# Designing the Value Proposition of Components with Vehicle Level Modeling of Fuel Economy and Emissions for Tier 1s

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**What if….**

- You could optimize your Tier 1 component for any OEM vehicle platform virtually?
- You could describe, in detail, the fuel economy and emissions value proposition of your components to OEMs, based on their own vehicles?

CSEG has developed a 1D Vehicle Level Model that speeds up your ability to iterate and refine your designs. The out of the box, optionally customizable, model, comes complete with the data and correlations you need to design your components for your customer's vehicle systems. The goal of this whitepaper is to outline the applications for a vehicle level model to predict fuel-efficiency and emissions.

# EXECUTIVE SUMMARY

Vehicle level modeling allows manufacturers to optimize and iterate quickly. A robust vehicle level model is normally only possible for the OEM who has access all of the complex vehicle data needed for such a model. CSEG has recently developed a robust model from multiple public and proprietary correlations that allow Tier 1s and other manufacturers to have this same flexibility. The most promising use of this technology is to evaluate the benefit of a particular technology at the vehicle level for fuel-economy and emissions improvement. This white paper explains the benefits and difficulties of vehicle level modeling, explores the modeling process and quantifies a few cases of optimization on a Class 8 truck using one of CSEG's vehicle level models.

## Develop Your Sales and Design Advantage with Vehicle Level Modeling

### Your Sales Advantage

You have already leveraged world class engineering resources in order to design a build an advanced component and control strategy. Now, imagine quantifying the value proposition on a specific customer vehicle and working to convince an OEM to test your component. What the marketing department will put together is usually a range of predictions for the fuel-economy and emissions impact on a vehicle under one set of driving conditions. However, those ranges are estimated and will vary under different drive-cycles and vehicle types. Is that enough to get you a seat at the table? OEMs need to see that the benefits being claimed are correctly quantified for their specific application. Vehicle level modeling can quantify the benefits of your product within a very tight range.

### The Design Cycle-Time Advantage

Testing is a critical part of the design cycle. Modeling is an important part of the design process that needs to be in lockstep with testing, preferably guiding it. However, did you know that model robustness is inverse to the amount of real world testing required?

Benefits of leveraging Vehicle Level Modeling in the design process include:

- Understanding the impact of different sub-systems on fuel-economy and emissions
- Help in development of individual components in context of specific vehicles and drive cycles
- Ability to develop smart control strategies along with smart technologies
- Value proposition to OEMs with impact of your technology at the vehicle level
- Determining the dynamic impact on fuel-economy and emissions

# CSEG – The Right Vehicle Level Modeling Partner

There are 3 major areas of services in 1-D system level modeling that CSEG offers:

- 1D vehicle thermal management using Flowmaster or
- Matlab-Simulink
- 1D engine modeling using GT power or Ricardo Wave

And the focus of this white paper:

- 1D fuel economy and emissions modeling using
- in-house proprietary vehicle level models

CSEG's engineers each have, on average, 15 years of advanced modeling and simulation experience. They are all considered experts in the modeling and simulation field, born out through multiple technical publications and presentations at industry conferences annually.

CSEG has created proprietary vehicle models with pre-populated data of specific vehicle types: Class 8 Truck, medium duty truck, typical passenger pick-up truck, SUV and various versions of passenger cars available on the market. CSEG's pre-packaged models not only have all the necessary equations, but also significant vehicle level data in the model. This detail makes the models them less data hungry than shell models thereby enabling a manufacturer to test their components in many driving conditions more quickly.

Manufacturers can add their own data to further fine tune the model for components or drive cycles. By starting with a fully populated and correlated model, the manufacturer can concentrate on their specific component without having to undertake the difficult task of complete model building and a subsequent large amount of data gathering.

## Sample Questions That a Vehicle Level Model Can Answer

**"Which real-life driving scenarios can cause vehicle overheating that cannot be reproduced?"** I.e.: driver aggressiveness, unique drives cycles, idle time, seals or ambient temp?

**"What is the right degree of electrification for different cars?"** Small car? Truck? Large Car? SUV?

**"What is the viable size, weight, cost, and backpressure for an exhaust heat recovery system in order to ensure viability?"**

**"How do these factors tie in with vehicle parameters such as engine size, vehicle weight and others?"**

**The Decision to In-Source or Outsource Model Building:**
**Which is right for you?**

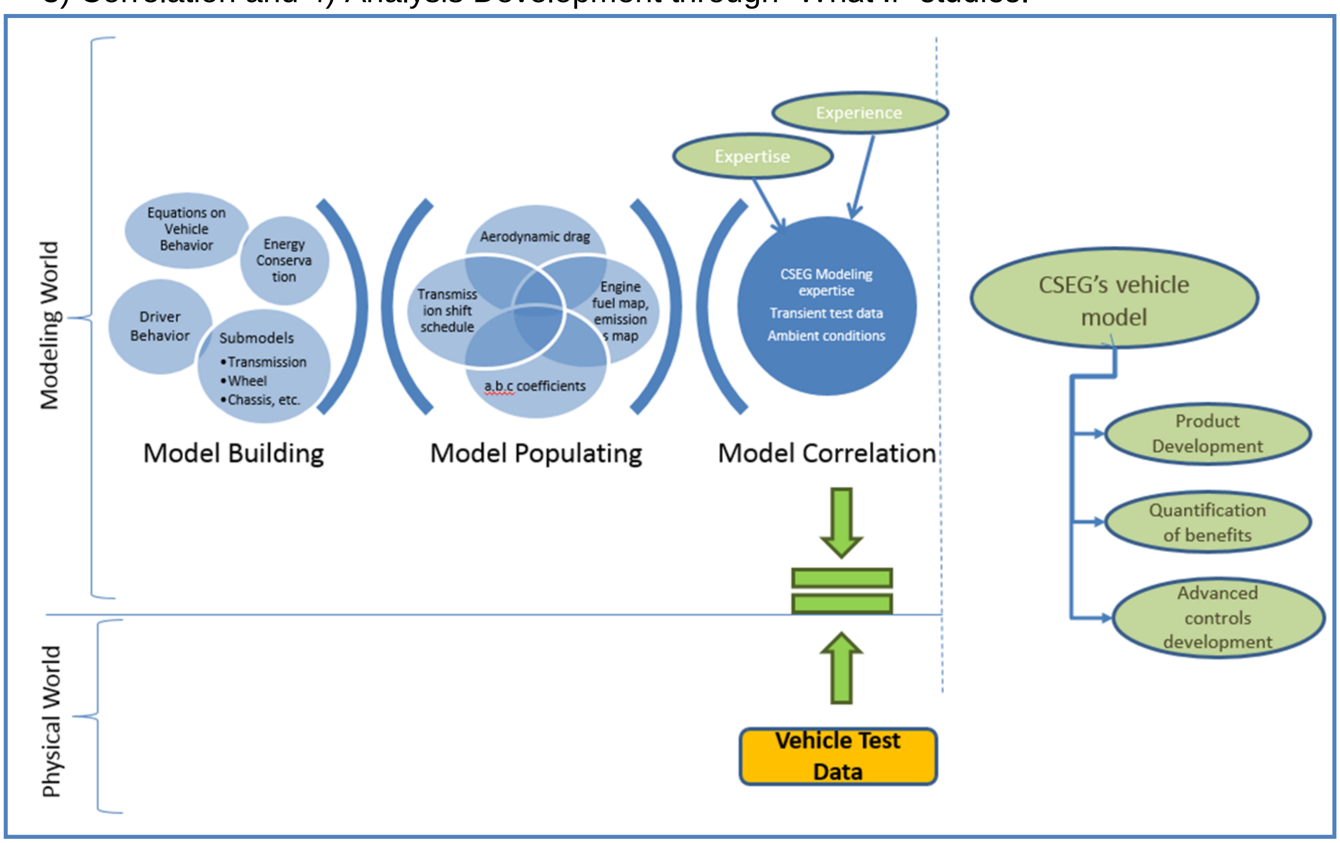
Many Tier 1s will have the internal engineering talent to attempt a vehicle level model. So how should they decide whether to insource or outsource the process? There are a few key factors to consider. Is the model available commercially already? Is a commercial solution customizable? Do engineers have other core design work that would be put on hold to develop a model? Can the engineers devote the necessary time, on an ongoing basis, to model refinement and correction? Can you be assured that an internally developed model will outperform a commercially available one?

The time needed to build real correlations and populate data is often underestimated. Refining a model and producing iterations can consume an entire department, annually. With CSEG's models engineers can be deployed to solving core design issues immediately, and do not need to spend time on developing a platform to solve problems. What about customization? CSEG's models are available for additional inputs by your team, if you have your own detailed proprietary data. CSEG is also available to train your engineers, facilitating knowledge transfer.

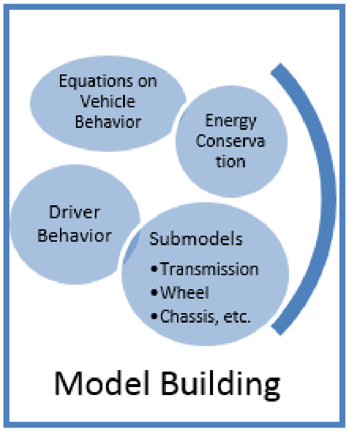
## The Vehicle Level Modeling Process

This section will take you through the modeling process and explain the steps and the common difficulties associated with each.

The entire modeling process is made up of four steps: 1) Model Building, 2) Model Populating, 3) Correlation and 4) Analysis Development through "What If" studies.



# Step 1: Model Building




Vehicle level modeling starts by building the mathematical model. The building blocks of the model are equations that can reduce how different parts of a vehicle work together in the real world to mathematical concepts. The engineer or programmer will start by finding the relevant equations in papers, academic journals and other literature.

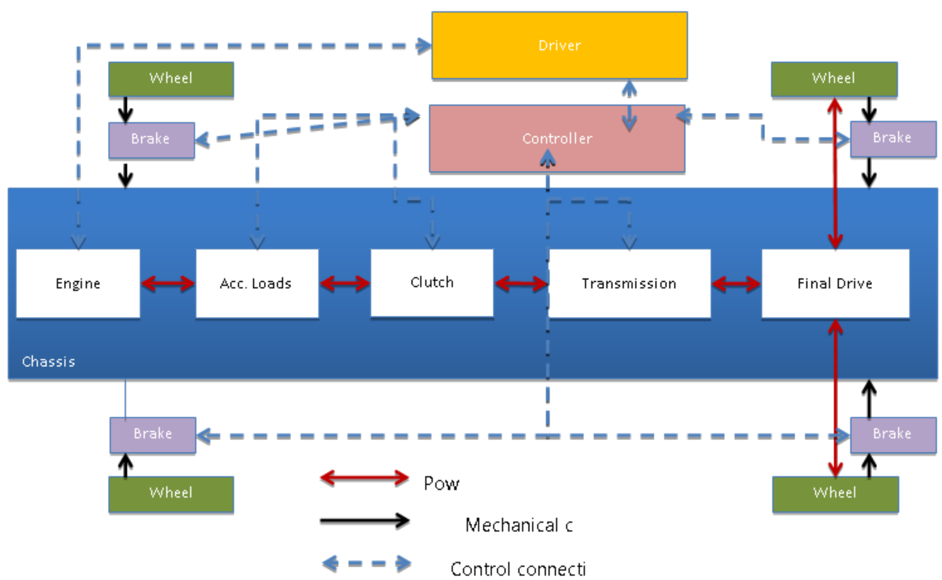
Equation building can be as simple as copying equations that have been developed by others. However, at CSEG we take a different approach. From years of experience in vehicle level modeling, we know what type of data is typically available for a subsystem, such as transmission, axel, final drive etc., and what level of detail is necessary to capture all the effects. We design and develop our subsystem equations and input data sheet in this way.

Typical software packages only give you this portion of the model, coming pre-programmed with equations for the particular task the software promises to solve, but not with a populated model or correlations.

**Why develop a "new model" with all of the commercial tools available today?**

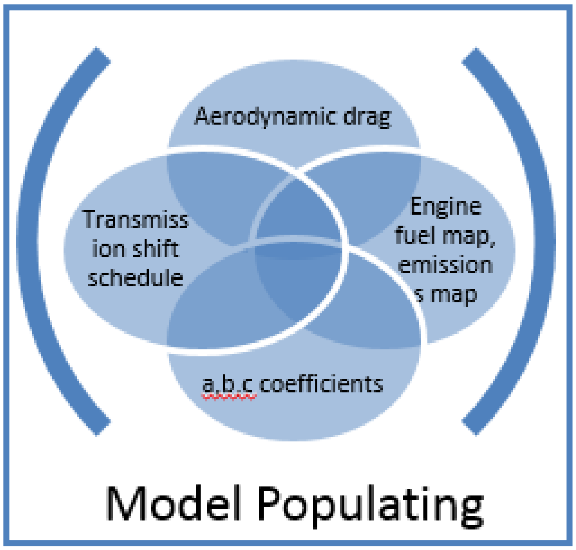
Commercial tools are very powerful and we at CSEG use them daily. There are four main reasons to build a new set of models:

1. They are a useful tool for end customers to quantify the benefit of their components, without having to build, and maintain, an expensive and specialized model from the ground up.
2. Data gathering for a vehicle level model is very time consuming. Our models have real vehicle data in the models already, so you don't need to waste time attempting to gather all the data.




3. Models still need to be correlated to real world test data. Our models are correlated.

# Step 2: Model Populating




The next step in the model building process is to populate the model with vehicle data for the particular vehicle under consideration. Typical fields to be populated include aerodynamic drag, vehicle weight, *a, b* and *c* coefficients, engine fuel map, transmission information, final drive efficiencies, and tire rolling resistance, among others. Accessory performance is also needed, such as the compressor / air conditioning load, and the alternator load.

This is also the point in the modeling process where those without large data sets will start to falter when producing models. Some data, such as vehicle weight, is easy to find, but others, such as accessory load as a function of vehicle load and temperature, are more difficult to find or do not exist. Most Tier 1 suppliers do not have the whole vehicle data necessary to fine tune a virtual platform for their component. Even for OEMs this data gathering exercise across engineering groups is a challenge.

What is quite a bit of work for OEMs is impossible for Tier 1's. Therefore, suppliers either solve the problem in other ways, such as modeling smaller sub-systems or by bypassing modeling altogether.

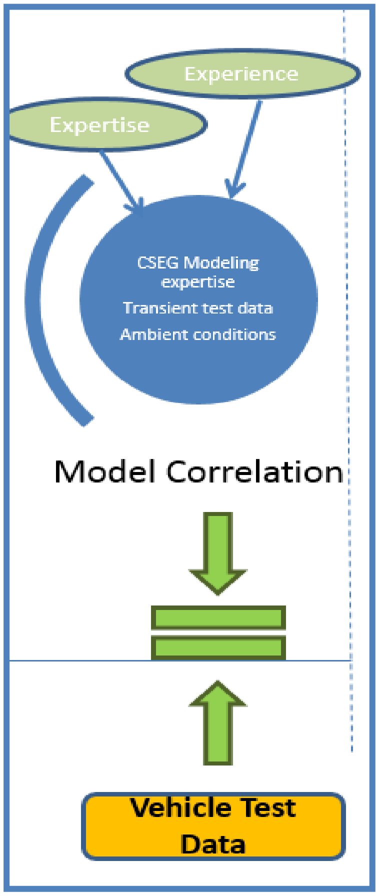
**Data Sources – Public Domain and CSEG Created**

CSEG has drastically simplified the input data requirements on the vehicle model through 3 main workflows:

- Collecting and implementing published correlations on component performance
- Developing CSEG's own proprietary data sets through testing some individual components in vehicle dynos to characterize their behavior
- Utilizing public domain published information from EPA, National Labs and Academia of typical vehicles

The process of finding publically available data and combining it with CSEG created data from component testing on dynos – has allow CSEG to program a model from a very rich base of data. This base allows a Tier 1 to have a vehicle at their fingertips, giving component manufacturers a seat at the modeling table.

## Step 3: Model Correlation




Step 3 of the modeling process is to execute the model and compare that data with real world vehicle test data. These data are available from multiple sources including the U.S. National Labs and Environmental Protection Agency.

The outcome of this step, however, is frequently surprising. The initial model will probably not match real world vehicle test data. Therefore, the execution includes going back and adjusting some assumptions so that the modeling better matches real test data within an acceptable range.

The model correlation activity is only 30% of the work of model building, but the catch is that it can only be done by experts in the field. Today, there is no "out of the box" solution for this step. The real subject matter expertise is in correlation of the model to the available test data.

These correlations become the new equations in the model and thus allow you to have a Vehicle Level Model.

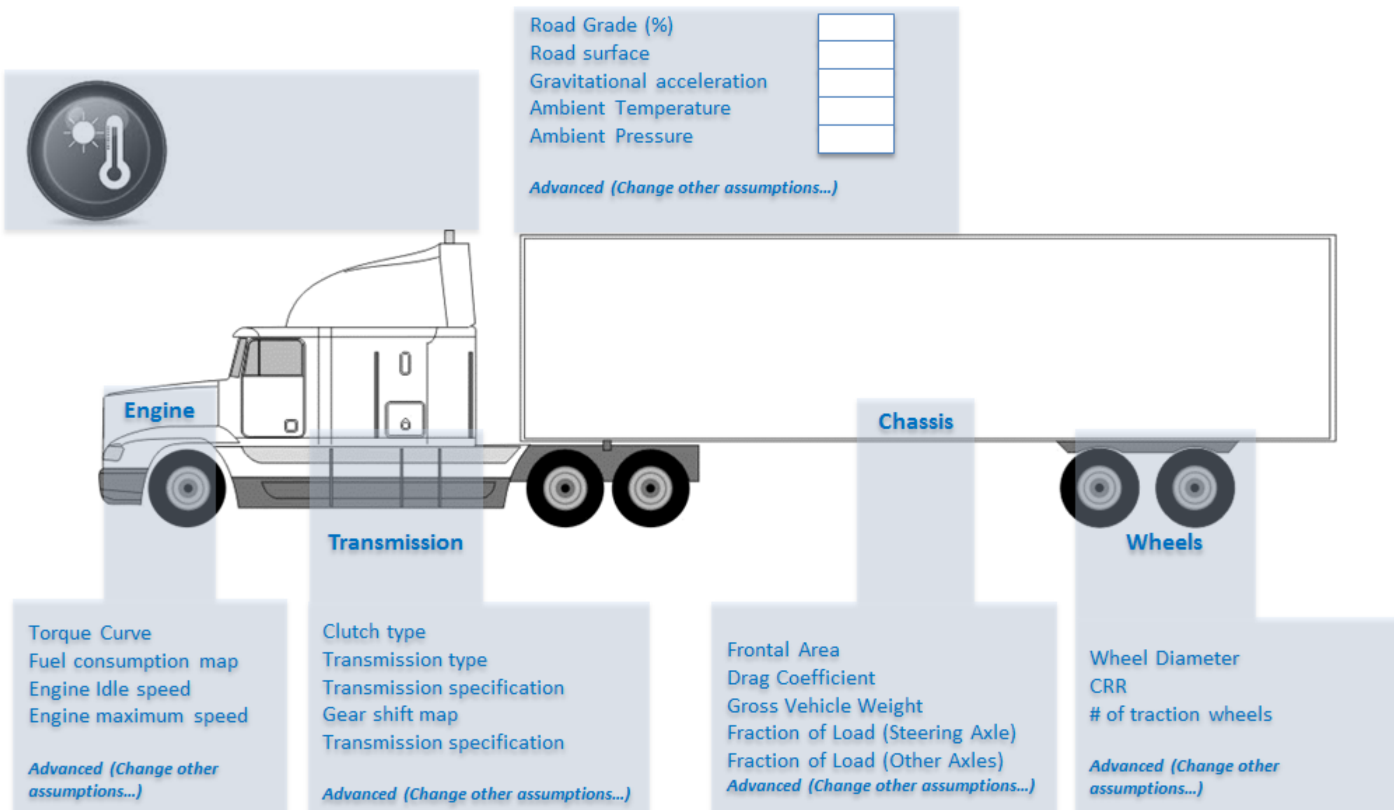
## Step 4: "What-if Studies" to help you quantify benefits to customers and make decisions

The last step in the model building process is to run multiple "What-If" studies using the components and drive cycles under consideration. This final step is important for iterating on the design or for quantifying the benefits for changed or added components.

CSEG has performed a vehicle level analysis assessing key areas of interest for truck OEMs. The following cases were developed using a correlated Class 8 vehicle level model.

Shown here is a Class 8 heavy duty truck model with the following specifications:

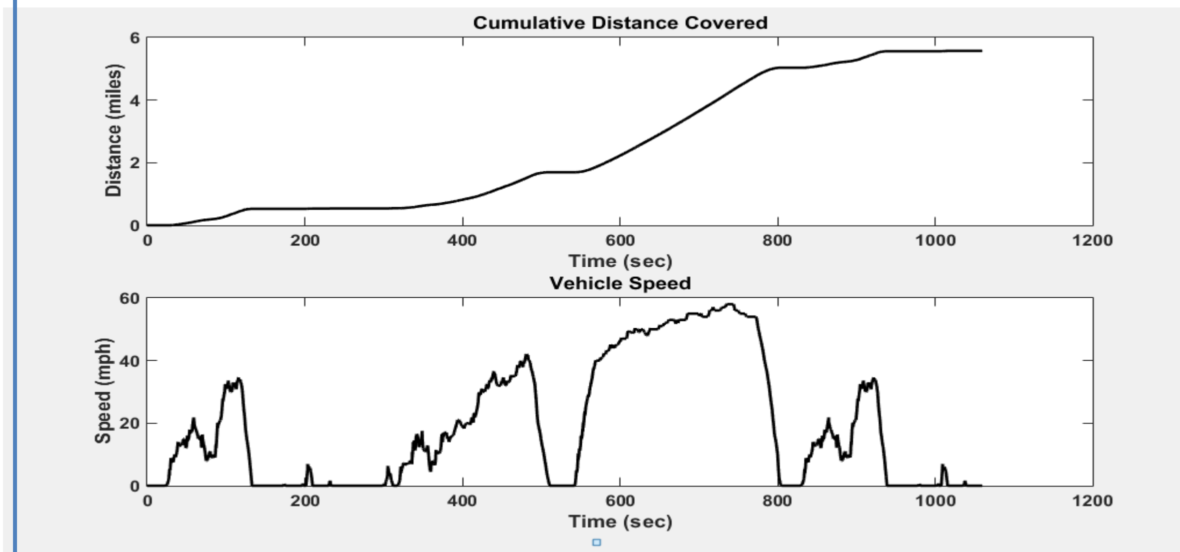
- Gross Vehicle Weight (GVW): 65,000 lb.,
- Automated Manual Transmission (10 speed),
- Low Roof Day-cab (9.5 ft. x 8 ft.) enclosed Van (Cd 0.6),
- Final Drive ratio: 2.64
- Bridgestone Average Tires (CRR 0.009)
- Vehicle model was validated for Heavy Duty Urban Dynamometer Driving Schedule (HD-UDDS) cycle.




A sensitivity study was done for the following key variables on fuel economy and $CO_2$ emissions.

A. Vehicle weight
B. Final Drive
C. Aerodynamic Accessories
D. Low rolling resistance tires vs. OEM tires
E. Manual vs. Automatic Transmission

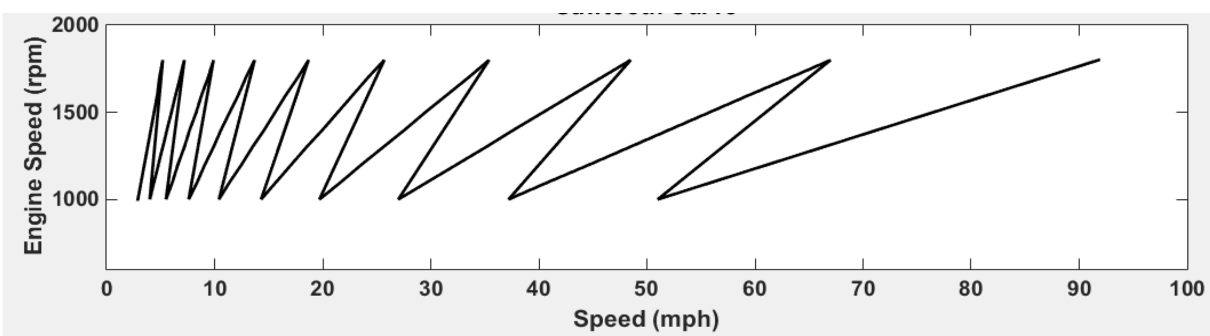
**HD-UDDS cycle**




Vehicle model validation was judged based on cumulative distance traveled (5.57 miles instead of the HD-UDDS standard of 5.55 miles), cycle average vehicle speed (18.92 mph instead of the HD-UDDS standard 18.83 miles/hr.) and cycle average fuel economy (6.67 mpg).

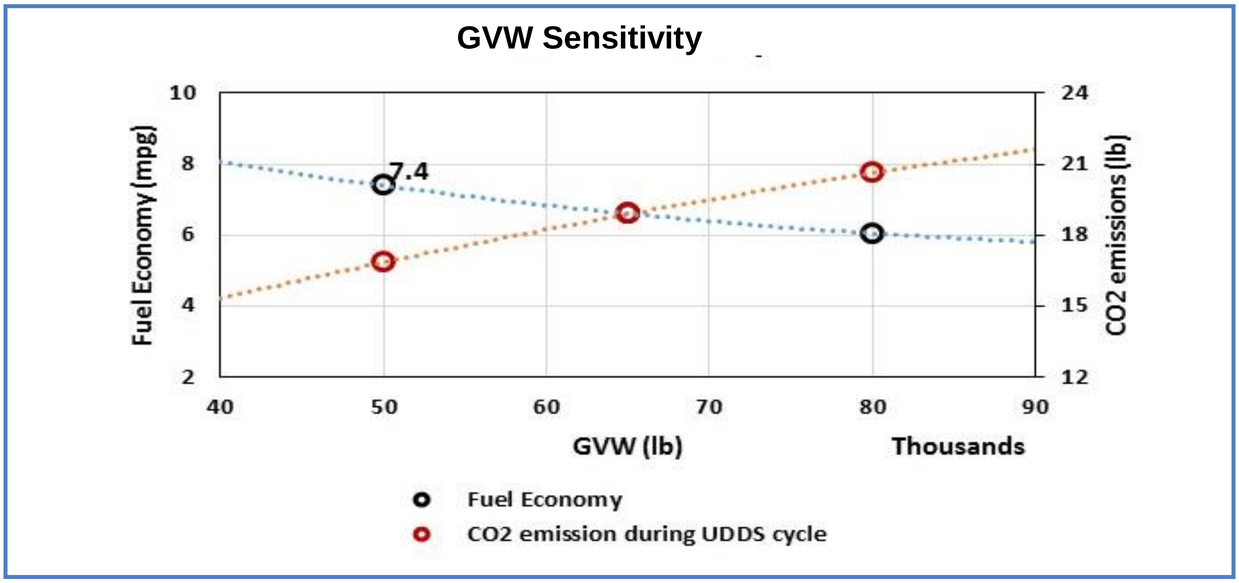
The figure below shows a saw tooth curve (engine speed plotted against vehicle speed).

**Saw tooth Curve**



### Impact of Vehicle weight

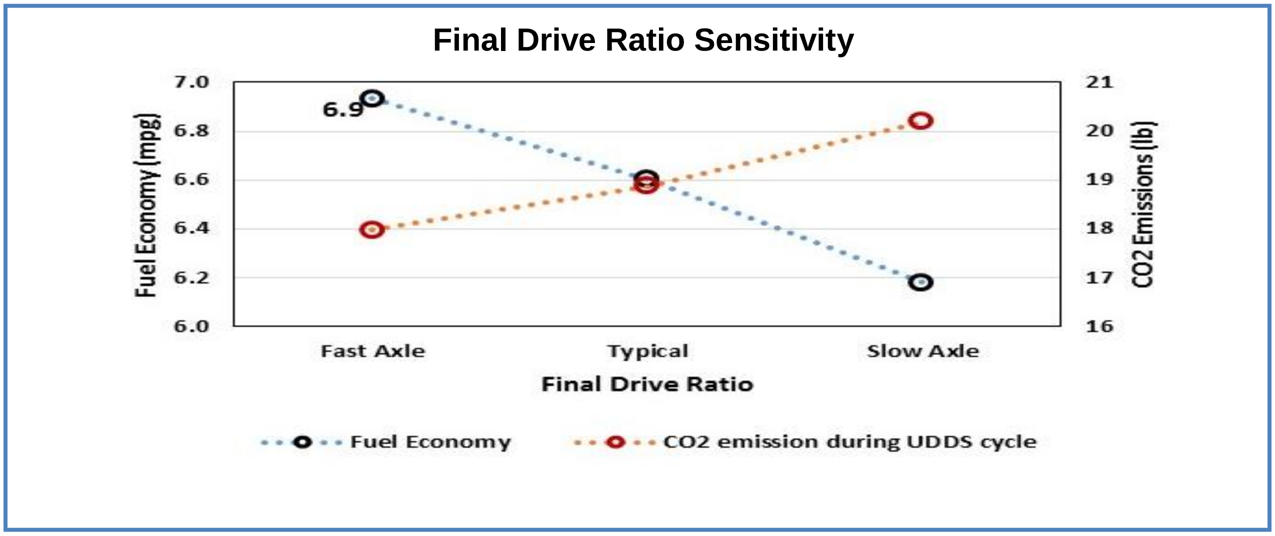
Vehicle weight affects fuel economy linearly. This plot quantifies the impact of Gross Vehicle Weight (GVW) on fuel economy and $CO_2$ emissions:




When GVW is reduced to 50,000 lbs. the fuel economy improved by 0.8 mpg. On the other hand, an increase in GVW from 65,000 lbs. to 80,000 lbs. resulted in a fuel economy penalty of 0.6 mpg.

### Impact of Final Drive

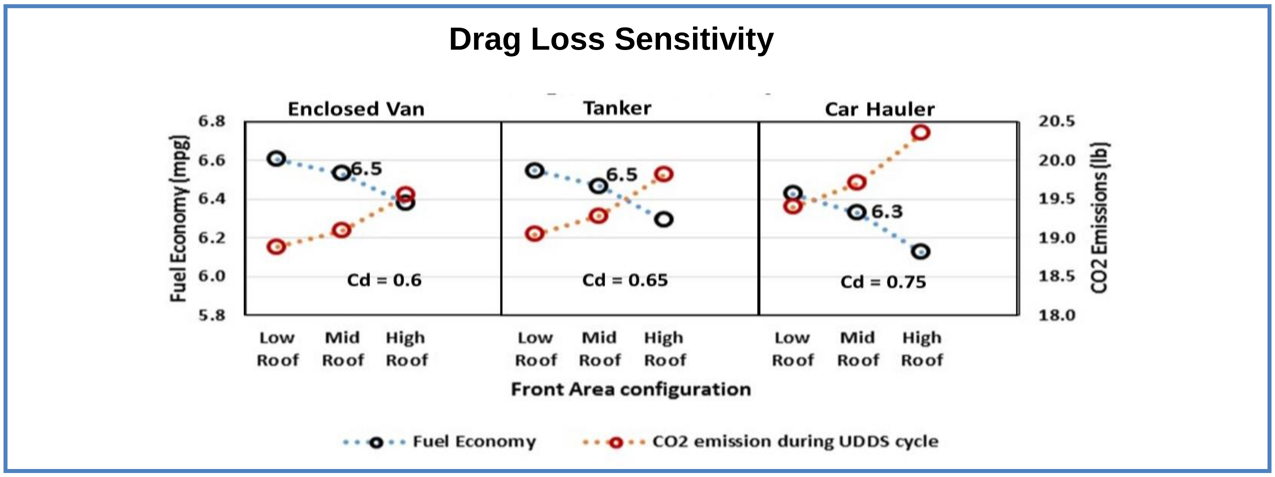
How would a mismatched final drive ratio affect fuel economy? This was estimated by changing the final drive ratio with fixed gear ratios and gear shift strategy. This plot compares fuel economy and $CO_2$ emissions for three different final drive ratios.



A fast axle (2.26) yields better fuel economy (by 0.7 mpg) when compared to a slow axle (3.08). But a fast axle ratio limits traction power as compared to a slow axle ratio.

**Impact of Aerodynamics**

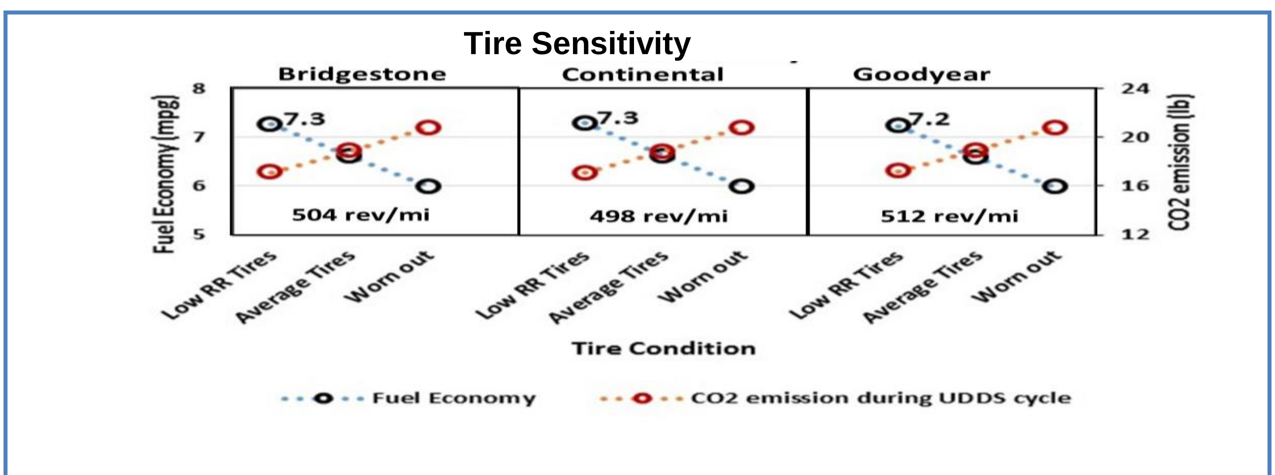
A study was performed to evaluate effect of drag coefficients and frontal area associated with low / mid / high roof. This plot compares fuel economy and $CO_2$ emissions for various combinations:




Fuel economy deteriorated by 0.2 ~ 0.3 mpg when going from a Low roof to a High roof whereas change in drag coefficients have reduced fuel economy by 0.2 mpg with 0.15 basis point increase in drag coefficient.

**Impact of low friction rolling resistance tires vs. OEM tires**

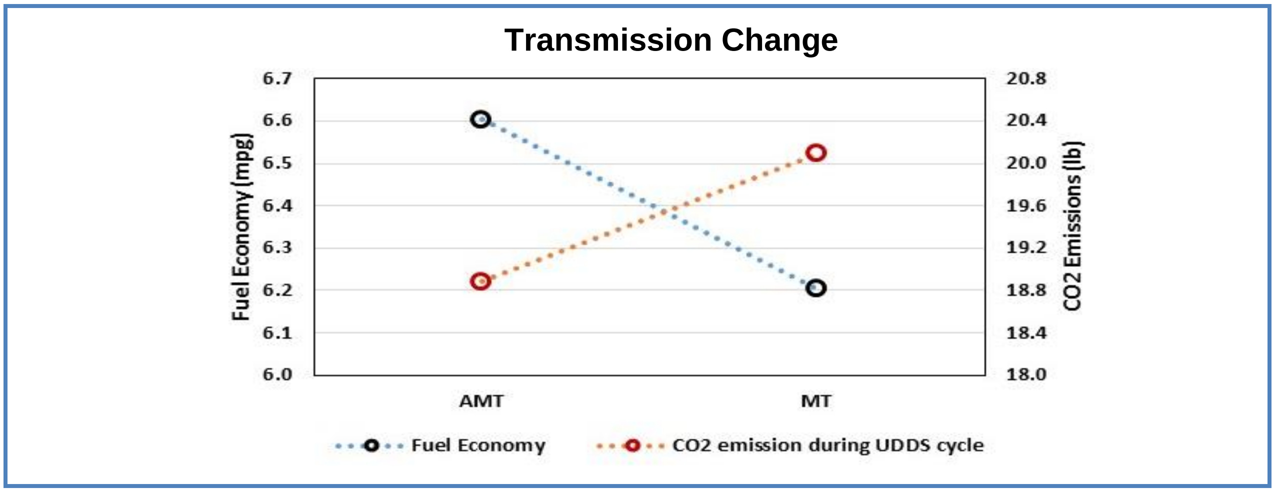
How much of an improvement in fuel economy will a Class 8 truck realize with low rolling resistance tires? The impact was estimated by studying the effect of tire condition (i.e., rolling resistance) and tire specification (i.e., dynamic rolling radius). The plot below shows the effect of tire condition and tire specification on fuel economy:



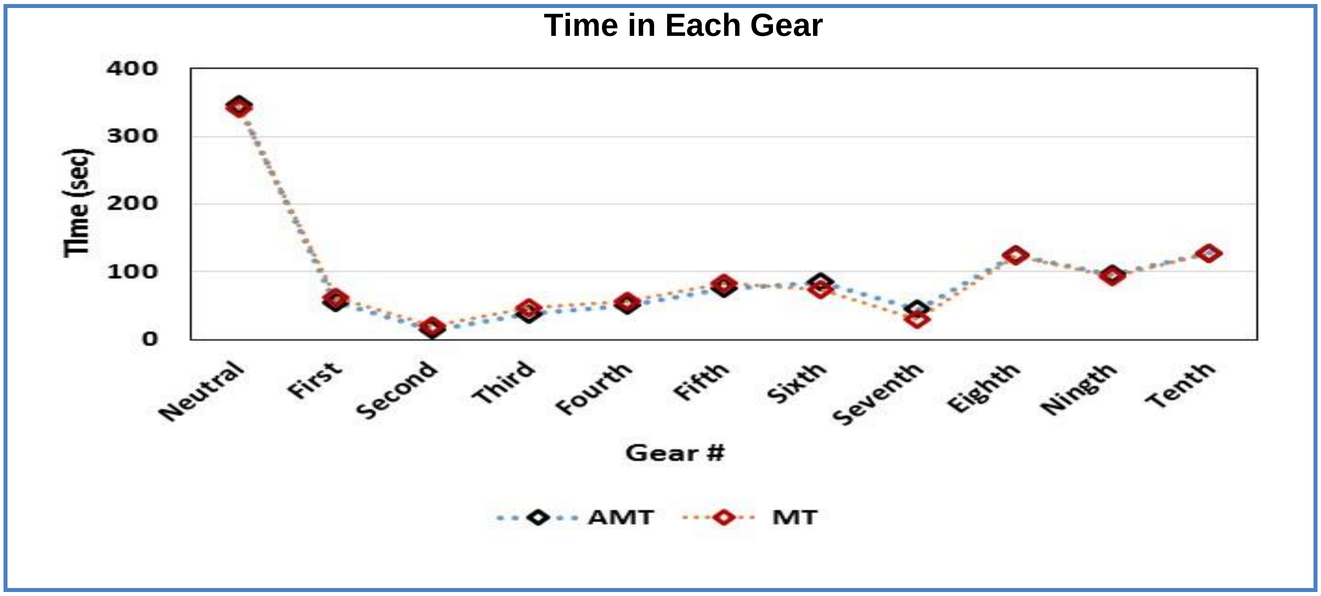
Low rolling resistance tires result in a fuel economy improvement by 1.3 mpg when compared to worn out or low pressure tires irrespective of tire specification.

**Impact of Transmission Type**

It is relatively difficult to mimic a manual transmission with appropriate driver behavior which leads to higher uncertainty in simulation. Manual transmission was implemented in the model by changing gear ratios and gear shift strategy representative of typical driver. For manual and AMT transmission, the top gear was engaged at the same vehicle speed. This plot shows fuel economy and $CO_2$ emissions for AMT and Manual Transmission.




A fuel economy improvement of 0.4 mpg was observed when changing from a Manal Transmission to an Automatic. This plot shows time in each gear for AMT and manual transmission:



The driver stays in $1^{st}$ to $5^{th}$ gear for a longer period of time and in $6^{th}$ to $9^{th}$ gear for a shorter period of time, when using a manual transmission, as opposed to an automatic transmission. This was implemented in the model using gear ratios and gear shift strategy. It is important to note that the time in top gear is exactly the same. It is important to note that simulation predictions with AMT have a smaller error band due to controlled gear shifting. Predictions using manual transmission have a higher error band due to driver variability.

## Summary

In this white paper we have covered the benefits of vehicle level modeling, the process of setting up the vehicle level model and results from a vehicle level model. The set-up, population and correlation issues that make vehicle level modeling difficult have been solved by CSEG through pre-populated vehicle level models.

Tier 1s and other manufacturers are now able to quantify, with a high level of certainty, the benefits that their components provide on multiple vehicles and drive cycles using a correlated vehicle model. Until now this was not possible for anyone besides an OEM.

Call CSEG today for a complimentary introduction to vehicle level modeling and to find out the specific benefits that it can provide to your company.  Call 1-781-640-2329

# About the Author

**Sudhi Uppuluri** has over 16 years of experience in the simulation industry including finite element analysis, external aerodynamics tools using vortex-lattice method, Matlab and Flowmaster. He worked as a consulting engineer and sales manager at Flowmaster USA for 8 years where he helped various large automotive, aerospace and power generation OEMs build thermo-fluid simulation models and integrate these tools within their design processes. He has various technical publications on related subjects in SAE and AIAA journals. He holds a Masters in Aerospace Engineering from the University of Illinois at Urbana-Champaign and a Certificate in Strategy and Innovation from the MIT Sloan School of business.

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**Recent Publications and Papers**

Uppuluri, S. and Naiknaware, A., "**Sensitivity Analysis of Key Engine and Vehicle Parameters in Engine Coolant Temperature Predictions,"** SAE Technical Paper 2015-01-0442, 2015, doi:10.4271/2015-01-0442.

S Uppuluri, A Naiknaware, Computational Sciences Experts Group, USA, "**Dual-Use Heater Core – Increase in Trailer Tow Capacity and Analysis of Control Set-Points with Active Grill Shutters",** VTMS12 Proceedings, Nottingham, UK

Uppuluri, S., Naiknaware, CSEG, LLC, "**Evaluation of Various Engine Control Strategies for Optimal Engine Thermal Operation**", 2014 SAE World Congress: Oral Only Talk

Uppuluri, S., Proulx, J., Marovic, B., and Naiknaware, A., **"Characterizing Thermal Interactions Between Engine Coolant, Oil and Ambient for an Internal Combustion Engine,"** SAE Int. J. Engines 6(2):827-832, 2013, doi:10.4271/2013-01-0960.

Uppuluri, S., CSEG, LLC, **"Analysis Led Design and Industry Trends in 1D Powertrain Simulation",** 2013 SAE World Congress: Oral Only Talk

Scott, T., Chang, F., Khandaker, M., and Uppuluri, S., **"Transient Thermal Modeling of Power Train Components,"** SAE Int. J. Passeng. Cars - Mech. Syst. 5(2):962-973, 2012, doi:10.4271/2012-01-0956.

Uppuluri, S., Computational Sciences Experts Group; Sadek S. Rahman, Chrysler Group LLC, "**Active Transient Thermal Management for improved Fuel economy**", 2012 SAE Thermal Management System Symposium

Chang, F., Malipeddi, S., Uppuluri, S., and Shapiro, S., "**Underhood Thermal Management of Off-Highway Machines Using 1D-Network Simulations**," SAE Technical Paper 2003-01-3405, 2003, doi:10.4271/2003-01-3405.

**<u>Other Professional Activities</u>**

Co-Organizer for SAE Thermal Management System Symposium conference

Co-organizer for SAE Work Congress "Thermal Modeling and Simulation" and "Hybrid Vehicle Simulation" sessions