

An Engine and Powertrain Mapping Approach for Simulation of Vehicle CO₂ Emissions

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ABSTRACT

Simulations used to estimate carbon dioxide (CO₂) emissions and fuel consumption of medium- and heavy-duty vehicles over prescribed drive cycles often employ engine fuel maps consisting of engine measurements at numerous steady-state operating conditions. However, simulating the engine in this way has limitations as engine controls become more complex, particularly when attempting to use steady-state measurements to represent transient operation. This paper explores an alternative approach to vehicle simulation that uses a "cycle average" engine map rather than a steady state engine fuel map. The map contains engine CO₂ values measured on an engine dynamometer on cycles derived from vehicle drive cycles for a range of generic vehicles. A similar cycle average mapping approach is developed for a powertrain (engine and transmission) in order to show the specific CO₂ improvements due to powertrain optimization that would not be recognized in other approaches. While a related paper [1] focuses primarily on simulation results, this paper summarizes the associated experimental results and development of the concept. Test results for an engine and a powertrain demonstrate the cycle average map is a smooth, continuous surface. The paper also compares accuracy of using the steady-state engine map versus the cycle average engine map. Considerations for using the cycle average map for vehicle simulation in the context of CO₂ regulations are also discussed with the conclusion that the cycle average map appears to be a technically viable approach to utilizing engine fuel consumption performance in a vehicle regulation.

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INTRODUCTION

An engine map is used to represent tested engine performance (fuel consumption, emissions, etc.) in a vehicle simulation in order to estimate drive cycle performance of the engine and vehicle [2, 3, 4]. The map is defined by triplets of engine speed, engine torque, and an engine performance parameter, for example brake specific fuel consumption. Figure 1 shows a schematic of the typical process to create such a map. An engine is run at steady speed and load conditions for some amount of time (usually minutes) for

stabilization and data acquisition. After data collection at one point, the speed and load are ramped to another steady condition and the process repeated. The number of points varies depending on the intended use of the map, but can be over 100. Figure 2 shows an example map. Figure 3 shows how the map is used as part of a vehicle simulation, with each simulation time step using the map to predict instantaneous fuel consumption based on the current speed and load.

the penalty for an engine performing worse than the standard. This approach will require some method of representing the actual engine performance in GEM. Consequently, EPA has made significant improvements over Phase 1 GEM. The detailed improvements and features of this new GEM are described by Newman et al. [9] In this GEM, a steady state map representation of the engine is expected to be proposed. For a regulation there are some different considerations for the engine information used in a vehicle simulation than for a product development effort. A more complete discussion of regulatory considerations is provided by Zhang et al. [1] Some key considerations relevant to the discussion in this paper are:

- The engine information should be accurate, auditable, and relatively easy to collect. These requirements are not always consistent with each other, so trade-offs between them are likely to be needed.
- The engine should be evaluated in a manner consistent with how it will be used in the vehicle regulation.
- With future emphasis on recognizing the benefits of engine and transmission integration, some form of powertrain (engine and transmission) representation is desired for the vehicle regulation. A consistent approach for modeling the engine and powertrain for the vehicle regulation is desirable.

Options for Engine Model

With the above requirements in mind, it is useful to step back and consider what options exist to provide appropriate engine information to the vehicle regulatory program. Wurzenberger et al. [4] have taken a comprehensive look at engine modeling options, but for this work we want to look at some broad categories with respect to considerations for use in a regulation. The table in the [Appendix](#) compares some traditional options.

Each of the options in the table has some positive and negative attributes. A generic map puts no burden on the engine manufacturer but also gives no credit to the vehicle for a well performing engine. A single cycle value is simple, connected to the criteria emissions program, and auditable but depends on a single cycle operation matching the engine's operation in the vehicle. A steady state map doesn't capture engine transient behavior, but perhaps a new type of map can be used.

To consider such a map, it's worth noting that the cumulative vehicle CO₂ on any drive cycle can be considered in parts as shown in [Figure 4](#). The engine CO₂ is just the cycle cumulative brake specific emissions of the engine that is typically measured and regulated. This value is a measure of the engine efficiency. The vehicle power demand is the cycle cumulative engine work normalized by the payload and distance travelled. Another way to consider this value is the average horsepower required to move a unit of payload at a given speed. It is a measure of the efficiency of the vehicle to move payload. Mathematically, these values can be calculated from any drive cycle simulation and combined to provide the overall drive cycle vehicle CO₂ emissions.

$$\text{Engine CO}_2 \times \text{Vehicle Power Demand} = \text{Vehicle CO}_2$$

$$\frac{\text{g}}{\text{hp}\cdot\text{hr}} \times \frac{\text{hp}}{\text{ton}\cdot\text{mph}} = \frac{\text{g}}{\text{ton}\cdot\text{mile}}$$

Figure 4. Relationship of engine brake specific CO₂, vehicle power demand, and vehicle emissions

The engine CO₂ part of [Figure 4](#) can be represented by a cycle average BSFC map. The engine is tested on a cycle that matches vehicle operation well and the cycle cumulative fuel consumption is measured. The cycle can then be changed to represent slightly different vehicle operation for a new value of fuel consumption. In this way a set of cycles can be tested to "map" the engine's cumulative cycle fuel consumption response. A schematic of this approach is shown in [Figure 5](#). An example cycle average map is shown in [Figure 6](#). The process for using it in a vehicle simulation is shown in [Figure 7](#). The entire cycle is simulated and then the cumulative cycle work, average engine speed, and average vehicle speed are used to interrogate the map for a cycle brake specific fuel consumption value. Then the relationship of [Figure 4](#) is used to calculate the vehicle cycle fuel consumption or CO₂. Zhang et al. [1] describe this process as an alternative certification approach, which is supported by a large number of simulations and also the results of this paper.

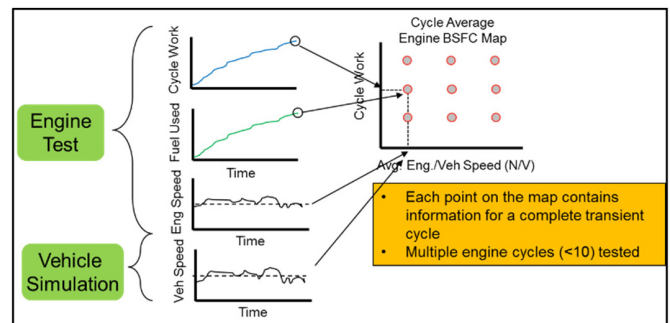


Figure 5. Cycle average map generation process

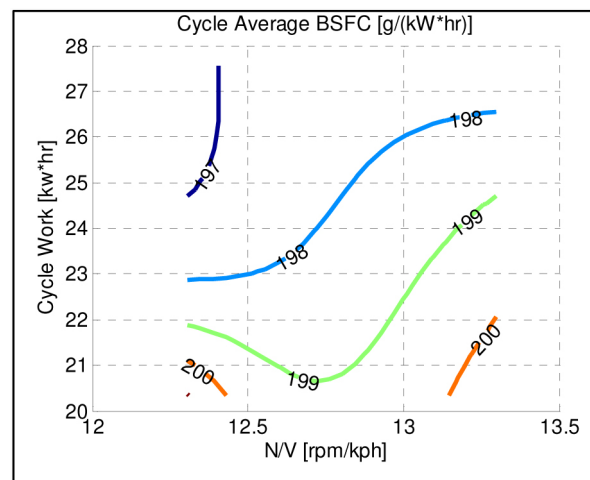


Figure 6. Example cycle average BSFC map for an ISX engine running the 55 MPH (88 KPH) GEM cycle

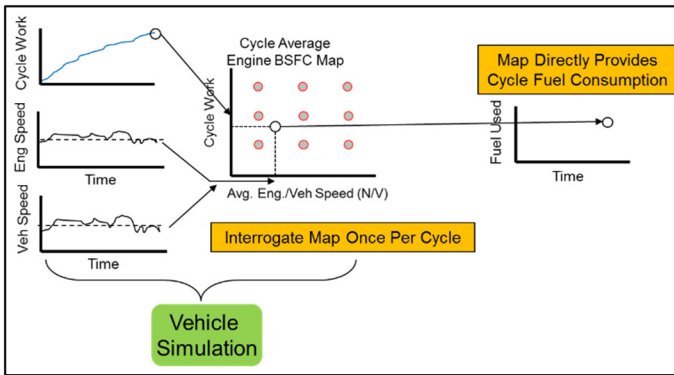


Figure 7. Process for using a cycle average BSFC map in a vehicle simulation

Average engine speed divided by average vehicle speed (denoted as N/V) has been used as a map axis to represent the nature of the engine speed operation on the cycle. Cycle work has been used as a second map axis to represent the engine loading on the cycle. These parameters are analogous to using engine speed and load as the axes for a steady state map. Other similarities between the steady state map and the cycle average map are:

- An engine test is completed with production controls in a 40 CFR Part 1065 capable test cell
- An extra test is required beyond what is used for the engine certification
- Points on the map can be audited
- Allows evaluation of the engine at speeds and loads that the engine sees in the vehicle

Based on the comparisons above, the cycle average map approach is a good alternative to investigate for modeling the engine performance in the vehicle CO₂ regulation protocol.

VALIDATION OF THE CONCEPT

Validation of the concept was first conducted through simulations using GEM [1]. In that study, a test matrix based on a Class 8 Kenworth T700 tractor with a Cummins ISX engine was carefully designed. It covered 32 vehicle configurations and three transmissions together with other relevant parameters, resulting in over one thousand simulations. In this paper, a hardware based approach with both engine and powertrain testing is used to further prove the concept. The combination of the two papers provides a complete picture of how this alternative certification concept has been developed and evaluated.

Similar to the study by Zhang et al. [1], some of the key questions to consider for the cycle average map are:

1. Is the map surface well behaved so that interpolation can represent points not tested?
2. How does the accuracy compare to a steady state map approach?
3. Is the test procedure robust and the results repeatable?

A first check of the surface shape was performed via simulation in GEM [1]. After reasonable results from a simulation study, two test programs were implemented to investigate the questions above. The first test program included only the engine and the second program included the powertrain (engine and transmission).

Engine Only Approach

Dykes and Dorobantu [10] describe the test setup in detail. The engine-only test cell as shown in Figure 8 was sized to accommodate a heavy-duty (HD) engine. A Cummins 15 liter ISX engine rated to 336kW (450 hp) with peak torque of 2375 Nm (1750 ft-lb) was used for the evaluation. A HD aftertreatment system was installed to meet the EPA and CARB emissions standards. The aftertreatment system utilized both a Diesel Particulate Filter (DPF) and a Selective Catalytic Reduction (SCR) system. To maintain a baseline condition for the DPF during testing, a DPF regeneration was forced prior to each set of tests to clean the DPF of stored particulates. The SCR system was operated during testing as would be witnessed in-vehicle operation to reduce NOx. The exhaust emissions were collected continuously using a Horiba Mexa7100D emission bench. The fuel was measured continuous during each test cycle using a ReSol RS438A-200 Fuel Flow Measurement System. The testing is completed using ultra low sulfur diesel fuel with a maximum sulfur concentration of 15 PPM. The engine intake air is temperature, humidity and pressure controlled to 25°C, 53% and 99kPa, respectively. All temperatures, pressures, fuel flow and emissions measurements were logged at a rate of 10 Hz.

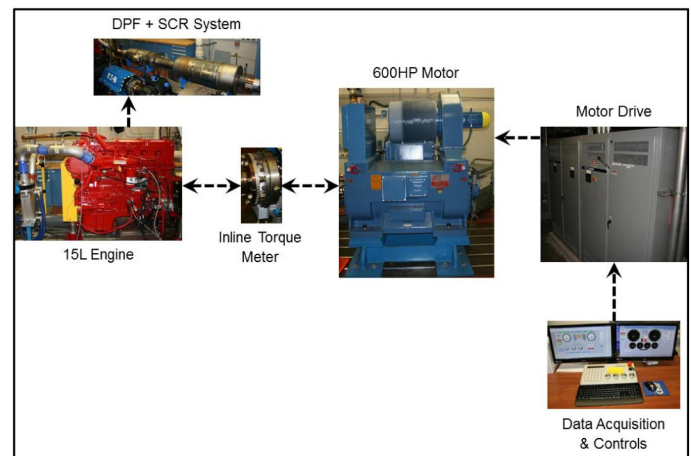


Figure 8. Engine only test setup [10]

The test cycles utilized for the engine only mapping approach were generated using GEM. Three separate vehicle configurations were input into the GEM model to generate speed and load points for each of the regulatory cycles (ARB, 65MPH, and 55 MPH). A total of nine traces were generated for each cycle. Each individual cycle was repeated two times consecutively and emission data sampled during the second cycle. A total of 27 engine tests were run (nine vehicle configurations x three test cycles). The vehicle configurations were chosen to provide a reasonably broad coverage of real-world