

Medium-Duty Vehicle Fuel Saving Technology Analysis to Support Phase 2 Regulations

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ABSTRACT

This paper presents the results of engine and vehicle simulation modeling for a wide variety of individual technologies and technology packages applied to two medium-duty vocational vehicles. Simulation modeling was first conducted on one diesel and two gasoline medium-duty engines. Engine technologies were then applied to the baseline engines. The resulting fuel consumption maps were run over a range of vehicle duty cycles and payloads in the vehicle simulation model. Results were reported for both individual engine technologies and combinations or packages of technologies. Two vehicles, a Kenworth T270 box delivery truck and a Ford F-650 tow truck were evaluated. Once the baseline vehicle models were developed, vehicle technologies were added. As with the medium-duty engines, vehicle simulation results were reported for both individual technologies and for combinations. Vehicle technologies were evaluated only with the baseline 2019 diesel medium-duty engine.

The vehicle technology combinations in the T270 delivery truck yielded from 1% to 12% fuel savings, averaged over all the duty cycles. Fuel savings for the diesel engine technology packages ranged from 1% to 5%, averaged over all the duty cycles. The simulation of gasoline engine technology packages produced from 6% to 9% and 6% to 10% for the V-6 and V-8 engines, respectively. The benefits of individual technologies vary widely depending on the drive cycles.

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INTRODUCTION

Medium- and heavy-duty (MDHD) trucks consume approximately 20% of U.S. transportation fuel and emit 20% of vehicle-related greenhouse gases (GHGs) [1]. As a result of the significant contribution to overall GHGs from MDHD vehicles in the U.S., the National Highway Traffic Safety Administration (NHTSA) and the United States Environmental Protection Agency (EPA) finalized regulations to reduce fuel consumption and GHG emissions from medium- and heavy-duty trucks in 2011 [2]. Phase 1 of this program affects model years 2014 to 2018 vehicles. The agencies have proposed a Phase 2 rule which covers model year 2019 to 2027 vehicles [3]. To support the development of standards for Phase 2, NHTSA sponsored research at Southwest Research Institute (SwRI) to assess the technical feasibility of reducing MDHD vehicle fuel consumption.

This paper summarizes results for the vocational segment of the SwRI analysis. Detailed results from the analysis can be found in SwRI's 2015 report to NHTSA, along with a detailed assessment of a

Class 2b/3 pickup and a Class 8 tractor-trailer [4]. Vocational vehicle fuel use and CO₂ emissions represents one fifth of the MDHD total. Vocational vehicles span classes 2b through 8 and include any trucks that are not categorized as combination tractors, Class 2b/3 pickups, or 2b/3 vans. The vocational vehicle segment includes a wide range of Class 2b-8 heavy-duty vehicles ranging from 8,501 lb to greater than 33,000 lb GVWR.

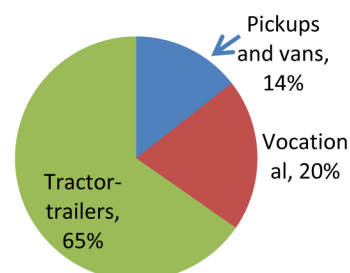


Figure 1. MDHD Fuel Consumption by Vehicle Category, CH

Nearly 90% of Class 4 through 7 trucks are powered by diesel engines, with about a 2% share for natural gas, less than 1% for propane, and the remainder gasoline. Gasoline engines are currently not offered in Class 8 vocational trucks, where diesel engines have a share of nearly 98%. Examples of vocational trucks include delivery trucks, dump trucks, cement trucks, buses, refuse trucks, and other vehicles. Vocational vehicles are typically sold as an incomplete chassis with multiple outfitters who complete the vehicle for sale.

Studies published prior to the release of the Phase 1 regulation, such as a National Academy of Sciences 2010 report [5] and TIAX 2009 study [6], reported that vocational vehicle fuel consumption can be reduced by more than 30% with engine and vehicle improvements from a 2009 vehicle baseline. The studies also found fuel consumption reductions of nearly 50% could be achieved in vocational vehicles if hybridization is included. This analysis provides an updated study of potential savings using a 2019 vocational vehicle baseline.

In the first step of the analysis, SwRI selected two vocational vehicles to evaluate. The selection was based on the availability of extensive test data from previous programs. The two models selected for the analysis, the Ford F-650 and the Kenworth T270 are shown in Figure 2 and Figure 3. SwRI used an in-house code called the Vehicle Simulation Tool for this analysis. This MATLAB-based model is similar to the National Renewable Laboratory ADVISOR simulation tool.



Figure 2. F-650 Tow Truck



Figure 3. Kenworth T270 Delivery Truck

The biggest difference between the F-650 and the T270 truck shown above is that the cargo box of the T270 is replaced by a flatbed in the F-650 for towing purposes. The flatbed greatly reduces the frontal area of the truck, which will reduce aerodynamic drag. At high road speed, the F-650 requires significantly less power than the T270. For example, at 65 MPH, the baseline F-650 has a power requirement of 88 kW, while the T270 demands 129 kW, a 47% increase. Table 1 summarizes vehicle and engine information for the two vehicles.

Table 1. Vehicle and Engine Classification

Weight Class	Vehicle	Diesel	Gasoline	Base Transmission
5	F-650 Tow Truck	Cummins 6.7 Liter 300 HP (base), 4.5 Liter 256 HP	3.5 L V-6, 6.2 L V-8	5-Speed Automatic
6	T270 Box Truck			

Three basic engines were evaluated in the F-650 and Kenworth T270: the medium-duty version of the Cummins ISB 6.7-liter diesel, a 6.2-liter naturally-aspirated gasoline V-8, and a 3.5-liter turbocharged, direct-injection V-6. In addition, a fourth engine variant was evaluated: a 4.5 liter 4 cylinder version of the diesel ISB engine. The ISB diesel is considered the baseline engine for these vehicles since it is the standard engine sold in the F-650 and T270 trucks. The engines-and the technologies to improve engine efficiency-were evaluated using GT-POWER models. Table 2 provides information for each engine.

Table 2. Engine Characteristics

Engine	Displacement (Liters)	Rated HP @ RPM	Torque Peak lb-ft @ RPM	Other
ISB MD	6.7	300 @ 2500	750 @ 1300	Full time EGR
V-6	3.5	370 @ 5500	420 @ 3500	Turbo, DI
V-8	6.2	316 @ 5500	400 @ 4200	NA, PFI

The baseline engine fuel consumption maps created in GT-POWER were validated against the dynamometer tested fuel consumption of 2011 or 2012 model diesel and gasoline engines. Changes such as the addition of friction reduction technology were then made to the diesel engine model to adjust the 2011 engine to a configuration that would be compliant with the engine standards required by the Phase 1 regulation in 2017 through 2019. The 2019 compliant engine maps were then used in the vehicle simulation tool to estimate fuel consumption.

Experimental data from other projects was used by SwRI to calibrate the engine models before additional technologies were added to the simulations.¹ In many cases, detailed combustion heat release data was available from engine testing for the technologies being

1. A separate SAE paper, 2015-01-2778, describes the simulation approach, model calibration, and validation for both engine and vehicle models.

evaluated. This allowed heat release, EGR rates, and other parameters to be input directly into the model, rather than estimated by GT-POWER. The project team also used actual turbocharger efficiency maps as inputs to the model, although these maps were not necessarily from the engine being simulated. The turbo maps were scaled up or down to achieve the required air flow for each specific engine technology simulated.

Each engine fuel map and vehicle model was exercised over a range of drive cycles at zero payload, 50% payload, and 100% payload. The range of drive cycles is critical in order to exercise the technologies over a range of speeds and loads. In EPA's Phase 1 MDHD GHG compliance model ("GEM"), vocational vehicles are certified on cycles that include an urban stop-and-go cycle developed by CARB, a 55 MPH steady-state cruise, and a 65 MPH steady-state cruise. The cruise cycles do not include any grade, so they effectively represent a single operating point for the engine. The World Harmonized Vehicle Cycle (WHVC) cycle includes urban, rural, and European-style motorway segments. The Combined International Local and Commuter Cycle (CILCC) and Parcel delivery cycles are stop-and-go cycles meant to reflect delivery truck operation. The reason for exploring several duty cycles is to develop an understanding of how different engine and vehicle technologies perform across a range of drive cycles. Certain technologies may be insensitive to payload or drive cycle, while others can be extremely sensitive.

RESULTS

Table 3 shows fuel economy in the T270 with the baseline ISB diesel, V-6 gasoline, and V-8 gasoline engines, evaluated over the six drive cycles. The diesel engine (ISB) compared to the V-8 gasoline engine provided the greatest fuel savings: 15% to 23%. The diesel also performed better than the V-6 gasoline engine, delivering 6% to 16% fuel savings over the V-6 gasoline engine. In general, the diesel engine performs best on the steady state cycles, such as the 55 mph and 65 mph, but it doesn't do as well on transients such as the CARB cycle. This is because the cruise cycles impose a higher average power demand on the engine, and the more load put on the diesel engine, the better it performs relative to the gasoline engines. However, vocational vehicles typically travel on a more transient cycle represented more closely by the Parcel cycle and the other transient cycles.

Table 3. T270 Fuel Economy (MPG) with the 2012 baseline ISB, V-6, and V-8 at 50% Payload

Drive Cycle	ISB (mpg)	3.5L V-6 (mpg)	6.2L V-8 (mpg)
CARB	7.7	6.8	6.1
55 MPH	9.7	7.7	7.4
65 MPH	8.0	6.1	6.0
WTVC	9.2	7.8	7.3
CILCC	7.6	7.1	6.2
Parcel	5.8	5.4	4.9

On all drive cycles and payloads but one (65 MPH at full GCW), the V-6 performed better than the V-8. The biggest benefits were at light loads on low-speed drive cycles. The diesel provided up to 30% fuel savings as compared to the 6.2L V-8 on higher-speed and higher-load drive cycles.

After baseline engine configurations for model year 2019 were developed for the three engines in GT-POWER, technologies were applied to the engines to reduce fuel consumption. The technologies were selected based on a literature search, presentations from technical meetings, and input from vehicle and engine manufacturers. Four technologies were applied to the ISB diesel engine and these were modeled in GT-POWER: 1) reduced exhaust restriction; 2) reduced engine friction; 3) EGR removal; and 4) 5% turbo efficiency improvement.

Seven technologies were evaluated on the 3.5 liter V-6 turbocharged, stoichiometric, DI gasoline engine. These included: 1) VVA²; 2) cylinder deactivation; 3) lean burn GDI; 4) cooled EGR; 5) cooled EGR + downspeeding; 6) reduced engine friction; and 7) high efficiency turbo. Six technologies were evaluated on the 6.2 liter V-8 gasoline engine: 1) stoichiometric GDI; 2) lean burn GDI; 3) VVA; 4) cylinder deactivation; 5) cooled EGR; and 6) reduced engine friction.

For the diesel engine, a map of estimated friction (FMEP) reduction was applied in the model. The map assumed a 10% improvement at high speed and load, increasing to 35% reduction at low speed and light load. For the two gasoline engines, the FMEP reduction assumption was a flat 10% across the speed/load range. A large number of friction reduction features could be implemented to reach such improvements, including a variable-speed water pump, variable-displacement oil pump, reduced piston cooling, improved bearings, valve train friction reduction, rings and liners, and low viscosity lube oil. Engine friction reduction on the gasoline engines included the above technologies, except for piston cooling and valve train friction reduction. FMEP reduction offers significant potential for improving diesel engine efficiency in medium-duty trucks. Fuel consumption benefits of 2.4% to 8.5% were found, with the larger benefits occurring on lightly-loaded vehicles on low-speed drive cycles.

The effect of exhaust system backpressure was explored on the diesel engine. A 50% reduction in backpressure had very limited fuel consumption benefits of zero to 0.5%, depending on the drive cycle and payload.

For the diesel, a high engine-out NOx approach (no EGR and a more efficient turbo) can also provide a significant benefit, though this approach assumes future technical advances in aftertreatment that would mitigate the effects of higher engine-out NOx and allow for OBD compliance. This approach is also not compatible with potential future reductions in NOx limits.

For the 3.5 liter turbocharged V-6, adding VVA to reduce pumping work was predicted to provide a fuel consumption benefit of about 3%. Cylinder deactivation can provide up to a 2% benefit on very lightly-loaded drive cycles, but zero at high speed. Lean-burn GDI

2. VVA includes variable timing, lift, and duration.