

Summary of In-use NOx Emissions from Heavy-Duty Diesel Engines

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ABSTRACT

As part of the 1998 Consent Decrees concerning alternative ignition strategies between the six settling heavy-duty diesel engine manufacturers and the United States government, the engine manufacturers agreed to perform in-use emissions measurements of their engines. As part of the Consent Decrees, pre- (Phase III, pre-2000 engines) and post- (Phase IV, 2001 to 2003 engines) Consent Decree engines used in over-the-road vehicles were tested to examine the emissions of oxides of nitrogen (NOx) and carbon dioxide (CO₂). A summary of the emissions of NOx and CO₂ and fuel consumption from the Phase III and Phase IV engines are presented for 30 second "Not-to-Exceed" (NTE) window brake-specific values. There were approximately 700 Phase III tests and 850 Phase IV tests evaluated in this study, incorporating over 170 different heavy duty diesel engines spanning 1994 to 2003 model years. Test vehicles were operated over city, suburban, and highway routes. The results show that the post Consent Decree engines' 30 second NTE brake-specific NOx values were below the NOx NTE allowance limit.

INTRODUCTION

Diesel engines are widely used power plants due to their durability, high thermal efficiency, and superior fuel efficiency compared to other types of internal combustion engines. With no reliable cost-effective alternative method of power production with the same advantages, diesel engines will continue to be used in the near future for commercial and industrial applications. Pollutants are a major issue from diesel engines, with NOx and airborne PM receiving particular interest. These pollutants and others in diesel exhaust have been identified with adverse health effects [1, 2]. To reduce air pollution, the Environmental Protection Agency (EPA) and other regulatory agencies worldwide have tightened diesel engine emissions standards over the last two decades [3].

In-use emission testing is looked upon as a viable means to collect real-world data for compliance monitoring and inventory modeling to the atmosphere from on- and off-road sources. In-use emissions testing in the United States was motivated by the Consent

Decrees between the six settling heavy duty diesel engine manufacturers and the US Government in 1998 due to alternative injection control strategies being employed when the engine was used in certain real-world cycles as opposed to when the engine was exercised over the certification cycle. Though the intention of the more advanced timing control strategy was to reduce fuel consumption and increase engine longevity, it resulted in increased oxides of nitrogen (NOx) emissions [4]. An outcome of the Consent Decrees was that heavy duty engine manufacturers were required to evaluate the emissions from their engines as they are operated over the road starting in 2006 [4]. Measuring in-use emissions from heavy duty vehicles, and hence heavy duty engines, poses many challenges due to the inherent environment in which the equipment must be installed and operated. Issues with measuring in-use emissions have been, and will continue to be, addressed between the Engine Manufacturers Association, the US EPA, and other participants [5].

For a given engine (hardware) configuration, the emissions released into the environment at a given speed and load will be dependant primarily on the fuel composition, ambient environment, injection control strategy, air system design and control, valve actuation, and aftertreatment devices. The ambient environment, injection control strategy, and aftertreatment device(s) can be dynamically linked in a control space with input from engine sensors that are used to determine start of injection, injection duration, injection pressures, and possibly injection rate shape. Generally, ambient air temperature, barometric pressure, manifold air temperature, manifold air pressure, oil temperature, coolant temperature, fuel temperature, fuel rail pressure, exhaust gas recirculation (EGR), exhaust temperature, exhaust backpressure, and engine speed are parameters that may be used in the injection control algorithm of a modern (2007 and newer) on-road heavy-duty diesel engines in the United States.

To fulfill the initial requirements of the Consent Decrees, the engine manufacturers contracted West Virginia University (WVU) to evaluate technology (circa 1999) for in-use emissions testing of on-road heavy-duty diesel



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powered vehicles (Phase I), develop routes to evaluate the emissions from these engines (Phase II), evaluate the emissions from pre-Consent Decree engines (Phase III, pre-2000 engines), and evaluate the emissions from post Consent Decree engines (Phase IV, 2001 to 2003 engines). The United States Environmental Protection Agency (US EPA) oversaw the test program. The prevailing NO_x emissions standards in place during the Phase III and Phase IV programs are shown in Table 1 for medium heavy-duty diesel engines (MHHDE) and for heavy heavy-duty diesel engines (HHDDE). The NTE values presented in this table will be compared to the data collected in this program. Although the values listed in this table are the ones specified by EPA regulations, it is possible for an engine to be certified at a higher or lower value based on banking and credit programs or if the manufacturer selected to pay non-conformity penalties. Additionally, engines are certified in an engine dynamometer laboratory using "certification" fuel specified in 40 CFR 86, Subpart N [3]. Note that the NTE and supplemental emissions test (SET) standards were only in effect starting in 1998 and that standards were changed during the 1998, 1999, and 2002 model years. It is noted that the HDDE FTP NO_x emissions limits have been reduced by 50% between the 1994 and 2003 model year engines evaluated in this test program and the SET and NTE limits have been reduced by over 50% between the 1998 and 2003 model year engines. Although not illustrated here, these limits continue to be reduced for the present and near term (2010) HDDEs. Additionally, the NTE limits presented in Table 1 do not include what is called the "in-use testing measurement allowance," of 0.5 g/hp-hr for NO_x that was in place during this program.

Table 1 NO_x emissions standards (g/bhp-hr).

Year	bsNO _x (g/hp-hr)					
	FTP		SET		NTE	
	HHDDE	MHDDE	HHDDE	MHDDE	HHDDE	MHDDE
1994	5	5	na	na	na	na
1995	5	5	na	na	na	na
1996	5	5	na	na	na	na
1997	5	5	na	na	na	na
1998 ¹	4	4	na	na/6	na	na/7
1999 ²	4	4	6	6/4	7	7/5
2000	4	4	6	4	7	5
2001	4	4	6	4	7	5
2002 ³	4/2.5	4/2.5	6/2.5	4/2.5	7/3.13	5/3.13
2003	2.5	2.5	2.5	2.5	3.13	3.13

1: emissions change starting in 10/01/1998

2: emissions change starting in 07/31/1999

3: emissions change starting in 10/01/2002

note: 2003 and later years: bsNO_x+NMHC (not bsNO_x alone)

note: consent decree in effect from 10/01/98 - 10/01/2002

This work was conducted between 1999 and 2006. Testing occurred in weather that ranged from hot summer days with clear skies and temperatures in the 90's °F to snowy nights with temperatures below 20 °F. It is noted that the present manufacturer in-use test program has ambient temperature, and other parameters, limits or windows but these limits were not in effect for this program. A summary of the findings from the Phase III and Phase IV programs is presented. The results are presented based on engine model year and vehicle class without identification of the engine manufacturer.

VEHICLE, ENGINE, AND FUEL SELECTION

The Consent Decrees specified that the manufacturers had to select engine families to be tested that were based on sales volume. For a given engine family, multiple engines, normally four, were tested over the routes selected during Phase II. The engines could be in any type of vehicle and included Class 4 (utility truck) to Class 8 (over-the-road tractor-trailer) vehicles. There was a wide range of engine displacements and hence power ratings with the rated power ranging from 150 to 600 hp. Vehicles included utility trucks, cargo vans, school buses, transit buses, cement mixers, tri-axle dump trucks, and fifth-wheel truck-trailers. Vehicles were to be tested at 95% of their gross vehicle weight rating (GVWR). Vehicles with an 80,000 lb GVWR were also tested at a second weight of 60,000 lb. The vehicle GVWR was divided into five different classifications based on Federal specifications and is shown in Table 2. Additionally, Class 8 vehicles were divided into two subclasses, "a" and "b," to be able to identify those vehicles that are typically single axle tractor-trailers (8a) and dump trucks and those vehicles that are typically tandem (and tri-) axle tractor-trailers (8b). It is noted that this sub-classification is not an industry standard and was done to partition the Class 8 vehicles to discern differences within this class for data analysis.

Table 2 Vehicle class range.

Class	GVWR (lb)
4	14,000 to 16,000
5	16,000 to 19,500
6	19,500 to 26,000
7	26,000 to 33,000
8a	33,000 to 66,000
8b	66,000 to 80,000

The distribution of engine rated power is shown in Figure 1 and the vehicle class distribution is shown in Figure 2. Table 5 in the Appendix gives a summary of the vehicles included in this analysis. As shown in Figure 1, there is a bimodal distribution of the engine power with the greatest number of engines tested in the 500 to 550 hp range followed by the 200-250 hp range. The upper distribution corresponds to the number of Class 8 vehicles tested. The rated power for Class 8 vehicles ranged from 260 to 600 hp while for Class 4 to Class 7 vehicles' rated engine power ranged from 150 to 270 hp.

It is noted that the majority of engines in Class 8 vehicles have a displacement greater than 10 liters.

Vehicles were selected with an emphasis of procuring the vehicles from as many different sources and locations so as to not bias the results. The only selection criteria for a vehicle were the engine family required to be tested and that the vehicle and engine were in normal and safe operating conditions. Once an engine family was identified, calls were placed to local rental agencies to identify possible vehicles with the selected engine model. For some engines, trucking companies were contacted to use their vehicles as part of the test program. For the engines typically found in buses, school districts and transit agencies were contacted for use of these vehicles. If an engine family could not be identified through these means, the engine manufacturer was consulted to identify additional fleets to contact. Generally, WVU was able to independently identify vehicles to be tested without input from the engine manufacturer. The owner of the vehicle was compensated monetarily based on the normal rate that they receive for their service. There were a few vehicles that were supplied to the test program at no or reduced cost and were generally the buses provided by school districts and transit agencies.

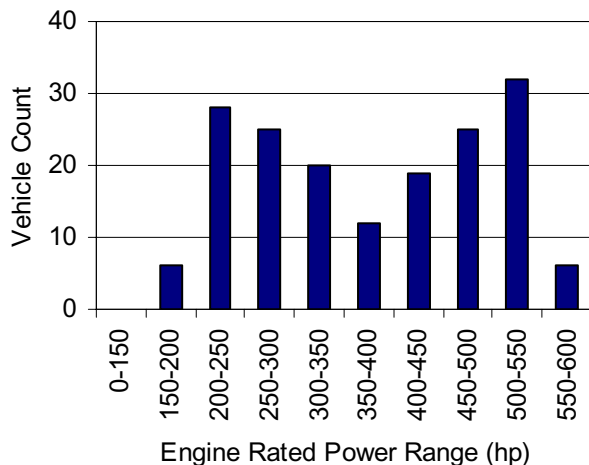


Figure 1 Distribution of the engines' rated power.

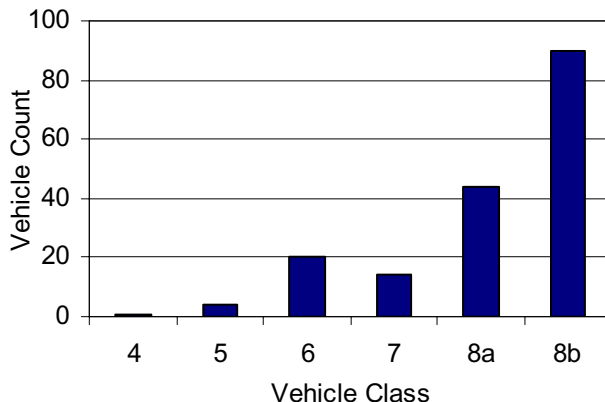


Figure 2 Distribution of the vehicle class.

Most of the vehicles required the driver to hold a valid commercial driver's license (CDL). The majority of the driving was performed by the WVU engineers,

technicians, and students assigned to this program. However, a few of the companies supplied their own drivers as condition to renting the vehicle. There were no requirements to the selection of the driver as long as the driver held the appropriate valid license and had sufficient experience driving similar vehicles. As a result, driver changes were often experienced while testing a given vehicle. However, cursory data examination indicated minimal impact on a test vehicle's averaged emissions data.

Vehicles and engines were inspected prior to instrumentation installation and testing. The required pre-use checks that are performed for commercial drivers were followed. For instance, vehicles with air brakes were checked and adjusted where required. The exhaust system was visually inspected and minor repairs were made if necessary, since exhaust system integrity is important for mass flow determination. Vehicle and engine conditions were recorded on paper forms and documented through digital photographs. Only those vehicles that were in "normal" operating condition and with no obvious engine or drivetrain problems were used in this test program. Additionally, the engine control unit (ECU) was interrogated to identify any active error codes. If any error codes were identified, such as if the check engine light (malfunction indicator lamp, MIL) was illuminated, the US EPA contact in charge of the test program would make the determination on the course of action to remedy the error. It is noted that there were no vehicles rejected in this program because of maintenance issues or any other problems. However, there were a few occurrences where a vehicle was procured and delivered to the test site but the engine was from an incorrect engine family. These occurrences were deemed a miscommunication between the owner and WVU. As such, the data presented herein is believed to be a random sample of the in-use HDDEs available at the time of testing with no biases in the selection of the engine or vehicle other than engine families, and the number engines for each family, as specified by the US EPA.

The method to load the vehicles or adjust the weight distribution needed to be as efficient as possible since the vehicle cost was based on a daily rate. Vehicles were loaded to the required test weight by a variety of methods. It is noted that there can be inconsistencies in the definition of the GVWR found in the literature. The vehicle manufacturer stamps the maximum load that can be placed on each axle, and the vehicle also carries a data plate with maximum weight information. In the case of tractor-trailers, the data plate shows permissible load for the tractor alone, and it is the gross combined weight that is of interest. However, federal or state highway departments specify the maximum load that a given vehicle axle configuration can be placed on the road. Specifically, bridges are typically the limiting road structure and govern the maximum load; this is referred to as "bridge law." Therefore, WVU defined the GVWR as the maximum bridge law load or governing law. For

fifth wheel tractor-trailers, WVU-owned tandem or tri-axle trailers were loaded with concrete blocks of various sizes, which were arranged on the bed of the trailer and secured. For other vehicles, the same concrete blocks were used where they could be loaded onto or into the vehicle. For vehicles that could not be loaded with these blocks, such as buses, bags of various materials were used to load those vehicles. Initially, bags of shelled corn were used but was abandoned in favor of bags of pellets used for wood burning stoves. Bags of sand, or other fine grain material, were not used since these materials are difficult to clean if the bag is ripped or torn.

All engines were fueled with on-road diesel fuel that was in the tank when WVU received the vehicle. Generally, number 2 (D2) diesel was used but there was a select number of vehicles with engines that required number 1 diesel to be used. There were no provisions to account for the properties of the fuel used or to account for the emissions generate from the fuel in the tank. However, fuel samples were collected and retained. Through the course of testing of a vehicle, the tank(s) would be filled from local (Morgantown, WV and Pittsburgh, PA) filling stations. The selection of the filling station was based on the driver's preference or convenience at the time the vehicle needed to be refueled. It has been documented that there can be differences in the emissions produced based on in-use fuel properties [6, 7].

TEST EQUIPMENT

Many reports and papers have been written regarding the details of the test equipment and routes used in the collection of the data and the details are not repeated here [8-13]. However, a short narrative is given to provide the reader with background.

The data acquisition system developed by WVU was a computer platform constructed of National Instruments components and consisting of a data acquisition card, signal conditioning unit, temperature and voltage cards. The data acquisition system had multiple serial port inputs for allowance of many different measurements to be taken all at once. Vehicle and engine parameters such as engine speed, engine power, and vehicle speed were broadcast by the vehicle's ECU within accordance of the SAE J1708/1587 and J1939 protocols at up to a 10 Hz data rate with a Dearborn protocol adaptor [11-16]. Vehicle position and speed were recorded from a global positioning satellite (GPS) receiver at a 1 Hz rate. Emissions values were recorded from serial and analog signals from the emissions equipment at a 5 Hz data rate. A Visual Basic program was written at WVU to collect all of the signals and combine them into one file. A separate Visual Basic program was written to post-process the collected data and reduce the data into engineering units and integrated values. Although the Consent Decrees only required 1 Hz data rates, the final data was reported at a 5 Hz data rate based on WVU's engine and chassis laboratory experience of the engine transients expected during in-use testing. This required

those signals reported at slower rates, such as GPS, to be up-sampled using linear interpolation. Engine speed and load and emissions were collected at least at a 5 Hz rate.

The emissions of NO_x and CO₂ were measured and reported with a Horiba MEXA 120 zirconium oxide and Horiba BE140 non-dispersive infrared detectors, respectively. An electrochemical NO sensor was operated in parallel with the MEXA 120 to provide a redundant NO_x value as a quality assurance check; however, this data was not reported as the NO_x value, only the MEXA 120 value was used to report the NO_x emissions. Note that a Horiba MEXA 720, an upgrade of the MEXA 120, was used for a portion of the Phase IV data collection since the MEXA 120 was not available to be procured during the later periods of testing. The MEXA 120 and 720 are fundamentally the same unit with the MEXA 720 capable of reporting oxygen concentration and air-to-fuel ratio. These additional capabilities of the MEXA 720 were not utilized in the reporting of this data; only the NO_x signal was utilized in this test program. A significant effort was spent in the Phase I program on the selection of these instruments and the sampling system [8]. Every effort was spent to provide the highest possible accuracy and precision while being portable and robust. The emission analyzers and sampling system was designed to correlate back to 40 CFR 86, Subpart N as close as possible since this regulation was used to certify these engines [3]. Figure 3 shows a photograph of the emissions sampling box and data acquisition box that were placed on or in the test vehicles.



Figure 3 WVU MEMS data collection (left) and emissions sampling box (right).

Measurement of engine torque, and hence power, is problematic from in-use vehicles. Due to time and cost constraints, it was impractical to measure the engine shaft torque directly; it would take too long to modify the engine-transmission to insert a measurement device. Additionally, the measurement of torque between the transmission outlet and rear differential shaft does not provide an accurate value of the engine torque since transmission efficiencies are not readily available and since trucks and buses can have substantial auxiliary

loads that are counted among the brake loads. As part of the Phase I assessment, it was determined that the only practical means to obtain a torque value was from the available signals in the ECU [17]. This required that only electronically-controlled vehicles could be tested and that the percent load value was used to infer the torque. For Phase III, this excluded some vehicles with mechanically-controlled engines. However, post Consent Decree engines were required to broadcast a torque value directly. All ECU signals were recorded with a Dearborn heavy-duty protocol adaptor [16].

Finally, direct measurement of exhaust flow rate was determined as the best approach to determine the emissions mass rate. The Annubar™ flow meter was installed into a section of exhaust pipe with absolute and differential pressure transducers and thermocouples housed in an enclosure close to the Annubar™ meter. To account for the wide range of flow rates encountered in the testing, three different exhaust pipe sizes (4", 5", and 6") were selected with the appropriate Annubar™ meters for each pipe size range. The Annubar™ size was selected so that the differential pressure differential would range from approximately one inch of water at idle to approximately 20 inches of water at rated power, or maximum flow conditions; this provided sufficient dynamic range of available transducers while minimizing the backpressure effects of inserting the Annubar™ sensor in the exhaust stream on the engine performance. It is noted that the 20 inches of water differential pressure was across the Annubar™ meter and not additional engine backpressure; engine backpressure would have been a few additional inches of water pressure due to the additional exhaust pipe length and Annubar™ meter. The differential pressure transducer had changeable diaphragms to further maximize the full-scale range of the transducer for the exhaust flow rate. The use of these three pipe sizes and selectable differential pressure transducer diaphragms permitted the installation of one of these flow meters for the engine under test with available off-the-shelf exhaust fittings and clamps while providing a sufficiently accurate differential pressure transducer range for the flow rate experienced during a test.

NTE ZONE REQUIREMENT

The Consent Decrees required that the brake-specific mass values of the regulated emissions be measured within a "not-to-exceed" (NTE) region under the maximum speed-load (lug) curve. It is noted that heavy-duty engines are certified in an engine dynamometer test cell prescribed by the federal test procedure (FTP) certification program where the emissions and work are integrated over the entire 20 minute test [3]. THE FTP includes operation within the NTE, but also includes idle and light load operation along with motoring conditions. The NTE regulation required engine speed and torque to be independently measured for the NTE zone determination. Figure 4 illustrates the NTE area with the associated boundaries. The NTE zone is defined in the

Consent Decrees and is bounded by engine speeds 15% above the ESC speed,

$$n_{15\%ESC\text{Speed}} = n_{lo} + 0.15(n_{hi} - n_{lo}), \quad (1)$$

engine loads greater than 30% of maximum, and engine power greater than 30% of maximum. The ESC is the European Stationary Cycle, from which the SET was developed, and the ESC speed is defined in these procedures. In Equation 1, n_{lo} is defined as the lowest engine speed at which 50% of the maximum power occurs, while n_{hi} is defined as the highest engine speed where 70% of the maximum power occurs. The Consent Decrees require that exhaust emissions be reported for engines operating within the NTE zone averaged for a period of at least 30 consecutive seconds. If the engine was operated within the NTE region for greater than 30 seconds, then multiple 30 second NTE zones would be defined and the brake-specific mass emissions would have been calculated for each zone per the Consent Decrees requirements. It is noted that there are "dual lug curve maps" employed in some engines that provide higher torque and power when the vehicle is placed in cruise control mode. There were no provisions to account for when the engine selected a higher power map. This effect would have only been experienced for the Phase III engines since the Phase IV engines (with a few exceptions) were direct torque broadcast from the engine manufacturer. Neglecting this higher torque or power setting results in a conservative estimation of the brake-specific emissions since the work (integration of power over time) is in the denominator of the brake-specific calculation. Moreover, a higher torque map will "push" the lower end of the NTE curve up relative to the lower torque map. This will result in NTE events being included in the analysis that should have been discarded.

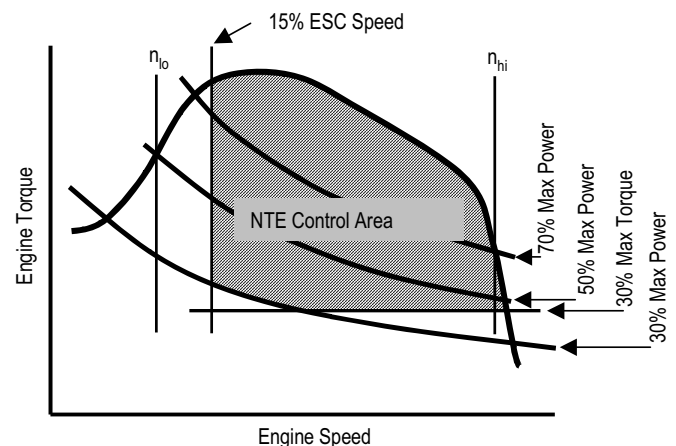


Figure 4 Example NTE area definition.

In addition to the 30-second NTE zone definition, the data were examined on a continuous NTE zone basis (the time between when the engine enters and exits the NTE for longer than 30 seconds) and on an integrated route basis (over the entire test period). The continuous NTE zone was examined by WVU to minimize errors

delay and dispersion affects and the integrated route method was examined by WVU as a surrogate to the FTP. However, the integrated route method may have suffered from accuracy issues when the engine operates outside the NTE zone, particularly for the Phase IV engines, since the manufacturer was not obliged to report an accurate torque value outside the NTE zone. It is noted that although the continuous NTE and integrated route data were calculated by WVU, the engine manufacturers were only obliged to report the 30-second NTE data per Consent Decrees requirements and only these data are presented here.

ROUTES

The routes developed during the Phase II work are summarized below. The routes were selected to provide road conditions that would provide high number of NTE events, ensure that the vehicle could be operated at 65 mph for 15 minutes (Consent Decree requirement), and the test be conducted within two hours for calibrating/zeroing/spanning the equipment (WVU quality assurance procedure).

SALTWELL

The Saltwell route was split into outbound and return journeys. The route originated at the WVU Sabraton facility (greater Morgantown area) close to an entrance ramp accessing I-68 west. The route proceeded to I-79, and followed I-79 south to the turnaround point at the I-79 Saltwell Rd. Exit (near Clarksburg, WV). The total distance was 58.7 miles. The interstate was posted at 70 mph, but there were two curves with advisory signs below that speed. The outbound leg was designated Sab2SW and the return leg was designated SW2Sab.

MORGANTOWN

This route originated at the WVU Sabraton facility and proceeded through suburban and urban settings on two and four lane roads, then joined I-79 south to I-68 east, to return to the starting point. The total distance was 20.4 miles. Posted speeds of 35, 40, and 50 mph existed on the urban and suburban routes, and the interstate sections were posted at 70 mph. This route is designated as Mrgtwn.

BRUCETON MILLS

This route was divided into outbound and return journeys. The route originated at the WVU Sabraton facility close to the Sabraton entrance ramp on I-68 east, and continued on I-68 where a climb of a sustained 5% grade existed, followed by transient road grades to the turnaround point at Bruceton Mills, WV. The total distance was 39.7 miles. The interstate was posted at 70 mph, but the 5% descent on the return journey was posted at 50 mph for trucks and was preceded by a mandatory truck stop for checking brakes. In the high-speed freeway operation, dramatic reductions in vehicle speed were encountered as the vehicle climbed the hills along the route. In the case of this route, truck speed

restrictions and necessary precautions during the steep descent on the return leg of the journey reduced the operating speed on I-68 westbound. The outbound leg was designated Sab2BM, and the return leg was designated BM2Sab.

WASHINGTON/PITTSBURGH ROUTE

This route originated in Washington, PA, which is located near the intersection of I-70 and I-79. The route proceeded from Washington on US Rte. 19 north through suburban areas toward Pittsburgh, followed PA State Rte. 51 (US truck Rte. 19) to I-279 south, to I-79 south, and then returned to the first rest area in West Virginia along this interstate. For the first and second leg, the interstate speed limit was 55 mph, and the suburban road speed limits varied from 25 to 45 mph. The final leg consisted of all highway driving with a transition from 55 mph to 65 mph. The first leg was designated WashPA1 (12.2 miles), the second leg as WashPA2 (23.4 miles), and the third leg as WashPA3 (51.7 miles).

Between the Phase III and Phase IV programs, the WashPA3 cycle was modified to include the route back to the Sabraton area and was termed the WashPA32Sab route. This route terminated at the end of the ramp at Exit 4 on I-68 east. The total distance for this route was 66.4 miles. Additionally, a Sabraton to Washington, PA, route (Sab2Wash), was developed to streamline the testing and consisted of highway operation, began at the Exit 4 I-68 ramp in Morgantown, WV. It continued on I-68 west to I-79 north. The route continued on I-79 north into Pennsylvania, and ended alongside the exit ramp at Exit 19B on I-79 north in Washington, PA. The total distance for this route was 52.7 miles.

ROAD LOAD POWER

The power, and hence work, required to propel the vehicle is dependent on the load applied to the vehicle. These loads include aerodynamic drag, the vehicle's rolling resistance, the climbing force due to variations in road grade, and the inertial or acceleration resistance [18]. Equation 2 below is the required vehicle power; the engine power would be greater than this due to drivetrain efficiency. This equation and the contribution from each term may be helpful in interpreting the results presented below.

$$P = \left(\frac{1}{2} \rho V^2 C_D A + fmg + \sin(\theta)mg + m \frac{dV}{dt} \right) V \quad (2)$$

Because of the characteristics of in-use, on-road emissions testing, the power required to propel a vehicle through a route will vary from one test to another for a vehicle. One should not expect the repeatability of the brake-specific emissions that is found in an engine dynamometer test laboratory, let alone the repeatability of the work, due to the non-conservative load of wind drag being a cubic with vehicle speed varying fan loads.

and varying traffic conditions found in in-use emissions testing. The reader is encouraged to refer to equation 2 when comparing the results from one route to that of another route. As described in the route description, there are significant differences in the elevation change and average vehicle speed, resulting in differences in the measured parameters. For example, for highway operation, a prevailing headwind or a change in speed of 10 miles per hour can alter the total road load power by 20 to 30% through the drag term.

RESULTS

The Phase III and Phase IV data consists of over 1700 individual test runs over 14 different routes. Phase III vehicles were driven over 18,000 miles and Phase IV vehicles traveled over 32,000 miles.

It is noted that not all vehicles were tested over each route and that there were changes between the Phase III and Phase IV programs. Common routes between the two phases included WashPA1, WashPA2, and Mrgtwn while the WashPA3 (Phase III) and WashPA32Sab (Phase IV) are the same route for the first 51.7 miles with an additional 15.7 miles of driving added to the WashPA32Sab route. Four of the routes were used exclusively for one manufacturer for a select number of vehicles and will not be discussed here. Summary statistics are provided for the other 10 routes. Two of these 10 routes, Sab2SW and SW2Sab, were not included in the summary of the emissions data since these two routes showed similar results to other routes. The Sab2BM and BM2Sab were included in the analysis since these two routes have a significant hill climb during each route and provided high power emissions data.

VEHICLE AND ENGINE STATISTICS

The data has been summarized in an attempt to provide the scientific community with the greatest breadth of in-use data to date. Specifically, this data gives a snapshot of modern, electronically-controlled heavy-duty diesel engines manufactured between 1994 and 2003. Much of the data has been presented as an average with one standard deviation of the data given as an "error" bar. Care should be exercised when examining the charts presented below since some of the average data presented are for a limited number of vehicles (<10 tests) and the tables presented in the Appendix should be consulted for the number of tests for a given data point.

A summary of the Phase III and Phase IV average vehicle speed and engine work for each of the routes are given in Figure 9 and Table 5 in the Appendix for the six classes of vehicles. The top chart in this figure illustrates the average vehicle speed. As illustrated in this figure, the WashPA1, WashPA2, and Mrgtwn routes have the lowest average speed since these three routes have a significant amount of the route through city and suburban driving with low posted speed limits. There is not much impact of the vehicle class with average speed

for the WashPA1 route but there is some variation with the WashPA2 and Mrgtwn routes, with the heavier vehicles exhibiting a lower average speed, since these two routes have suburban and highway driving. The Sab2BM and BM2Sab routes have relatively low average vehicle speeds for all classes even though posted speed limits are 70 mph for a large portion of these routes. It is evident from these low average speeds that the hill climbs place a significant load on the vehicle's engine. It is noted that the Class 4 vehicles had a significantly higher average speed but there were only three tests for this weight class. The BM2Sab route had a slightly higher average vehicle speed compared to the Sab2BM due to the difference in elevation change between these two routes. The Sab2SW and SW2Sab were also highway routes with a majority of the posted speed limit at 70 mph. However, these two routes had rolling hills with smaller hill climbs than the Bruceton Mills routes. The two SW routes exhibited similar characteristics to the two BM routes. The remaining three routes, Sab2Wash, WashPA3, and WashPA32Sab all exhibited similar average speeds. The WashPA3 route exhibited higher average speeds for the Class 4 and 6 vehicles but there were a limited number of vehicles in these classes for this route.

The ECU-derived engine work is shown in the second plot in Figure 9 and illustrates the required engine work was dependent on the posted speed limit (wind load), traffic conditions (acceleration), and road inclination along the vehicle's tires friction load. The required work was also dependent on the length of the route as illustrated in the difference between the Sab2Wash and WashPa1 work. Additionally, the difference in the work for a vehicle class for a given route illustrates that the greater the mass of the vehicle the greater the required work.

One of the difficulties in modeling atmospheric loading from on-road engines in the past was the disconnect between engine certification being performed in an engine dynamometer laboratory where the emissions are reported on a brake-specific mass basis but in-use vehicle activity is reported on a mileage basis. The bottom two plots in Figure 9 were created in an attempt to provide a work conversion factor that can be used to take the engine dynamometer-based brake-specific data and convert it to vehicle-based data. For a given test, the integrated work was divided by the integrated distance and then that value was divided by the test weight. This allows the data shown in the figure to be multiplied by the engine certification data and the gross vehicle weight to obtain a distance-specific mass emissions value. This value can then be used to obtain the total mass of emission emitted by the vehicle based on its driving distance. As exhibited in this figure, this ratio is dependent on vehicle class and somewhat dependent on the route. However, the route dependency may be an artifact of the accuracy of the ECU-reported values at low engine loads and short test durations. The average value for the work conversion