StorageX Seed Fund Final Report

Transitioning to clean energy transportation services: Life-cycle cost analysis for vehicle fleets
Stefan Reichelstein & Stephen Comello

Context & Objective
With the transition towards renewable power gaining momentum, the global quest for energy decarbonization is increasingly focused on the transportation sector. The impending climate crisis, in combination with concerns about local air pollution, provide a growing impetus to replace internal combustion engines with zero-emission drivetrains. Yet, the economics of clean energy drivetrains, potentially powered by batteries, hydrogen or biofuels, remains a topic of intense debate for both passenger- and cargo transportation services. The central question addressed in this study is how a fleet operator should combine alternative drivetrains with different environmental and economic characteristics so as to meet a given transportation service profile in a cost-efficient manner.

One major contribution of our study is the development of a model framework for identifying cost-efficient vehicle fleets according to a cost metric called the Levelized Cost per X-mile (LCXM). Applicable to any kind of transportation service (passenger and cargo), the LCXM reflects the unit cost of a transportation service, such as a ton- or passenger-mile delivered. Our unit cost concept of the LCXM is related to the Total Cost of Ownership (TCO), a life-cycle cost metric that has been widely used in transportation studies and captures the total discounted cost of acquiring, operating, and selling a vehicle. The LCXM metric extends TCO in the direction of the Levelized Cost of Electricity (LCOE), a unit cost measure commonly used in the energy literature. Our model is predicated on the notion that operating costs are driven by the hours of vehicle operation.

The LCXM metric is shown to yield the cut-off points in terms of annual operating hours that make one drivetrain more economical than another. The cut-off points, in turn, provide the decision criterion for choosing the cost-efficient shares of alternative drivetrains in a fleet that is to meet a given demand schedule or load profile. Thus, the LCXM concept provides a unified framework for examining the (i) cost competitiveness of individual vehicles, (ii) optimal mix of alternative drivetrains in a fleet, (iii) efficient dispatch of alternative drivetrains, and (iv) effect of the characteristics of multi-dimensional duty cycles on the composition of cost-efficient vehicle fleets. Finally, as a lifecycle cost measure, the LCXM also accounts for any environmental externalities that are captured in terms of their pecuniary costs.

The second major contribution of this study is to apply the LCXM model framework in the current economic context of an urban bus service provider in California as a case in point. Relying on recent measurements of cost and operational performance per bus in the provider’s fleet as well as real-time protocols for bus dispatches to routes served, this study specifically contrasts the life-cycle cost of battery-electric buses with that of diesel buses.

Analytical procedure
For a generic transportation service that carries physical objects across locations, the measure of output will generally be ‘X-miles’ (or ‘X-kilometers’ with straightforward conversion). In the context of cargo transports, this measure frequently becomes ton-miles, i.e., if on average z tons of cargo are transported for y miles, the vehicle delivers z·y ton-miles. Similarly, in the context of passenger travel, the corresponding measure could be passenger-miles. For passenger cars, the appropriate measure may simply be miles if the primary purpose of the service is to transport the driver of the vehicle.

Our model is predicated on the notion that operational costs incurred are driven by the total time the vehicle is in operation. For a given T-year planning horizon, we denote by \( \vec{h} = (h_1, \ldots, h_T) \) the usage

---

1 A comprehensive description of the work presented here is found in, Comello, S., Glenk, G. & Reichelstein, S. Transitioning to clean energy transportation services: Life-cycle cost analysis for vehicle fleets. Applied Energy. 285, 116408, 2021.
profile of a vehicle, where \(0 \leq h_i \leq 8,760\) is the utilization in hours of operation in year \(i\). The number of miles traveled in year \(i\) is then given by the average velocity in miles/hour, \(a(\theta)\), multiplied with \(h_i\). Velocity depends on the characteristics of the duty cycle, \(\theta\), a multi-dimensional parameter that captures the relevant performance requirements in a specific transportation context. For transit buses, for instance, the duty cycle reflects the specifics of the route, including the number of bus stops per mile, the ambient temperature, and the topography of the route.

The number of passengers or tons of cargo transported in any given year is also determined by the utilization in that year. Allowing for the possibility of a non-linear relation, we let the function \(b_i(h_i|\theta)\) represent the average number of passengers or tons transported if the vehicle travels \(a(\theta)\cdot h_i\) miles in year \(i\). The total number of X-miles then becomes:

\[
X_i(h_i|\theta) = b_i(h_i|\theta) \cdot a(\theta) \cdot h_i
\]

Turning to cost components, let \(v\) denote the initial acquisition expenditure for the vehicle. At the end of its useful life, the vehicle may yield a salvage value \(\lambda \cdot v\), with \(0 < \lambda < 1\). In terms of annual operating costs, we distinguish between variable and fixed costs in year \(i\). The variable component, \(w_i(h_i|\theta)\), varies with the hours of operation in year \(i\). Fixed costs, \(F_i(\theta)\), are by definition use-independent. Applicable examples for variable operating costs include fuel, spare parts, and the prorated salary for the driver. In contrast, insurance, registration, and certain maintenance activities are fixed costs. In the specific case of an electric vehicle, the cost of the battery warranty, where the potential replacement cost of the battery during the useful life of the vehicle is ‘smoothed’ through periodic warranty payments, would be considered a fixed cost.

Aggregation of the different cost components into a single unit cost number requires a ‘levelization’ factor given by the discounted number of X-miles that the vehicle travels over its useful life. Let \(r\) denote the applicable cost of capital that investors require for a project, with \(\gamma = 1/(1+r)\) denoting the corresponding discount factor. A final cost category stems from corporate income taxes and a depreciation tax shield that a firm or individual may be subject to. This cost category can be summarized, including the potential salvage value, in a factor \(\Delta\) that adjusts the acquisition cost of the vehicle.

Overall, the levelized cost per X-mile is then defined as the sum of three components:

\[
LCXM(h_i|\theta) = w(h_i|\theta) + f(h_i|\theta) + c(h_i|\theta) \cdot \Delta
\]

Results

The preceding framework is applied to the current economic environment of an urban bus service provider as a case in point. Urban bus service providers have been among the first fleet operators to replace diesel-powered vehicles with battery-electric or even hydrogen-electric buses. Stanford University in California initiated this transition a number of years ago. The university provided detailed records of its bus service based on multiple information systems pertaining to energy and fleet management, covering all relevant cost and operational data.

To compare the life-cycle cost of the two drivetrains for different duty cycles, the calculations focus on two distinct routes, referred to as Route A and B. They reflect opposite ends of the range of duty cycles operated by Marguerite, with the number of bus stops per mile at 1.11 and 2.67 and the average velocity at 7.40 and 3.01 miles per hour for Route A and Route B, respectively. Since topography and ambient temperature of all campus routes are virtually identical, Routes A and B generally yield corner solutions for the set of routes operated by Marguerite. While this set reflects common duty cycles for fairly flat topographies in a Mediterranean climate, we might expect regions with more diverse route characteristics to exhibit a wider range of velocity figures. The table below shows average values for the main life-cycle cost components. The net acquisition cost represents the initial purchasing price minus the salvage value and, for electric buses, a capital incentive of $100,000 granted by the California Air
Resources Board. The variable cost comprises fuel costs and variable maintenance costs but excludes the salary of drivers, which is the same across drivetrains.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Diesel</th>
<th>Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable cost per hour (Route A)</td>
<td>$26.25</td>
<td>$2.02</td>
</tr>
<tr>
<td>Variable cost per hour (Route B)</td>
<td>$16.79</td>
<td>$4.77</td>
</tr>
<tr>
<td>Fixed cost per year</td>
<td>$5,054</td>
<td>$5,913</td>
</tr>
<tr>
<td>Net acquisition cost</td>
<td>$425,189</td>
<td>$601,300</td>
</tr>
<tr>
<td>Useful lifetime</td>
<td>12 years</td>
<td>12 years</td>
</tr>
<tr>
<td>Cost of capital</td>
<td>5.00%</td>
<td>5.00%</td>
</tr>
</tbody>
</table>

The figure below depicts the levelized cost curves per mile (LCM) for both drivetrains by route. Beyond the unique critical utilization value, $h^*$, electric buses entail a lower life-cycle cost. These cut-off values amount to 996 hours for Route A and 2006 hours for Route B, marked by the solid vertical lines. The substantially lower cutoff value on Route A mainly reflects that the ratio of the variable costs per hour for the two drivetrains is relatively large on that route. The critical utilization value for the average duty cycle (number of stops per mile) of the entire Marguerite system amounts to 1453 hours.

The next figure depicts the daily load profiles of buses operating in the Marguerite fleet. If hypothetically all Marguerite buses were to run on Route A, the efficient number of diesel and electric buses would amount to 7 and 22, respectively. The corresponding values for Route B are 18 and 11. Since the functions are decreasing, the efficient number of electric buses for Route B is smaller than on Route A, as the corresponding critical utilization factor $h^*$ is larger for Route B. Though the proportion of the two competing drivetrains within the fleet differ significantly for Routes A and B, diesel buses will be dispatched only within the ‘rush-hour’ periods corresponding to peak demand. The load profile depicted in below is an overlay of the hourly profile for individual days in 2019. The more the daily profiles overlap, the darker is the shade of gray. The upper twin peaks represent load profiles on weekdays, while the lower twin peaks display the profile for weekend days.
Conclusion & Future Work

The LCXM metric is calibrated and applied in the context of an urban bus service as a case in point, where the output measure is either miles traveled, or passenger-miles delivered. The findings of this empirical analysis still point to a significant role for diesel buses during peak demand across all types of routes. The critical utilization quantity is highly dependent on route-specific characteristics, and so is the economically efficient proportion of electric drivetrains within a fleet that is required to meet a given load profile. At the same time, the optimal share of diesel buses within a fleet is forecast to diminish substantially in the next five years, provided recent improvements in electric drivetrains continue.

A promising direction for future work is to consider the resale value of the batteries of the battery-electric buses (or any vehicle for that matter) at the end of their first life. It would be informative to see how sensitive the earlier estimates on the life-cycle cost of transportation services are to the inclusion of a resale option in the secondary market. This future work would seek to develop an economic valuation framework that determines the fair market value (FMV) of batteries entering their 2nd-life based on their assessed state of health (SOH) at the end of their first life. This FMV must also take into account the expected salvage value that end-of-life EV batteries are likely to yield once the nascent recycling industry for batteries reaches full scale.