

Analysis Process for Truck Fuel Efficiency Study

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ABSTRACT

Medium- and Heavy Duty Truck fuel consumption and the resulting greenhouse gas (GHG) emissions are significant contributors to overall U.S. GHG emissions. Forecasts of medium- and heavy-duty vehicle activity and fuel use predict increased use of freight transport will result in greatly increased GHG emissions in the coming decades. As a result, the National Highway Traffic Administration (NHTSA) and the United States Environmental Protection Agency (EPA) finalized a regulation requiring reductions in medium and heavy truck fuel consumption and GHGs beginning in 2014. The agencies are now proposing new regulations that will extend into the next decade, requiring additional fuel consumption and GHG emissions reductions. To support the development of future regulations, a research project was sponsored by NHTSA to look at technologies that could be used for compliance with future regulations.

Data presented in this paper detail how engine and vehicle simulation models were developed for current medium and heavy duty vehicles and then validated against available test results. In addition, the paper describes how potential future engine and vehicle technologies were added to the baseline models to simulate future improvements in medium and heavy duty vehicle fuel consumption and GHG emissions. Wherever possible, experimental data was used as inputs to the models or to validate the simulation results. The effect of drive cycle on engine efficiency is also explored.

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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 [1]. Phase 1 of this program affects model year 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 the analysis approach used to evaluate potential fuel saving technologies for trucks ranging from Class 2b (3/4 ton pickup trucks) up through Class 8 long haul tractor-trailer trucks. The analysis was done by simulation of engines and vehicles. A wide range of both engine and vehicle fuel saving technologies has been explored over a number of drive cycles. Experimental data from

both vehicle and engine testing was used as model inputs or to validate and support the analysis wherever possible. A wide range of technologies was evaluated, but not all possible technologies. Some technologies are difficult to simulate, or require extensive validation data that was not available. The agencies and SwRI agreed upon the technology list that was evaluated in this project.

Detailed results of the program are provided in SwRI's three reports to NHTSA [3, 4, 5]. Results for medium-duty vocational trucks are also provided in SAE Paper 2015-01-2769 [6], while results for long haul tractor-trailer trucks are available in SAE Paper 2015-01-2775 [7]. This paper describes the modeling methodology and model verification. Previous work that was used to support the Phase 1 regulations can be found in [8, 9].

METHODOLOGY

Vehicle Modeling Tool

Southwest Research Institute has developed a number of simulation tools for vehicle performance and fuel economy evaluation. The most commonly used ones are PSAT and Raptor. PSAT is a powertrain

System Analysis Toolkit) was the first forward-looking (integral-approach) modeling tool developed in the MATLAB/Simulink environment. PSAT was developed for The United States Council for Automotive Research (USCAR) during the Partnership for a New Generation of Vehicles (PNGV) Initiative. SwRI provided a version of PSAT to Argonne National Lab, who utilized it for its DOE-funded programs and continued to upgrade and sell the tool to the rest of the automotive industry. RAPTOR, on the other hand, was co-developed by SwRI and Chrysler Corp for generating validated NHTSA Corporate Average Fuel Economy (CAFE) numbers on specific vehicle platforms. These two tools are still used in the industry.

SwRI has also utilized other simulation tools and upgraded them to meet its client's needs. One of these tools is SwRI's Vehicle Simulation Tool (VST). This software is based on NREL's original Advisor vehicle simulator offered by NREL and utilized worldwide by hundreds of users. The main difference between Advisor and PSAT is that Advisor utilizes a backward-looking simulation algorithm that starts from the vehicle speed requirements during a cycle and then determines the powertrain demand, using a differentiation rather than an integration approach. The advantage of using the VST's differentiation approach is that each vehicle variant that is simulated is forced to precisely run the cycle in the same manner, regardless of the vehicle configuration. An integration approach (like PSAT) must utilize a driver model to modulate the accelerator pedal and brakes to follow the cycle. Even though this approach can be more representative of a real driver's behavior, one cannot guarantee that every vehicle configuration will follow the drive cycle in precisely the same way. When small variations in vehicle or powertrain parameters need to be evaluated, which is the case in this NHTSA program, a backwards looking approach is better suited for such simulation requirements. VST uses a backward looking algorithm. In addition, the execution of backward-looking representations can offer other benefits as well, such as an execution speed that is at least one order of magnitude faster than forward-looking representations. Since thousands of simulation runs were necessary to conduct this fuel economy study, SwRI chose to use VST for all configurations and analyses described in this paper.

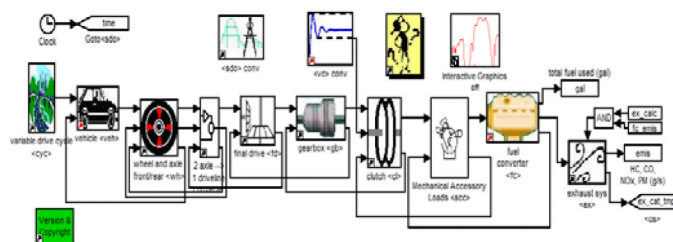


Figure 1. Top-Level Simulink Diagram of the Vehicle Model

The Matlab-based SwRI Vehicle Simulation Tool was used for vehicle level simulations. The VST models used experimentally derived aerodynamic drag and rolling resistance data obtained from coastdown testing. Extensive data provided by the manufacturers was also used to create a complete file of input data on each vehicle. SwRI's VST tool incorporates improvements to the original NREL component models, and enhanced functionalities in ways that allow the user to define each component of the vehicle. VST can simulate and post-process the

results in an efficient and timely manner. Each component's set of parameters is defined in a MATLAB scripting format that is used in conjunction with a Simulink model as shown in Figure 1.

SwRI's VehSim tool was validated against available chassis dynamometer test data as shown in Figure 2. These results are for the baseline Ford F-650 tow truck with the diesel engine. Not shown here are results for model validations of other vehicles evaluated in this study, although the level of agreement was similar. The results showed good agreement in terms of following the desired vehicle speed trace and transmission shift schedule. As a result, the two engine speed traces are also very similar.

The fuel flow trace on the upper right of the figure shows much more fluctuation for the simulation than for the chassis dyno test, but this result is misleading. The chassis dyno fuel flow results are effectively low pass filtered (smoothed) by the fuel flow measurement system. The chassis dyno fuel flow tends to be higher than the simulation when the vehicle is stationary. This is driven by variations in accessory load, such as the cooling fan. In the simulation, an average accessory load is applied over the whole cycle. The total quantity of fuel used for fuel economy computations on the chassis dynamometer, however, was measured by a separate, more accurate volumetric means. In every case, the difference in total fuel consumption between the chassis dyno cycle test and the simulation was less than 5%.

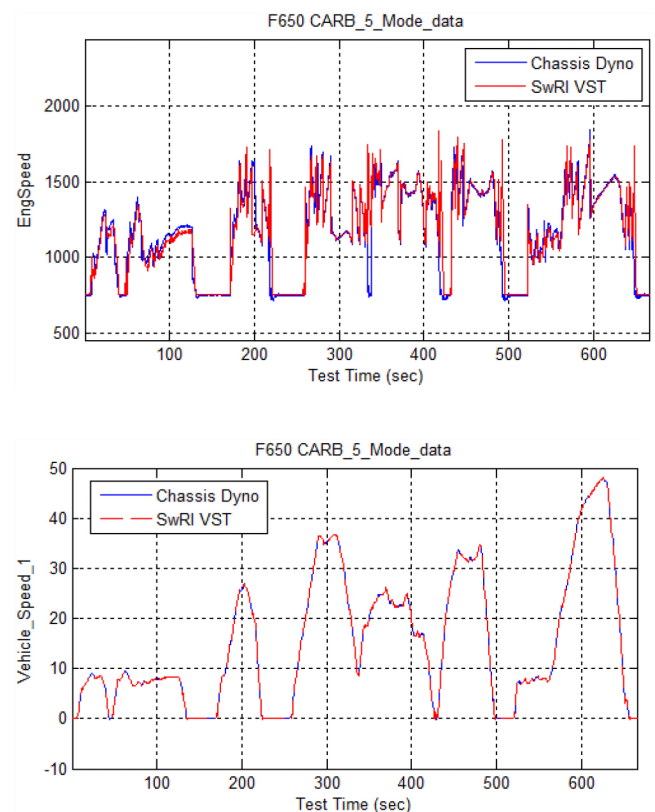


Figure 2. Validation of SwRI's VST Simulation Tool against Chassis Dyno Data for a Representative Vehicle Similar to one of the Vehicles Evaluated in this Study

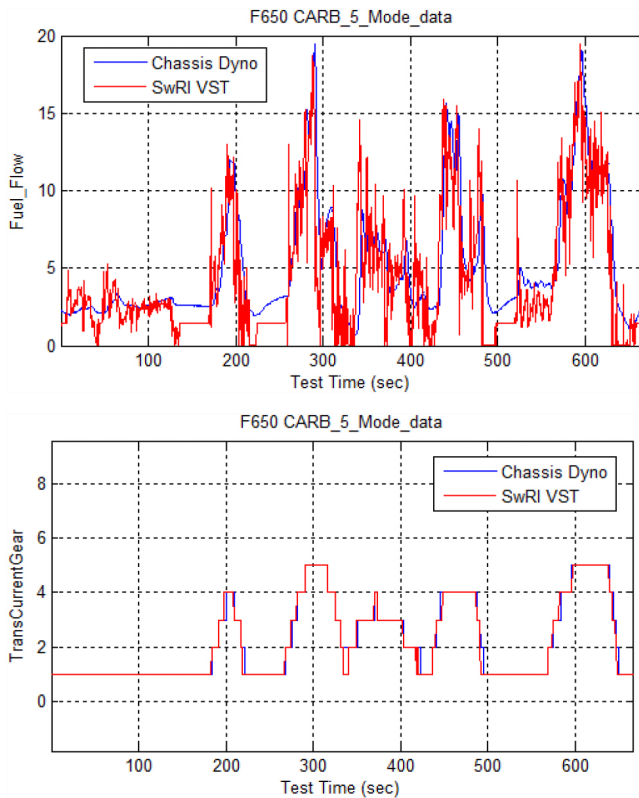


Figure 2. (cont.) Validation of SwRI's VST Simulation Tool against Chassis Dyno Data for a Representative Vehicle Similar to one of the Vehicles Evaluated in this Study

Drive Cycles

A total of eleven vehicle drive cycles were used in the study. The NESCCAF cycle was developed to represent a typical line haul tractor-trailer type of operation. There are brief urban/suburban sections at the beginning and end of the cycle, to represent getting to and from the highway. The main portion of the cycle consists of five cruise segments at speeds of 65 to 70 MPH. One of the cruise segments has an alternating $\pm 1\%$ grade, and a second cruise segment has an alternating $\pm 3\%$ grade. The NESCCAF cycle is the only cycle that includes grades. Because tractor-trailer trucks cannot normally maintain cruise speed on a 3% grade, the cycle was given a feature that extended the drive time to force the vehicle to complete the required distance, including distance on the grades. [Figure 3](#) shows the vehicle speed vs. time trace, and [Figure 4](#) shows the grade vs. time trace. This cycle was only used for tractor-trailer trucks.

As part of this study, SwRI performed minor custom modifications to the simulation tool in order to accommodate some specific requirements for this study. The most significant modification was the introduction of an adaptive driving cycle algorithm to guarantee that the vehicle drives the same distance regardless of powertrain limitations or the severity in road grade. This was particularly important when assessing the fuel economy of the vehicle on the NESCCAF cycles with grade. An example of results from the resulting algorithm (see [Figure 5](#)) shows the original and the adapted

cycle traces. The drive cycle includes periods of 3% grade from around 2900 seconds to 3800 seconds. Because the vehicle does not have enough power to maintain speed on the 3% grade, the actual speed falls short of the target. The algorithm automatically compensates by adding additional time to ensure that the vehicle covers the same distance, regardless of the speed achieved. Note that if two vehicles have different speeds on the 3% grade, they will require a slightly different total amount of work to complete the cycle, even though both travel the same distance. This is because aerodynamic drag is a speed squared term. A comparison of two vehicles which have different minimum speeds on a grade may thus be considered “unfair”, but this reflects what happens on the road, where a lower performance vehicle will have a slightly lower vehicle power demand, and thus slightly lower fuel consumption at the same engine thermal efficiency.

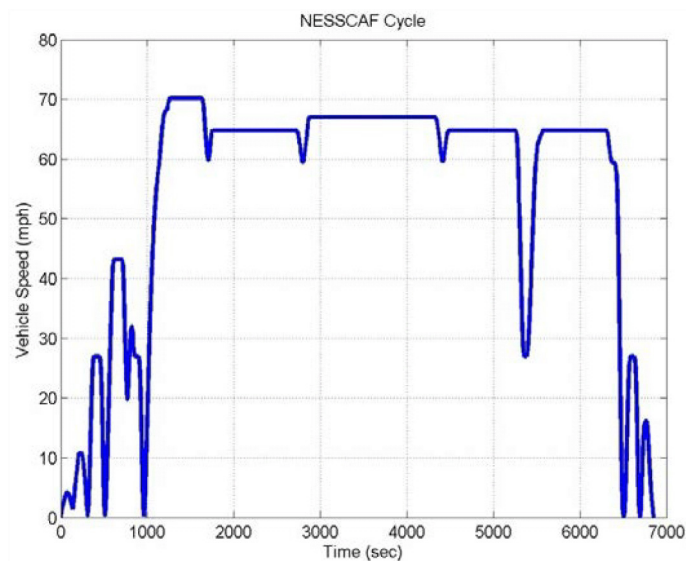


Figure 3. NESCCAF long-haul truck drive cycle speed vs. time history

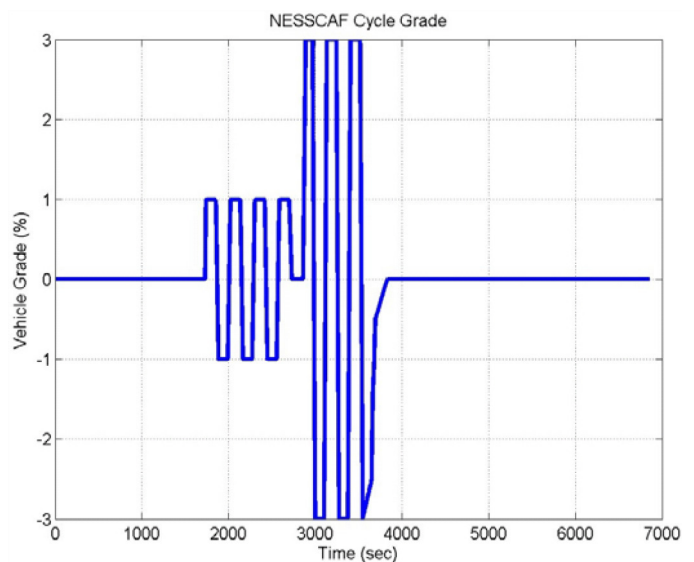


Figure 4. NESCCAF long-haul truck drive cycle grade vs. time history