

Simulated Fuel Economy and Emissions Performance during City and Interstate Driving for a Heavy-Duty Hybrid Truck

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ABSTRACT

We compare the simulated fuel economy and emissions for both conventional and hybrid class 8 heavy-duty diesel trucks operating over multiple urban and highway driving cycles. Both light and heavy freight loads were considered, and all simulations included full aftertreatment for NO_x and particulate emissions controls. The aftertreatment components included a diesel oxidation catalyst (DOC), urea-selective catalytic NO_x reduction (SCR), and a catalyzed diesel particulate filter (DPF). Our simulated hybrid powertrain was configured with a pre-transmission parallel drive, with a single electric motor between the clutch and gearbox. A conventional heavy duty (HD) truck with equivalent diesel engine and aftertreatment was also simulated for comparison. Our results indicate that hybridization can significantly increase HD fuel economy and improve emissions control in city driving. However, there is less potential benefit for HD hybrid vehicles during highway driving. A major factor behind the reduced hybridization benefit for highway driving is that there are fewer opportunities to utilize regenerative braking. Our aftertreatment simulations indicate that opportunities for passive DPF regeneration are much greater for both hybrid and conventional trucks during highway driving due to higher sustained exhaust temperatures. When passive DPF regeneration is extensively utilized, the fuel penalty for particulate control is virtually eliminated, except for a 0.4%-0.9% fuel penalty due to a slightly increased exhaust backpressure.

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INTRODUCTION

U.S. highway petroleum consumption is nearly 12 million barrels per day, and more than 24% of this is due to heavy-duty (HD) trucks [1]. Thus, HD truck hybridization should be seriously considered in the national energy strategy to increase fuel economy, reduce greenhouse gases, and reduce our dependence on imported oil. If fuel consumption by HD trucks can be reduced just 5%-10% using hybridization, this would result in a very significant reduction in annual fuel consumption by the nearly two million highway tractors on U.S. roads.

It has been clearly demonstrated that hybridization can be beneficial for light-duty (LD) vehicles [2, 3, 4]. Studies have shown that hybridization can boost LD fuel economy by more than 30% on the highway and 50% in the city [5]. Substantial efforts are now underway to demonstrate the benefits of hybridization in medium-duty (MD) and heavy-duty (HD) vehicles also (e.g., buses, delivery trucks, and utility trucks), especially where stop-and-go driving offers many opportunities for regenerative braking [6, 7, 8, 9, 10, 11, 12]. An earlier result reports a 20% fuel economy

improvement for a MD hybrid truck in urban use [7]. The fuel economy of a recently tested hybrid city bus was estimated to have improved about 36%, and chassis dynamometer measurements have indicated even higher fuel efficiency benefits of 42%-54% [6]. Engine-out emissions from the hybrid bus were also reported to be significantly less [6].

Hybridization is emerging in the HD truck market, and several manufacturers currently offer class 8 hybrid vehicles for specific applications [13-14]. However, basic information on the potential benefits of HD hybridization in class 8 trucks is still limited in the open literature [12]. This is particularly true regarding emissions, emission controls, and their relationship to fuel economy. Developing a better understanding of the fuel efficiency-emissions control interactions for HD hybrids is critical because of the rapidly evolving aftertreatment technologies and the simultaneous constraints imposed by evolving emissions regulations [15].

Like other diesel-powered vehicles in the U.S., class 8 HD trucks are typically required to remove carbon monoxide (CO), hydrocarbons (HCs), nitrogen oxides (NO_x), and particulate matter (PM) from their exhaust [15-16]. The



current leading emission control technologies for diesel exhaust include diesel oxidation catalysts (DOCs), urea-selective catalytic NO_x reduction (urea-SCR), and catalyzed diesel particulate filters (DPFs). DOCs oxidize CO and HCs, urea-SCR reduces NO_x to nitrogen gas, and DPFs trap and oxidize particulates. The direct fuel consumption of DOC and SCR catalysts is quite small, but DPFs can consume substantially more fuel in order to overcome the associated engine back pressure and to raise the exhaust temperature sufficiently to oxidize trapped particulate matter. In addition, the operating envelope of current HD engines is often constrained by emissions regulations to regions of speed and load where fuel efficiency is low. With sufficiently effective aftertreatment, it is possible to modify engine operation such that it is more efficient, while still maintaining the required limits for tailpipe emissions. Thus it is important to understand the combined performance of the engine and aftertreatment components when they are fully integrated and operated together with the electric drive system in hybrid vehicles. We have found in our studies that the optimal global performance of hybrid systems can be quite different from the optimal performance points for individual drivetrain components.

In the following sections, we summarize simulated fuel economy and emissions results for both conventional and hybrid class 8 HD trucks powered by the same 15-L diesel engine. These truck simulations utilized transient engine and aftertreatment models developed at the Oak Ridge National Laboratory (ORNL) which are implemented in Autonomie [17], a powertrain and vehicle systems simulation platform developed at Argonne National Laboratory with support from DOE. Autonomie is an open architecture and math-based simulation environment designed to support the integration and analysis of powertrain/propulsion systems and technologies for evaluation of fuel economy improvement under dynamic/transient testing conditions. It is the principal integrated vehicle simulation tool used by the DOE Vehicle Systems Simulation Tech Team.

We used Autonomie to simulate the HD truck performance under multiple types of city and highway driving cycles with three different levels of load. In this paper, we present results for a single parallel hybrid powertrain configuration and engine-battery control strategy. Since we are primarily concerned with general trends, we expect that the hybrid and aftertreatment system configuration and control options used here could be further optimized in the future. Thus the present results should be considered only as a preliminary first step in determining the potential benefits that can be achieved with HD hybridization.

COMPONENT MODELS AND SIMULATION CONDITIONS

Transient Engine Model

Since the reaction performance of aftertreatment devices depends critically on exhaust temperature and composition, it is important to accurately model the transient behavior of engine-out exhaust properties as a function of speed, load, and previous history (e.g., exhaust composition and temperature during cold-start and start-stop transients). The common approach used previously in many vehicle simulations has been to employ static steady-state maps to predict engine-out exhaust temperature and species based solely on the instantaneous speed and load. However, it is not possible to use steady-state maps to characterize the hysteresis associated with the complex transients occurring during realistic driving. This is especially true when engine start/stop events are included. We have addressed this issue by developing dynamic correction factors for steady-state maps that account for recent engine history to give more accurate estimates of engine-out temperature and emissions. These correction factors are modeled as dynamic first-order lags that are calibrated with transient engine data and/or known engine characteristics. Details of the approach used are explained more fully in a previous publication [18].

DOC Model

DOCs are designed to catalytically oxidize unburned HC and CO in lean exhaust. In advanced aftertreatment trains, DOCs are typically placed upstream of the NO_x and particulate control devices because the catalyst can also oxidize NO in the engine exhaust to NO₂, improving the efficiency of downstream NO_x and particulate removal. Details of the DOC model used in the paper have been introduced in a previous publication [19]. Briefly, three global one-step reactions are considered, including CO oxidation, HC oxidation, and NO oxidation. We assume that the global performance of the DOC device can be approximated by a single, representative one-dimensional channel with transient plug flow. All reactions are assumed to occur in the washcoat. All hydrocarbons are represented by their propylene (C₃H₆) equivalent. The DOC model also includes a differential energy balance to track axial and temporal temperature variations. The initial conditions, engine-out temperature and species variations, and ambient heat loss are all included. The kinetic parameters used in this study for estimating the oxidation rates of CO, HC, and NO were based on typical literature values and adjusted slightly to match experimental dynamometer measurements as reported in [19].

SCR Model

Urea-SCR is the leading technology competing with lean NO_x traps (LNTs) for removing NO_x from lean engine

exhaust. Urea-SCR systems inject aqueous urea slurry into hot engine exhaust, resulting in the formation of ammonia (NH_3), which then reacts with NO_x over the SCR-catalyst to form nitrogen gas (N_2). The SCR model used here was structured using 1-D differential transient balances similar to the above DOC model. For the present study we utilized a modified version of a previously published SCR model [19] with updated estimates for the reaction rate parameters. In this version of the model, it is assumed that the rate limiting steps in the SCR device occur after urea is converted to NH_3 , thus there is no accounting for vaporization and thermolysis of the urea slurry. The present model accounts for three main global catalytic surface reactions: 1) the standard reaction between NH_3 and NO ; 2) the fast reaction between NH_3 with equimolar levels of NO and NO_2 ; and 3) the reaction between NH_3 and NO_2 . The effects of NH_3 adsorption and desorption and gas phase reactions involving NH_3 , O_2 , and nitrogen oxides were also included, but N_2O formation was not considered here. Details of the SCR model and associated kinetic parameter estimates based on laboratory measurements of a commercial Cu-chabazite zeolite catalyst are summarized in the [Appendix](#), where details of the SCR model validation are also included. While it is likely that estimates for the reaction rate parameters will continue to evolve as more laboratory measurements become available, we expect that the general trends resulting from the present SCR model are correct.

Catalytic DPF Model

Catalyzed diesel particulate filters remove particulates from the engine exhaust by mechanical filtration and then subsequently oxidizing the solid carbon and residual HCs. Adequate oxidation of the particulate is necessary in order to prevent buildup of back pressure, which penalizes engine output. In many cases, the oxidation process must be stimulated by burning additional fuel to raise the exhaust temperature to the particulate ignition point. Thus accurate simulation of the accumulated DPF soot levels is vital for determining fuel economy. In this study, we used a simplified 3-zone catalytic DPF model, which accounts for DPF performance in terms of an inlet channel zone, an outlet channel zone, and the filter wall. Temperatures can vary from zone to zone, but they are assumed to be uniform within each zone. Exhaust PM is assumed to be deposited evenly in the filter walls. Thus the transient behavior of the DPF is approximated with a small set of ordinary differential equations (ODEs) that account for the global mass and energy balances in each zone. In the present study, we triggered regeneration if DPF back pressure and temperature reached specified thresholds. Regeneration was accomplished by boosting fuel addition at a fixed level for a constant period. Details of the oxidation kinetics and pressure drop estimates have been published elsewhere [20]. In cases where engine out temperatures and catalyst activity are sufficient to create self-sustaining oxidation reactions sufficient to keep

the particulate buildup below the critical thresholds, no active regeneration events are required. This is the operating condition that is frequently referred to as passive DPF regeneration, and it was an important factor in this study as explained below.

Conventional and Hybrid Powertrain Configurations

As a reference for comparison with HD hybrid trucks, we defined a conventional Class 8 HD truck configuration in Autonomie. The truck was equipped with a 2007 certified, 15-L, 6-cylinder diesel engine (engine rated power: 485 hp) and a 10-speed manual transmission. This vehicle configuration was used for the model since ORNL has conducted extensive in-fleet testing with a similar vehicle [21] and has validated the Autonomie model for this vehicle against the measurements.

Compared to later engines (e.g. those certified for 2010), we recognize that the 2007 diesel engine does not utilize the same innovative combustion and EGR technologies. However, we were constrained at the time by the lack of availability of both emissions maps and on-the-road data for more recent engines. More recently we have obtained information for a 2010 certified engine and these will be utilized in future studies. However, based on current information, we expect the general trends with the different drive cycles to be similar for both engines.

For the 2007 engine, we utilized interpolated steady-state maps for fuel consumption, engine-out temperature, and engine-out emissions based on proprietary chassis dynamometer measurements. Parameters for transient corrections were also added as described above. The coefficients of drag and rolling resistance used in the truck simulation assume 0.58 and 0.007, respectively, while frontal area was set at 10m^2 .

To ensure that the above assumptions are reasonable, we compared the resulting Autonomie simulations for two different drive cycles with chassis measurements from a similar vehicle made at West Virginia University (WVU) [22]. The two drive cycles were the UDDS Truck cycle, which is characteristic of urban driving (5.45 mi in 1051 sec), and a measured drive cycle, designated as ORNL4LS, which is characteristic of non-interstate highway driving (15.40 miles in 1277 s). The WVU measurements were made on a 2005 Volvo VN 610 tractor powered by a Cummins ISX 475 15-L diesel engine with a 10-speed manual transmission and a loaded weight of 18,700 kg. The predicted and measured fuel economies were 4.55 mpg vs. 4.63 mpg, respectively, over the UDDS Truck cycle and 6.26 mpg vs. 6.10 mpg, respectively, for the ORNL4LS cycle. [Figure 1](#) illustrates the comparative transient fuel consumption and engine power plots for the two cycles.

For class 8 HD hybrid truck simulations, we specified a pre-transmission parallel configuration with a single motor between the clutch and gearbox (see [Figure 2](#)). The selected

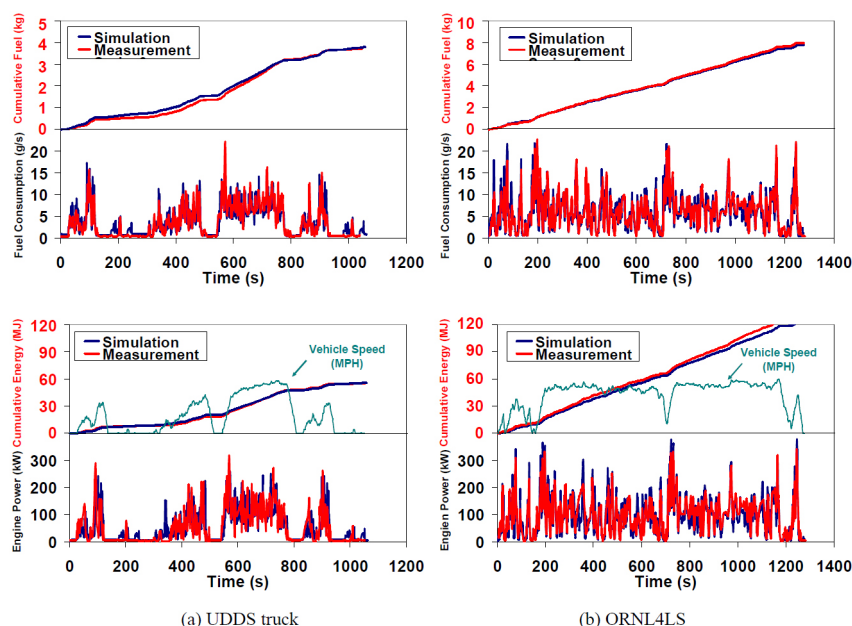


Figure 1. Comparison of fuel economy and engine power over the UDDS truck and ORNL4LS drive cycles.

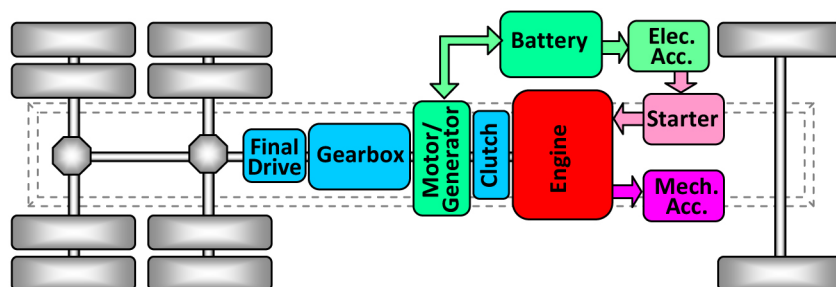


Figure 2. Schematic of the parallel HD hybrid configuration.

electric motor and battery were rated at 150 kW and 180 kW, respectively. Other powertrain components and parameters are the same as those utilized in the conventional HD truck simulations. The default vehicle level hybrid controller from Autonomie was used to manage powertrain components (such as engine, electric motor and transmission) and maximize fuel consumption [12]. The controller commands the engine to be on if vehicle speed or power requests exceed specified thresholds, if the motor is saturating, or if the battery state-of-charge (SOC) is below a threshold value. Otherwise, the engine is off and all power is supplied by the motor. Motor torque assist is utilized when the requested torque exceeds engine peak torque at the current speed. The clutch is engaged if the engine is on, while it is disengaged any time that the engine is off but the electric motor may be operating. During braking, the engine is turned off and the motor acts as a generator to provide power back to the battery. If braking power during regeneration exceeds the battery power charging limit, it is assumed that the recovered braking power is equal to the maximum battery power charging power. This simple hybrid control strategy does not

adjust with the truck's load, and is also not a synergistic strategy that considers tailpipe emissions. This approach is admittedly rather simplistic, so there are several opportunities for improving the control strategy to achieve a more robust design.

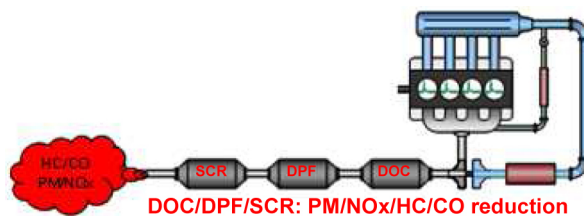


Figure 3. Configuration of the simulated DOC/CDPF/SCR aftertreatment train system.

To account for emissions controls, we assumed that both the conventional and hybrid trucks were equipped with a 5.8-L DOC, a 19-L catalyzed DPF, and a 24-L SCR catalyst, positioned as shown in Figure 3. By locating the DPF upstream of the SCR catalyst, chances for positive

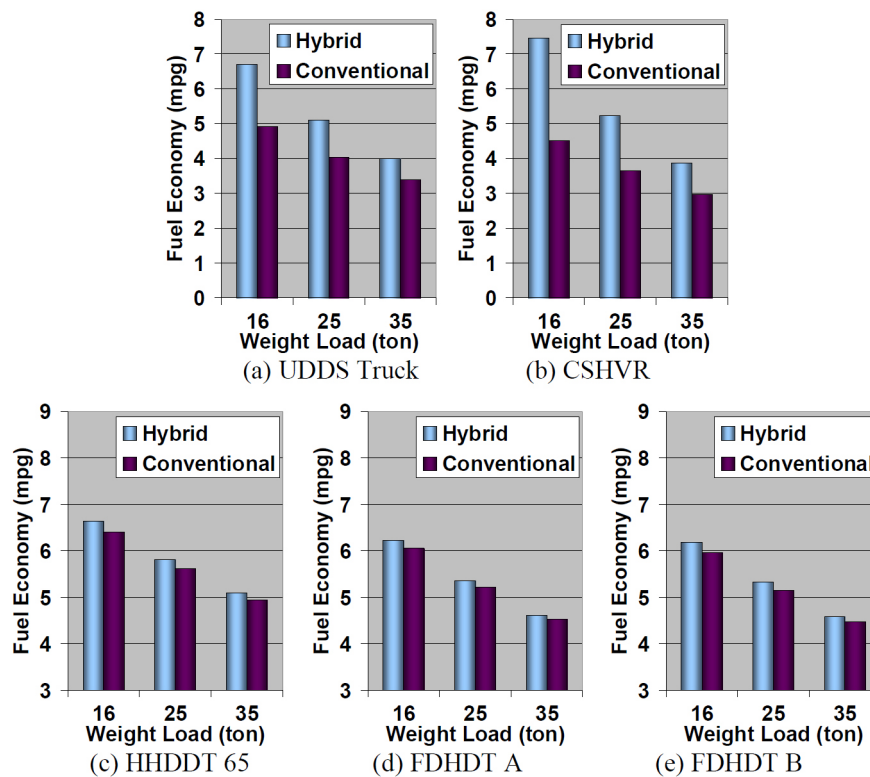


Figure 4. Comparison of simulated cumulative fuel consumption for conventional and hybrid HD trucks operating over five different driving cycles.

regeneration of the DPF were increased, thereby potentially reducing the need to expend extra fuel for DPF regeneration. In the present study, we did not consider the heat loss of exhaust tubes connected between these components. The power consumed for urea dosing is not also considered due to the small low-pressure urea injection rate, which is not likely to significantly affect the fuel economy.

Simulations for both trucks included two different urban (non-grade) cycles: the Urban Dynamic Driving Schedule (UDDS) Truck cycle and the City-Suburban Heavy Vehicle Route cycle (CSHVR) [24]. We also included three highway cycles: the Heavy Heavy-Duty Diesel Truck cycle (HHDDT65) [24] and two cycles adapted from the Freeway-Dominant Heavy Duty Truck (FDHDT) driving conditions, which include significant grades [22]. Regarding these measured cycles, the first is identified as FDHDT A and covers 196.4 miles in 3.72 hours. The second is identified as FDHDT B and covers 262.7 miles in 5.29 hours. Unlike the city driving cycles, HHDDT65, FDHDT A and FDHDT B account for trips consisting of three basic segments: (1) leaving the city and entering interstate highway; (2) nearly constant-speed driving on the highway; and (3) leaving the highway and returning to the city. These cycles do not have significant vehicle stops except at the beginning and end. However, the FDHDT A and FDHDT B cycles combine elements of HHDDT65 with longer highway driving. All cycles were assumed to begin with a 20°C cold start. More

details about the cycles are provided later in the discussion of results.

Weight is also a major factor for class 8 HD truck fuel economy [23]. To account for this effect, we simulated three different truck weights: 16,000kg (light), 25,000kg (medium), and 35,000kg (heavy). For the hybrid truck cases, an additional 400kg was included to account for the weight penalty of the motor, battery, and accessory components.

RESULTS AND DISCUSSIONS

Using the above assumptions and computational tools, we compared both the fuel economy and emissions for the conventional and hybrid HD trucks with three different weights over five different cycles. In this section, we present results of the simulations conducted.

Fuel Economy

Over the UDDS Truck and CSHVR urban cycles, we found that the simulated hybrid truck had significantly better fuel economy (see Figures 4(a) and 4(b)). The estimated cumulative fuel saving for the hybrid were up to 36.4% and 64.8% for the UDDS and CSHVR cycles, respectively. Figures 5(a) and 5(b) illustrate the engine on/off activity in the 16,000-kg truck (i.e. 16,400kg for the hybrid) over the UDDS Truck and CSHVR cycles. From these figures we see that the hybrid operates frequently in an electric mode under low acceleration and deceleration conditions in city driving.

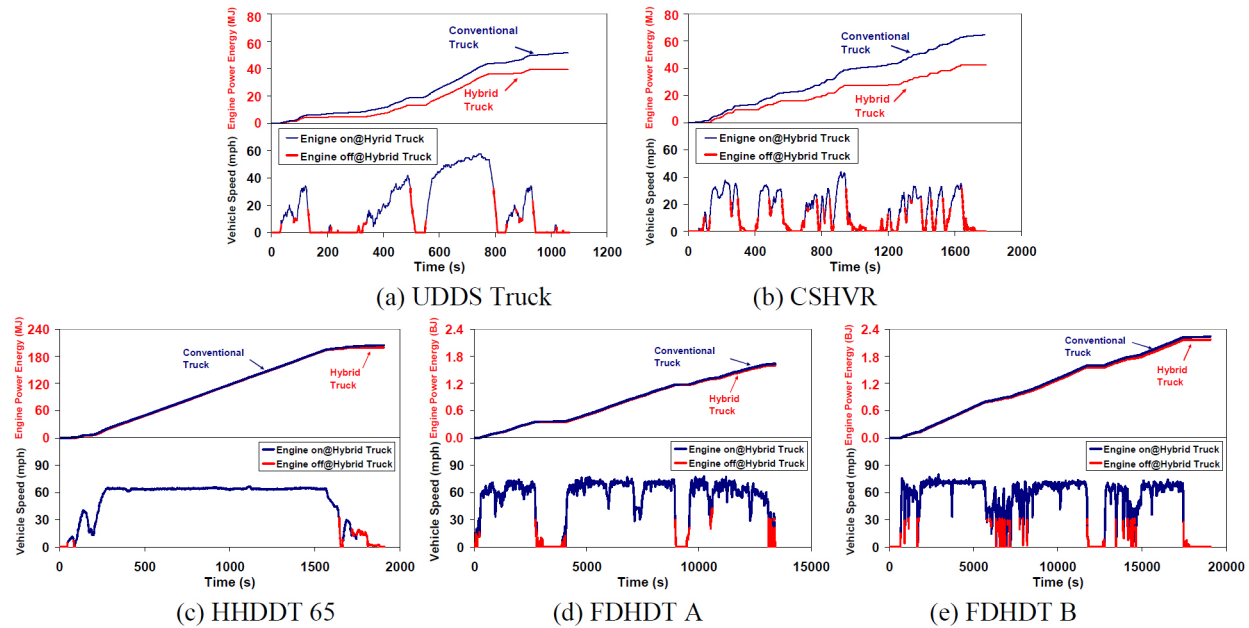


Figure 5. Comparison of engine power demands for the simulated 16,400-kg conventional and hybrid trucks over five different driving cycles.

The high frequency of deceleration also provides many opportunities for regenerative braking. The fuel saving is greater for the CSHVR cycle than for the UDSS Truck cycle because there are more opportunities for regenerative braking.

Figure 4 also illustrates that the fuel economy improvement due to hybridization decreased significantly with weight. For example, the hybrid fuel economy benefit is reduced from 36.4% to 17.8% between the light and heavy load cases for the UDSS Truck cycle. For the CSHVR cycle the mpg benefit from hybridization decreased from 64.8% to 30.4% between the light and heavy load cases. A major factor behind the effect of load in our simulations is that the heavier loads increased the engine power demand, thus reducing the electric motor contribution. For example, the simulated duration of electric motor operation for the three loads shifted from 990s to 909s to 817s, respectively, as the load increased from light to heavy over the 1780s of the CSHVR. However, even with heavy loads, the fuel savings of the hybrid has a large potential to reduce the annual fuel consumption. Thus, these results confirm that hybridization should be of great benefit for HD trucks in city conditions, such as for Class-8A HD buses and utility vehicles.

Compared to the urban drive cycles, the estimated benefits of hybridization were significantly less in simulated highway driving, as depicted in Figures 4(c)-(e). The estimated fuel saving for the hybrid truck in these cycles ranged from 3.2%-3.7% for the HHDDT65 cycle, 1.9%-2.8% for the FDHDT A cycle, and 2.5%-3.6% for the FDHDT B cycle. One major factor in these cases was that the opportunities for regenerative braking were much fewer than for city driving. Much more time was spent in these cycles at

constant speed, except when the truck left the highway or interstate and returned to city roads (see Figures 5(c)-(e)). Thus, achieving fuel saving from hybridization is much more challenging for freeway driving.

Another factor that explains the fuel saving difference between city and highway driving is the average engine efficiency in the two driving environments. As depicted in Figures 6 and 7, there are significant differences between these environments in the amount of time the engine spends in higher efficiency speed-load regions of its operating envelope. In highway driving, the engine must maintain relatively higher speed and load for both hybrid and conventional trucks, thus it generally operates in regions of higher efficiency. In city driving however, the electric motor allows the engine to spend a much larger fraction of the time operating at more fuel efficient speeds and loads, thereby resulting in higher average cycle efficiency for the hybrid truck. Another way of explaining this point is that the engine efficiency of conventional HD trucks is very low under typical city driving, and hybridization makes it possible to operate the engine much more optimally under these conditions. On the highway however, the average engine efficiency of conventional HD trucks is much better, and thus there is less room for improvement. This same trend was consistent for all our simulated truck loads.

In general, the above results for highway driving conditions fall within the range predicted in other studies [12, 24], which show 1.4%-5.3% of hybridization fuel saving for highway driving conditions, respectively. However, the impact of hybridization on the fuel savings that can be achieved is very sensitive to the particular driving cycles considered. With more frequent stops, the fuel savings

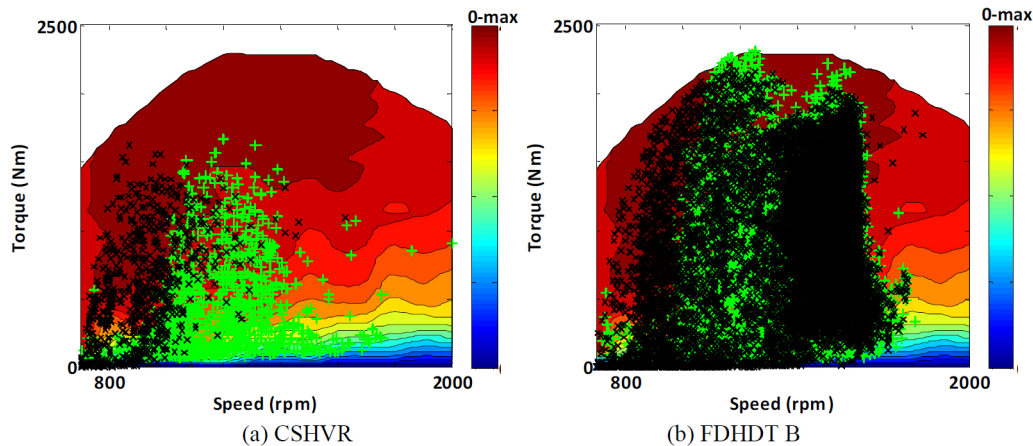


Figure 6. Simulated engine efficiency distributions for the light-load conventional and hybrid trucks operating over the CSHVR and FDHDT B cycles. Dark crosses are for the conventional truck and green are for the hybrid.

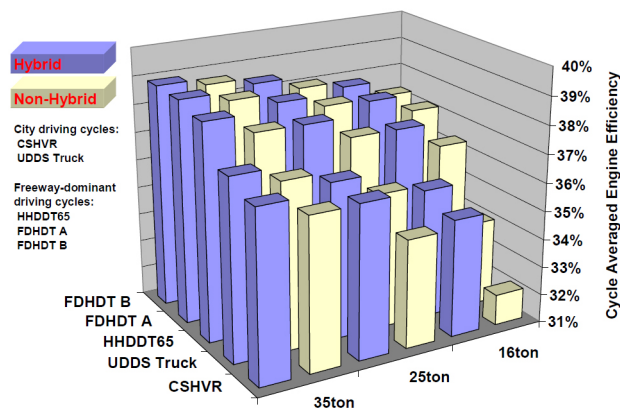


Figure 7. Cycle-averaged engine efficiencies for the conventional and hybrid trucks for different loads and driving cycles

benefits could be larger because part of the kinetic energy lost to braking can be recovered. Additionally, the magnitude of fuel savings is also a function of the component sizes employed in the hybrid system.

Although the model predictions presented here show a decrease in the hybrid fuel savings for the drive cycles in which a grade is present (FDHDT A and B) as compared to the HHDDT65 cycle without grade, the acceleration characteristics of the cycles are quite different, and we cannot conclude that the presence of the grade is responsible for this decreased benefit. These measured cycles are believed to be typical of operations for a class 8 tractor-trailer operating in a mountainous terrain, and the comparisons are included only to demonstrate the effect that a particular usage has on fuel consumption.

One may also ask if the hybrid system is likely to provide a greater or lesser improvement during urban driving when a grade is present. The results of this study cannot be used to draw any conclusions in this regard, although we would expect that significant grades in urban driving would require additional braking. There would therefore be more

opportunities for the regenerative braking system to recover energy that would otherwise be lost when a grade is present. The fuel efficiency of a non-hybrid vehicle is therefore expected to be worse when grades are present, but the hybrid system could very likely mitigate the deteriorated efficiency, leading to even greater benefits for the hybrid system than for cases when no grade is present. A more detailed study of this effect should be pursued in future research.

Emissions

The key tracked emissions in this study were carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). To summarize our simulated emissions results, we quantify emissions levels in terms of g/mile, instead of g/kw-hr in order to more directly compare the net emissions differences between the hybrid and conventional truck. In city driving, where there was less fuel consumption and higher engine efficiency, the hybrid truck generated lower CO and HC emissions in the engine exhaust, as depicted in Figure 8. Engine-out NO_x emissions from the hybrid truck were also lower. However, engine-out PM