

Comparative Study of Hybrid Powertrains on Fuel Saving, Emissions, and Component Energy Loss in HD Trucks

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ABSTRACT

Two hybrid powertrain configurations, including parallel and series hybrids, were simulated for fuel economy, component energy loss, and emissions control in Class 8 trucks over both city and highway driving conditions. A comprehensive set of component models describing engine fuel consumption, emissions control, battery energy, and accessory power demand interactions was developed and integrated with the simulated hybrid trucks to identify heavy-duty (HD) hybrid technology barriers. The results show that series hybrid is absolutely negative for fuel-economy improvement of long-haul trucks due to an efficiency penalty associated with the dual-step conversions of energy (i.e. mechanical to electric to mechanical). The current parallel hybrid technology combined with 50% auxiliary load reduction could improve fuel economy by 5-7% in long-haul trucks, but a profound improvement of long-haul truck fuel economy requires innovative technologies for reducing aerodynamic drag and rolling resistance. The simulated emissions control indicates that hybrid trucks produce less carbon monoxide (CO) and hydrocarbons (HC) emissions than conventional trucks. The results further indicate that the catalyzed diesel particulate filter (CDPF) played an important role in CO oxidation besides particulate matter (PM) emissions control. Limited ammonia (NH₃) emissions could be slipped from the urea selective catalytic reduction (SCR) designed for reducing nitrogen oxides (NO_x), but the average NH₃ level are below 20 ppm. Meanwhile the estimations show 1.5-1.9% of equivalent fuel-cost penalty due to urea consumption in the simulated cases.

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INTRODUCTION

The petroleum consumption of heavy-duty (HD) trucks, including both Class 7 and 8 trucks, is around 2.2-2.4 million barrels per day, nearly 12% of the total U.S. petroleum consumption [1]. If fuel consumption by HD trucks can be reduced by just 5-10%, this would lead to a very significant reduction in annual fuel consumption as well as fuel cost.

Studies have shown that hybridization can significantly increase fuel economy of light-duty (LD) vehicles [2, 3, 4, 5, 6, 7, 8]. These results illustrate that hybridization increases LD vehicle fuel economy by more than 30% on the highway and 50% in the city [5, 6, 7, 8]. Considerable efforts have also been conducted for medium-duty (MD) vehicles (e.g. transit buses, delivery trucks, and utility vehicles), especially the stop-and-go driving of which offers many opportunities for regenerative braking [9, 10, 11, 12, 13, 14]. The fuel economy of a recently tested hybrid city bus was estimated to have improved about 20-40% based on their daily revenue service [14], and chassis dynamometer measurements have indicated even better fuel efficiency benefits of 42-54% [9]. HD truck hybridization has also been considered in playing a significant role to increase fuel economy, reducing greenhouse gases and imported oil dependence [15-16].

Several manufacturers have started to offer Class 8 hybrid vehicles for specific applications [15, 16, 17, 18]. However, understanding the potential benefits of hybridization in Class 8 trucks is still insufficient [14]. This is due to the fact that hybridization technology implementation into a HD truck implies a complex integration of mechanical and electric propulsion systems [20-21]. It requires not only the optimized combination of engine, aftertreatment devices, motor and battery [16], but also the understanding of comprehensive information for the power demanded from a HD vehicle, including auxiliary loads as well as aerodynamic drag, rolling resistance, and drivetrain losses [19, 22]. Thus, developing a better understanding of the battery energy, fuel efficiency, emissions control, and power demand (including auxiliary loads) interactions in HD hybrids is critical to support research, development and demonstration that enable achieving the goals with commercially viable products and systems [19].

The goal of this study is to use computational simulations to compare the estimated fuel economy and emissions of Class 8 trucks powered by the commercial 2010 compliant 15-L diesel engines with those incorporating parallel and series hybrid electric powertrain configurations. The emphasis is to identify potential advantages and technical barriers for hybrid truck

technologies for the Class 8 truck sector. To keep the problem tractable, the authors' consideration was restricted to parallel and series hybrid powertrain configurations and appropriate engine-battery control strategies to reveal general trends rather than identify optimal combinations of all possible parameters. The impact of accessory electrification on fuel economy and truck performance is also addressed in the paper.

In the following sections, the simulated fuel economy and emissions results are summarized for both conventional and hybrid Class 8 trucks. The simulations utilized the ORNL transient engine, Li-ion battery, and full aftertreatment models, as well as the auxiliary load model, which are implemented in Autonomie [23], a powertrain and vehicle systems simulation platform developed at Argonne National Laboratory with support from DOE. Autonomie was used to simulate the HD truck performance under city, highway, and freeway-dominated heavy-duty driving cycles.

COMPONENT MODELS AND SIMULATION ASSUMPTIONS

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. This issue has been addressed 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 were 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 being added to the engine from combustion or lost to the surroundings. The predicted fuel consumption and exhaust properties by the model were validated very well with various transient measurements from both lean and stoichiometric engines. Details of the approach used are explained more fully in a previous publication [24].

Full Aftertreatment Train Model

A full aftertreatment train system model was developed to account for CO/HC/NOx/PM emissions controls required by EPA regulation standards. The model consists of DOC, CDPF and SCR, positioned as shown in Figure 1. By locating the DPF upstream of the SCR catalyst, chances for passive

regeneration of the DPF are increased, thereby potentially reducing the need to expend extra fuel for DPF regeneration. Once the aftertreatment train system model is integrated with the above transient engine model, the engine and aftertreatment models are capable of understanding the interactions among the battery energy, fuel efficiency, emissions control, power demand (including auxiliary loads) for HD hybrids. Below are the brief descriptions of the DOC, catalyzed DPF and SCR models used in the simulations.

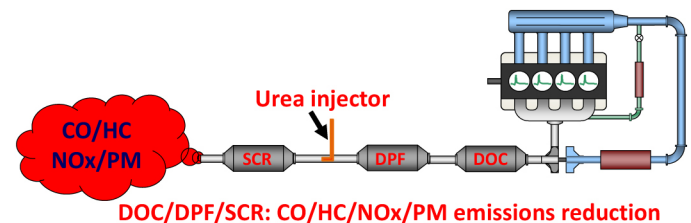


Figure 1. Configuration of the simulated DOC/CDPF/SCR aftertreatment train system.

DOCs are designed to catalytically oxidize unburned HC and CO in lean exhaust. In advanced aftertreatment trains, DOCs are typically placed upstream of the NOx and particulate control devices because the catalyst can also oxidize NO in the engine exhaust to NO₂, improving the efficiency of downstream NOx and particulate removal. Details of the DOC model used in the simulations have been introduced in a previous publication [25]. Briefly, three global one-step reactions are considered, including CO oxidation, HC oxidation, and NO oxidation. It is assumed 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 [25].

Urea-SCR is the leading technology competing with lean NOx traps (LNTs) for removing NOx from lean engine exhaust. Urea-SCR systems inject aqueous urea slurry into hot engine exhaust, resulting in the formation of ammonia (NH₃), which then reacts with NOx over the SCR-catalyst to form nitrogen gas (N₂). The SCR model used here was structured using 1-D differential transient balances similar to the above DOC model. For the present study the authors utilized a modified version of a previously published SCR model [25] 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 NH₃, 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 NH₃ and NO, 2) the fast reaction between NH₃ with equivalent 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 [16], where details of the SCR model validation are also included.

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. This study 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, the DPF model is assumed to trigger regeneration if its back pressure and temperature reach 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 [26]. 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.

Auxiliary Load Model

Since real auxiliary loads demanded in HD trucks are very complex and obtaining these data is extremely challenging, the data from open literature were utilized to develop a simple model where all the auxiliary loads for conventional and hybrid HD trucks were classified as either mechanical energy (ME) or electrical energy (EE) [22, 27-28] (see Table 1). For a conventional truck, this auxiliary-load model accounts for belt-drive mechanical energy consumption of air-brake compressor, engine fan, air-conditioning compressor, lubricant oil pump, power steering, engine coolant pump, and transmission-fluid pump. Meanwhile, a typical constant electrical load of 600 W electricity is assumed to be employed in a conventional vehicle, based on calculation from SAE J1343 [28]. All these mechanical loads are considered as functions of engine speed, driving conditions, driver response for load demand, and 'on' time required for each accessory component.

Table 1. Auxiliary-load comparison between conventional and hybrid trucks. ME and EE represent mechanical and electrical energy, respectively.

Conventional HD Truck Auxiliary Component Loads (Blue: ME; Red: EE)	Hybrid HD Truck Auxiliary Component Loads (Blue: ME; Red: EE)
Air-Brake Compressor	Air-Brake Compressor
Engine Fan	Engine Fan
Air-Conditioning Compressor	Air-Conditioning Compressor
Lubricant Oil Pump	Lubricant Oil Pump
Power Steering	Power steering
Coolant Pump	Coolant Pump
Transmission-Fluid Pump	Transmission-Fluid Pump
Electrical Control & Loads	Battery Cooling Fan
	Electrical control
	Electrical Control & Loads

For a hybrid truck, all the above mechanical auxiliary loads are replaced with electrical load, and not considered as functions of engine speed any more. Additionally, the hybrid auxiliary-load model includes electrical energy consumption of 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 was developed for each auxiliary device to describe the critical 'on' time required for each accessory component. Details of the auxiliary-load model are introduced in the [Appendix](#).

Li-ion Battery Model

To utilize appropriate engine-battery control strategies to reveal general trends, the authors developed an equivalent-circuit battery dynamic model that accounts for additional battery physics using electrical circuit analog components based on the open literature [29, 30, 31]. 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, respectively. The model is capable of effectively simulating both the steady-state and transient battery responses that have been observed in Li-ion batteries. The model has been validated with experimental measurements from the open literature [29], and 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 to within 1% except when the accumulated charge level is below 5%. The primary reason for the discrepancy is due to large non-linear changes in ohmic

resistance and capacitance at very low charge levels. This implies that future model improvements will be needed to simulate very low charge levels, but there should be little impact on battery simulations in vehicle systems, where battery charge is typically maintained above that cutoff. The battery model has been implemented into the current vehicle system model and confirmed that it can be used to simulate any power size of Li-ion battery package through various parallel and/or series battery cell connections.

Truck Powertrain Configurations

To identify energy saving potential from HD hybrid trucks, a baseline conventional Class 8 truck configuration was specified using Autonomie. This baseline truck configuration was adopted from the authors' previous truck model developed for a Class 8 truck powered with a 2004 Cummins ISX 475 15-L diesel engine [16]. The previous conventional truck model has been validated well against the experimental data measured from a 2005 Volvo tractor powered by the same 2004 Cummins diesel engine at West Virginia University (WVU) over multiple truck cycles [16, 32]. Figure 2 shows an example of comparison of fuel economy between the simulation and the measurements. The predicted and measured fuel economies were 4.55 mpg vs. 4.63 mpg, respectively, for the measured cycle.

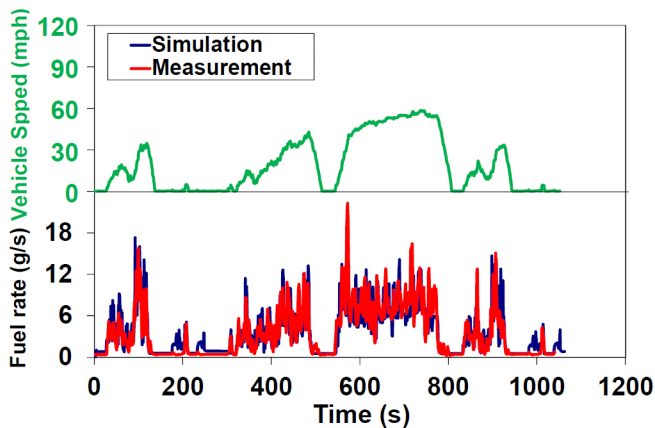


Figure 2. Comparison of fuel economy over the urban dynamic driving schedule (UDDS) truck.

Considering the fact that the 2004 diesel engine is an older model, the new baseline truck was powered by a 2010 certified, Cummins 15-L, 6-cylinder diesel engine (engine rated power: 391kW) and a 10-speed manual transmission (see Figure 3(a)). Table 2 lists the basic specifications of the baseline Class 8 conventional truck. For the 2010 engine, the interpolated steady-state maps for fuel consumption, engine-out temperature and emissions were developed based on chassis-dynamometer measurements. Parameters for transient corrections used in the current engine model were also added as described in [24]. Compared to previously comparable engine maps such as 2004 and 2007 Cummins 15-L diesel engines, this 2010 certified diesel engine achieves better engine efficiency and low engine-out PM emissions with the penalty of higher NO_x emissions and

lower exhaust temperature, as reflects the current engine technology trend is more reliant on advanced aftertreatment for improved fuel economy.

Table 2. Specifications of the baseline conventional transit truck.

Diesel engine (2010 certified)	Max torque	2400 Nm@1300 rpm
	Max power	391 kW@1700 rpm
	Idle speed	625 rpm
Manual Transmission Gear ratios	1st gear	14.78
	2nd gear	11.00
	3rd gear	8.17
	4th gear	6.00
	5th gear	4.46
	6th gear	3.31
	7th gear	2.46
	8th gear	1.83
	9th gear	1.34
	10th gear	1.0
Final Drive	Final ratio	2.64
Wheel	Wheel radius	0.53m
Chassis	Vehicle mass	16,000-35,000 kg
	Frontal area	10.38 m ²
	Rolling resistance coeff	0.007
	Aerodynamic drag coeff	0.58

For Class 8 hybrid truck simulations, two hybrid powertrain configurations were specified, including a pre-transmission parallel configuration with a single motor (see Figure 3(b)), and a series configuration without a transmission (see Figure 3(c)), respectively. T/C in these figures represents torque coupler, which is a device designed for combining the mechanical power outputs from different power sources in hybrid vehicles. In the modeled vehicles, all mechanical loads in the conventional truck were assumed to be replaced with electrical loads in both parallel and series hybrid trucks. It is also assumed that the electrical power generated from the generator in the series hybrid could directly drive motor or charge battery subject to the hybridization control strategy. The selected electric motor and battery for the hybrid trucks were listed in Table 3. 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 fuel consumption [15, 23]. Moreover, sustainable charge control strategies were adopted for both parallel and series hybrid trucks.

For the simulated parallel hybrid, the controller commands the engine '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 tractive power is supplied by the motor. Torque assist is utilized when the requested tractive torque

exceeds engine peak torque at the transient speed. The engine 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. In the controller, the demanded engine torque is determined based on the calculation of requested tractive load, motor load (including battery charging and vehicle propulsion), and accessory load. 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. However, hydraulic braking is demanded if SOC is above a threshold charge, if vehicle or motor speed is below the lower limit value, or if vehicle deceleration is above the maximum regeneration limit.

Similar to the parallel hybrid truck, the controller in the simulated series hybrid also commands the engine to be 'on' if vehicle speed or power requests exceed specified thresholds, if the battery discharging load is saturating, or if the battery state-of-charge (SOC) is below a threshold value. Otherwise, the engine is off. Unlike the parallel hybrid, the series controller manages the engine load mainly based on battery and generator load

requests. The braking regeneration strategy in the series hybrid truck is the same as the strategy used in the parallel hybrid truck. During braking, the engine is turned off.

These hybrid control strategies do not track with the truck's load, and are also not a synergistic strategy that considers tailpipe emissions. The approaches are admittedly somewhat simplistic, so there are several opportunities for future study to improve the control strategy to achieve a more robust design.

Table 3. Specifications of hybrid electrical components.

Component	Parameters	Parallel	Series
Motor	Max power	220 kW	420 kW
	Continuous power	100 kW	200 kW
	Max torque	1680 Nm	3210 Nm
	Max power	6100 rpm	6100 rpm
	Idle speed	1000 rpm	1000 rpm
Battery	Capacity	35 kWh	64 kWh
	Peak chg power	212 kW	386 kW
	Peak dis power	225 kW	408 kW
	Normal Voltage	375 V	375 V
Mass penalty	Hybrid components	400 kg	500 kg

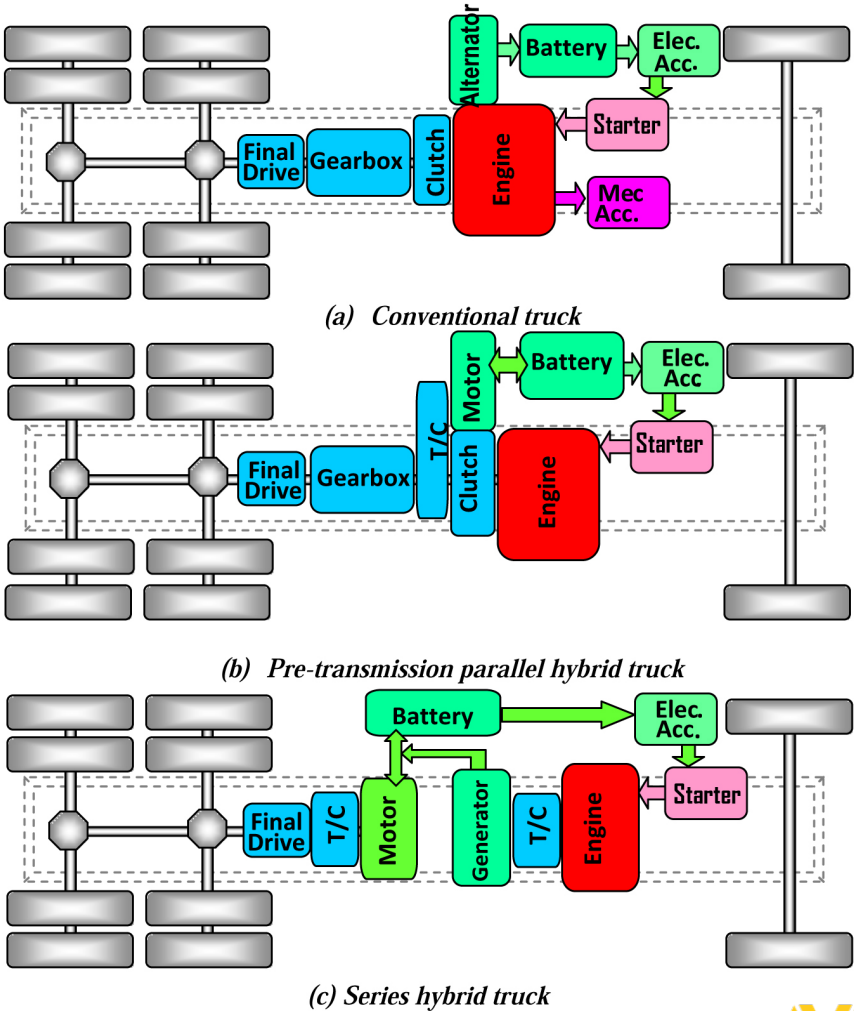


Figure 3. Schematic of the conventional, parallel and series HD hybrid configurations, where T/C represents torque converter.

For the aftertreatment train system, both the conventional and hybrid trucks were assumed to have a 5.8-L DOC, a 19-L catalyzed DPF, and a 24-L SCR catalyst, positioned as shown in Figure 1. In the present study, the heat loss of exhaust tubes connected between these components was not considered. The power consumed for urea dosing is also not considered due to the small low-pressure urea injection rate. For example, in the EcoFit UL2 urea dosing system developed by Cummins Emissions Solutions, the adopted pump provides 4.4m pressure head with a flow capacity of 5-20kg/hr. It is not expected that the power demands from such a pump will significantly affect the fuel economy [33].

Simulations for these trucks included two urban and highway (non-grade) cycles: the UDDS Truck cycle and the Heavy Heavy-Duty Diesel Truck cycle (HHDDT65) [34]. The simulations also included one cycle adapted from the Freeway-Dominant Heavy Duty Truck (FDHDT) driving conditions, which include significant grades [35] (see Figure 4). The FDHDT covers 196.4 miles in 3.72 hours. Unlike the HHDDT65, the FDHDT cycle combines 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 shown in Figure 4.

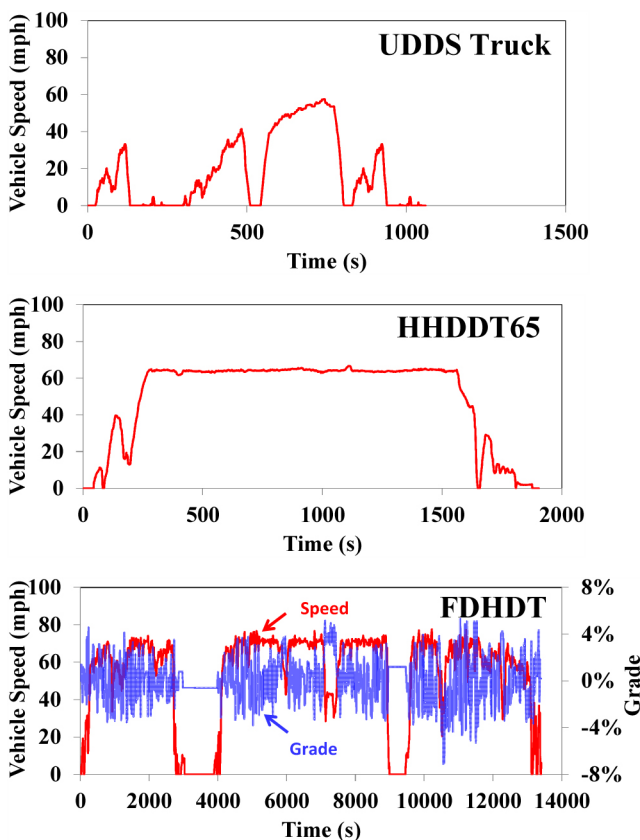


Figure 4. Speed and grade profiles of representative HD drive cycles

Weight is also a key factor for Class 8 truck fuel economy [34]. 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, additional 400

kg and 500 kg for parallel and for series hybrid powertrains, respectively, were included to account for the weight penalty of the motor, battery, and accessory components.

RESULTS AND DISCUSSIONS

In this section, the results of the simulated fuel economy and emissions are presented for the conventional and hybrid HD trucks with three different masses over different drive cycles, and then discuss the sensitivity of auxiliary load reduction on HD truck fuel savings and the opportunities of series hybrid powertrain technology for HD vehicles are discussed.

Fuel Economy

Over the UDDS Truck cycle, both the simulated parallel and series hybrid trucks accomplish significantly better fuel economy than the comparable conventional truck (see Figures 5(a)). The estimated cumulative fuel energy savings are 27.5-34.1% for parallel hybrid and 16.1-29.1% for series hybrid, respectively. Compared to the urban drive cycles, the estimated benefits of hybridization are very tiny for parallel powertrain and even negative for series powertrain under the simulated highway driving conditions, as depicted in Figures 5(b)-(c). In detail, the estimated fuel saving for the parallel hybrid truck in these cycles is ranged from 3.2-4.5% for the HHDDT65 cycle and 2.1-3.5% for the FDHDT cycle. For the simulated series hybrid truck, its fuel economies are significantly less than not only the parallel hybrid truck, but also the conventional truck over both HHDDT65 and FDHDT cycles.

Here the trend impact of truck weight and hybrid powertrain on fuel economy over the HHDDT65 cycle is similar to the FDHDT cycle, and both show the negative impact of series hybrid powertrain on fuel economy over highway driving. The simulated difference of fuel economy between the two drive cycles is that the former is slightly higher than the latter. This could be mainly due to the fact that FDHDT is a real-road drive cycle with grade (see Figure 4). To avoid redundant simulation, the FDHDT cycle is just discussed for highway driving for the rest of the paper.

Figure 6 shows the statistical time distribution for engine operating efficiency, which demonstrates that the series hybrid allows engine operating more time than the parallel hybrid at the most efficient operating conditions. This apparently counters the results for fuel economy plotted in Figure 5. Thus, it is necessary to exploit the energy loss distribution for the conventional, parallel and series hybrid trucks, shown in Figure 7. In the studies, hybrid truck energy loss was normalized based on the conventional truck fuel energy consumption level. It is observed in Figure 7 that both the simulated parallel and series hybrid trucks reduce braking energy loss over the city and highway driving, but the series hybrid truck is better at braking energy recovery due to its large motor and battery sizes. However, compared to conventional and parallel hybrid trucks, the series hybrid truck leads to substantially more energy loss for the motor and generator. For example, the