ABSTRACT

Hybrid electric vehicles have demonstrated their ability to significantly reduce fuel consumption for several medium- and heavy-duty applications. In this paper we analyze the impact on fuel economy of the hybridization of a tractor-trailer. The study is done in PSAT (Powertrain System Analysis Toolkit), which is a modeling and simulation toolkit for light- and heavy-duty vehicles developed by Argonne National Laboratory. Two hybrid configurations are taken into account, each one of them associated with a level of hybridization. That increases the braking energy recuperation rates. We first analyze the benefits of the two hybrid configurations on standard cycles. We then compare fuel economy results from a short standard highway cycle with a longer cruising scenario to illustrate the sensitivity of the benefits to the drive cycle. Finally, using simulation involving a grade scenario of periodical hills that we designed for this project, we show hybridization can be beneficial on hilly terrain.

INTRODUCTION

Hybridization can lead to significant fuel consumption reduction, which has now been demonstrated in numerous applications for buses [1,2,3], delivery trucks, and utility trucks [4]. However, little work has been published on the application of that technology to class 8 line-haul trucks, even though line-haul trucks consume about 20% of the total U.S. truck fuel use [5]. This work attempts to quantify the impact of line-haul truck hybridization through the use of PSAT (Powertrain System Analysis Toolkit), which is a modeling and simulation toolkit for light- and heavy-duty vehicles developed by Argonne National Laboratory [6, 7]. This work was done to support the National Academy of Science Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles [8,9].

Most of the energy losses occurring in a truck come from the engine. Operating the engine more efficiently can be achieved mainly in two ways: not using the engine at all during low-efficiency operation moments, or shifting the operation point to a more efficient level – for example, by increasing the engine output and storing it in an energy storage system, or by decreasing the engine speed.

The losses due to the tires and aerodynamic losses cannot be displaced by hybridization, because the vehicle follows the same cycle and requires the same amount of power regardless of the source of power. The losses due to the driveline could be in part displaced if the electric power source is put closer to the wheels (e.g., series w/o transmission, post-transmission parallel, in-hub motors), but that is not a practical solution for heavy-duty applications.
The accessory load can be affected by hybridization because some of the mechanical accessories (pumps, compressors, etc.) can be replaced by electric systems, which are more efficient [10]. Electric accessories also allow the engine not to be used when it is inefficient – at idle, for example – and can use energy recuperated from regenerative braking. Accessory electrification is a difficult exercise to replicate in simulation because it requires knowledge of the mechanical accessory load in both conventional and hybrid cases. In this study, Accessory electrification is addressed by shifting some of the load from mechanical to electrical accessories.

A conventional vehicle loses much of the kinetic energy it acquired during acceleration through friction when breaking. A regenerative braking system can recover part of this energy and recharge the energy storage system, and that energy can in turn be used for the accessory load and/or for propulsion.

Hybridization could lead to other indirect fuel savings opportunities that are not necessarily well represented in a cycle-type testing procedure (either actual on a dynamometer or in simulation). If acceleration capability is improved or shifting time is reduced, the vehicle will be less likely to “lose” the trace – where the vehicle speed drops below the target trace speed – and will not need to accelerate as much later, but will perform more “work” (i.e., go a greater distance). On the other hand, the availability of improved performance can lead the driver to request more power in real-world driving conditions, possibly leading to a less efficient use of the hybrid system.

**HARDWARE DESIGN**

**HYBRID CONFIGURATIONS OVERVIEW**

A hybrid vehicle can have one or more electric machines that can be positioned at various points of the powertrain, leading to a large number of configurations. The main configuration families [11] are:

**Series.** In a series configuration [1,3,11], the vehicle is propelled only by electrical power. The engine output power is converted into electricity through a generator and then is either stored in the battery or converted back into mechanical power by the propulsion motor. This configuration is generally the easiest to implement because the propulsion is 100% electric and the generator set is almost an independent system, relatively easy to control. A drawback of this configuration is that both electric machines have to be oversized: the propulsion one to match the vehicle power/torque requirements, and the generator to match the engine power. Another drawback is that at cruising speed the de facto electric transmission has a poor efficiency due to the double conversion of engine mechanical energy.

**Parallel.** In a parallel configuration the vehicle can be propelled directly by the engine or the electric motor(s), or by both at the same time. The vehicle usually has at least one clutch and a multispeed gearbox, similarly to a conventional model. That leads to a relatively good efficiency at cruising speeds, because the engine power goes straight to the wheels via the gearbox and the driveline. The electric machine can either provide positive torque, contributing to the propulsion of the vehicle, or recharge the energy storage by diverting part of the engine torque. There are several variants of the configuration, based on the position of the electric machine.

In a starter-alternator position, the electric machine is between the engine flywheel and the clutch in mild-hybrids, allowing the engine stop/start when the vehicle is stopped. Its main advantage is its ease of implementation and cost effectiveness. However, expected gains are limited by the level of regenerative braking.
In a pre-transmission position [11], the electric machine is between the clutch and the gearbox. In a post-transmission, the electric machine is between the gearbox and the final drive (or transfer case). When the clutch is open the engine is disconnected from the drivetrain but the electric machine is not, allowing an electric-only mode. Post-transmission is not very practical for class 8 trucks due to the lack of torque multiplication for the electric machine. For both pre- and post- transmission configurations, the clutch control is often a challenging engineering problem.

**Series-parallel.** This configuration combines the benefits of the series and parallel pre-/post- transmission configurations. When the clutch is open, the engine can be off, or it can be on and generate electricity through the generator, creating a series path. Generally the series-path is used at low speeds, while parallel is chosen for higher cruising speeds. The series-parallel can be combined with gearboxes with a lower number of gears.

**Power-split.** This configuration is used by Toyota (e.g., Prius) and Ford (e.g., Escape). The engine and a motor-generator are connected to a planetary gearset, to the output of which another motor-generator is connected. This is not a practical solution because it leads to significant oversizing on heavier vehicles in order for them to be able to operate in a broad range of operations.

**Multi-mode power split.** A multi-mode transmission combines several power-split modes, each of them suitable for different operational requirements; in this way component oversizing is not needed. This powertrain configuration can also be combined with fixed gear(s) – adding parallel paths – for extra flexibility on grades or cruising. It is used in buses [2].

**CONFIGURATIONS SELECTED FOR THE STUDY**

Two hybrid configurations were selected for this study: series-parallel and starter-alternator. The conventional series configuration is not well suited for tractor-trailer applications because it is not efficient at cruising highway speeds, which is the most frequent use of such a truck. A multimode hybrid with fixed gears could be an option, but due to the complexity of its design and its control, it will not be considered in this study. The parallel pre-transmission is similar to the series-parallel.

The series-parallel with one electric machine in pre-transmission position (between the clutch and the gearbox) is chosen to be a full-hybrid, with electric-only mode capability. Thanks to another electric machine, the series mode will allow easy engine starts, as well as a recharging capability when the vehicle is stopped.

![Figure 1 – Schematic of the Series-Parallel Configuration (Full-Hybrid)](image-url)
The starter-alternator is selected for a “mild-hybrid” truck, i.e., with engine shut-downs at idle, and mild assists and regenerative braking possible, but with no electric-only mode. Thanks to a low-power electric machine and low-energy battery, the mild-hybrid requires lower upfront investment than the full-hybrid option.

![Diagram of Starter-Alternator Configuration (Mild-Hybrid)](image)

**Figure 2 – Schematic of the Starter-Alternator Configuration (Mild-Hybrid)**

**COMPONENT SIZING**

For light-duty applications, typical sizing requirements are made of four criteria: acceleration (e.g., 0 to 60 mph time), passing (30 to 50 mph time), gradeability at a given speed, and top speed [12]. The same type of requirements could be applied to tractor-trailers. However, there is no industrywide standard, because trucks are customized to fleet requirements. Another major difference between the two applications is that heavy-duty vehicles often operate at maximum power, especially during grades. Starting from a conventional truck, no engine downsizing can be done because the battery energy is limited to a short duration. In this study the engine size is therefore the same as in the conventional version.

Table 1 summarizes the component sizing for this study. In the case of the less expensive and simpler starter-alternator, the electric machine power is set at 50 kW. For the series-parallel truck, the same size of electric machine is used for the generator (motor 2), while the propulsion electric machine (motor 1) has 200 kW power. The battery power matches the electric machine power. The battery energy is 25 kWh for the full-hybrid – enough to provide an average 1.5 kW load for 10 hours within the 90–30% battery state-of-charge (SOC) operating window. In the case of the mild-hybrid, the battery is only 5 kWh to limit the cost of the system. For both hybrid trucks, the gearbox remains unchanged compared with the conventional. In the case of the series-parallel, the number of gears could probably be reduced with a longer use of the series mode. There is certainly room for improvement in the combination of sizing and control strategies and that could be a full study in itself.

To illustrate the sensitivity of fuel savings to mass, or the lack thereof, two different masses are sometimes used in this study: 26,000 kg (half-loaded trailer) or 36,300 kg (fully loaded truck, gross vehicle weight). In most of these cases the figure for only one mass is shown, and the figure for the other mass is in the appendix.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Mild Hybrid</th>
<th>Full Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Power (kW)</td>
<td>317</td>
<td>317</td>
<td>317</td>
</tr>
</tbody>
</table>

Table 1: Summary of Component Sizes
CONTROL DESIGN

The vehicle level controller manages the different hybrid powertrain components: engine, electric machine(s) and transmission (clutch and gearbox) in order to optimize fuel consumption, while maintaining the battery state-of-charge within appropriate levels. Table 2 summarizes the control for both configurations.

Table 2: Summary of Control Strategy

<table>
<thead>
<tr>
<th></th>
<th>Mild Hybrid</th>
<th>Full Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine ON/OFF</td>
<td>ON when the vehicle is moving.</td>
<td>ON if the power request is above a certain threshold, or if motor is saturating.</td>
</tr>
<tr>
<td></td>
<td>OFF when the vehicle is stopped.</td>
<td>OFF if the power request is below a certain threshold, and below a vehicle speed threshold.</td>
</tr>
<tr>
<td>SOC Regulation</td>
<td>Hysteresis: if SOC is below a threshold, engine is ON and charges the battery until the SOC reaches a higher threshold. The level of torque assist depends on the SOC.</td>
<td>Hysteresis: if SOC is below a threshold, engine is ON and charges the battery until the SOC reaches a higher threshold. The level of torque assist depends on the SOC.</td>
</tr>
<tr>
<td>Shifting/Transmission</td>
<td>Same shifting control as for conventional manual.</td>
<td>Series mode at low speeds, parallel otherwise; clutch open when engine is off. Quick shifting time due to speed synchronization by electric motors.</td>
</tr>
<tr>
<td>Torque Assist</td>
<td>Difference between requested torque and peak engine torque if the engine is saturating.</td>
<td>Difference between requested torque and peak engine torque if the engine is saturating.</td>
</tr>
<tr>
<td>--------------------</td>
<td>--------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Percentage of total torque demand, when it is high enough.</td>
<td>Percentage of total torque demand, when it is high enough.</td>
</tr>
<tr>
<td></td>
<td>No assist above a vehicle speed threshold that depends on SOC.</td>
<td>No assist above a vehicle speed threshold that depends on SOC.</td>
</tr>
<tr>
<td>Braking</td>
<td>Engine fuel is cut off.</td>
<td>Engine fuel is cut off.</td>
</tr>
<tr>
<td></td>
<td>Clutch locked to allow regenerative braking.</td>
<td>Clutch locked if engine is ON, open otherwise.</td>
</tr>
</tbody>
</table>

**STANDARD DRIVE CYCLES RESULT**

All versions of the truck (conventional, mild-hybrid, and full-hybrid) were simulated on various standard cycles [9], both highway (HHDDT 65, HHDDT Cruise, HHDDT High Speed) and transient/urban (HHDDT Transient, UDDS Truck). Table A-1 in the Appendix summarizes the main characteristics of each cycle. All results are “charge-balanced,” meaning the battery energy used during the cycle is negligible compared with the fuel consumption. The results are presented for the half-loaded trailer, while the figures corresponding to the fully loaded trailer are in the Appendix (Figures A-1 through A-5).

Figure 3 shows the fuel consumption of all three trucks, while Figure 4 illustrates the fuel savings compared with conventional. Fuel savings are lower on the highway cycles for both hybrids, which is to be expected because the hybrid system does not contribute much at cruising speeds where the engine already operates efficiently. The fuel savings also tend to be lower with added mass. Fuel savings are due to several factors: no engine idling when vehicle is at a stop, regenerative braking, use of “free” braking energy for accessories, and, for the full-hybrid, electric propulsion in low-load situations. It is, therefore, in urban driving, with its numerous accelerations, decelerations, and stops, that hybridization is the most beneficial.
Figure 3: Fuel Consumption of Conventional and Hybrid Trucks (50% Load) on Standard Cycles

Figure 4: Hybrid Truck Fuel Consumption Reduction with Respect to Conventional Truck (50% Load) on Standard Cycles

Figure 5 shows the fraction of the total braking energy that is recovered at the wheel – which does not include driveline and electric machine losses involved in the channeling of that energy into the battery. The recovery rate depends on the cycle aggressiveness during deceleration. On the HHDDT Cruise cycle, which has the lowest deceleration levels among the cycles, the full-hybrid manages to recover almost all of the braking energy – mechanical brakes are almost never used – but only half of it in the HHDDT 65. The mild-hybrid recovers about 25% of the braking energy on most cycles, peaking at 55% on the HHDDT Cruise. This is due to the much lower power of the electric machine, combined with a higher torque interruption time during shifting. Increased mass results in higher braking force or power for the same deceleration and, as a consequence, a heavier truck is more likely to reach its regenerative braking torque limitation sooner than a lighter one; hence the lower figures for the fully loaded truck.
The engine efficiency does not improve significantly in most cases, as shown on Figure 6. In particular, in the mild-hybrid case, the engine efficiency can even be slightly lower than in the conventional case. The main difference in engine operations between the conventional and the mild-hybrid is that the engine is shut down when the vehicle is stopped for the mild-hybrid, whereas the operations are similar when the vehicle is moving. In addition, the mechanical accessory load is much higher for the conventional (5 kW vs. 1 kW), and additional load generally improves efficiency. For the full-hybrid, the efficiency improvements are limited on the highway cycles but are significant on the transient/urban cycles, where the low-efficiency operations can be replaced by electric-only mode.

**Figure 5: Percentage of Braking Energy Recovered at the Wheels (50% Load)**

**Figure 6: Average Engine Efficiency of Conventional and Hybrid Trucks (50% Load) on Standard Cycles**

**DRIVE CYCLE SENSITIVITY**

A typical drive on the highway would, however, be longer, so one possible way of simulating such a trip would be to simply iterate the same cycle several times – but it would then include unrealistic stops. To avoid this...
issue, a new cycle was designed based on the original HHDDT 65. The initial acceleration and final deceleration part were kept, while several iterations of the cruising part were inserted in between them, resulting in a longer cycle that does not include intermediate stops. Five iterations of the HHDDT 65 cycle correspond to a 2h39, 132-mile trip, while the new cycle is 1h57, 118 miles. A schematic of the two options can be found in Figure A-6 in the Appendix.

Figure 7 shows the impact on fuel consumption of removing stops from a highway cycle. All trucks, hybrids and conventional, have lower fuel consumption on the cycle without stops. The conventional truck benefits the most – 4.2% improvement when fully loaded. Because four accelerations from 0 to 65 mph were removed, the engine runs at full (and efficient) load more often. A hybrid benefits less, because it can recover part of the kinetic energy acquired during acceleration anyway, so acceleration and braking are not as penalizing. As a result, the fuel consumption reduction achieved through hybridization is much lower in the cycle without stops. In the case of the full-hybrid, the consumption reduction is more than halved (5.3% fuel saved on a cycle with stops; 2.4% fuel saved on a cycle without stops).

![Figure 7: Reduction in Fuel Consumption When Stops Are Removed; with Respect to Conventional Without Stops; and with Respect to Conventional with Stops (50% Load)](image)

This example illustrates the sensitivity of hybridization to the driving cycle, especially when the cycle consists mainly of cruising at highway speeds. Adding idling periods would also impact results.

**HYBRIDIZATION AND GRADE**

In the previous simulations, the road driven was flat. In real-world, trucks regularly drive uphill or downhill. Driving downhill may involve braking, which can be an opportunity for fuel savings when using regenerative braking. Because of the lack of real-world drive cycles that included grade, idealized sinusoidal road profiles were created for this project to illustrate the potential benefits of hybridization in a “hilly” terrain. The elevation of such a road is a sinusoidal function of the horizontal distance, with a “hill” period varying between 1 and 3 km. Maximum grades also vary from 0 to 4%. All combinations of maximum grade and period were analyzed. Figure 8 shows an example of elevation change as a function of horizontal distance for roads with the same maximum grades (3%) but different hill periods.
ADAPTIVE CONTROL

The control described previously was designed to ensure proper SOC fluctuations, but at steady speed with grades, further tuning is needed to take full advantage of the hybrid system. To ensure that all recoverable energy while braking downhill is recovered and that it is fully used for the next ascent or for accessories, the control was tuned for each cycle to ensure a relatively optimal operation on grades. The results may therefore be slightly optimistic for hybrids, but an intelligent controller (e.g., GPS based) should be able to come close in real-world driving. Grade-recognition look-ahead controllers already exist for automated shifting and cruise control, as well as in hybrid controls [13,14,15].

SIMULATION PARADIGM

A simulation performed on a time basis, as in PSAT, may in some cases lead to an incorrect representation of how a trip is performed – the same reasoning applies to dynamometer tests with a vehicle speed trace. When the simulation is performed based on time, the vehicle speed and grade targets are given at each time step. So long as the vehicle follows the speed trace closely, the difference between what the vehicle is supposed to do (per the cycle) and what it actually does (in simulation) is negligible. This is a nonissue for light-duty applications, where the vehicle is always able to meet the trace. On the other hand, heavy-duty vehicles, especially tractor-trailers, often operate close to their peak power, creating more chances that the vehicle cannot follow the trace. A lower speed than the trace leads to a lower traveled distance, and to a different type of work performed.

In the case of the sinusoidal grades studied here, the conventional vehicle is not able to keep the target speed at some of the highest grades. The full-hybrid loses less speed in the steepest grades because the electric motor can assist at the peak of the grade. As a result, the conventional truck completes a shorter distance on the uphill than the full-hybrid. It is as if the conventional were driving on a road with the same downhills, but with shorter uphills. Figure 9 (as well as Figure A-7 in the Appendix) compares the non-completion of the scheduled work for the three powertrains.

The quantitative impact on fuel consumption of the power/torque limitation is not addressed in this study, but the reader should keep in mind the uncertainty added by an inability to follow the trace. Another uncertainty in
the representativeness of this simulation is the constant speed assumption. It may be the case that an actual driver will not brake downhill so that he can be at a higher speed before starting the next hill. If there is no braking, there is little or no gain to expect from hybrid models.

Figure 9: Share of Uphill Distance Not Completed (100% Load)

RESULTS

As shown on Figure 10, the motor’s mechanical power varies periodically, with a positive peak during the uphill, where it assists the engine, and a negative one during the downhill, where it regenerates energy from braking. Doing so allows the battery SOC to remain balanced. Figure 11 shows how those peaks are affected by hill period or maximum grade. The maximum torque during assist is lower (in absolute value) than during braking, because part of the recovered braking energy is used for the accessories. For the mild-hybrid truck, the motor reaches its rated power when braking for grades 3% and higher when half-loaded and 2.5% and higher when fully loaded. The full hybrid hits its regenerative braking limit only when fully loaded at or above 3.5% grade.
The fuel savings achieved by both hybrid trucks are showed on Figure 12. At 1% grade, there is no need for the driver to brake in order to stay at 60 mph, and regenerative braking is not possible, so hybridization gains are limited. At 2% grade, there is a limited amount of braking, but even at full recuperation rate, the energy recovered is not enough to supply the energy for the accessory load. Charge balancing is difficult to achieve in that mode, and charging from the engine may occur, which explains the difference in trends. At or above 2.5%, the downhill grade is steep enough to recover enough energy for the accessory load and for some torque assist.

Above 3% grade, the mild-hybrid savings stop increasing because the additional braking energy available cannot be recovered by the small motor. For high grades, the fuel savings for the full hybrid are all the higher that the hill period is shorter. This is due not to the hybrid itself, but to the conventional, which consumes more fuel when the hill period is shorter (and elevation is lower).
The theoretical example of a road with a sinusoidal elevation profile shows that hybridization with adaptive control strategy can lead to significant fuel savings – up to 16% for a fully loaded full-hybrid truck. Further investigation using real-world drive cycles and grade would be required to verify the real-world representation of the sinusoidal road scenario.

**SUMMARY/CONCLUSIONS**

In this study, the potential of hybridization for heavy-duty line-haul tractor trailer trucks was evaluated using Argonne’s modeling and simulation tool, PSAT. Two different vehicles were defined. The full-hybrid truck is a series-parallel hybrid with large electric components (battery, motors) and offers the highest fuels savings, thanks to features such as electric-only mode. The mild-hybrid requires smaller components, and therefore less upfront investment, while still featuring start/stop and regenerative braking. Hybridization leads to significant
fuel consumption reduction in urban driving: 20–40% for the full-hybrid and around 10% for the mild-hybrid. On longer, highway-type cycles, those gains are significantly reduced to single-digit figures. When cruising on roads with moderate and short grades, hybrids can also bring fuel savings. By recuperating the energy needed to brake downhill and reusing it for assist or accessories, the fuel savings can be up to 8% for a mild hybrid and 16% for a full-hybrid, both fully loaded, in the case of a regularly undulating road – which may be a best-case scenario.

We also identified several elements that would require further exploration. The design adopted for the hybrid has endless possibilities because many combinations of configurations, ratios, and component sizes can be simulated. Cost and return-on-investment should also be taken into account when selecting the design. Furthermore, some energy management strategies, such as torque assist, are more difficult to apply for a heavy-duty truck because they often operate at, or close to, peak power and complicate battery SOC management. Road recognition, using GPS, for example, will probably be essential to designing the optimal controllers. We also pointed to the issue of representativeness of time-based duty-cycles (for both simulation and dynamometer testing), which disfavor vehicles that can follow the target speed more closely than the baseline vehicles. This is the case for the hybrids which follow the trace better, but their additional work is not taken into account in the fuel consumption figure. A short highway cycle also leads to too-optimistic results, because it creates stops/accelerations that would not occur on a typical multihour trip. The possible change of driving behavior when confronted with the expanded capabilities of a hybrid truck should also be taken into account. Finally, hybridization can foster accessories’ electrification, leading to further fuel savings.

Future work will address some of the challenges and unknowns of line-haul truck hybridization: design optimization, cost evaluation, control optimization, evaluation on real-world drive cycles and with a distance-based driver model, and accessories’ electrification.

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APPENDIX

Table A-1: Main Characteristics of Drive Cycles

<table>
<thead>
<tr>
<th>Average Speed (mph)</th>
<th>Maximum Speed (mph)</th>
<th>Maximum Acceleration (m/s²)</th>
<th>Maximum Deceleration (m/s²)</th>
<th>Distance (mi)</th>
<th>Duration (s)</th>
<th>Time Stopped (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel Consumption (gal/100mi)</td>
<td>Fuel Savings (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------</td>
<td>------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HHDDT 65</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cruise</td>
<td>50</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Speed</td>
<td>50.2</td>
<td>-1.2</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Transient</td>
<td>15.3</td>
<td>-2.4</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td><strong>UDDS Truck</strong></td>
<td>18.7</td>
<td>-2.1</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure A-1: Fuel Consumption of Conventional and Hybrid Trucks (100% Load) on Standard Cycles

Figure A-2: Hybrid Trucks Fuel Consumption Reduction with Respect to Conventional Truck (100% Load), on Standard Cycles
Figure A-3: Percentage of Braking Energy Recovered at the Wheels (100% Load)

Figure A-4: Average Engine Efficiency of Conventional and Hybrid Trucks (100% Load) on Standard Cycles

Figure A-5: Fuel Consumption Reduction When Stops Are Removed; with Respect to Conventional Without Stops; and with Respect to Conventional with Stops (100% Load)
Figure A-6: HHDDT 65 Cycle Repeated Five Times with Stops (left) and Without Stops (right)

Figure A-7: Share of Uphill Distance not Completed (50% Load)

Figure A-8: Share of Uphill Distance not Completed (100% Load)
Figure A-9: Fuel Consumption of Conventional, Mild-Hybrid and Full Hybrid Trucks (50% load) on a Sinusoidal Road as a Function of Grade (and for Various Hill Periods).

Figure A-10: Fuel Consumption of Conventional, Mild-Hybrid and Full Hybrid Trucks (100% load) on a Sinusoidal Road as a Function of Grade (and for Various Hill Periods).