Reforming electricity rates to enable economically competitive electric trucking

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Full working paper and all citations are available at http://eta-publications.lbl.gov/sites/default/files/working_paper_003_reforming_electricity_rates_jun_2019.pdf
Executive summary (1/4)

The imperative to decarbonize long-haul, heavy-duty trucking for mitigating both global climate change as well as air pollution is clear. Given recent developments in battery and ultra-fast charging technology, some of the prominent barriers to electrification of trucking are dissolving rapidly.

Here we shed light on a significant yet less-understood barrier, which is the general approach to retail electricity pricing. We show that there is a near-term pathway to $0.06/kWh charging costs that will make electric trucking substantially cheaper than diesel. This pathway includes:

1) **reforming demand charges** to reflect true, time-varying system costs;
2) **avoiding charging** during a few specific periods (<45 hours in a year) when prices are high;
3) **achieving charging infrastructure utilization of 33% or greater.**

However, without reforming demand charges and low utilization of charging infrastructure, charging costs more than quadruple (to $0.28/kWh).

We also illustrate that a substantial share of current trucking miles within select large regions of the United States can be reliably electrified without constraining electricity generation capacity as it exists today. Using historical hourly electricity price and load data for last 10 years and future projections in Texas and California, we show that electricity demand is at least 10% lower than yearly peak demand for at least 15 hours on any given day.

In sum, with electricity rates that closely reflect actual power system costs of serving off-peak trucking load, we show that electric trucks can provide overwhelming cost savings over diesel trucks.
(Left) Variation in truck charging cost by utilization, for static vs. dynamic, system-reflective electricity pricing. SCE is Southern California Edison. (Right) Proportion of hours in ERCOT (2010-2018) and CAISO (2012-2018) above given charging cost.

Note: Diesel breakeven range is based on $3.16/gal diesel, and battery costs between $170/kWh and $100/kWh.
Estimated unit truck charging costs across customer scenarios and utilization factors (left), and unit charging cost needed to break even with diesel trucking (right) Note: Diesel breakeven range is based on $3.16/gal diesel, and battery costs between $170/kWh and $100/kWh.
Pathway from conditions that result in non-competitive electric trucks (low utilization, standard non-peak-coincident demand charges, and no wholesale pricing) to conditions that result in increasingly competitive electric trucks (peak-coincident demand charges, wholesale pricing, and—eventually—high utilization). Diesel breakeven figures reflect battery costs between $170/kWh and $100/kWh, and $3.16/gal diesel costs.
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The imperative to decarbonize long-distance trucking is clear

- Road freight accounted for ~8% of global GHG emissions in 2015
- More than 90% of global emissions growth from road freight vehicles from 2000-2015 was in emerging economies; the majority of this growth is attributable to large trucks

Electrification also has potential to mitigate NOx emissions, which are disproportionately emitted by heavy-duty trucking

- In the US, heavy-duty trucking is expected to contribute 1/3 of NOx emissions from the transportation sector by 2025
- In India, heavy-duty trucking emits 55% of NOx from the transportation sector

Electrification of this sector has been seen as challenging, but recent developments suggest that it is becoming more feasible:

- **Battery costs are falling:** At the end of 2017, lithium-ion battery prices had fallen to $175/kWh, an 80% drop from their cost in 2010; BNEF projects a cost of $100/kWh by 2026
- **Generation costs are falling:** The cost of electricity generation is dropping as wind and solar prices have become cheaper than coal and natural gas
Demand charges incurred during fast-charging sessions could threaten the economics of electric trucks

- Electric utilities commonly impose per-kW demand charges that charge customers for their maximum instantaneous demand in a given period.
- Non-peak-coincident demand charges are levied regardless of whether the individual customer’s peak occurs at a time that disproportionately burdens the grid.
- Thus, non-coincident demand charges may unnecessarily impede electrification, especially when utilization is low and charges are not yet spread out over many kWh sold.
- Direct-current fast-charging (DCFC) is seen as important for quick fillup times but will be impacted by demand charges due to its high power draw.
- An analysis of a light-duty EVgo charging station with low utilization showed that demand charges made up over 90% of the electricity cost.
- Time-varying pricing, rather than non-peak-coincident demand charges, can better align tariffs with the actual costs the customer imposes on the system.
With charging costs between $0.11 and $0.18/kWh, electric trucking will break even with diesel

- Cost of charging, including amortized infrastructure costs, is key to whether electric trucking is competitive with diesel
- If the cost of charging is >$0.18/kWh, fuel cost savings will be less than the cost of electrifying the truck
- In contrast, with charging costs <$0.11/kWh, the economic case for electrification is clear

**Electric truck fuel cost savings vs. unit charging costs.** At charging costs of $0.06/kWh (inclusive of amortized infrastructure costs), an electric truck’s fuel cost savings are $251,000 (NPV), providing net savings of $61,000 (18% of lifetime diesel fuel cost) over the truck’s lifetime at battery price of $170/kWh, or up to $148,000 (44% of lifetime diesel fuel cost) at a battery price of $100/kWh.

*Notes: Fuel cost savings are based on $3.16/gal diesel, 5.9 mi/gal diesel fuel efficiency, and 2.1 kWh/mi electric fuel efficiency. Incremental cost is based on the cost of a 1,000-kWh battery costing between $170/kWh and $100/kWh.*
The two principal objectives of this work are to illustrate that it is feasible for trucks to avoid charging on-peak, and to estimate the cost of truck charging.

This work has two principal objectives:

1. Illustrate that it is feasible for trucks to avoid charging during peak demand hours when the power grid is truly constrained.

2. Estimate the achievable cost of electric truck DC fast-charging under different electricity pricing regimes, with and without dynamic energy and T&D pricing.
Key findings: historical load analysis

Both CAISO and ERCOT have abundant opportunities for trucks to charge without imposing a need for new generation capacity on the system

- Most hours of the year do not come close to drawing on full system generating resources: since 2010, most hours have had a >20% margin between hourly load and annual peak:
  - 91% of hours in ERCOT
  - 96% of hours in CAISO

- On average, while maintaining a 10% margin between hourly load and annual peak:
  - 724,000 truck-charges/day (272 million truck-miles/day) could be delivered in ERCOT
  - 489,000 truck-charges/day (183 million truck-miles/day) could be delivered in CAISO

- On the most capacity-constrained day of the 9 years analyzed:
  - 239,000 truck-charges/day (89 million truck-miles/day) could be delivered in ERCOT
  - 177,000 truck-charges/day (67 million truck-miles/day) could be delivered in CAISO
Key findings: historical price analysis

Both CAISO and ERCOT have abundant hours with low-priced energy in which truck charging can be competitive with diesel

- Energy price required to support diesel-competitive charging ranges from ~$65/MWh at high battery prices to ~$127/MWh at low battery prices
- Most hours in ERCOT and CAISO support diesel-competitive truck charging
- Analysis presented uses hourly energy price data from 2011-2018 in ERCOT and 2012-2018 in CAISO
- Hours with average real-time energy prices of $30/MWh / $60/MWh or less:
  - ERCOT: 74% / 96%
  - CAISO: 53% / 95%
- Average energy price in 8 lowest-priced hours of each day / most expensive day in range:
  - ERCOT: $20/MWh / $58/MWh
  - CAISO: $27/MWh / $78/MWh
Key findings: projected price/load analysis

Price and load trends that support off-peak competitive truck charging are projected to continue into the future

- Plentiful off-peak charging opportunities in terms of both price and load are projected to be present under high wind and solar penetrations in 2030
- Average amount of spare capacity to support truck charging increases in both ERCOT and CAISO
- Average energy prices during the 8 cheapest hours decreases in ERCOT and increases in CAISO, but still supports competitive charging costs

<table>
<thead>
<tr>
<th>Hourly load patterns</th>
<th>Historical</th>
<th>Projected</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of hours with &gt;10% margin between hourly load and annual peak load</td>
<td>98%</td>
<td>99%</td>
</tr>
<tr>
<td>% of hours with &gt;20% margin between hourly load and annual peak load</td>
<td>91%</td>
<td>96%</td>
</tr>
<tr>
<td>Average number of 750-kWh truck-charges available per day</td>
<td>724,000</td>
<td>489,000</td>
</tr>
<tr>
<td>Number of 750-kWh truck-charges available on the most constrained day</td>
<td>239,000</td>
<td>177,000</td>
</tr>
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<table>
<thead>
<tr>
<th>Wholesale energy price patterns</th>
<th>Historical</th>
<th>Projected</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of hours ≤ $30/MWh</td>
<td>74%</td>
<td>53%</td>
</tr>
<tr>
<td>% of hours ≤ $60/MWh</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>Average price of 8 cheapest hours ($/MWh)</td>
<td>$20</td>
<td>$27</td>
</tr>
<tr>
<td>Average price of 8 cheapest hours on the most expensive day ($/MWh)</td>
<td>$58</td>
<td>$78</td>
</tr>
</tbody>
</table>
Key findings: estimated charging cost (1/2)

Charging can be delivered for as little as $0.06/kWh, including amortized infrastructure costs, well below breakeven with diesel

- Given the opportunity for trucks to charge off-peak and in low-cost hours, we estimate that truck charging can be delivered at a lowest unit charging cost of about $0.06/kWh, including amortized infrastructure costs
  - Assumes ERCOT energy prices and 33% station utilization

- The economics of truck charging vary significantly based on demand-charge design and station utilization

- In a scenario with higher demand charges and lower utilization, unit charging cost rises to $0.28/kWh
  - Assumes SCE tariffs and 10% station utilization

- Breakeven unit charging cost with diesel ranges from $0.08-$0.26/kWh depending on diesel price and battery cost

<table>
<thead>
<tr>
<th>Battery price ($/kWh)</th>
<th>Unit charging cost to break even with diesel trucking ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.15 0.08</td>
</tr>
<tr>
<td>170</td>
<td>0.18 0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diesel price ($/gal)</th>
<th>Breakeven unit charging cost ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.81</td>
<td>0.15</td>
</tr>
<tr>
<td>3.16</td>
<td>0.18</td>
</tr>
<tr>
<td>4.20</td>
<td>0.26</td>
</tr>
</tbody>
</table>
Unit charging cost varies substantially based on tariff structure, particularly demand charge design, and utilization rate.
Key findings: savings sensitivities

Almost all scenarios considered demonstrate net savings of electric trucking over diesel

- Net benefit from electrification varies depending on diesel prices and battery costs
  - We vary battery costs between $100/kWh (2025 costs) and $170/kWh (2018 costs)
  - We vary diesel prices between $2.81/gal (TX costs), $3.16/gal (national average), and $4.20/gal (CA costs)

- In ERCOT, the maximum benefit from electrification of a truck amounts to 44% savings ($148,000) over the truck’s lifetime diesel costs; in CAISO, maximum benefit is 56% savings ($246,000)

- The only scenario where electrification leads to net financial losses is in SCE, which has the highest charging costs, when diesel prices are low and battery prices high

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ERCOT</th>
<th>CAISO</th>
<th>SCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging cost ($/kWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.06</td>
<td>$0.07</td>
<td>$0.13</td>
<td></td>
</tr>
<tr>
<td>Diesel price ($/gal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2.81</td>
<td>$3.16</td>
<td>$4.20</td>
<td>$4.20</td>
</tr>
<tr>
<td>Battery price ($/kWh)</td>
<td>$24,000</td>
<td>$61,000</td>
<td>$159,000</td>
</tr>
<tr>
<td>8%</td>
<td>18%</td>
<td>36%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Net savings with electrification, as dollar figure and as percentage of lifetime diesel fuel costs
We have identified a near-term pathway to charging costs that would make the lifetime cost of electric costs lower than diesel

- Our modeling identifies a near-term pathway to charging costs that would make the lifetime cost of electric trucks substantially lower than that of diesel trucks (see next slide)
  - (Left panel) Conditions resulting in non-competitive electric truck economics: standard non-peak-coincident demand charges, retail electricity prices, 10% utilization
  - (Center panel) Conditions resulting in competitive truck economics: still 10% utilization, but assuming policies that improve economics (critical-peak demand charges and access to wholesale electricity prices)
  - (Right panel) Result of policies from center panel successfully promoting electric truck deployment and driving up station utilization, lowering unit costs and making electric trucks clear winners over diesel

- Achieving low charging costs could drive a positive feedback loop, with lower charging costs driving higher truck deployment and station utilization, which in turn lowers unit costs further
Low utilization, non-peak-coincident demand charges, and retail pricing (on the left) result in high charging costs that can be progressively transformed.
**Discussion: importance of demand-charge reform**

Replacing non-peak-coincident demand charges with time-varying rates is key to electric truck economics and minimizing total system cost

- Revising or replacing demand charges in electricity rate structures is key to electric truck economics, particularly early in electrification when utilization is low
  - ERCOT’s critical-peak demand charge structures helps electric trucking be competitive even at low utilization, if charging is exclusively off-peak
  - SCE’s non-coincident-peak demand charge comprises 31% of charging cost at low (10%) utilization

- Even SCE’s new EV-specific tariff contains non-peak-coincident demand charges

- Instead of non-coincident demand charges, time-varying rates that reflect time-varying costs imposed on the grid by a customer are a more economically efficient approach to cost recovery

- Encouraging off-peak charging aligns customer incentives with choices that minimize total system cost
  - Demand-wise, off-peak charging periods are sufficient to charge over 100% of all truck-miles driven in Texas and California
  - Price-wise, most hours could be considered off-peak, with fewer than 45 hours/year in ERCOT and CAISO having charging costs >$4/gal diesel equivalent
Institutional advances are needed to exploit opportunities in electric trucking

- Electric trucking has the potential to be cost-competitive with diesel
- However, institutional advances (i.e., electricity tariff reform) are needed to exploit opportunities in electric trucking that have arisen from advances in battery and fast-charging technologies
- Utilities and grid operators nationwide are experiencing similar trends that could support truck electrification
  - Low wholesale energy prices
  - Stronger diurnal energy price profiles
- Valuable areas for further research include
  - Estimating achievable utilization of charging stations
  - Assessing intra-zonal variability in grid conditions instead of ISO-wide variability
  - Understanding impact of truck electrification on the transmission grid
Appendix: Methodology
We selected two contrasting states and regulatory regimes to sit our analysis; within these states, we modeled three different scenarios

- We investigate the feasibility of off-peak charging and the cost of DCFC across two contrasting states and regulatory regimes:
  - Texas because ERCOT is among the most liberalized of US electricity markets, and is the only ISO with an energy-only wholesale market and retail competition
  - California because it is a leader in clean energy technology and policy (including EV policy) and has vertically integrated utilities

- We model two realistic scenarios and one illustrative scenario (a CAISO customer with the delivery charges of an ERCOT customer) to understand the impact of tariff design on charging costs

- We highlight how differences in electricity policy and regulation affect the economics of electric truck charging

<table>
<thead>
<tr>
<th>Territory / scenario</th>
<th>ERCOT</th>
<th>SCE</th>
<th>CAISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility service arrangement</td>
<td>ERCOT direct-access customer</td>
<td>Southern California Edison full-service customer</td>
<td>CAISO direct-access customer with modified delivery charges</td>
</tr>
<tr>
<td>Realistic under current regulation?</td>
<td>Yes</td>
<td>Yes</td>
<td>No, illustrative</td>
</tr>
</tbody>
</table>
Our research objectives translate into three methodological sections

**Objectives**

1. Illustrate that it is feasible for trucks to avoid charging during peak demand hours when the power grid is truly constrained.
2. Estimate the achievable cost of electric truck DC fast-charging under different electricity pricing regimes, with and without dynamic energy and T&D pricing.

**Methods**

1. Analyze off-peak periods in historical and projected energy price and demand data from ERCOT and CAISO.
2. Assess achievable unit charging cost across three scenarios in Texas and California.
3. Translate unit charging cost into per-mile trucking cost to compare electric trucking to diesel.
Methodology: price and demand analysis

First, we conducted an analysis of off-peak prices and demand using historical and forecasted data for both ERCOT and CAISO

- We analyze data on demand and wholesale energy prices in ERCOT and CAISO to assess the prevalence of off-peak periods that could support truck charging on these grids
  - Historical data: 2010-2018 load data; 2011-2018 price data (ERCOT) or 2012-2018 (CAISO)
  - Projections: 2030 projection assuming 40% penetration of variable renewable energy (balanced levels of wind and solar)

- “Off-peak” in this paper is taken to mean:
  - Hours with demand at least 10% below yearly peak demand (i.e., analogous to the concept of critical peak pricing—only extreme system conditions are considered “on-peak”)
  - Hours with low enough electricity prices to support competitive truck charging

- Identifying off-peak windows is critical to see if truck charging can avoid incurring new generation capacity buildout

- We only analyze ERCOT and CAISO data and not SCE data because SCE’s tariffs do not reflect real-time system conditions
Methodology: unit charging cost (1/3)

Second, we modeled unit charging cost across our three different scenarios

\[
\text{Unit charging cost} = \text{Levelized cost of equipment} + \text{Cost of electricity}
\]

\[
\text{Cost of electricity} = \text{Cost of generation} + \text{Cost of T&D}
\]

- Unit charging cost is a function of levelized cost of equipment and electricity cost
- The levelized cost of equipment is the minimum price per kWh delivered that the service provider should charge customers to break even on investment in the charging equipment and grid interconnection
  - It is a function of:
    - The useful service life of the charging equipment
    - The utilization rate of the charging equipment in terms of average kWh/day delivered to customers out of total possible kWh/day that could be delivered
  - To analyze charging equipment cost, we model a transmission-connected 9.4-MW DCFC station (see next slide)
- The cost of electricity is a function of the cost of generation (i.e., energy production) and the cost of transmission and distribution (T&D)
  - All have fixed and variable cost components
  - Generation and T&D costs are recovered differently across ERCOT, CAISO, and SCE
We based our modeling of unit charging cost on a 9.4-MW DCFC station capable of simultaneously charging 5 trucks

- To analyze unit charging cost, we model a DC fast-charging station with the following characteristics:
  - 9.4 MW total capacity
  - 5-truck simultaneous charging capacity, assuming 1-MWh battery/truck* and 75% depth of recharge
  - 30-minute charging time (DC fast charging)
  - 33% utilization rate with sensitivity of 10%
  - Transmission-connected

- Truck charging is assumed to be scheduled during the 8 hours of the day with lowest-cost electricity

- Model is based on long-range combination trucks charging at public truck stops; grid-connection and land cost values reflect this scenario

- Size of truck battery pack (1 MWh) based on Tesla 500-mile-range semi; unit charging costs do not change for smaller capacity battery packs
Unit charging cost components were estimated from the bottom up across the three different scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ERCOT</th>
<th>SCE territory</th>
<th>CAISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimation method for customer in ERCOT</td>
<td>Modeled as the unit charging cost for a retail customer able to access wholesale energy prices in ERCOT territory.</td>
<td>Modeled as the unit charging cost for a retail customer on SCE’s real-time pricing program.</td>
<td>Illustrative; modeled as the unit charging cost for a retail customer able to access wholesale energy prices in CAISO territory, but (1) paying the same T&amp;D charges as in ERCOT, and (2) not paying for resource adequacy.</td>
</tr>
<tr>
<td>Estimation method for customer in SCE territory</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Estimation method for direct-access customer in CAISO</td>
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</table>

**Electricity**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Cost</th>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation</td>
<td>Modeled as the price a retail electric provider would pay to pass through the real-time price to a retail customer:</td>
<td>$27/MWh</td>
<td>Modeled as the price a large customer connected at the transmission level would pay on SCE’s 2017 real-time price tariff:</td>
<td>$38/MWh</td>
</tr>
<tr>
<td>T&amp;D</td>
<td>Modeled as the T&amp;D charges paid by a transmission-connected customer in Oncor service territory, charging only at non-critical-peak times:</td>
<td>$2/MWh</td>
<td>Modeled as the price of a large customer connected at the transmission level on SCE’s 2018 real-time price tariff:</td>
<td>$49/MWh</td>
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</tbody>
</table>

**Infrastructure** (Capital costs and $/MW costs levelized over 20-year lifetime and baseline 33% capacity utilization (with sensitivity of 10% utilization) using 7% cost of capital)

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical equipment</td>
<td>Modeled as the average of best-case electric vehicle supply equipment (EVSE) costs, taken to be (1) the balance of system (BOS) costs of grid-tied storage, and (2) industry-projected EVSE costs:</td>
<td>$18/MWh</td>
</tr>
<tr>
<td>Grid connection</td>
<td>Modeled as the average U.S. grid connection cost for utility-scale solar photovoltaic (PV) projects:</td>
<td>$5/MWh</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Modeled as the cost of (1) inverter maintenance for a PV plant, (2) preventive maintenance and inspection, averaged for both an existing electric bus charging station and the electrical/wiring inspection costs of a PV plant, and (3) estimated structural maintenance:</td>
<td>$5/MWh</td>
</tr>
<tr>
<td>Installation</td>
<td>Modeled as the installation costs associated with grid-tied storage plus land costs in California and Texas:</td>
<td>$8/MWh</td>
</tr>
</tbody>
</table>
Methodology: per-mile trucking cost

Finally, we translated our unit charging cost estimation into a per-mile trucking cost in order to compare electric to diesel trucking costs.

$$\text{Fuel cost per mile (Diesel)} = \frac{\text{Diesel fuel price}}{\text{Fuel efficiency diesel}}$$

$$\text{Fuel cost per mile (Electric)} = \frac{\text{Unit charging cost}}{\text{Fuel efficiency EV}} + \text{Battery depreciation cost}$$

We assume the incremental cost of an electric truck relative to a diesel truck is simply the cost of the battery (minus cost of diesel engine/transmission, plus difference in cost of diesel and electric drivetrains), and that the battery depreciates at a constant rate per mile.

Under our approach, a lower fuel cost per mile automatically translates into a lower total cost of ownership, because total cost of all other truck components is assumed to be identical.

<table>
<thead>
<tr>
<th>Inputs: electric</th>
<th>Inputs: diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel efficiency</td>
<td>Fuel efficiency</td>
</tr>
<tr>
<td>0.48 mi/kWh</td>
<td>5.87 mi/gal</td>
</tr>
<tr>
<td>Battery capital costs</td>
<td>Diesel price</td>
</tr>
<tr>
<td>$100/kWh and $170/kWh</td>
<td>$3.16/gal (national),</td>
</tr>
<tr>
<td></td>
<td>$2.81/gal (TX), $4.20/gal (CA)</td>
</tr>
<tr>
<td>Battery cycles</td>
<td>Miles/lifetime</td>
</tr>
<tr>
<td>2000/lifetime</td>
<td>1,000,000</td>
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<td>Battery depth of discharge</td>
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<td>75%</td>
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</tr>
<tr>
<td>Miles/year</td>
<td></td>
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<tr>
<td>68,000</td>
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