FLEET PERFORMANCE AND COST EVALUATION OF A SHARED AUTONOMOUS ELECTRIC VEHICLE (SAEV) FLEET: A CASE STUDY FOR AUSTIN, TEXAS

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ABSTRACT
Shared Autonomous Vehicles (SAVs) have gained significant public interest as a possible cheaper, safer and more efficient version of today’s transportation networking companies (TNCs) and taxis. One way to expand on the possible benefits of an SAV fleet is through electric vehicles (EVs) which are more energy efficient, more reliable, quicker, and may reduce system-wide emissions when coupled with renewable power. EVs are quickly becoming more financially viable as the price of these vehicles drops and charging infrastructure is appearing in a greater number of locations across the world. EVs are disadvantaged by their relatively short range and long recharge times, so it is important to understand how these factors will affect an electrified SAV (SAEV) fleet in terms of vehicle miles traveled (VMT), vehicle productivity, and response times.

Perhaps the most important factor to consider before implementation is cost, since it is quite unlikely that a fleet operator will elect to use an EV fleet when a gasoline fleet is more profitable. This study makes in-depth estimates of the cost of this SAEV fleet based on vehicle purchasing costs, vehicle maintenance, batteries, electricity, charger construction (including land acquisition and paving), charger maintenance, insurance, registration and general administrative costs. These costs are estimated at low-, high- and mid-cost scenarios, where mid-cost is the most expected.

This study performed a simulation of SAEVs across the Austin, Texas 6-county region under 6 different fleet scenarios to assess what factors make the fleet the most profitable and provide the best customer experience. The simulation process features thoughtful charging strategies, dynamic ridesharing, mode choice, and a calibrated search algorithm. Results showed that for all metrics studied, the gasoline hybrid-electric (HEV) fleet performed better than EV fleets, while remaining more profitable, providing response times of 4.5 minutes compared to 5.5 minutes. The HEV fleet is the more profitable option until the cost of gasoline exceeds $10 per gallon or the cost of a long-range EV falls below $16,000 through subsidies. Of all the EVs studied, the
long-range fast-charging scenario not only provides the best service in terms of all metrics studied but is by far the most profitable. Even though EVs may not be financially advantageous in the near term, the environmental benefits could be substantial; EVs have the potential to provide zero-carbon transportation when coupled with a renewable power grid. Gasoline vehicles have no such potential. Environmentalism tends to have little effect on financial decisions, but a carbon tax could change that perspective.

MOTIVATION
An exciting application of self-driving automated-vehicle technology is one-way car-sharing, similar to services like Car2Go and transportation network companies such as Lyft – but without a driver. Shared autonomous vehicles (SAVs) are envisioned to eventually save many travelers money and time, while reducing personal-vehicle fleet sizes in use today (Fagnant and Kockelman, 2016). One way to extend such benefits is to use an electric vehicle (EV) fleet (as in Chen et al. 2016 and Chen and Kockelman 2016). EVs are especially suited for the heavy use (longer daily travel distances) experienced by shared fleets due to their relatively low energy and maintenance needs (U.S. DOE, 2016). A system of shared autonomous electric vehicles (SAEVs) can carry a relatively high fixed cost due to smaller scale production and the cost of large batteries, which provide greater range before charging is required, and additional charging infrastructure, but may reduce overall costs via lower energy and maintenance needs. EVs are also expected to reduce environmental costs in most locations, especially where renewable feedstocks are part of the power grid (Reiter and Kockelman, 2016). As the price of EV technology continues to fall (Nykvist and Nilsson, 2015) and charging facilities become more convenient, EVs may become financially advantageous over traditional, petroleum-fueled vehicles. With heavy use of a shared fleet (e.g., over 100 miles per day per vehicle, rather than 20 mi [Fagnant and Kockelman 2016]), vehicle turnover will be faster, leading to quicker adoption of new EV technologies (Martinez, 2015). However, all-electric (non-hybrid) EVs are limited by their range (the distance an EV is able to drive on a single charge) and battery charge times, which tend to require two to 20+ times as long as gas station refueling, depending on the power current.

Any self-driving fleet will incur high fixed costs, at least in the early stages of the technology’s release, so scenarios under which such a fleet is cost effective, compared to a gasoline-powered fleet, should be explored before making this large capital investment, granted such scenarios even exist. Slow charge times and poor battery-capacity have been major barriers for EV adoption by households in the US and elsewhere (Stephens, 2013), but these barriers are steadily falling as charge times under an hour are becoming increasingly available in fast-charge locations [see, e.g., https://www.tesla.com/supercharger] (Bullis, 2013). Battery ranges are rising with new vehicles such as Chevrolet Bolt (Chevrolet, 2016) and Tesla Model 3 (Tesla Motors, 2016) both expected to deliver 200 miles of range for under $40,000. The recent, dramatic, drop in battery prices will also play a big role in EV adoption, now at an estimated $190 per kilowatt-hour (kWh), roughly one fourth what they cost back in 2009 (Voelcker, 2016).

This study simulates various cost scenarios using the data found in Loeb et al. (2016) to help a fleet operator determine if an SAEV fleet is a wise and feasible option, which types’ charge speeds and range are the most reasonable and financially advantageous, and how these results compare to simulations of an all-gasoline fleet.
LITERATURE REVIEW

There are many works that simulate SAV fleets to analyze performance in terms of response times, empty mileage, vehicle replacement rates and more. Very few works, however, make strong efforts to determine the cost of these fleets for a fleet operator and only Chen et al. (2016) study the cost of an electrified SAV fleet.

Like much of the charging algorithm, the methods for financial analysis in this work were modeled closely after Chen et al. (2016). Their study is unique because it finds costs for an electrified SAV fleet as opposed to a gasoline-powered one. They also assumed the fleet operator will be responsible for costs associated with owning and maintaining chargers in addition to the vehicles. They found that an SAEV fleet can be offered at $0.66 to $0.74 per mile when accounting for vehicle costs, battery replacements, vehicle maintenance, insurance & registration, electricity (to charge vehicles), charging stations, station maintenance and general administrative costs. Unfortunately, costs of procuring and transforming land for charging stations were neglected. Also electricity costs did not consider hefty load factor adjustments needed for fast-charging.

Burns et al. (2013) investigated costs of an SAV fleet using agent-based simulations modeling in several major US cities. They found that an SAV system could operate at costs of $0.32 to $0.39 per mile considering cost of vehicles with depreciation, financing, insurance, registration, taxes, fuel, maintenance & repair, and overhead. Their findings were somewhat unusual with average response times less than 15 seconds for vehicle replacement rates of about 6 and response times of less than 45 seconds under a replacement rate close to 9. These remarkable findings are likely thanks to the highly simplified and unrealistic model they employed.

Fagnant and Kockelman (2016) and Atasoy et al. (2014) use a more basic approach to SAV cost calculations. Fagnant and Kockelman assumed a cost of $70,000 per SAV and $0.50/mile operating costs per AAA (2012) (note that this figure is virtually the same in AAA’s 2015 report). Assuming a fare of a flat $2.65 plus $1.00 per mile, they used a profit maximizing function to size the SAV fleet. This provided a fleet with a vehicle replacement rate of 8.7. Atasoy et al. performed a similar optimization analysis assuming costs of $200 per day per vehicle and $0.20 per km ($0.12/mile) operating costs.

METHODS

This financial study is carried out using a simulation of a SAEV fleet on the Austin, Texas, 6-county region. The simulator is an add-on for the MATSim program created by Bösch et al. (2016) that was modified for this study to accommodate electric vehicles. MATSim is a transportation simulator that seeks a dynamic user equilibrium with a co-evolutionary process among individual agents across a network. The MATSim inputs are activity-based tour patterns for each simulated agent and a network. MATSim uses the tour data to assign mode, paths and departure times for each agent to maximize its’ individual utility. The tour patterns were produced by Liu et al. (2016) using NHTS and U.S. Census data and they produced the network data using OpenStreetMap. As one of its many outputs, MATSim can produce a concise trip table with each agent’s origin-departure pairs, departure times and arrival times. The simulator
Each trip start time is registered as a request, and the simulator will search for the SAEV that can serve the trip the most quickly. It was found that keeping a vehicle search radius of 9 seconds, for 10 seconds after the trip is registered, gives noticeable improvement to response times. The SAEV will pick up passengers and take them to their destinations; the duration of each trip is generated when a vehicle needs to charge, but does not have the range to access a station. Empty travel is not modeled in the MATSim trip file, so empty VMT (vehicle-miles traveled) must be estimated via teleporting. Charging stations are generated by the program before the simulation through a 30-simulation-day phase, where a station is generated when a vehicle needs to charge, but does not have enough range to access a charging station. A more detailed explanation of this simulation can be found in Loeb et al. (2016) however, several additional modifications were included for this study. The most significant of these modifications are a mode choice model and a dynamic ridesharing model.

Mode Choice Model

Many of the trips produced in the MATSim trip file are not reasonably serviceable by the SAV fleet due to their spatial distribution, trip length, or other factors that lead to traveler wait times of tens of minutes or even hours. In former uses of this model, Bösch et al. rejected requests when they were in the system for more than 10 minutes. Loeb et al. (2016) would reject any request in excess of 75 km (46.6 miles). Unfortunately, neither of these models have any kind of stochastic behavior and do not acknowledge that trips longer than 75 km may have short wait times or that many travelers may be willing to wait longer than 10 minutes. A very basic response-time-based Logit model was implemented to eliminate certain trips on the basis of wait times. It is modeled as though each traveler is given an accurate estimate of response time before making a request and may choose to make or decline the request based on this response time; the longer the response time, the greater the probability of rejecting the trip. The equation for logit used in this study takes the form:

\[
P(\text{reject}) = 1 - \min\left(\frac{2e^{\beta t + \beta t^2}}{1 + e^{\beta t + \beta t^2}}, 1\right)
\]

\[\text{(1)}\]

Where \(P(\text{reject})\) is the probability that a traveler will chose to reject a ride given response time \(t\), \(\beta_t\) is the time coefficient and \(\beta\) is the alternative specific constant (ASC). The multiplier of 2 in the numerator is there to scale the probability to show that simulated travelers already wish to use the SAEV service and will change their mind if and only if the response time is unreasonable to them. For example, a response time of 0 minutes, and an ASC of 0 gives a 0% probability of rejecting the trip. Without the multiplier, this probability is 50%, which does not make sense for this model. The multiplier of 2 will give a rejection probability of 0% for any zero-minute response time given any positive ASC. The role of the ASC here is to provide a range of response times short enough to never be rejected. The time coefficient, \(\beta_t\), is found from Gaudry and Tran (2011) who calculated the time coefficient on waiting for a taxi to be \(-0.1351 \text{ util/min}^{-1}\). An ASC of 1 util was chosen to give a tail of approximately 7.5 minutes wherein a user will not reject a trip. A graph for \(P(\text{reject})\) can be found in Figure 1.
Dynamic Ridesharing

Because traffic assignment is performed upstream of the SAEV code, dynamic ridesharing capabilities are somewhat limited. This is because, geographically, only the end points of each vehicle-trip is known, and it will "teleport" between them. Therefore, once an SAEV is headed for a destination, it may not change course before its intended arrival time. The only thing this means for ridesharing is that an SAEV may accept a ride request while carrying a passenger, but it may not change course until it arrives at its intended destination. The way this is dealt with in the code is using a first-in-last-out (FILO) pattern for pickups and drop-offs. The reasoning may be best demonstrated with an example, shown in Figure 2. Suppose a traveler, traveler A located at Origin A on the University of Texas campus, requests a ride downtown to 6th Street to Destination A at 09:55. The code determines that the SAEV denoted by the black rectangle is the closest eligible vehicle and assigns it to traveler A and the vehicle's arrival time to Origin A is determined to be 9:57. At 09:56, while en-route, the vehicle receives a request from traveler B, in the West Campus neighborhood also headed downtown to 6th Street. The vehicle accepts this request, and continues on to pick up traveler A and the vehicle's arrival time at Origin B is determined to be 10:00. traveler A boards the vehicle at 9:57 and they continue to Origin B, but again, on the way, at 9:59, the vehicle receives a request from traveler C on 16th Street headed to Wooldridge Square on 4th Street. This trip is also accepted. The vehicle continues to pick up traveler B, then picks up traveler C without interruption.
At this point, it might be intuitive to drop off traveler A first. Unfortunately, travel times between Origin C and Destination A are not in the MATSim trip file, and so must be estimated through teleportation. On the other hand, the trip between Origin C and Destination C are in the trip file, so that travel time is well estimated through traffic assignment. Therefore, in order to preserve the highest degree of realism, the last traveler picked up must be the first to be dropped off. This
may appear to be unfair, but the algorithm enforces the rule that no traveler may experience a delay greater than 20% to their in-vehicle travel time (IVTT). For example, suppose that traveler A’s initial travel time, given in the MATSim trip file, is 25 minutes. This means that the maximum allowable IVTT for traveler A is 30 minutes (120% of 25 minutes). When the vehicle received the request from traveler B, the code calculated a travel time of 27 minutes, traveling from Origin A to Origin B to Destination B to Destination A. Then when receiving the request from traveler C, the code verified that the travel time from Origin A to Origin B to Origin C to Destination C to Destination B to Destination A was 29 minutes. This is less than 30 minutes so traveler C imposes an acceptable delay on traveler A. Likewise, it is verified that traveler C imposes an acceptable delay on traveler B. Travelers will always share rides if doing so minimizes response time and no more than four travelers may share a vehicle.

RESULTS

Shown in Table 1, six scenarios were simulated for this study to learn about vehicle replacement rate, response times, vehicle occupancy, empty VMT, vehicle replacement rate and more. There were 41,242 agents in the simulation: a 2% random sample of the region’s population. This sample includes the agents who rejected their trips as a result of the mode choice model and a small portion of the agents whose trips were rejected due to exceeding the vehicle range (5.4% for the 60 mile range and 0% for 200+ mile ranges). Therefore, the number of agents actually using the service is reduced by the proportion shown in “% of Trips Unmet”.

Vehicle replacement rate is a metric to assess the relative size of the SAEV fleet. As in Fagnant and Kockelman (2016), vehicle replacement rate is determined using NHTS data assuming the average conventional vehicle performs 3.05 trips per day on days when it is in use. Dividing an SAEV’s daily trips by 3.05 yields an estimate of the number of conventional vehicles it is effectively replacing on the road. Average vehicle occupancy is estimated to be biased low in this study since certain types of shared trips were not simulated in the upstream MATSim traffic assignment. Examples include a parent chauffeuring a child or a family going out to dinner. Therefore, in theory AV0 should be greater than one even without a DRS model. However every trip request is registered in isolation.

Response time indicates the time it takes for a vehicle to arrive at a traveler’s location after a request is made. The fleets studied were a gasoline-powered hybrid-electric vehicle (HEV) fleet as a base case, standard SAEV, fast charging SAEV, long range SAEV, long range + fast charge SAEV and lastly long range + fast charge SAEV with reduced fleet size. A summary of the outcome of these simulations are in Table 1.
As expected, these results indicate that the HEV fleet was able to serve travelers the best, rejecting only 1.62% of trips and meeting trips with an average response time of 4.45 minutes. Also, not surprisingly, the standard SAEV fleet served travelers the worst rejecting 55% of trips due to poor response time and another 5.4% on the basis of trip length leading to a vehicle replacement rate of only 3.75. These results can be improved significantly by either improving vehicle range or charge times. Either of these improvements brings vehicle replacement close to 8. The biggest feature of increased vehicle range is improved empty VMT at 7.88% compared to 14.2% for the fast charging (low-range) scenario. Fast charging on the other hand improves response times to 6.16 minutes on average compared to 8.76 minutes on average for the long range (slow-charging) scenario. Combining fast charging and long range improves both of these metrics yielding 6.86% empty VMT and 5.49-minute average response times with a replacement rate over 9. Since the long-range, fast-charging scenario performs quite well, reducing the fleet size was tested to improve replacement rates. The replacement rates did rise to 11.5, but average response times exceeded 9 minutes.

**TABLE 1: Key findings from 6 simulation scenarios including a gasoline-powered HEV base-case for 41,242 agents**
Financial Analysis

To determine which of these scenarios is most likely to be implemented, these results must be studied from the fleet operator’s perspective to understand which of these fleets is the most profitable. This warrants a full cost analysis. Costs were estimated from various sources for capital expenses, vehicle and charger maintenance, electricity and vehicle fees. These costs were split into high, low and medium (most likely) estimates, as shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Low Cost</th>
<th>Mid Cost</th>
<th>High Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle Capital</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAEV (per vehicle)</td>
<td>$30,000</td>
<td>$40,000</td>
<td>$50,000</td>
</tr>
<tr>
<td>LR SAEV (per vehicle)</td>
<td>$40,000</td>
<td>$50,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>Replacement battery (per kWh) + $50 install</td>
<td>$100</td>
<td>$145</td>
<td>$190</td>
</tr>
<tr>
<td><strong>Vehicle Operations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance (per mile)</td>
<td>$0.054</td>
<td>$0.061</td>
<td>$0.066</td>
</tr>
<tr>
<td>General Administration</td>
<td>$0.044</td>
<td>$0.11</td>
<td>$0.18</td>
</tr>
<tr>
<td>Insurance &amp; Registration (per vehicle-year)</td>
<td>$550</td>
<td>$1,110</td>
<td>$2,220</td>
</tr>
<tr>
<td>Electricity (per kWh)</td>
<td>$0.08</td>
<td>$0.10</td>
<td>$0.20</td>
</tr>
<tr>
<td>Attendants ($/hour)</td>
<td>$10.00</td>
<td>$12.00</td>
<td>$15.00</td>
</tr>
<tr>
<td><strong>Charging Infrastructure</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Level II Charging (per charger)</td>
<td>$8,000</td>
<td>$12,000</td>
<td>$18,000</td>
</tr>
<tr>
<td>Level II Annual Maintenance (per charger)</td>
<td>$25</td>
<td>$40</td>
<td>$50</td>
</tr>
<tr>
<td>Level III Charging (per charger)</td>
<td>$10,000</td>
<td>$45,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Level III Annual Maintenance (per charger)</td>
<td>$1,000</td>
<td>$1,500</td>
<td>$2,000</td>
</tr>
<tr>
<td>Land Acquisition (per vehicle space)</td>
<td>$1,980</td>
<td>$3,460</td>
<td>$6,900</td>
</tr>
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</table>

TABLE 2: Low, medium and high price estimates for needed expenses to implement an SAEV fleet

Vehicle costs were estimated based on popular production EVs, such as the 2017 Chevrolet Volt and 2017 Mitsubishi i-MiEV, with all-electric ranges (AERs) of 53 and 59 miles, respectively. These ranges are not far from the 60-mile assumption for short-range SAEVs used here. These two models presently have MSRP's of $33,220 (Chevrolet, 2016a) and $22,995 (Mitsubishi Motors, 2016) respectively. As for long-range EVs, the 2016 Tesla Model S 90d has a 294-mile range and costs $89,500 (Tesla Motors, 2016a). The Model S is a luxury, high-performance sedan with more range than needed. Tesla anticipates releasing the Model 3 at just $35,000 in the year 2018 with a range of 215 miles (Tesla, 2016b). This will be Tesla's first experience with an "economy" EV, so this price (and release date) carries no strong guarantees. These prices do not include government rebates, which are due to be phased out in the near future (IRS, 2016), so should not be depended upon for this study. Vehicle autonomy is reported by ENO (2013) to have an estimated marginal cost of $25,000 to $50,000 but this cost could come down to $10,000 after at least 10 years. For this analysis it is assumed that autonomy will have a marginal cost of $5,000 to $25,000, and that regular range SAEV, without autonomy will cost $25,000 and a long range SAEV will be $35,000. With the autonomy package this gives prices of $30,000 to
$50,000 for short range SAEVs and $40,000 to $60,000 for long range SAEVs. The cost of HEVs is estimated as $20,000 without autonomy.

Similar to Chen et al. (2016), SAEVs are anticipated to last 215,000 miles, similar to the average lifespan of a NYC taxicab (New York City Taxi & Limousine Commission, 2014). A battery's usable life is estimated at roughly 100,000 miles based on standard practice by OEMs to warranty their batteries for this distance plus various reports such as Saxton (2013). A battery will then need to be replaced at least once during a vehicle's lifetime, but it would not be a good investment to replace the battery a second time since the vehicle will be very close to (if not in excess of) the end of its service-life. Replacement batteries are expected to cost between $100 and $190 per kWh per estimates from GM and Tesla (Voelcker, 2016), substantially lower than recent estimates of $268/kWh in 2015 and $1,000/kWh in 2008 (IEA, 2016). It's assumed that a trained technician could replace a battery in about an hour working at $50 an hour. Vehicle operation and maintenance costs are assumed to be similar to those for conventional, privately-owned gasoline vehicles, which AAA (2015) estimates to be 5.4 to 6.6 cents per mile for various vehicle types. Changes to insurance premiums are a big unknown pending state and federal legislation and substantial safety research. Some estimate increases to premiums by a factor of 3 or 4 (e.g. Burns et al., 2013) which may be the case in the near term as this technology is in its early stages. Currently three states (California, Nevada, and Florida) have adopted requirements for $5 million insurance premiums for AVs (Technology Law and Policy Clinic, 2015), with other states looking to follow suit (PennDOT, 2016). On the other hand, a greater number of studies anticipate decreases in insurance premiums (e.g. KPMG, 2015) and the possibility of their elimination (that is by assuming 100% manufacturer liability). AAA's 2015 estimated annual average insurance costs for privately-held cars is $1,100, so an SAV's annual insurance cost is assumed to vary between $555 and $2,200, anticipating both sides of this scenario (half and double). SAVs will be used very intensely, but are expected to operate in a safer manner; this uncertainty is represented in the wide range of insurance cost estimates.

Electricity costs are estimated by Mickelson (2016) to be $0.08 to $0.20 per kWh. This is assuming load factors ranging from 20% to 80%. Load factor is the ratio of average usage to maximum usage, for example, if a certain station has a peak usage of 100 kW one day, but a monthly average of 20 kW, its load factor would be 20% (20kW/100kW). A load factor of 100% is the best case scenario. Unfortunately, as shown in Table 1, only two of the five EV fleets have charging stations that typically adhere to this load factor range. The data in Mickelson (2016) does not extend below load factors of 10%, so these costs are not well known. However, there are several possible strategies to increase load factor and bring electrical costs to a reasonable level. These include keeping batteries on site to store charge slowly in off-peak periods, use of renewable energy sources (primarily solar) on site, queueing vehicles at stations rather than allowing many to charge at once, or directing vehicles to different stations where demand is lower. The latter two strategies would have an effect on overall fleet performance, but a substantial effect is not anticipated. Given all these possibilities, it is assumed a fleet manager would find ways to keep load factors high.

Land on which charging stations will be built is estimated using Zillow.com's classifieds of land for sale in the Austin area (http://www.zillow.com/austin-tx/land/). By compiling all listings available on November 18, 2016, the average land costs are $20.81/ft² with a median of $11.84.
The first, second (median) and third quartiles of this data can be used for a high, medium and low estimate of land costs: $6.11, $11.84 and $27.24 per square foot respectively. Some of these lots would require paving which is estimated at $1.25 to $1.50 per square foot for an average parking lot (Brahney, 2015). To be safe, $1.50 is added to each estimate for paving. The space occupied by a single vehicle was compared to the compact EV, the Nissan Leaf which is 175 in. long and 70 in. wide (Nissan, 2016). Adding 24 in. to each dimension for a safe spacing between vehicles yields a footprint of 130 ft$^2$ per vehicle. Multiplying by land and pavement prices gives $990, $1,730, and $3,540 of total pavement costs per vehicle space provided. It is then assumed that each vehicle will require on average two vehicle-spaces to allow for vehicle movement within the station leading to $1,980, $3,460 and $6,900 for each vehicle at a station. It is possible that additional space will be needed to store vehicles not in use, but this space is not assumed since free parking will likely be available in most suburban areas. The HEV fleet would need even more space since it is assumed that this fleet will spend nothing on land acquisitions.

Capital costs, namely acquisition of land and provision of charging infrastructure, are reduced to a per-mile basis by assuming a ten-year payback period aggregated over all mileage accrued over these years. Increases in demand for SAEV use over this 10-year period are considered accounted for in the increased revenue they provide.

Level II chargers are estimated by the U.S. DOE (2012) to cost between $8,000 and $18,000, including installation, hardware, materials, labor and administration fees, with $25 to $50 annual maintenance cost per Level II charger. The U.S. DOE (2012) and New York City Taxi & Limousine Commission (2013) estimate that Level III charger provision cost from $10,000 to $100,000, including those same fees (listed above) and $1,000 to $2,000 in annual maintenance costs per charger. The number of required chargers at each site is found here by summing the maximum number of SAEVs present at each charging station over the course of the simulation day. General administration costs were estimated by APTA (2015) Public Transportation fact book using the costs found for vanpooling data, since this was the most similar mode. They estimated $57.6 million per year for 1,319 million passenger-miles or 4.34 cents per passenger-mile. Chen et al. (2016) estimate 18.4 cents per mile for this expense (though this expense is not included in their final cost estimates), which serves as an upper estimate on this cost. Gasoline-powered fleets are assumed to have the same associated costs, as applicable, with fuel prices ranging from $2.00 to $4.00 per US gallon, operating at 50 miles per gallon with a total range of 525 miles, similar to the Honda Civic, Toyota Prius and many similar vehicles. The gasoline-powered vehicles will need attendants to give them fill-ups at fuel stations. The fuel stations occupied by an attendant in the simulation were the 19 charging stations generated using the long-range (200-mile) scenario. Each station is manned by one attendant whose hourly wages vary across $10, $12 and $15. If fuel stations are manned 24-hours per day, the cost will be $4,560 to $6,840 daily. It is reasonable to assume this task could be undertaken by just 19 attendants since the HEV fleet required on average approximately 2,600 fill-ups over the simulation day or 6 fill-ups per attendant per hour. Fares are assumed to be a flat $1 per mile, not far from the cost of typical TNCs today. The resulting revenue from this strategy is not the focus, but rather relative daily profits between scenarios. The costs and profits per service-mile for the three cost scenarios are shown in the Tables 3, 4 and 5.
<table>
<thead>
<tr>
<th>Low-cost estimates (cents per occupied mile)</th>
<th>Gasoline-powered</th>
<th>Standard SAEV</th>
<th>Long-Range (LR) SAEV</th>
<th>LR, FC SAEV</th>
<th>Fast-Charge (FC) SAEV</th>
<th>LR, FC SAEV Reduced Fleet</th>
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<td>Electricity/fuel</td>
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<td>3.41</td>
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<td>10.5</td>
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<td>Vehicle Purchase Costs</td>
<td>14.0</td>
<td>20.7</td>
<td>23.6</td>
<td>22.6</td>
<td>19.0</td>
<td>22.8</td>
</tr>
<tr>
<td>Battery Costs</td>
<td>0.00</td>
<td>1.10</td>
<td>3.39</td>
<td>3.35</td>
<td>1.11</td>
<td>3.42</td>
</tr>
<tr>
<td>Total cost</td>
<td><strong>29.2 ¢/mi</strong></td>
<td><strong>39.9</strong></td>
<td><strong>42.3</strong></td>
<td><strong>41.0</strong></td>
<td><strong>37.8</strong></td>
<td><strong>41.4</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mid-cost estimates (cents per occupied mile)</th>
<th>Gasoline-powered</th>
<th>Standard SAEV</th>
<th>Long-Range (LR) SAEV</th>
<th>LR, FC SAEV</th>
<th>Fast-Charge (FC) SAEV</th>
<th>LR, FC SAEV Reduced Fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity/fuel</td>
<td>6.39 ¢/mi</td>
<td>4.51</td>
<td>4.26</td>
<td>4.21</td>
<td>4.57</td>
<td>4.29</td>
</tr>
<tr>
<td>Vehicle Maintenance, General Administration &amp; Attendants</td>
<td>18.4</td>
<td>19.7</td>
<td>18.6</td>
<td>19.9</td>
<td>18.7</td>
<td></td>
</tr>
<tr>
<td>Insurance/Registration</td>
<td>0.71</td>
<td>1.73</td>
<td>0.93</td>
<td>0.74</td>
<td>0.10</td>
<td>0.66</td>
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<tr>
<td>Charger Costs (Land + Infrastructure + Maintenance)</td>
<td>0.00</td>
<td>3.57</td>
<td>1.35</td>
<td>2.15</td>
<td>6.30</td>
<td>2.19</td>
</tr>
<tr>
<td>Vehicle Purchase Costs</td>
<td>19.6</td>
<td>27.7</td>
<td>29.4</td>
<td>28.3</td>
<td>25.3</td>
<td>28.4</td>
</tr>
<tr>
<td>Battery Costs</td>
<td>0.00</td>
<td>1.58</td>
<td>4.91</td>
<td>4.85</td>
<td>1.60</td>
<td>4.95</td>
</tr>
<tr>
<td>Total cost</td>
<td><strong>45.1 ¢/mi</strong></td>
<td><strong>58.7</strong></td>
<td><strong>59.4</strong></td>
<td><strong>58.6</strong></td>
<td><strong>58.7</strong></td>
<td><strong>59.2</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 3: Low-cost estimates, per occupied-mile, for a combined SAEV-HEV fleet (¢/mile)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>TABLE 4: Mid-cost estimates, per occupied-mile, for a combined SAEV-HEV fleet (¢/mile)</th>
<th>Gasoline-powered</th>
<th>Standard SAEV</th>
<th>Long-Range (LR) SAEV</th>
<th>LR, FC SAEV</th>
<th>Fast-Charge (FC) SAEV</th>
<th>LR, FC SAEV Reduced Fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.45 min</td>
<td>9.82 min</td>
<td>8.76 min</td>
<td>5.49 min</td>
<td>6.16 min</td>
<td>9.55 min</td>
</tr>
<tr>
<td></td>
<td>28.5</td>
<td>11.4</td>
<td>23.4</td>
<td>28.2</td>
<td>24.3</td>
<td>35.1</td>
</tr>
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</table>
TABLE 5: High-cost estimates, per occupied mile, for a combined SAEV-HEV fleet

<table>
<thead>
<tr>
<th>High-cost estimates (cents per occupied mile)</th>
<th>Gasoline-powered</th>
<th>Standard SAEV</th>
<th>Long-Range (LR) SAEV</th>
<th>LR, FC SAEV</th>
<th>Fast-Charge (FC) SAEV</th>
<th>LR, FC SAEV Reduced Fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity/fuel</td>
<td>8.52 ¢/mi</td>
<td>9.03</td>
<td>8.51</td>
<td>8.42</td>
<td>9.15</td>
<td>8.58</td>
</tr>
<tr>
<td>Vehicle Maintenance, General Administration &amp; Attendants</td>
<td>26.5</td>
<td>28.3</td>
<td>26.7</td>
<td>26.4</td>
<td>28.7</td>
<td>26.9</td>
</tr>
<tr>
<td>Insurance/Registration</td>
<td>1.43</td>
<td>3.47</td>
<td>1.86</td>
<td>1.48</td>
<td>2.00</td>
<td>1.33</td>
</tr>
<tr>
<td>Charger Costs (Land + Infrastructure + Maintenance)</td>
<td>0.00</td>
<td>5.71</td>
<td>2.16</td>
<td>4.29</td>
<td>12.6</td>
<td>4.38</td>
</tr>
<tr>
<td>Vehicle Purchase Costs</td>
<td>25.2</td>
<td>34.6</td>
<td>35.3</td>
<td>34.0</td>
<td>31.6</td>
<td>34.1</td>
</tr>
<tr>
<td>Battery Costs</td>
<td>0.00</td>
<td>2.06</td>
<td>6.42</td>
<td>6.35</td>
<td>2.09</td>
<td>6.47</td>
</tr>
<tr>
<td>Total cost</td>
<td>61.6 ¢/mi</td>
<td>83.2</td>
<td>81.0</td>
<td>80.9</td>
<td>86.1</td>
<td>81.8</td>
</tr>
<tr>
<td>Total daily profit per vehicle ($1/mi fare)</td>
<td>$163</td>
<td>$30</td>
<td>$62</td>
<td>$79</td>
<td>$42</td>
<td>$83</td>
</tr>
<tr>
<td>Profit per revenue-mile ($1/mi fare)</td>
<td>38.4 ¢/mi</td>
<td>16.8</td>
<td>19.0</td>
<td>19.1</td>
<td>13.9</td>
<td>18.2</td>
</tr>
<tr>
<td>Avg. Response Time Per Trip</td>
<td>4.45 min</td>
<td>9.82 min</td>
<td>8.76 min</td>
<td>5.49 min</td>
<td>6.16 min</td>
<td>9.55 min</td>
</tr>
<tr>
<td>Avg. Daily Trips per Vehicle</td>
<td>28.5</td>
<td>11.4</td>
<td>23.4</td>
<td>28.2</td>
<td>24.3</td>
<td>35.1</td>
</tr>
</tbody>
</table>

This analysis indicates that starting an SAEV fleet from the ground up is not financially advantageous over a traditionally-fueled SAV fleet. This comes from the higher cost of EVs, extra empty VMT, replacement batteries and building and operating charging stations. However, if an SAEV fleet is implemented, it is clear that the fast-charging, long-range fleet is the most profitable, earning significantly greater profit than the other fleets. Since EVs are quickly gaining market penetration, however, there could be certain future scenarios under which an electrified fleet is the most economical option. Some possibilities to explore are increases in the price of gasoline, exceptionally inexpensive electrical generation or inexpensive EVs. These scenarios were studied for the mid-cost scenario to determine the break-even point at which fast-charging long-range SAEVs and HEV SAVs are equally profitable.

For the first scenario, a gasoline price of $10.00 (exactly) per gallon leads to daily profits of $170.19/vehicle and $170.15/vehicle for the EV and HEV fleets respectively (comparing fleets of the same size). The U.S. has never experienced these types of oil prices, but this is not far from prices seen in much of Europe in recent years. For electricity costs, even making electricity along with charging infrastructure free does not close the gap bringing the long-range, fast-charge fleet up to $196.33/vehicle, shy of $233.55/vehicle daily profit for the HEV fleet. For vehicles, the price of a long range EV would have to fall, through subsidies, from an estimated $50,000 per vehicle to $31,300. This includes the estimated $15,000 autonomy package indicating a vehicle base price of $16,300 or an $18,700 subsidy (more than double today’s subsidies). Additionally, the batteries would need to last the lifetime of the vehicle to save on
replacement costs. A $16,300 sticker price is not out of the question, as there are several base-
model economy vehicles under $15,000 available in the U.S.

CONCLUSIONS
This study simulated a fleet of shared autonomous electric vehicles serving requests of 41,242
agents across the Austin, Texas network to determine which fleet scenarios were most
advantageous to the operator and the users. It was found that in every studied metric, using a
short-range and slow-charging vehicle was the worst option and that a fast-charging, long-range
fleet was the best option. This was decided on the basis of response times, empty VMT,
replacement rates and profitability. The long-range, fast-charging fleet, however was not able to
compete with a gasoline HEV fleet which achieved 19% better response times, 12% less empty
VMT, 17% better replacement rate and 37% higher profits. The disparity in profitability only
arises when gasoline prices remain under $10 per gallon and long-range EVs cost over $16,300.

Future works should focus on getting a more in-depth understanding of vehicle occupancy by
recognizing trips that are already combined for everyday vehicle trips. Also, strategies for
reducing load factors are crucial for the viability of this fleet, and they should be simulated to
determine their affects on costs and vehicle performance.

A fully electrified fleet is not advantageous to the operator right now, but public EV charging
stations are becoming more widely available. EVs are becoming cheaper to own and operate, and
the future of fossil fuels is not clear. The cost to run this EV fleet is still quite low on a per-
mileage basis—less than driving a personal vehicle 10,000 miles per year (AAA, 2015) for the
low- and mid-range cost estimates. It is good to know there are alternatives to fossil fuels that
can be profitable for such a fleet with the uncertain future of our climate and fossil fuel prices.

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