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Atmospheric Carbon Dioxide and Nitrogen Oxides Emissions Data for 2003-2005 Model Year Trucks

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Abstract

Heavy-duty trucks account for a substantial portion of the atmospheric carbon dioxide (CO_2) and nitrogen oxides (NO_x) inventory. The data presented in this paper will help the research community be interested in developing models that predict the NO_x and CO_2 levels in real use. Continuous data of emissions were recorded from chassis dynamometer testing of five 2003-2005 model year (MY) heavy-duty trucks. The instantaneous emissions rate was plotted against axle power in all cases. The effect of vehicle test weight and the drive cycle employed on the relation between emissions rate (grams per sec) and axle power was studied. The NO_x/CO_2 ratio was found to be independent of the test cycle. The average NO_x/CO_2 ratio for the 2003-2005 MY trucks was found to be 0.0051, which agrees reasonably well with the estimated ratio of 0.0048, based on certification standards. The data were compared to those from 1994-2002 MY trucks; the average NO_x/CO_2 ratio for those trucks was 0.0141. For the 2003-2005 MY trucks, the distance specific NO_x (grams per mile) and the fuel economy (miles per gallon) were less than those of 1994-2002 MY trucks.

Keywords

Emissions Inventory, Chassis Dynamometer, Instantaneous Emissions, NO_x/CO_2 Ratio, Certification

1. Introduction

The purpose of this paper is to provide NO_x and CO_2 emissions data from the 2003-2005 model year (MY) heavy-duty trucks. The 2003-2005 trucks are still widely in service in the United States and do not have either

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diesel particulate filters (which became common after US 2007 regulations) or selective catalytic reduction (which was adopted only since the 2010 regulations). Some may favor using these older trucks in service because they are simpler in controls. The average vehicle miles travelled (VMT) by heavy duty trucks (defined as heavier than 26,000 lb) that are older than 5 years is more than 40% of the total VMT by all the heavy duty trucks according to the recently released Vehicle Inventory and Use Survey (VIUS) data [1]. The 2003-2005 MY trucks are about 7 - 9 years old and these trucks contribute about a sixth of the total VMT by all heavy duty trucks in the US. However, the emissions contribution from these trucks will be disproportionate to their VMT contribution due to the new stringent regulations. For example, these older trucks have NO_x emissions about 10 times that of the new trucks due to new regulations. Hence, they contribute to total NO_x emissions at about 3 times that of the new trucks.

Though heavy-duty diesel vehicles comprise only 2% of the on-road vehicle population by count, they operate for long hours at high loads. A study indicated that almost half of the on-road emissions of NO_x were from heavy-duty diesel vehicles [2]. In 2000, Yanowitz *et al*. [3] argued that over the last two decades, the emissions of particulate matter (PM) from heavy-duty diesel engines had decreased, but NO_x emissions had not. The EPA NO_x emissions standard for 1994 MY heavy-duty diesel engine was 5.0 g/bhp-hr and was 4.0 g/bhp-hr for 1998 MY engines. For 2004 MY engines, the limiting value of NO_x (including non-methane hydrocarbons) for certification was 2.4 g/bhp-hr. Since the NO_x standard in the US dropped substantially in 2004 and Not-To-Exceed (NTE) regulations were espoused, a reduction of NO_x has been observed during chassis dynamometer testing [4]. This decrease came after the United States Environmental Protection Agency (USEPA), the United States Department of Justice, CARB and engine manufacturers (Caterpillar, Cummins, Detroit Diesel, Volvo, Mack Trucks, Renault and Navistar) reached a settlement [5] in October of 1998 to limit NO_x emissions from heavy-duty diesel engines. In December 2000, the EPA introduced new emission standards for MY 2007 and later heavy-duty engines [6].

In 1999, Ramamurthy and Clark [7] discussed the contribution that heavy-duty vehicle emissions make to the atmospheric NO_x levels for 1994-1999 MY trucks. This paper attempts to extend that work by providing emissions data found for typical 2003-2005 MY heavy-duty trucks by analyzing the data in a manner similar to the one followed in reference [7], and to compare some of the interesting data with those of 1994-2002 MY trucks.

2. Available Data

The data used in this paper were obtained from chassis testing on five heavy-duty trucks from the E-55/59 program [8]-[10], which was jointly sponsored by the Coordinating Research Council (CRC), CARB, USEPA, Department of Energy (DOE), Office of Freedom CAR and Vehicle Technologies, National Renewable Energy Laboratory (NREL), South Coast Air Quality Management District and Engine Manufacturers Association. Data were obtained from the chassis dynamometer testing at the West Virginia University Transportable Heavy-Duty Vehicle Emissions Testing Laboratories (TRANS-LAB). A comprehensive explanation of the experimental procedures can be found in prior papers [11]-[13]. A brief description of the experimental set up is as follows. The dynamometer was a platform with flywheels, power absorbers and rollers. The vehicle was mounted on a test bed with the drive wheels on rollers. The rear wheels were allowed to rotate freely on the rollers. The power was absorbed from the vehicle wheel hubs by the power absorbers mounted on either side of the chassis bed, simulating the load on the vehicle. The power absorbers simulated real-world driving conditions by accounting for the aerodynamic and the frictional load. The flywheels were connected to the vehicle hubs and the vehicle load was established using a coast down procedure on the dynamometer. The torque produced by the vehicle was translated to the sensors through shafts and gear boxes. Sum of the readings of the sensors on either side should be equivalent to the axle torque. The vehicle was driven to follow the speed-time trace of the desired drive cycle. The target speed was provided on the computer screen to the driver while the test was running and the vehicle was driven to meet that speed which simulates the drive cycle used. The emissions were measured with exhaust gas analyzers and a data acquisition system. The losses associated with the tire-roller interaction have been discussed elsewhere [14].

3. Vehicles Tested on the Chassis Dynamometer

The data that were used in this analysis were from trucks identified as CRC-34, CRC-38, CRC-39, CRC-40, and CRC-63 in reference [8]. Two of these trucks, CRC-34 and CRC-40, had engines manufactured by Detroit Diesel, and two others, CRC-38 and CRC-39, had engines manufactured by Cummins and the other truck had a Caterpillar engine. The first four engines were equipped with a cooled EGR to reduce the emissions of NO_x [15]-[18]. EGR was proven most effective in reducing NO_x at high loads of engine operation [19]. The vehicles were loaded on the dynamometer at three test weights of 30,000, 56,000, and 66,000 lb. The specifications of the trucks are presented in the **Table 1**. The odometer readings suggest that the engine and the emissions control systems would be in good working order.

4. Drive Cycles Used for the Chassis Dynamometer Data

The drive cycles suitable for trucks and buses for chassis dynamometer testing have been presented previously [20]. The data used in this analysis arose from E-55/59 chassis testing that was performed on the Urban Dynamometer Driving Schedule (UDDS) and the Heavy Heavy-Duty Diesel Truck (HHDDT) drive schedule [8]. The UDDS is a seventeen minute cycle with a peak speed of 60 mph and is representative of the heavy-duty driving in US urban conditions. The development and examination of HHDDT schedule was presented elsewhere [21] [22]. The HHDDT schedule consists of five modes (Idle, Creep, Transient, Cruise and High-speed cruise). The creep mode represents very low speed truck operation with a maximum speed of 8.24 mph. The transient mode of HHDDT is a ten-minute drive that mimics the vehicle stopping and going at an average speed of 20 mph. It involves sharp accelerations and decelerations with a peak speed of less than 50 mph. The cruise mode of HHDDT cycle, which is representative of truck driving on the interstate, is a 2000 second cycle with constant peak speed of approximately 60 mph for about 1400 seconds. The high-speed cruise mode is represented by HHDDT_S. It has an average speed of 50 mph and a maximum speed of 67 mph and it represents expressway truck driving. The speed time traces of all the cycles have been provided elsewhere [20] [21].

5. Time-Alignment of Emissions with Axle Power

The transient emissions data acquired [8] have a time delay associated with them relative to the speed and load history on the engine. The time delay between the power and emissions data is mainly due to the time taken for the exhaust to travel to the analyzers and the response time of the analyzers. To account for the delay in emissions measurement, the data from reference [8] were time-shifted with respect to power, which was considered (as a simplification) to be the single engine variable that influenced emissions production. The power and the measured emissions mass rate were time-aligned using the cross correlation technique, which has been presented earlier elsewhere [23]-[26].

6. Dispersion of Axle Power

Apart from time delay, emissions data can also be dispersed over a period of time when measured by the analyzer, *i.e*. the specific operating condition experienced by the engine may be sudden or momentary, but the measured response can be dispersed in time with the measured amplitude of a peak or a valley of emissions mass rate smaller than the peak actually produced by the engine at the manifold. Hence, the emissions data reported by the analyzers could be substantially different from the instantaneous emissions at the tailpipe. The reconstruction of the instantaneous emission signal from the continuous measured emissions involved numerical computations. The reverse transform process has several constraints and is prone to numerical instabilities [27]

Table 1. Details of the vehicles tested.

Vehicle Identity	Engine	Engine hp & Displacement	Vehicle Model Year	Odometer Reading (miles)	Test Weights (lb)
CRC-34	DDC Series 60	500 hp & 12.7 liters	2004	19,094	30,000, 56,000 and 66,000
CRC-38	Cummins ISX	530 hp & 15 liters	2004	2829	30,000, 56,000 and 66,000
CRC-39	Cummins ISX	530 hp & 15 liters	2004	45	56,000
CRC-40	DDC Series 60	500 hp & 14 liters	2004	8916	56,000
CRC-63	Cat 3406 E	475 hp & 15.1 liters	2005	2731	56,000

[28]. Hence the dispersion of the emission data was simulated by dispersing the axle power according to the dispersion function which was obtained in a manner similar to the one proposed by Ramamurthy and Clark [29] [30]. Separate dispersion functions were used for NO_x and CO_2. An instantaneous pulse of NO_x (or CO_2) was injected into the dilution tunnel and the analyzer generated an impulse response (dispersion function) that corresponded to NO_x (or CO_2) data. A more elaborate description of the test set up and the procedure followed to obtain dispersion functions has been presented by the authors in their other studies [28] [31]. Since the emissions measured by the analyzer are dispersed, when they are compared against power, the power needs to be dispersed to negate the effect of emissions dispersion. Even though "dispersed axle power" does not have any physical significance, it can account for the dispersion associated with the emissions data if the emissions data vary. The effects of dispersion can be obtained by simply time dispersing the axle power as shown in **Figure 1**. It shall be noted from the figure that the correlation between the time-shifted CO_2 and dispersed axle power (R^2 of 0.86) was found to be better than the correlation between the time-shifted CO_2 and un-dispersed axle power (R^2 of 0.79). In both of the above cases, the data were time-aligned first.

7. Emissions Data

Second-by-second continuous data of two consecutive transient mode runs on CRC-40 loaded at 56,000 lb were presented (**Figure 2**). The results affirmed the run to run consistency by showing similar trends of emission mass flow rate against the dispersed axle power. The data scatter arose in this plot because the same power may be delivered to the axle with different combinations of engine torque and speed. More complex engine controls for the 2003-2005 MY trucks blurred the relationship between fuel consumption and axle power over the whole operating envelope relative to the earlier model year trucks discussed in reference [7]. Data might also have scatter because of imperfections in time-alignment and variations in dispersion. As shown in **Figure 2**, the emission rates for three different trucks on the HHDDT_S showed similar trends. In **Figure 2** and **Figure 3**, the few high values of CO_2 corresponded to high acceleration on some of the peaks of the HHDDT_S. The reader is cautioned not to interpret the intercept at zero power as low idle emissions. This is because the intercept is based on range of data and type of fit (quadratic, cubic or exponential). Moreover, CO_2 emissions will be higher at the beginning of any acceleration period (the moment when the vehicle is accelerated) when the power is nearly zero. This is because the instantaneous emissions at the start of acceleration signify a finite value in the CO_2 emissions when the power is still not transmitted to the axle. For these reasons, the carbon dioxide emissions at zero power were over-estimated and hence the intercepts did not fall within the range of idle emissions data [32] obtained from the trucks in the E-55/59 program.

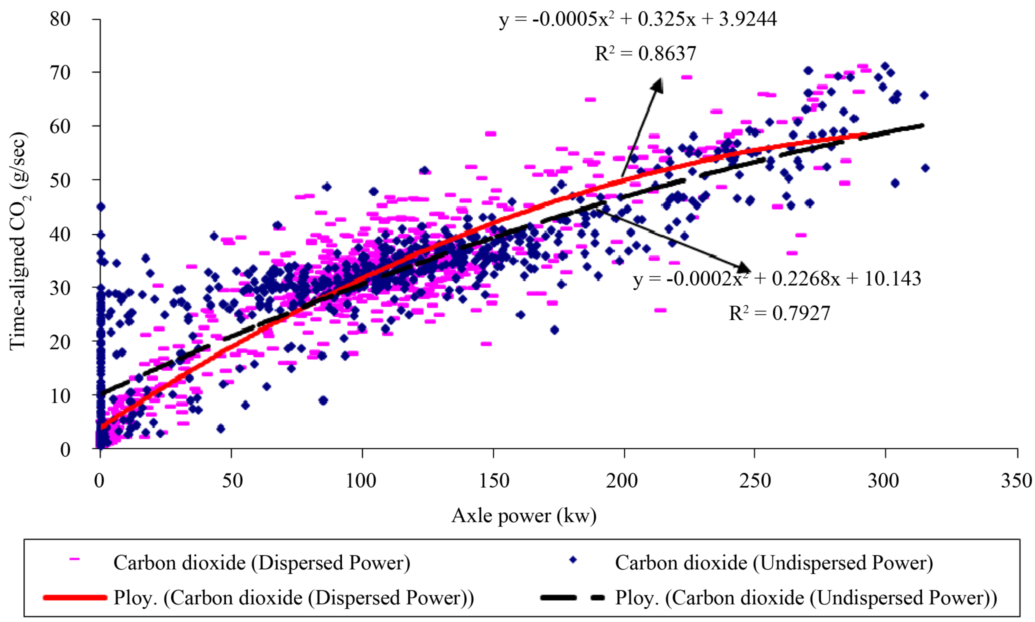


Figure 1. The effect of dispersion on the correlation between mass emissions rate and axle power.

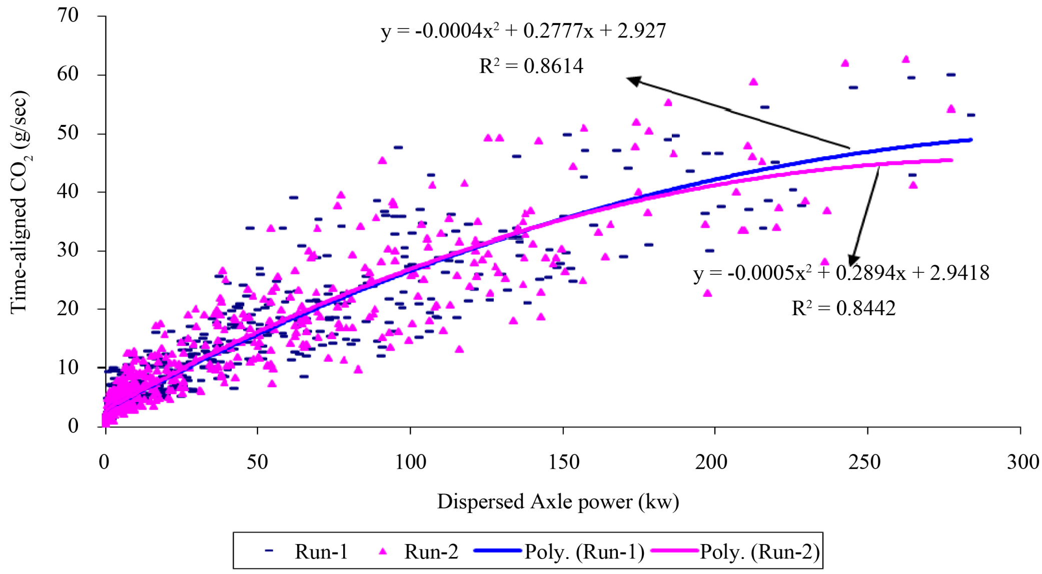


Figure 2. CO_2 mass emissions rate for two consecutive runs tested on the HHDDT_S.

While CO_2 correlated well (R^2 of 0.86) with dispersed axle power, NO_x did not (R^2 of 0.53). This is because the CO_2 was representative of the fuel consumed by the vehicle, and hence it correlated well with power, but the linear dependence of NO_x on power was affected by the NO_x control methods such as cooled EGR and retardation of fuel injection timing. The engines with EGR also employed variable geometry turbochargers (VGT) [33]-[35]. These technologies employed multi-dimensional control that affected the linear dependence of NO_x on power. The increasing complexity of engine controls suggests that NO_x may not be well correlated with power for recent MY vehicles, whereas NO_x correlations with power were good for most older trucks [7]. For five vehicles tested on Central Business District (CBD) cycle and WVU 5-peak test cycle, NO_x mass rate had showed a good correlation with power (with an average R^2 of about 0.85) [7].

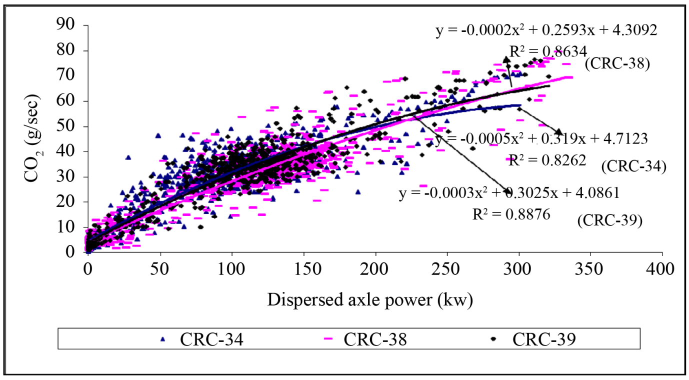
Cycle-specific emissions from heavy-duty vehicles were examined as well. **Figure 4(a)** shows the CO_2 emissions rate from CRC-34 loaded at 56,000 lb and tested on cycles. Since all cycles do not utilize the vehicle's power output capability similarly, emissions rates at the same axle power vary from cycle to cycle. However, differences in the emissions rate curves were not substantial. Even if a single best fit line were used for the data from all the three drive cycles, the R^2 values for each of the cycles would not vary even by 5% from those in **Figure 4(a)**. The apparent deviation in the curves in **Figure 4(b)** in the 200 - 280 kw power range is merely an effect of curve fitting to the data. For linear fits, the curves show negligible deviation from one another (**Figure 4(c)**). In fact, the lines representing the transient mode of HHDDT_S and the UDDS had exactly same slopes and almost the same intercepts and hence the lines overlapped.

To understand the effect of test weight on cycle emissions mass rate (g/s), data were considered from CRC-34 loaded at three different weights: 30,000, 56,000 and 66,000 lb and tested on the HHDDT_S. Emissions mass rates of CO_2 and NO_x as a function of dispersed axle power are shown in **Figure 5**. The best fits of the three curves have similar slopes and intercepts. This suggests that the test weight does not significantly affect the CO_2 and NO_x power-specific emissions mass rates from the engine.

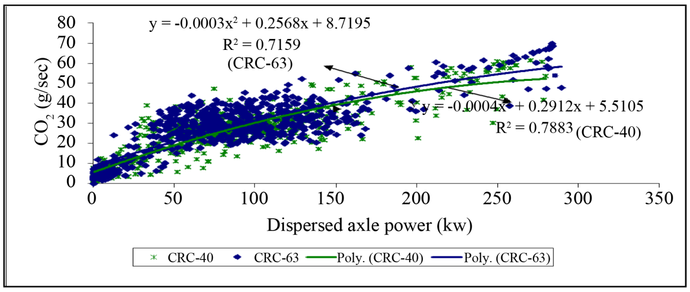
8. Comparison with Old Truck Data

The 2003-2005 MY truck emissions data were compared to the emissions data from 1994-2002 MY trucks. These data were also obtained from the E-55/59 study [8]. The emissions data were collected from twelve 1994-2002 MY trucks. These trucks were loaded at 56,000 lb and were driven through the HHDDT drive cycle.

The averages from transient cycle for the 1994-2002 MY trucks were compared with the corresponding averages from the transient mode of HHDDT schedule of the 2003-2005 MY trucks. The comparison is shown in **Figure 6(a)**. In **Figure 6**, the trucks are grouped based on their vehicle MY so that the reader could appreciate the emission trends across model years. The truck-to-truck standard deviations are represented by the error bars.



(a)



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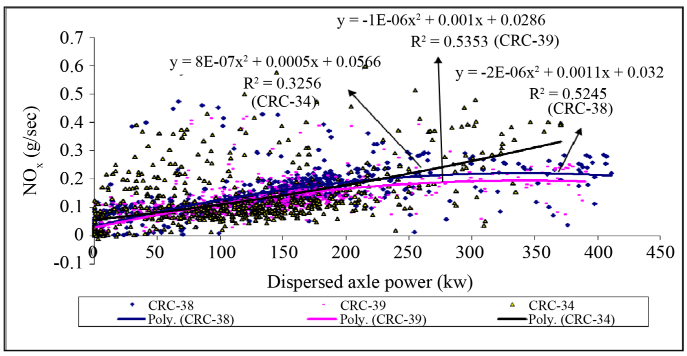

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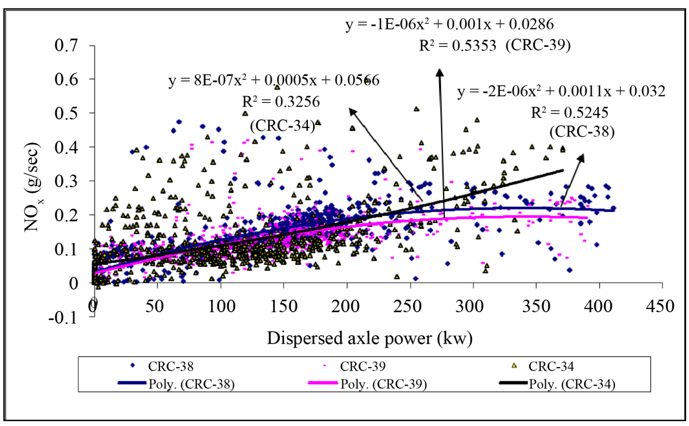
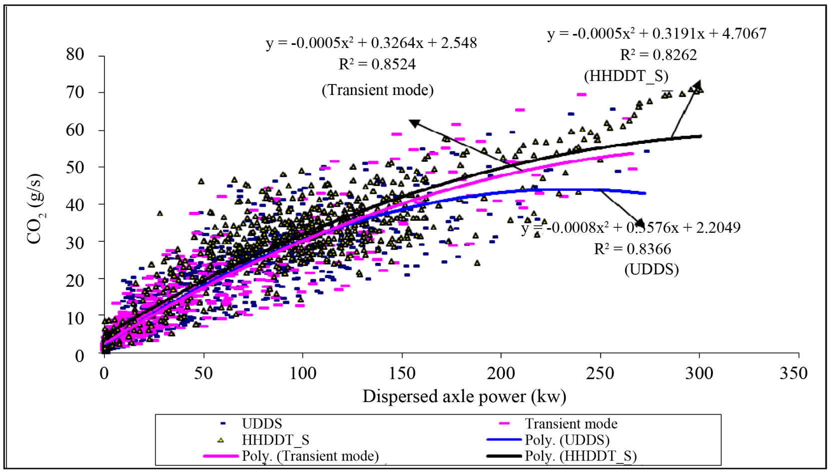
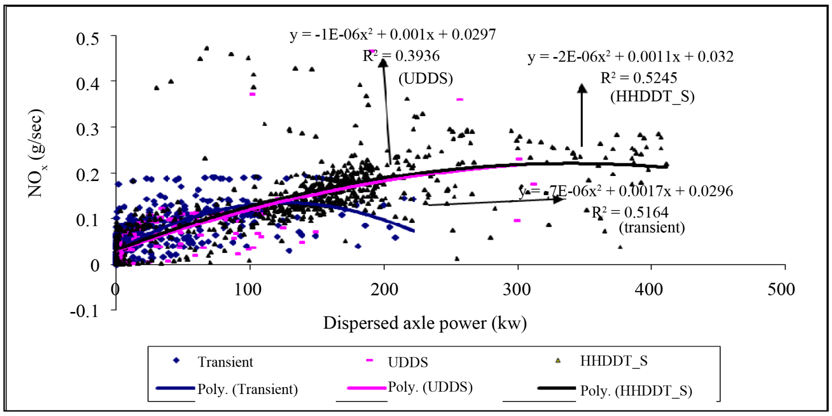


(d)

Figure 3. Mass emissions rate for five 2003-2005 MY trucks loaded at 56,000 lb and tested on the HHDDT_S. (a) (b) CO_2; (c) (d) NO_x.



(a)



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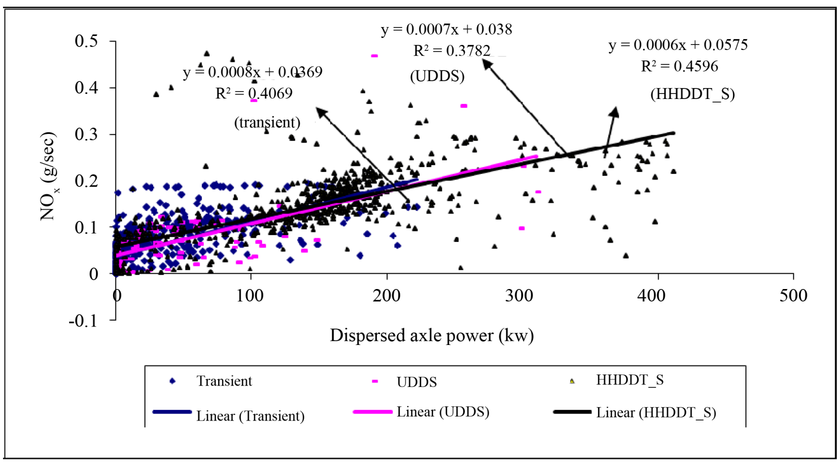
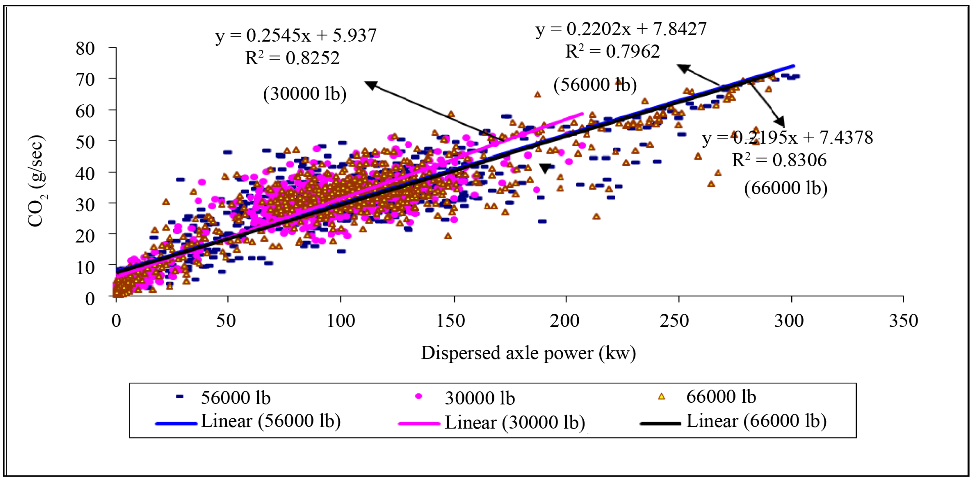


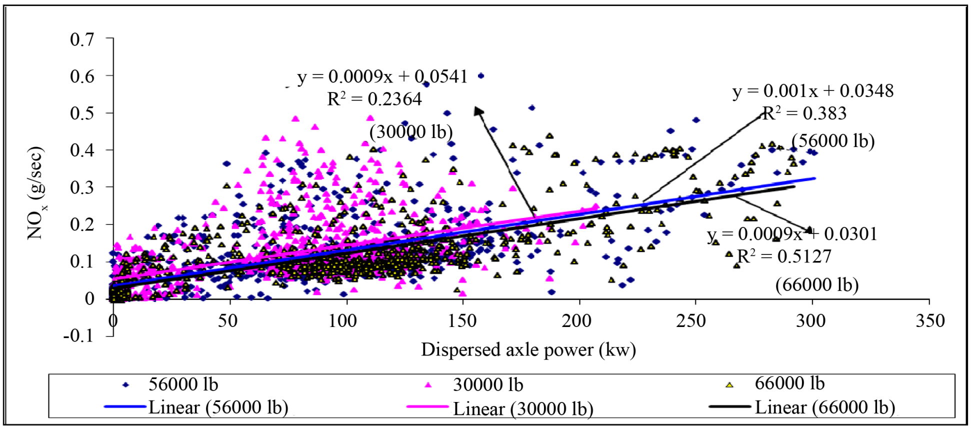
(c)

Figure 4. Mass emissions rate for CRC-34 (MY 2004) loaded at 56,000 lb and tested on three different cycles. (a) CO_2; (b) NO_x; (c) NO_x (with linear curve-fit).

The comparison of the averages based on the HHDDT_S is also shown in **Figure 6(b)**. NO_x emissions showed reduction both in grams per cycle and grams per mile. The time rate of emissions (g/min), fuel economy (miles per gallon) and the distance specific emissions (g/mile) in transient and high-speed cruise were compared with those from the earlier MY trucks. When compared to the 1994-1998 MY trucks, the 2003-2005 MY trucks



(a)



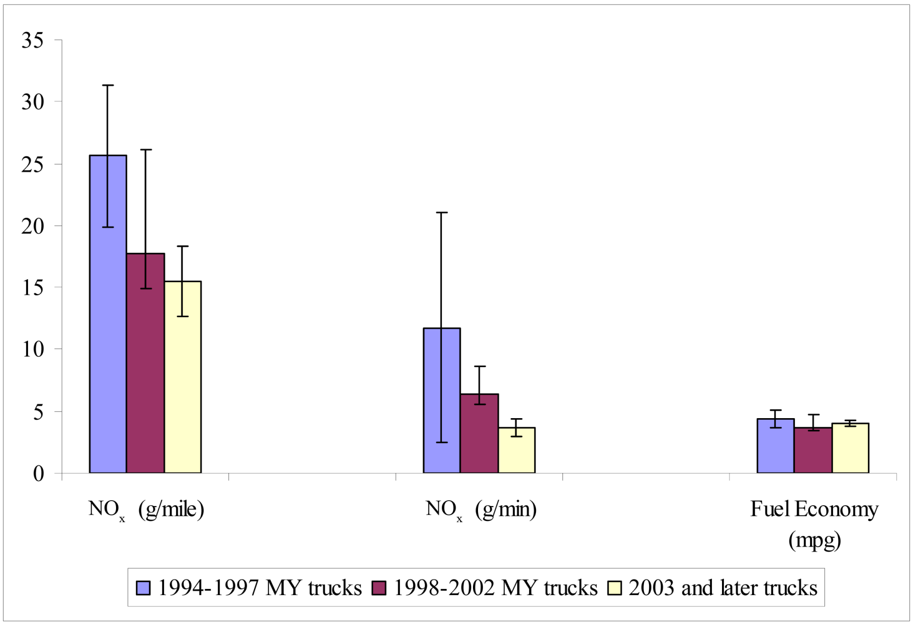
(b)

Figure 5. Mass emissions rates for CRC-34 (MY 2004) loaded at three different test weights and tested on the HHDDT_S. (a) CO_2; (b) NO_x.

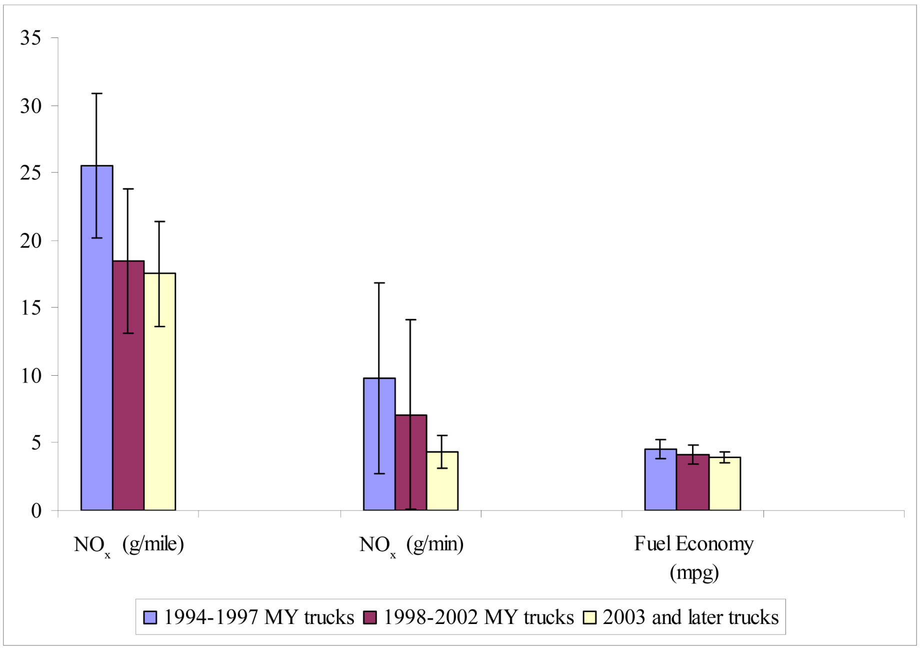
showed a decrease of about 40% in distance specific emissions. Note that the certification level for NO_x has dropped about 40% from 4 g/bhp-hr for the 1998 MY heavy-duty engines to 2.4 g/bhp-hr for the 2004 and later MY heavy-duty vehicles.

9. NO_x/CO_2 Ratio

NO_x/CO_2 ratio can be useful in representing the emissions as a mass fraction of the burnt fuel. It differs from brake-specific NO_x because it takes into account the reduced engine efficiency during low power operation. **Figure 7** presents the data from CRC-34 loaded at 56,000 lb and tested on three different cycles. **Figure 8** represents the data from the five trucks (described in **Table 1** and from reference [8]) loaded at 56,000 lb and tested on THE HHDDT_S cycle. In both of these plots, the data did not follow a trend. This suggests that the ratio is independent of the test cycle and the vehicle. The ratio was found to be higher at lower axle power because of the advanced injection timing at idle and lighter loads. The average value of the ratio for the 2003-2005 MY trucks was 0.0051. The corresponding ratio for all of the vehicles considered in the earlier study [7] by Ramamurthy and Clark was 0.0141. This decrease of the ratio could be attributed to the more stringent standards and NO_x reduction technologies after October 2002 (The 2004 standards were brought forward to October 2002 under the Consent Decree). For 2004 and later MY engines, the limiting average value of NO_x (including non methane hydrocarbons) for transient FTP is 2.4 g/bhp-hr. It should be noted that the transient FTP certification considers only the cycle average, but it does not put a limit on the peak emissions in the cycle. In other words, at



(a)



(b)

Figure 6. (a) Comparison of transient cycle emissions of the 2003-2005 MY trucks with those of earlier MY trucks; (b) Comparison of high-speed cruise emissions of the 2003-2005 MY trucks with those of earlier MY trucks.

certain times during the cycle, the NO_x value is allowed to exceed 2.4 g/bhp-hr. This is unlike NTE certification which puts a cap on the maximum power specific emissions. Hence, based on these standards, the limiting ratio should be 2.4 g of NO_x per 525 g (approximately) of CO_2; hence the ratio for certification should be 0.0046. This was comparable to the 2003-2005 MY truck average of 0.0051. From the earlier study by Ramamurthy and Clark [7], the average NO_x/CO_2 for the older MY trucks was 0.01. In another similar study conducted by Khan and Clark [36], the average NO_x/CO_2 ratio for the E-55/59 trucks from 1991-2004 MY tested on the transient

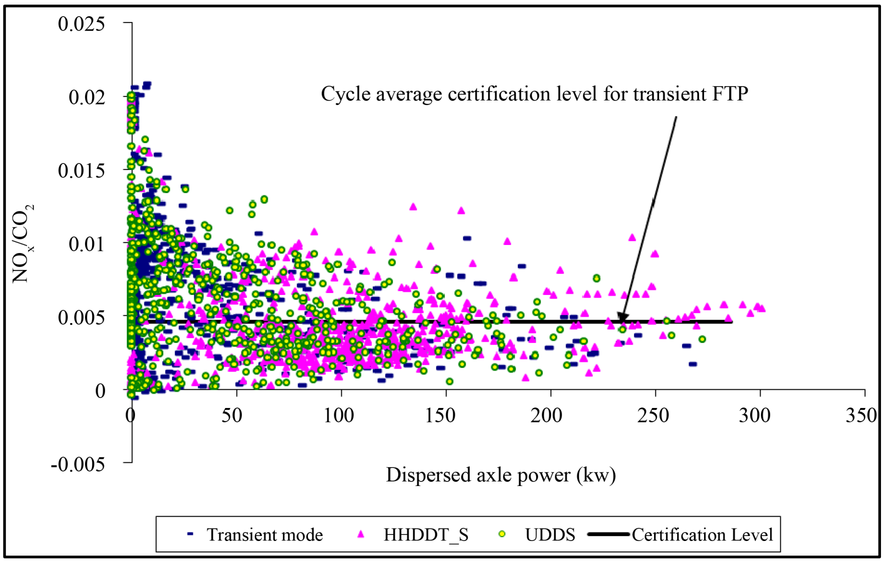


Figure 7. NO_x/CO_2 vs. dispersed axle power for CRC-34 (MY 2004) loaded at 56,000 lbs.

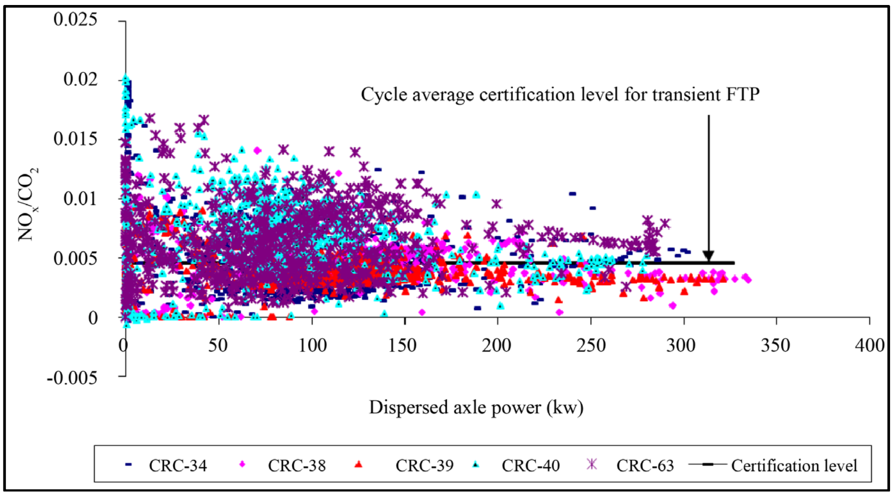


Figure 8. NO_x/CO_2 vs. dispersed axle power for five 2003-2005 MY trucks loaded at 56,000 lb and tested on the HHDDT_S.

mode was found to be 0.0089.

10. Conclusion

The main objective of this paper is to provide the research community with power specific CO_2 and NO_x emissions levels for the 2003-2005 MY heavy-duty vehicles. Five different trucks were tested on the UDDS and the transient and high-speed cruise modes of the HHDDT. For all the cycles, the emission rates increased with increasing power. However, the linear dependence of mass rate on power was different for CO_2 and NO_x. The CO_2 mass rate was correlated well with the power ($R^2 = 0.85$), but the R^2 value for correlation of NO_x with power ($R^2 = 0.50$) was significantly lower than the R^2 value for correlation for earlier MY vehicles ($R^2 = 0.85$ from the study by Ramamurthy and Clark [7]). This is attributed to the complex emission controls employed by the modern trucks. For example, with multiple injections or cooled EGR in use, NO_x emissions are governed less simply by injection timing. The cycle-to-cycle variation of the emission rates was studied and second-degree polynomial equations were developed for each cycle. The effects of three test weights on the emission rates were presented. The linear fits for the three weights had similar slopes and intercepts. This suggested that the test weight does not significantly affect the CO_2 and NO_x emissions rate against power. NO_x/CO_2 ratio was computed for the 2003-2005 MY trucks for all the cycles. The average NO_x/CO_2 ratio of 0.0051 was in a good agreement with the current certification level of 0.0046. The time rate (g/min) and the distance specific (g/mile) NO_x for transient and high-speed cruise modes were compared with those from the earlier MY trucks (1994-2002). When compared to the 1994-1998 MY trucks, the 2003-2005 MY trucks showed a decrease of about 40% in distance specific NO_x emissions in both the transient and high-speed cruise. The drop is in conjunction with the drop in the acceptable levels for certification.

Acknowledgements

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