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ABSTRACT

Societal and governmental pressures to reduce diesel exhaust emissions are reflected in the existing and projected future heavy-duty certification standards of these emissions. Various factors affect the amount of emissions produced by a heterogeneous charge diesel engine in any given situation, but these are poorly quantified in the existing literature. The parameters that most heavily affect the emissions from compression ignition engine-powered vehicles include vehicle class and weight, driving cycle, vehicle vocation, fuel type, engine exhaust aftertreatment, vehicle age, and the terrain traveled. In addition, engine control effects (such as injection timing strategies) on measured emissions can be significant. Knowing the effect of each aspect of engine and vehicle operation on the emissions from diesel engines is useful in determining methods for reducing these emissions and in assessing the need for improvement in inventory models. The effects of each of these aspects have been quantified in this paper to provide an estimate of the impact each one has on the emissions of diesel engines.

INTRODUCTION

Prediction of heavy-duty diesel vehicle emissions inventory is substantially less mature than the prediction of gasoline passenger car emissions. However, diesel vehicles are now receiving attention, because they are acknowledged to be significant contributors to the atmospheric inventory of particulate matter (PM) and NO_x. Societal and legislative pressures to monitor and abate diesel vehicle emissions are rising. Also, the activity of heavy-duty vehicles is projected to continue to increase over the next decade. Sales of class 8 [more than 14,969 kg (33,000 lb) gross weight] vehicles in 1999 in the United States exceeded 250,000 units. Presently, the heavy-duty diesel emissions inventory is based on emissions factors developed from certification data gained using a stationary engine dynamometer, and there is no sophisticated accounting for the application of that engine in the vehicle or the nature of vehicle behavior. This paper reviews chassis dynamometer data, existing emissions data in the literature, and modeling to examine those factors that most affect diesel vehicle emissions, which are usually expressed in units of emissions mass per unit distance traveled (e.g., g/km). The main parameters that affect the emissions from compression ignition engines include vehicle class and weight, driving cycle, vehicle vocation, fuel type, engine exhaust aftertreatment, vehicle age, and the terrain traveled. In addition, the effects of engine controls, such as injection timing strategies, on measured emissions must be addressed.

IMPLICATIONS

Heavy-duty vehicle contributions to the emissions inventory are poorly documented and presently are based on engine certification emissions data. This paper clarifies the effect of various factors in truck and bus usage that can have an effect on diesel emissions and cause the reality to stray from the idealized model. In this way, modelers can identify shortcomings in the inventory and begin to address improved models. In particular, the investigation highlights the effects of vehicle use, load, age, and maintenance on emissions, with emphasis on the production of NO_x and particulate matter (PM).

VEHICLE CLASS AND WEIGHT

The effect of vehicle class on emissions is significant, yet there is little detailed information available on this factor. Vehicle classes are defined by several entities, including the American Automotive Manufacturers Association (AAMA), and are usually based on the gross vehicle weight rating (GVWR) as shown in Table 1. The GVWR is the maximum weight a vehicle is allowed to achieve, including the vehicle, driver, payload, and fuel. Unfortunately, registration weight and GVWR often do not agree.

For heavy-duty vehicles, emission regulations are imposed on the engine regardless of the class of vehicle or specific use of the vehicle in which the engine may be installed. The federal testing procedure prescribed in the Code of Federal Regulations, Title 40, Part 86, Subpart N[1] is a transient test used to establish engine certification to emissions standards that are, thus, based solely on the engine performance. Conversely, the light-duty certification test employs a chassis dynamometer and is affected by road-load power and vehicle weight. All AAMA class 1

Table 1. Vehicle classes as defined by the AAMA.

Class	GVWR (kg)	GVWR (lb)
1	2721 and less	6000 and less
2	2722–4536	6001–10,000
3	4537–6350	10,001–14,000
4	6351–7257	14,001–16,000
5	7258–8845	16,001–19,500
6	8846–11,793	19,501–26,000
7	11,794–14,969	26,001–33,000
8	14,970 and more	33,001 and more

and some class 2 trucks may be emissions-certified using the light-duty automotive approach.

The effect of vehicle class on emissions will first be addressed from an analytical point of view. To compare two vehicles of different truck classes, a theoretical model of a vehicle operating at a constant speed was employed. A simple road-load relation considering aerodynamic drag, tire rolling resistance, and grade is shown in eq 1.

$$P = \tfrac{1}{2}\rho_a C_d A V^3 + \mu M g V + M g V \sin\theta \qquad (1)$$

where P is power required to maintain a steady speed, ρ_a is density of air, C_d is aerodynamic drag coefficient of the vehicle, A is frontal area of the vehicle, V is speed at which the vehicle is traveling, μ is tire rolling resistance coefficient, M is mass of the vehicle, g is acceleration due to gravity, and θ is angle of inclination of the road grade.

The three main factors that cause a vehicle to demand engine power are vehicle speed, weight, and the incline traveled. Note that this is for a steady-state (constant speed) case only. As the required power increases, the amount of fuel burned to produce that power also increases, and the rate of regulated emissions produced will generally increase. [Note, however, that brake-specific emissions levels of some constituents, such as hydrocarbons (HC), may be high at low power ratings.] This implies that emissions will directly vary with truck class. The higher truck classes are heavier and, thus, produce more regulated emissions. This implication will be further investigated in the following discussion.

A comparison of a pickup truck [3629 kg (8000 lb) GVWR, class 2] and a tractor truck [18,143 kg (40,000 lb) GVWR, class 8] powered by the same engine shows the trend of higher emissions through fuel consumption. An estimate of fuel economy was made from the energy the vehicle required for a particular section of travel. Typical fuel economies are 13.1 L/100 km (18 mi/gal) and 33.6 L/100 km (7 mi/gal) for the pickup truck and the tractor truck, respectively. The fuel economy differs between these two trucks by a factor of 2.5, while the corresponding weight differs by a factor of 5. This indicates that the fuel consumption is not directly proportional to weight but that it does increase as the vehicle weight increases. It is well documented[2] that, for a given engine meeting a given emissions standard, emissions of NO_x may be related closely to CO_2 emissions, so that the higher fuel consumption implies higher emissions levels of NO_x. Figure 1 shows the ratio of emissions from the class 2 and class 8 model trucks as speed varies on different grades.

It is evident that, if two trucks employ the same engine, all else being equal, the heavier vehicle will demand higher energy (as axle-kilowatt-hour or akW-hr). Energy at the rear wheels, given units of akW-hr, differs from engine energy, given units of bkW-hr (brake-kilowatt-hour), by the factor of drivetrain efficiency. Auxiliary and fan engine loads also increase the brake-to-axle power ratio. Such variation would be accounted for if emissions variations were linear with power, as is NO_x[2], and if differences in the demanded energy were appropriately modeled. By this argument, even if the emissions in g/akW-hr (or g/bkW-hr) were similar for the two vehicles, the emissions in g/km would vary by a factor of the ratio of the akW-hr/km used by each vehicle.

Heavy-duty vehicle engines are certified to emissions levels in units of g/bhp-hr (equivalently g/bkW-hr), so if two vehicles have an engine certified to the same standard, then their emissions in g/km will be influenced solely by the ratio of bkW-hr/km. In this case, one would argue that in regular service, a light–heavy-duty pickup truck (at 15 L/100 km economy) would emit at ~40% of the rate, in g/km, of a tractor-trailer (at 78 L/100 km economy). This is the argument embodied in the present inventory process, but it is flawed if the emissions rates are nonlinear with respect to power demand (as CO and PM are known to be) or if “off-cycle” operation induces NO_x emissions rates that differ from certification rates, in units of g/bhp-hr.

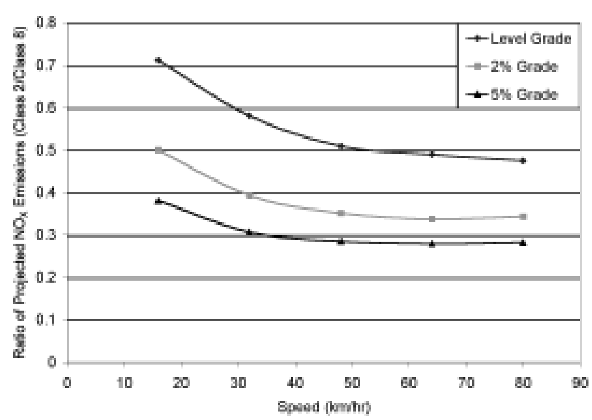

Figure 1. Ratio of class 2/class 8 NO_x emissions for varying grades and speeds.

For a comparison of truck classes from test data, the emissions of two different heavy vehicles with the same engine were compared, noting that these two trucks have a different vocation, transmission, and horsepower rating. These vehicles had different engine power ratings of 224 kW (300 hp) for the tractor truck and 207 kW (277 hp) for the transit bus. Each vehicle was tested on a different test cycle; however, the two different cycles are the most similar test vehicles available from the West Virginia University (WVU) Transportable Laboratory[3] database when comparing transit bus data to truck data. The bus was tested on the central business district (CBD) Cycle,[4] and the tractor truck was tested on the Truck-CBD Cycle (also called the Modified CBD Cycle).[5] The Truck-CBD Cycle has slower acceleration ramps so that a vehicle with a lower power-to-weight ratio and with an unsynchronized manual transmission (tractor truck) can follow the scheduled speed.

The tractor truck exhibited lower emissions of NO_x, HC, and PM of 26, 8.2, and 30%, respectively. The total emissions of CO were higher for the tractor truck by 12%. It is evident from these data that conclusions based on vehicle class alone are not reliable and that vocation (as mimicked by the test cycle) and transmission type must be considered. The results are opposite of the expected lower emissions from the less powerful bus engine.

Testing performed using a bus from the Flint Mass Transit Authority has also been used for various comparisons.[6] Testing was performed on this bus using several different driving test cycles run consecutively. The bus was outfitted with a Detroit Diesel Series 50 engine coupled to a five-speed automatic transmission. The engine was a four-cylinder unit, having 8.5 L of displacement rated at 205 kW (275 bhp) operating on No. 2 diesel. Although these are data from just one bus, many other similarly equipped buses were tested at this Flint site and showed consistent bus-to-bus correlation of emissions data for operation on the CBD Cycle.

The data collected from the Flint Mass Transit Authority bus contained one portion in which the test weight of the bus was varied while tested on the CBD Cycle. Table 2 shows the emissions results from this testing. For the test weight set at 17,237 kg (38,000 lb) (max GVWR for the vehicle), the CO and PM (in units of g/km) were both considerably higher than for the lighter test weights. However, NO_x (in units of g/km) was relatively insensitive over the range of test weights.

Table 2. Emission results from varied test weights for the Flint bus driven on the CBD cycle.

Test Weight (kg)	17,237	14,889	12,542
NO_x (g/km)	19.1	20.0	17.8
CO (g/km)	4.29	2.80	2.83
HC (g/km)	0.09	0.09	0.09
PM (g/km)	0.21	0.14	0.13

Research by Graboski et al.[7] for the Northern Front Range Air Quality Study (NFRAQS) reported emissions testing on 21 different heavy-duty vehicles using the WVU truck (i.e., 5-Peak) Cycle,[5] U.S. Environmental Protection Agency (EPA) Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles (UDDS or Test-D),[8] and the CBD Cycle as described in SAE J1376.[4] Results of NFRAQS included comparisons to the GVWR of the vehicles against the emission results. The conclusion by Graboski et al.[7] was that a heavier vehicle uses more fuel and, thus, produces more exhaust gas on a g/km basis. It was also noted that, as a vehicle following a cycle used more fuel, higher emissions were produced in units of g/km. For example, the CBD Cycle yielded the highest fuel consumption and also the highest emissions as compared with the other cycles.

TEST CYCLE EMISSIONS COMPARISON

The data from the trucks tested in the NFRAQS were evaluated by Coburn,[9] who concluded that more vehicles need to be tested to obtain reliable and precise estimates of average PM emissions. Also, the level of PM emissions measured depends on the driving cycle used to test the vehicle. The conclusions from Graboski et al.[7] indicate the trend of the CBD Cycle producing the highest emissions and the WVU 5-Peak Cycle producing the lowest emissions with the heavy-duty UDDS (Test-D) between them. This trend was attributed to the CBD Cycle being the most aggressive cycle with more acceleration ramps and more sustained high acceleration than the other cycles. One particular heavy-duty diesel-powered vehicle that was tested on all three cycles was a telephone truck of 8845 kg (19,500 lb) curb weight and 36,287 kg (80,000 lb) GVWR. It was a 1983 model year vehicle powered by a Cummins NTC400 with the odometer showing 80,876 mi (equivalently, 130,157 km). For the NFRAQS telephone truck data, NO_x ranged from 11.7 to 19.4 g/km for the three cycles used, which is a wider relative variation than for the WVU bus data discussed below.

A sequence of tests performed by the WVU Transportable Laboratory will be considered to evaluate the effect of driving test cycles on the emissions produced. From the WVU data on the Flint bus, it is evident that the units in which the emissions are expressed are significant. The comprehensive data are shown in Table 3. For example, considering NO_x, the NY Bus Cycle is highest of all the cycles in g/km but lowest in average g/sec. Also, the CBD Cycle and WVU 5-Peak Cycle yield similar emissions in g/km but emissions differing by a factor of 2 in g/akW-hr.

Table 3. Flint bus emissions for various test cycles at a test weight of 14,889 kg.

Cycle	g/km	g/cycle	Avg. g/sec	g/akW-hr	g/gCO_2	g/L Fuel
			NO_x			
CBD	20.0	62.0	0.1080	15.5	0.01145	30.7
WVU 5-peak	17.8	143.0	0.1682	26.0	0.02238	60.1
WVU 5-mile	15.4	123.8	0.1375	22.0	0.01868	50.1
NY-Bus	43.5	44.1	0.0735	28.4	0.01301	34.6
Test-D	16.7	148.5	0.1398	18.2	0.01536	41.1
			CO			
CBD	2.80	13.94	0.0243	3.50	0.0026	6.89
WVU 5-peak	0.81	6.50	0.0076	1.18	0.0010	2.73
WVU 5-mile	1.55	12.53	0.0139	2.23	0.0019	5.07
NY-Bus	27.5	27.91	0.0465	18.0	0.0082	21.9
Test-D	3.85	34.35	0.0323	4.21	0.0036	9.52
			HC			
CBD	0.087	0.28	4.93E–04	0.071	5.22E–05	0.140
WVU 5-peak	0.044	0.35	4.12E–04	0.063	5.48E–05	0.148
WVU 5-mile	0.037	0.30	3.34E–04	0.054	4.54E–05	0.122
NY-Bus	0.379	0.38	6.41E–04	0.248	1.13E–04	0.301
Test-D	0.037	0.33	3.13E–04	0.040	3.44E–05	0.092
			PM			
CBD	0.137	0.69	1.20E–03	0.172	1.27E–04	0.341
WVU 5-peak	0.050	0.40	4.71E–04	0.072	6.26E–05	0.169
WVU 5-mile	0.106	0.85	9.46E–04	0.152	1.29E–04	0.346
NY-Bus	0.827	0.84	1.40E–03	0.540	2.47E–04	0.658
Test-D	0.230	2.05	1.93E–03	0.252	2.12E–04	0.568

certification, (NO_x + HC) are regulated as a sum. Both the NFRAQS and the WVU data showed HC cycle-to-cycle variations of a factor of 2, when the units were in g/km, excluding the NY Bus Cycle.

Of specific interest is the comparison of the WVU data for the bus using the WVU 5-Peak Cycle and the WVU 5-Mile Route. Both cycles are similar except that the WVU 5-Peak Cycle does not demand full power from the bus engine upon acceleration. PM values in g/km for the full power operation (route) are slightly more than twice as high as for the cycle. This confirms the sensitivity of CO and PM emissions to engine loading, in contrast to the relative stability of the NO_x emissions in units of g/km.

A portion of testing at WVU involved testing a single truck on various different test cycles.[10] The results for NO_x in g/km are shown in Figure 2. The vehicle was a 1995 GMC box truck with a Caterpillar 3116 engine rated at 127 kW (170 hp). The fuel used was D2 diesel, and the vehicle has a GVWR of 9980 kg (22,000 lb). It is concluded that the test cycle used has a profound effect on PM emissions and a significant effect on NO_x emissions.

This is to be expected because the vital ratios of the cycles, such as akW-hr/km, vary widely. In currency of g/km, the WVU bus data show that virtually all cycles yield NO_x in the range of 15.4–20.0 g/km, with the NY Bus Cycle an outlier at 43.5 g/km. This is because the NY Bus Cycle covers a short distance over its duration relative to other cycles. One may conclude that NO_x data, in g/km, remain fairly consistent for most cycles in current use, provided that the cycle does not contain excessive idle or low power operation.

For diesel vehicles, variations in both CO and PM are acknowledged to be higher than those for NO_x, all else being equal. This is borne out by the data of both the NFRAQS and WVU studies. For the Flint bus, excluding the NY Bus Cycle as an outlier, emissions of CO in g/km varied by a factor of 5 over the four cycles used, and the NFRAQS data yielded a similar ratio. For PM in both studies, the range was a factor of 3–4, in g/km. One must conclude that the cycle chosen has a profound effect on PM and CO levels, if they are expressed in g/km. The WVU data showed that choice of units in g/akW-hr did not improve cycle-to-cycle agreement. Hydrocarbon emissions from diesel engines are customarily low and are of less interest in inventories than NO_x and PM emissions, although for 2002/2004

VEHICLE VOCATIONS AND LOCAL DRIVING ACTIVITY

The particular vocation or specific use of a vehicle can have an effect on the emissions produced. The transients and cruising behavior of each vehicle vocation, along with the load carried, can be reproduced in testing by changing the testing weight and the driving cycle. A driving

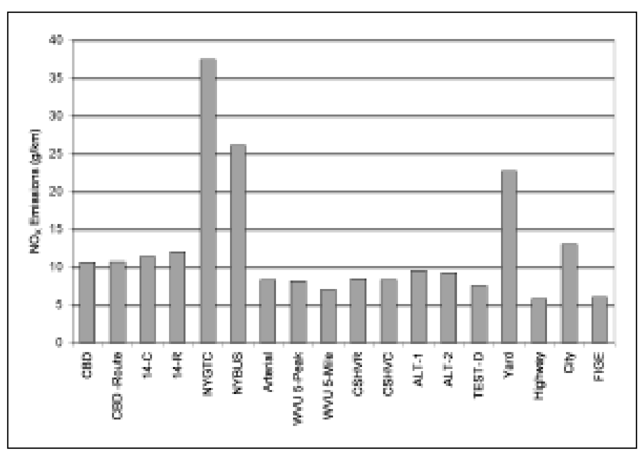

Figure 2. NO_x emissions from various test schedules on one truck.[10] The truck was a 1995 GMC tested at 9980 kg (22,000 lb) vehicle weight. The vehicle was equipped with a Caterpillar 3116 engine rated at 170 hp and an automatic transmission. The test fuel was No. 2 diesel.

cycle for a bus should produce the characteristics of a bus route (frequent stops, high acceleration, and low average speeds) and produce representative values of the exhaust emissions. This would also be true for a particular truck vocation; either a local delivery, long haul, or shipping yard route would be used where applicable. For example, the axle energy per distance used by a vehicle following different test cycles can indicate the difference in vocation. The same bus following the WVU 5-Mile Route and the NY Bus Cycle used 0.70 akW-hr/km (axle kilowatt-hour per kilometer) and 1.53 akW-hr/km for each cycle, respectively. The difference in the axle energy per distance has a direct effect on the emissions produced in mass per distance. If this vehicle were equipped with an engine that consistently produced 6.7 g/bkW-hr of NO_x (8.38 g/akW-hr assuming 80% overall drivetrain efficiency), then the WVU 5-Mile Route would produce 5.8 g/km of NO_x and the NY Bus Cycle would produce 12.8 g/km. Likewise, the PM emissions would be 0.12 g/km for the WVU 5-Mile Route and 0.25 g/km for the NY Bus Cycle, although in reality PM cannot be taken as energy-specific with reliability.

Comparing other vocations of a line haul tractor at steady cruise and a refuse truck operating on the New York Garbage Truck (NYGT) Cycle, similar results are obtained. The energy requirement for a 36,287 kg (80,000 lb) tractor trailer traversing flat terrain at 97 km/hr was calculated to be 1.5 akW-hr/km. Conversely, a refuse truck following the NYGT Cycle would use 1.1 akW-hr/km.

The analysis of vehicle weight using the road-load equation disregards the fact that the vehicle has to accelerate to the assumed steady-state condition. Under acceleration, it is assumed that a heavy vehicle is customarily using the maximum power available from its engine, thus producing the maximum amount of exhaust gas and typically high rates of NO_x and PM. So then, over a typical day of use for any vehicle, one that stops and then accelerates more often will produce higher distance-specific emissions, providing all else is held constant. This effect is from the differences in the use of the vehicle, also called the vehicle's vocation.

Research at WVU, funded by National Renewable Energy Laboratory, and leading to the development of the City-Suburban Heavy Vehicle Route,[11] included recording data from two delivery companys' tractor trucks as the drivers performed their respective tasks. Table 4 shows the data collected from this survey. It is evident that the primary difference between operation in yard, city, suburban, and interstate service lies in the average speed, whereas typical accelerations are similar, most likely requiring full engine power. The issue of the effect of vehicle vocation is difficult to tackle but is also covered, in part, by the discussion of test cycles above. It is evident that a line haul tractor may be expected to emit at lower levels in g/km than would an inner-city refuse truck, because long idle periods and stop-and-go operation will increase emissions in g/km.

Table 4. Combined survey data from Roadway and Overnite tractors.

Microtrip Type	Distance (km)	Average Speed (km/hr)	Average Acceleration (km/hr/sec)	Average Deceleration (km/hr/sec)
Interstate	319	52.5	0.98	–1.43
Suburban	246	28.6	1.32	–1.93
City	42	16.4	1.21	–1.80
Yard	8.8	10.1	1.17	–1.40
Suburban and city	288	25.7	1.29	–1.91

Local driving activity also affects heavy vehicle emissions but is difficult to quantify. For example, driving in a road system that requires frequent stops is likely to raise emissions. This is very close to the definition of vehicle vocations and also has an impact on the discussion on test cycles. Local driving habits will also affect the vehicle emissions due to driver-to-driver variations. The effect that these factors have on vehicle emissions is comparable with the effect of different driving cycles that mimic the particular driving patterns or vehicle uses.

FUEL DIFFERENCES

Fuels other than conventional diesel can provide a means of reducing heavy-duty engine emissions. Fuels such as compressed natural gas, liquefied petroleum gas, and various alcohols have been used but require engine modifications for operation. However, using a reformulated diesel or a diesel equivalent fuel that does not require engine modifications can produce significant reductions in engine emissions while avoiding the expense of vehicle modifications. Complete fuel reformulation would affect all heavy-duty diesel vehicles and has the potential to reduce NO_x and PM significantly.[12] Diesel fuel additives have also been used for reduction of emissions as shown by Lange et al.[13] and Green et al.[14] The most common additive has been a cetane number enhancer. The results show that a fuel with a higher cetane number ignites earlier and, thus, may use less fuel for the same power output. In some cases, earlier ignition may increase NO_x emissions, while in others, reduction of the premix fuel burn can reduce NO_x. Brown[15] states that the most beneficial and cost-effective solution to reduce exhaust emissions is high-quality, fully reformulated diesel combined with exhaust aftertreatment.

In the study by Graboski et al.,[16] the transient emissions from D2 diesel and biodiesel blends in a DDC Series

60 engine were investigated. The fuels tested were a reference diesel and 20, 35, and 65% biodiesel (methyl soy ester) blends in the reference diesel, as well as 100% biodiesel. This testing was performed on an engine dynamometer with NO_x, CO, HC, and PM recorded in g/bkW-hr. The biodiesel showed a strong trend of reduction in CO, HC, and PM, but an increase in NO_x emissions.

Recent emissions characterization by WVU included a fuel from Malaysia produced using a Fischer-Tropsch (F-T) process. This fuel is produced from natural gas and has similar physical properties to diesel fuel but usually with zero sulfur and very low aromatic levels. Transient engine tests were performed at WVU using the F-T fuel along with federal No. 2 and California No. 2 diesel. Table 5 shows the averaged results of three tests using these fuels on a Navistar 444 engine using the Federal Test Procedure engine cycle. Both the California diesel and the F-T fuel showed a substantial decrease of each exhaust gas component over U.S. federal diesel fuel. The F-T fuel produced the greatest gain of 65% reduction in HC. From this comparison, one can conclude that fuel type has the potential to provide a substantial reduction in emissions.

Clark et al.[17] recently compared a variety of diesel fuels and diesel fuel substitutes. Testing for this study included available diesel fuels, biodiesel blends (e.g., BD20 is 20% biodiesel), fuels from the Fischer-Tropsch process (termed F-T and MG), and a blend of the MG fuel with isobutanol. The results of the testing were then compared with similar studies by Graboski et al.[16] and Schaberg et al.[18] The PM results are shown in Figure 3. The fuels tested by Schaberg et al.[18] were diesel fuel from the Sasol slurry phase distillate process and blends of the two and are termed 2D, B1, B2, B3, N, K, and C. The comparison showed a maximum decrease of 66% in PM emissions for the fuels tested relative to No. 2 diesel.

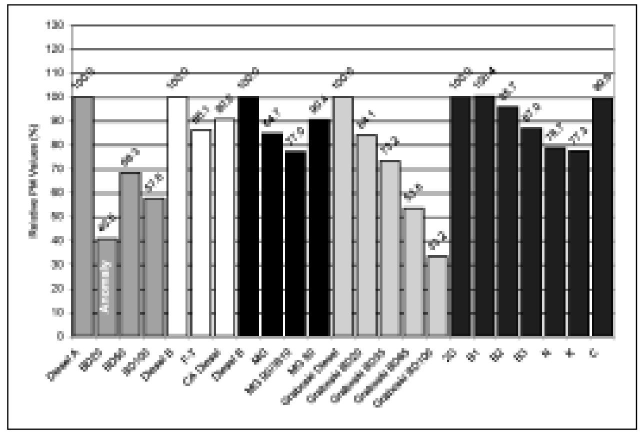

Figure 3. Normalized PM emissions results comparison for different fuel types reproduced from Clark et al.[17] Data are from studies by Schaberg et al.,[18] Graboski et al.,[16] and Clark et al.[17] For each study, the low-sulfur diesel results were set at 100%. The Clark et al.[17] BD20 results appear anomalous, but no corrective explanation can be found.

EXHAUST AFTERTREATMENT

Although only a small number of heavy-duty vehicles are equipped with any aftertreatment device, the effect on emissions can be substantial. The three primary types of diesel exhaust aftertreatment are diesel oxidation catalyst, particulate traps, and continuously regenerating traps (CRT). These have been tested in various studies and show promising results. An oxidation catalyst is similar in principle to the oxidizing section of a gasoline engine catalytic converter. It works by oxidizing the gaseous HC and CO in the exhaust to produce water vapor and CO_2.[19] While this type of aftertreatment is effective in reducing HC and CO, these are not the specific diesel exhaust pollutants that are desirable to eliminate. The quest for a lean burn NO_x reduction catalyst for diesel engines remains an unattained grail, although systems employing HC reductants and urea are now under investigation.

A particulate trap or filter is a device in which the PM is collected or filtered out of the exhaust and is regenerated by some external means. This is usually accomplished by heating the trap to burn the PM, using a fuel additive that causes regeneration, or employing a filter surface incorporating a catalyst. These methods are sometimes not effective in regenerating at low loads and low exhaust temperatures.[20]

The most recent type of exhaust aftertreatment developed is the CRT. This type of system combines an oxidation catalyst and a particulate trap filter that reduces both gaseous and particulate emissions. The exhaust gases first pass through the catalyst to oxidize CO and HC and also convert the majority of NO_x to NO_2, which is then used to oxidize the PM in the particulate trap.[19] This aftertreatment method continuously regenerates with no fuel additives or heater control system. A drawback of this system is that it requires low-sulfur diesel, because combustion of sulfur degrades the catalytic reactions in the system. Continuously regenerating particulate traps have the potential to reduce PM by a factor of 3.5, and reduction in NO_x is ~10%.[19,21]

The WVU Transportable Laboratory has performed testing on vehicles with and without catalytic converters. A refuse truck was tested in 1995

Table 5. Engine emissions comparison of various fuels.

Fuel	D2	CA D2	Difference (%)[a]	F-T	Difference (%)[a]
NO_x (g/bkW-hr)	7.04	6.38	–9.3	5.99	–15
CO (g/bkW-hr)	1.89	1.23	–35	1.02	–46
HC (g/bkW-hr)	0.31	0.20	–35	0.11	–65
PM (g/bkW-hr)	0.16	0.15	–8.3	0.13	–17

[a]Using D2 diesel as baseline.

with a catalytic converter manufactured by Donaldson. The vehicle was a 1992 model year with 90,952 km (56,515 mi) on a Cummins LTA-10 engine supplying power through a four-speed automatic transmission. This engine was rated at 194 kW (260 hp) operating on D2 diesel. The truck was driven on the WVU 5-Peak Cycle, and Table 6 shows the results of this comparison. Each of the exhaust gas constituents was lowered by use of the catalytic converter. The total PM was lowered the most at 24%, NO_x was lowered ~9%, and the CO was lowered the least at 8.3%. One may conclude that catalytic converters are successful in reducing HC and PM. Substantial reductions of only CO, HC, and perhaps fine PM can be expected on this basis.

VEHICLE AGE

There are two separate factors of vehicle age that affect the emissions produced. First, it is assumed that, as a vehicle ages and accumulates high mileage, the engine will slowly wear and produce higher emissions even though diesel engine deterioration is recognized to be slow for purposes of certification. This would imply that, for example, a 20-year-old vehicle would produce higher emissions after 20 years of use than it did when it was new. The second factor is the change in technology. The changing technology implies that the engines produced today are different than older ones and must meet more stringent emissions standards. There are few data available for an age comparison of the same truck that was tested new and after some certain useful life.

There is documentation by EPA on vehicle deterioration factors for heavy-duty vehicles. These deterioration factors are supplied by manufacturers and may be either additive or multiplicative in modifying the baseline emissions from a new engine. Generally, diesel engines are reported to deteriorate little over the first 466,710 km (290,000 mi) of use (the useable limit previously set by EPA). However, engines now last 800,000–1,600,000 km until the first rebuild. No data can be found to clarify deterioration in the final stages before the rebuild.

The age of the vehicle has a significant effect on emissions when pertaining to the technology in the particular model year in which the vehicle was made. From the EPA emissions standards that are used to certify engines, a 1998 model year, heavy-duty engine (used in a bus) would produce less NO_x by a factor of 2.5 and less PM by a factor of 12 relative to a 1988 model year engine. This is true only if the vehicle produces emissions that correlate directly to the emissions certification standards.

The effect of the technology level of the engine on vehicle emissions was determined by comparing test data from two different vehicles with the same model engine. These vehicles were tested by the WVU Transportable Laboratory in 1994. The engine was a Detroit Diesel Corporation 6V-92TA burning D2 diesel. This engine has six cylinders and a displacement of 9.05 L and produces 207 kW (277 hp). Table 7 shows the summary of vehicle information and the measured emissions from each vehicle.

The newer engine was made five years after the older engine and produced emissions that, for NO_x and CO, were lower than those of the older engine. The largest reduction offered by the newer engine was in CO and was 71%. The total HC production was 11% higher on the newer engine, but the PM was reduced by 45%. The HC and CO changes most likely imply a substantial reduction in elemental carbon in the PM. This simple comparison shows that for the majority of the exhaust gas constituents, reduction has occurred in the five-year time period. Interestingly though, the fuel economy of the newer vehicle experienced a decrease of 10%, most likely due in part to the retarding of the timing to meet NO_x emissions requirements.

Testing at WVU has included testing the same vehicle annually. Testing from the Bi-State Development Agency in St. Louis, MO, included a transit bus powered by a DDC 6V-92TA engine operating on D2 diesel. Table 8 shows the emissions over a span of 2 years as the bus

Table 6. Emissions results for comparison of exhaust aftertreatment.

Constituent	Without Catalytic Converter (g/km)	With Catalytic Converter (g/km)	Difference (%)[a]
NO_x	14.4	13.1	–9.1
CO	1.88	1.72	–8.3
HC	1.08	0.88	–18
PM	0.39	0.29	–24
Fuel economy	3.31	3.31	–0.2

[a]Without converter used for baseline.

Table 7. Vehicle specifications and emissions for vehicle age comparison.

Vehicle	1	2	
Type	Transit bus	Transit bus	
Model Year	1988	1993	
Transmission	3-speed auto.	4-speed auto.	
Test Weight	15,297 kg	15,048 kg	
Test Cycle	CBD	CBD	
Test Date	June 4, 1994	March 16, 1994	
Odometer	287,747 km	171,794 km	
			Difference[a]
NO_x (g/km)	23.7	15.5	–35 %
CO (g/km)	13.8	4.00	–71 %
HC (g/km)	1.99	2.20	+11 %
PM (g/km)	1.92	1.06	–45 %
Fuel Consumption (L/100 km)	75.6	84.0	+11 %

[a]Using 1988 bus as baseline.

Table 8. Emissions from one vehicle as mileage accumulated.

Odometer Reading (km)	NO_x (g/km)	CO (g/km)	HC (g/km)	PM (g/km)	Fuel Consumption (L/100 km)	Test Date
219,741	20.4	8.70	1.06	0.329	60.0	6/7/94
288,946	30.5	4.60	1.43	0.447	62.1	3/20/95
370,785	28.2	4.66	1.31	0.392	63.6	4/17/96

accumulated mileage (from 1994 to 1996). From these data, the only trend observed was that the fuel economy decreased as the mileage increased. The emissions show no definite trend of increasing or decreasing.

The NFRAQS testing compared the collected emissions data by emissions model year and mileage since last engine rebuild. A trend of reduced PM emissions was recorded by Graboski et al.[7] as model year increased; however, no trend of NO_x reduction was apparent from the chassis testing. The conclusions show that there was no change in emissions as the vehicle mileage since last rebuild varied, which supports the low deterioration factors currently in use.

The emissions certifications that an engine must meet are specified by year of manufacture. Although diesel engines produce far less CO and HC than standards allow, PM and NO_x are usually close to the limit. Small deviations from these levels may have occurred due to emissions credit banking, but it is evident that levels of NO_x and PM have been forced to decline through use of improved technologies over the years. For example, higher-pressure injection has emerged as a tool to reduce PM. A recent development of technology toward reducing diesel engine emissions is the use of exhaust gas recirculation (EGR). EGR provides an effective means of NO_x emissions reduction. There are many other methods of reducing emissions that would be considered technology advances, such as combustion chamber design and introduction of variable geometry turbochargers. More stringent emissions standards (such as the year 2007 EPA standards) suggest that emissions of NO_x and PM will be reduced in newer model engines, but existing data bear out only the substantial reduction in PM in actual vehicle use.[7,22,23]

TERRAIN TRAVELED

The effects of the terrain traveled by a vehicle are referred to as grade effects. The chassis testing performed on the WVU Transportable Chassis Laboratory uses power absorbers and inertial flywheels to provide a load to the vehicle based on a road-load equation.[3] For this equation, it is assumed that there are no hills, and the load is calculated for perfectly flat, level terrain. Although testing that includes terrain grade has been used in the evaluation of a hybrid fuel cell bus,[24] this is not typically applied to diesel vehicles. For a comparison of emissions produced from a vehicle traveling varying terrain, the theoretical power requirement can be determined. The power can then be related to the emissions rate for a particular vehicle from experimental brake-specific emissions data. A simple, theoretical road-load relation considering aerodynamic drag, tire rolling resistance, and grade is shown in eq 1 in the previous discussion of vehicle class and weight.

Ramamurthy et al.[25] plotted the relation between axle power and NO_x emissions rates for some typical diesel vehicles. This type of data may be used to project the NO_x emissions from vehicles under different use. Using the required power calculated from the road-load equation, the NO_x emissions rate can be predicted from the regression equation of the data and is shown in Figure 4. This is only the lower on-cycle portion of all the data from one test and is fairly consistent. However, all of the operating points of the test sequence do not produce emissions that fall along this line. When all of the points are considered, there is a bifurcation present in the data associated with off-cycle operation. The full data set can be seen in Figure 5 and is discussed in the next section dealing with injection timing variances, the cause of this bifurcation.

Effect of terrain has been estimated using a simple model. For this analysis, the incline grade was limited to 7% (~4° above horizontal). The required power for a model vehicle was determined from the road-load equation for constant grades. The model vehicle was a class 8 tractor-trailer, and steady-state cruising was used for the modeling. To climb a 7% grade, the model vehicle would use 205 kW to maintain a steady-state speed of 48 km/hr. Almost the same power (207 kW) is required for this vehicle to maintain a speed of 77 km/hr when climbing a 3.5%

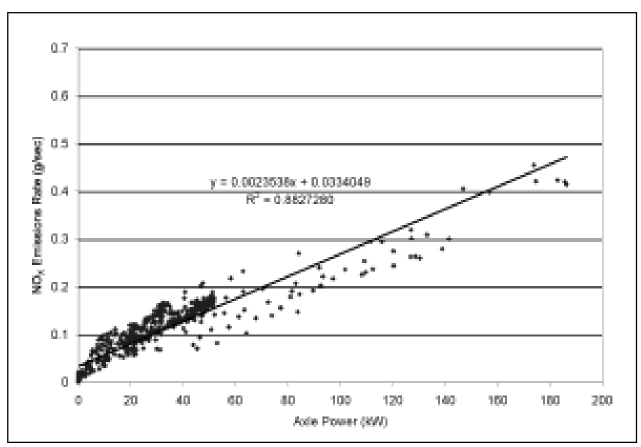

Figure 4. Smoothed axle power vs. shifted NO_x as used for terrain modeling.

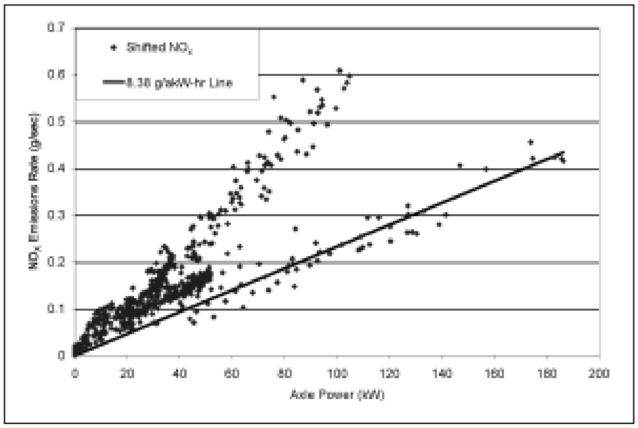

Figure 5. Smoothed axle power versus shifted NO_x showing bifurcation of data. The reader is encouraged to compare the slope of the 8.38 g/akW-hr (6.25 g/ahp-hr) line with the best-fit line of the low NO_x mode in Figure 4.

grade. The value of the required power is the same for each case and, when applied to the linear regression of the NO_x emissions, the emissions rate is the same. This shows that for ascending a grade, because NO_x emissions are often linear with power, a simple prediction can be made. An oscillating terrain simulation (ascending and descending grades) would be informative if such factors as vehicle braking and driver shifting patterns were known. Also, knowledge about the emissions produced from the vehicle when the engine is operating in a power absorbing or motoring mode is unavailable. Similar modeling for CO, PM, and HC would be useful, but nonlinearities make the results less certain.

A simpler method is to assume that a vehicle emits levels that correspond to the emissions standards. Using the axle power values from the model above, PM levels would vary from 11 to 35 g/hr considering a constant travel speed on level ground and on a 3.5% grade. This assumes an overall transmission efficiency of 80% and shows a difference by a factor of 3 for PM. This same procedure can be used for the other regulated emissions, and the accuracy of each depends on the ability of the vehicle to produce emissions that correspond to the certification levels.

INJECTION TIMING VARIANCES

Emissions of NO_x and PM are known to be affected strongly by the timing of the in-cylinder fuel injection in diesel engines. Indeed, it is common to present a hyperbolic NO_x-PM tradeoff curve for an engine, with more advanced timing at the same speed and load leading to higher NO_x and lower PM. Within a reasonable operating range, there is also a tradeoff between NO_x and efficiency, with advanced timing leading to a higher NO_x and higher thermal efficiency.

Many present-day electronically controlled engines do not embody timing throughout their operating range that reflects the timing employed during the engine certification test. Although this practice has been curtailed for the years 1999 and onward, a large portion of the fleet now has engines with off-cycle timing strategies. Deviations in timing during off-cycle operation may lead to emissions of NO_x that are higher than those that would occur during the certification test at the same engine speed and load. In some cases, available data support a binary timing map, with a high and a low NO_x emissions rate. Because history effects may determine which of the two timing choices is in effect, it is not always possible to predict unambiguously the NO_x emissions rate given the engine torque and speed.

Figure 5 presents a plot of chassis-based NO_x emissions versus power output at the rear axle for a late-model diesel truck. The lower NO_x data set, when plotted versus axle power, corresponds well to the line of 8.38 g NO_x/akW-hr. A certification rate of 6.71 g/bkW-hr, coupled with an assumed overall drivetrain efficiency of 80%, yields an 8.38 g/akW-hr value. The higher NO_x data set represents the off-cycle operating points.

All present-day truck emissions values used for inventory prediction rely on the certification data, but Figure 5 shows that certification data will underestimate NO_x emissions in off-cycle operation. For example, in Figure 5, the whole cycle required 7.41 akW-hr of energy from the truck and yielded 110.9 g NO_x. This corresponds to an actual emissions rate of 15.0 g/akW-hr for this cycle, in comparison to the 8.38 g/akW-hr value (approximately) that might be expected. The real NO_x value in this case was 1.8 times higher than the expected value.

Between the range of 60 and 97 kW, there are two noticeably different sets of data points, namely high NO_x and low NO_x modes. A least-squares line was fit to each set of data in this range and evaluated at the mid-point (78 kW). The results show that in high NO_x mode, 0.44 g/sec of emissions were produced, and in low NO_x mode, 0.18 g/sec were produced. These two modes differ by a factor of 2.4 at the 78-kW point of operation, where the low NO_x mode corresponds well with certification data. Bifurcations in timing cause accurate emission predictions to be unreasonably difficult. The authors have observed that the choice of injection timing may be triggered by modest variations in driving style over the same chassis cycle, so that significantly different NO_x emissions may arise for fairly similar truck behavior.

Timing variations influence the overall emissions inventory in two ways. First, the timing variations cause the actual NO_x inventory to be higher than predicted based on certification data, and second, the timing variations cause the actual PM inventory to be lower than predicted

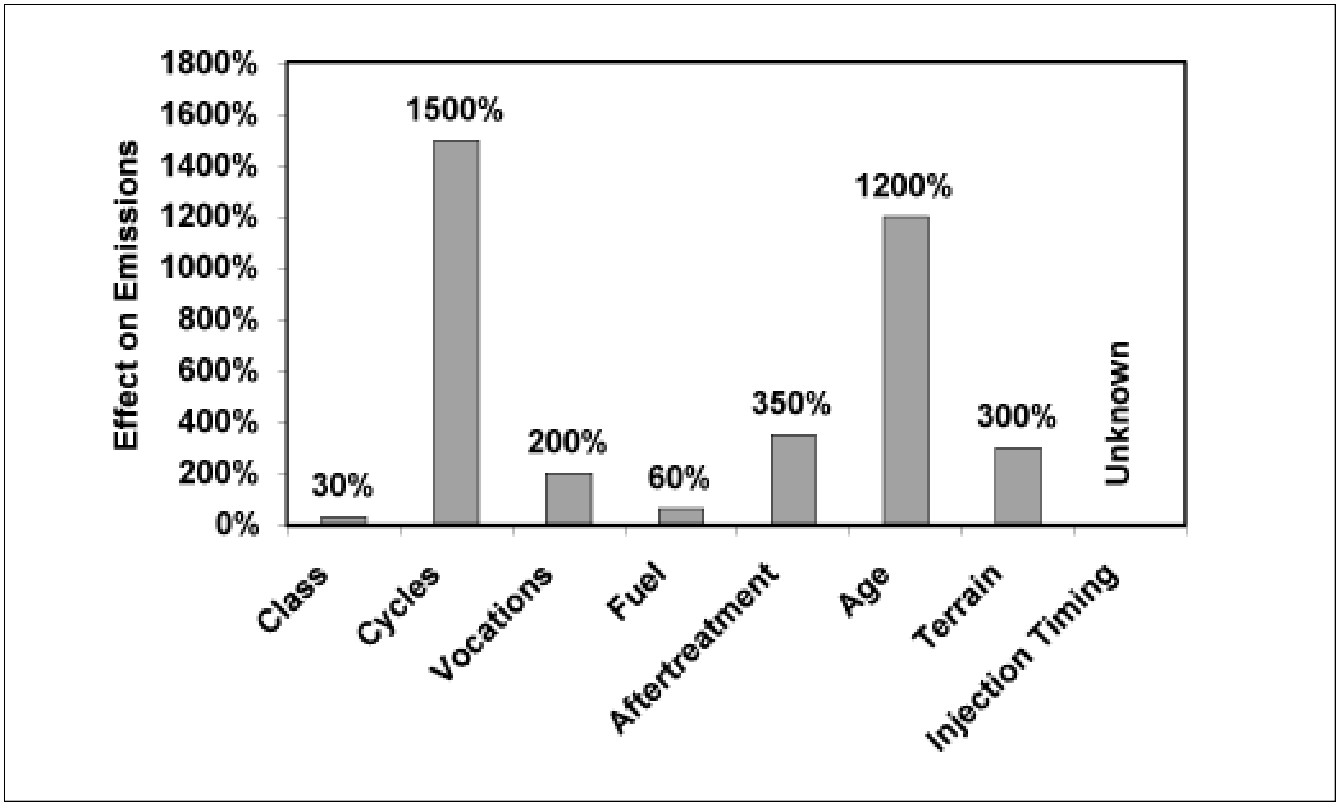

Figure 6. Effect of various factors on PM emissions. Each bar represents a specific comparison discussed in the text and cannot be taken to represent all cases encountered.

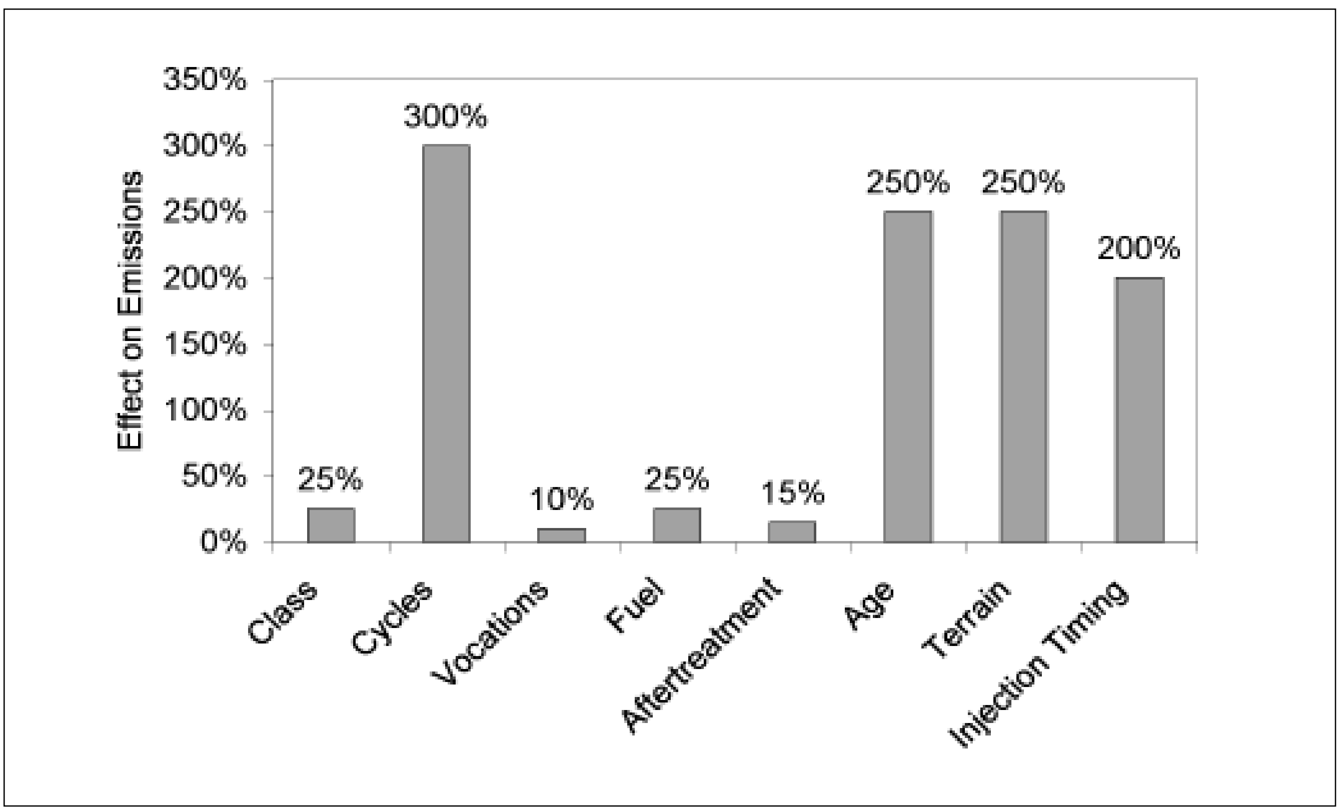

Figure 7. Effect of various factors on NO_x emissions. Each bar represents a specific comparison discussed in the text and cannot be taken to represent all cases encountered.

based on certification data. Timing variations in electronically controlled diesel engines present the single greatest obstacle to present-day mobile source emissions inventory prediction. This factor also can corrupt conclusions while comparing other factors. The advanced technology applied to heavy-duty vehicles would be expected to lower emissions to comply with recent regulations. However, vehicles with advanced electronic controls may emit in practice at higher levels than certification data would suggest.

CONCLUSIONS

For each of the factors in the previous sections, a relative comparison was made to estimate the effect of that particular factor on the emissions produced. The analysis was completed using comparisons of measured data and analytical modeling. Figures 6 and 7 graphically represent the results of these comparisons, and each bar depicts the amount a factor could change the emissions of PM and NO_x. These two emissions species are of the most interest in compression ignition engines because the production of HC and CO from diesel engines are typically well below the standards. The largest effect on emissions was exemplified by the driving cycle that is used to test the vehicle. The test data comparisons showed that the PM emissions could vary by a factor of 15 and NO_x emissions could vary by a factor of 3 when measured using different chassis dynamometer test schedules. This reinforces the fact that the test schedule must be correctly matched to the vehicle and accurately mimic real-world use. The injection timing variances, which lead to off-cycle operation, also affect the measured emissions. The data comparisons show that injection timing variances can increase NO_x emissions by a factor of 2 depending on operating conditions. The extent to which off-cycle emissions affect the measured emissions is difficult to predict, because the frequency and duration of off-cycle operation are obscure.

REFERENCES

1. Protection of the Environment. *Code of Federal Regulations,* Part 86, Subpart N, Title 40, 1996.
2. Ramamurthy, R.; Clark, N.N. *Environ. Sci. Technol.* **1999**, *33,* 55-62.
3. Lyons, D.W.; Bata, R.M.; Wang, W.G.; Clark, N.N.; Palmer, G.M.; Howell, A.D.; Loth, J.L.; Long, T.R. *Design and Construction of a Transportable Heavy-Duty Vehicle Emission Testing Laboratory;* SAE Special Publication P-256; Society of Automotive Engineers: Warrendale, PA, 1991.
4. *Fuel Economy Measurement Test (Engineering Type) for Trucks and Buses, SAE Handbook, Vol. 4;* SAE J1376; Society of Automotive Engineers: Warrendale, PA, 1993.
5. Clark, N.N.; McKain, D.L.; Messer, J.T.; Lyons, D.W. *Chassis Test Cycles for Assessing Emissions from Heavy-Duty Trucks;* SAE 941946; Society of Automotive Engineers: Warrendale, PA, 1994.
6. Clark, N.N.; Lyons, D.W.; Bata, R.M.; Gautam, M.; Wang, W.G.; Norton, P.; Chandler, K. *Natural Gas and Diesel Transit Bus Emissions: Review and Recent Data;* SAE 973203; Society of Automotive Engineers: Warrendale, PA, 1997.
7. Graboski, M.S.; McCormick, R.L.; Yanowitz, J.; Ryan, L. *Heavy-Duty Diesel Vehicle Testing for the Northern Front Range Air Quality Study;* Colorado School of Mines: Fort Collins, CO, 1998.
8. EPA Urban Dynamometer Driving Schedule for Heavy-Duty Engines. *Code of Federal Regulations,* Part 86, Subpart M, Title 40, 1996.
9. Coburn, T. *Statistical Analysis of Particulate Matter Emissions from Light-Duty and Heavy-Duty Diesel Vehicles;* NREL/TP-540-224942; National Renewable Energy Laboratory: Golden, CO, 1998.
10. Nine, R.D.; Clark, N.N.; Norton, P. *Effect of Emissions on Multiple Driving Test Schedules Performed on Two Heavy Duty-Vehicles;* SAE 2000-01-2818; Society of Automotive Engineers: Warrendale, PA, 2000.
11. Clark, N.N.; Daley, J.J.; Nine, R.D.; Atkinson, C.M. *Application of the New City-Suburban Heavy Vehicle Route (CSHVR) to Truck Emissions Characterization;* SAE 1999-01-1467; Society of Automotive Engineers: Warrendale, PA, 1999.
12. *Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects;* Health Effects Institute: Cambridge, MA, 1995.
13. Lange, W.W.; Cooke, J.A.; Gadd, P.; Zürner, H.J.; Schlögl, H.; Richter, K. *Influence of Fuel Properties on Exhaust Emissions form Advanced Heavy Duty Engines Considering the Effect of Natural and Additive Enhanced Cetane Number;* SAE 972894; Society of Automotive Engineers: Warrendale, PA, 1997.
14. Green, G.J.; Henly, T.J.; Starr, M.E.; Assanis, D.N.; Syrimis, M.; Kanafani, F. *Fuel Economy and Power Benefits of Cetane-Improved Fuels in Heavy-Duty Diesel Engines;* SAE 972900; Society of Automotive Engineers: Warrendale, PA, 1997.
15. Brown, S.J. An Experimental Investigation of Affordable Alternative Fuel and Exhaust Aftertreatment Options for Urban Buses. In *Trucks and Buses, the Results of Real-World Emissions Testing, Millbrook Proving Ground Seminar Proceedings;* Millbrook Proving Ground Ltd.: Millbrook, Bedford, United Kingdom, 1997.
16. Graboski, M.S.; Ross, J.D.; McCormick, R.L. *Transient Emissions from No. 2 Diesel and Biodiesel Blends in a DDC Series 60 Engine;* SAE 961166; Society of Automotive Engineers: Warrendale, PA, 1996.
17. Clark, N.N.; Atkinson, C.M.; Thompson, G.J.; Nine, R.D. *Transient Emissions Comparisons of Alternative Compression Ignition Fuels;* SAE 1999-01-1117; Society of Automotive Engineers: Warrendale, PA, 1999.
18. Schaberg, P.W.; Myburgh, I.S.; Botha, J.J.; Roets, P.N.; Viljoen, C.L.; Dancuart, L.P.; Starr, M.E. *Diesel Exhaust Emissions Using Sasol Slurry Phase Distillate Process Fuels;* SAE 972898; Society of Automotive Engineers: Warrendale, PA, 1997.
19. Galey, M.H. Catalyst and CRT Technologies for Control of Heavy Vehicle Exhaust Emissions. In *Trucks and Buses, the Results of Real-World Emissions Testing, Millbrook Proving Ground Seminar Proceedings;* Millbrook Proving Ground Ltd.: Millbrook, Bedford, United Kingdom, 1997.
20. Bach, E.; Zikoridse, G.; Sandig, R.; Lemaire, J.; Mustel, W.; Naschke, W.; Bestenreiner, G.; Brück, R. *Combination of Different Regeneration Methods for Diesel Particulate Traps;* SAE 980541; Society of Automotive Engineers: Warrendale, PA, 1998.
21. Hawker, P.; Hüthwohl, G.; Henn, J.; Koch, W.; Lüders, H.; Lüers, B.; Stommel, P. *Effect of a Continuously Regenerating Diesel Particulate Filter on Non-Regulated Emissions and Particulate Size Distribution;* SAE 980189; Society of Automotive Engineers: Warrendale, PA, 1998.
22. Clark, N.N.; Prucz, J.C.; Gautam, M.; Lyons, D.W. *The West Virginia University Heavy-Duty Vehicle Emissions Database as a Resource for Inventory and Comparative Studies;* SAE 2000-01-2854; Society of Automotive Engineers: Warrendale, PA, 2000.
23. Yanowitz, J.; McCormick, R.L.; Graboski, M.S. In Use Emissions from Heavy-Duty Diesel Vehicles; *Environ. Sci. Technol.* **2000**, *34* (5), 729-740.
24. Wimmer, R.R.; Clark, N.N.; McKain, D.L.; Fletcher, J. *Emissions Testing of a Hybrid Fuel Cell Bus;* SAE 980680; Society of Automotive Engineers: Warrendale, PA, 1998.
25. Ramamurthy, R.; Clark, N.N.; Atkinson, C.M.; Lyons, D.W. *Models for Predicting Transient Heavy-Duty Vehicle Emissions;* SAE 982652; Society of Automotive Engineers: Warrendale, PA, 1998.

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