

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

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ABSTRACT

This paper presents the fuel consumption results of engine and vehicle simulation modeling for a wide variety of individual technologies and technology packages applied to a long haul heavy duty vehicle. Based on the simulation modeling, up to 11% in fuel savings is possible using commercially available and emerging technologies applied to a 15L DD15 engine alone. The predicted fuel savings are up to 17% in a Kenworth T700 tractor-trailer unit equipped with a range of vehicle technologies, but using the baseline DD15 diesel engine. A combination of the most aggressive engine and vehicle technologies can provide savings of up to 29%, averaged over a range of drive cycles. Over 30% fuel savings were found with the most aggressive combination on a simulated long haul duty cycle. Note that not all of these technologies may prove to be cost-effective. The fuel savings benefits for individual technologies vary widely depending on the drive cycles and payload.

CITATION: Badain, N., Reinhart, T., Cooper, C., MacIsaac, J. et al., "Heavy-Duty Vehicle Fuel Saving Technology Analysis to Support Phase 2 Regulations," *SAE Int. J. Commer. Veh.* 8(2):2015, doi:10.4271/2015-01-2775.

INTRODUCTION

Medium- and heavy-duty (MDHD) trucks (Classes 2b - 8) 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 [1]. Phase 1 of this program affects model years 2014 to 2018 vehicles. The agencies are currently working on a proposal for Phase 2 [2]. 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 heavy-duty long haul combination tractor-trailer 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 of two Class 5 and 6 vocational trucks [3]. Figure 1 shows that tractor-trailer vehicle fuel use and CO₂ emissions represents about two thirds of the MDHD total. The specific vehicle simulated in this study is a sleeper cab combination tractor, which represents 39% of the total fuel use. In 2011, all tractor types (high-, mid- and low-roof

sleepers, and day cabs) represented about 10% of the MDHD trucks sold that year. Over 98% of combination tractor-trailer vehicles are powered by diesel engines, with the remainder being powered by natural gas.

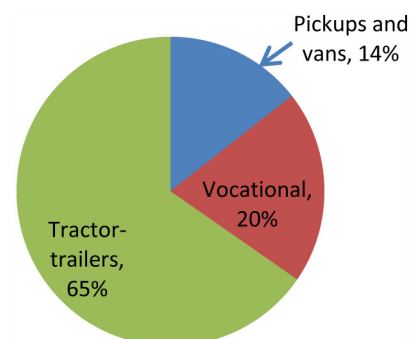


Figure 1. MDHD CO₂ Emissions by Vehicle Category [15]

Studies published prior to the release of the Phase 1 regulation, such as a National Academy of Sciences 2010 report [4] and TIAX [5], reported that up to 50% of tractor-trailer fuel consumption can be eliminated with engine and vehicle improvements, compared to a 2009 vehicle baseline. The 50% fuel savings figure includes technologies not considered in this study, such as hybrid systems and

controls features that provide driver management and coaching. This analysis provides an updated study of potential savings using a 2019 vocational vehicle baseline.

The technologies evaluated in this study were selected by SwRI and NHTSA with input from EPA and other organizations. Certain types of technology such as driver management features and GPS-linked adaptive cruise control were not considered, because the simulation tools could not adequately capture their performance. Hybrid systems were also not considered, since previous studies had found relatively modest fuel savings on long haul cycles, and hybrid systems are both heavy and expensive. Some potentially impractical technologies, such as EGR delete and a 60% reduction in exhaust system backpressure, were included in order to get a better understanding of the fuel consumption impact of these parameters. A companion paper describes the project methodology in more detail [12], and another companion paper describes the results for medium-duty trucks [13].

In the first step of the analysis, SwRI selected a long haul tractor-trailer vehicle to evaluate. The selection was based on the availability of extensive test data from previous programs. The vehicle model selected for the analysis, the Kenworth T700, is shown in Figure 2. SwRI used an internally developed Vehicle Simulation Tool called VST for this analysis. This MATLAB-based model is similar to the National Renewable Laboratory ADVISOR simulation tool. Table 1 summarizes some of the important characteristics of the T700.



Figure 2. Kenworth T700 Tractor and Standard 53 Foot Box Van Trailer

Table 1. Parameters of the baseline Kenworth T700 Tractor and Standard 53 Foot Box Van Trailer

Weights:	
Empty	33,690 lb
50% Payload	56,980 lb
100% Payload	80,000 lb
Drag Coefficient Cd	0.639
Rolling Resistance Crr	0.005608
Transmission	10-Speed Automated Manual
Engine RPM, Top Gear @ 65 MPH	1,368
Transmission Efficiency	Measured Map
Axle Efficiency	Measured Map
Total Accessory Power Demand	6,650 Watts

Only one engine was evaluated in the Kenworth T700: the Detroit Diesel DD15, a 15-liter diesel inline 6-cylinder, with the basic specifications shown below:

- Single Fixed Geometry Turbo
- Auxiliary Power Turbine (Turbocompound) with geared link to engine
- 4 valves per cylinder
- 376 kW @ 1800 rpm & 2200 Nm @ 1240 - 1400 rpm
- Bosch amplified common rail fuel system (ACRS), 2200 bar maximum injection pressure

The engine-and the technologies to improve engine efficiency-were evaluated using GT-POWER models. Note that the DD15 engine is not available in a T700 truck. The T700 tested to provide baseline weight, aerodynamic drag, and tire rolling resistance data was powered by a Cummins ISX engine. The reason for using the T700 with the DD15 is that extensive test data was available to independently calibrate both the vehicle and engine models.

The 2011 model DD15 that served as the baseline for this project has a couple of features that are unique in the North American market. One feature is turbocompound, which is an additional power turbine located between the standard turbocharger and the exhaust aftertreatment. The power turbine is geared to the crankshaft, so it supplies additional power to the crankshaft. The turbocompound turbine also produces a significant backpressure, which enables EGR flow with a conventional fixed geometry turbocharger. The second unusual feature of this engine is the amplified common rail fuel system. This system offers some scope for rate shaping of injection events by varying injection pressure during a single injection event.

The baseline DD15 engine maps in GT-POWER were validated to within +/- 3% against the dynamometer tested fuel consumption performance of the 2011 model year engine. This version of the DD15 is fitted with an exhaust power turbine unit which was mechanically linked to the engine crankshaft (turbocompound). Measured combustion data was used as an input to the GT model. Measured EGR rates were also applied directly in the GT model, using a controller. The only non-measured data was the turbo maps used for both the main turbo & the power turbine. In this case, for the main turbo a similarly sized engine turbo map was used & scaled to achieve the required flowrates and pressure drops, and for the power turbine another turbo map was sourced and scaled accordingly.

To validate the DD15 model, several parameters calculated by the model were compared to actual engine test results. Plots showing some of the baseline results are shown in Figures 3, 3a and 3b. Additional validation information is provided in Appendix B of [3].

The technology evaluations were then performed using the baseline model, with a full speed and load range fuel map being the ultimate output from the GT model, which was then used in the vehicle model and evaluated across the chosen drive cycles. Where required, experimental data from other projects was used by SwRI to calibrate

the models when additional technologies were added to the simulations, such as combustion model changes when EGR rates were modified significantly.

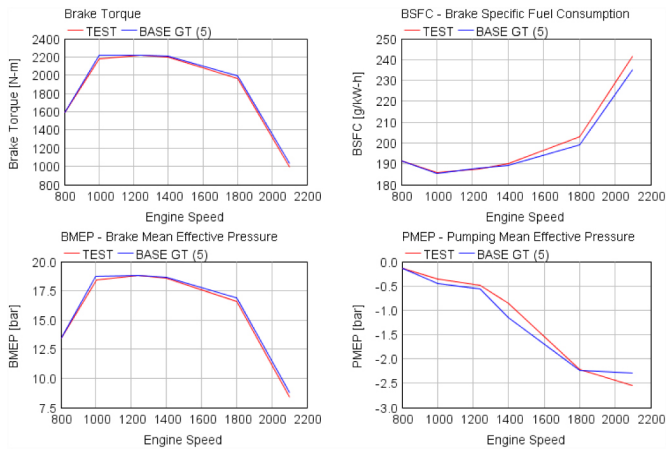


Figure 3. GT Power DD15 Baseline Engine validation

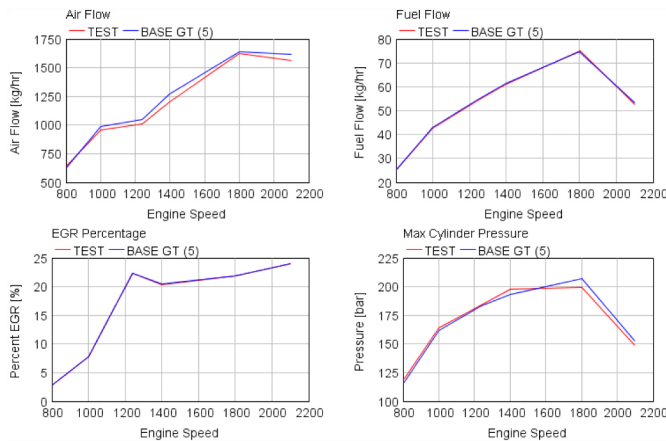


Figure 3a. GT Power DD15 Baseline Engine validation

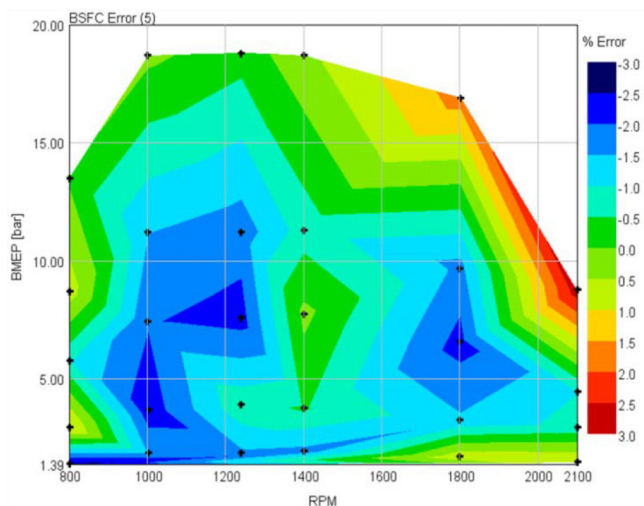


Figure 3b. GT Power DD15 Baseline Engine BSFC Error

Each engine and vehicle 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 operating conditions. In EPA's Phase 1 MDHD GHG compliance

model ("GEM"), tractor-trailer 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. For sleeper cab tractors, the certification result is heavily weighted towards the 65 MPH cruise cycle. The GEM 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, with a maximum speed of 53 MPH.

The NESCCAF cycle was developed on a previous project and represents an attempt to simulate a typical long haul duty cycle. This cycle includes some low speed driving and several high speed cruise segments at speeds from 65 to 70 MPH. The NESCCAF cycle also includes segments with $\pm 1\%$ and $\pm 3\%$ grades. These features result in the engine and vehicle being exercised over a wider range of conditions than in the other drive cycles. 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 2 shows fuel economy of the T700 with the baseline DD15 diesel, over 5 drive cycles for 3 payload ratings. The payloads correspond to an empty vehicle weight of 33,960 pounds for 0% payload, with 2 increments of 23,020 pounds of payload to provide 50% & 100% payload. At 100% payload, the total vehicle weight is 80,000 pounds.

As expected, the higher payload always has a fuel consumption penalty, and those drive cycles with the highest penalty for additional payload have more accelerations in the cycle. Acceleration causes an inertia power demand (power required to accelerate the vehicle), and this power demand is directly proportional to weight. The 65 MPH cruise cycle has the least payload sensitivity. For this cycle, the inertial power demand is zero (no accelerations) and the aerodynamic drag is high. Aerodynamic drag is a function of vehicle speed but is independent of payload, so fuel consumption becomes less sensitive to payload at higher road speeds.

Table 2. T700 Fuel Consumption (gallons per 100 miles) with the baseline DD15 at 3 Payloads

Drive Cycle	Percent Payload		
	0%	50%	100%
CARB	17.0	21.6 (+27.4%)	26.5 (+56.3%)
55 MPH	10.8	12.3 (+13.9%)	13.9 (+28.7%)
65 MPH	13.2	14.8 (+11.8%)	16.4 (+23.6%)
WHVC	13.0	16.1 (+23.8%)	19.5 (+50%)
NESCCAF	13.5	15.2 (+12.6%)	17.2 (+27.8%)

Note: the number in brackets indicate the $\square$ increase in fuel consumption for each payload from the 0 payload condition

Assumptions for accessory power demand also play a role in the fuel consumption results shown in Table 2. Based on a literature review, the following accessory power demands were applied as a steady state load on the engine:

Air conditioner	1,500 Watts
Cooling fan	2,000 Watts
Alternator	1,250 Watts
Power steering	1,250 Watts
Air compressor	650 Watts
Total accessory power	6,650 Watts

In actual driving, these accessory power demands will vary as a function of time and engine speed. However, simulating these varying demands is very challenging. For example, determining when the cooling fan clutch would engage would require a sophisticated model of the vehicle cooling system, along with assumptions about ambient temperature and wind. Once engaged, fan power demand is a function of engine speed cubed. Rather than deal with this complexity, average power demand values from the literature were applied as a steady state load over the entire drive cycle.

Engine Technology Evaluation

After validation of the baseline engine configuration, the engine model in GT-POWER was developed to represent a variety of technologies to reduce fuel consumption. The technologies were selected based on a literature search, presentations from technical meetings, and input from vehicle and engine manufacturers. In addition to the baseline engine, a further 19 technologies were assessed.

A summary of the results for the 50% payload variant is shown in Table 3 and Figure 4, with a more detailed analysis of the results in the following text. A full set of results can be found in SwRI's 2015 report to NHTSA [3].

DD15 Engine Technology List:

1. Baseline DD15 engine
2. Optimized Turbocompound (Opt. TCPD)
3. Electric Turbocompound (Elec. TCPD)
4. No EGR
5. Turbocompound Removed (No TCPD)
6. EGR & Turbocompound Removed (No EGR or TCPD)
7. Asymmetric Turbo (Asym. Turbo)
8. Reduced Exhaust Backpressure (Low Back Press.)
9. Reduced Inlet Restriction (Low Intake Rest.)
10. Reduced Charge Air Cooler Restriction (0 CAC rest.)
11. Reduced Engine Friction (Low FMEP)
12. High Efficiency Turbo (+5% Turbo Eff.)
13. No EGR, No Turbocompound, High Efficiency Turbo (No EGR, TCPD, +5%T)

14. Downsized A
15. Downsized B
16. Downsized at Constant Torque
17. Downsized at Constant BMEP
18. Variable Valve Actuation (VVT)
19. Water-Based Bottoming Cycle (Water BC)
20. R245 Refrigerant-Based Bottoming Cycle (R245BC)

Table 3. Fuel savings results of DD15 engine technologies, using baseline T-700 Tractor-Trailer, and relative to the baseline engine

Technology	Percent Fuel Savings on Drive Cycle at 50% Payload				
	CARB	55 MPH	65 MPH	WHVC	NESCCAF
2. Opt. TCPD	0.6	0.7	0.6	0.6	0.4
3. Elec. TCPD	0.9	0.9	0.9	0.9	0.9
4. No EGR	0.3	0.7	0.6	0.4	0.6
5. No TCPD	1.2	0.7	1.2	1.0	1.0
6. No EGR or TCPD	1.6	1.6	2.0	1.5	1.7
7. Asym. Turbo	1.3	0.8	1.3	1.1	1.1
8. Low Back Pres.	0.4	0.3	0.4	0.4	0.5
9. Low Intake Rest.	0.1	0.0	0.1	0.1	0.1
10. 0 CAC Rest.	0.1	0.1	0.1	0.1	0.1
11. Reduced FMEP	4.6	3.1	2.1	3.9	2.3
12. + 5% Turbo Eff	2.3	2.4	2.8	2.3	2.5
13. No EGR, no TCPD, +5% T	2.5	2.5	3.1	2.5	2.8
14. Downsized A	3.9	2.7	2.0	3.4	2.4
15. Downsized B	4.2	0.8	4.0	3.1	3.8
16. Downsized Torque	3.7	1.8	2.0	2.9	2.0
17. Downsized BMEP	3.9	1.5	1.6	2.7	1.9
18. VVA	N/A	N/A	N/A	N/A	N/A
19. Water BC	N/A	4.1	4.6	N/A	4.7
20. R245 BC	N/A	2.8	2.7	N/A	2.6

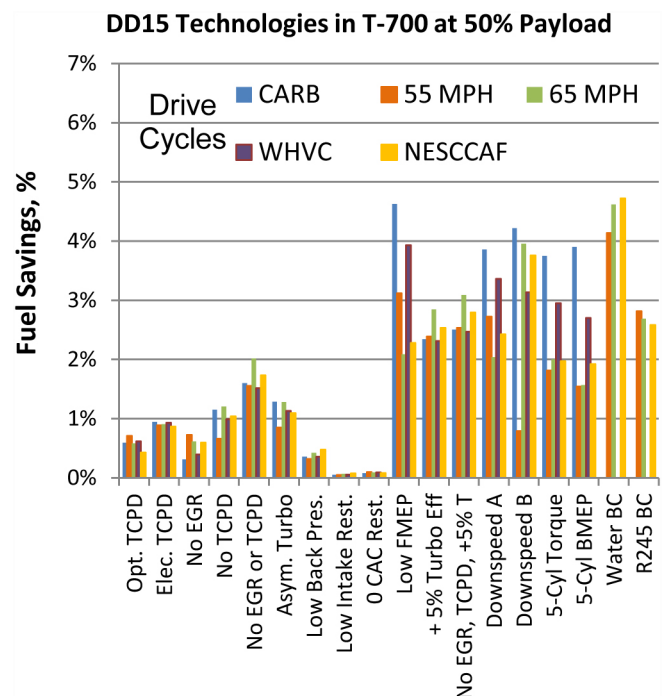


Figure 4. Fuel savings results of DD15 engine, using baseline T-700 Tractor-Trailer

DD15 Technology #2: The Optimized Turbocompound technology represents an effort to modify the base engine by going to a power turbine that is downsized, in an effort to extract more exhaust energy at cruise conditions. The penalty for this is higher backpressure (and thus pumping loss) on the engine at high speed and load. In the simulated drive cycles, the engine rarely operates near rated speed, so this penalty is insignificant. Nevertheless, as the results in [Table 3](#) and [Figure 4](#) show, the benefit from downsizing the turbocompound is small (under 1%), regardless of the drive cycle.

DD15 Technology #3: An electric turbocompound uses the output of the power turbine to drive a generator. The electricity is then used to drive an electric motor which is connected to the crankshaft. This allows the power turbine speed to be independent of engine speed, which helps achieve better turbine efficiency across a wider portion of the engine operating range. However, as the results show, the fuel consumption and GHG benefit is limited to 0.8% to 1% on all of the drive cycles. In switching from mechanical to electric turbocompound, the mechanical transmission is deleted and replaced with a generator, power electronics, and a motor. As a result, the electric turbocompound system will be more complex and expensive than the mechanical turbocompound.

DD15 Technology #4: Driving EGR flow in an engine requires pumping work. The exhaust manifold pressure must be maintained higher than the intake manifold pressure in order for EGR to flow. Removing EGR has two benefits: pumping work can be reduced, and combustion heat release rates will increase. In the case of the DD15 engine, however, removing EGR does not eliminate much pumping work, because the power turbine keeps exhaust manifold pressure high. As a result, removing EGR has only a marginal benefit on this engine - less than 1%. Note that this no-EGR technology involves very high engine-out NO_x, which in turn requires a very high SCR conversion efficiency and high urea consumption, which could present significant challenges in OBD. Another caveat is that we did not change the combustion duration, because we lacked the engine experimental data to do so. In practice, combustion duration without EGR will be somewhat shorter, which should improve engine efficiency.

DD15 Technology #5: For 2013, Detroit removed the turbocompound system from one version of the DD15. SwRI simulated this approach in two steps. In the first step, we removed the turbocompound system, but retained a standard dual entry fixed geometry turbocharger and the EGR system. This technology is labeled "No TCPD" in the table and figure. The turbo was rematched to accommodate the removal of the turbocompound power turbine. This configuration is not able to flow EGR at lower engine speeds. One option is to add an intake throttle to drive EGR flow. This approach would increase fuel consumption at lower engine speeds, due to pumping losses. The other alternative is a higher conversion efficiency SCR and higher urea consumption, which is the option modeled here. It is something of a surprise that removing the turbocompound system provides a slight fuel consumption benefit of 0.7% to 1.3% on all drive cycles and over all payloads. Note, however, that none of the evaluated drive cycles and payloads requires the engine to operate at full load for a significant period of time, and turbocompound performs best at full load.

DD15 Technology #6: Once the turbocompound system is removed, the engine can benefit from not requiring backpressure to drive EGR flow. This technology simulation determined that the benefit, assuming no changes in turbocharger efficiency, approaches 2%. Note again that this no-EGR technology involves very high engine-out NO_x, which in turn requires a very high SCR conversion efficiency and high urea consumption. The high urea consumption in turn drives user cost up. A larger, heavier urea tank may also be required. One caveat is that we did not change the combustion duration, because we lacked the engine experimental data to do so. In practice, combustion duration without EGR will be somewhat shorter, which should improve engine efficiency. Achieving very high NO_x conversion efficiency across the entire operating range is a significant technical challenge. Providing OBD functionality that can detect any problems in such a system with sufficient resolution is an even larger challenge.

DD15 Technology #7: This technology is a simulation of the 2013 model DD15 recently introduced by Detroit. In this version, there is no turbocompound. The conventional dual entry turbocharger is replaced by an asymmetric dual entry, fixed geometry turbocharger. One turbine volute is substantially smaller than the other. The small volute imposes a backpressure on the front 3 cylinders, enabling EGR flow from these three cylinders. The back 3 cylinders are able to run with a positive intake to exhaust pressure ratio, also known as a positive Δp . There is a wastegate on the larger turbine volute, which can be modulated to retain the desired back pressure on the front 3 cylinders, so that they achieve the required EGR flow. This technology provided results 0.8% to 1.6% better than the baseline across the range of drive cycles and payloads. Note that none of the simulated drive cycles and payloads require full engine power for a significant period of time. It should be noted that this technology approach is currently unique to Detroit (Daimler) engines in the heavy-duty industry. All other manufacturers use a variable geometry turbocharger to regulate the manifold pressure ratio and thus EGR flow. In the past, several researchers have found benefits from adding turbocompound, but a paper from Daimler describing the new version of the DD15 [8] provides experimental data similar to SwRI's simulation results.

DD15 Technology #8: Engine efficiency can be improved by reducing restrictions on air flow. Modern aftertreatment systems impose higher back pressure on the engine than the muffler-only systems used before 2007. For this technology simulation, exhaust back pressure was reduced by about 60%. This amount of back pressure reduction would be very difficult to achieve in production feasible hardware, but even with the very optimistic reduction in back pressure, the effect was 0.5% or less for all drive cycles and payloads.

DD15 Technology #9: This simulation evaluated the effect of lower restriction through the intake air system, air filter, and plumbing connecting to the turbocharger compressor inlet. A 50 - 60% reduction in restriction was modeled. Very small benefits (under 0.1%) were found for all drive cycles and payloads.