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Prediction of In-Use Emissions of Heavy-Duty Diesel Vehicles from Engine Testing

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A model of a heavy-duty vehicle driveline with automatic transmission has been developed for estimating engine speed and load from vehicle speed. The model has been validated using emissions tests conducted on three diesel vehicles on a chassis dynamometer and then on the engines removed from the vehicles tested on an engine dynamometer. Nitrogen oxide (NO_x) emissions were proportional to work done by the engine. For two of the engines, the NO_x/horsepower(HP) ratio was the same on the engine and on the chassis dynamometer tests. For the third engine NO_x/HP was significantly higher from the chassis test, possibly due to the use of dual engine maps. The engine certification test generated consistently less particulate matter emissions on a gram per brake horsepower-hour basis than the Heavy Duty Transient and Central Business District chassis cycles. A good linear correlation ($r^2 =$ 0.97 and 0.91) was found between rates of HP increase integrated over the test cycle and PM emissions for both the chassis and the engine tests for two of the vehicles. The model also shows how small changes in vehicle speeds can lead to a doubling of load on the engine. Additionally, the model showed that it is impossible to drive a vehicle cycle equivalent to the heavy-duty engine federal test procedure on these vehicles.

Introduction

Since 1985, engine manufacturers have been required to conduct a certification emissions test, known as the heavy-duty engine federal test procedure (HDE-FTP), on a representative example of each heavy-duty engine model prior to use of the engine in an on-road vehicle. These emissions measurements and engine sales data have been used to generate the heavy-duty vehicle emissions factors for several generations of the U.S. EPA's MOBILE and PART air emissions models. However, a recent review (*1*) found that the measured emissions trends from in-use heavy-duty vehicles differ considerably from those predicted from the results of the certification engine tests and also vary considerably from those predicted by the MOBILE5 and PART5 models on a model year basis (*2*). Estimates of vehicle emissions are necessary to determine the effectiveness of heavy-duty engine regulations, for pollutant inventories needed to understand air pollution problems, and for air quality planning purposes. A clearer understanding of in-use emissions has been hampered by inconsistencies in testing conditions, most significantly inertial weight and driving cycle, and differences between the drive trains in vehicles using identical engines. These three factors, which are also widely variable under real life conditions, cause significant differences in emissions (*3*).

Others have approached the problem of predicting in-use emissions in different ways. Ramamurthy et al. (*4*) found that it was possible to develop reasonably good (nonlinear) correlations between instantaneous power at the wheels and NO_x emissions, while ignoring the variability of driveline efficiency. Since driveline efficiency was not known, it was not possible to compare their results directly to engine test results, although their approach could be used to make rough estimates as to the expected changes in NO_x emissions due to changes in inertial weight and driving cycle. They found that horsepower (HP) at the wheels could not be correlated with CO.

McKain and others (*5, 6*) used a similar design for a manual transmission vehicle that would mimic the HDE-FTP by forcing the vehicle to remain in a single gear while controlling the engine speed and load through the throttle pedal and power absorbers at the wheels. Although they had some difficulty in matching HDE-FTP engine speed and load simultaneously, it was possible to linearly correlate NO_x in gram per brake horsepower-hour (g/BHP-h) from the engine with NO_x in gram per horsepower (g/HP-h) at the wheel from the various chassis tests. Assuming that NO_x is proportional to engine HP, these results from two different chassis over several different gears show that the two tested vehicles had the same driveline efficiency and that the driveline efficiency was relatively constant for the various gears tested. If driveline efficiency is constant for all vehicles with a manual transmission, then this approach may be applicable to other vehicles. However, the authors found that the emissions of CO, HC, and PM were not linearly correlated between the engine and the chassis tests, suggesting that their single gear approach was not adequately matching transient operation between engine and chassis testing.

Outlined here is a methodology for relating emissions from engine testing to various chassis driving cycles and inertial loads, using a computer model of a driveline. This model is known as the Colorado School of Mines Transmission Model (CSMTM). The CSMTM was developed to provide a closer link between engine speed and load and those parameters that could be measured during a chassis test and to better understand the effect of automatic transmissions on engine operation. Automatic transmissions are installed in approximately 55% of all new heavy-duty vehicles (*7*). All of the work discussed here was on vehicles with automatic transmissions.

The test vehicles were two buses and a snowplow truck. The testing methods and results have previously been reported by McCormick et al. (*8*) and are only briefly summarized here. The two buses were driven over two different driving cycles, the Heavy Duty Transient (HDT) cycle (also known as the Urban Dynamometer Driving Schedule) and the Central Business District (CBD) cycle. The snowplow truck was tested using only the HDT cycle but over a range

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TABLE 1. Vehicle and Engine Descriptions

vehicle make	engine model	model year	engine HP	fuel injection	GVWR	odometer mileage
Navistar	Navistar DTA-466 SN 862790 family DTA-466-E250	1993	250	mechanical (1)	36 220	37 009
Neoplan	DDC series 50 SN 04R0001731 model 6047GB28DD2 family PDD08.SFZK7	1993	275	electronic (1)	38 000	85 200 since rebuild
Neoplan	DDC series 50 SN 04R0002933 model 6047GK28DD3 family PDD08.SFZK7	1993	275	electronic (2)	38 000	65 234

of simulated inertial weights. The engines were then removed from the vehicles and tested on the engine dynamometer, using the engine certification transient test cycle.

Ryan (*9*) used the results of ref *8* along with the Allison Transmission's proprietary transmission model, SCAAN, to estimate the equivalent vehicle mass for a small portion of the engine transient test. Their analysis was limited by the capabilities of the SCAAN model to a short section of the engine certification test. The SCAAN model was intended for open throttle conditions only, and these conditions occur only during short sections of the engine cycle. Moreover, they were required to select an acceleration section that began from idle so that they could correctly determine the starting speed for the acceleration. For the short acceleration section they were able to model, they found that only if the engine and transmission were installed in an extremely light truck (on the order of 12 000 lbs) could the rate of increase in engine rotational speed be maintained under the low loads specified by the engine certification test. The work reported here was intended to build upon this previous investigation and determine whether the disparity between the engine test and in-use driving was representative of the entire engine test and to understand the emissions implications.

Methods

Description of Vehicles and Engines. Properties of the three vehicles and engines tested are listed in Table 1. The first vehicle was a plow/dump truck owned by the Colorado Department of Transportation (CDOT), with a Navistar DTA-466 medium-heavy-duty engine with mechanical control. The transmission was an Allison MT-643, and the torque convertor was an Allison TC-378. This vehicle and engine will be referred to as mechanical 1. The other two vehicles were identical Neoplan transit buses operated by the Denver Regional Transportation District (RTD). The engines for these vehicles were electronic 1993 DDC series 50 diesel engines, certified as heavy-heavy-duty urban bus engines, and the transmissions and torque convertors were Allison HTB-748s and Allison TC-495s, respectively. The second set of vehicles and engines are referred to as electronic 1 and electronic 2. All engines were certified at 1993 emissions levels and do not employ a diesel oxidation catalyst.

Fuel Analysis. The testing reported here was carried out using a fuel representative of wintertime diesel fuel in the Denver region (NFRAQS fuel). The fuel characteristics are described elsewhere (*8*).

Engine Testing. Emissions testing for the engines was performed by the heavy-duty transient test as outlined in the Code of Federal Regulations (*10*). This test consists of a series of load and speed test points through which the engine must be run transiently while emissions are measured using specified procedures. The emissions of regulated pollutants are reported in g/BHP-h and must be below the standards set for the model year. Engine and chassis testing were done in immediate succession. The engine was not operated or modified in any way between the two types of testing.

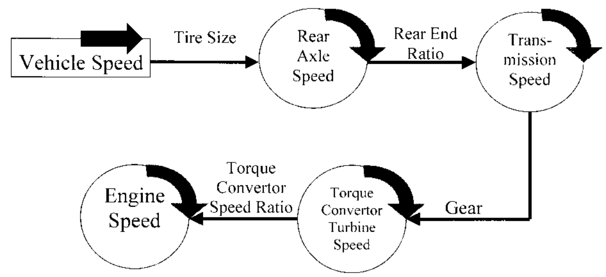

FIGURE 1. Algorithm for calculating engine speed from vehicle speed.

Chassis Testing. In a chassis dynamometer test, a vehicle is placed on a set of a rollers and driven over a speed versus a time trace, with the equivalent speed calculated by the rotational speed of the wheels at the rollers. The inertial load on the vehicle is simulated by the chassis dynamometer rollers along with variable weight flywheels. Road drag and air friction are estimated from published studies (*11*) and simulated electronically and thus can be modeled exactly. An important point is that engine starting is included in the test. For all three vehicles, inertial weight was set at approximately the average of the rated gross vehicle weight (GVWR) and the curb weight. For the electronic vehicles (transit buses), this was 90% of GVWR while for the mechanical vehicle (snowplow truck), it was 70% of GVWR. For the mechanical vehicle, inertial settings of 97% and 47% of GVWR were also examined. The vehicle speed is managed by the vehicle driver. The cycle is displayed for the driver using a prompt that shows the driver the current speed and the cycle speed required 30 s into the future. A single driver was used for all chassis testing performed under this program. Chassis dynamometer testing methods are reported in detail elsewhere (*3*, *8*).

In this study two chassis test cycles were used. The Urban Dynamometer Driving Schedule for heavy-duty vehicles or HDT cycle (*12*) is an 18-min cycle in which the driver is required to operate the vehicle at various speeds and accelerations that are intended to be representative of heavy-duty driving in U.S. urban areas. The 9-min CBD cycle (*13*) consists of 14 successive identical series of an acceleration followed by a steady cruise and a deceleration to represent how a delivery truck or bus performs during an inner-city trip.

CSM Transmission Model

Rotational speeds at various points in the driveline are calculated using the algorithm shown schematically in Figure 1. Engine HP is calculated as the HP needed at the wheel, plus HP losses through the driveline, and HP required to operate various auxiliary systems including the fan, alternator,

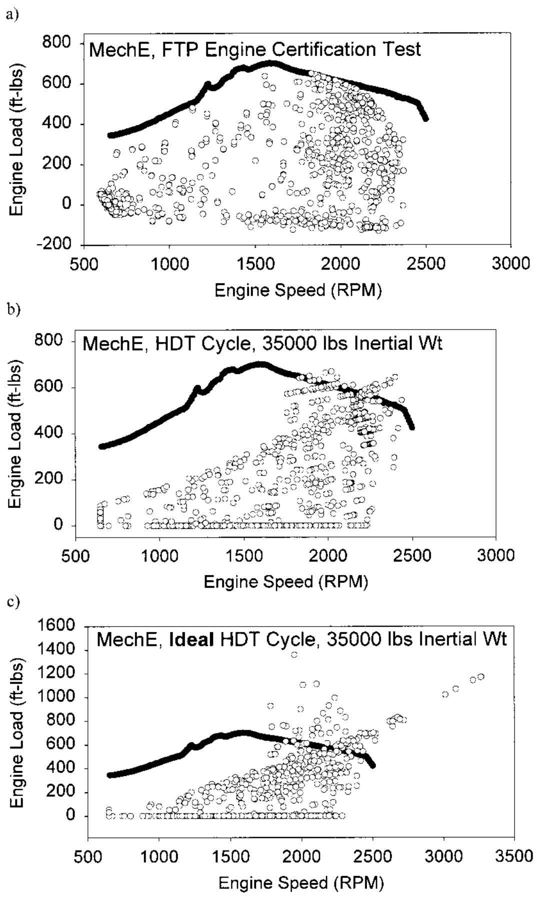

FIGURE 2. (a) Engine speeds and loads for the engine certification test for the mechanical engine. The black line is the engine map. (b) Engine speeds and loads for the HDT cycle run at 35 000 lbs inertial weight. (c) Engine speeds and loads for the ideal HDT cycle.

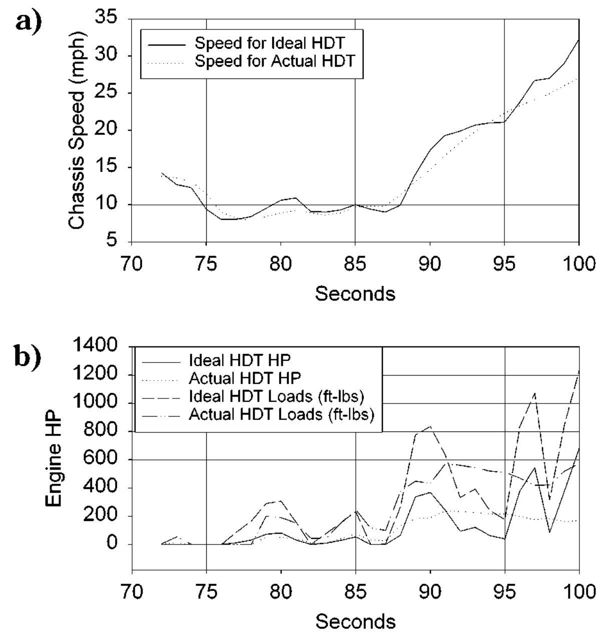

FIGURE 3. Effect of small changes in speed (a) on the engine load and HP (b) for the mechanical vehicle at an inertial weight of 35 000 lbs (97% GVWR), HDT cycle.

and air conditioner. HP at the wheel is a sum of the power needed to accelerate the vehicle and the power needed to overcome road friction and air drag. The driveline losses are a function of rotational speed and load at various points in the driveline and can be obtained as a series of empirical relationships specific to the components in each vehicle. The HP used by the auxiliary systems is dependent on engine rotational speed. These calculations are presented in greater detail in the Appendix (see Supporting Information).

Results and Discussion

Engine Speeds and Loads. The CSMTM estimates engine speeds and loads from a series of second-by-second vehicle speeds. For example, Figure 2b shows engine speed and loads for the mechanical vehicle driving the HDT at an inertial weight of 35 000 lbs. There are several points that lie outside the engine "map", i.e., the projected load exceeds the maximum load that the engine is capable of at the given rotational speed. The engine map is generated on the engine dynamometer for the fully warmed engine at essentially steady-state conditions. The throttle is set at full open, and the engine speed is gradually increased, allowing the engine to exert the maximum load of which it is capable at each rotational speed point. It should not be possible for the engine to operate at points outside of the engine map. These outliers could be due to transient operation, an engine warmed differently than for mapping, or due to inaccuracies in the measurement of vehicle speed, which is only measured to the nearest one-tenth of a mile per hour (mph). A difference of one-tenth of a mile per hour at certain points would bring most of these data back within the engine map.

For comparison with the chassis cycle, the engine test for the mechanical engine is also shown in Figure 2a. The most obvious difference between the two tests is in the low rpm range. In the low engine rpm range, the torque convertor slips to prevent high torque operation during the chassis test. High torque operation at low rpms is included in the engine test. Many of the speed/load points in the engine test occur in the zone prevented by the torque convertor during chassis testing. Therefore, it is not possible to develop a vehicle speed cycle that would mimic the engine operation of the HDE-FTP for these vehicles and possibly for any vehicle with an automatic transmission.

If it were possible to match the vehicle speeds required in an HDT cycle perfectly with 35 000 lbs inertial weight, then the engine speeds and loads would be those shown in Figure 2c. As that figure of a *hypothetical* run in which the driver matches the speeds of the ideal HDT exactly makes apparent, the ideal HDT cycle would require engine loads that are above the capacity of this engine. It might be possible to drive these cycles at lower inertial weights with the mechanical vehicle. However, this vehicle cannot make the accelerations required and could not drive the ideal HDT cycle when loaded to 33 500 lbs. The reason this discrepancy was not detected in the laboratory is explained below.

Small changes in vehicle speeds during accelerations can result in large differences in the load on the engine. For example, seconds 72–100 of the HDT test cycle are shown in Figure 3. Figure 3a shows how the mechanical vehicle was actually driven in comparison to the ideal vehicle speeds set in the HDT cycle. Figure 3b shows ideal and actual engine load and HP calculated from the CSMTM. At second 90, vehicle actual speed is only 2 mph below the ideal cycle speed. However, this small speed difference translates into a lowering of required HP and torque by nearly 50%.

Although not shown here, the engine speed and load results for the electronic vehicles are similar to those of the mechanical vehicle. The ideal HDT also cannot be driven by the fully loaded electronic vehicles. More complete results are included as Supporting Information.

NO_x Emissions versus Horsepower. Figure 4 compares NO_x versus engine HP for all three engines on both engine and chassis tests. The results of both tests show that for all

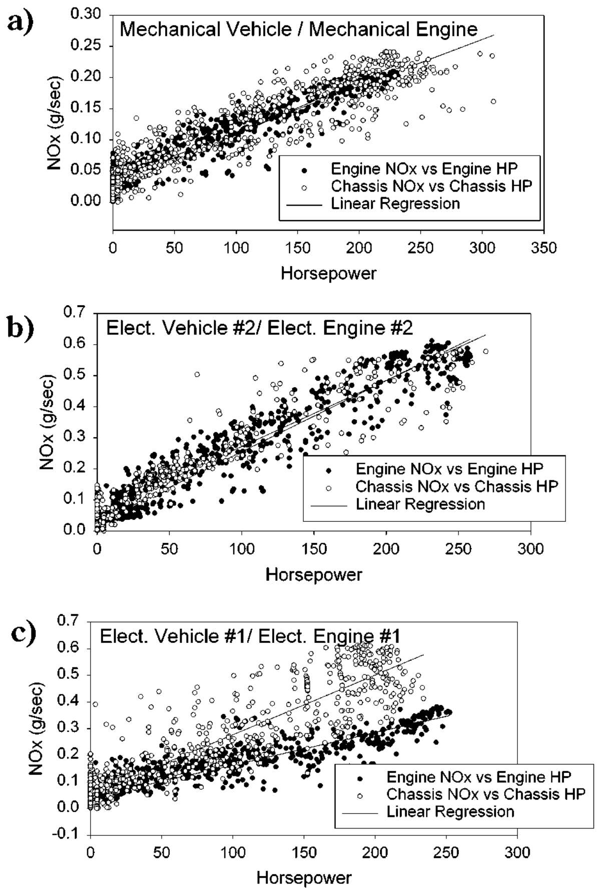

FIGURE 4. NO_x vs engine HP for (a) the mechanical vehicle, HDT chassis cycle, 35 000 lbs inertial weight and for the mechanical engine run on the engine certification test. Chassis, NO_x (g/s) = 7.48E−4 × HP + 0.037 (r^2 = 0.86); engine, NO_x (g/s) = 8.62E−4 × HP + 0.022 (r^2 = 0.93). (b) Electronic vehicle 2, CBD chassis cycle, 33 500 lbs inertial weight and for the electronic engine 2 run on the engine certification test. Chassis, NO_x (g/s) = 2.13E−3 × HP + 0.059 (r^2 = 0.88); engine, NO_x (g/s) = 2.29E−3 × HP + 0.026 (r^2 = 0.93). (c) Electronic vehicle 1, HDT chassis cycle, 33 500 lbs inertial weight and for the electronic engine 1 run on the engine certification test. Chassis, NO_x (g/s) = 2.24E−3 × HP + 0.0123 (r^2 = 0.86); engine, NO_x (g/s) = 1.22E−3 × HP + 0.041 (r^2 = 0.85).

three engines NO_x emissions are proportional to HP on a second by second basis. For the mechanical engine and electronic engine 2, the NO_x vs HP lines are the same for both engine and chassis tests. This similarity between engine and vehicle results for the mechanical engine and mechanical vehicle and electronic engine 2 and electronic vehicle 2 suggests that the model accurately predicts engine HP from vehicle speed. However, for electronic engine 1, the chassis and engine test NO_x vs HP lines are of different slope. The engines and other driveline components in electronic vehicles 1 and 2 have identical model names and numbers. The difference between the engine and the chassis NO_x vs HP regressions cannot be attributed to errors in the model since there are numerous NO_x g/s emission points from the chassis test that are significantly higher than the highest NO_x g/s emissions that occur during the engine test. Our conclusion is that this disparity in engine and vehicle emissions is due to dual mapping, i.e., the practice of having different fuel injection strategies for in-use operation and engine testing conditions. Use of this type of engine computer program has been determined by the U.S. EPA to be an emissions control defeat device. It should be noted that negative HP measurements (where the engine is absorbing power) in both the engine test and the calculated chassis cycles were set to 0.

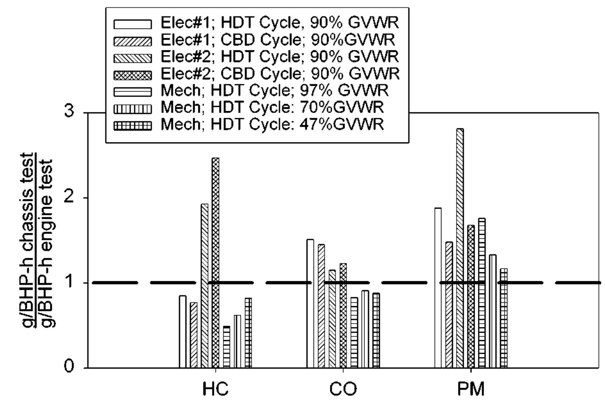

FIGURE 5. Comparison of emissions in g/BHP-h between chassis tests and engine tests.

It would be expected that during these periods there is no combustion in the engine, and thus no NO_x would be generated.

The results of Clark et al. (*14*), who graphically reported second-by-second NO_x emissions and engine HP for the engine certification test, seem to indicate a similar relationship. Ramamurthy et al. (*4*) compared NO_x emissions from several chassis cycles to HP at the wheels and found that NO_x was correlated with HP at the wheel, although the relationship was not linear. This is not in conflict with the findings of this study since their analysis did not consider losses in the driveline. They found that the slope of their correlation line was in all cases less than 1.

Other Pollutants. On the basis of the NO_x vs HP discussion above, it is reasonable to conclude that chassis testing in conjunction with a transmission model can be used to determine if in-use NO_x emissions differ significantly from engine certification test emissions (whether through dual mapping or deterioration). It is also apparent that, in the absence of dual mapping and deterioration, the engine test accurately predicts in-use emissions of NO_x on a g/BHP-h basis. It is then of interest determine how accurately the engine test can predict in-use emissions of other pollutants on a g/BHP-h basis, i.e., how representative the engine test is of in-use operating conditions for other pollutants.

A comparison of engine test emissions with brake-specific chassis test emissions estimated using CSMTM is shown in Figure 5. For completeness, electronic engine 1 has been included in this graph although, as noted above, this engine may use different fuel injection strategies during engine and chassis testing, and those strategies may affect the emissions of pollutants other than NO_x. Figure 5 shows that chassis HC emissions are not well predicted by the engine test although there is no consistent bias. HC emissions from diesel vehicles are often very small in comparison to HC from spark ignition vehicles and, in our experience, are difficult to measure accurately. Carbon monoxide emissions (on a g/BHP-h basis) are reasonably consistent between the engine and the chassis tests, and the engine certification test consistently underestimates PM emissions on a g/BHP-h basis. PM emissions are also very sensitive to inertial weight.

One possible explanation of the PM bias is suggested by results collected by Hofeldt and Chen (*15*), who measured transient carbon (not total PM) emissions from diesel buses during the CBD cycle. They found that acceleration transients accounted for roughly 80% of the particulate mass emitted over the cycle but only 45% of the fuel consumption, although the peak carbon emissions were correlated with steep transients in fueling rates. Assuming fuel consumption is roughly proportional to cycle work (or HP-h), the acceleration transients are responsible for a disproportionate fraction of the brake-specific PM emitted.

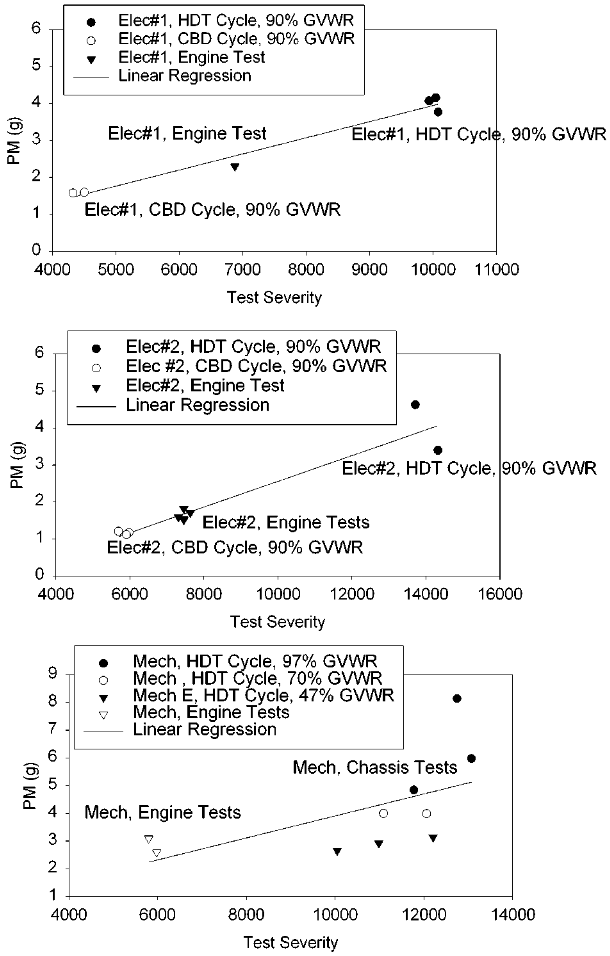

FIGURE 6. Relationship between severity of test ($\int_{cycle}(dHP_{accel}/dt)\,dt$) and total PM emissions. Electronic vehicle and engine 1, PM (g) = (4.36E−4 × (test severity)) − 0.41; $r^2 = 0.97$. Electronic vehicle and engine 2, PM (g) = (3.48E−4 × (test severity)) − 0.92; $r^2 = 0.91$. Mechanical vehicle and engine: PM (g) = (3.96E−4 × (test severity)) − 0.052; r^2=0.35.

Hofeldt and Chen (*15*) conclude that these increases in carbon emissions are due to the rate of increase of fuel injected into the engine. If their conclusion is true, then one would expect that faster rates of increase in engine HP would generate more carbon (on a g/BHP-h basis) than slower rates of increase. Additionally, more time spent during a cycle increasing the HP (as opposed to steady-state or deceleration) would also be expected to increase PM emissions. We propose that the quantity $\int_{cycle}(dHP_{accel}/dt)\,dt$ is an appropriate parameter to determine test severity in terms of acceleration and to predict PM emissions. The integrand, dHP_{accel}/dt, is the rate of HP increase, and periods of HP decrease (where $dHP/dt < 0$) and stability ($dHP/dt = 0$) are ignored because they do not require fueling. As shown in Figure 6, the relationship between total cycle PM emissions in grams and test severity ($\int_{cycle}(dHP_{accel}/dt)\,dt$) for both electronic engine/vehicle 1 and electronic engine/vehicle 2 is linear. The engine certification test is less severe than the HDT cycle but more severe than the CBD cycle at the tested inertial weight and, consequently, yields total cycle PM emissions between the two tests. It is important not to confuse the fact that total PM emissions are shown in this case to be proportional to test severity, while PM on a g/BHP-h basis is dependent on both test severity and total work done during the test. Thus, PM in g/BHP-h can be higher for test cycles with a lower test severity rating. The good linear correlation found between test severity and PM emissions for electronic vehicle 1, which is believed to employ different injection timing strategies for engine and chassis testing, supports the contention that fueling rates rather than injection timing is the controlling factor in PM emissions under the tested conditions. For the mechanical engine, the emissions data are more scattered. This may reflect a more variable response of the mechanically controlled engine to the exact details of driving. As with the two electronic engines, the PM emission appears to be a function of the cycle severity.

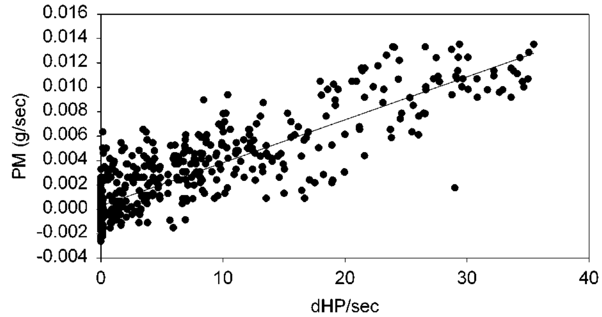

FIGURE 7. Continuous PM emissions vs rate of HP increase for Cummins ISM running the HDE-FTP. Data were smoothed over 10-s averages. Equation of regression line is PM (g/s) = 3.52E−4 × dHP/s + 0.00029; $r^2 = 0.77$.

To support the thesis that PM emissions are dependent on the rate of HP increase, continuous particulate matter emissions data collected by others during an HDE-FTP using a tapered element oscillating microbalance (TEOM) (*16*) were examined. This test was conducted on a Cummins M11 370 HP engine using typical in-use diesel fuel. The TEOM measures the weight of the filter collecting PM from the engine exhaust multiple times throughout the emissions test. In this experiment, measurements of PM were made at a rate of 5 Hz. There is considerable oscillation in the weight measured, perhaps due to the intermittent condensation and evaporation of water (*17*), so it was necessary to smooth the data over 10-s intervals. Other potential sources of error in the TEOM measurements include the loss and the uptake of organic species from the filter head due to variations in temperature and pressure. Additionally, pressure and temperature changes as well as external vibrations can have a mechanical effect on the tapered element, which can affect the accuracy of individual measurements (*18*). Nonetheless, the smoothed data showed a good correlation ($r^2 = 0.77$) between dHP_{accel}/dt and PM and a probability of more than 0.999 (p-factor <0.001) that there is a correlation between these two variables, as shown in Figure 7. The intercept is approximately zero. Interestingly, the slope of this line as well as all of the regression lines for the other engines (Figure 6) is very similar (PM ≈ 4E−4 dHP/s + constant), suggesting that this slope may be common to all modern engines.

Discussion. The CSMTM represents the driveline of a heavy-duty truck in order to estimate engine speeds and loads from vehicle speed data. The CSMTM has been used to calculate engine HP from vehicle speed measurements. The model shows that vehicles exercise the engine differently than in the engine certification test. Engine testing results have shown that NO_x is proportional to engine HP for the vehicles tested here. The similarity between engine and chassis NO_x vs HP plots in the case of two of the vehicles verified the accuracy of the model and indicated in the third case that one of the vehicles appeared to be using different fuel injection strategies during engine testing and chassis testing. The engine certification test was shown to provide an approximate prediction of CO emissions from the HDT and CBD chassis cycles on a g/BHP-h basis. However, the engine certification test consistently underestimates chassis test PM emissions on a g/BHP-h basis. Chassis hydrocarbon emissions are also not well predicted by the engine test on a g/BHP-h basis, although there is no consistent bias.

Chassis and engine cycle total PM emissions were found to correlate with a test severity parameter defined as the integral of the rate of HP increase over the test cycle. It was also shown that real-time PM emissions (via TEOM) are linearly correlated with the rate of HP increase. The CSMTM was also used to demonstrate that small changes in vehicle speeds during accelerations (±2 mph for a few seconds) can lead to large changes in load on the engine and possibly large changes in emissions. This suggests that heavy-duty chassis testing laboratories need to develop approaches to carefully and repeatably control vehicle speed during accelerations.

Acknowledgments

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Supporting Information Available

Appendix and table showing the calculations of rotational speed and gear of driveline. This material is available free of charge via the Internet at http://pubs.acs.org.

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