PRODUCTION OF NOx FROM TRACTOR-TRAILER OPERATION

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Diesel engines emissions have received a great deal of attention over the past three decades. U.S. emissions standards for 2007 demand that new heavy-duty automotive diesel engines emit no more than 0.2 g/bhp-hr of oxides of nitrogen (NOx) and 0.01 g/bhp-hr of particulate matter (PM). New standards also focus on in-use emissions and the Environmental Protection Agency have promoted the measurement of on-board emissions for both compliance and inventory. The objective of this study was to compare engine operating parameters and NOx emissions produced from a tractor-trailer operating under different test routes and weights. A 1996 Tractor with a 410 kilowatt Caterpillar engine was tested previously with the WVU Mobile Emissions Measurement System (MEMS) and this data set was examined. A comparison between test weights of 9,408 kg and 27,905 kg was undertaken for a test route called the Bruceton Route away trip, which involved a sustained hill climb. The results from Bruceton Route showed that the engine spent only 10.7% of its time at maximum percent load for the 9,408 kg test weight and that time increased to 41% for the 27,905 kg test weight. NOx emissions were grouped in vehicle speed increments of 20 miles per hour (mph) over the complete test run and were plotted against vehicle speed and the percent of time that the vehicle spent in each speed bin. The results from the Bruceton Route away trip at test weight of 9,408 kg showed that the vehicle produced most of NOx at vehicle speeds between 61 mph and 70 mph. When compared to the results from the Bruceton Route away trip at the 9,408 kg test, the vehicle produced most of NOx rather at a lower vehicle speed bin at the 27,905 kg test. Test results from the Bruceton Route away trip were also compared to the test results from the Saltwell Route, which involved freeway travel with rolling terrain. The comparison from the 27,905 kg tests showed that the vehicle spent 41% of it time at maximum percent load at the Bruceton Route away trip and that time decreased to 29.3% at the Saltwell Route. Overall, it was evident that both the routes and test weights affected distance specific NOx and the engine operating envelope.

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INTRODUCTION

Traditionally heavy-duty diesel engines were certified in a test cell and the certification data were used even for emissions inventory computations. In recent years, diesel emissions research has focused on on-board measurements which provide insight into real-world vehicle activity and emissions. Existing literature (Cocker et al., 2004, and Weaver et al., 2004) demonstrated the development and operation of Portable Emissions Measurement System (PEMS) for both passenger car and heavy-duty vehicle applications. Truex et al., (2000) developed a Fourier Transform Infrared Spectroscopy based system for a passenger car application to measure ultra low level oxides of nitrogen (NOx) and Non-Methane Hydrocarbons (NMHC). A recent paper (Oestergarrd et al., 2004) showed that the On-Board emissions measurement system (Model OBS-1300, developed by the Horiba Instruments) and the Mobile Emissions Measurement System (MEMS, developed by the West Virginia University) correlated with the test cell measurements within 11% difference. Another paper (Krishnamurthy and Gautam, 2005) presented a preliminary development of a test data quality assurance methodology for emissions measured using any PEMS. Although exhaust mounted NOx sensors now exist (see www.siemensvdo.com), they are not yet incorporated into diesel engine feedback controls.

Despite the growing use of the PEMS, little has been published in the open literature about the effect of load and terrain on engine operation and resulting emissions. Strimer et al. (2005) have studied the effects of test weight on emissions of carbon dioxide (CO_2) and NOx from a 1996 tractor-trailer. Strimer's study showed, as expected, higher Not-To-Exceed Zone NOx emissions mass rate and lower fuel economies at heavier vehicle loads. This study has examined the Strimer et al. database further and compared test results from the Bruceton and Saltwell Routes. The main goals were to explore the effects of test routes and weights on the NOx production and the engine operating parameters.

VEHICLE AND TEST ROUTE

The vehicle tested by Strimer et al. (2005) was a 1996 Tractor (Peterbilt) and was powered by a 410 kilowatt (kW) Caterpillar engine. The on-board data logging system employed was the MEMS (Gautam et al., 2001). The system utilized a Mexa-720 and a Horiba B-140 sensor to measure NOx and CO_2. Table 1 lists the vehicle descriptors. Figure 1 presents an engine map based on manufacturer's torque-speed points for the Caterpillar engine. An actual engine map would not have the inflection points. The rated speed for the engine was advertised as 1800 revolutions per minute (rpm).

Table 1. Vehicle Description.

Parameter	Descriptions
Vehicle Type	Tractor
Model Year	1996
Transmission	18 Speed
Differential Ratio	3.55
Engine Manufacturer	Caterpillar
Engine Model	3406E
Engine Configuration	6 cylinder, inline
Engine Displacement	14.6 L
Maximum Power	410 kW
Idle Speed	600 rpm
Rated Speed	1800 rpm
Engine Protocol	SAE J1587

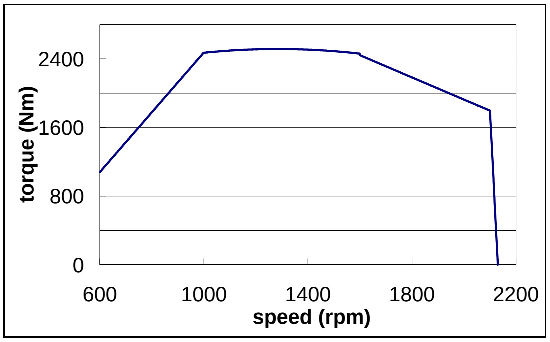

Figure 1. Manufacturer's Engine map.

The vehicle was operated on the Bruceton and Saltwell Routes at 9,408 kg (bobtail) and 27,905 kg (typical U.S. average vehicle load, using a trailer carrying concrete barriers). The Bruceton Route away trip, which involved hill climbing on the freeway, started at Westover, WV and ended at Bruceton Mills, WV. Most travel was on Interstate 68. The Saltwell Route, which involved freeway travel with rolling terrain, also started at Westover, WV and ended at Saltwell, WV, on Interstate 68 and 79. Figures 2 and 3 present a Global Positioning Sensor (GPS) map of the test routes.

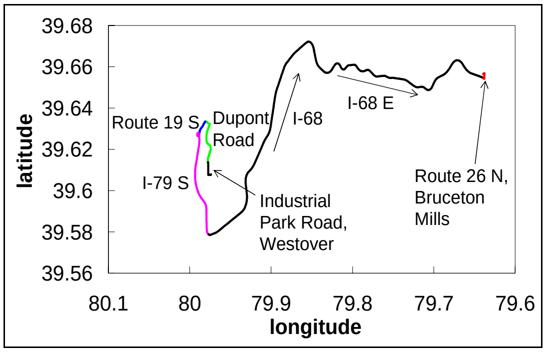

Figure 2. Bruceton away trip GPS map.

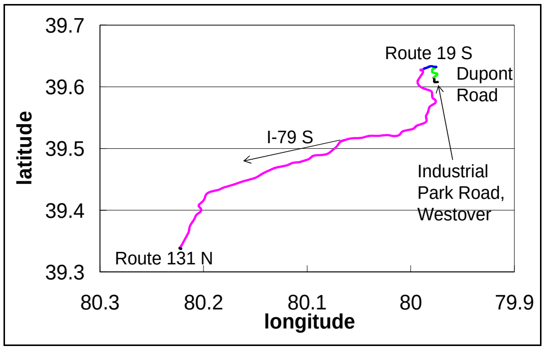

Figure 3. Saltwell Route GPS map.

RESULTS AND DISCUSSION

Bruceton Route away trip results

The driving distance for the Bruceton Route away trip (uphill) was approximately 48 kilometers (km). The vehicle spent 1997 seconds and 2296 seconds to travel this distance at the 9,408 kg and 27,905 kg tests, respectively. The average vehicle speeds were 86 and 76 km/h at the 9,408 kg and 27,905 kg tests, respectively. The maximum vehicle speeds were 134 km/h at the 9,408 kg test and 126 km/h at the 27,905 kg test. Figure 4 presents the vehicle speed and 1/gear ratio as a function of time for the Bruceton Route away trip at 27,905 kg test weight. The gear ratio was calculated as the ratio between the drive axle shaft rotational speed and engine speed and is presented in Equation 1. The drive axle shaft rotational speed was calculated base on the vehicle speed and tire diameter and is presented in Equation 2. The gear ratio changes indicated the vehicle gear shifting events during the hill climbing. The "hill 1", "hill 2", and "hill 3" events marked in Figure 4 represented distinct inclines in the Bruceton Route away trip. At "hill 2" the vehicle was shifted to operate at a higher gear ratio (1.17 and 1.38) two times and the operating times for each higher gear ratio were longer than the shifting events for "hill 1" and "hill 3". The maximum allowable vehicle speed due to a posted speed limit at "hill 2" was 80 km/h. Figure 5 presents a similar plot for a return trip (downhill) for the Bruceton Route 27,905 kg test. The Figure 5 behavior is a close reflection of the Figure 4 behavior, showing that this truck was capable of maintaining similar uphill and downhill speeds.

$$GR = \frac{SS}{ES} \quad (1)$$

$$SS = \frac{VS}{\pi \cdot D} \cdot (1.58 \times 10^{-5} \frac{in}{mile}) \cdot DR \quad (2)$$

where,

GR=gear ratio,
SS=rotational drive axle shaft speed, rpm,
ES=engine speed, rpm,
VS=vehicle speed, mph,
D=tire diameter, in,
DR=differential ratio=3.55

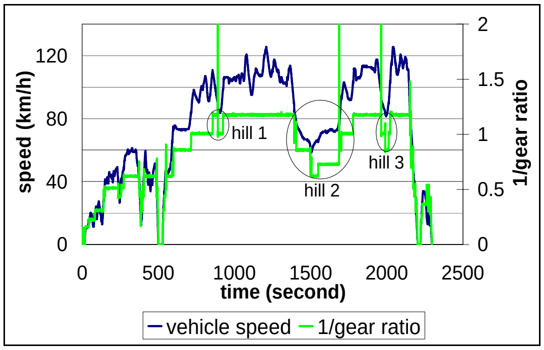

Figure 4. Bruceton Route away trip at 27,905 kg, vehicle speed and gear ratio.

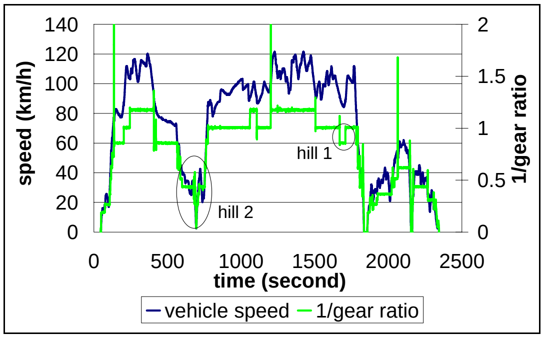

Figure 5. Bruceton Route return trip at 27,905 kg, vehicle speed and gear ratio.

The engine behavior on the Bruceton Route away trip (uphill) was examined and the results are shown in Figures 6 and 7. The bubble sizes on the figures represent the bubble areas and the bubbles represent the time that the engine spent in each engine speed and torque bin. The % speed was calculated based on the manufacturer's idle and rated engine speeds and the % torque was the % load broadcast from the engine. Thus, overspeed above 100% is possible because of the fact that high idle speed was above the rated speed and some engine overspeeding occurred during downhill motoring operation. In general, the engine spent most of its time operating at above 60% of the rated engine speed at both test weights. For the 9,408 kg test, the engine spent 76% of its time operating at above 60% of the rated engine speed and that time increased to 81% for the 27,905 kg test. However, the engine spent 41% of its time operating at the maximum percent load for the 27,905 kg test compared to only 10.7% for the 9,408 kg test. This result showed that the driver favored lower gears at the heavier test weight. In between 0 and 10 % of the maximum percent load, the engine operation times were 40.5% for the 9,408 kg test and 36.2% for the 27,905 kg test.

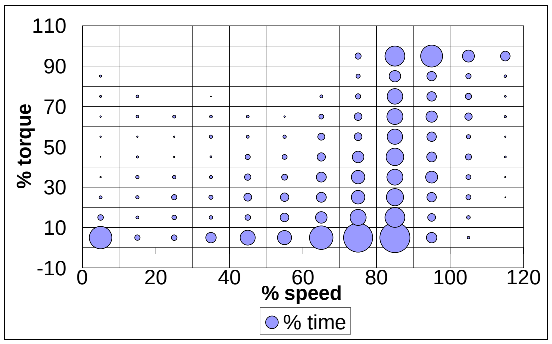

Figure 6. Bruceton Route away trip at 9,408 kg, % torque versus % speed.

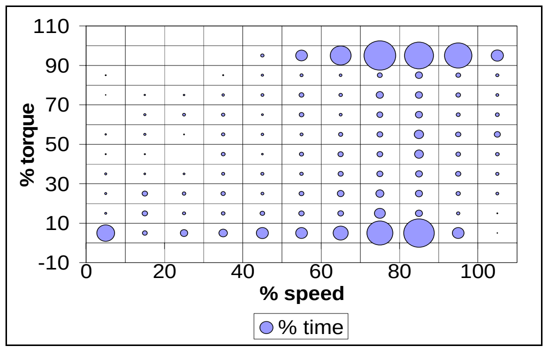

Figure 7. Bruceton Route away trip at 27,905 kg, % torque versus % speed.

Figure 8 presents the engine behavior for the Bruceton Route return trip (downhill) at the 27,905 kg test. The results from the Bruceton Route away trip and return trip were expected to differ from each other. However, Figures 7 and 8 disagree with this expectation. It was known that the Bruceton Route away trip was not a "pure" uphill route; there were some down hills. Figure 4 showed a period of gear ratio decrease immediately after the gear ratio increase at the "hill 1", "hill 2" and "hill 3", and they evidenced the down hills at the Bruceton Route away trip. It was these down hills at the Bruceton Route away trip and the up hills at the Bruceton Route return trip caused the similarity in Figures 7 and 8. However, the numerical results from Figure 8 does show differences compared to Figure 7. The total test time was 2296 seconds for the away trip and 2301 seconds for the return trip for the 27,905 kg test at the Bruceton Route. The engine spent 41.2% of its time operating at between 0 and 10% of the maximum percent load. At the maximum percent load bin, the engine operation time was 33.6%. The results from the Bruceton Route away trip at the same test weight shown in Figure 7 were opposite to the return trip results. With lower fueling percentages during the return trip downhill operation, the vehicle was able to operate at high engine speed and yet very low percent load.

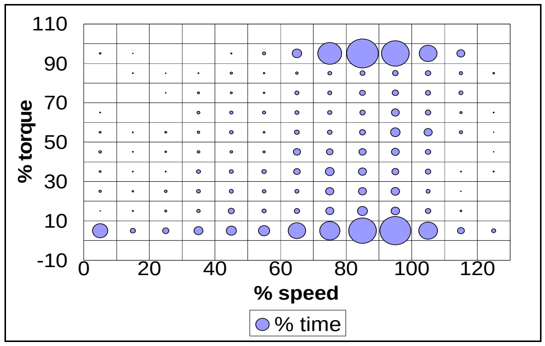

Figure 8. Bruceton Route return trip at 27,905 kg, % torque versus % speed.

Figures 9 and 10 present the NOx distributions for the Bruceton Route away trips for the 9,408 kg and 27,905 kg tests, respectively. Data were grouped in increments of 20 km/h, and the bubbles in Figures 9 and 10 represent the percentages of the total NOx emitted within each vehicle speed bin. The vehicle emitted a total of 1969 grams (g) and 3916 g of NOx at the 9,408 kg and 27,905 kg tests, respectively. Figure 9 illustrates that the vehicle emitted 73.5% of the total NOx at vehicle speeds between 100 km/h and 120 km/h at the 9,408 kg test and the vehicle spent 54.7% of it time operating at this speed bin. Compared to the 27,905 kg test, shown in Figure 10, the vehicle spent only 33.6% of its time operating at this speed bin and emitted 30.6% of the total NOx at the same speed bin. However, for the 27,905 kg test, the vehicle spent 33.6% of it time operating at vehicle speeds between 60 km/h and 100 km/h and emitted 56.1% of the total NOx compared to only 11% operation time and 7.06% of the total NOx at the same speed bin for the 9,408 kg test. For the 27,905 kg test, the vehicle operated at lower speeds when climbing the hills compared to the 9,408 kg test.

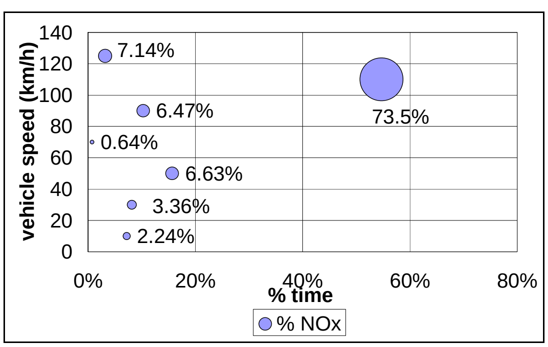

Figure 9. NOx distribution for the 9,408 kg test at the Bruceton Route away trip.

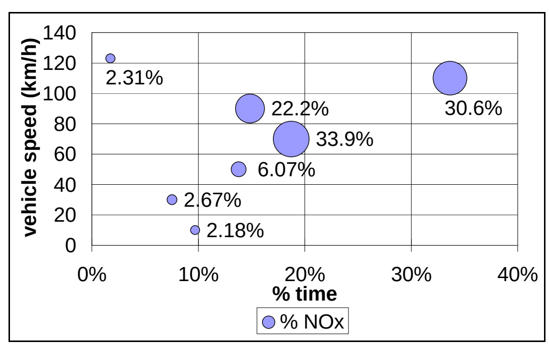

Figure 10. NOx distribution for the 27,905 kg test at the Bruceton Route away trip.

<u>Saltwell Route results</u>

The Saltwell Route was also 48 km in distance and the vehicle spent 2079 seconds and 2578 seconds to travel this distance for the 9,408 kg and 27,905 kg tests, respectively. Figure 11 presents the vehicle speed and 1/gear ratio as a function of time at the 27,905 kg test. The figure shows a major vehicle speed decrease at times between 1200 and 1800 seconds.

This vehicle speed valley shown in the figure was due to the road construction encountered on the Saltwell Route during the test operation. The average vehicle speeds were 84 and 69 km/h for the 9,408 kg and 27,905 kg tests, respectively. It is this road construction that caused in part the lower average vehicle speed for the 27,905 kg test. The maximum vehicle speeds were 128 km/h and 115 km/h for the 9,408 kg and 27,905 kg tests, respectively.

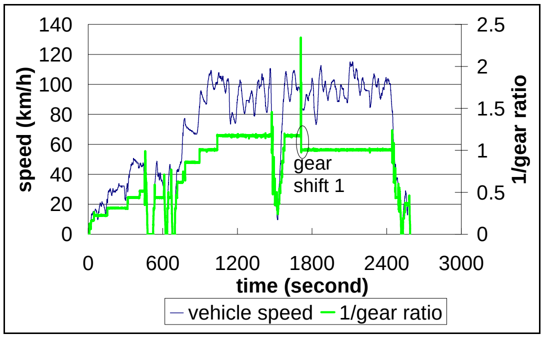

Figure 11. Saltwell Route, vehicle speed and gear ratio.

The engine behaviors on the Saltwell Route are shown in Figures 12 and 13. Similar to the Bruceton Route results, the engine spent 77% and 69% of the times operating at above 60% of the rated engine speed for the 9,408 kg and 27,905 kg tests, respectively. This is not surprising, since heavy-duty vehicles are usually driven with the engine operating between the peak torque speed and the rated speed. Since the elevation changes on the Saltwell Route were lower than on the Bruceton Route, the engine operating times at the maximum percent load were also shorter on the Saltwell Route. The engine spent only 4.1% and 29.3% of the time operating at the maximum percent load on the Saltwell Route for the 9,408 kg and 27,905 kg tests, respectively. In between 0 and 10% of the maximum percent load, the engine operation times were 34% and 38% for the 9,408 kg and 27,905 kg tests, respectively. The Bruceton Route results presented in above showed with this time percentage value decreased by 4.3% when the test weight increased from 9,408 kg to 27,905 kg. However, the Saltwell Route results presented here showed that it increased 4%. This was due to the extra wait time that resulted from the road construction encountered when performing the 27,905 kg test on the Saltwell Route.

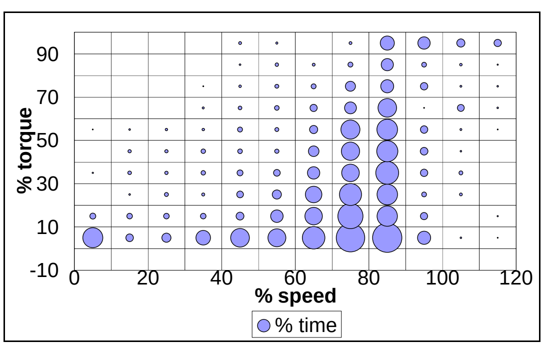

Figure 12. Saltwell Route at 9,408 kg, % torque versus % speed.

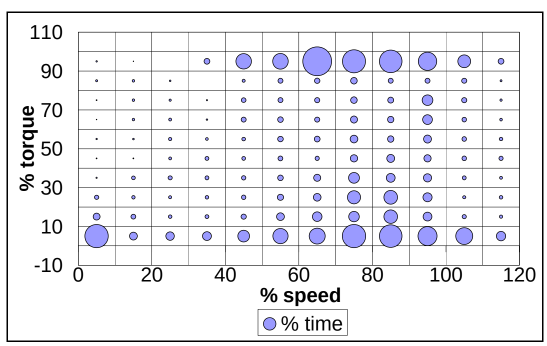

Figure 13. Saltwell Route at 27,905 kg, % torque versus % speed.

The vehicle emitted a total of 1680 g and 3192 g of NOx at the Saltwell Route for the 9,408 kg and 27,905 kg tests, respectively. The NOx distributions over the complete test periods are shown in Figures 14 and 15. The vehicle spent 54% of its time operating at vehicle speeds between 100 km/h and 120 km/h and emitted 71.8% of the total NOx for the 9,408 kg test. For the 27,905 kg test, the vehicle only spent 19.2% of its time at the same vehicle speed bin and emitted 19.9% of the total NOx. With a heavier vehicle loading, the vehicle operated with lower road speeds through the rolling terrain and NOx emissions were higher in the lower vehicle speed bin. For the 27,905 kg test, the vehicle emitted 65% of the total NOx at vehicle speeds between 60 km/h and 100 km/h compared to only14% for the 9,408 kg test. The Bruceton Route results presented that the vehicle emitted 5.6% and 4.9% of the total NOx at vehicle speeds between 0 and 40 km/h for the 9,408 kg and 27,905 kg tests. Due to the road construction encountered for the 27,905 kg test on the Saltwell Route, the vehicle spent a longer time operating at low vehicle speeds and NOx emissions doubled (increased from 5.7% to 11.8%) in the same vehicle speed bin.

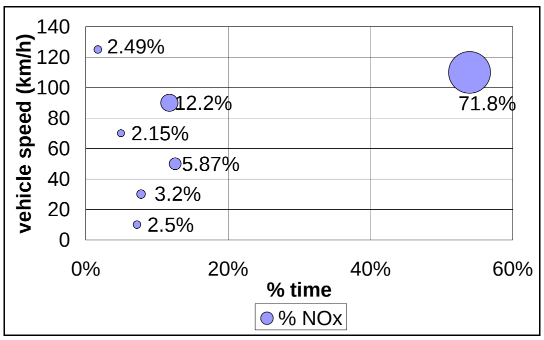

Figure 14. NOx distribution for the 9,408 kg test at the Saltwell Route.

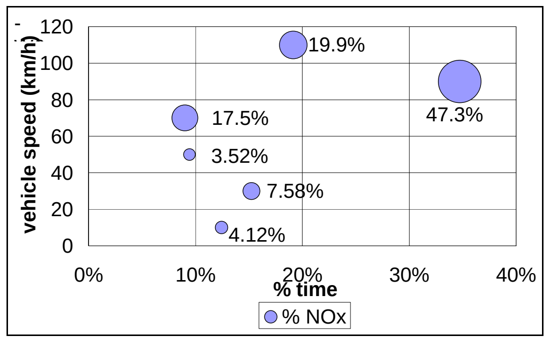

Figure 15. NOx distribution for the 27,905 kg test at the Saltwell Route.

Table 2 summarizes the vehicle NOx emissions for the Bruceton Route away trip operation. In this particular study, percent time and average power were the dominating parameters that affected NOx emissions. Table 2 demonstrated that at vehicle speeds between 40 km/h and 60 km/h, the engine consumed 38.5 kW of power and emitted 6.63% of the total NOx. Even though the engine consumed 105 kW of power at vehicle speeds between 60 km/h and 80 km/h, it only emitted 0.64% of the total NOx. This is because the vehicle only spent 0.75% of its time operating at vehicle speeds between 60 km/h and 80 km/h. Table 3 summarizes the vehicle NOx emissions from the Saltwell Route operation. Overall, NOx emissions increased as both percent time and average power increased.

Table 2. Bruceton Route away trip NOx Emissions.

	9,408 kg Test		
Vehicle Speed (km/h)	**Average Power (kW)**	**% NOx**	**% Time**
0-20	7.07	2.24%	7.21%
20-40	36.2	3.36%	8.16%
40-60	38.5	6.63%	15.7%
60-80	105	0.64%	0.75%
80-100	73.2	6.47%	10.3%
100-120	171	73.5%	54.7%
120-130	331	7.14%	3.18%
	27,905 kg Test		
Vehicle Speed (km/h)	**Average Power (kW)**	**% NOx**	**% Time**
0-20	27	2.18%	9.7%
20-40	79.3	2.67%	7.53%
40-60	113	6.07%	13.8%
60-80	366	33.9%	18.7%
80-100	289	22.2%	14.9%
100-120	185	30.6%	33.6%
120-130	254	2.31%	1.75%

Table 3. Saltwell Route NOx Emissions.

	9,408 kg Test		
Vehicle Speed (km/h)	**Average Power (kW)**	**% NOx**	**% Time**
0-20	9.53	2.5%	7.2%
20-40	29.2	3.2%	7.77%
40-60	51.6	5.87%	12.6%
60-80	40.4	2.15%	4.95%
80-100	105	12.2%	11.8%
100-120	137	71.8%	53.9%
120-130	168	2.49%	1.71%
	27,905 kg Test		
Vehicle Speed (km/h)	**Average Power (kW)**	**% NOx**	**% Time**
0-20	20.7	4.12%	12.4%
20-40	95.7	7.58%	15.2%
40-60	59.9	3.52%	9.44%
60-80	312	17.5%	9.02%
80-100	229	47.4%	34.7%
100-120	190	19.9%	19.1%

CONCLUSIONS

A 1996 Tractor was tested on the MEMS. The engine behavior and NOx distribution were examined on the Bruceton and Saltwell Route. The results showed that the engine spent most of its time operating at above 60% of the rated engine speed on both routes. With heavier test weight, the engine spent a longer time operating at the maximum percent load and NOx emissions (mass rates, or total cycle mass) were higher, on both routes. Due to the hill climbing nature of the Bruceton Route, the engine spent longer times operating at the maximum percent load compared to the Saltwell Route operations. Considering the road load equation, the power consumption was higher at the Bruceton Route due to higher road grade, holding mass, wind drag, and vehicle acceleration terms as constant. Thus, NOx mass emissions were also higher at the Bruceton Route operations. However, if NOx emissions were evaluated on a mass-distance specific basis (e.g. in units of g/ton-km), it would be lower at the higher test weight.

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