Abstract
In this paper, researchers at the National Renewable Energy Laboratory present the results of simulation studies to evaluate potential fuel savings as a result of improvements to vehicle rolling resistance, coefficient of drag, and vehicle weight as well as hybridization for four powertrains for medium-duty parcel delivery vehicles. The vehicles will be modeled and simulated over 1,290 real-world driving trips to determine the fuel savings potential based on improvements to each technology and to identify best use cases for each platform. The results of impacts of new technologies on fuel saving will be presented, and the most favorable driving routes on which to adopt them will be explored.

Introduction
This study explores modeling the fuel savings potentials of a variety of vehicle optimization scenarios across several powertrains in a medium-duty (MD) parcel delivery vehicle application. Vehicle modeling was performed using real-world data captured from hundreds of vehicles operating across the United States, totaling in excess of 1,000 days of operation. The real-world data used in this project was obtained from several geographic locations, including California, Minnesota, Arizona, Maryland, and Texas, in partnership with parcel delivery industry leaders. These drive cycles were used to explore the benefits of reductions in rolling resistance, aerodynamic drag, and vehicle mass for typical class 5/6 step vans such as is shown in Figure 1.

The National Renewable Energy Laboratory’s (NREL’s) Future Automotive Systems Technology Simulator (FASTSim), a high-level advanced vehicle powertrain systems analysis tool supported by the U.S. Department of Energy’s Vehicle Technologies Office was selected as the modeling platform for use in this study [1]. FASTSim was chosen over alternative modeling options due to its quick and simple approach for comparing powertrains and for its ability to perform large-scale batch simulations in a time-efficient manner.

Table 1. Specifications of the four MD trucks

<table>
<thead>
<tr>
<th>Powertrain Type</th>
<th>Engine (kW)</th>
<th>Weight (kg)</th>
<th>Coeff. of Rolling Resistance</th>
<th>Coeff. of Aerodynamic Drag</th>
<th>Frontal Aerodynamic Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Conv.</td>
<td>149</td>
<td>6,990</td>
<td>0.0071</td>
<td>0.71</td>
<td>6</td>
</tr>
<tr>
<td>Gasoline Conv.</td>
<td>223</td>
<td>6,423</td>
<td>0.0092</td>
<td>0.70</td>
<td>6</td>
</tr>
<tr>
<td>Diesel HHV</td>
<td>209</td>
<td>8,171</td>
<td>0.0092</td>
<td>0.70</td>
<td>6</td>
</tr>
<tr>
<td>Diesel HEV</td>
<td>149</td>
<td>7,375</td>
<td>0.0092</td>
<td>0.70</td>
<td>6</td>
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</table>
In characterizing the fuel consumption from MD vehicles, it is essential that the vehicles are tested or simulated under typical in-use behavior. In this study, several cycles covering a wide range of driving conditions were used. The vehicles were tested over the New York Composite (NY Comp); Heavy Heavy-Duty Diesel Truck (HHDDT); City Suburban Heavy Vehicle Cycle (CShVC); Hybrid Truck Utility Forum Class 4 (HTUF); and Baltimore Custom Cycle (BCC), an NREL custom cycle that includes very aggressive driving behavior representative of real-world parcel delivery vehicle driving behavior in Baltimore, on the chassis dynamometer at the ReFUEL Laboratory to provide continuous fuel rate data. Table 2 shows the characteristics of the standard driving cycles, as well as the custom BCC. The detailed driving information can also be found in our previous research [10]. The parcel delivery trucks were modeled in FASTSim. The truck models were then calibrated by comparing the total fuel consumption (FC) from the chassis dynamometer test and the FASTSim simulation. The relative errors achieved for diesel trucks were all within 5.25%. The results showed that the truck models were sufficiently calibrated and could be used as the basis for future parametric studies. The validation results are summarized in Table 3.

Table 2. Driving cycle characteristics

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Kinetic Intensity (1/mile)</th>
<th>Average Speed (mph)</th>
<th>Stops per Mile</th>
<th>Distance (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NY COMP</td>
<td>8.29</td>
<td>11.4</td>
<td>8.49</td>
<td>1.18</td>
</tr>
<tr>
<td>HHDDT</td>
<td>0.17</td>
<td>35.59</td>
<td>1.63</td>
<td>26.05</td>
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<tr>
<td>CSHVC</td>
<td>2.38</td>
<td>14.15</td>
<td>1.95</td>
<td>6.68</td>
</tr>
<tr>
<td>BCC</td>
<td>1.35</td>
<td>22.57</td>
<td>1.37</td>
<td>20.42</td>
</tr>
<tr>
<td>HTUF</td>
<td>1.51</td>
<td>22.49</td>
<td>2.51</td>
<td>11.17</td>
</tr>
</tbody>
</table>

Table 3. Summaries of test and validation results

<table>
<thead>
<tr>
<th>Cycle</th>
<th>RefUEL Lab (mpg)</th>
<th>FASTSim (mpg)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Conv.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NY COMP</td>
<td>7.15</td>
<td>7.47</td>
<td>4.46</td>
</tr>
<tr>
<td>HHDDT</td>
<td>11.47</td>
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<td>-5.06</td>
</tr>
<tr>
<td>CSHVC</td>
<td>9.48</td>
<td>9.46</td>
<td>-0.21</td>
</tr>
<tr>
<td>BCC</td>
<td>8.52</td>
<td>8.44</td>
<td>-1.02</td>
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<tr>
<td>Gasoline Conv.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>NY COMP</td>
<td>5.77</td>
<td>5.36</td>
<td>-7.26</td>
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<td>HHDDT</td>
<td>9.18</td>
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<td>-4.78</td>
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<tr>
<td>CSHVC</td>
<td>7.85</td>
<td>7.32</td>
<td>-6.75</td>
</tr>
<tr>
<td>BCC</td>
<td>6.54</td>
<td>6.97</td>
<td>6.53</td>
</tr>
<tr>
<td>Diesel HHV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>10.84</td>
<td>11.13</td>
<td>2.67</td>
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<tr>
<td>HHDDT</td>
<td>11.28</td>
<td>11.46</td>
<td>1.60</td>
</tr>
<tr>
<td>CSHVC</td>
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<td>12.28</td>
<td>-0.42</td>
</tr>
<tr>
<td>BCC</td>
<td>10.19</td>
<td>10.53</td>
<td>3.35</td>
</tr>
<tr>
<td>Diesel HEV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTUF</td>
<td>10.00</td>
<td>10.05</td>
<td>0.46</td>
</tr>
<tr>
<td>HHDDT</td>
<td>10.50</td>
<td>10.92</td>
<td>4.00</td>
</tr>
<tr>
<td>NY COMP</td>
<td>8.81</td>
<td>8.66</td>
<td>-1.70</td>
</tr>
</tbody>
</table>

Statistics of Driving Trip Characteristics

More than 1,400 vehicle-day data were collected from MD parcel delivery trucks. After removing vehicle-days with fewer than five miles or more than 150 miles of driving, this study used the remaining 1,290 vehicle-days to support the analysis.
Impact of Parametric Reduction on Fuel Consumption

Rolling Resistance Reduction

Tire rolling resistance is proportional to the product of the coefficient of rolling resistance, vehicle mass, and gravity acceleration, which accounts for around 30% of the vehicle’s resistance to forward motion [12]. The conventional diesel parcel delivery truck was simulated on FASTSim over 1,290 real-world trips by changing the rolling resistance at a constant weight and aerodynamic drag. Figure 5 shows the impacts of rolling resistance reduction and average speed on FC over 1,290 trips at a constant test weight and aerodynamic drag. The impacts of rolling resistance reduction and KI on fuel saving are depicted in Figure 6. Clear trend lines are demonstrated on both plots, which means both average speed and KI can be used for a study of trip characteristics. It also can be seen that 0.5%-1.6% fuel saving would be achieved with a reduction of 10% in rolling resistance, depending on the trips.

The daily fuel savings (in gallons) for the 1,290 vehicle-days were calculated using equation 1.

\[
daySaving = dayFuelSavingRate \times dayVMT
\]

where \( dayFuelSavingRate \) is the daily fuel savings per mile and \( dayVMT \) is the 1,290 vehicle daily trips. Figure 7 shows the daily fuel savings when the rolling resistance is reduced by 5% to 20%. Total daily fuel savings of 1,290 vehicle-days are also displayed on the plot.

Assuming the parcel delivery trucks are used 5 days a week for 50 weeks a year, 1,290 vehicle-days equal 5.15 vehicle-years. The lifetime fuel saving would be 256 gallons, assuming a vehicle life of 15 years. The cost effectiveness of the upfront cost is less than $921 to reduce rolling resistance by 10%, assuming a $3.60 per gallon projected diesel price [13].

Incremental rollout of adopting lower rolling resistance was investigated, beginning with the most favorable driving routes. Figures 8 and 9 show the distributions of probability and cumulative percentage of daily fuel saving when reducing rolling resistance by 5% and 10%. The areas to the right of the vertical lines achieve more fuel saving than the total average fuel saving shown in Figure 8. Figure 9 shows that 40% of the total trips will achieve more than average daily fuel savings. Figures 10 and 11 show daily fuel savings versus the characteristics of driving profiles, which depicts the most favorable trips on which to adopt the new technology. This analysis suggested that the parcel delivery fleet might need to first install equipment to reduce the rolling resistance on trucks driving long distance, low-KI, high-speed trips.

Figure 5. Impacts of rolling resistance reduction and average speed on FC reduction

Figure 6. Impacts of rolling resistance reduction and KI on FC reduction

Figure 7. Daily fuel savings with reduced rolling resistance

Figure 8. Probability distribution of daily fuel saving with reduction in rolling resistance

Figure 9. Cumulative percentage distribution of daily fuel saving with reduction in rolling resistance

Figure 10. Daily fuel savings versus driving profile

Figure 11. Daily fuel savings versus driving profile
Aerodynamic Drag

The metric for evaluating aerodynamic losses is aerodynamic drag, which is a force opposing the motion of the vehicle caused by the resistance of ambient air. Quantitatively, the aerodynamic drag is proportional to the product of the coefficient of aerodynamic drag, the frontal area, and the square of vehicle velocity. Reducing the frontal area usually sacrifices interior size and thus has limited value in reducing aerodynamic drag. Driving slower can also reduce the drag force. However, changing the actual road speed is not realistic, so reducing the drag coefficient is the main way to reduce aerodynamic drag. The conventional diesel parcel delivery truck was simulated on FASTSim over 1,290 real-world trips by changing aerodynamic drag at a constant weight and rolling resistance. Figure 12 shows the impacts of aerodynamic drag reduction and average speed on FC reduction over 1,290 vehicle-day trips. It can be seen that 0.5%-5% fuel saving would be achieved with a 10% aerodynamic drag reduction, depending on the trips.

The daily fuel savings due to aerodynamic drag reduction are demonstrated in Figure 13. Fuel savings for 1,290 total trips are displayed on the plot. Assuming the parcel delivery trucks are driven 5 days a week for 50 weeks a year, 1,290 vehicle-days equal 5.15 vehicle-years. The lifetime fuel saving would be 396 gallons, assuming a vehicle life of 15 years. The cost effectiveness of the upfront cost is less than $1,426 to reduce aerodynamic drag by 10%, assuming a $3.60 per gallon projected diesel price [13].
The vehicle weight affects the engine power required to propel the vehicle through acceleration, rolling resistance, and hill climbing. Reducing the vehicle’s weight could either save fuel or increase the freight carried. The parcel delivery truck was simulated in FASTSim by reducing the curb weight by 5% to 20% over 1,290 real-world trips at a constant aerodynamic drag and rolling resistance.

Figure 17 shows the impacts of weight reduction and average speed on FC over 1,290 day trips. An FC reduction up to 6% was achieved when the curb weight was reduced by 10%. There would be more impact in the real world if grade information were included. The daily fuel savings with weight reductions are demonstrated in Figure 18, with the 1,290 total trips savings displayed on the plot.

Assuming the parcel delivery trucks are driven 5 days a week for 50 weeks a year, 1,290 vehicle-days equal 5.15 vehicle-years. The lifetime fuel saving would be 1,016 gallons, assuming a vehicle life of 15 years. The cost effectiveness of the upfront cost is less than $3,659 to reduce vehicle mass by 10% assuming a $3.60 per gallon projected diesel price [13].

Similarly, the most favorable driving routes on which to adopt lightweight material vehicles were researched. The distribution of cumulative percentage of daily fuel savings when reducing aerodynamic drag by 5% and 10% is shown in Figure 19. A total of 49% of the trips achieve greater-than-average daily fuel saving. Figures 20 and 21 demonstrate the detailed information of fuel savings versus the characteristics of driving profiles. The vehicle speed and KI are not the only key factors that determine the daily fuel savings because the weight affects FC through acceleration and rolling resistance. Trips traveled at large speed over a long distance with large acceleration should be good candidates on which to use lighter-weight trucks.
**Daily Fuel Saving Comparison among Three Technologies**

As seen above, the daily fuel savings significantly differ when different technologies are examined. Figures 22 and 23 show the distributions of probability and cumulative percentage of daily fuel savings when rolling resistance, aerodynamic drag, and weight are reduced by 10%. Overall, with the same amount of technology reduction, the fuel savings are largest for a reduction in weight and least with a reduction in rolling resistance, which is consistent with our observations. It should be noted that fuel savings due to reduced rolling resistance are larger than with same amount of reduction in the aerodynamic drag at low speeds.

**Hybridization**

The use of HEVs allows truck manufacturers to simultaneously improve fuel efficiency and performance. Furthermore, HEV technology could provide a technological and commercial bridge from today’s conventional powertrains for future fuel cell powertrains [14]. HHVs use hydraulic pumps and motors with low-pressure and high-pressure reservoirs to absorb and deliver torque from the drivetrain, which is also practical for commercial truck applications. Both HEV and HHV save fuel because of the following:

- Optimum engine operating region: The engine operates closely to its best fuel efficiency line.
- Engine shut off: Fuel efficiency is very low when the engine operates at a low speed. The engine is shut off when its speed is below a certain threshold to save fuel.
- Regenerative braking: A regenerative brake recovers the kinetic energy produced when braking into electrical energy which can be stored in the energy storage system for future use.

Three trucks with the same specifications (as shown in Table 1) are used to support this analysis. The baseline truck is a conventional gasoline parcel delivery truck, and the two hybrid trucks are an HEV and an HHV. The three trucks were simulated in FASTSim over 1,290 real world trips. The daily fuel savings with hybridization are demonstrated in Figure 24. The total fuel savings over the 1,290 vehicle-days are displayed on the plot.

Assuming the parcel delivery trucks are driven 5 days a week for 50 weeks a year, 1,290 vehicle-days equal 5.15 vehicle-years. The lifetime fuel savings would be 11,377 gallons and 10,509 gallons for HEV and HHV, respectively, assuming a vehicle life of 15 years. The cost effectiveness of the upfront costs is less than $40,956 for the HEV and $37,831 for the HHV to reduce vehicle mass by 10%, assuming a $3.60 per gallon projected diesel price [13].

Likewise, the most favorable driving routes on which to use hybridized parcel delivery trucks were investigated. Figure 25 shows the distribution of cumulative percentage of daily fuel savings when replacing a conventional truck with an HEV or HHV. As observed above, HHVs and HEVs share similar fuel saving behaviors in which approximately 44% of the total trips achieve greater-than-average daily time fuel saving. The detailed information for fuel savings due to hybridization versus the characteristics of the driving profiles is demonstrated in Figures 26 and 27. It should be noted that only the HEV scenarios are shown in the plots since HEVs and HHVs share similar fuel saving behavior. From these figures, we can see that trucks traveling on trips with lower average speeds and high KIs have the largest benefit because the truck has more energy recovery in stop-and-go scenarios. Unlike with reductions in rolling resistance, aerodynamic drag, and weight, the trip distance are not the key factors that determine the fuel saving with hybridization because a long travel distance normally means that trucks travel most of the time on highways.
The impacts of reductions in rolling resistance, aerodynamic drag, and weight, as well as hybridization of the vehicles on fuel savings were investigated, and the most favorable driving routes on which to adopt new technologies were suggested by simulating parcel delivery trucks using FASTSim over 1,290 real-world driving trips. The study revealed that reductions up to 2%, 4%, and 6% in FC were achieved when reducing rolling resistance, aerodynamic drag, and curb weight by 10%, respectively, depending on the characteristics of the driving trips. Overall, with an average of over 12,000 gallons fuel saved daily, the fuel savings due to hybridization surpassed that of reductions in rolling resistance, aerodynamic drag, and weight. This study proposed that, if the cost of new technologies is known, depending on the circumstances it may be more cost effective to adopt one technology to save fuel, or it may be more beneficial to adopt another.

References


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**Definitions/Abbreviations**

BCC - Baltimore Custom Cycle  
CSHVC - City Suburban Heavy Vehicle Cycle  
FASTSim - Future Automotive Systems Technology Simulator  
FC - fuel consumption  
HEV - hybrid electric vehicle  
HHDDT - Heavy Heavy-Duty Diesel Truck  
HHV - hydraulic electric vehicle  
HTUF - Hybrid Truck Utility Forum Class 4  
KI - kinetic intensity  
MD - medium duty  
NREL - National Renewable Energy Laboratory  
NY COMP - New York City Composite  
ReFUEL - Renewable Fuels and Lubricants