Exploring Fuel Saving Potential of Long-Haul Truck Hybridization

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ABSTRACT
We report results of comparisons the simulated fuel economy for parallel, series, and dual-mode hybrid electric long-haul trucks, in addition to a conventional powertrain configuration, powered by a commercial 2010-compliant 15-L diesel engine over a freeway-dominated heavy duty truck driving cycle obtained via measurement during normal driving conditions. The results indicate that both parallel and dual-mode hybrid powertrains are capable of improving fuel economy by 7-8%. However, there was no significant fuel economy benefit for the series hybrid truck because of internal inefficiencies in energy exchange. When reduced aerodynamic drag and tire rolling resistance are combined with hybridization, there is a synergistic fuel economy benefit for appropriate hybrids that increases the fuel economy benefit to more than 15%. Long-haul hybrid trucks with reduced aerodynamic drag and rolling resistance offer lower peak engine loads, better kinetic energy recovery, and reduced average engine power demand. Thus we expect that hybridization with load reduction technologies offer important potential fuel energy savings for future long-haul trucks.

INTRODUCTION

Class 8 long-haul trucks are the largest CO_2 emitters and fuel users, consuming nearly two-thirds of the fuel among all heavy-duty (HD) trucks (*1*). The benefits of hybridization have been previously recognized for trucks in urban environments, but the benefits are less clear in the case of long-haul trucks that operate primarily over highways. For example, it has been argued that long-haul trucks have been so well optimized already that there is little opportunity to generate additional significant benefits with hybrid technology (*2*). This is supported by the recognition that long-haul driving involves relatively steady speeds, and thus there are few opportunities for regenerative braking. However, it also seems reasonable that even small fuel-efficiency increases might be important for long-haul trucks because of their extremely high annual mileage and fuel consumption (*2*). For example, even a 5-10% reduction in fuel consumption could lead to a large net savings in annual fuel cost.

Current hybrid vehicle powertrains are constructed in three main configurations: parallel, series, and series-parallel (or dual mode) (*3*, *4*). In a parallel configuration, the truck is propelled separately by either the engine or electric motor, or by both at the same time. The presence of two power sources makes it possible to keep the electric motor and battery smaller and reduce hybrid vehicle cost (*5*). In a series configuration, propulsion is provided entirely by an electric motor, and the engine drives a generator that converts the mechanical power into electricity. The electricity either directly powers an electric motor (which drives the wheels) or it is stored in a battery for future use. Series hybrids usually require larger motors and batteries, increasing the cost significantly. While series hybrids have some advantages in heavy stop-and-go conditions and allow the engine to operate at a peak efficiency condition most of the time it runs, there is an efficiency penalty associated with the dual-step conversion of energy (*5-6*). Series-parallel (or so-called dual-mode) hybrids are more complex than either series or parallel systems. The dual-mode hybrids are designated with the ability to operate in either series mode at lower speeds or parallel mode at highway speeds (*6*). Each of these different hybrid configurations has unique advantages in specific driving conditions. However, there is very limited information about hybridization in long-haul trucks. Thus we were motivated to conduct this study in an attempt to better understand the potential value of hybridization in both current and future long-haul trucks over real-world driving conditions.

In this paper, long-haul hybrid trucks with each of the above configurations were simulated to estimate their relative fuel economy and energy savings in real-road driving conditions. We also simulated combinations of the hybrid powertrains and other advanced technologies for reducing aerodynamic drag and rolling friction. As a reference point, we assumed that the trucks were powered by a commercial 2010-compliant 15-L diesel engine. The fuel efficiency of these hybrids was compared with a truck having a conventional powertrain powered by the same engine. Our goal was to identify potential advantages and also possible technical barriers for applying hybridization to long-haul trucks. The simulations utilized transient engine, Li-ion battery, aerodynamic drag, rolling resistance, and auxiliary load models developed at the Oak Ridge National Laboratory (ORNL), which are implemented in the Autonomie software platform (*6*). We used these tools to simulate the HD truck engine performance with and without other advanced load reduction technologies over a freeway-dominated heavy duty truck driving cycle measured in normal on-road driving conditions.

LITERATURE REVIEW OF HYBRID FUEL ECONOMY

Several studies have shown that hybridization can considerably increase fuel economy of light-duty (LD) vehicles. The results reveal that LD vehicle hybridization can increases fuel economy by more than 30% and 50%in highway and city drive conditions, respectively (*7*-*8*). Hybridization also provides significant fuel saving for medium-duty (MD) vehicles, especially frequent stop-and-go driving that is typical of utility vehicles, pickup and delivery trucks, and transit buses, which offers many opportunities for regenerative braking (*9*-*10*). The U.S. Environmental Protection Agency (EPA) and the DOE estimate that the fuel consumption of pick-up and delivery trucks and transit buses could be reduced by 25 to 50 percent with hybrid powertrain technology (*9*-*10*).

Hybrid technology in Class 8 HD applications is still in the early stages. Unlike LD and MD vehicles with substantial regenerative braking energy related to heavy "stop-and-go" driving, long-haul trucks typically operate in highway with limited regenerative braking energy so that the designated hybrid LD/MD systems do not fit long-haul trucks (*11*). A great amount of effort has been put into modeling and simulation to evaluate the benefits of hybrid technologies and to assist with sizing hybrid drivetrain components. The simulated results illustrate that Class 8 hybrid trucks can improve fuel economy more than 30% in city driving condition (*3*, *12*-*13*). Compared to city driving conditions, HD long-haul hybrid trucks achieve much less benefits, typically gaining 3 to 6%, over highway conditions (*3*, *12*-*14*). For highway conditions with significant grades, hybrid benefits are strongly influenced by the hybrid control strategy employed. For example, a 55 mph vehicle speed constraint considered in the control strategy could yield fuel savings of 2-4% (13). For long-haul trucks, this level of fuel savings from hybrid technology is still attractive to fleets (*12*), because it could still save significant annual fuel costs due to the extremely high annual mileage and high fuel consumption that are typical of these vehicles.

Consequently, the major manufacturers, including Peterbilt, Volvo, and ArvinMeritor etc., started to offer Class 8 hybrid vehicles for specific applications (*15*-*17*). Most of these hybrid trucks are parallel hybrid systems, but dual-mode hybrids are also delivered by ArvinMeritor. In the dual-mode hybrid, the truck is propelled by an electric motor under 48 mph, transitioning to diesel power at highway speeds (*17*). The limited tested results conducted by National Renewable Energy Laboratory (NREL) with Coca-Cola show that the prototype Class 8 parallel hybrid tractors with an Eaton hybrid system demonstrated 13.7% higher fuel economy than the comparable conventional tractor over combined city and highway driving (*2*).

However, there are few open data and reports available for detailed comparisons among the various hybrid powertrain and maximizing their potential benefits in long-haul trucks. This is mainly due to the fact that the implementation of hybrid technology into a HD truck implies a complex integration of mechanical and electric propulsion systems (*18*). It requires not only the optimized combination of engine, aftertreatment devices, motor and battery, and drivetrain, but also the understanding of comprehensive operational data for the power demanded from a HD vehicle, including auxiliary loads, aerodynamic drag, rolling resistance, and drivetrain losses (*18*-*19*). Thus, developing an accurate modeling capacity that can accurately evaluate the interactions between the battery energy, emissions control, and power demands (including auxiliary loads) and correctly determine the fuel efficiency and emissions in HD hybrids is critical for the successful development of commercially viable products and systems.

METHODOLOGY

Hybrid Truck Modeling

To evaluate the energy savings from long-haul hybrid trucks, a baseline conventional (or non-hybrid) Class 8 truck configuration was specified using Autonomie. This baseline non-hybrid truck configuration was adopted from a previous truck model developed by ORNL for a Class 8 truck powered with a 2004 Cummins ISX 475 15-L diesel engine (*13*). The non-hybrid truck model has been validated against experimental data measured from a 2005 Volvo tractor powered by a 2004 Cummins diesel engine at West Virginia University (WVU) over multiple truck cycles (*20*). The predicted and measured fuel economies were 4.55 mpg vs. 4.63 mpg, respectively, for a measured UDDS truck cycle. Considering the fact that the 2004 diesel engine is an older model, the new baseline truck was updated to include an engine model representing a 2010-certified Cummins 15-L, 6-cylinder diesel engine and a 10-speed manual transmission. Table 1 lists the basic specifications of the baseline Class 8 conventional truck.

For the Class 8 hybrid truck simulations performed, three hybrid powertrain configurations were specified, including a pre-transmission parallel configuration with a single motor, a series configuration without a transmission, and a pre-transmission parallel-series configuration with two motors. In the modeled vehicles, all mechanical loads in the conventional truck were assumed to be replaced with electrical loads in the hybrid trucks. The selected electric motor and battery for the hybrid trucks are listed in Table 1. Other powertrain and drivetrain components are the same as those utilized in the simulated conventional HD truck. The default vehicle level hybrid controllers from Autonomie were used to manage powertrain components (such as the engine, electric motor and transmission) and maximize the fuel efficiency (*21*). All of the hybrid truck simulations adopt sustainable charge control strategies, and there are no vehicle speed constraints imposed. This allows the hybrid to maximize the energy savings. For the dual-mode hybrid, the hybrid is assumed to operate in series mode below 15 mph and parallel mode at highway speeds.

Engine Model and Performance Map

A model of a Cummins ISX 475 15-L, 6-cylinder diesel engine, which is certified to 2010 EPA emissions regulations, was used in the simulated trucks, and the modeling was based on static steady-state maps to predict engine fuel consumption solely on the instantaneous speed and load. The 2010 Cummins engine performance maps were derived from measurements on an engine dynamometer at the ORNL Vehicle System Integration (VSI) Laboratory. To further characterize the hysteresis associated with the complex transients occurring during realistic driving, dynamic correction factors for steady-state maps were developed and added to account for recent engine history to give more accurate estimates of engine performance. These correction factors are modeled as dynamic first-order lags associated with heat-up or cool-down of major engine components and the rate at which excess heat is added to the engine from combustion or lost to the surroundings. The engine model was developed in Matlab/Simulink format. The fuel consumption and exhaust properties predicted by the model compared very well with various transient measurements from both lean and stoichiometric engines, as the errors between the predictions and measurements are within 5-10%, reported in a previous publication by the present authors (*22*).

Li-ion battery model

An equivalent-circuit battery dynamic model was developed to account for the Li-ion battery physics using electrical circuit analog components based on the open literature (*6*). These components include voltage sources, variable resistors, and capacitors. More specifically, the equivalent circuit model accounts for open circuit voltage, ohmic resistances in the connector, electrodes and electrolyte, and two sets of parallel resistor-capacitor combinations to reproduce the effects of mass transport and the electric double layer. The model is able to effectively simulate both the steady-state and transient battery responses that have been observed in Li-ion batteries. The model has been well validated with experimental measurements from the open literature (*23*). For example, the simulated voltage profiles using the model for a Li-Ion battery subjected to periodic pulse discharges and charges matched the experimental Li-ion observations within 1% error except that the accumulated charge level is below 5%. The battery model has been implemented into the current vehicle system model and used to simulate any size of Li-ion battery package through flexible parallel and/or series battery cell connections.

Auxiliary Load Model

Data from the open literature were utilized to develop a transient auxiliary load model (*6*). For a conventional truck, this auxiliary load model accounts for the mechanical energy consumption of the belt-driven air-brake compressor, engine fan, air-conditioning compressor, lubricant oil pump, power steering, engine coolant pump, and transmission-fluid pump. Meanwhile, a typical constant value for the electrical load of 600W is assumed to be employed in a conventional vehicle, based on a calculation based on SAE J1343 (*24*). All mechanical loads are considered as functions of engine speed, driving conditions, driver response for load demand, and 'on' time required for each accessory component. For a hybrid truck, all the above mechanical auxiliary loads are replaced with electrical loads, and are no longer considered as functions of the engine speed. Additionally, the hybrid auxiliary load model includes electrical energy consumption for battery cooling and electrical device cooling, which are important in hybrid vehicles. The 'on' time required for each component also depends on the drive cycle to reflect realistic transient demands. To keep the problem simple, a set of simple on/off duty cycles were developed for each auxiliary device in order to describe the critical 'on' time required for each accessory component (*6*).

Transient Driving Cycles

The fuel economy and exhaust emissions of heavy-duty vehicles can be tested on a chassis dynamometer using different emissions test schedules such as the Urban Dynamometer Driving Schedule (UDDS) truck cycle and the Heavy Heavy-Duty Diesel Truck (HHDDT) cycle. Although these driving cycles include the basic operating conditions of heavy-duty trucks, they do not reflect the real driving conditions for Class 8 long-haul trucks. To evaluate the fuel consumption of long-haul trucks over real road conditions, a freeway-dominant heavy duty truck (FDHDT) driving cycle was selected from ORNL duty cycle data (*20*). The drive cycle was measured during normal operations from class-8 tractor-trailers in a fleet engaged in freight delivery. The FDHDT covers 196.4 miles in 3.72 hours and includes significant grades (see Figure 1). The cycle is dominated by highway operating conditions, but also contains significant idling and limited city driving conditions. Specifically, the cycle comprises 12%, 13% and 75% time for idle, 0-50mph, and above 50mph, respectively. Such a cycle has been found to be rather typical of highway dominant trucking operations (*25*), and the driving cycle is able to reasonably reflect the impact of real road conditions on long-haul truck fuel consumption.

RESULTS

Weight is a key factor for Class 8 long-haul truck fuel economy (*20*). To account for this effect, three different truck masses were simulated, including 16,000 kg (light), 25,000 kg (medium), and 35,000 kg (heavy). For the hybrid truck cases evaluated, the additional mass listed in Table 1 was included to account for the weight penalty imposed by the motor, battery, and accessory components.

Figure 2 summarizes fuel economy results for non-hybrid and hybrid trucks over the freeway-dominated heavy-duty truck driving cycle. We observe that the estimated benefits of hybridization are significantly different between the hybrid powertrain technologies. Both parallel and dual-mode hybrid powertrain technologies are capable of improving fuel economy by 7-8%. Compared to the parallel configuration, the dual-mode hybrid achieves nearly 0.5% better fuel economy. The reason why the dual mode hybrid does not give better energy saving is that the driving cycle includes rather limited periods of stop and go as would be experienced in city driving conditions. The figure also reveals that the fuel economy of the simulated series hybrid truck is substantially less than not only the other hybrid trucks, but also the non-hybrid truck. This is caused by an effective efficiency penalty for the series hybrid associated with the dual-step conversion of energy (i.e., mechanical to electric to mechanical).

The detailed component energy losses for the simulated conventional, parallel, series, and dual-mode hybrid trucks are shown in Figure 3. In the analysis, each hybrid truck energy loss was normalized based on the conventional truck fuel energy consumption level. As expected, the series hybrid truck leads to substantially higher energy loss for the motor and generator. For example, the energy loss of the motor and generator in the series hybrid is 7.4%, but the corresponding losses are just 1.0% and 0.8% for the parallel and dual-mode hybrids, respectively. This is not surprising with the unique operating mode of mechanical - electric - mechanical energy conversions, including averaged 91% generator efficiency in the mechanical to electric energy conversion and averaged 90% motor efficiency in the electric to mechanical energy conversion, in the series hybrid, which causes significant motor and generator energy losses and more than offsets the higher engine efficiency. Consequently, the series hybrid powertrain leads to insignificant or even a negative impact on fuel economy over the FDHDT cycle. Series hybrids may provide advantages only if the energy savings associated with the improved engine efficiency are greater than the energy loss due to the dual-step conversions of energy. This typically occurs in heavy stop-and-go, low-speed conditions such as transit buses. It is noted that the authors have performed a similar comparison of hybrid and conventional powertrains for transit buses (*9*), and it was found that the series hybrid configuration can yield improved fuel economy for some drive cycles.

We also observe that all the hybridization technologies reduce cumulative accessory loads (see Figure 3) and peak accessory loads (see Figure 4). Accessory loads represent 2.3% of the conventional truck's energy losses, but it is reduced by more than by 40% for the hybrid configurations (e.g. 1.2-1.4%), which provides over 2% fuel savings by itself. As shown in Figure 3, the main energy losses (other than the engine losses) for long-haul trucks are from aerodynamic drag and rolling resistance. Compared to the aerodynamic load and rolling resistance losses, the braking energy loss is also much smaller. Thus it is particularly important to manage the energy losses relevant to rolling resistance and aerodynamic load for improving long-haul truck fuel economy. This has been emphasized in the roadmap and technical white papers presented by the 21st Century Truck Partnership (*18*).

The above results have been confirmed to be at quite similar levels in simulations using another measured freeway drive cycle selected from ORNL duty cycle data (*20*). The second cycle covers 262.7 miles in 5.29 hours and the simulation includes actual road grade. This indicates that the characterized impact of hybrid technology on long-haul truck fuel economy is typical and representative of real-road driving conditions. We also simulated the hybrid trucks over the HHDDT 65 cycle, a chassis dynamometer test developed by the California Air Resources Board with the cooperation of WVU. The results show there is an 11%-13% fuel economy improvement for parallel and dual-mode hybrids while the overall trend is similar to the above observations. The reason for the increase in the fuel economy enhancement for the HHDDT 65 cycle is probably due to its ignoring real grade.

DISCUSSION

Hybrid technologies typically achieve better vehicle energy saving through kinetic energy recovery, optimized engine operation at higher efficiency, and reduced engine power demand for low loads and idle. However, kinetic energy recovery is very limited for a long-haul truck which may stop only a couple times every 200 or 300 miles (see Figure 3). The simulated results reveal that long-haul truck hybridization could play an important role in optimizing engine operation at higher efficiency and reducing engine power demand for low loads and idle. Figure 5 gives an example of the impact of the medium load parallel hybrid on the truck engine efficiency, speed and power. In this case, hybridization boosts the cycle-averaged engine efficiency from 40.5% up to 41.8% compared to the non-hybrid truck (see Figure 5(a)). Moreover, hybridization enables engine-off operation during more than 33% of the drive cycle, at low load and idle conditions. Figure 5(a) demonstrates that the engine turnoff takes place mostly at low loads (e.g. <100kW), as shown in the green-colored zone. This is further confirmed in Figures 5(b) and 5(c), which indicate frequent opportunities for engine-off operations at low load demand during the highway driving with real grade. The detailed results show that 42% of engine loads in the simulated conventional truck during the drive cycle are below 100 kW, including 11% idle time. This fact reflects that there is a unique potential of hybrid technology to improve long-haul truck fuel economy. The fuel savings opportunities can be rather different than in other applications, but the analysis shows that the fuel savings of hybrid trucks can still be significant.

A question that, to the authors' knowledge, has not been addressed previously is whether the fuel savings benefit from hybridization could be enhanced if significant power demand reduction technologies are implemented in future trucks. As discussed previously, the energy losses relevant to aerodynamic drag and rolling resistance are much larger than the drivetrain losses and auxiliary loads. The hybrid models already include an auxiliary load reduction (see Figure 4). However, the impact of aerodynamic drag and rolling resistance is critical to consider. The 21st Century Truck Partnership has identified a 30% and 35% reduction in aerodynamic drag and rolling resistance, respectively. Therefore, for this study the simulation tool was used to evaluate the impact of the targeted aerodynamic drag and rolling resistance reductions on the fuel economy of hybrid trucks. We chose the parallel hybrid truck as our studied case, but an additional 120kg is considered in the study to account for extra equipment that may be required for the load reduction technologies.

Figure 6 shows the fuel economy for the non-hybrid and parallel hybrid trucks with the targeted aerodynamic drag and rolling resistance reductions. Compared to the non-hybrid trucks with the same improvement in aerodynamics and rolling resistance, the hybrid technology increases fuel economy more than 15%, which is about 7-8% greater improvement than the cases without the targeted aerodynamic drag and rolling resistance reductions shown in Figure 2. This indicates that hybrid technology has a potential to achieve much better fuel energy savings in future long-haul trucks with load reduction technologies, compared to the current truck technologies. Figures 7 and 8 show an example of the hybrid configurations' fuel savings with load reduction technologies for the medium load case. The pink-colored zone in Figure 7 is the heavy load reduction in the simulated trucks with lower aerodynamic drag and rolling resistance, and the green-colored zone is the engine low-load cutoff due to hybridization. In the green-colored zone, the load cutoff for the case of aerodynamic drag and rolling resistance reductions is higher than the cases without aerodynamic drag and rolling resistance reductions. Consequently, the engine-off percentage in the former is up to 43% compared to 33% for the latter. This is also confirmed indirectly by Figure 8, which compares the component energy losses of the simulated non-hybrid and hybrid trucks with and without the aerodynamic drag and rolling resistance reductions. Relative to the conventional powertrain cases, hybrid technology reduces the engine energy loss by 5.5%, as engine losses in the conventional and hybrid cases are 59.8% and 54.3% of total fuel energy, respectively. In the cases with load reduction technologies, engine loss in the hybrid case is 40.5%, which is 9.1% less than the comparable non-hybrid case.

An interesting result shown in Figure 8 is that an additional benefit is predicted from lower rolling resistance and aerodynamic drag which result in more energy available for regenerative braking during decelerations from high speed. The result shows that there is a 1.6% increase in braking energy for the conventional non-hybrid case with lower rolling resistance and aerodynamic drag, but only 0.2% higher braking for the comparable hybrid. It means that 1.4% more energy is recovered during regenerative braking in the hybrid case. Our simulation experience illustrates that extra benefit for the hybrid becomes more significant with lower values of rolling resistance and aerodynamic drag coefficients. In hybrid vehicles, the more regenerative braking energy is available, the more fuel energy saving could be achieved.

On the other hand, from Figure 8, we observe that the aerodynamic drag and rolling resistance reductions significantly increase fuel economy of both non-hybrid and hybrid trucks. This is not surprising because aerodynamic drag and rolling resistance losses are the two major component losses other than the engine. These results highlight the importance of reducing aerodynamic drag and rolling resistance losses, but also show the additional benefits obtained by integrating the load reduction technologies with hybrid technology in future long-haul trucks.

The above observations have also been confirmed in simulations using the HHDDT 65 and another real-road drive cycle. The fuel economy improvement from hybridization in the presence of aerodynamic and rolling resistance load reductions for the HHDDT 65 cycle is in the 18%-21% range, which is higher than the 15% improvement predicted for the FDHDT cycles. These gains indicate that the fuel savings due to truck hybridization when the other load reductions are implemented is quite significant compared to the expected improvements from vehicle technologies such as weight reduction and waste heat recovery, although some other individual technologies, such as engine efficiency and aerodynamic drag reductions, may offer even greater fuel savings than hybridization.

CONCLUSION

Our simulation results indicate that both parallel and dual-mode hybrid powertrain technologies, for the baseline vehicle configuration without road load reductions, are capable of improving fuel economy by 7-8% over the simulated FDHDT cycle with real grade. This is possible because the engine is able to operate more frequently at speeds and loads near its optimal effieincy point and because accessory loads are reduced. The fuel saving benefit is predicted to be even better for the HHDDT 65 cycle. On the other hand, there does not appear to be a significant benefit for series hybridization in this context, because of the large efficiency penalty associated with converting propulsion energy from mechanical to electrochemical and then back to mechanical form.

The component energy loss analysis shows that kinetic energy recovery (regenerative braking) is very limited for a long-haul truck, which may only stop a couple times every 200 or 300 miles. Thus regenerative braking alone cannot provide a strong motivation for long-haul hybridization. However, if new approaches for reducing drag and rolling resistance can be included in advanced hybrid truck designs, there is a remarkable synergistic effect with engine efficiency and load demands that increases fuel economy by more than 15% relative to conventional trucks with the same aerodynamic and rolling loss reductions. This unexpected synergy between hybridization and drag and rolling resistance illustrates the importance of full system energy analysis when considering the relative benefits of different advanced technologies.

Considering long-haul hybridization combined with future technologies for aerodynamic drag and rolling resistance reduction, our simulations show that a hybrid powertrain configuration could increase the fuel economy by more than 15% relative to the conventional powertrain with the same aerodynamic and rolling loss reductions. Long-haul hybrids with significant aerodynamic drag and rolling resistance reduction can minimize heavy-load demand, recover more kinetic energy, and leverage engine-off operations so as to reduce the engine energy losses. In particular, the load cutoff in the case of aerodynamic drag and rolling resistance reductions is significantly higher than the baseline cases. This indicates that hybrid technology has the potential to provide even better fuel savings in future long-haul trucks with load reduction technologies than for current truck technologies.

In summary, In summary, our computational simulations suggest that hybridization does offer potential fuel efficiency advantages for long-haul trucks. But achieving the full benefits of this potential will require proper selection of hybrid configuration and synergistic combinations with other advanced technologies, such as truck designs with lower aerodynamic drag and tires with reduced rolling resistance. Since the present study is based on computational models that are not as yet fully validated with experiments, future studies should focus on re-evaluating the predicted trends as more actual drive cycle data for hybrid truck prototypes become available.

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TABLE 1 Specifications of the Simulated Conventional and Hybrid trucks.

Powertrain Component	Parameter	Conventional	Parallel	Series	Parallel-Series
Engine	Peak thermal eff	45%			
	Max power	391kW@1700rpm			
	Idle speed	625 rpm			
Final Drive	Final ratio	2.64			
Wheel	Wheel radius	0.53 (m)			
Chassis	Frontal area	10.38			
	Rolling resis coeff	0.007			
	Aerodyn drag coeff	0.58			
Transmission	Model	10-speed manual	10-speed manual	Fixed gear ratio	10-speed manual
Motor	Max power	-	220 kW	420 kW	220 kW / 75 kW
	Continuous power	-	100 kW	200 kW	100 kW / 34 kW
Battery	Capacity	-	35 kWh	64 kWh	35 kWh
	Peak chg power	-	212 kW	386 kW	212 kW
	Peak dis power	-	225 kW	408 kW	225 kW
	Normal voltage	-	375 V	375 V	375 V
Mass penalty	Hybrid components	-	400kg	500kg	450kg

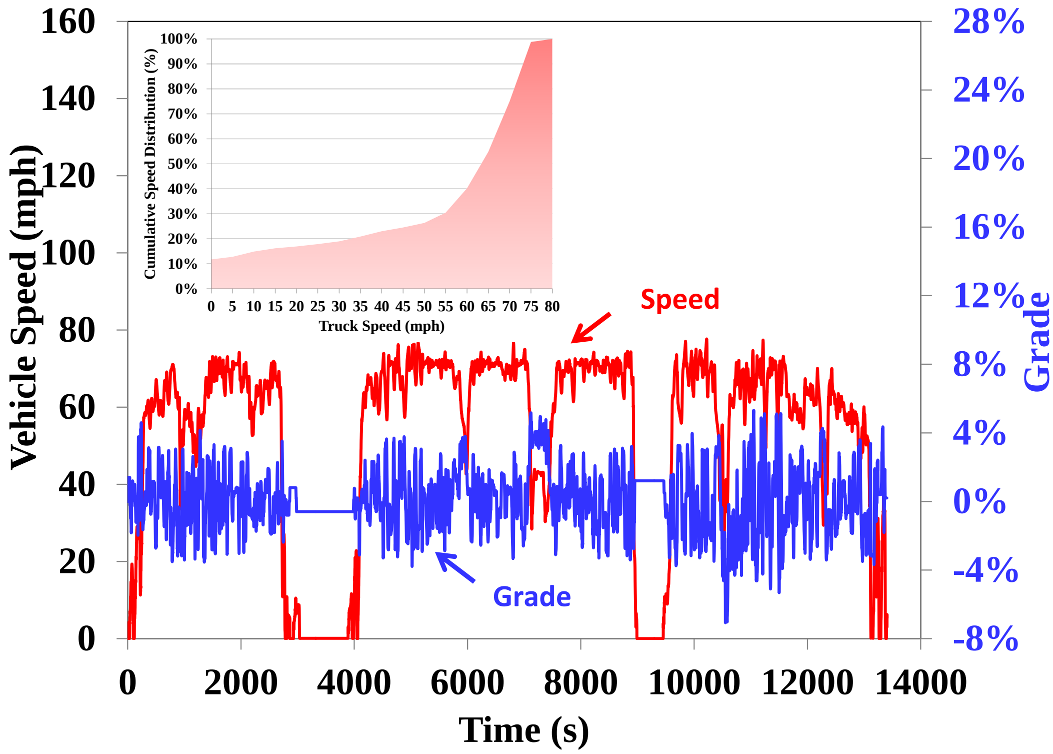


FIGURE 1 Speed profile of the simulated freeway-dominated heavy duty truck driving cycle with real grade.; 1 mph=1.61 km/hr.

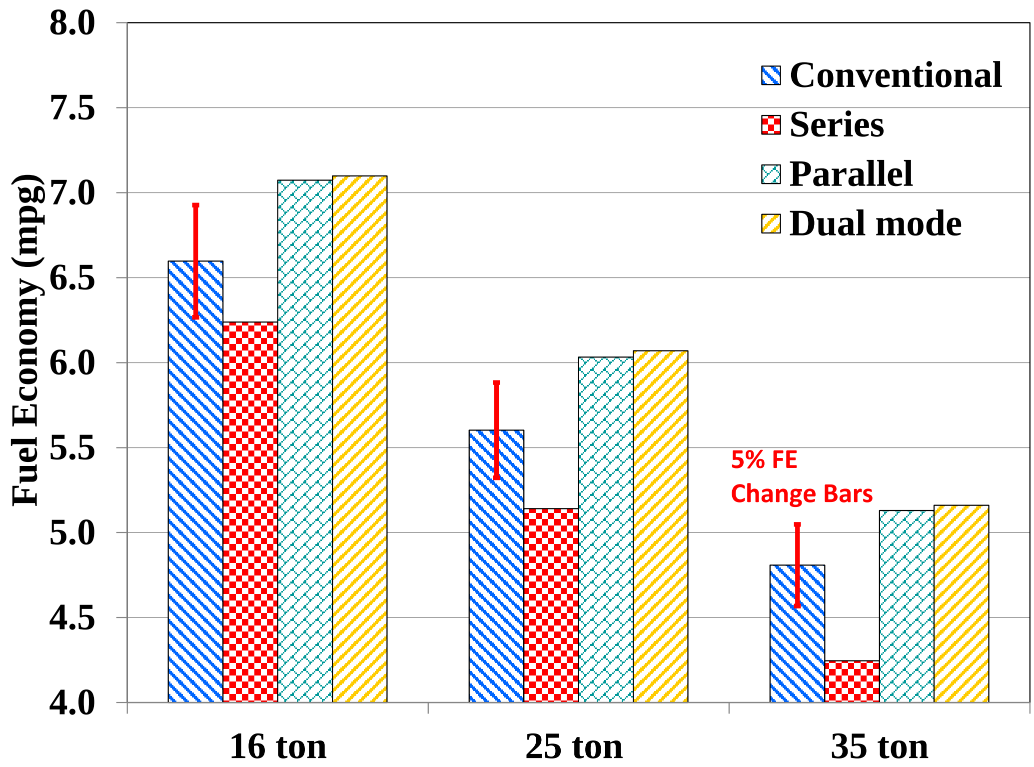


FIGURE 2 Comparison of fuel economy among conventional and hybrid trucks over the freeway-dominated heavy-duty truck driving cycle; 1 mpg=0.425 km/liter.

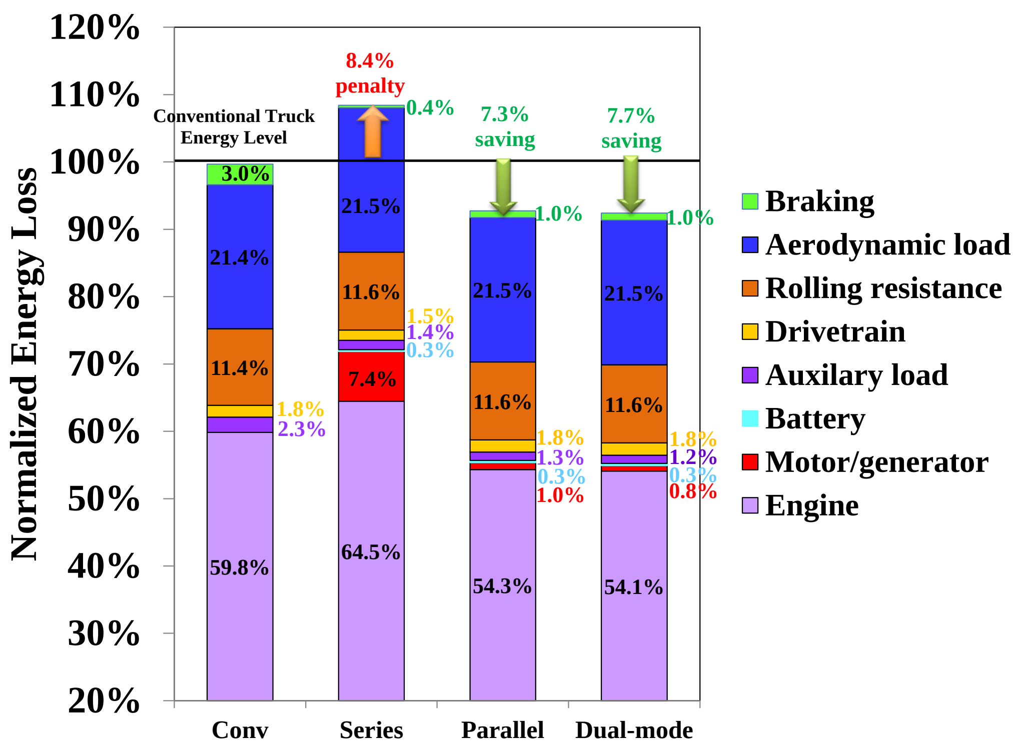


FIGURE 3 Energy loss distribution for the medium load conventional and hybrid trucks operating over the FDHDT cycle. The energy losses are shown relative to the conventional truck's overall energy use.

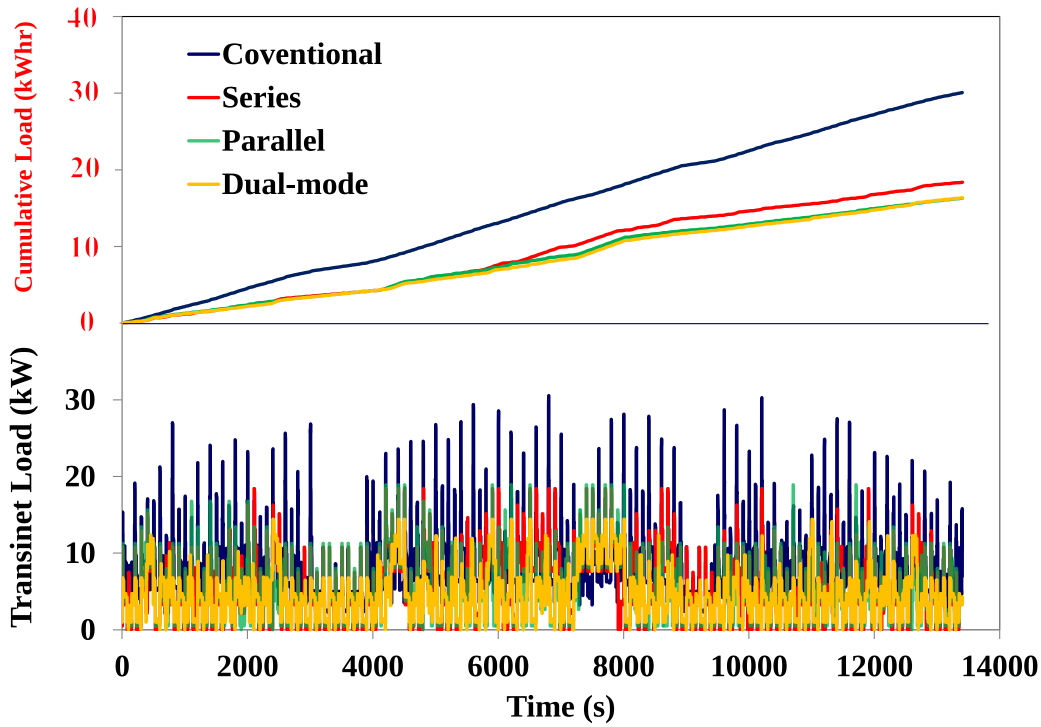
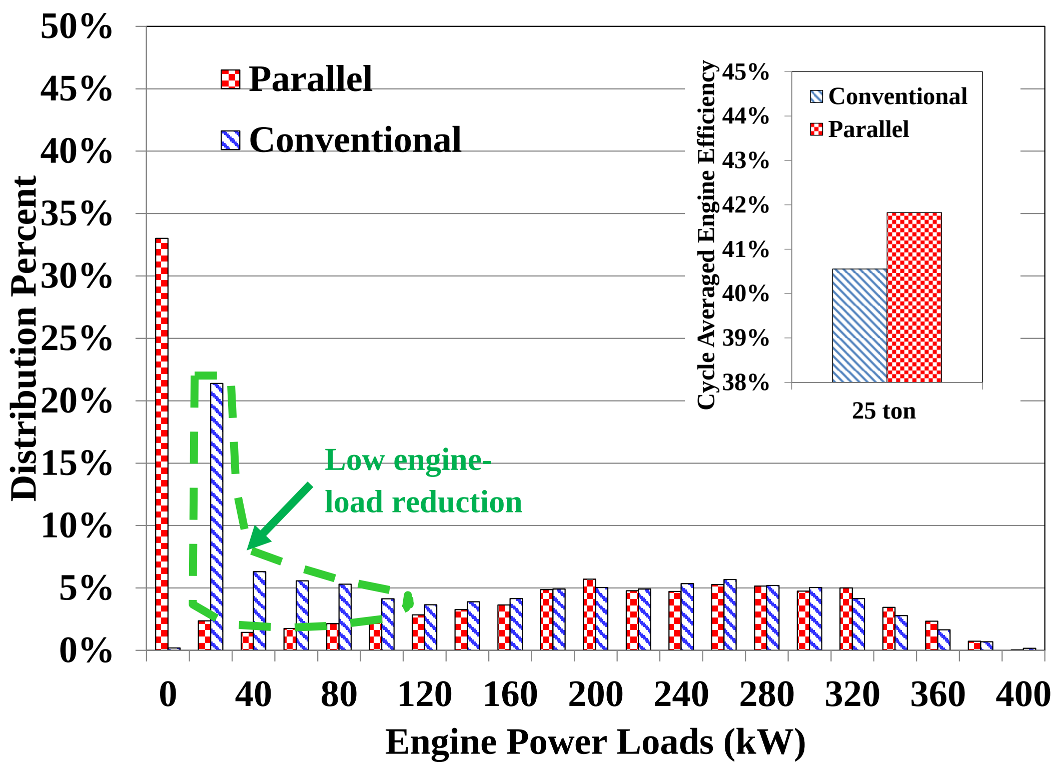
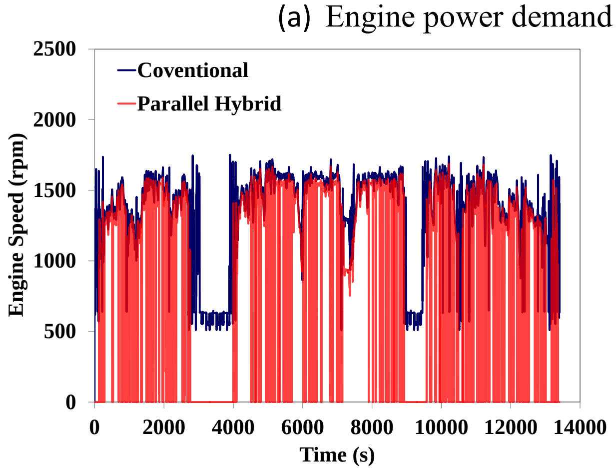
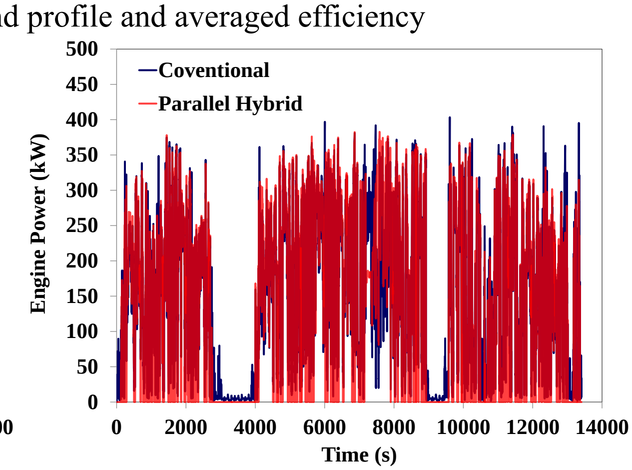


FIGURE 4 Accessory loads for the conventional and hybrid trucks operating over the FDHDT cycle at the medium load level.



(a) Engine power demand profile and averaged efficiency





(b) Engine speed at medium load (c) Engine power at medium load

FIGURE 5 Impact of the medium-load parallel hybrid on truck engine power demand, efficiency, and transient speed and power load over the FDHDT cycle.

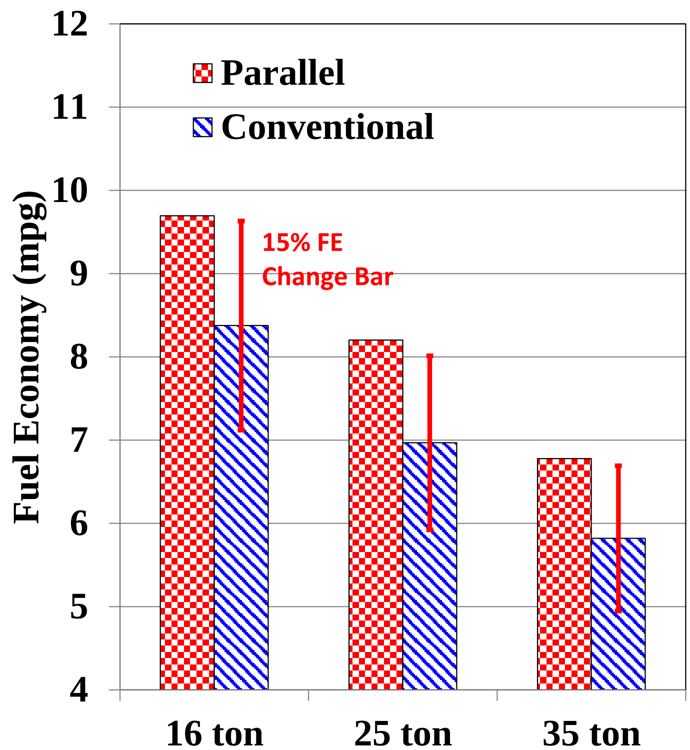


FIGURE 6 Comparison of fuel economy of the parallel hybrid truck with the targeted aerodynamic drag and rolling resistance reductions over the freeway-dominated heavy duty truck driving cycle; 1 mpg=0.425 km/liter.

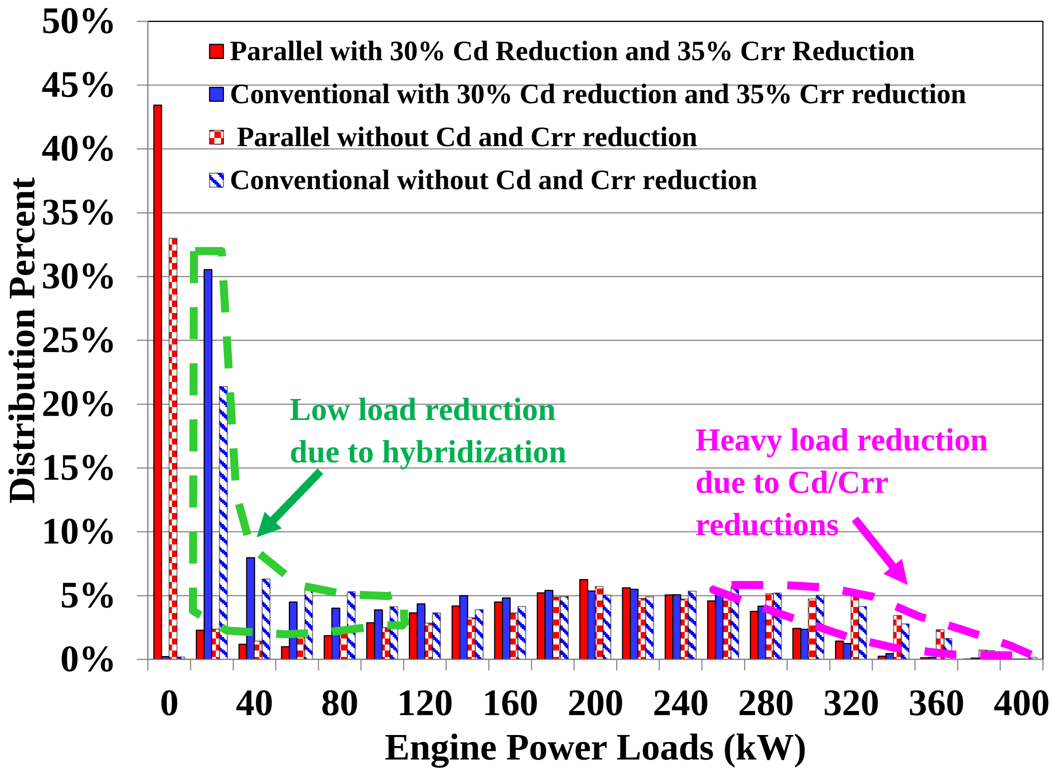


FIGURE 7 Impact of the medium-load parallel hybrid on truck engine power demand over the FDHDT cycle. Cd is aerodynamic drag coefficient, and Crr is rolling resistance coefficient.

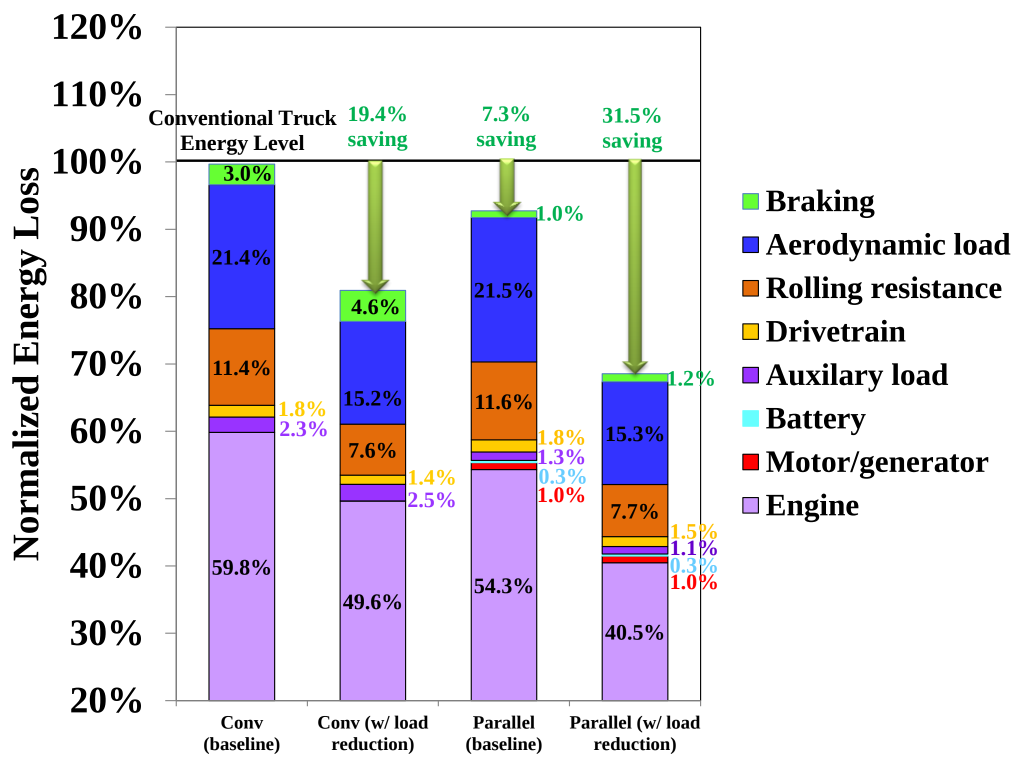


FIGURE 8 Component energy loss of the medium-load conventional and hybrid trucks, with and without the targeted aerodynamic drag and rolling resistance reductions respectively, operating over the FDHDT cycle. The energy analysis is based on the baseline conventional truck energy level.