

Development of Greenhouse Gas Emissions Model (GEM) for Heavy- and Medium-Duty Vehicle Compliance

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ABSTRACT

In designing a regulatory vehicle simulation program for determining greenhouse gas (GHG) emissions and fuel consumption, it is necessary to estimate the performance of technologies, verify compliance with the regulatory standards, and estimate the overall benefits of the program. The agencies (EPA/NHTSA) developed the Greenhouse Gas Emissions Model (GEM) to serve these purposes. GEM is currently being used to certify the fuel consumption and CO₂ emissions of the Phase 1 rulemaking for all heavy-duty vehicles in the United States except pickups and vans, which require a chassis dynamometer test for certification. While the version of the GEM used in Phase 1 contains most of the technical and mathematical features needed to run a vehicle simulation, the model lacks sophistication. For example, Phase 1 GEM only models manual transmissions and it does not include engine torque interruption during gear shifting. The engine control is simplified and does not include fuel cut-off during decelerations and the agencies pre-specified the engine fuel maps. These simplifications are acceptable as far as certification is concerned, since the Phase 1 certification process only requires up to five user inputs (aerodynamic drag coefficient, tire rolling resistance, vehicle speed limit, weight reduction, and idle reduction), and all other vehicle parameters and their inputs are pre-specified by the agencies.

Moving forward, the proposed Phase 2 standards are predicated on the performance of a broader range of technological improvements than in Phase 1. Consequently, a more comprehensive vehicle simulation model is required. This paper describes a new version of this vehicle simulation model defined as Phase 2 GEM. In order to qualify this model, comprehensive validations were carried out against 130 vehicle variants including a number of medium- and heavy-duty trucks. Good agreement between simulation and test results were obtained, demonstrating that this model is technically sound and ready for the next phase of the GHG emission certification.

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INTRODUCTION

In 2011, The Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued the first-ever U.S. regulatory program to reduce greenhouse gas emissions (GHG) and improve the fuel efficiency of medium- and heavy-duty vehicles. Under this rule called Phase 1, the agencies adopted a regulatory structure that included a vehicle simulation procedure for certifying tractors and the chassis of vocational vehicles. Consequently, the agencies developed the Greenhouse Gas Emissions Model (GEM) [1] to serve these purposes for Phase 1, which was consistent with recommendations of the National Academy of Sciences (NAS) to use vehicle simulation to demonstrate compliance [2]. GEM is currently being used to certify the fuel consumption and CO₂ benefits of the Phase 1 rulemaking for all heavy duty vehicles except for pickups and vans, which require a chassis dynamometer test for certification. As the model is designed for vehicle compliance, it is not designed for research and development. Rather, it is purposely made to be less configurable than similar commercial products, and its only outputs are GHG emissions and fuel consumption. This approach gives a simple and

compact tool for vehicle compliance without the overhead and costs of a more flexible model. GEM was designed to meet the following requirements:

- Capability to model a wide variety of medium- and heavy-duty vehicles over different cycles
- Open source code, thus providing transparency in the model
- Free public access without any sort of license required
- Ease of use with minimal to no prior experience
- Inclusion of both optional and preset elements
- Tool management by EPA for compliance purposes

Because of these unique requirements for the purpose of compliance, the agencies were not aware of any existing commercial tool meeting all of the above requirements during the Phase 1 GEM development. To assure that the vehicle simulation tool is of the highest quality, EPA completed an independent peer review of its GEM model to confirm that the structure and overall development resulted in a tool that is simple, accurate and well suited to the diversity of vehicles for which it is applied.



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While Phase 1 GEM contains most of the technical and mathematical features needed to run a vehicle simulation, the model lacks sophistication. For example:

- Only manual transmissions are used in the model for all vehicle simulations, which is not always the case for real world applications, especially for vocational vehicle applications
- The model did not include engine torque interruption during gear shifting
- Engine control is simplified, with no fuel cut-off feature during deceleration
- Only the agencies' pre-specified engine fuel maps are used

These are acceptable limitations because the Phase 1 certification process only requires up to five user inputs, and all other vehicle parameters and their inputs are pre-specified by the agencies. For example, the Phase 1 version of GEM only recognizes the benefits of aerodynamic improvement, tire rolling resistance, speed limiter, weight reduction, and idle reduction (for high roof sleeper cab tractors), and only recognizes tire rolling resistance for vocational vehicles.

Carrying forward the success of the first ever Phase 1 GHG rulemaking for medium- and heavy-duty vehicles, where Phase 1 GEM has been adopted by all vehicle and engine manufacturers with positive acceptance, the agencies are proposing a Phase 2 GHG rulemaking. One of the major differences between Phase 1 and Phase 2 is that Phase 2 standards are predicated on the performance of a broader range of technological improvements than Phase 1. The examples of these technologies include changes to the driveline, the engine and the transmission, as well as better integration of engines and transmissions. Furthermore, the agencies include the concept of technology improvement inputs, allowing the user to obtain technology benefits that are not fully captured by the GEM model. Therefore, a more comprehensive vehicle simulation model is required. This paper describes a new version of this vehicle simulation model, referred to as Phase 2 GEM.

It should be mentioned that before the agencies developed this Phase 2 GEM, we recognize that many outstanding vehicle models are available on the market which can meet the technical features the agencies require. Examples of these vehicle models include Autonomie developed by Argonne National Laboratory [3], GT-Suite developed by Gamma Technologies [4], and VECTO developed by the European Commission's JRC [5]. However, none of them can meet the entire compliance tool requirements mentioned above. As a result, the agencies have decided to continue developing their own vehicle model for the Phase 2 rulemaking based on Phase 1 GEM.

MODEL CODE DESCRIPTION

EPA developed Phase 1 GEM, which is a forward-looking MATLAB/Simulink-based model for heavy-duty (Class 2b-8) vehicle compliance in 2011 [6]. The underlying GEM code was originally developed to simulate a broad range of vehicle speeds over essentially any in-use duty cycle. However, the official version that is used for determining compliance with the Phase 1 standards

incorporates the regulatory duty cycles into the code. In other words, manufacturers cannot run other duty cycles with the official version of GEM. We propose to continue this approach for Phase 2.

In order to meet proposed Phase 2 rulemaking requirements in recognizing most of the technologies that are measured in both engine and chassis dynamometers, the Phase 2 version of GEM has been considerably enhanced compared to Phase 1 GEM. Specifically, the agencies are proposing to implement the following key technical features into GEM:

- A new engine controller, which includes engine fuel cut-off during braking and deceleration, and a more realistic engine idle speed controller
- New transmission models, which include upgraded manual transmissions, along with newly developed automatic and automated manual transmissions
- An upgraded driver model with distance compensation that will drive the certification drive trace over a prescribed distance regardless of increased drive time due to vehicle underperformance, for example

The GEM architecture is comprised of four systems: Ambient, Driver, Powertrain, and Vehicle as seen in [Figure 1](#). With the exception of Ambient and Driver, each system consists of one or more subcomponents. The function of each system and its respective component models, wherever applicable, is discussed in this paper. Many changes and modifications described in this paper have resulted from numerous constructive comments from both the public and GEM peer reviewers [7]. The model has been upgraded to improve the fidelity of the model and to better match the function of the simulated vehicles, which also meets our primary goal to accurately reflect changes in technology for compliance purposes. As part of this effort, substantial effort has been put forth to accurately track and audit power flows through the model to ensure conservation of energy. The following paragraphs describe the main features of this model.

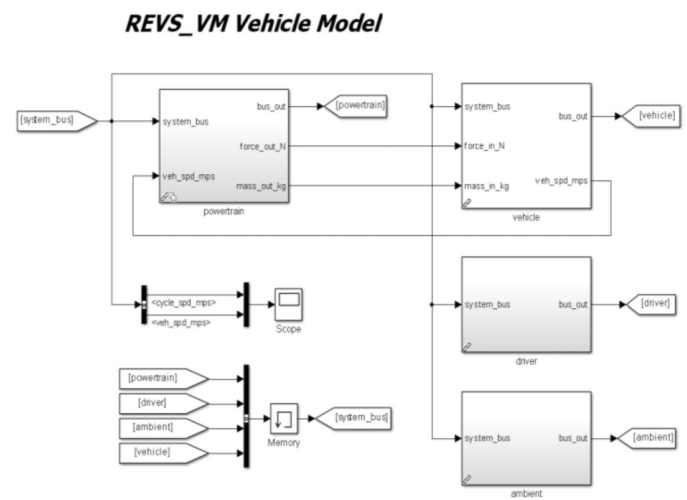


Figure 1. GEM model structure

Take Off (PTO) to operate auxiliary equipment, such as refuse compactors or lift forks. These would also be modeled as a mechanical accessory. The mechanical accessory load is proposed to be a constant power load for all vehicles. The actual power consumed for this loss would differ for actual vehicle configurations, but the agencies do not propose to allow users to change this value in GEM.

Electric Subsystem

The electric subsystem is modeled as a constant power loss. The power consumed for this loss is based on the vehicle subcategory. It represents the power loss associated with the starter, electric energy system, alternator and the electrically driven accessories. This simplification has a negligible impact on the fuel consumption and CO₂ emissions results.

Transmission Subsystem

The transmission subsystem features four different variants representing the three major types of transmissions that are currently in use in the heavy-duty sector, which are the transmission types on whose performance the various proposed standards are predicated. The variants are manual transmission (MT), automated manual transmission (AMT), and automatic transmission (AT) (planetary gear set with torque converter). The different transmission models are built from similar components, but each features a unique control algorithm matching behaviors observed during vehicle testing.

Transmission Gear Selection

All of the transmission models use a dynamic shift algorithm to determine the operating gear over the cycle for compliance purposes [9]. This employs a rule based approach utilizing the engine torque curve and fuel map to select gears that optimize efficient engine operation and provide a torque reserve as a traditional transmission calibration would.

Clutch

The clutch model in Phase 2 GEM replaces the simplified model found in Phase 1 GEM. The original clutch model had no transition between the fully engaged and fully disengaged states and provided no commensurate torque impulse to the driveline. In the new clutch model, engagement and disengagement occur over time, torque is conserved across the clutch and the inertial effects of accelerating and decelerating the upstream inertias are captured. Clutch lockup is not detected by speed match, instead corresponding torques are applied to drive the speeds together at a desired rate. This reduces the required inputs and allows lockup to occur at the desired time.

Gearbox

The gearbox model has also been substantially revised in Phase 2 GEM to provide more realistic operation. The gearbox contains gear ratios and efficiencies for each gear. Each gear also has spin (churning) loss torques that can vary by current gear number and input speed. GEM assumes higher efficiency for direct drive than any other gear for manual and automated manual transmissions. Shifting

behavior is more realistic than the Phase 1 GEM with appropriate delays provided by a synchronizer clutch model. This layout is most similar to a manual transmission, but the application for a planetary gearbox is a reasonable approximation as this type of gearbox can utilize a variety of topologies. The gearbox rotational inertias are split between a common input inertia, common output inertia and a gear specific inertia. The common inertias represent rotational inertia always coupled to the input or output shafts. The gear specific inertias are added or removed as gears are engaged or disengaged and incur additional losses.

Hydrodynamic Torque Converter

The new torque converter model for Phase 2 GEM simulates a lockup-type torque converter. The torque multiplication and resulting engine load are calculated via torque ratio and K-factor curves that vary as a function of speed ratio. A base torque ratio curve is used for all simulations and the K-factor curve is scaled based on the engine torque curve to provide a good match between the torque converter stall speed and the engine's speed at maximum torque. This approximation could result in some simulation differences for highly specialized vehicles equipped with torque converters matched to their specialized duty cycle, but for the vast majority of vehicles, the effect of this approximation on simulated CO₂ emissions is negligible. The lockup behavior of the torque converter is accomplished by integrating a clutch model similar to the one discussed previously. The torque converter model also contains a pump loss torque that varies with input speed to simulate the power required to operate the pump on an automatic transmission.

Manual Transmission & Control

The manual transmission (MT) is composed of the clutch and gearbox systems discussed above. The gearbox spin losses for a particular simulation are scaled with the vehicle class. The manual transmission features minimal gear specific inertia. Control of the MT is accomplished via a low speed clutch engagement model that gets the vehicle moving by feathering the clutch during launch. Shifts are accomplished by reducing the requested engine load, disengaging the clutch, shifting the gearbox to the new gear and reengaging the clutch. In heavier vehicles shifting is accomplished by double-clutching to match transmission input speeds rather than relying purely on the gearbox synchronizers.

Automatic Transmission & Control

The automatic transmission (AT) is composed of the torque converter and gearbox systems discussed above. The gearbox gear specific inertias and spin loss torques are higher as would be expected from a conventional planetary automatic transmission gearbox. The AT is allowed to shift under load. During upshifts and torque converter lockup the engine output torque is slightly reduced to minimize the resultant torque pulse encountered by decelerating the engine inertia.

Torque converter lockup will be controlled by a predetermined lockup table or lockup strategy algorithm and at this time is not expected to be among the available user input, with the possible exception of indicating the lowest gear in which lockup may occur.