost of batteries down, making them more economically competitive.

While shifting to the electric fleet ecosystem would impose a heavy burden on taxi business owners during the transition period, the per-km cost differences between BEV taxi (with the most economical recharging options) and ICEV taxi are marginal and will drop further as the battery production increases. Figure 3 depicts the additional gas tax (relative to China's gas tax level of about 50¢/L (Shih, 2015)) needed to cover the incremental cost incurred due to the fleet electrification, given the various conditions of battery cost. Although BEV taxi fleet relying upon fast chargers (conventional fast for a single shift; fast with extra vehicles for double shifts) requires minimum extra gas tax imposition compared to the other options in 2017, we find that per-km cost of battery swapping will improve at an even faster rate when the battery costs drop. We compute that when the non-swappable battery cost decreases to $250/kWh (/$220/kWh) or the swappable battery cost drops to $310/kWh (/$180/kWh), double-shift (/single-shift) BEV taxi ecosystems relying on fast charging with extra vehicles (/conventional fast) or battery swapping will achieve cost parity with the existing ICEV taxi system. On the other hand, electric taxis recharged by conventional Level 2 or conventional fast chargers without extra vehicles are very unlikely to become economically favorable to fleet owners in the next decade unless being strongly supported by a high gasoline tax[13]; this finding highlights the importance of supporting the right business models in order to accelerate the fleet transition to electric drive.

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[13] Our previous study predicted that the non-swappable battery pack price would fall to about $124/kWh by 2030 (Hsieh et al., 2019). By incorporating the battery price projections with the gas tax analysis, we find that double-shift BEV fleet relying on Level 2 charging with extra vehicles will be cost-competitive with ICEV in 2030. However, double-shift (/single-shift) BEV fleet relying on conventional fast (/conventional Level 2) will still need a 16% (/223%) increase in the gas tax to reach cost parity with an ICEV taxi fleet.

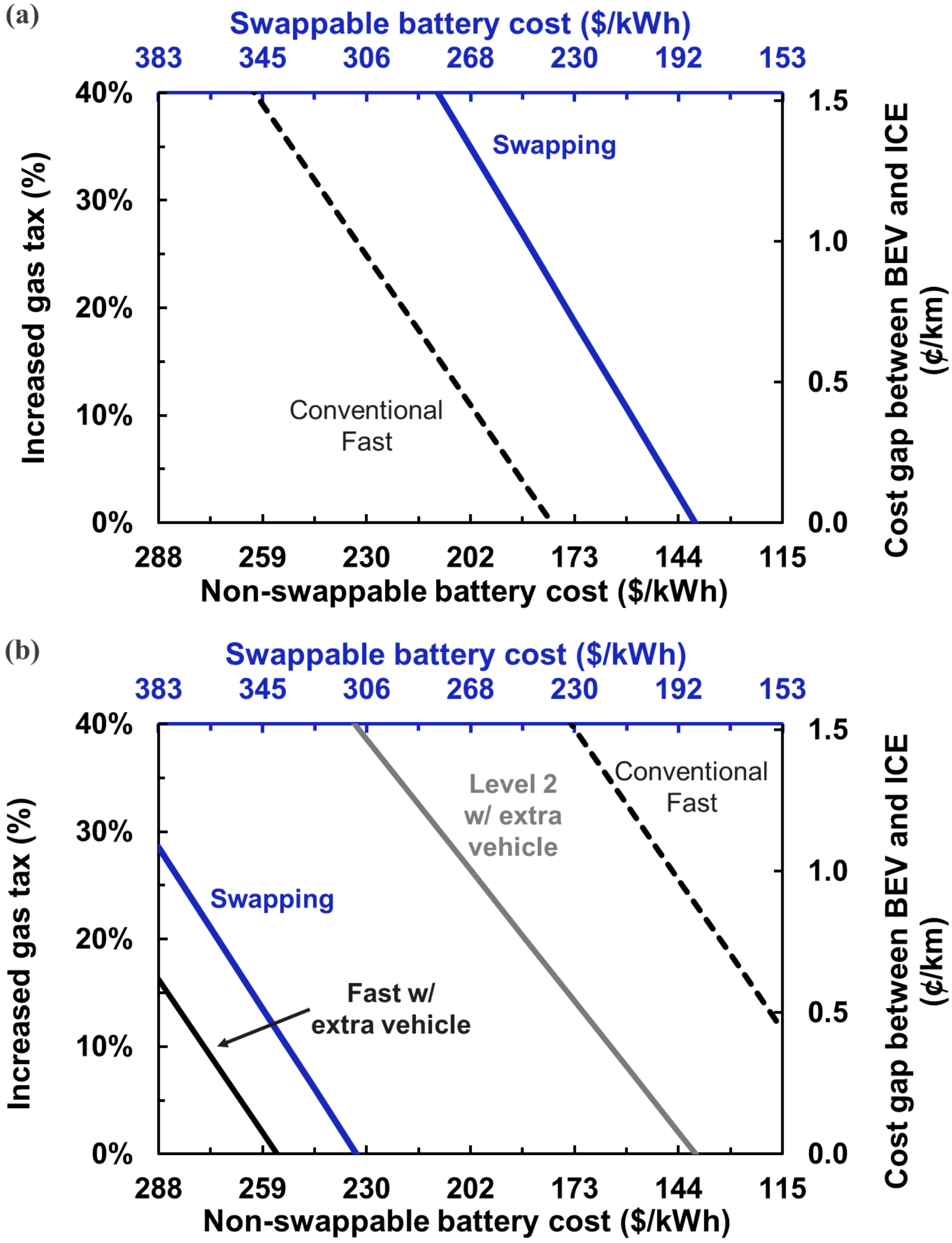

Figure 3. Increased gas tax needed (left ordinate; relative to 50 ¢/L) to close the cost gaps (right ordinate) between the existing ICEV taxi system and BEV taxi ecosystems with (a) a single shift or (b) double shifts per day at different levels of battery costs (x-axes). Each increment in the x-axes represents a 10% decrease in battery costs relative to the base year

2017 level (i.e., $288/kWh for a non-swappable battery and $383/kWh for a swappable battery). This policy analysis emphasizes the importance of choosing the right recharging business models for the electrified fleet.

4. Conclusion

Although vehicle electrification offers a wide range of societal benefits, high opportunity costs tied to the charging times remains an impediment to widespread electric fleet adoption. These costs are not insignificant, raising concerns about the technology’s commercial viability. This paper demonstrates the potential for alternative BEV recharging modes to assuage these concerns.

We propose alternative business models—e.g., BEV charging with extra vehicles— that enable double-shift taxis to keep operating on the road generating revenue by having a sufficient extra number of charged and readily available replacements. Adoption of this strategy imposes higher capital costs, but helps avoid the high opportunity costs associated with Level 2 charging, dramatically improving the performance of the Level 2 charged fleet ecosystem. This, combined with the improved battery lifespan, ultimately makes Level 2 charging with extra vehicles mode a more attractive option than conventional fast charging. A BEV fleet with these aforementioned business models is still much more expensive (by 11% - 64%) than the existing gasoline-powered taxi system. For BEV taxis to compete on price and performance with ICEV taxis, we find that a more economical recharging option—either fast charging with extra vehicles or battery swapping—is needed for taxis with multiple shifts per day. Although the battery swapping scenario requires higher upfront investments, it emerges as a cost-effective alternative on a per-kilometer basis; this is mainly because of the ability of swap stations to serve a higher number of BEVs than a Level 2/ fast charger. Indeed, battery swapping at this moment does not seem suitable to the market for privately owned vehicles owing to the big concern of cross-brand compatibility and battery ownership, but our analysis shows that it is already economically competitive in large dense closed systems.

Electrified taxi ecosystems are currently strongly supported by government subsidies and even driven by mandates in a few Chinese cities—such as Beijing, Taiyuan, and Shenzhen (Zhang, 2018). Yet as battery technology becomes more mature in the future, the incremental costs of BEV over ICEV will be shrinking owing to the dropping battery costs. We ascertain that cost parity will be achieved by 2022 for BEV taxi fleets relying upon either battery swapping (for double shifts) or fast chargers (conventional fast for a single shift; fast with extra vehicles for double shifts). Considering the fact that paying subsidies is an unsustainable government policy and enforcing mandates might not be suitable to many other cities, we investigate an alternative policy lever—raising the gasoline tax to support the recharging alternatives—that could incentivize BEV use in the fleet industry. We demonstrate that with the right BEV recharging business models, the government could cover the cost gaps by modestly raising the gas tax. Moreover, the need for mandates or increased gas tax to support BEV taxi adoption will diminish in the coming years as battery costs drop rapidly.

In the future transportation sector, a major evolution will be the movement toward electric mobility, along with a growing BEV ridesharing market and (eventually) BEV autonomous vehicles being introduced to urban fleets. These transformations require efficient (or even fully automated) recharging mechanisms so that electric cars can always be on the roads satisfying people's travel demand. Furthermore, providing affordable tailpipe emission-free taxi/rideshare services would make cities healthier for residents and help reduce greenhouse gas emissions, making the whole society more sustainable and livable. Our work, using the real-world financial data in Beijing, demonstrates that a network relying on either fast charging with extra vehicles or battery swapping is essential to accelerate the electrification of high-use vehicles, providing the reference for urban transformations toward a sustainable future.

5. Conflicts of Interest

There are no conflicts to declare.

6. Acknowledgements

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