DEVELOPMENT OF IN-USE TESTING PROCEDURES FOR HEAVY-DUTY DIESEL-POWERED VEHICLE EMISSIONS

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FOREWORD

This report was prepared by the Department of Mechanical and Aerospace Engineering, College of Engineering and Mineral Resources, West Virginia University, WV with funding provided by the Settling Heavy-Duty Diesel Engine (S-HDDE) manufacturers (Caterpillar, Inc.; Cummins Engine Company, Inc.; Detroit Diesel Corporation; Mack Trucks, Inc.; Navistar International Transportation Corporation; Volvo Truck Corporation). Included herein is a summary of the work that was completed as part of the Phase II workplan and submitted to the S-HDDE manufacturers. Specifically, the work is aimed at meeting the requirements of Consent Decrees entered into by the United States and the S-HDDE manufacturers.

The objective of this study was to develop in-use testing procedures that will be employed in Phases III and IV of the in-use testing program as required by the Consent Decrees. Candidate routes that have been identified in this study represent urban, suburban, and highway driving, as well as hill climbs. This report also includes the in-use testing procedures for conducting on-road emissions testing of heavy-duty diesel-powered vehicles with the best available on-road mobile emissions measurement system. Extensive laboratory and in-use evaluations, conducted at West Virginia University (WVU), have shown that the Mobile Emissions Measurement System (MEMS) integrated by WVU is the most capable device for providing accurate and repeatable in-use emissions data from heavy-duty diesel-powered vehicles, and meets the requirements of the Consent Decrees. Details of the MEMS and the other available on-road emissions measurement systems (OREMS), such as the Real-time On-Road Vehicle Emissions Reporter (ROVER), have been presented in the Phase I Final Report, submitted on March 10, 2000.

The authors express their sincere appreciation to all those who have provided assistance in the laboratory and in-field testing, data analysis, and report writing. A number of faculty members, staff, and students at West Virginia University contributed to this report. Special recognition for their significant contributions goes to Robert Craven, Andy Pertl, Ben Shade, Wes Riddle, Eric Meyer, and Andy Fuller.

EXECUTIVE SUMMARY

Heavy-duty diesel engines (HDDE) are one of the major contributors to the ambient levels of oxides of nitrogen and fine particulate matter. Engine manufacturers are now marketing engines that have significantly lower levels of regulated exhaust emission constituents compared to a few years ago. To ensure that the lower emissions targets are attained, it is essential that the exhaust emissions of diesel-powered vehicles be measured under real-world, on-road driving conditions.

In 1998, six settling heavy-duty diesel engine (S-HDDE) manufacturing companies entered into individual agreements with the United States government. The settling HDDE manufacturers contracted West Virginia University (WVU) to perform Phases I and II of the Consent Decrees that initiate activities to evaluate available technologies and propose a mobile measurement system that could be used to perform in-use emissions testing of heavy-duty diesel-powered vehicles. The work conducted under Phase I of this program was presented in the Phase I Final Report that was submitted to the S-HDDE on March 10, 2000. This report is a summary of the work that was completed to meet the Phase II requirements of the Consent Decrees.

The objective of this study was to develop in-use testing procedures that will be employed in Phases III and IV of the in-use testing program. Four candidate routes have been identified and discussed in this report. Two of the routes comprise urban, suburban, and highway driving conditions, whereas the other two mainly consist of highway driving, with a minimal amount of suburban driving. It has been seen that vehicles operating on a route may fail to remain in the "Not-to-Exceed" (NTE) zone for 30 seconds or more, due to low power demand during low-speed cruise and loss of engine shaft power during manual gear changes. While city operation will yield little NTE zone availability, freeway driving will include NTE zone activity during hill climbs and during sustained high-speed operations. Vehicles with manual transmissions will spend a smaller fraction of time in the NTE zone compared to vehicles with automatic transmissions, because automatic shifting of gears can occur under load.

This report also presents in-use testing procedures for conducting on-road emissions testing of heavy-duty diesel vehicles with the best available on-road mobile emissions measurement system. Extensive laboratory and in-use evaluations, conducted at WVU during Phase I, have shown that the Mobile Emission Measurement System (MEMS) integrated by WVU is the most capable device for providing accurate and repeatable in-use emissions data from heavy-duty diesel-powered vehicles, and meets the requirements of the Consent Decrees. While the procedures presented in this report are based upon the use of MEMS for on-road emissions testing, they could be adapted to other on-road mobile emissions measurement systems.

WVU has evaluated on-road brake-specific emissions from heavy-duty diesel-powered vehicles with the MEMS, and compared the results with those obtained from simulated runs of the same routes on the WVU Transportable Heavy-duty Vehicle Emissions Testing Laboratory. Tests on the chassis laboratory conducted with both the MEMS and the chassis laboratory's research grade emissions analyzers showed very good agreement between the integrated mass-specific NOx emissions results. Additionally, the results obtained with the MEMS from the on-road tests and the chassis laboratory simulation of the same driving route, indicate that the differences in the integrated brake specific NOx mass emissions were less than 5%.

This report highlights the need to develop a quality assurance project plan to ensure that the data generated from the in-use emissions testing program is of the highest quality.

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1 INTRODUCTION

1.1 Overview

On behalf of six major diesel engine manufacturing companies engaged in satisfying the requirements of the Consent Decrees, West Virginia University (WVU) has engaged in research related to the on-road measurement of gaseous emissions produced by heavy-duty diesel-powered vehicles. In Phase I of the present program a critical literature review of currently available technology that could facilitate on-road measurement was completed. Also during this phase, the researchers evaluated this technology in the laboratory and demonstrated the efficacy of optimal technology in the field. This report presents the second phase of the program, in which WVU has developed in-use testing procedures that will be employed to conduct on-road emissions testing of heavy-duty diesel-powered vehicles in Phases III and IV of the program, per requirements of the Consent Decrees. As part of this development process, WVU has identified candidate driving routes over which heavy-duty diesel-powered vehicles may be driven to evaluate emissions. A test vehicle was driven over these routes and the data so gained are reviewed in the report below. This report also presents emissions testing procedures and a quality control/quality assurance (QC/QA) plan that are recommended to serve as guidelines for future in-use testing.

1.2 Requirements for Routes

The Consent Decrees describes the research to be performed in selecting and evaluating routes in Paragraph 48. The following language from the Mack Truck, Inc. Consent Decree illustrates the requirements:

> 48. In Phase II of the In-Use Testing Program, Mack shall develop in-use testing procedures to be used in connection with Phases III and IV of the In-Use Testing Program. The development of in-use testing procedures shall be based on testing of HDDEs engaged in a variety of typical on-road missions, and in a variety of seasonal conditions, and shall utilize engines extending over various stages of their Useful Life. The testing procedures shall include the identification of candidate driving routes representing typical urban, suburban, and highway driving. The candidate routes shall be of sufficient length to take 45 minutes when driven at posted speeds. At least one (1) candidate driving route shall include a portion where at least 15 minutes of operation at 65 mph or greater is permitted and generally attained by trucks.

Similar requirements are specified for the other S-HDDE manufacturers.

2 IDENTIFIED ROUTES

In the first two phases of this effort, the researchers employed a Mack CH613 over-the-road tractor, equipped with a 400 hp E7 engine and a Fuller 10 speed unsynchronized transmission, for on-road testing as well as a second E7 engine, matched to the one in the vehicle, for engine dynamometer testing. In examining the routes presented above, WVU continued to employ the Mack tractor, in conjunction with a tandem axle trailer that could be loaded with concrete road barriers to vary the combination weight. Test weights used were approximately 60,000 lbs., confirmed with weigh tickets for all of the routes. However, one of the routes was driven with an unloaded trailer, resulting in a GVW of 29,000 lbs. These weights varied slightly during operation, due to fuel consumption and changes in vehicle occupants in the cab during testing.

Throughout operation on the routes, the truck was equipped with measuring equipment to determine the engine speed and broadcast percent load from the electronic control unit (ECU) of the truck engine. The ECU also provided the vehicle speed, but it was found that this speed was in error because the ECU, being configured for research, was not calibrated to the precise final drive ratio and rolling tire diameter. Therefore, vehicle speed was also measured using a global positioning sensor (GPS). One route was also performed with the WVU Mobile Emissions Measurement System (MEMS) in place. This apparatus and its use are discussed in a separate section in this report.

In Phase I of this program, the translation of the “percent load,” broadcast by the engine, into a torque estimate was addressed. This process required knowledge of the engine lug down (full power) curve and the broadcast percent load under idle conditions throughout the engine speed range. This methodology was described in detail in the Phase I report. The same methodology was used in the examination of routes to yield torque from the truck engine during operation.

Four distinct routes have been identified and are discussed below. Two of the routes comprise urban, suburban, and highway driving conditions, whereas the other two mainly consist of highway driving, with a minimal amount of suburban driving. It should be noted that completion times and distances that are presented for each route must be regarded as approximate, since each instance of use of the route will differ slightly.

The Consent Decree identifies a realm of engine operation, defined as a "Not to Exceed" (NTE) zone, in which emissions may be compared against standards. Figure 1 shows this zone. For the routes discussed below, engine speed and torque were examined, and those sections falling within the NTE zone were determined. For examination of emissions from a vehicle operating on a route, the engine must remain in the NTE zone for a minimum of 30 seconds, per Consent Decrees requirements.

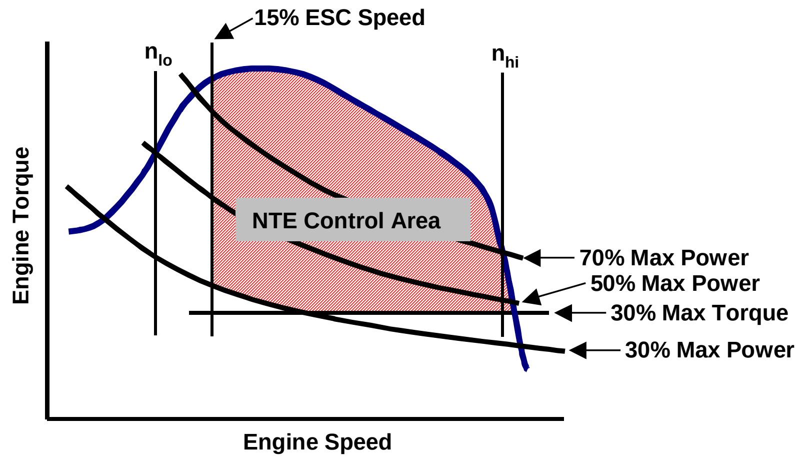


Figure 1 Example NTE zone definition.

In this report, all charts which illustrate integrated 30 second windows are based upon the time at which the integration starts. That is, a 30 second window assigned at a time of 540 seconds corresponds to the integrated window from 540 to 540+30=570 seconds.

Section 2.1 to Section 2.4 describe the four routes that were developed in this study. Plots of vehicle speed, engine speed, ECU-derived torque, and ECU-derived engine power for the first leg of the one of the routes are illustrated in Section 2.1, as an example. The plots for the remaining routes are given in Appendix A.

2.1 Route 1: Saltwell Round Trip

This route may be split into outbound and return journeys. The route originates at the WVU facility in Sabraton (Greater Morgantown Area), close to an entrance ramp onto I-68 west, proceeds to I-79, and follows I-79 south to the turnaround point at the I-79 Saltwell Rd. Exit (near Clarksburg, WV). The total distance is 58.7 miles. The interstate is posted at 70 mph, but there are two curves with advisory signs below that speed. The outbound leg is designated SAB2SW and the return leg is designated SW2SAB. The engine speed and ECU-derived engine torque for the SAB2SW route are shown in Figure 2, while the vehicle speed and ECU-derived engine power are shown in Figure 3. Vehicle speed, engine speed, ECU-derived engine torque, and ECU-derived engine power for the complete Saltwell route are illustrated in Figure A1 to Figure A6 in Appendix A.

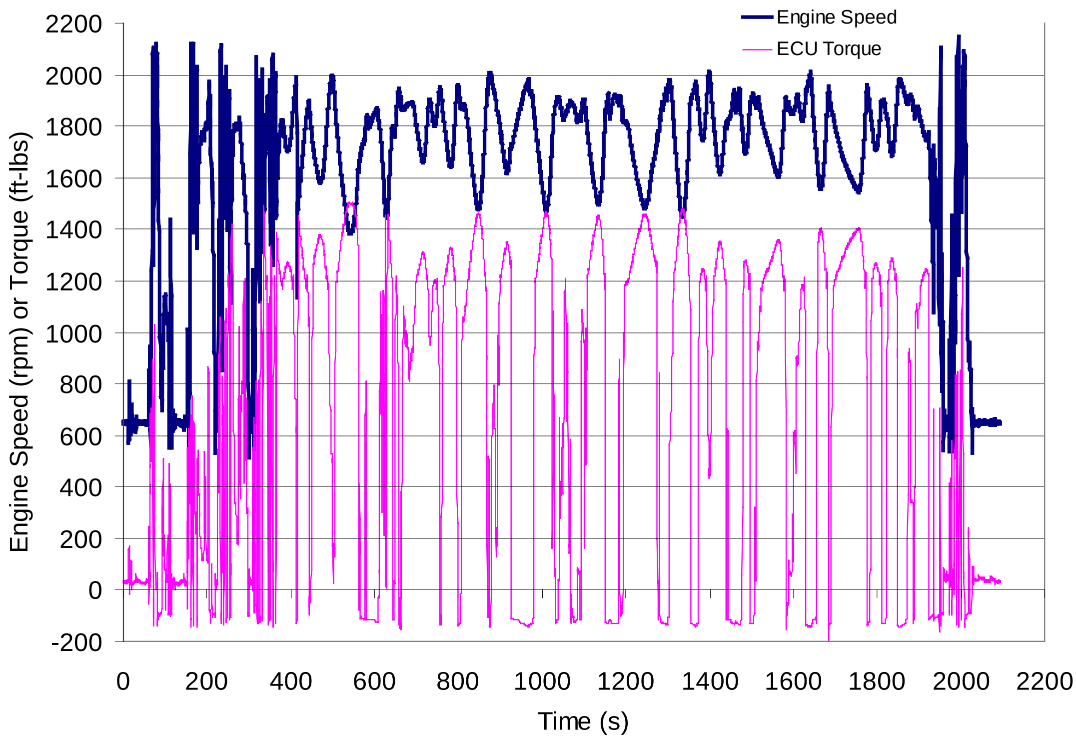


Figure 2 SAB2SW engine speed and ECU-derived torque.

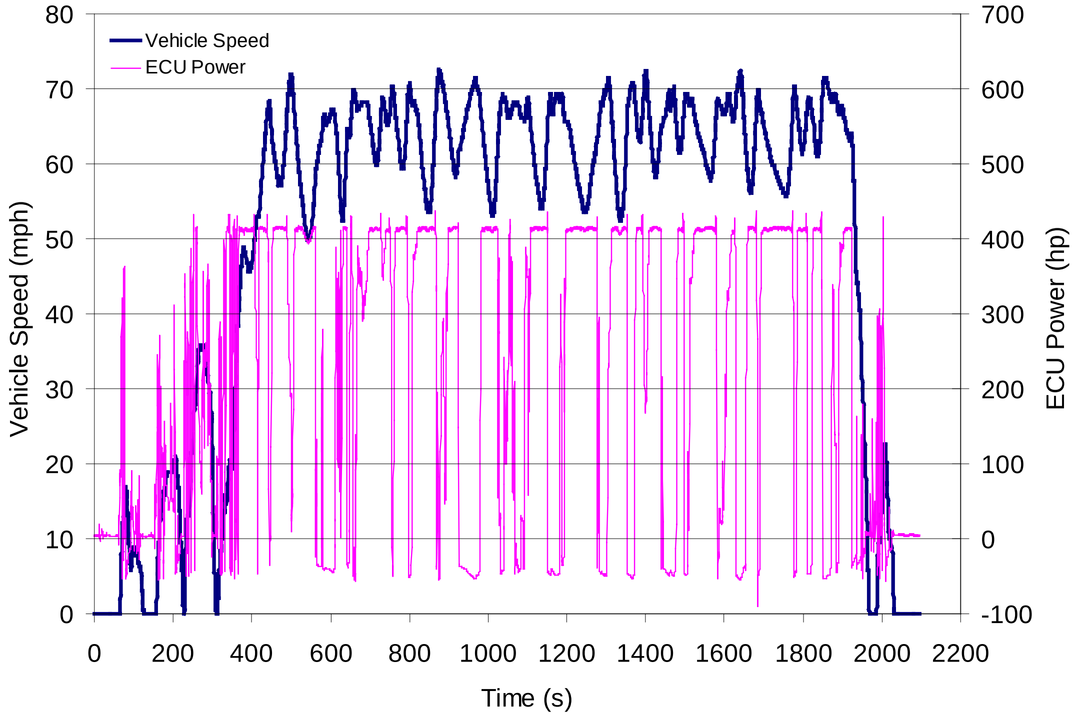


Figure 3 SAB2SW vehicle speed and ECU-derived power.

The requirements of Paragraph 48 of the Consent Decrees were examined to determine a typical tractor's performance. The on-road vehicle speed plot for the Mack CH tractor and an unloaded trailer are shown in Figure 4, as an example of the attainable speed for a tractor-trailer on a route that is characteristic of 70 mph highway operation. The test weight for this route was 29,000 lbs. As shown in this figure, an average speed of 66 mph is attainable for more than 15 minutes over two portions of this route, but the vehicle speed ranges from 55 to 75 mph. The fluctuation in vehicle speed can be attributed to a slightly rolling terrain and mostly to variable traffic patterns. It should be noted that although a continuous 15 minutes of 65 mph average vehicle speed can be obtained, NTE zone duration might not be 15 minutes, due to gear shifting in a vehicle with a manual transmission. Prevailing traffic conditions will dictate NTE zone determination.

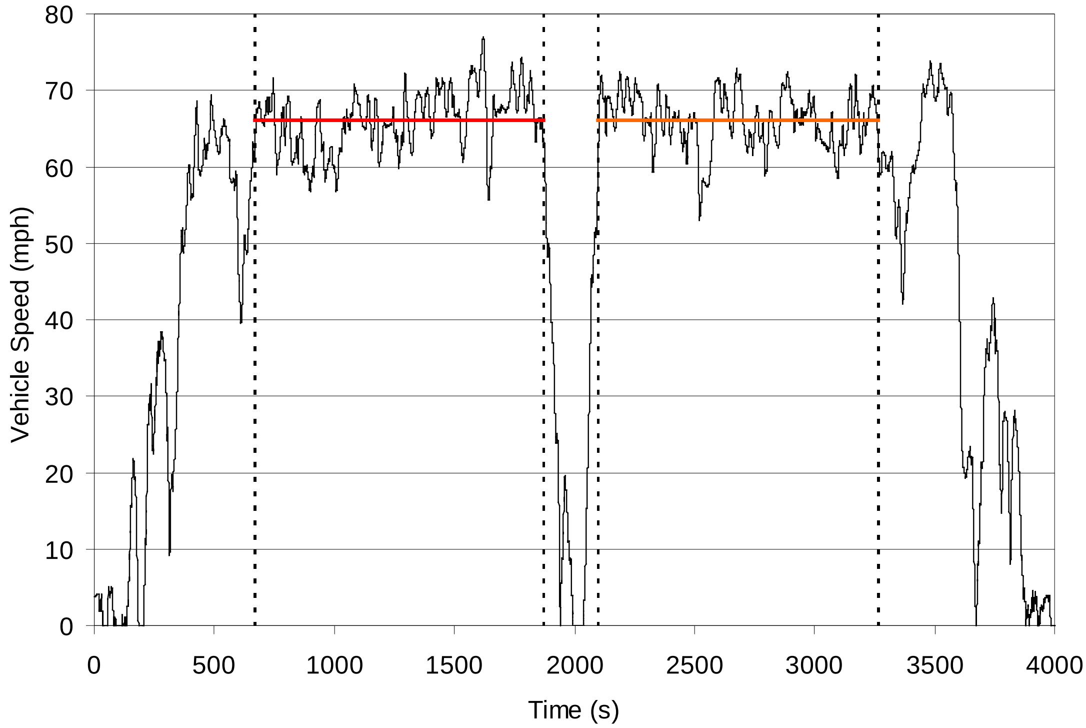


Figure 4 Mack CH tractor Saltwell route (SAB2SW and SW2SAB) vehicle speed history (no load on trailer).

2.2 Route 2: Morgantown Route

This route originates at the WVU facility and proceeds through suburban and urban settings on two and four lane roads, then joins I-79 south to I-68 east, to return to the starting point. The total distance is 20.4 miles. Posted speeds of 35, 40, and 50 mph exist on the urban and suburban routes, and the interstate sections are posted at 70 mph. Vehicle speed, engine speed, ECU-derived engine torque, and ECU-derived engine power for the Morgantown route are illustrated in Figure A7 to Figure A9 in Appendix A.

2.3 Route 3: Sabraton to Bruceton Mills Round Trip

This route may be split into outbound and return journeys. The route originates at the WVU facility close to the Sabraton entrance ramp on I-68 east, and continues onto I-68 where a climb of a substantial 5% grade exists, followed by up and down grades to Bruceton Mills, WV, which is the turnaround point on I-68. The total distance is 39.7 miles. The interstate is posted at 70 mph, but the descent on the return journey is posted at 50 mph for trucks, and incorporates a mandatory stop for brake check. The outbound leg is designated SAB2BM, and the return leg is designated BM2SAB. Vehicle speed, engine speed, ECU-derived engine torque, and ECU-derived engine power for the Bruceton Mills route are illustrated in Figure A10 to Figure A15 in Appendix A.

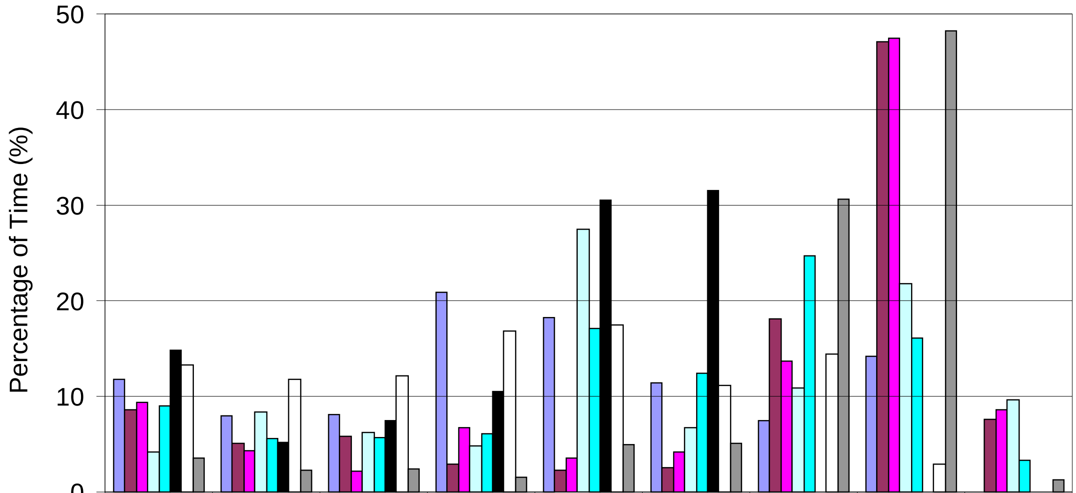
In the high speed freeway operation shown in these figures, reductions in vehicle speed are evident as the vehicle climbs hills along the route. In the case of this route, truck speed restrictions and necessary precautions during the steep descent on the return leg of the journey reduce the operating speed on I-68 westbound (BM2SAB).

2.4 Route 4: Washington/Pittsburgh Route

This route originates in Washington, PA, which is located near the intersection of I-70 and I-79. The route proceeds from Washington on US Rte. 19 north through suburban areas towards Pittsburgh, follows PA State Rte. 51 (US truck Rte. 19) to I-279 south, to I-79 south, and then returns to the first rest area in West Virginia. For the first and second leg, the interstate speed limit is 55 mph, and the suburban road speed limits vary from 25 to 45 mph. The final leg consists of all highway driving with a transition from 55 mph to 65 mph. The total distance is 87.4 miles. The first leg is designated WASHPA1, the second leg as WASHPA2, and the third leg as WASHPA3. Vehicle speed, engine speed, ECU-derived engine torque, and ECU-derived engine power for the Pittsburgh route are illustrated in Figure A16 to Figure A24 in Appendix A.

2.5 Summary of Candidate Routes

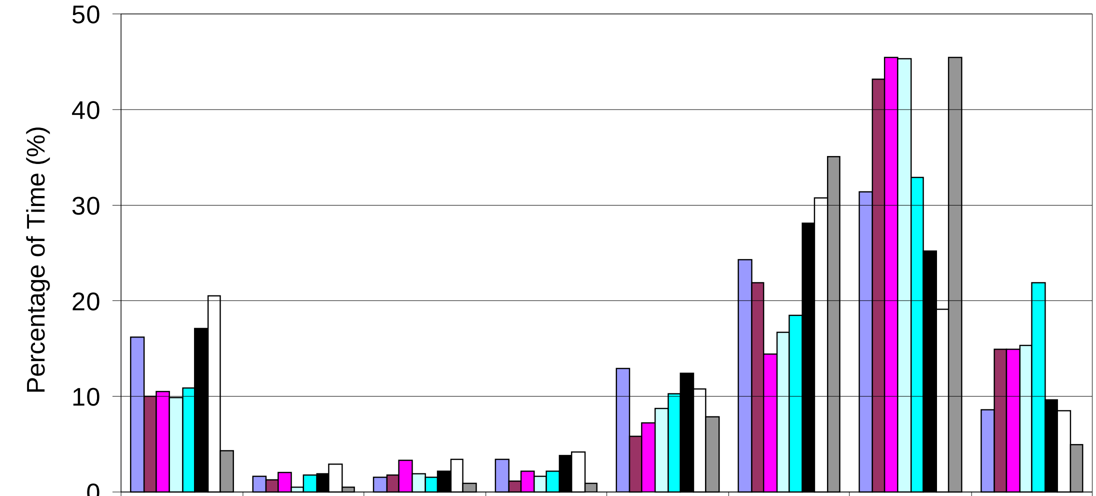
The proposed candidate routes, discussed above and illustrated in Appendix A, are summarized in the histograms in Figure 5 to Figure 7 for the vehicle speed, engine speed, and ECU-derived engine power, respectively. All data was collected using a Mack CH tractor and a trailer loaded to a nominal 60,000 lbs GVW. As illustrated in Figure 5, the vehicle speed is segmented into 10 mph bins, with the exception of the 0 to 10 mph range that is subdivided into two bins. The first two bins, namely 0 to 1 mph bin, and the 1 to 10 mph bin, account for vehicle stops. The Morgantown route, SAB2SAB, illustrates that a significant portion of total driving time (~50%) is spent at rest or at low vehicle speed. The Saltwell route, SAB2SW and SW2SAB, shows a significant amount of highway driving (>60%). The two Pittsburgh routes, WASHPA1 and WASHPA2, represent urban and suburban driving, while the third route, WASHPA3, represents highway driving.



Veh. Spd. (mph)	0 - 1	1 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70 - 80
SAB2SAB	11.80	8.00	8.15	20.87	18.18	11.33	7.47	14.19	0.00
SAB2SW	8.55	5.04	5.83	2.90	2.34	2.51	18.15	47.07	7.62
SW2SAB	9.34	4.33	2.21	6.70	3.49	4.12	13.73	47.51	8.58
SAB2BM	4.23	8.32	6.22	4.85	27.43	6.66	10.91	21.80	9.59
BM2SAB	9.00	5.62	5.71	6.05	17.14	12.37	24.71	16.09	3.31
WAHSPA1	14.80	5.22	7.53	10.46	30.46	31.52	0.00	0.00	0.00
WASHPA2	13.29	11.81	12.16	16.89	17.45	11.10	14.37	2.93	0.00
WASHPA3	3.57	2.28	2.47	1.53	4.92	5.02	30.67	48.28	1.27

Figure 5 Vehicle speed histogram for the candidate routes. Mack CH tractor and trailer with a nominal 60,000 lbs GVW.

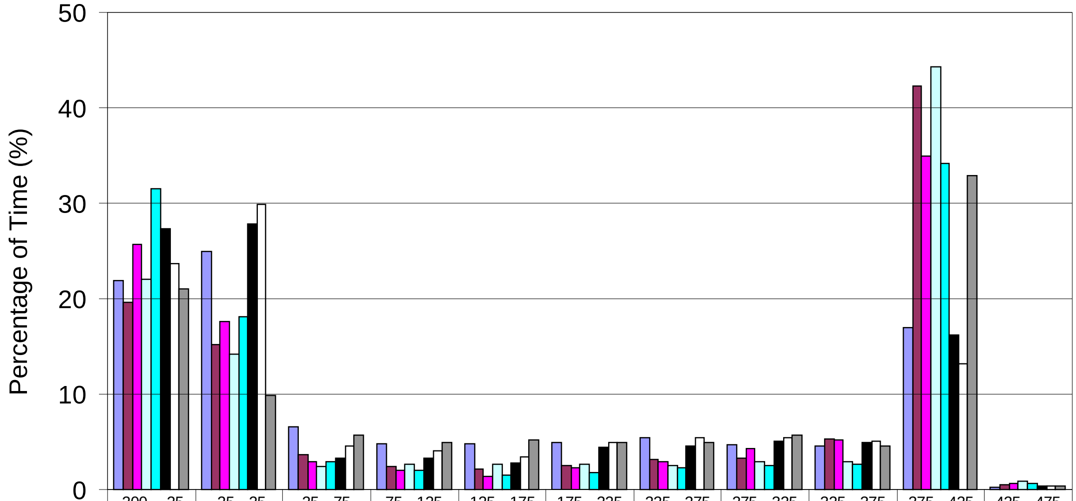
Engine speed (Figure 6) is segmented into 200 rpm bins, with the exception of the first and last bins. The first bin ranges from 0 to 700 rpm in order to identify idle operation, when the vehicle is stopped. The last bin ranges from 1900 to 3000 rpm to account for the high idle or governed engine speed point. As illustrated in this figure, the engine speeds for each route follow similar trends. Generally, 10 to 20% of the route time is spent with the engine at idle. However, the majority of the time is spent near the rated speed of 1800 rpm.



Eng. Spd. (rpm)	0 - 700	700 - 900	900 - 1100	1100 - 1300	1300 - 1500	1500 - 1700	1700 - 1900	1900 - 3000
SAB2SAB	16.22	1.69	1.49	3.42	12.86	24.30	31.43	8.59
SAB2SW	9.99	1.23	1.80	1.14	5.81	21.95	43.17	14.90
SW2SAB	10.50	1.97	3.34	2.20	7.19	14.42	45.40	14.98
SAB2BM	9.81	0.53	1.96	1.69	8.68	16.77	45.31	15.27
BM2SAB	10.86	1.83	1.51	2.20	10.31	18.48	32.86	21.93
WAHSPA1	17.04	1.87	2.12	3.79	12.35	28.13	25.14	9.57
WASHPA2	20.46	2.87	3.40	4.14	10.79	30.78	19.10	8.45
WASHPA3	4.36	0.56	0.89	0.87	7.84	35.04	45.44	4.99

Figure 6 Engine speed histogram for the candidate routes. Mack CH tractor and trailer with a nominal 60,000 lbs GVW.

ECU-derived engine power (Figure 7) is segmented into 50 hp bins, with the exception the first bin that covers a wider range. The first bin ranges from -200 to -25 hp to identify engine motoring during descents. It should be noted that the last bin, 425 to 475 hp, is greater than the engine rating of 400 hp. This is attributed to errors inherent of ECU-derived power values. As illustrated in this figure, the ECU-derived power for each route follows similar trends. Generally, 40 to 50% of the route time is spent with the engine operating at motored or idle conditions, as illustrated by the first two bins. However, outside the first two bins the engine is observed to be operating near the rated power of 400 hp.



ECU Power (hp)	-200 - -25	-25 - 25	25 - 75	75 - 125	125 - 175	175 - 225	225 - 275	275 - 325	325 - 375	375 - 425	425 - 475
SAB2SAB	21.95	24.97	6.62	4.81	4.78	4.97	5.38	4.69	4.53	17.01	0.28
SAB2SW	19.56	15.18	3.62	2.40	2.14	2.48	3.16	3.34	5.26	42.29	0.56
SW2SAB	25.75	17.65	2.96	2.05	1.46	2.24	2.91	4.35	5.13	34.89	0.62
SAB2BM	21.96	14.13	2.40	2.69	2.61	2.60	2.59	2.89	2.86	44.36	0.90
BM2SAB	31.52	18.16	2.91	2.01	1.47	1.80	2.23	2.58	2.62	34.13	0.58
WAHSPA1	27.31	27.88	3.27	3.26	2.82	4.42	4.58	5.01	4.91	16.19	0.35
WASHPA2	23.72	29.83	4.55	4.08	3.47	4.88	5.43	5.47	5.08	13.18	0.32
WASHPA3	21.01	9.85	5.71	4.92	5.13	4.92	4.89	5.70	4.55	32.96	0.36

Figure 7 ECU-derived engine power histogram for the candidate routes. Mack CH tractor and trailer with a nominal 60,000 lbs GVW.

Table 1 presents each route, with the attendant distance, time taken for completion, and approximate 30 second NTE window availability. It is evident that vehicles operating on a route may fail to remain in the NTE zone for 30 seconds or more, due to low power demand during low-speed cruise and loss of engine shaft power during manual gear changing. This implies that little NTE zone operation will be provided by city operation. On freeways, vehicles will remain in the NTE zone during hill climbs and during sustained high-speed operation. It is anticipated that vehicles with automatic transmissions will spend a greater fraction of time in the NTE zone than trucks with manual transmissions, because automatic shifting of gears can occur under load.

The availability of NTE zone windows ($A_{NTE,}$ in Table 1) provides a measure of the continuity of the data points within the NTE zone. For example, a hypothetical route that alternated 5 seconds in the NTE zone with 5 seconds out of the NTE zone would never have a 30 second window, and would therefore have an NTE zone window availability of 0. On the other hand, a hypothetical route of 32 data points, all of which are in the NTE zone, should have an NTE zone window availability of 1. This leads to the equation of NTE zone window availability as follows

$$A_{NTE} = \frac{N_{30sNTEWindows}}{N_{NTEPoints} - 30 + 1}, \quad (1)$$

where $N_{30sNTEWindows}$ is the number of 30 second NTE zone windows and $N_{NTEPoints}$ is the total number of NTE zone points, recorded at 5 Hz. A summary of the NTE zone availability for each of the routes is detailed in Table 1. As illustrated in this table, the routes with a majority of highway driving, Saltwell and Bruceton Mills, have a higher portion of NTE zones than do the mix of urban, suburban, and highway routes of Morgantown and Washington. Replicate runs of the routes have shown that the NTE zone availability of the route is repeatable for normal traffic conditions.

Table 1 Route comparison with respect to NTE zone.

Route	No. of 5 Hz Data Points	Time (Min.)	Distance (Miles)	No. of Points In NTE	Percent in NTE	$N_{30sNTE\ Windows}$	A_{NTE}
Saltwell Road							
SAB2SW	10473	34.9	29.2	6063	58%	1916	0.32
SW2SAB	10584	35.3	29.5	5381	51%	1361	0.25
Total	21057	70.2	58.7	11444	54%	3277	0.29
Morgantown							
SAB2SAB	11631	38.8	20.4	4652	40%	908	0.20
Bruceton Mills							
SAB2BM	8541	28.5	20.0	4925	58%	2214	0.45
BM2SAB	8667	28.9	19.6	3885	45%	1953	0.51
Total	17208	57.4	39.7	8810	51%	4167	0.47
Washington							
WASHPA1	7701	25.7	12.2	2879	37%	266	0.09
WASHPA1	15676	52.3	23.4	5705	36%	901	0.16
WASHPA1	17041	56.8	51.7	9583	56%	2788	0.29
Total	40418	134.7	87.4	18167	45%	3955	0.22

3 ON-ROAD AND CHASSIS OPERATION OF MEMS

Two on-road tests and two chassis-based laboratory tests were performed with the Mack CH tractor that was used in the route development to evaluate the MEMS performance. The gross vehicle weight for these tests was a nominal 60,000 lbs. Two of the routes described above were used for the on-road tests. One of the on-road routes was replicated on a chassis dynamometer to provide a means to compare on-road MEMS data with laboratory data. A steady-state cycle was also used to evaluate MEMS on the chassis dynamometer. The results from the on-road and laboratory testing are described below.

3.1 On-Road Testing

Two routes were selected for the on-road MEMS evaluation. The SAB2SW route was selected to evaluate a highway driving route, and the SAB2SAB route was selected to evaluate a combination of urban, suburban, and highway driving routes. The results for the two routes are summarized in Table 2 and illustrated in Figure 8 to Figure 11, for the SAB2SAB route, and Figure 12 to Figure 15, for the SAB2SW route, for 30 second integrated NTE zone data. The integrated brake-specific mass emissions of carbon dioxide (CO_2) and oxides of nitrogen (NOx), the integrated ECU-derived power, and integrated mass emissions of CO_2 and NOx are shown in Table 2. It should be noted that, although humidity data was acquired, only uncorrected data is presented in this report.

Table 2 Summary of MEMS on-road integrated 30 second windows test results.

		CO_2 g/bhp-hr	NOx* g/bhp-hr	ECU Power hp-hr	CO_2 g	NOx* g
SAB2SW	Max.	501.0	6.902	3.457	1712.5	20.28
	Min.	427.4	4.444	1.754	937.6	11.37
	Ave.	481.5	5.305	3.228	1557.1	17.11
	Std. Dev.	11.6	0.567	0.284	149.4	1.47
SAB2SAB	Max.	505.0	5.788	3.459	1714.7	18.10
	Min.	399.8	4.265	2.332	932.4	11.47
	Ave.	480.5	5.030	3.185	1533.9	15.99
	Std. Dev.	17.1	0.322	0.311	182.0	1.61

* NOx reported as uncorrected values.

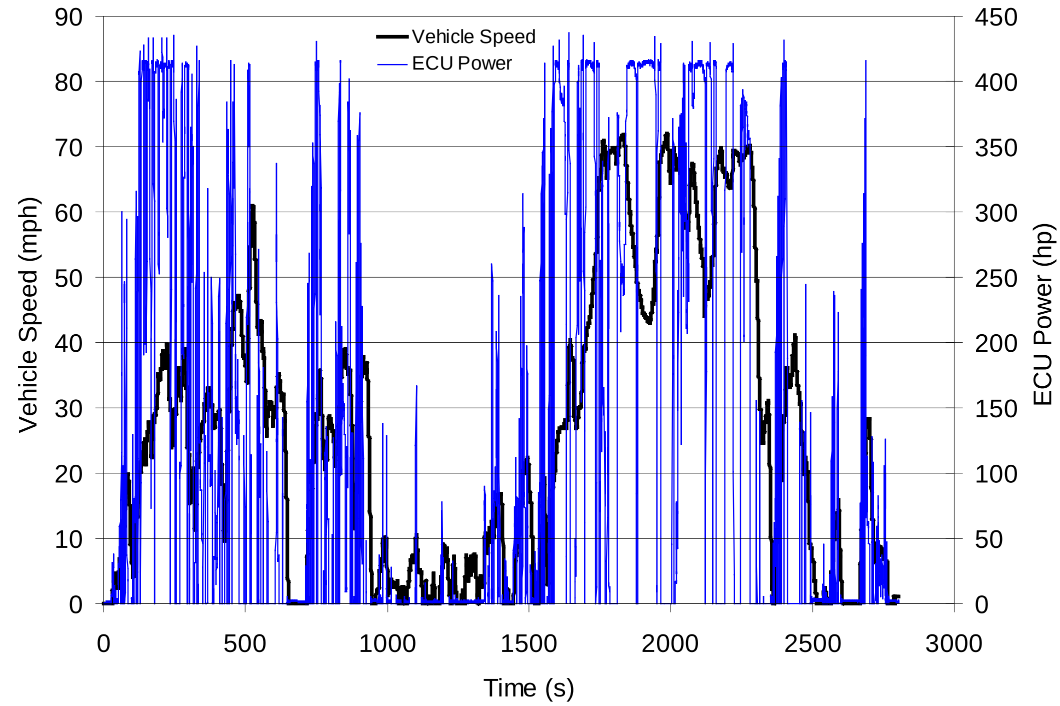


Figure 8 Mack tractor on-road SAB2SAB vehicle speed and ECU power history traces.

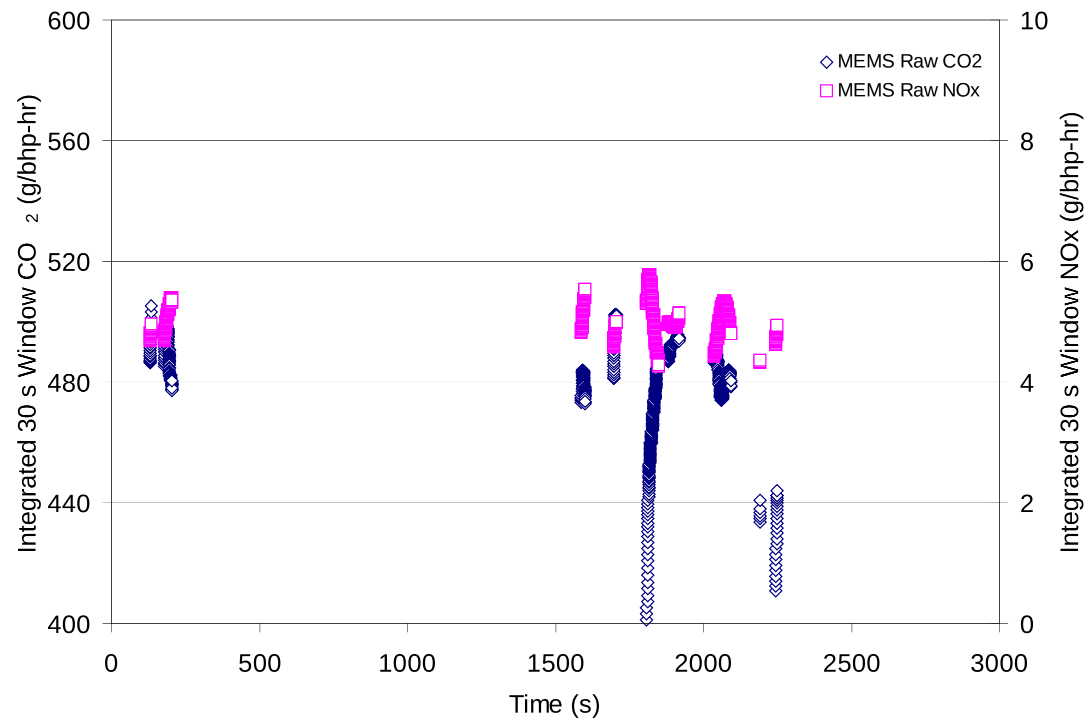


Figure 9 Mack tractor on-road integrated 30 second brake-specific mass emissions windows, SAB2SAB route.

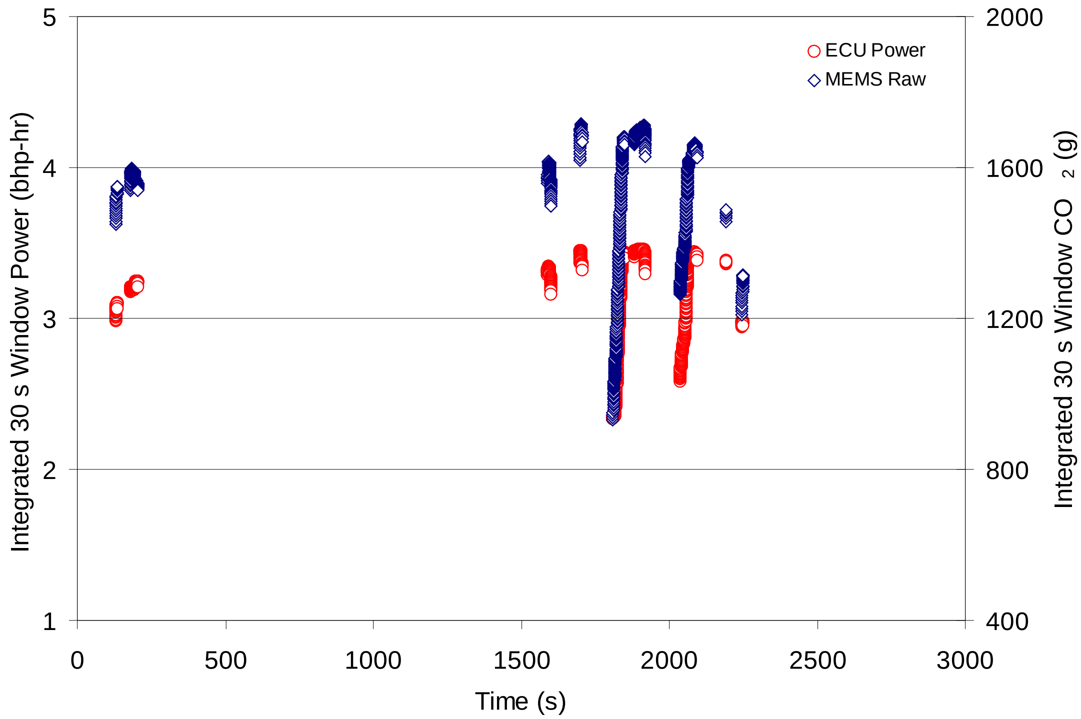


Figure 10 Mack tractor on-road integrated 30 second power and CO_2 mass emissions windows, SAB2SAB route.

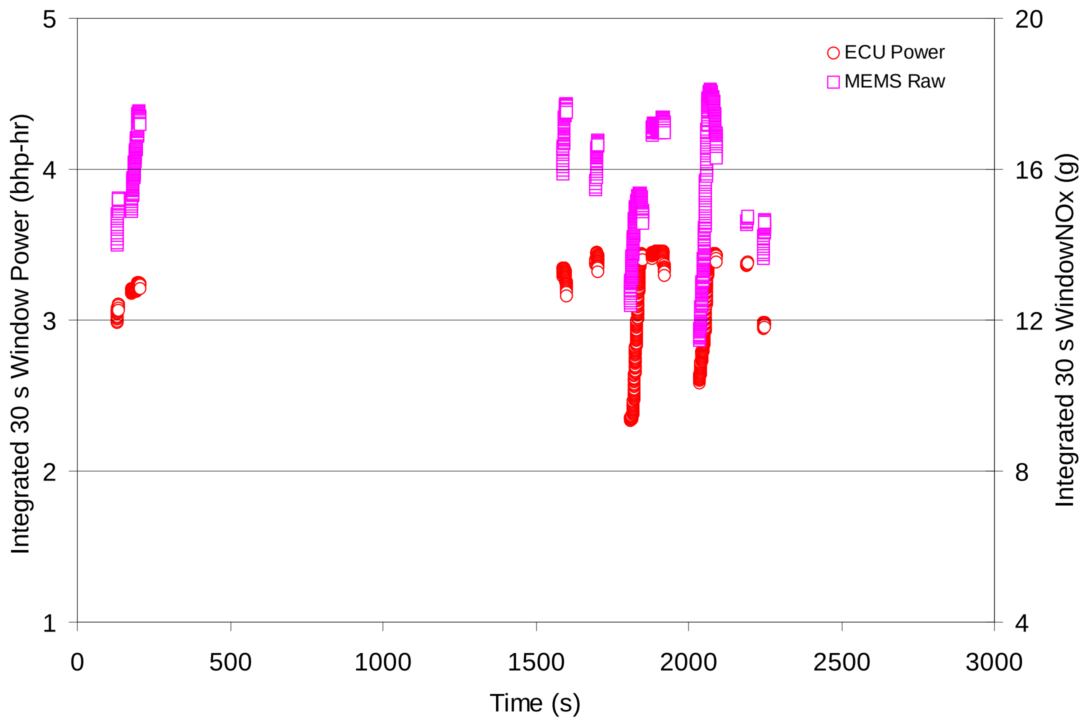


Figure 11 Mack tractor on-road integrated 30 second power and NOx mass emissions windows, SAB2SAB route.

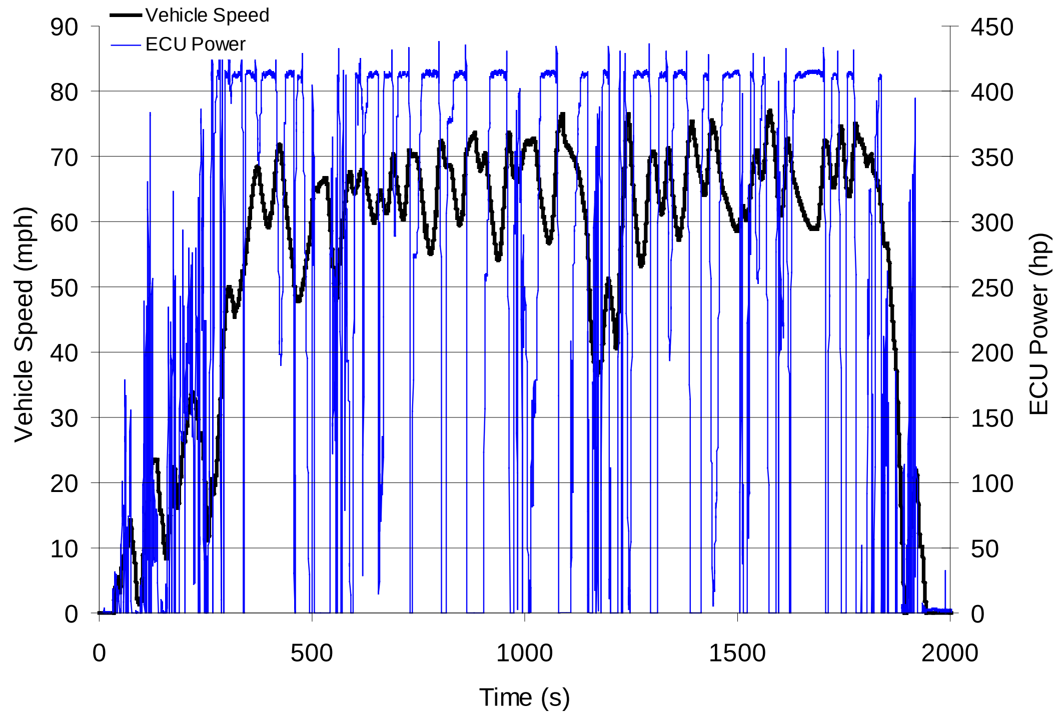


Figure 12 Mack tractor on-road SAB2SW vehicle speed and ECU power history traces.

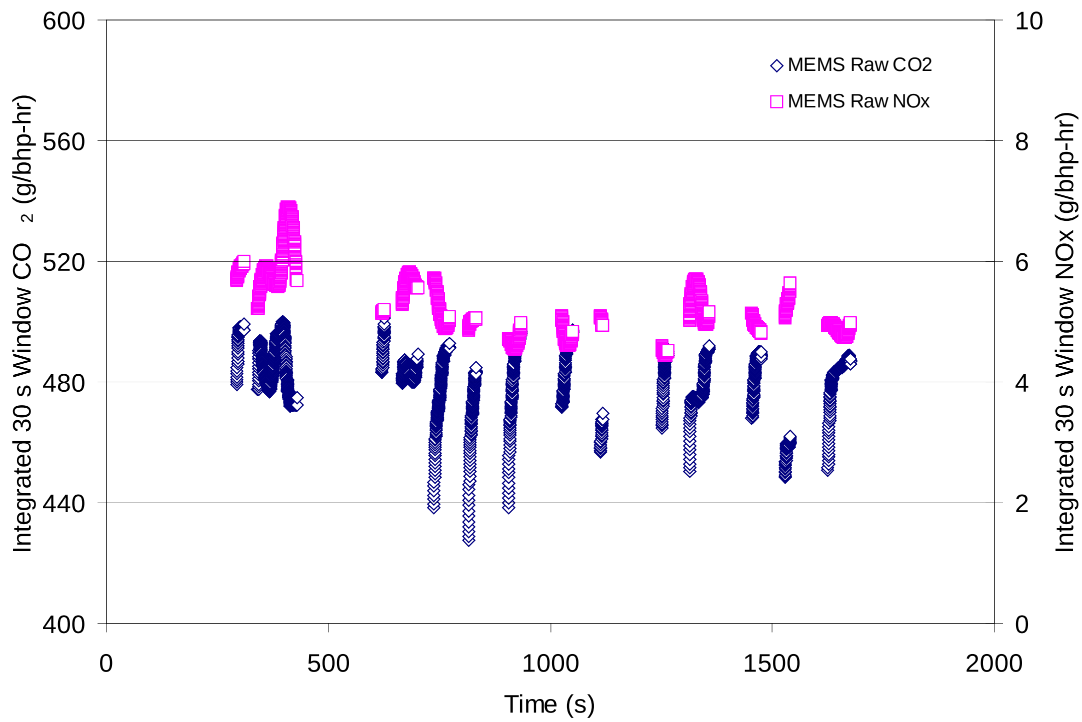


Figure 13 Mack tractor on-road integrated 30 second brake-specific mass emissions windows, SAB2SW route.

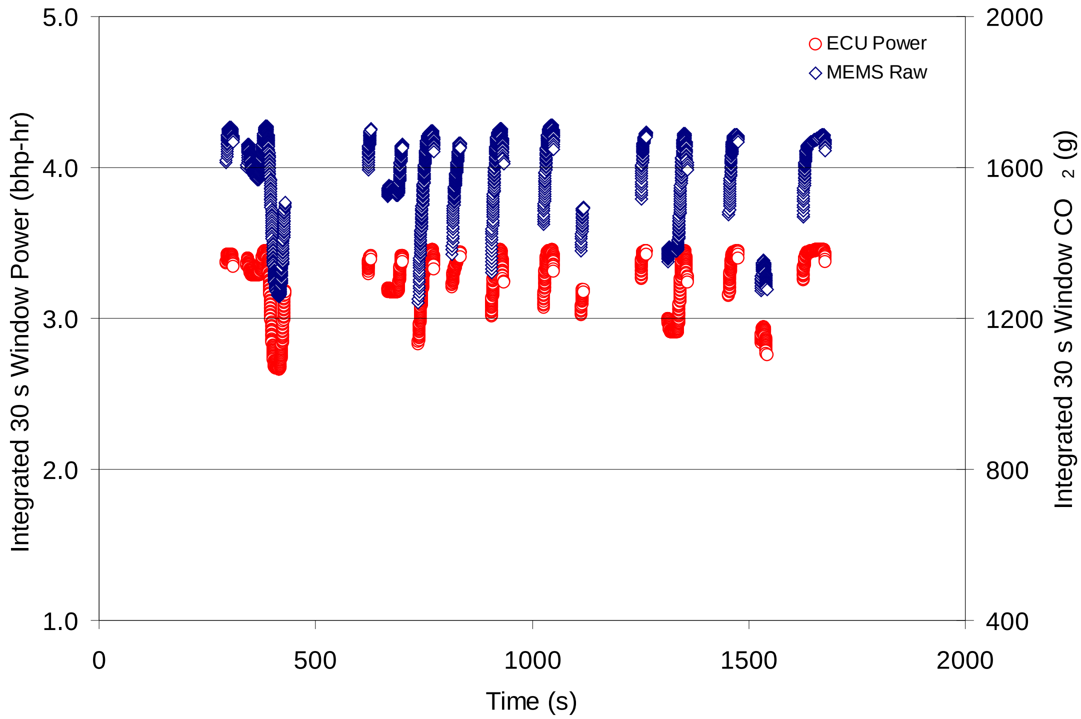


Figure 14 Mack tractor on-road integrated 30 second power and CO_2 mass emissions windows, SAB2SW route.

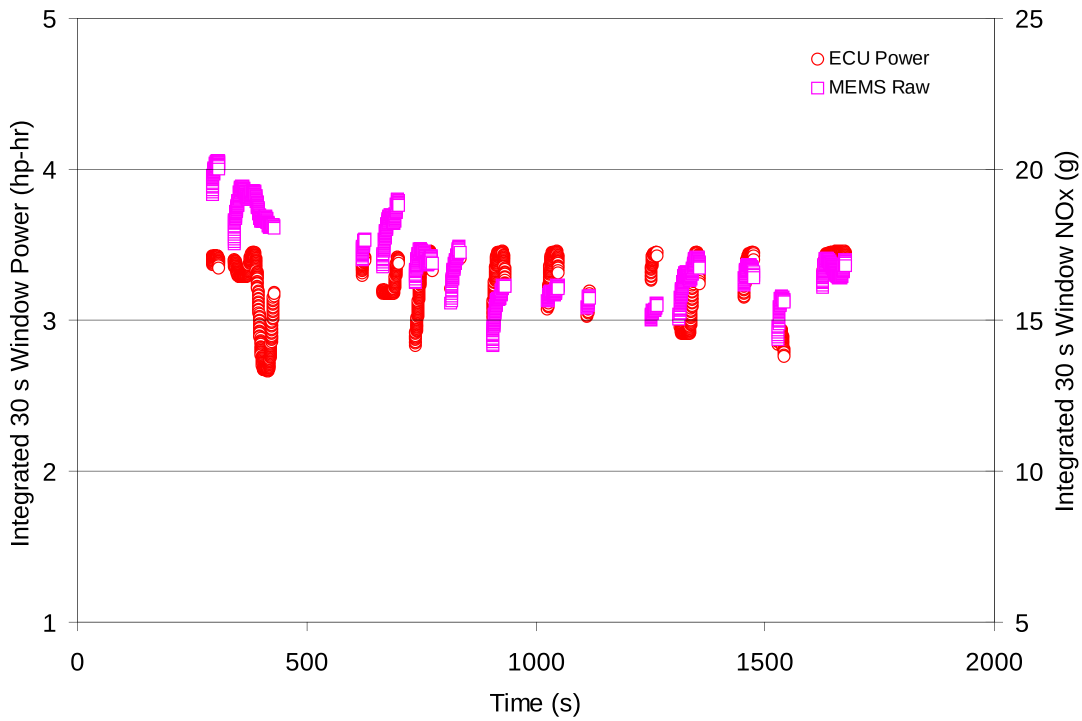


Figure 15 Mack tractor on-road integrated 30 second power and NOx mass emissions windows, SAB2SW route.

As illustrated in Figure 8, and discussed in the route development section above, there is a wide range of vehicle speeds in the SAB2SAB route. The SAB2SW route includes mainly highway driving. The ECU-derived engine power also illustrates the wide range of engine operation for these two routes. From the vehicle speed and ECU-derived power, it can be observed that common highway operation of HDDE vehicles does not necessarily correspond to zones of NTE operations. Gear changes during ascents and engine motoring during descents have dramatic impacts on engine power demands. Even level vehicle operation is significantly affected by prevailing traffic conditions. One of the longer NTE zones encountered in this testing was for the SAB2SW route, and it lasted for approximately 88 seconds (from 341 to 429 seconds).

The results of the on-road tests illustrate that the average brake-specific CO_2 mass emissions are 481 g/bhp-hr for the Morgantown (SAB2SW and SAB2SAB) routes. The average brake-specific mass emissions of NOx range from 5.31 g/bhp-hr, for the SAB2SW route, to 5.03 g/bhp-hr, for the SAB2SAB route. The maximum and minimum brake-specific mass emissions of CO_2 vary by approximately 100 g/bhp-hr, with a maximum standard deviation of 17.1 g/bhp-hr. However, the maximum and minimum span for the brake-specific mass emissions of NOx range from 4.44 to 6.90 g/bhp-hr for the SAB2SW route and from 4.27 to 5.79 g/bhp-hr for the SAB2SAB route. One explanation for the high brake-specific NOx mass emissions for the SAB2SW route shown in Figure 13 may be attributed to the ECU-derived power. As shown in Figure 13, the locations of greatest brake-specific NOx mass emissions coincide with periods of relatively low integrated power, as shown in Figure 14 and Figure 15. Errors in the broadcast ECU data, and the resulting ECU-derived power, may account for the low integrated power values.

As illustrated in the above figures, the integrated 30 second windows for power or mass emissions have the greatest change (slope) when entering an NTE zone from a motored condition. When the vehicle transitions from a downhill to a level or an uphill condition there is a rapid increase in engine load leading into the NTE zone. As a result, diffusion of measurements in time prevent precise alignment of mass emissions and power when processing the data.

3.2 Chassis Dynamometer

The Morgantown route (SAB2SAB), presented above, was transcribed in its entirety for use as a target trace in a chassis dynamometer test of the emissions produced by the Mack CH613 tractor. It should be noted that the on-road route consisted of rolling terrain resulting in engine loading that is significantly influenced by inclination. Chassis dynamometer vehicle loading is based upon flat road load equations and does not simulate road-grade loading. Therefore, the engine experienced different loading conditions on the chassis dynamometer compared to the on-road test. Further emissions measurements were made at various steady state speeds with the engine under load within the NTE zone. The steady state test consisted of three different vehicle speeds with varying amount of road load applied throughout the test. During the chassis tests, which were conducted using one of the WVU Transportable Heavy Duty Vehicle Emissions Testing Laboratories, emissions from the truck were measured both with the MEMS and the total dilute exhaust research grade analyzer system.

The WVU Transportable Heavy-Duty Vehicle Emissions Testing Laboratory has been in full-time operation since 1992, and provides exhaust emissions measurements according to the procedures set forth by the Code of Federal Regulations (CFR) 40, Part 86, Subpart N. The emissions measurement system and total exhaust double-dilution tunnel (CFV-CVS) system were designed coincident to those at the WVU Engine and Emissions Research Laboratory (EERL) as described in the Phase I report. With maintenance schedules, operation procedures, and system verification measures (for example the use of standard reference materials) that mimic those used at the EERL, the chassis laboratory is capable of producing emissions measurements at a level of accuracy equal to those made by the EERL.

The results for the two chassis dynamometer tests are summarized in Table 3 and illustrated in Figure 16 to Figure 20, for the SAB2SAB test, and Figure 21 to Figure 25, for the SSTEST test, for 30 second integrated NTE zone data. The integrated brake-specific mass emissions of CO_2 and NOx, the integrated ECU-derived power, and the mass emissions of CO_2 and NOx are shown in Table 3. A comparison of the integrated brake-specific CO_2 and NOx mass emissions between the MEMS and the laboratory data are shown in Table 4 for the two tests. It should be noted that, although humidity data was acquired, the NOx data presented for this work has not been corrected.

Table 3 Summary of MEMS chassis laboratory integrated 30 second windows test results.

		CO_2 g/bhp-hr	NOx* g/bhp-hr	ECU Power hp-hr	CO_2 g	NOx* g
SAB2SAB	Max.	510.0	6.947	3.449	1722.9	16.35
	Min.	438.0	3.948	2.097	959.3	8.53
	Ave.	484.1	4.605	3.006	1458.9	13.73
	Std. Dev.	17.5	0.610	0.530	278.9	2.34
SSTEST	Max.	531.7	4.411	3.005	1500.5	13.06
	Min.	497.0	3.467	1.583	786.5	5.65
	Ave.	511.9	3.818	2.240	1144.4	8.61
	Std. Dev.	8.9	0.238	0.333	153.7	1.71

* NOx reported as uncorrected values.

Table 4 Summary of MEMS and chassis laboratory integrated mass emissions cycle test results.

		CO_2 g	NOx* g
SAB2SAB	Laboratory	43217	429.1
	MEMS	41287	406.0
	Per. Diff.	-4.5%	-5.4%
SSTEST	Laboratory	30672	234.6
	MEMS	30004	229.5
	Per. Diff.	-2.2%	-2.2%

* NOx reported as uncorrected values.

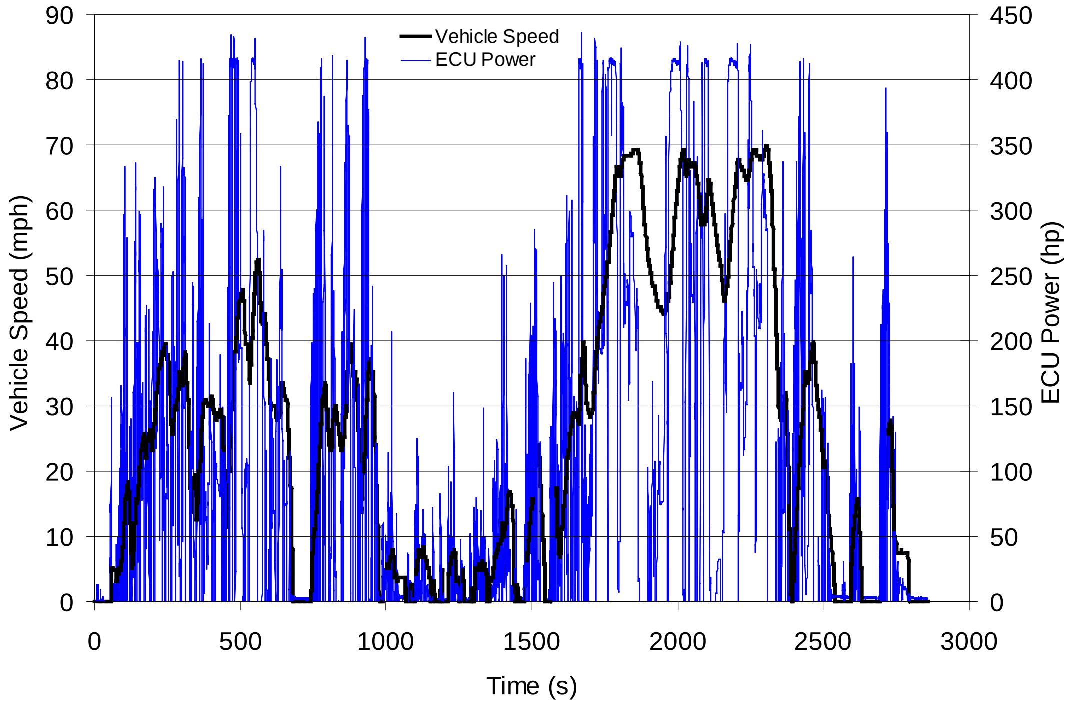


Figure 16 Mack tractor chassis dynamometer SAB2SAB vehicle speed and ECU power history traces.

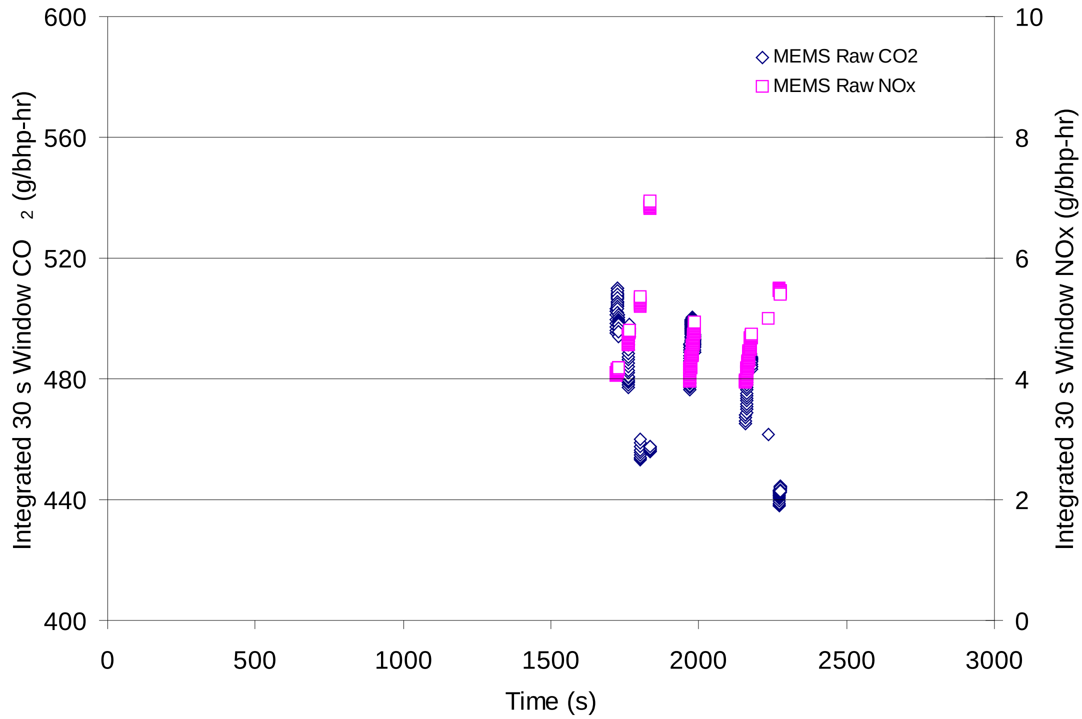


Figure 17 Mack tractor chassis dynamometer integrated 30 second brake-specific mass emissions windows, SAB2SAB cycle.

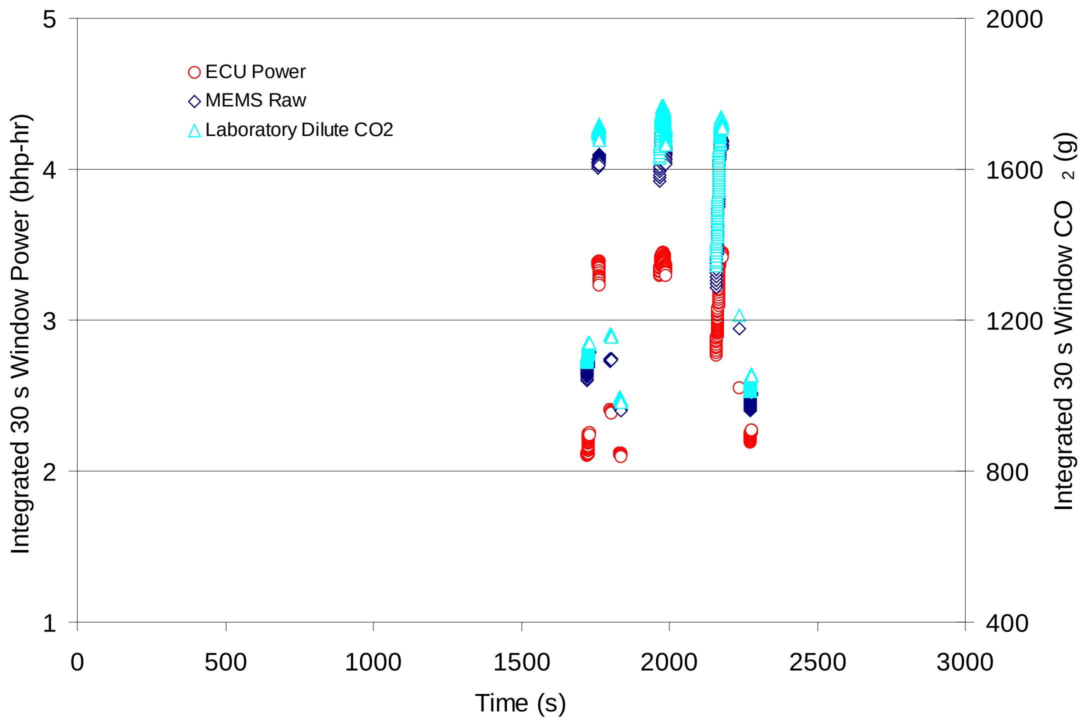


Figure 18 Mack tractor chassis dynamometer integrated 30 second power and CO_2 mass emissions windows, SAB2SAB cycle.

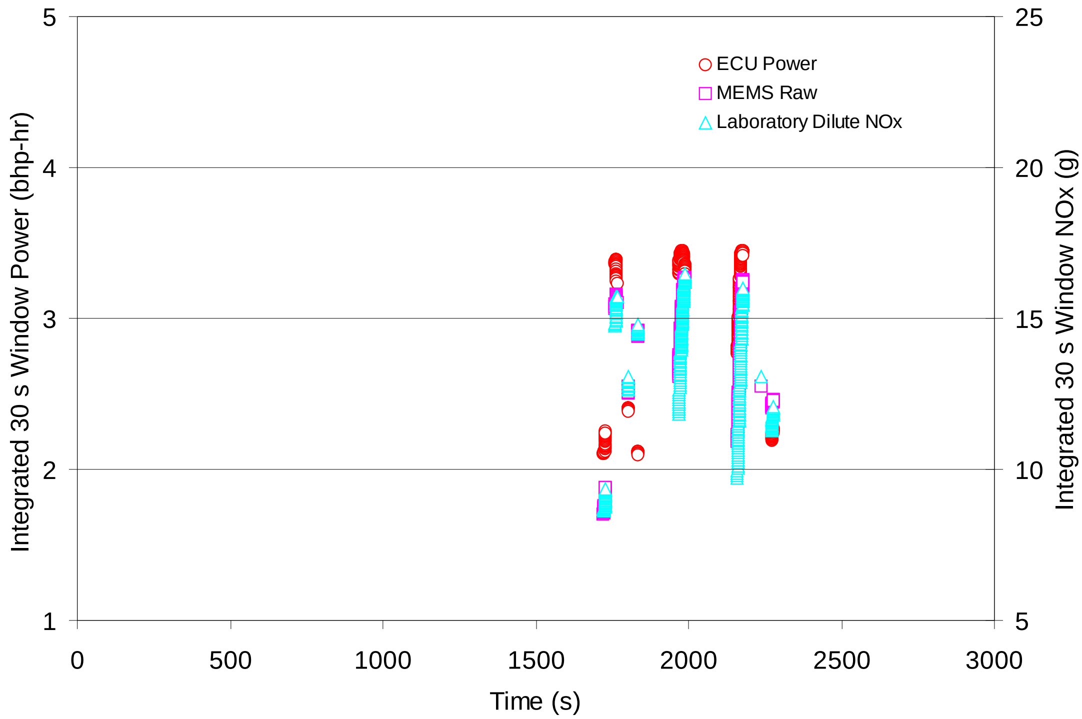


Figure 19 Mack tractor chassis dynamometer integrated 30 second power and NOx mass emissions windows, SAB2SAB cycle.

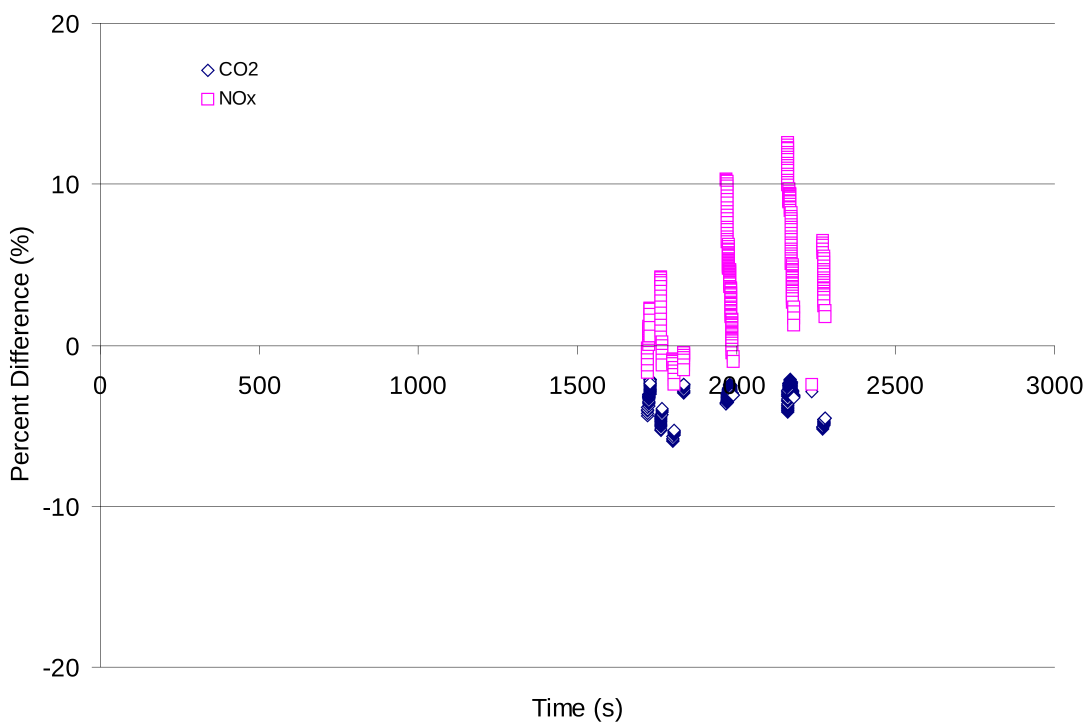


Figure 20 Mack tractor chassis dynamometer integrated 30 second brake-specific mass emissions percent differences between MEMS and laboratory, SAB2SAB cycle.

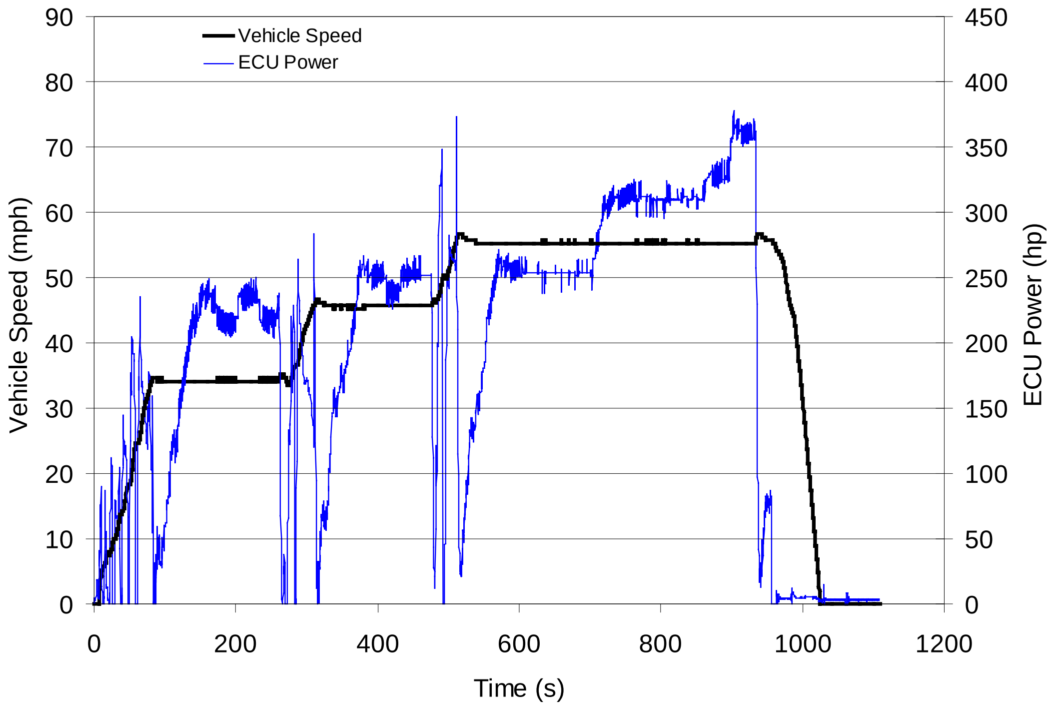


Figure 21 Mack tractor chassis dynamometer SSTEST vehicle speed and ECU power history traces.

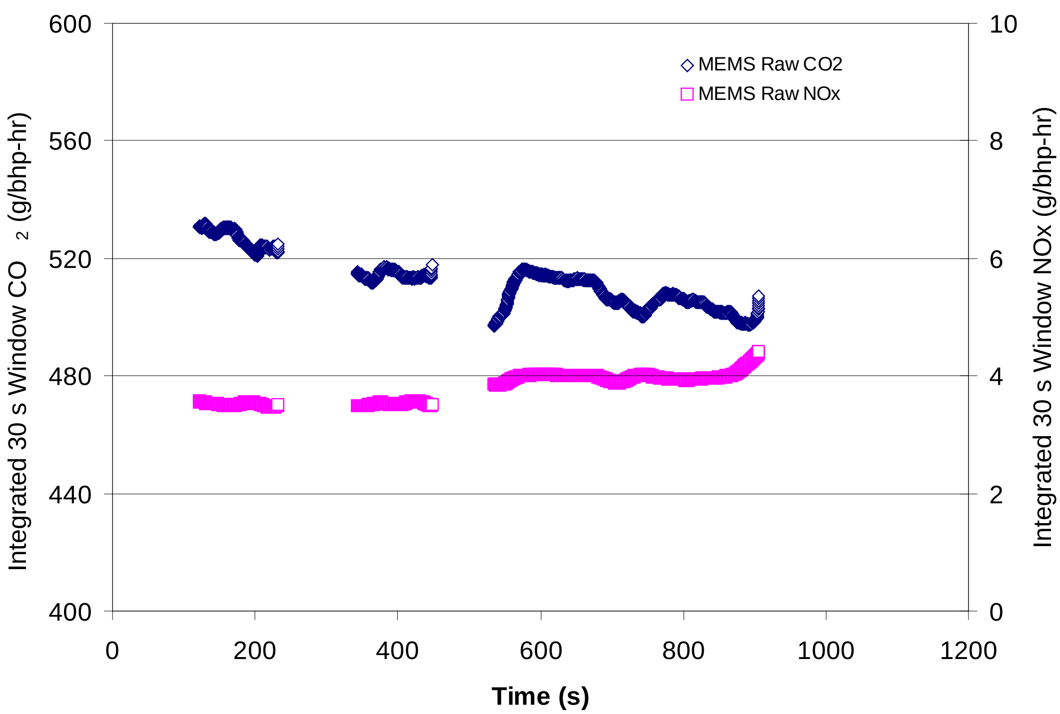


Figure 22 Mack tractor chassis dynamometer integrated 30 second brake-specific mass emissions windows, SSTEST cycle.

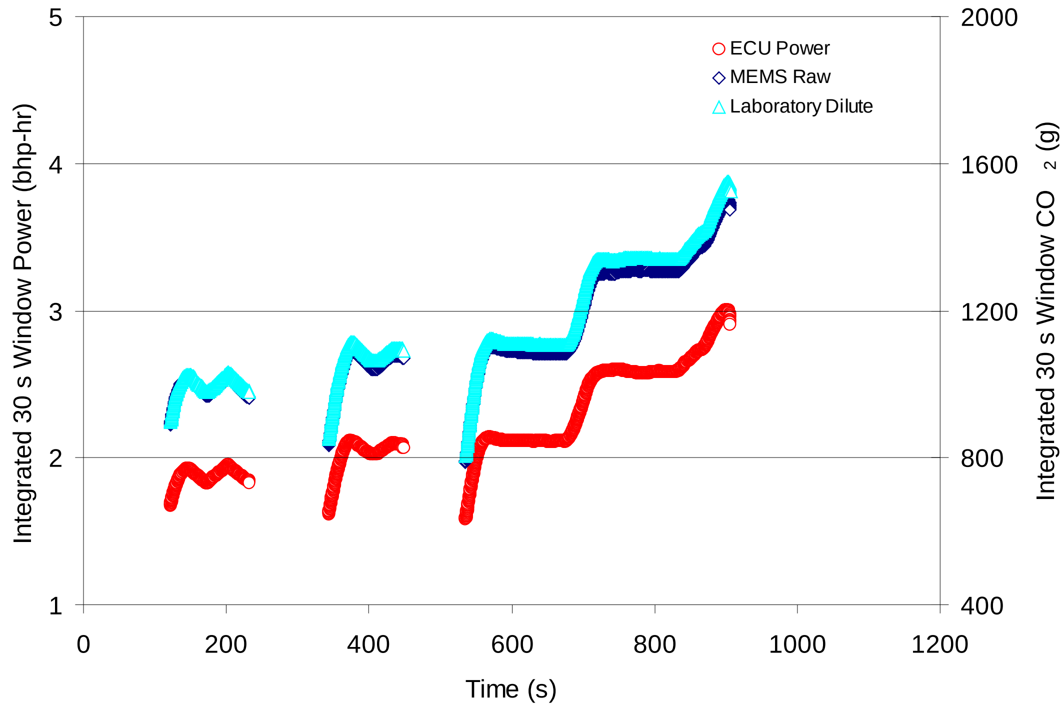


Figure 23 Mack tractor chassis dynamometer integrated 30 second power and CO_2 mass emissions windows, SSTEST cycle.

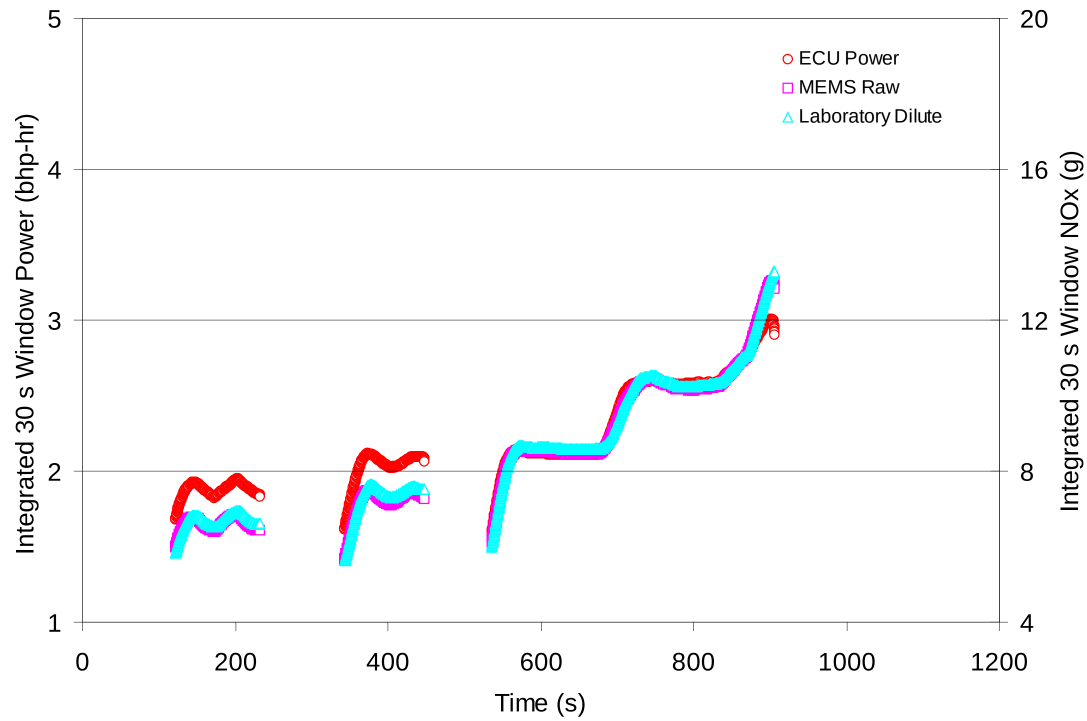


Figure 24 Mack tractor chassis dynamometer integrated 30 second power and NOx mass emissions windows, SSTEST cycle.

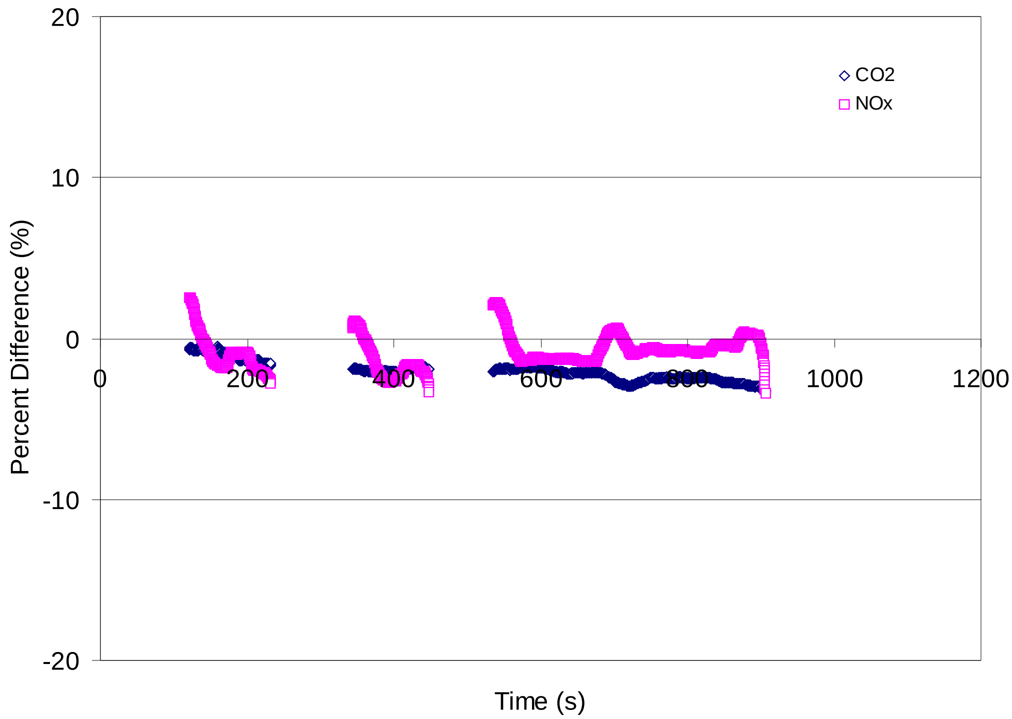


Figure 25 Mack tractor chassis dynamometer integrated 30 second brake-specific mass emissions percent differences between MEMS and laboratory, SSTEST cycle.

The MEMS results from the chassis dynamometer tests show that the average brake-specific mass emissions of CO_2 varied from 484 g/bhp-hr, for the SAB2SAB simulation cycle, to 512 g/bhp-hr, for the SSTEST test. The average brake-specific mass emissions of NOx range from 4.61 g/bhp-hr, for the SAB2SAB cycle, to 3.82 g/bhp-hr, for the SSTEST test. The span for the brake-specific mass emissions of CO_2 had a range of approximately 70 g/bhp-hr, with a standard deviation of 17.5 g/bhp-hr, for the SAB2SAB cycle. However, the SSTEST test had a range of only 35 g/bhp-hr, between the minimum and maximum, with a standard deviation of only 8.9 g/bhp-hr. The maximum and minimum span for the brake-specific mass emissions of NOx ranges from 3.95 to 6.95 g/bhp-hr for the SAB2SAB cycle, and from 3.47 to 4.41 g/bhp-hr for the SSTEST test.

Similar results were obtained with the MEMS for both on-road and chassis dynamometer test bed vehicle operations. As illustrated in the on-road SAB2SAB test, Figure 4 to Figure 11, and the replicated chassis dynamometer SAB2SAB test, Figure 16 to Figure 20, the brake-specific CO_2 and NOx mass emissions followed similar trends. Observed variations may be attributed to the errors associated with the inference of power from ECU broadcast data.

A comparison of CO_2 mass emissions data from the MEMS and the laboratory for integrated 30 second NTE zones that occurred during the SAB2SAB chassis dynamometer test indicates good agreement. As shown in Figure 20, the difference in brake-specific CO_2 mass emissions between MEMS and the laboratory varied from –2.2 to –6.0%, with an average difference of –3.3%. However, the differences between MEMS and the laboratory for brake-specific NOx mass emissions varied from –2.4 to 12.6%, with an average difference of 4.4%. A very good agreement between MEMS and the laboratory was observed for both CO_2 and NOx for the SSTEST test. As illustrated in Figure 25, the difference in the brake-specific CO_2 mass emissions varied between –0.51 and –3.30%, with an average difference of –2.1%. Likewise, differences in brake-specific NOx mass emissions varied between –3.45 and 2.52%, with an average difference of –0.84%.

3.3 Summary of MEMS Results

As illustrated in the above figures, the integrated 30 second windows for the power or mass emissions have the greatest change (slope) when entering an NTE zone from a motored condition. When the vehicle transitions from a downhill to a level or an uphill condition there is a rapid increase in engine load leading into the NTE zone. A comparison between the on-road SAB2SAB test and the replicate SAB2SAB chassis dynamometer test exhibited similar trends.

A summary of the integrated brake-specific CO_2 and NOx mass emissions for the two on-road and two chassis dynamometer tests is given in Table 5. The test time, average brake power, cycle work, and duty factor is given for each test. As illustrated in this table, the brake-specific mass emissions for all the tests are similar. It should be noted that the NOx brake-specific mass emissions are reported as corrected values in this table. The NOx correction factors were obtained according to CFR 40 Part 86 procedures using on-board ambient temperature, pressure, and relative humidity sensors that are incorporated into the MEMS. The good agreement between the integrated mass emissions as measured by the MEMS and the research-grade analyzers of the chassis laboratory (Table 4) indicates that the on-road emissions data are faithfully recorded with the MEMS. This conclusion is further reinforced by the good agreement exhibited between the values obtained from the actual driving route (on-road test) and chassis-based cycle replication of the SAB2SAB route (Table 5).

Table 5 Summary of MEMS integrated cycle test results.

	Test Time hr	Ave. Brake Power hp	Work hp-hr	Duty Factor(1) -	CO_2 g/bhp-hr	NOx g/bhp-hr
On-Road SAB2SW	0.557	231.60	128.88	0.557	501.3	4.386
SAB2SAB	0.779	120.88	94.19	0.291	0.779	4.627
Chassis SAB2SAB	0.784	101.48	79.52	0.244	519.2	4.411
SSTEST	0.303	190.48	57.62	0.458	520.7	3.501

(1) Duty factor defined as the average ECU-derived brake power divided by the maximum power (lug curve) of the engine.

4 PROCEDURES

Candidate driving routes representing typical urban, suburban, and highway driving have been discussed in Chapter 2 of this report. WVU has developed in-use testing procedures that will be used in connection with Phases III and IV of the In-Use Testing Program. The procedures will be used for in-use emissions testing of heavy-duty diesel-powered vehicles with the best available on-road emissions measurement system (OREMS). Extensive laboratory and on-road evaluations, conducted with the currently available OREMS, have revealed that the system integrated by WVU, the MEMS, yielded the most accurate and repeatable results. The Phase I Final Report describes the MEMS in detail. The development of in-use testing procedures has been based upon testing of HDDEs engaged in typical on-road missions, and in a variety of seasonal conditions. A brief overview of the MEMS is followed by a set of procedures for conducting in-use emissions testing of heavy-duty diesel-powered vehicles. WVU will modify the procedures depending upon the feedback from the US EPA regarding the MEMS.

4.1 Overview of MEMS

4.1.1 Exhaust Mass Flow

The MEMS relies upon a differential pressure flow meter for the direct measurement of exhaust flow rate. Currently, an Annubar or a venturi flow meter is incorporated into the MEMS. These devices can account for the exhaust pulsations that are produced by an internal combustion engine, and, when used in the same nominal pipe size as the vehicle's exhaust system, produce minimal additional exhaust backpressure on the engine. For on-road testing, three different nominal flow meter sizes are employed. To calculate exhaust mass flow rate, a differential pressure transducer, an absolute pressure transducer, and a temperature transducer are used to interpret the flow meter signal.

4.1.2 Engine Torque and Speed

Engine torque and speed are available via an ECU protocol adaptor through a serial interface with the data acquisition system. Engine torque is inferred from the ECU's broadcast signal of percent load, the measured zero flywheel load curve, and the manufacturer supplied lug curve. Engine speed is available directly from the ECU broadcast. Engine load and speed data are available at a 10 Hz rate.

4.1.3 Emissions Sampling System

The MEMS employs a non-dispersive infrared (NDIR) solid-state detector for the measurement of CO_2, and a zirconium oxide (ZrO_2) sensor for NOx determination. An electrochemical cell is employed as a QC/QA measure. It should be noted that, although the NDIR system is capable of measuring hydrocarbons (HC) and carbon monoxide (CO), the resolution of the microbench is substandard for diesel applications.

4.1.4 Exhaust Sample Conditioning System

A schematic of the proposed sampling system for MEMS is shown in Figure 26. The generalized system consists of a sampling probe, a heated line, a heated filter, a heated-head pump, an external nitrogen dioxide (NO_2) converter, and a thermoelectric chiller. The MEMS sampling probe is a 0.25-inch diameter stainless steel tube with nine sampling holes, designed in accordance with the CFR 40 Part 89.412.96. The sampling line is a 0.25-inch stainless steel reinforced Teflon tube with the wall temperature maintained at 250°±20° F. A heated filter assembly and heated-head diaphragm pump route the sample through a NO_2 converter. Prior to introduction into the gas analyzers/sensors, a thermoelectric chiller is used to remove sample water vapor and reduce the sample stream temperature to levels compatible with the measurement devices. It should be noted that the pump is capable of providing flow rates in excess of those required by the analyzers. This in turn, minimizes the residence time of the sample within the heated sampling line, resulting in improved transient resolution. The excess flow is by-passed upstream of the NO_2 converter.

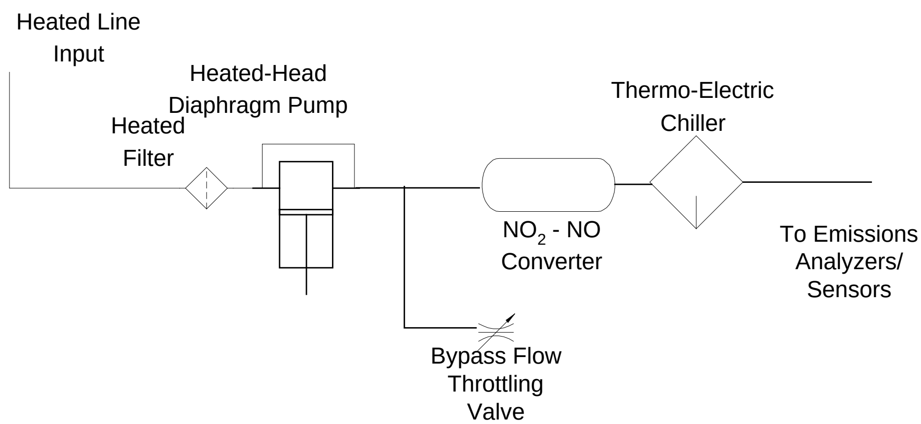


Figure 26 Proposed MEMS sampling system.

4.1.5 Vehicle Speed and Distance

Vehicle speed is available via ECU broadcast, which permits the inference of vehicle distance traveled. However, due to the variety of in-field arrangements of drivetrain components, a GPS is used to provide a QC/QA measure for ECU-inferred vehicle speed measurements. Testing experience has suggested that the GPS signal provides an accurate and precise means of measuring vehicle speed.

4.1.6 Data Acquisition, Reduction, and Archival System

The data acquisition system employed by the MEMS is a National Instruments PXI-1025. The platform consists of a National Instruments multifunction 6071E data acquisition card that interfaces to a signal conditioning box, a National Instruments Temperature/Voltage 4351 card, and a RS-232 serial card. The configuration employs a National Instruments PXI-8156B embedded computer, which allows access to two serial ports, a USB port, a GPIB interface, as well as hard, floppy, and CD drives.

4.2 Vehicle Selection

Vehicle selection and recruitment will be a relatively complex task. However, the selection of test vehicles will have to be done in collaboration with the manufacturers because of issues related to the broadcast of engine performance parameters (engine speed and percent load) via the ECU. Vehicles should be randomly selected from a limited number of families during the period when electronically-controlled engines were introduced into the market. Only those engines that are equipped with ECU's that provide either percent load or torque (considered very unlikely), and speed signals can be tested. Lug curves should be obtained from the manufacturer for the selected test vehicles to enable translation of percent load data to engine torque values.

Only engines with a SAE J1587 or J1939 interface can be tested for the Consent Decrees work, due to the availability of the percent load signal from the ECU. As illustrated in the tables below, not all manufacturers' post 1988 model years can be tested per requirements of the Consent Decrees. The nomenclature used in Table 6 to Table 10 is as follows: A=SAE J1922, B=SAE J1587, C=SAE J1939. As illustrated in the tables, the earliest engine from Cummins that can be tested is a model year (MY) 1991; Caterpillar MY 1991, but may be difficult to find an engine until MY 1994; Volvo MY 1994; Mack MY 1995; and Detroit Diesel 1994.

Table 6 Cummins Engine Corporation protocol usage chart (A: SAE J1922, B: SAE J1587, C: SAE J1939).

	Engine								
Model Year	L10	M11	N14	Sig600	ISX	ISL	ISM	ISC	ISB
1988									
1989									
1990									
1991	A, B		A, B						
1992	A, B		A, B						
1993	A, B		A, B						
1994		A, B	A, B						
1995		A, B, C	A, B, C						
1996		A, B, C	A, B, C						
1997		A, B, C	A, B, C						
1998		A, B, C	A, B, C	B, C			B, C	B, C	B, C
1999		A, B, C	A, B, C	B, C	B, C	B, C	B, C	B, C	B, C
2000		A, B, C	A, B, C	B, C	B, C	B, C	B, C	B, C	B, C
2001		A, B, C	A, B, C	B, C	B, C	B, C	B, C	B, C	B, C
2002									
2003									

Table 7 Caterpillar, Inc. protocol usage chart (A: SAE J1922, B: SAE J1587, C: SAE J1939).

	Engine		
Model Year	3406	3176/C-10/ C-12	3100
1988*	B		
1989*	B	B	
1990*	B	B	
1991*	A, B	A, B	
1992*	A, B	A, B	
1993*	A, B	A, B	
1994	A, B	A, B	
1995	A, B	A, B	B
1996	A, B	A, B	B
1997	A, B	A, B	B
1998	A, B	A, B	B
1999**	A, B, C	A, B, C	B, C
2000**	A, B, C	A, B, C	B, C
2001**	A, B, C	A, B, C	B, C
2002**	A, B, C	A, B, C	B, C
2003**	A, B, C	A, B, C	B, C

* Sold mostly mechanical engines in this time period.

** GM chassis did not have the J1939 data link, non-GM did (3100 only).

J1587 has been installed in all electronic engines and chassis. J1922 and J1939 are in the ECU but not always used in the trucks.

Table 8 Volvo Truck Company protocol usage chart (B: SAE J1587, C: SAE J1939).

	Engine	
Model Year	12l	7l
1988*		
1989*		
1990*		
1991*		
1992*		
1993*		
1994	B	
1995	B	
1996	B	
1997	B	
1998	B, C	B, C
1999	B, C	B, C
2000	B, C	B, C
2001	B, C	B, C
2002	B, C	B, C
2003	B, C	B, C

* Sold only mechanical engines in this time period.

Table 9 Mack Trucks Inc. protocol usage chart (B: SAE J1587, C: SAE J1939).

	Engine Controller		
Model Year	V-Mac I(1)	V-Mac II	V-Mac III
1988	X		
1989	X		
1990	X		
1991	X		
1992	X		
1993	X		
1994	X		
1995		B	
1996		B	
1997		B	
1998		B	
1999			B, C
2000			B, C
2001			B, C
2002			B, C
2003			B, C

(1) V-Mac I did not include a percent load signal and cannot be used.

Table 10 Detroit Diesel Corporation protocol usage chart (A: SAE J1922, B: SAE J1587, C: SAE J1939).

	Engine Controller			
Model Year	*On-Highway DDEC® II*	*On-Highway DDEC® III*	*On-Highway DDEC® IV*	*On-Highway DDEC® V*
1988*	B			
1989*	B			
1990*	A, B			
1991*	A, B			
1992*	A, B			
1993*	A, B	A, B, C		
1994		A, B, C		
1995		A, B, C		
1996		A, B, C		
1997		A, B, C	A, B, C	
1998			A, B, C	
1999			A, B, C	
2000			A, B, C	
2001			A, B, C	
2002			A, B, C	B, C
2003				B, C

* Calibration of torque output signal not institutionalized prior to 1994. Prior years cannot be used.

Once the test vehicles are received, they will have to be inspected and prepared for on-road testing. The S-HDDE should provide support, through their reliability/field-service representatives, in the inspection of all potential test vehicles. The intake air filters should be replaced on all vehicles prior to any testing. The test fuel should be the vehicles' in-use fuel. It should be noted that the in-use fuel type (diesel no. 1 or diesel no. 2) may differ from the fuel which was used to generate the lug curves (to be provided by the manufacturer). Further, it should be noted that, because the vehicles will be tested on an in-use commercially available on-highway diesel fuel, the emissions may differ from those obtained from vehicles operated on certification diesel fuel.

Vehicles with fifth-wheel trailering capability and a gross vehicle weight rating (GVWR) of 80,000 lbs. should be tested with the vehicle loaded to within 5% of the GVW rating. Fifth-wheel equipped trucks with GVWR's other than 80,000 lbs. should be tested with the vehicle loaded to within 5% of GVWR. It should be noted that the GVWR approved by the state in which the vehicle is operated (and tested) will override all other GVW ratings. Under no circumstances should the vehicles be loaded to greater than the GVWR.

Concrete barriers may be mounted on a flat-bed trailer to load trucks with fifth-wheel trailering capability. Concrete blocks of varying weights can also be used to provide weight adjustments in order to meet the requirements of the Consent Decrees.

4.3 Definition of MEMS Test Terminology

For MEMS testing, a test route (or route) will be defined as any candidate on-road driving schedule. A segment of a route will, therefore, be defined as any portion of a route. A route sequence is comprised of a test route and the subsequent replicates of this route. Finally, a vehicle test series will be defined as all MEMS testing activities that are performed for a given vehicle. That is, a vehicle test series is comprised of one or more route sequences.

4.4 Preliminary Test Information

1. All vehicle performance/maintenance inspection is to be performed prior to the installation of the MEMS. Any identified problems should be documented on the appropriate pre-test data sheet(s), see Attachment 1 and Attachment 2.
2. The vehicle identification number (VIN) and engine identification number should be recorded and compared to the manufacturer's documentation. This information will be used to verify that the lug curve, provided by the manufacturer, is correctly assigned to the specific test vehicle/engine combination. The engine lug curve information for the test vehicle should be recorded on the respective pre-test data sheet(s), along with all pertinent vehicle information, such as VIN, GVWR, etc. (see Attachment 1).
3. Prior to MEMS installation, the vehicle should be weighed on a reference scale in order to provide an accurate measurement of "as-tested" vehicle weight. This value should be used to supersede manufacturer data for all data reporting/processing purposes.
4. Vehicle loading should be accomplished according to the GVWR approved by the state in which the vehicle is operated (and tested). The specific state ratings should override all other GVW ratings. Under no circumstances should the vehicles be loaded to greater than the GVWR. For vehicles with fifth-wheel trailering capability and a gross vehicle weight rating (GVWR) of 80,000 lbs., the vehicles should be tested with the vehicle loaded to within 5% of the GVW rating. Fifth-wheel equipped trucks with GVWR's other than 80,000 lbs. should be tested with the vehicle loaded to within 5% of the GVWR.
5. A visual safety inspection of the vehicle should be performed prior to any on-road testing. The focus is not the insurance of current vehicle performance status, but rather safety issues related to the driveline, braking system, and general vehicle integrity. The pre-test vehicle checks shall be recorded in the data sheets shown in Attachment 1 and Attachment 2.
6. Vehicle fuel supply tanks should be visually inspected to ensure that there is no contamination with off-highway fuel. At the onset of testing, the supply tanks should

be filled with locally-available on-highway grade diesel fuel. For emissions data reduction purposes, the fuel properties for current on-highway diesel fuel, per CFR 40 specifications, should be used.

7. The ECU protocol adapter should be inspected by the appropriate calibration personnel. The performance of each adapter is very unique and the manufacturer serial number of the specific adapter used for each vehicle test should be recorded in a pertinent data sheets. The performance specifications of each protocol adapter significantly affects time-alignment procedures that are performed during post-test data reduction.

4.5 Installation Procedures

1. In order to accommodate the additional power requirements necessitated by a MEMS, a portable generator set is recommended that is capable of providing 5kW of 120 volts AC power. Such a system reduces problems associated with off-peak charging vehicle operations during a test, which poses significant limitations on the use of power inverters. The generator set should be installed on the vehicle using DOT-approved tie-downs, and the grounding strap should be securely attached to the vehicle chassis. Supply power cords should be routed so as to prevent damage, and strain relief should be employed to accommodate relative movement of the chassis/body.
2. Securely mount the MEMS data acquisition system in the cab of the test vehicle. Both the signal conditioning enclosure and computer should be secured with load straps to prevent movement. Supply power to the MEMS data acquisition components and turn these units on.
3. Supply power to the emissions analyzer components at least one hour prior to testing in order to allow temperatures to stabilize. Note: the pump head temperature controller must reach 250°F before the pump is turned on in order to prevent seal failure.
4. Connect the signal conditioning enclosure to the computer's data acquisition card using the supplied interface cable. This cable is system specific – no alterations or substitutions should be performed.
5. Select the appropriate size exhaust flow meter test section. The selection criteria shall be based upon engine size, vehicle exhaust configuration, and manufacturer specifications for maximum allowable engine exhaust backpressure. Further details on selection criteria will become available pending the final approval of the MEMS.
6. Select the appropriate range of the differential pressure transducer. This selection is largely based upon the selection of the exhaust flow meter test section.
7. Install the exhaust flow meter test section on the vehicle exhaust system. When installing the exhaust flow meter test section, the alignment of the flow device should be verified. All connection interfaces should be cleaned and sealed with high-temperature aluminum tape. These connections should be lap fit connections (butted connections are not recommended) and the appropriate lap-fit exhaust clamps should be used in order to minimize leakage. These interfaces should be visually inspected before the initial test cycle and between each subsequent test cycle. The exhaust flow meter test section shall be installed at the end of the exhaust system. For dual exhaust

configurations, a Y-connection shall be implemented so that the entire exhaust stream is sampled by the exhaust flow meter test section.

8. Securely install the exhaust flow rate measurement pressure transducer enclosure onto the exhaust flow meter test section.
9. Connect the differential and absolute pressure ports to the respective pressure transducers. The lines should be routed in such a manner as to prevent pinching or rupturing. All lines should be strain-relieved in order to prevent damage due to on-road vibration and relative movement between the flow meter test section and the transducer enclosure.
10. Install the pre- and post-thermocouples into the exhaust flow meter test section at their respective locations.
11. Connect the pressure transducer box and thermocouples to the data acquisition system. It is recommended that the wiring be routed through side access doors or through the passenger-side window of the vehicle's cab. In any event, the wiring should be routed in such a manner as to prevent pinching and should be strain-relieved in order to prevent damage due to on-road vibration and relative movement between vehicle chassis/body components.
12. Install the relative humidity transducer on the outside of the cab in a location that is shielded from direct air flow and contamination from road debris. The location should be as close to the exhaust flow meter test section as possible to minimize data acquisition cable connection requirements.
13. Install the thermocouple near the location of the humidity sensor. The thermocouple should be shielded from any radiative effects of the road or vehicle exhaust.
14. Install ambient absolute pressure transducer in the cab of the test vehicle. The mounting location shall be selected such that air motion effects on the sensor are minimized.
15. Connect the relative humidity sensor, thermocouple, and ambient absolute pressure transducer to the data acquisition system. It is recommended that the wiring be routed through side access doors or through the passenger-side window of the vehicle's cab. In any event, the wiring should be routed in such a manner as to prevent pinching and should be strain-relieved in order to prevent damage due to on-road vibration and relative movement between vehicle chassis/body components.
16. Identify the ECU protocol(s) that are compatible with the test vehicle.
17. Locate the ECU and connect the appropriate protocol adapter. The interface connections shall be routed in such a manner as to provide minimum interference to vehicle occupants. In addition, the unit should be securely mounted in the cab of the test vehicle in a location that does not permit unnecessary moisture, vibration, or excessive operating temperatures.
18. Connect the protocol adaptor to the data acquisition system via a serial port interface. Correct communication is verified by a status light on the protocol adapter, with the vehicle's engine running.

19. Securely attach the GPS signal antenna to the chassis of the test vehicle. The antenna should be mounted at the highest possible location, without risking interference with any obstructions encountered during on-road operation. Attachment shall be accomplished with either a magnetic or fixed mount post, and it is preferred that the location be chosen so as to facilitate common routing of data acquisition cables with those used for the exhaust flow rate measurement.

20. The GPS unit should be securely mounted in the cab of the test vehicle in a location that does not interfere with vehicle occupants. The mounting location should also be shielded from unnecessary moisture, vibration, or excessive operating temperatures.

21. Connect the GPS antenna to the GPS unit. It is recommended that the wiring be routed through side access doors or through the passenger-side window of the vehicle's cab. In any event, the wiring should be routed in such a manner as to prevent pinching and should be strain-relieved in order to prevent damage due to on-road vibration and relative movement between vehicle chassis/body components.

22. Connect GPS unit to the data acquisition system via a serial port interface.

23. Supply accessory power to the GPS unit.

24. Install the exhaust sampling system and emissions analyzer enclosure in the cab of the test vehicle. The devices should be securely mounted so as to minimize the effects of on-road vibrations. Mounting locations should be chosen such that minimal variations of temperature occur (shielded from drafts). The mounting location should be free of moisture to prevent component failure and any associated electrical shock hazards. The unit should be secured with load straps to prevent movement, and the mounting location should be chosen so that the unit's cooling fans are unobstructed. Sample stream exhaust lines should be routed outside of the vehicle's cab in order to prevent contamination of the vehicle cabin environment. These lines should be routed in such a manner as to prevent pinching or rupturing and should be strain-relieved in order to prevent damage due to on-road vibration.

25. Connect the inlet of the heated sampling line to the sampling probe port located on the exhaust flow rate measurement tube. Connect the outlet of the heated sampling line to the inlet port on the MEMS exhaust sample conditioning unit. No alterations or substitutions to the sampling line or sampling system should be implemented, due to the associated variations that would be observed in system response times. It is recommended that the sampling line be routed through side access doors or through the passenger-side window of the vehicle's cab. In any event, the sampling line should be routed in such a manner as to prevent pinching and should be strain-relieved in order to prevent damage due to on-road vibration and relative movement between vehicle chassis/body components.

26. Prior to supplying power, visually inspect all external wiring connections.

27. Verify the generator fuel tank level. Start the generator and verify that supply power is available.

28. Supply power to the exhaust sampling system and emissions analyzer enclosure, and ensure that all components are operational.

29. Connect the mouse and parallel Zip® drive to the data acquisition computer.
30. Supply power to the data acquisition computer, Zip® drive, and signal conditioning enclosure, and turn all units on.
31. Ensure that the data acquisition computer boots and that the Zip® drive is operational.
32. Final note for MEMS installation instructions: all data acquisition interface connections shall be according to MEMS system operation diagrams (to be provided with the approved version of the MEMS).

4.6 Pre-test Procedures

1. Verify that all MEMS system connections (wiring, sample tubes, etc.) are securely attached.
2. Log onto the data acquisition computer and start the MEMS data acquisition program. Verify that all pertinent measurement data is being recorded (spot check).
3. Start the vehicle and establish ECU communications via the MEMS data acquisition system output and protocol adapter status indicator (where applicable).
4. A leak check shall be performed on the exhaust flow rate measurement pressure transducers (both differential and absolute) and associated lines. The test should be performed by capping the lines at the port locations and pressurizing the systems. System integrity should be verified using a Heise handheld pressure calibrator, model PTE-1, that is interfaced with MEMS operating software via a serial port connection.
5. After a leak check of the transducer lines has been performed, the calibration of the differential and absolute pressure transducers should be verified using, for example, the Heise PTE-1 handheld pressure calibrator. This verification shall be performed at least once a day, during a vehicle test series. The differential pressure range depends upon the flow meter pipe diameter, exhaust system layout, and exhaust flow rate. Typical ranges for the differential pressure calibrator are 0 to 10 and 0 to 25 inches H_2O. A typical range for the absolute pressure calibrator is 0 to 60 inches Hg.
6. ECU engine speed broadcasts should be qualified with a secondary measurement device during each MEMS installation. After the secondary measurement device is installed the engine should be operated throughout the engine speed range. Data should be logged using the ECU verification procedure of the MEMS data acquisition program. Any observed inconsistencies between the ECU broadcast data and the measurements made with the secondary technique should be recorded in the pre-test data sheet(s) and corrected.
7. A series of vehicles tests shall be initiated by establishing a zero flywheel torque curve. The engine of each vehicle tested will be operated from curb idle to governed speed using either the electronic speed control (cruise control) or manual operator control. This curve shall be established in an increasing then decreasing fashion over the range of engine operating speeds. ECU broadcast data shall be recorded during this procedure and used to establish parasitic and frictional losses.

8. Before each day of testing, the exhaust flow rate measurement device should be cleaned by purging the system at the transducer connections with pressurized air. This back-flush procedure is used to remove condensation and diesel particulate matter from the pressure lines and associated flow tube pressure measurement ports.

9. Prior to each test, the differential pressure transducer will be balanced by connecting the two measurement lines and establishing a zero output value. In addition, the output of the absolute transducers will be adjusted to read the current ambient barometric pressure value. Current barometric pressure readings will be provided via a calibrator, such as a Heise pressure transducer calibrator.

10. Ambient temperature and pressure measurements should be made with independent devices and compared to pre-test values measured with MEMS components. In addition, the MEMS humidity measurement sensors will be compared to the measurements made with a sling psychrometer and local airport readings. The ambient test conditions data sheet (see Attachment 3) shall be completed.

11. As a pre-test inspection, the exhaust flow rate measurement pressure transducers' signal and emissions measurement system integrity shall be verified by acquiring data for 30 seconds with the vehicle engine idling. This data should be examined for any anomalies, and corrective measures should be initiated if any were identified.

12. At the beginning of each sequence, the sample filter, located in the heated filter holder, should be replaced. Through the test sequence the inlet depression reading on the sample line supply gage should be monitored. If the sample inlet pressure gage reaches 15 inches H_2O, the test should be aborted and the filter should be replaced.

13. Perform a leak-test on the sampling lines by capping the lines at the sampling probe and inspecting that sample flow rates return to zero while the pump is running. The leak-test should be performed prior to each route and following any sample filter replacement.

14. Verify that all temperature controllers are set at the correct operating values:

    Heated Sampling Line – 250 °F
    Heated Sample Filter – 250 °F
    Heated Head Pump – 250 °F
    Internal Sample Lines – 250 °F
    NO_2 Converter – 400 °F
    Internal MEMS Emissions Measurement Chamber – 120 °F

15. The system shall be allowed to stabilize at these conditions for at least one hour prior to the start of a test.

16. With the sample pump operating, set exhaust sample flow rates for the sampling system. The sample stream must be controlled at 3.5 lpm for the zirconium-oxide NOx, at 3 lpm for the NDIR CO_2 bench, and 0.5 lpm for the electrochemical cell NO sensor. The sample flow rates are measured by the two flow meters that are located upstream of the ZrO_2 and CO_2 emissions sensors. First, ensure that the flow rate control valve for the electrochemical cell is in the fully closed position. Next, set the flow meter for the ZrO_2 sensor at 3.5 lpm by adjusting the bypass flow throttling valve located upstream

of the NO_2 converter. The sample flow to the CO_2 analyzer is then regulated by opening the bypass valve located at the inlet to the electrochemical cell. This procedure will establish the necessary 3 lpm and 0.5 lpm flow rates to the CO_2 analyzer and electrochemical cell, respectively.

17. Connect regulated calibration gases to the input ports of the capillary gas divider. The diluent shall consist of N_2, regulated at 18 psig. The component gas shall consist of calibration grade gas, regulated at 21 psig. The accuracy of the CO_2 and NO calibration gases should be certified by the supplier to have an accuracy of ±1% accuracy, traceable to NIST.
18. Connect output of the capillary gas divider to the calibration port located at the inlet of the heated sampling line. Verify that the recommended flow rates are achieved while flowing the calibration gases. Adjust flow rates using the integrated control provided by the capillary gas divider. Excess calibration gas should be vented to the atmosphere to ensure adequate "flooding" of the heated line inlet. The flooded probe approach is recommended in order to verify sampling system integrity.
19. Perform calibrations on the emissions analyzers/sensors. Multipoint regression curves should be developed in order to provide the best possible accuracy. The least-squares best fit linear or non-linear calibration curve value (depending upon the specific sensor/analyzer used) shall not deviate from the measured value by more than 4%.
20. The calibration curve shall be archived per the software operation procedures (to be provided with the final approved MEMS).
21. The analyzer check-off data sheet (see Attachment 4) shall be completed prior to commencement of on-road testing. Ensure that all QC/QA reports are completed and signed.

4.7 Test Procedures

1. At the onset of a test series, a "zero-run" will be performed in order to identify problems related to vibration. The vehicle will be driven once over a portion of a test route with the systems operating and acquiring ambient data for at least a 15 minute sampling period. This shakedown can be used to find poor electrical connections as well as problems related to electrical cables. During this test, the background quantities of CO_2 and NOx will be monitored to account for ambient contributions, which are not expected to be a factor in raw exhaust gas constituent analysis. The differential pressure transducer shall be used to monitor a zero difference, and the absolute pressure transducer will measure barometric conditions. The data collected during this "null-test" shall be inspected for anomalies, and will provide a verification of the MEMS' operational integrity. In addition, GPS data will be correlated with vehicle speed data derived from the ECU in order to compensate for drivetrain changes or inadequately calibrated control units. This "zero-run" test shall be performed at least once a week during the vehicle test series.
2. Data logging shall be initiated 60 seconds prior to the start of the on-road test cycle.
3. All measurement data shall be logged continuously throughout the test route and for a period of 60 seconds after the test route has been completed.

4. At the conclusion of each test route, the relevant information should be entered onto the appropriate test data sheet(s).
5. Between each route, a zero and span procedure should be performed on the emissions measurement sensors/analyzers, as well as the exhaust flow rate measurement pressure transducers, according to the procedures set forth in the previous pre-test procedures section.
6. The pre-test procedures prescribed above should be performed. Between-route inspections of the generator fuel tank level should be performed and the supply tank should be filled between each route.

4.8 Post-test Procedures

1. After each route, the differential and absolute pressure transducers shall be referenced against pre-test values. Any drift exceeding 4% of the fullscale value will nullify the results for that route. Similarly, the zero/span values of the emissions measurement devices shall be compared to the pre-test calibration values. Again, any drift exceeding 4% of the fullscale value will nullify the results for that route.
2. At the conclusion of a route, the MEMS humidity measurement sensors shall be compared to the measurements made with a sling psychrometer to verify the continuous data that was logged throughout the test cycle.

4.9 Conclusion of Test Day

1. Back up data onto a ZIP® disk and transfer to data reduction server.
2. Turn off the emissions sampling system and all measurement devices.
3. Remove power from the system.

4.10 Conclusion of Vehicle Test Series

1. A “zero-run” should be repeated for a portion of one of the routes. This test shall be performed at weekly intervals throughout the vehicle’s test series. This test shall be used as a final in-field determination of data quality, identifying possible problems that may have manifested themselves during the test sequence.
2. Disconnect the heated sampling line from the exhaust sampling port.
3. Disconnect all data acquisition cables and transducer lines.
4. Remove MEMS components.
5. Restore vehicle exhaust system to original, pre-test configuration.
6. Record the data filename and all other information in the field log and custody record (see Attachment 5). Complete and sign all QC/QA reports.

4.11 Data Reduction Procedures

All data reduction procedures are based upon the recommendations of CFR 40 Part 89 and SAE J177 and J1003. Data reduction shall be performed by a host computer that serve as a daily download terminal for all recorded raw MEMS data. Data reduction software provides post-processing of all measurements recorded throughout the test. Time-alignment of events is accomplished by referencing measurements to engine power that is inferred from ECU broadcasts. This technique necessitates the accurate determination of protocol communication time-stamps. Periodic assessment of protocol performance should be performed in order to ensure the continued accuracy of post-process time alignment procedures. Details of the time-alignment procedures will be documented in a forthcoming report.

4.12 Quality Control/Quality Assurance (QC/QA)

A QC/QA program should be developed and integrated in order to assure generation of measurement of data of the highest quality.

The responsibility for QC/QA should rest with a designated QC/QA officer who should report to the project director. The QC/QA officer is independent of the functional groups that generate measurement data. An engineer and a technician, neither of whom are directly related to data gathering, reduction, or analyses, shall assist the QC/QA officer in the QC/QA effort. The engineer should not be part of the measurement data generation team.

The QC/QA engineer should work with the project team to ensure that the daily activities are logged, calibration gases meet the stated requirements (discussed in the enclosed description of the QC/QA plan), that all instruments, sensors, sample conditioning systems, and computers are maintained and operated in accordance with the stated plan. In addition verifications should be made that the instruments are warmed-up, stabilized, and have undergone all the necessary checks and calibrations. It should be the QC/QA engineer's responsibility to ensure that all tests are conducted in accordance with the stated plan and that the data will be gathered and archived for subsequent review by the engineer-in-charge. The data should then reviewed by the QC/QA engineer and passed on for review by the QC/QA officer.

4.13 MEMS QC/QA

Presented herein are the quality control and quality assurance procedures for the evaluation of on-road emissions produced by heavy-duty diesel engine vehicles using the MEMS.

4.13.1 Emissions Testing

The MEMS is capable of measuring regulated and non-regulated diesel-powered vehicle emissions such as NOx and CO_2. The MEMS can also measure CO and total HC, but the uncertainty levels are excessively high. Reliable sampling is assured through system design, periodic system inspection, and scheduled instrument calibration. The procedures outlined in this QC/QA plan should be performed for each vehicle during on-road testing as an integral part of all on-road testing programs.

4.13.2 Sampling Line and Probe

Because of the nature of the MEMS, its components have been designed to withstand a significant mechanical stress during operations. Meticulous care should be taken in verifying that emissions measurement equipment is in order before commencement of emissions testing. Prior to the performance of a test schedule, supervisory personnel shall verify that the multi-orifice sample probe in the exhaust stack is properly placed and that the integrity of the sampling systems has been maintained. The sampling line should be leak checked (by pressurization) and back-flushed with high pressure air in order to clean the lines of residual particulate matter. The heated sampling line and the associated control system (PID temperature controller and associated thermocouple) shall check to ensure continuity between the controller, heater element, and thermocouple. The temperature settings also shall be verified to ensure that the line is maintained at 250°F. It shall be verified that all connections on the sampling lines are insulated and/or insulated and heated in order to avoid cold spots. Sample line temperatures, shall be sampled and recorded at 5 Hz at various locations throughout each test.

4.13.3 Heated Pump/Flow Rates

Periodically, flow rates through the sampling system shall be checked, for example, with a Gillian bubble flow meter.

4.13.4 Exhaust Flow Measurement Tube

The exhaust flow measurement tube shall be attached to the heavy-duty diesel exhaust stack. This may require a substantial amount of effort if the exhaust system configuration is such that the flow tube cannot be easily attached. The connection interfaces shall be sealed using a high-temperature aluminum tape and periodically checked to ensure system integrity. The exhaust flow measurement tube shall not be insulated.

4.13.5 Vehicle Fuel Supply

Vehicle fuel supply tanks shall be visually inspected to ensure that there is no contamination with off-highway fuel. At the onset of testing, the supply tanks should be filled with locally-available on-highway grade diesel fuel. For emissions data reduction purposes, fuel properties for current on-highway diesel fuel, per CFR 40 specifications, will be used. No fuel analysis shall be performed for the in-use testing, unless explicitly required and provided for by the project funding agency.

4.13.6 Vehicle Identification/Engine Identification

When received, the vehicle identification number and engine number should be recorded and compared to the manufacturer's documentation (Attachment 1). This information shall be used to verify that the lug curve, provided by the manufacturer, is correctly assigned to the specific test vehicle/engine combination. Test vehicle information sheet (Attachment 1) completed.

4.13.7 Vehicle Inspection

A visual safety inspection of the vehicle is essential prior to any on-road testing. This inspection is not meant to replace that provided for by the manufacturer or local service representatives. The focus is not the insurance of current vehicle performance status, but rather safety issues related to the driveline, braking system, and general vehicle integrity.

4.13.8 Vehicle Test Weight Determination

Prior to testing, the vehicle should be weighed on a reference scale in order to provide an accurate measurement of "as-tested" vehicle weight. Such data is imperative since it is not uncommon to encounter an HDDE with a GVWR tag that is not representative of the vehicle's usage. Such problems arise because GVW ratings assigned by a state Department of Transportation (DOT) may be different from the GVWR stamped on the vehicle doorpost, which reflects the vehicle's original configuration. This value should be used to supersede manufacturer data for any data reporting/processing.

4.13.9 Redundant Temperature Measurements

Redundant temperature measurements are provided for by the MEMS in order to reduce the effects of vibration. Multiple thermocouples are employed in order to minimize errors associated with broken wires and poor connections.

4.13.10 Calibration and Calibration Gases

The gases used to calibrate the emissions measurement instruments shall be certified by the supplier to have an accuracy of 1% traceable to NIST. It is recommended that the same gases may be used for calibration and zero/span procedures. All emissions measurement instruments shall be calibrated using appropriate ranges of calibration gas for the vehicle being tested. These calibrations are performed before each series of tests. Multipoint calibration curves for the NOx and CO_2 measurement devices should be constructed using the NIST-traceable calibration gases and a gas divider. The instrument readings shall be allowed to stabilize at each measurement point and a computer averaged reading of the instrument shall be recorded. No gas cylinder shall be used if the pressure drops below 200 psig.

4.13.11 Additional Calibration and Maintenance Procedures

In addition to the calibration procedures, each analyzer shall be subjected to a range of checks and maintenance procedures as described below.

4.13.11.1 <u>NO_2 Converter</u>

On a monthly basis, a NOx efficiency test should be performed in order to ensure that the NO_2 converter (which converts NO_2 to NO) is performing satisfactorily. A conversion efficiency of less than 90% shall be considered a failure and maintenance shall be performed to rectify the situation.

4.13.11.2 <u>CO_2 Analyzer</u>

Since moisture can affect the operation of the NDIR analyzers used for carbon dioxide, a water interference check shall be performed by bubbling calibration gases through a container of distilled water. The exhaust sample stream shall be passed through a thermoelectric chiller to lower the dew point and remove water vapor from the stream before it reaches the analyzers.

The water interference test establishes the water removal efficiency of the thermoelectric chilling unit and identifies possible water interference problems in the NDIR measurement scheme.

4.13.11.3 Pressure Transducer Calibration

Pressure transducers' calibration shall be verified during each installation onto a test vehicle using, for example, Heise PTE-1 handheld pressure transducer calibrator. Any problems identified with the transducers shall be directed to the respective manufacturers. The Heise handheld calibrator shall be returned yearly to the manufacturer for recalibration, per Heise requirements.

4.13.11.4 Temperature Sensor Performance Verification

Thermocouple performance shall be verified using a Fluke thermocouple calibrator. Redundant temperature measurements are employed by the MEMS in order to prevent problems associated with broken wires and poor connections. Such problems are inherent due to vibrations and repeated system assembly/disassembly. The Fluke calibrator is returned to the manufacturer on a yearly basis, per Fluke requirements.

4.13.11.5 Global Positioning Sensor Verification of ECU Vehicle Speed Data

Although vehicle speed is not directly needed to satisfy the Consent Decrees' requirements of reporting the emissions in brake-specific units, it is important in evaluating the vehicle's test route and for identifying urban, suburban, and highway NTE zone locations. The accuracy of the vehicle speed signal from the ECU cannot be ensured, due to in-field modifications of associated chassis drivetrain parameters such as gear ratios, tire sizes, and even amount of tire wear. The addition of a GPS unit will complement the ECU vehicle speed data and serve as a check for all vehicles operating in the field.

4.13.11.6 Electrochemical Cell Measurements for Verification of Zirconium Oxide NOx Measurements

Due to the limited in-field performance data associated with the ZrO_2 sensor that serves as the primary NOx measurement device, an electrochemical cell is employed in the MEMS as a QC/QA measure. Such a technique is used to identify problems that are not encountered during pre- and post-test procedures, yet may manifest themselves during the test.

4.13.11.7 Protocol Adapter Performance Assessment

Vehicle ECU protocol adapters have been shown to exhibit substantial variations in performance, most notably in the time clock algorithms that are used to provide time-stamps of broadcast data. In order to provide the highest level of data logging accuracy, each ECU will be assigned a proportionality constant that will be used to correlate its broadcast time stamps with a standard clock value. The unique performance of each protocol adapter used by the testing agency/group shall be assessed, and the units shall be tracked in-field based upon manufacturer serial number. Periodic re-assessment of the adapter's performance shall also be performed.

4.13.11.8 Verification of ECU Engine Speed Broadcast Accuracy

ECU engine speed broadcasts shall be qualified with a secondary measurement device during each MEMS installation on a test vehicle.

4.13.11.9 Data Analysis and Reporting

Quality assurance for data reported from testing is achieved using multiple checks. First, the MEMS operators, including the senior supervisory personnel as well as technicians, shall gain experience in testing different vehicle/engine/fuel combinations. This experience will be valuable in quality assurance since it allows the operators to identify problems.

As a test is performed, data is logged to a local hard disk on the data acquisition computer. A data reduction program is used to extract emissions data and translate it into the appropriate units using calibration files. Post processing of the engine lug curves, provided by the manufacturer, and the constructed zero flywheel load curve, derived from in-field measurements, are critical to overall data accuracy. All data is reduced according to guidelines presented in CFR 40 Part 89, and SAE J177 and J1003. Supervisory personnel shall examine the data to determine the accuracy so that equipment malfunctions may be identified and promptly corrected.

5 CONCLUSIONS

West Virginia University has developed procedures for in-use emissions testing of HDDE's engaged in a variety of on-road activities and operating under a variety of ambient conditions. The testing procedures also include four candidate driving routes. Two of the routes comprise urban, suburban, and highway driving conditions, whereas the other two mainly consist of highway driving, with a minimal amount of suburban driving. It has been seen that vehicles operating on a route may fail to remain in the "Not-to-Exceed" (NTE) zone for 30 seconds or more, due to low power demand during low-speed cruise and loss of engine shaft power during manual gear changes. While city operation will yield little NTE zone availability, freeway driving will encounter NTE zone activity during hill climbs and during sustained high-speed operations. Vehicles with manual transmissions will spend a smaller fraction of time in the NTE zone compared to vehicles with automatic transmissions, because automatic shifting of gears can occur under load.

WVU has evaluated on-road brake-specific emissions from heavy-duty diesel powered vehicles with the MEMS, and compared the results with those obtained from simulated runs of the same routes on the WVU Transportable Heavy-duty Vehicle Emissions Testing Laboratory. Tests on the chassis laboratory conducted with both the MEMS and the chassis laboratory's research grade emissions analyzers showed very good agreement between the integrated mass-specific NOx emissions results. Additionally, the results obtained with the MEMS, from the on-road tests and the chassis laboratory simulation of the same driving route, indicate that the differences in the integrated brake specific NOx mass emissions were less than 5%.

The report recommends the development of a quality assurance project plan/ quality control plan to ensure data generation of highest quality. A QA/QC plan has been developed and presented in this report.

NOMENCLATURE AND ABBREVIATIONS

bhp	Brake Horsepower
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOT	Department of Transportation
ECU	Electronic Control Module
EERL	Engine and Emissions Research Laboratory at West Virginia University
g	Grams
g/bhp-hr	Unit of brake-specific mass emissions.
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbon
HDDE	Heavy-Duty Diesel Engine
hr	Hour
lpm	Liters per Minute
MEMS	Mobile Emissions Measurement System Designed and Integrated by WVU
MY	Model Year
NDIR	Non-Dispersive Infrared
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
NTE	Not to Exceed
OREMS	On-Road Emissions Measurements System
PI	Principal Investigator
QC/QA	Quality Control/Quality Assurance
ROVER	Real-time On-road Vehicle Emissions Reporter
S-HDDE	Settling Heavy-Duty Diesel Engine
VIN	Vehicle Identification Number
WVU	West Virginia University
ZrO_2	Zirconium Oxide

APPENDIX A PROPOSED ROUTES

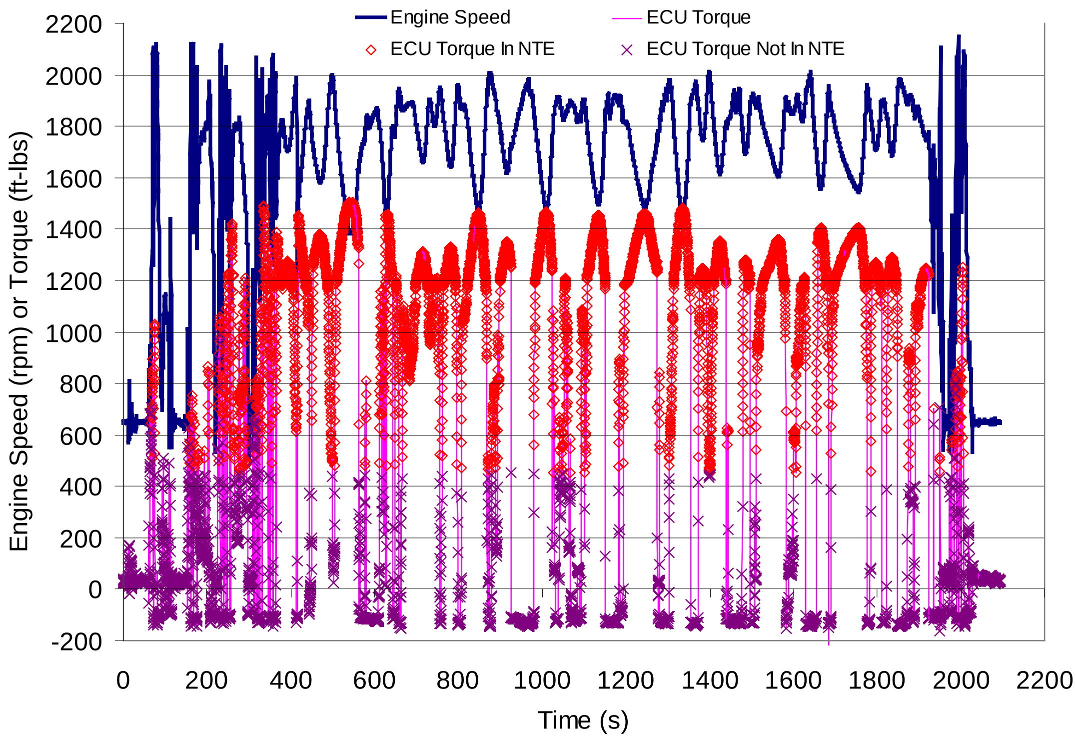


Figure A1 Engine speed and torque for SAB2SW leg of the Saltwell route.

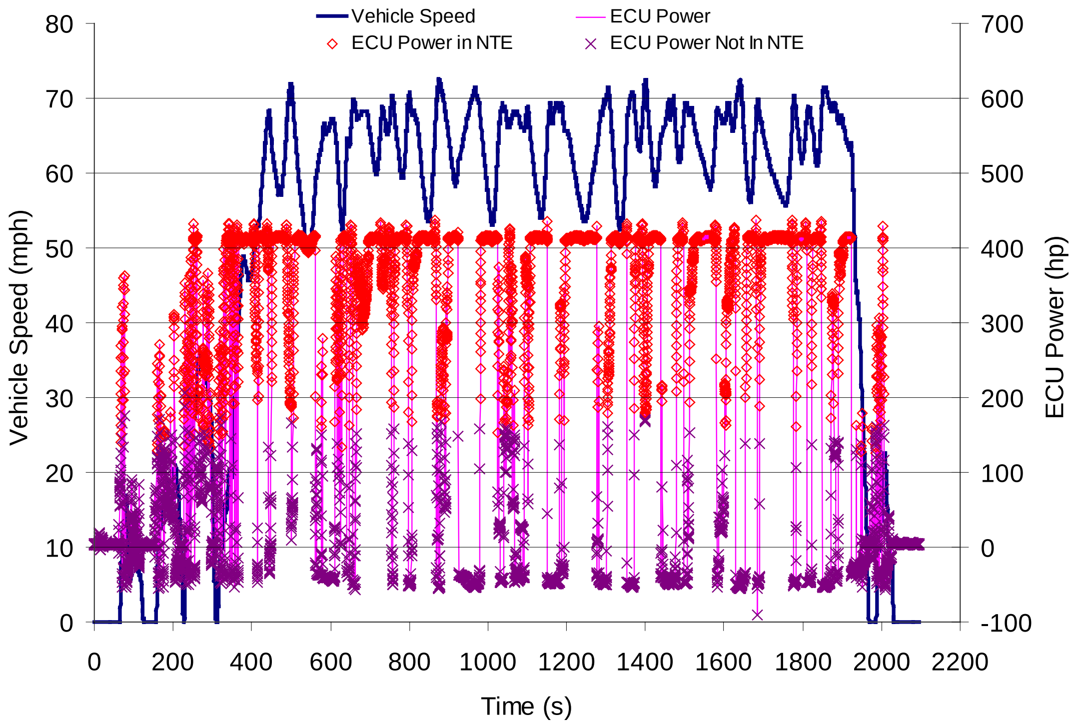


Figure A2 Vehicle speed and power for SAB2SW leg of the Saltwell route.

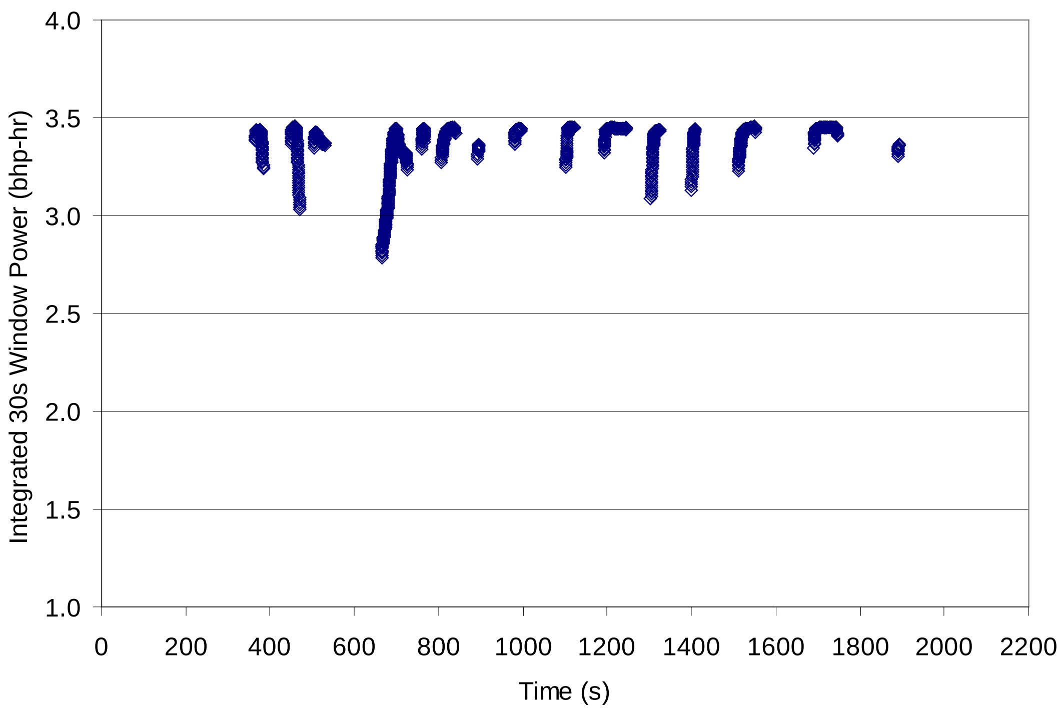


Figure A3 Integrated power over 30 s windows that are within the NTE zone for the SAB2SW leg of the Saltwell Route.

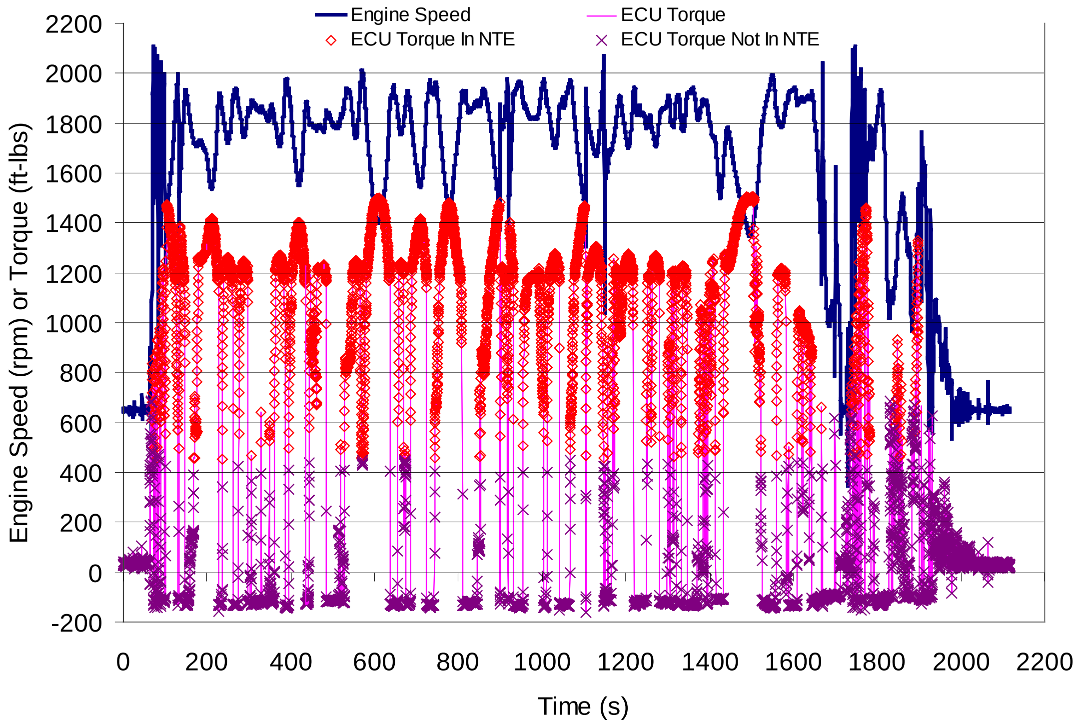


Figure A4 Engine speed and torque for SW2SAB leg of the Saltwell route.

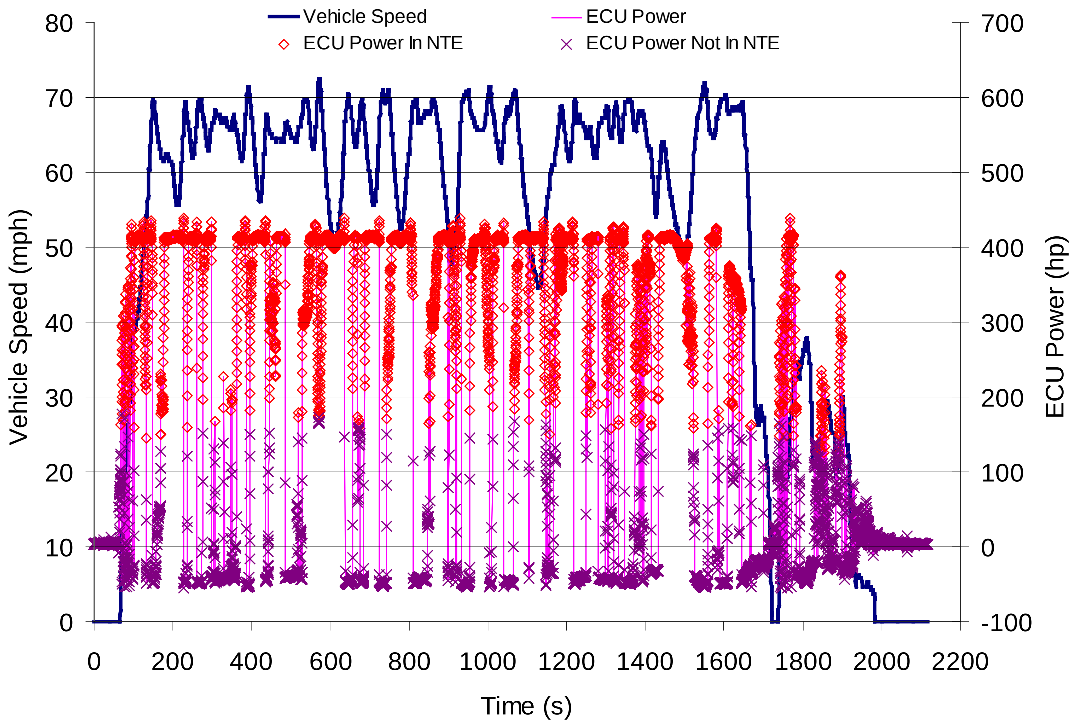


Figure A5 Vehicle speed and power for SW2SAB leg of the Saltwell route.

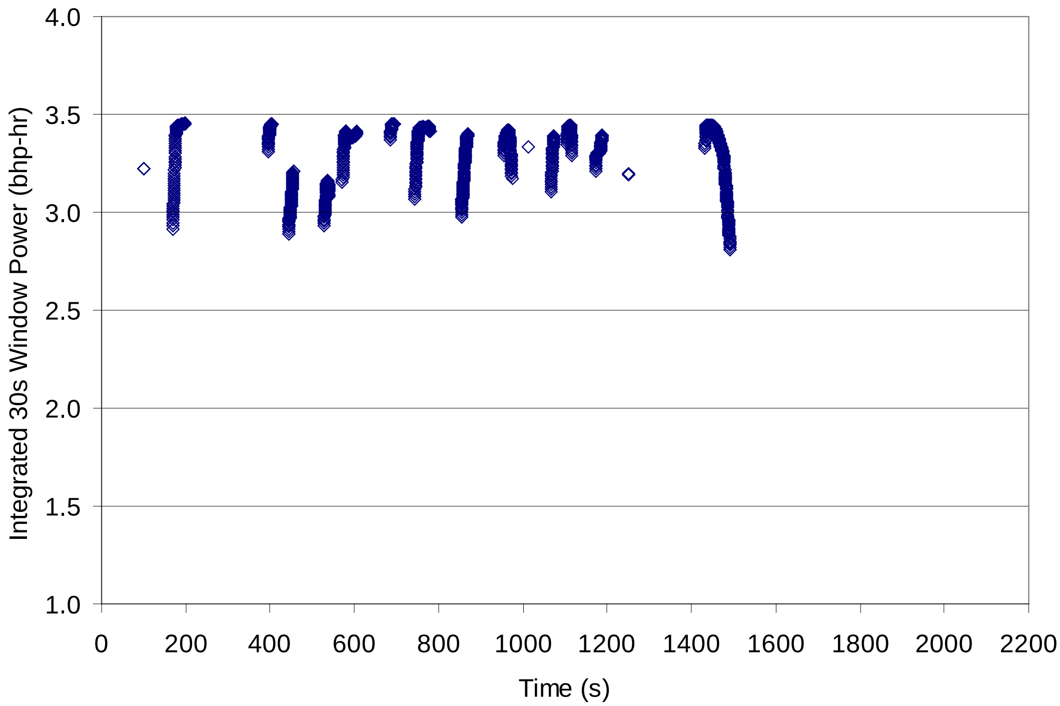


Figure A6 Integrated power over 30 s windows that are within the NTE zone for the SW2SAB leg of the Saltwell Route.

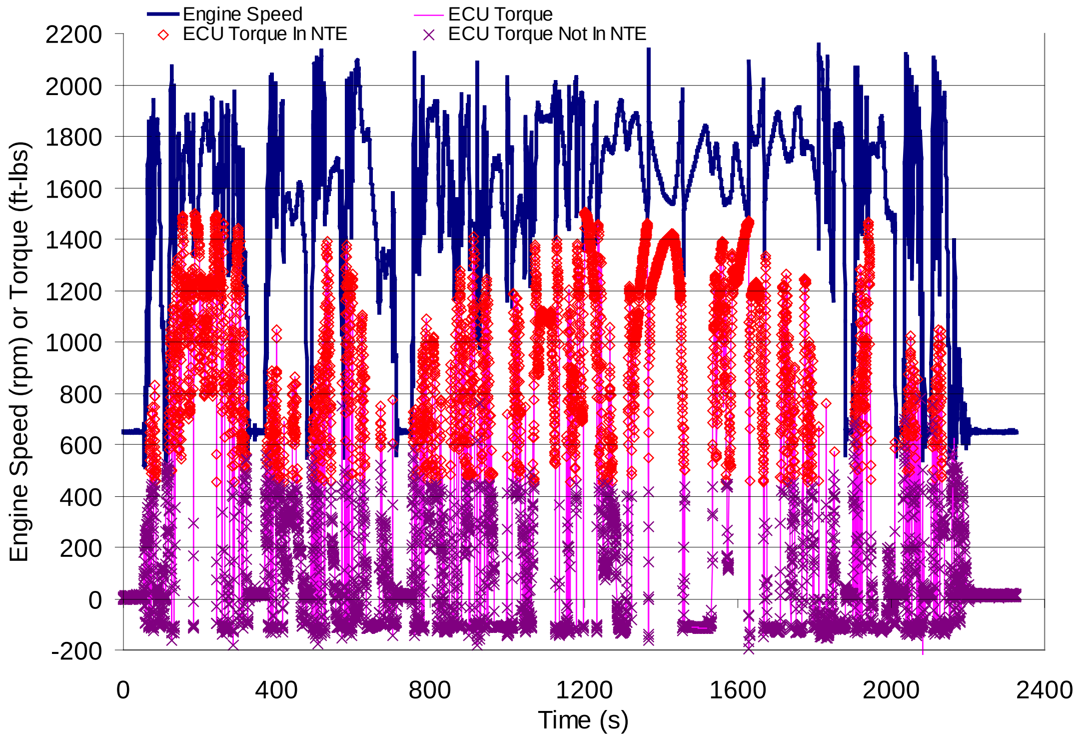


Figure A7 Engine speed and torque for SAB2SAB Morgantown route.

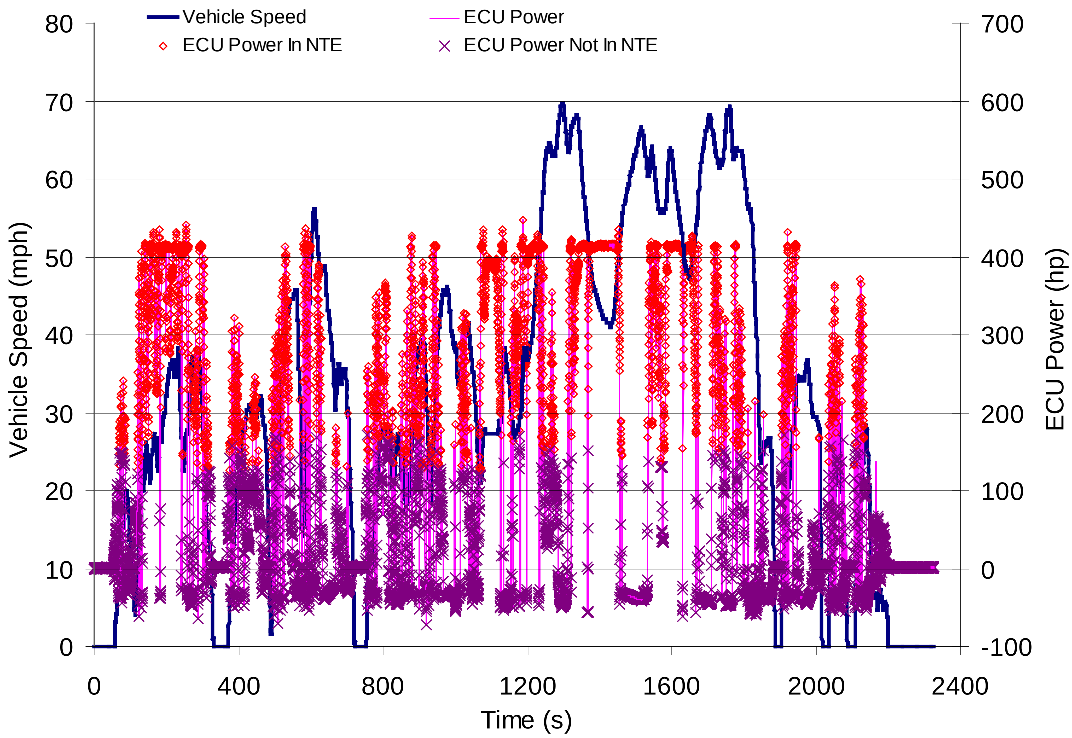


Figure A8 Vehicle speed and power for SAB2SAB Morgantown route.

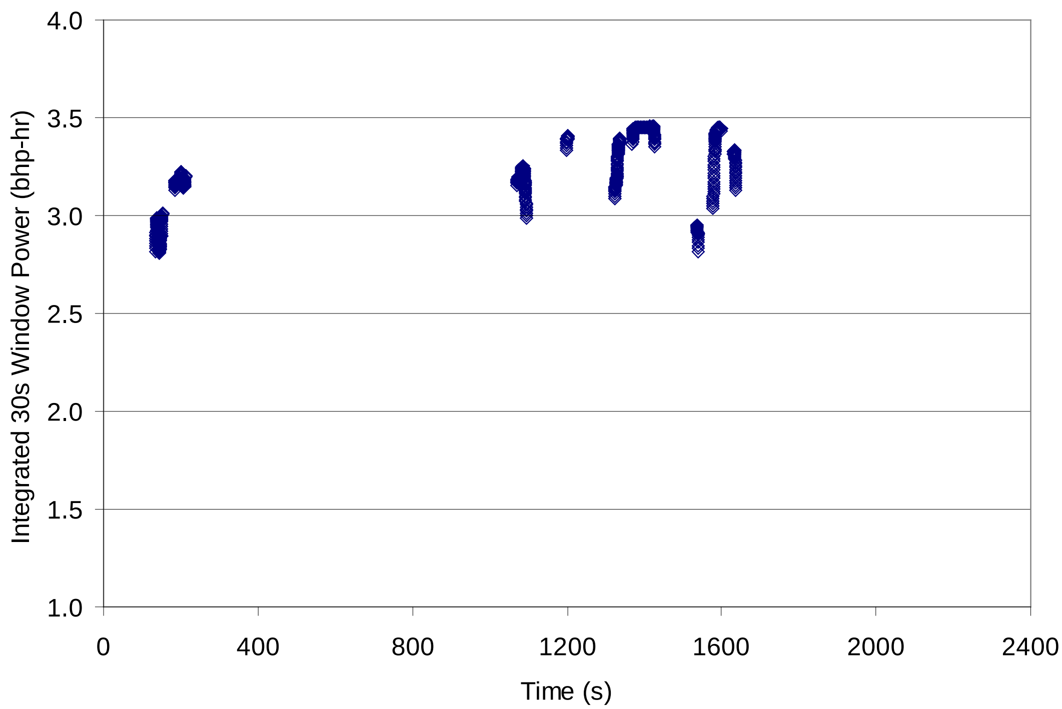


Figure A9 Integrated power over 30 s windows that are within the NTE zone for the SAB2SAB Morgantown Route.

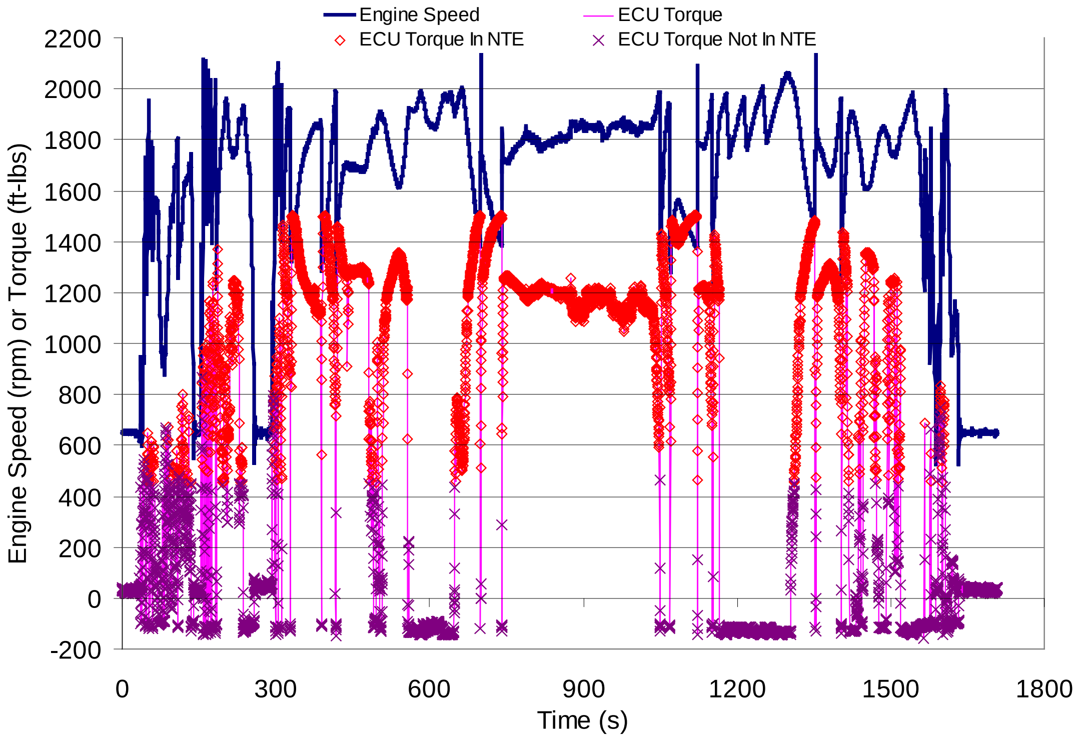


Figure A10 Engine speed and torque for SAB2BM leg of Bruceton Mills route.

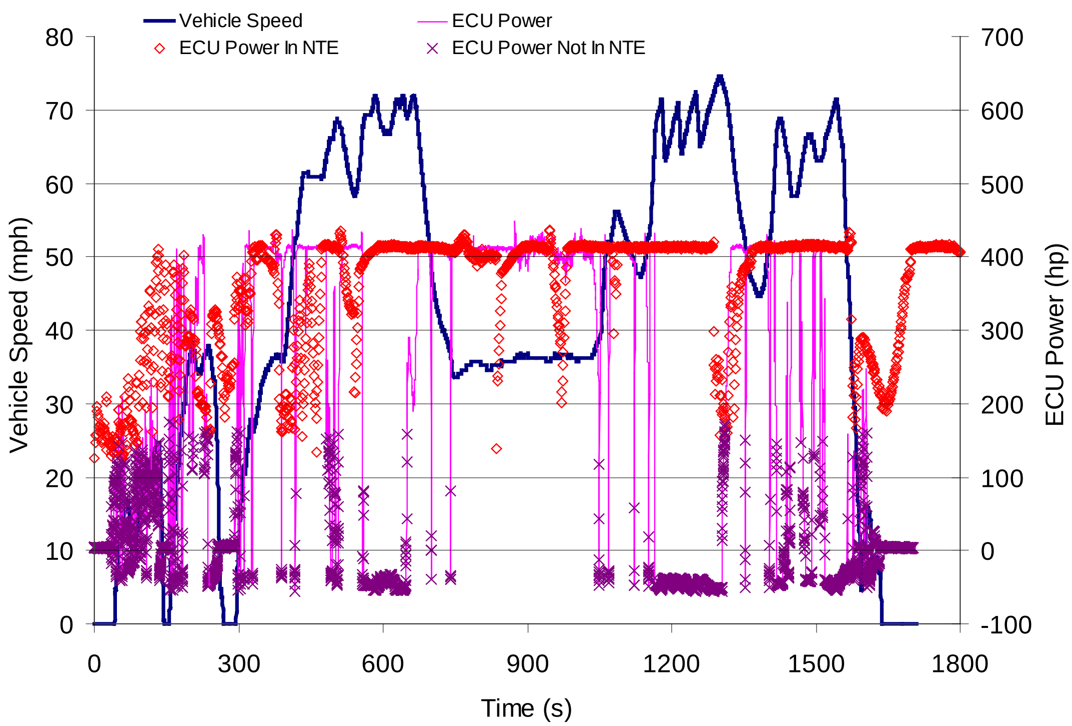


Figure A11 Vehicle speed and power for SAB2BM leg of Bruceton Mills route.

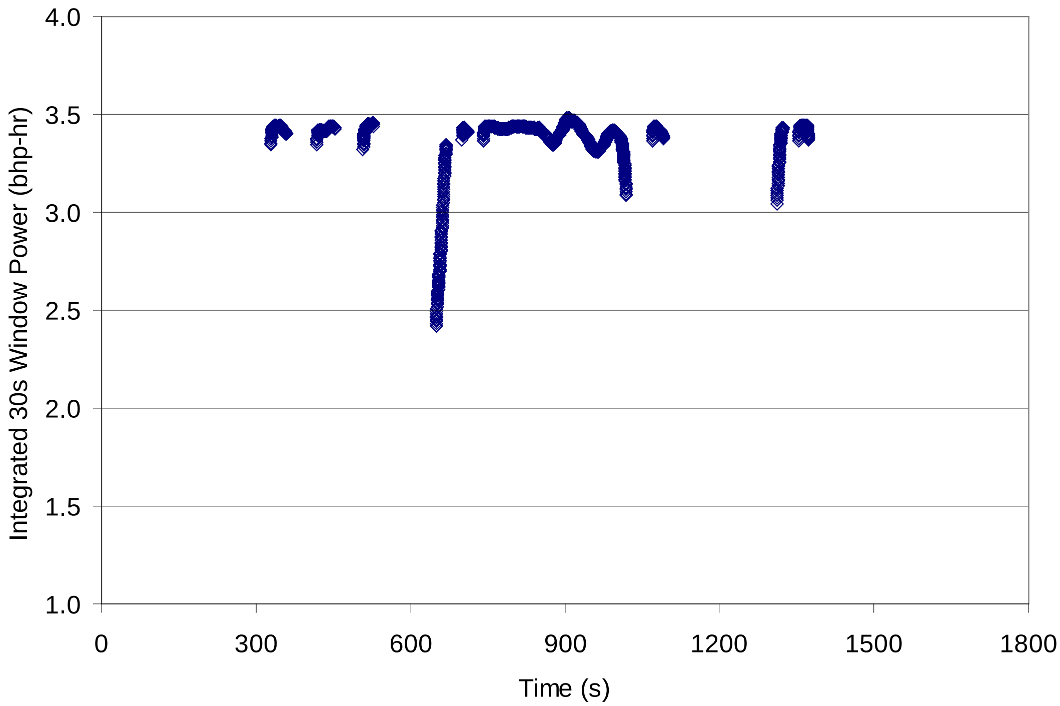


Figure A12 Integrated power over 30 s windows that are within the NTE zone for the SAB2BM leg of Bruceton Mills route.

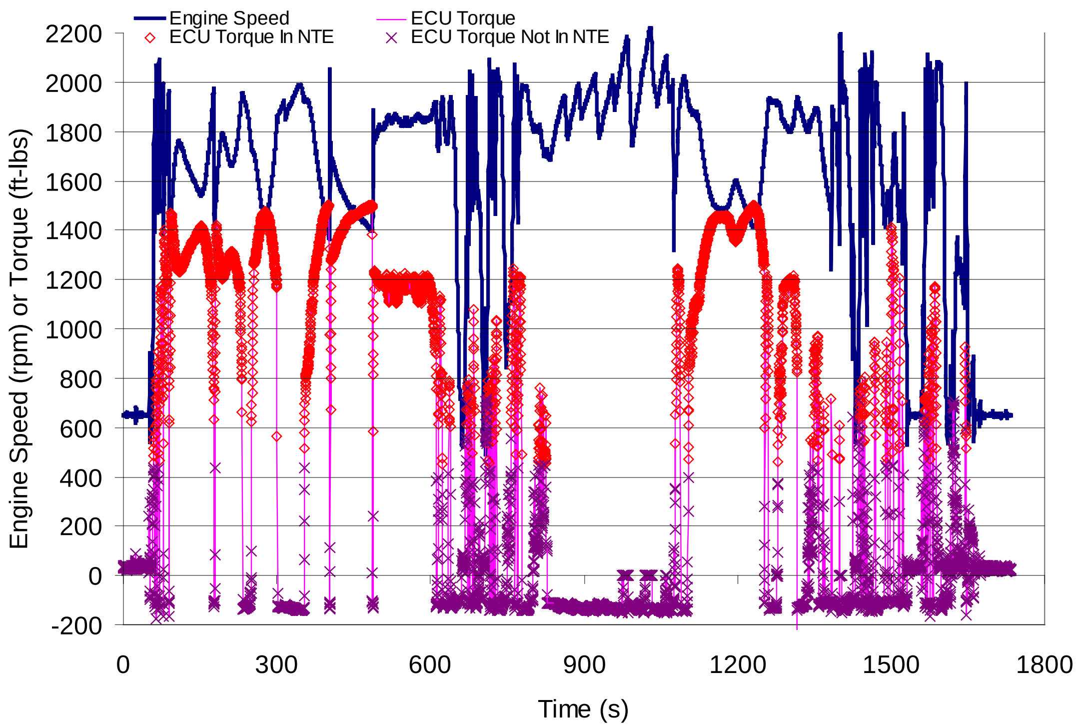


Figure A13 Engine speed and torque for BM2SAB leg of Bruceton Mills route.

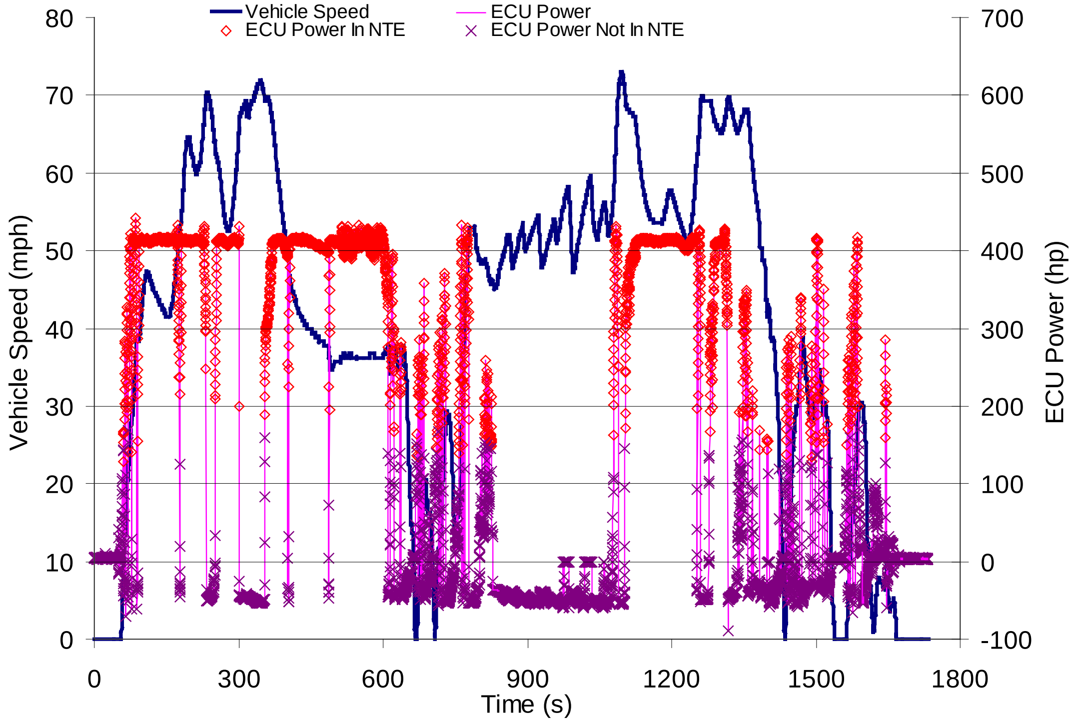


Figure A14 Vehicle speed and power for BM2SAB leg of Bruceton Mills route.

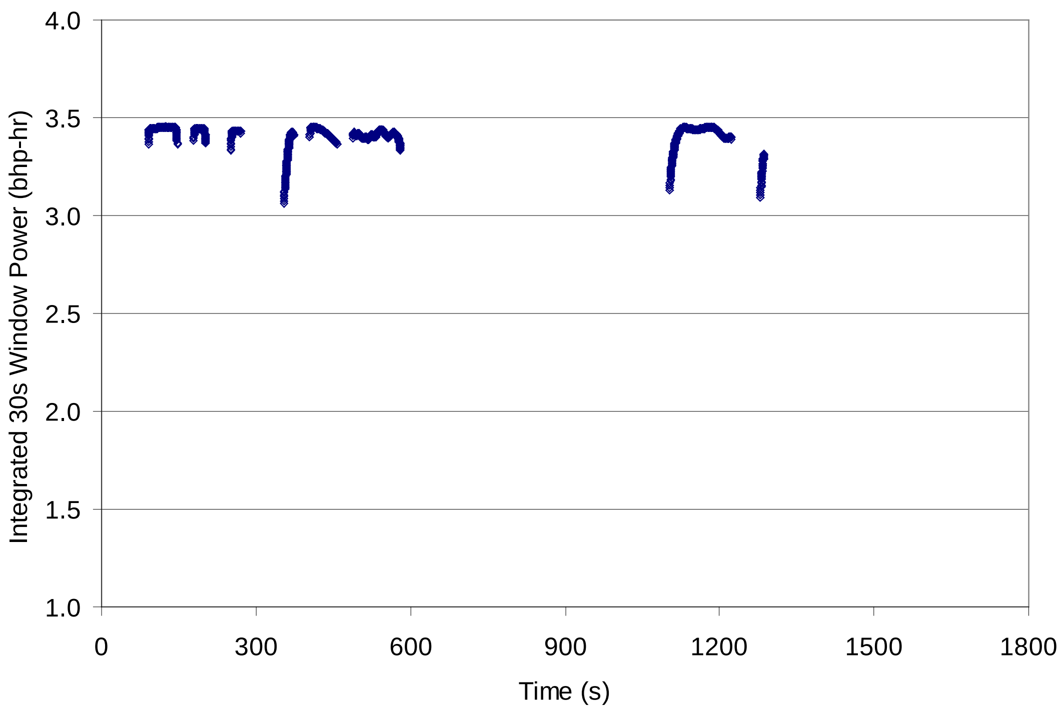


Figure A15 Integrated power over 30 s windows that are within the NTE zone for BM2SAB leg of Bruceton Mills route.

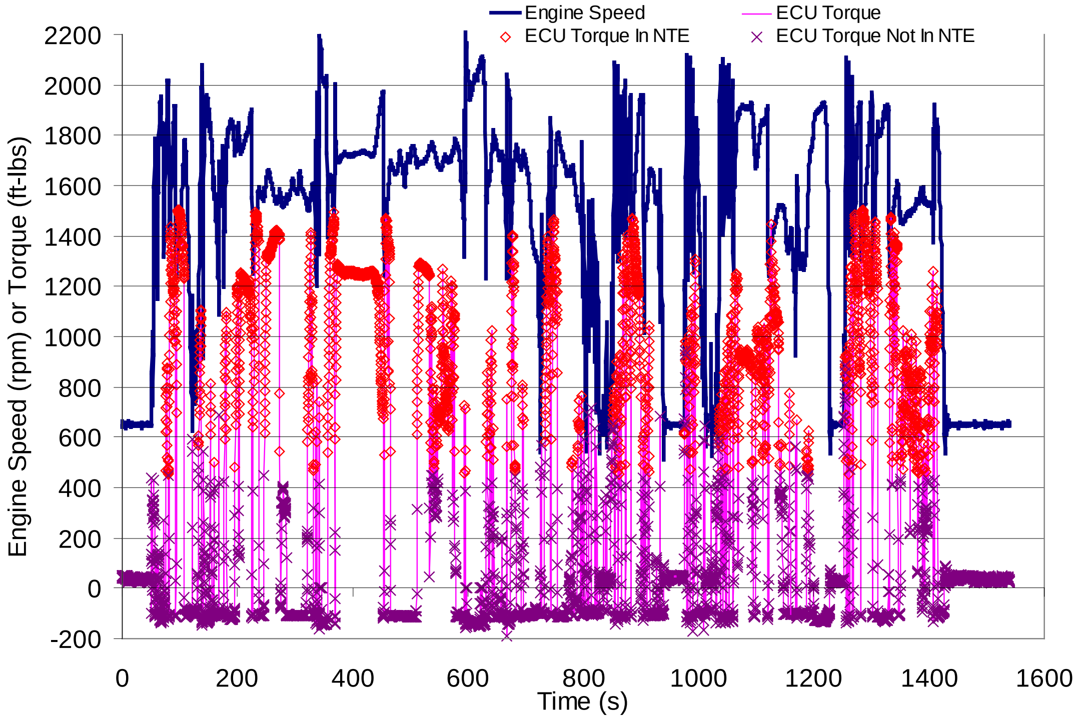


Figure A16 Engine speed and torque for WASHPA1 leg of Pittsburgh route.

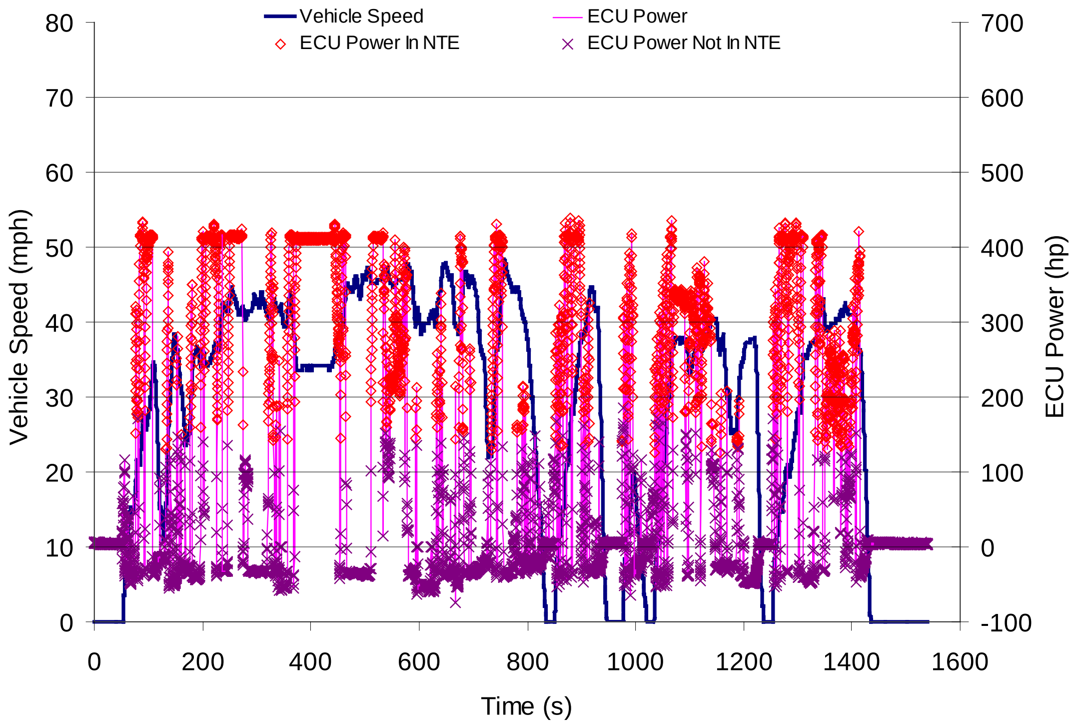


Figure A17 Vehicle speed and power for WASHPA1 leg of Pittsburgh route.

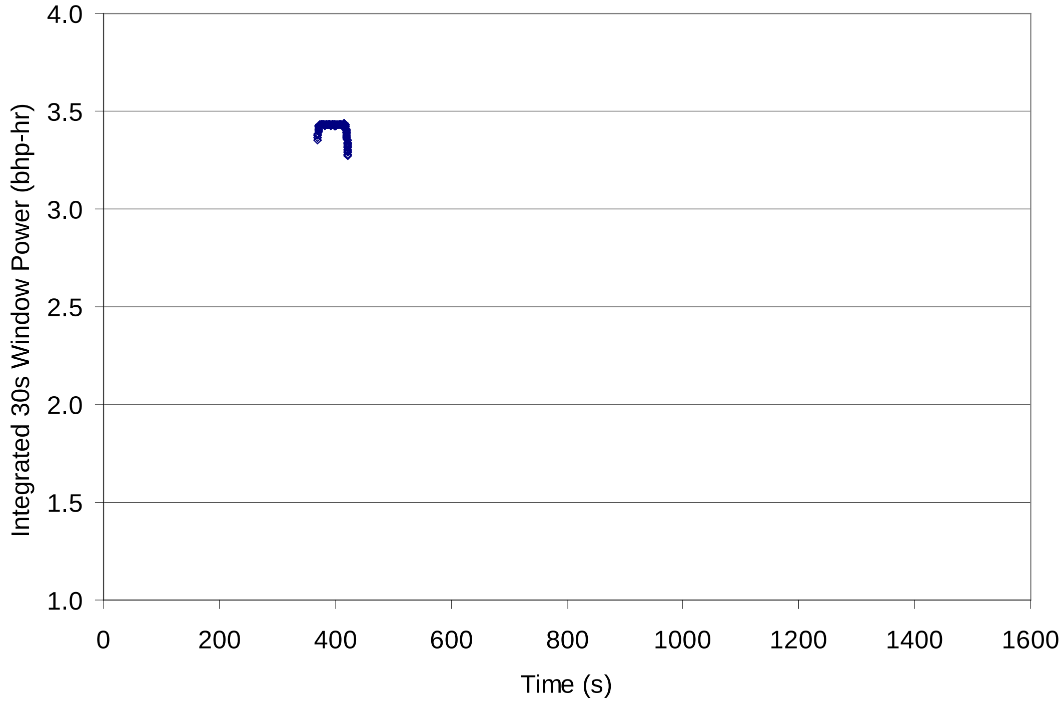


Figure A18 Integrated power over 30 s windows that are within the NTE zone for WASHPA1 leg of Pittsburgh route.

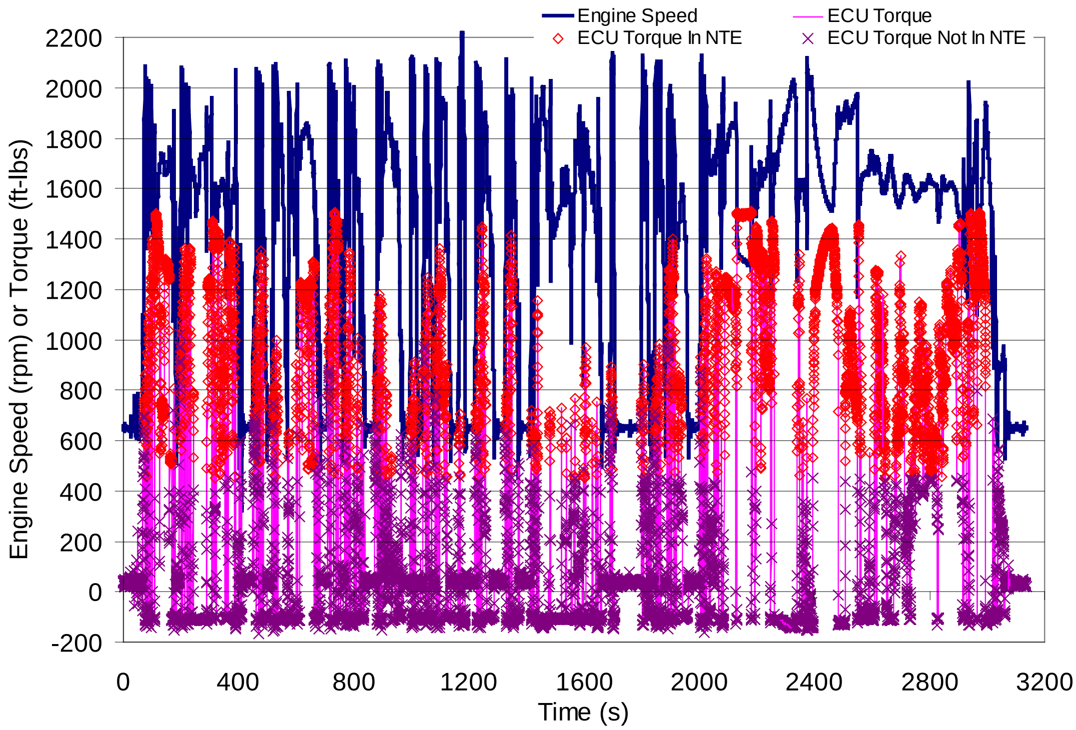


Figure A19 Engine speed and torque for WASHPA2 leg of Pittsburgh route.

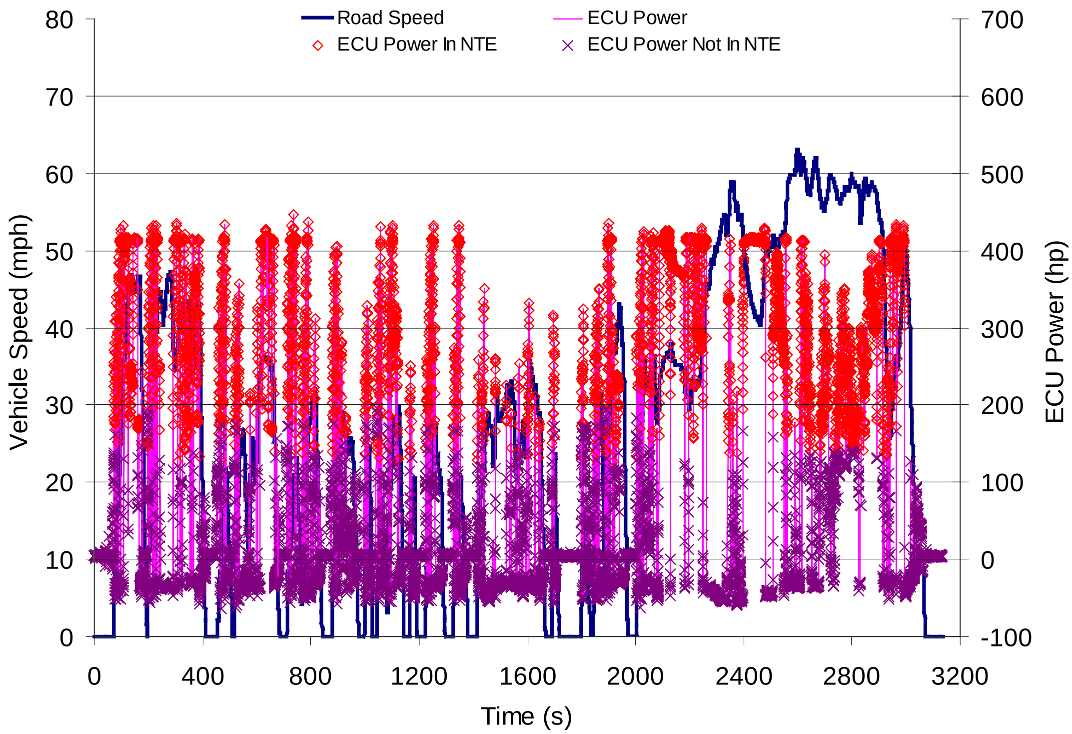


Figure A20 Vehicle speed and power for WASHPA2 leg of Pittsburgh route.

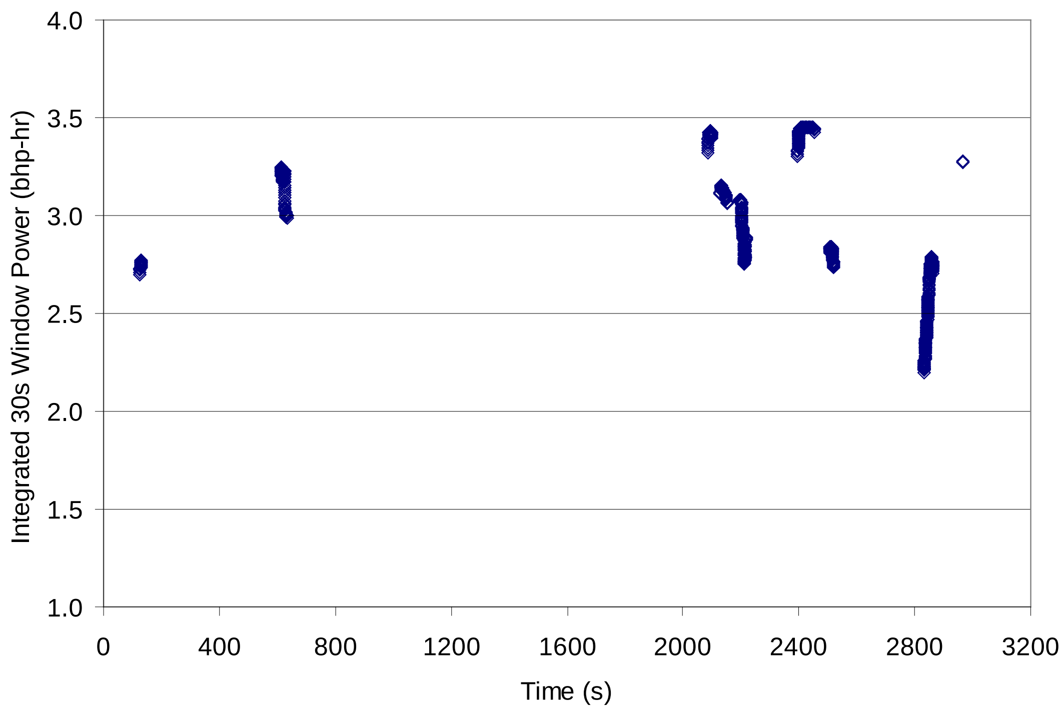


Figure A21 Integrated power over 30 s windows that are within the NTE zone for WASHPA2 leg of Pittsburgh route.

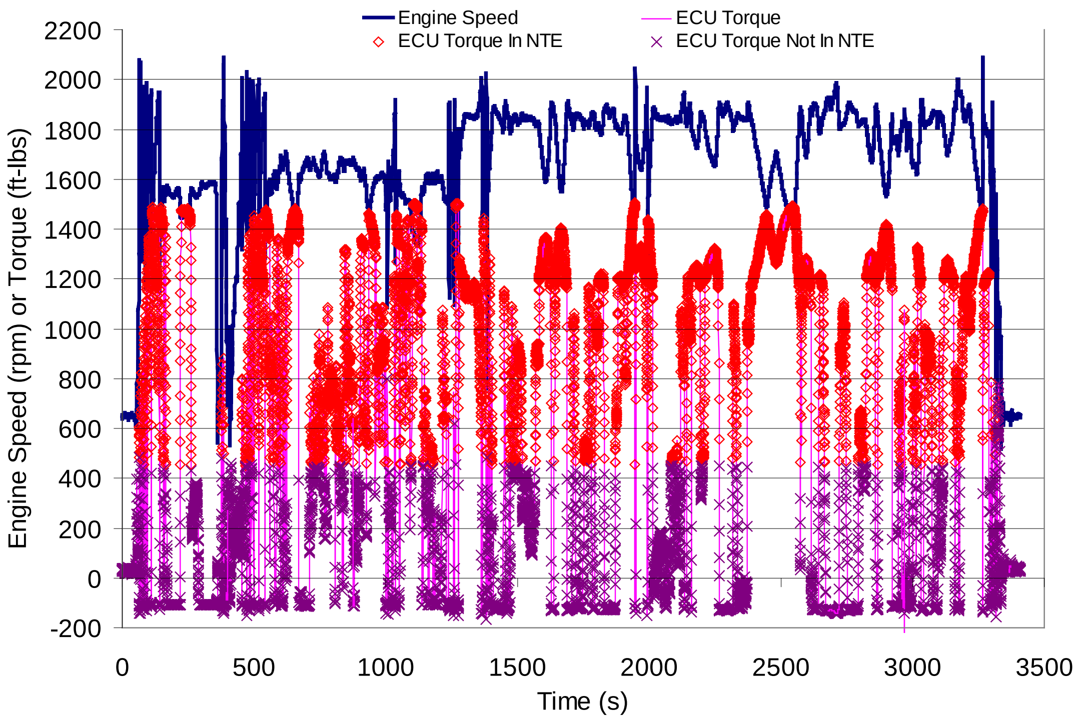


Figure A22 Engine speed and torque for WASHPA3 leg of Pittsburgh route.

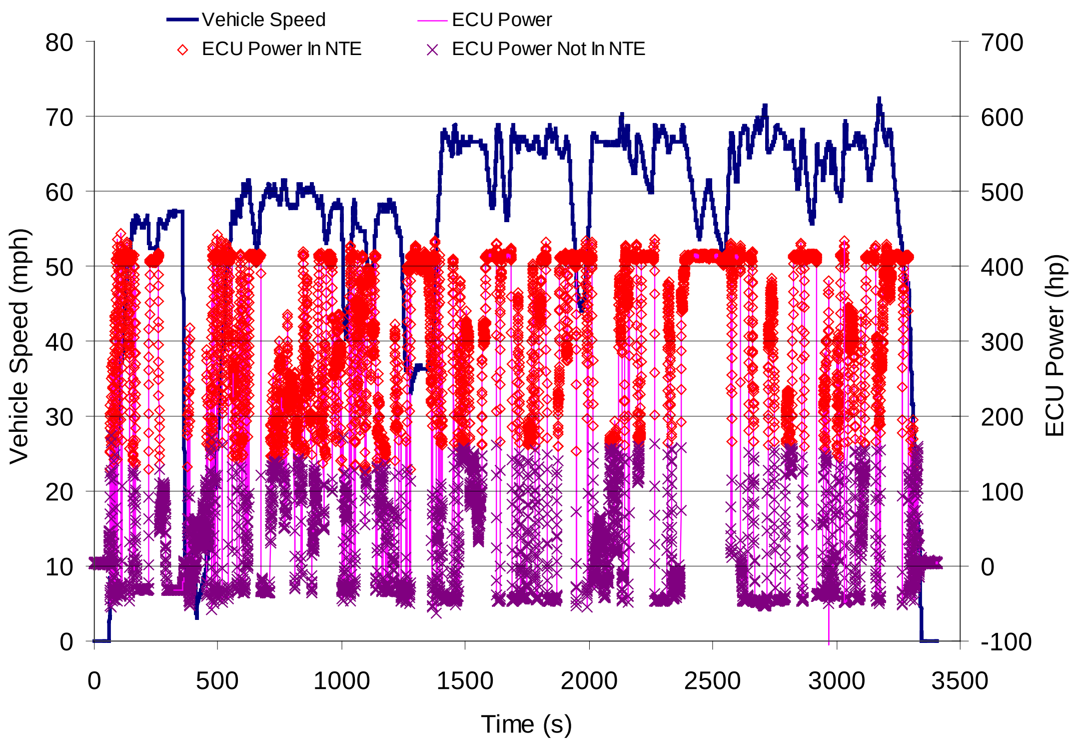


Figure A23 Vehicle speed and power for WASHPA3 leg of Pittsburgh route.

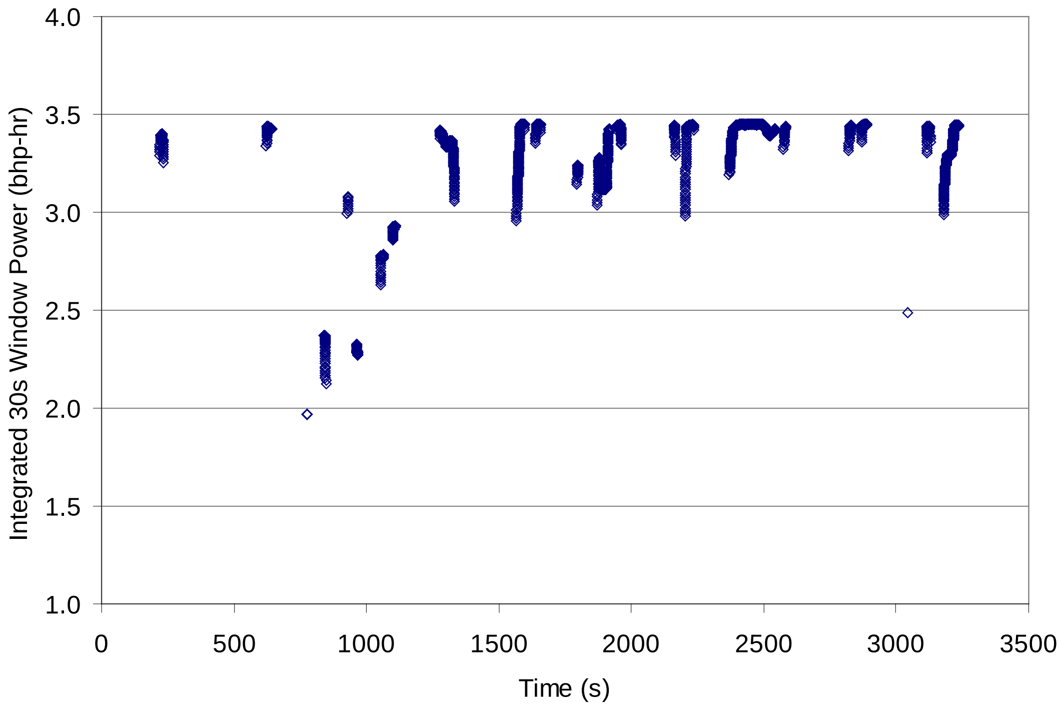


Figure A24 Integrated power over 30 s windows that are within the NTE zone for WASHPA3 leg of Pittsburgh route.

ATTACHMENT 1

Test Vehicle Information
S-HDDE Project

Vehicle #:	Test Date:	Driver:	
Test Route		Location:	
Vehicle Owner:			
Vehicle type:			
Vehicle Manufacturer:			
VIN # (17 Digit):			
License plate #:			
Vehicle model year:			
Transmission type: ❒Auto ❒Manual		Speeds:	
Odometer reading:		Hub meter reading	
Gross vehicle weight rating (GVWR)	Front:	Intermediate:	Rear:
Vehicle curb weight:	Front:	Intermediate:	Rear:
Tail pipe diameter (in):			
Exhaust stack configuration:			
Number of axles:			
Tire size:	Rim size		
Fuel tank(s) capacity	gallons	Number of tanks	
Engine rebuilt? ❒Yes ❒No		Year rebuilt:	
Engine manufacturer:		Engine model/year	
Engine ID#:		Engine displacement:	liters
Number of cylinders			
Engine rated power:	hp	@	RPM
Engine peak torque:	ft-lbs	@	RPM
Governed speed			
Idle:	RPM		
High idle:	RPM		
Manufacturer supplied lug-curve available:	❒Yes	❒No	
Manufacturer supplied lug-curve Reference #:			
Zero-flywheel load curve (Test Agency Generated) I.D. #:			
ECU Protocol: ❒ J1587		❒ J1939	
Fuel type:			
Oil type/weight:			
Particulate trap ❒Yes ❒No	Manufacturer		
Catalytic converter ❒Yes ❒No	Manufacturer		

Signatures: Driver: ______________________ Engineer: ______________________

Date: ______________________ Date: ______________________

Test Crew: Engineer: ______________________
Driver: ______________________
Tech.: ______________________
Tech.: ______________________

Additional Comments

ATTACHMENT 2

Pre-Test Vehicle Checks

Vehicle #:	Test Date:	Driver:
Test Route:		Location:
Vehicle Owner:		Engine manufacturer:
Vehicle type:		Engine ID#:
Vehicle Manufacturer:		ECU: ❒ J1587 ❒ J1939
VIN # (17 Digit):		
License plate #:		
Vehicle model year:		
Engine:		

Fluid leaks	❒Yes	❒No	Comments:________
Fuel level	❒Full	❒Other	________
Oil level	❒Full	❒Low	Added: ________
Coolant level	❒Full	❒Low	Added: ________
Power steering fluid	❒Full	❒Low	Added: ________
Air cleaner changed	❒Yes	❒No	Comments:________
Belts	❒Good	❒Bad	❒Replaced
Air conditioning	❒None	❒Yes	❒Off
Visible exhaust leaks	❒Yes	❒No	❒Corrected________
Abnormalities	❒Yes	❒No	Comments:________

Vehicle Performance:

Starts	❒Easy	❒Other		
Throttle	❒Nomal	❒Touchy	❒Sluggish	❒Other ________
Breaks	❒Good	❒Poor	❒Touchy	❒Other ________
Transmission	❒Normal	❒Shifts hard		❒Other ________

Additional Comments:

____
____
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____

Signatures: Driver________________________________Engineer___________________________________

ATTACHMENT 3

Ambient Conditions Sheet

Vehicle #:	Test Date:	Driver:
Test Route:		Location:
Vehicle Owner:		Engine manufacturer:
Vehicle type:		Engine ID#:
Vehicle Manufacturer:		
VIN # (17 Digit):		
License plate #:		
Vehicle model year:		

Start of Test:

Weather Conditions: ❐Sunny ❐Cloudy ❐Rain ❐Snow ❐Sleet

Ambient Temperature:_________ °F ❐Measured ❐Airport ❐Other:____________________________

Relative Humidity: _________ % ❐Measured ❐Airport ❐Other:____________________________

Barometric Pressure _________ in Hg ❐Measured ❐Airport ❐Other:____________________________

End of Test:

Weather Conditions: ❐Sunny ❐Cloudy ❐Rain ❐Snow ❐Sleet

Ambient Temperature:_________ °F ❐Measured ❐Airport ❐Other:____________________________

Relative Humidity: _________ % ❐Measured ❐Airport ❐Other:____________________________

Barometric Pressure _________ in Hg ❐Measured ❐Airport ❐Other:____________________________

Signatures: Driver: ____________________________ Engineer: ____________________________

Date: ____________________________ Date: ____________________________

Test Crew: Engineer: ______________________________________

Driver: ______________________________________

Tech.: ______________________________________

Tech.: ______________________________________

Additional Comments

ATTACHMENT 4

Analyzer Check-off Sheet

Vehicle #:	Test Date:	Driver:
Test Route:		Location:
Vehicle Owner:		Engine manufacturer:
Vehicle type:		Engine ID#:
Vehicle Manufacturer:		
VIN # (17 Digit):		
License plate #:		
Vehicle model year:		

Leak checks completed:

Emissions	❐Yes	❐No
Flow Meter	❐Yes	❐No

Analyzer Calibration:

			Zero Values Pre / Post	
NOx	❐Yes	❐No	/	ppm
CO_2	❐Yes	❐No	/	%
Flow meter absolute pressure	❐Yes	❐No	/	in Hg
Flow meter differential pressure	❐Yes	❐No	/	in WC
Flow meter temperature	❐Yes	❐No	/	°F
Ambient temperature	❐Yes	❐No	/	°F
Relative humidity	❐Yes	❐No	/	%
Ambient absolute pressure	❐Yes	❐No	/	in Hg
ECU protocol adaptor	❐Yes	❐No		

Temperatures:

Sampling line temperature set point: ____________ °F
Sampling line temperature readout: ____________ °F
Heated filter temperature set point: ____________ °F
Heated filter temperature readout: ____________ °F
Enclosure temperature readout: ____________ °F
Heated pump (head) temperature: ____________ °F
NO_2 converter temperature readout: ____________ °F

Flow rates:

To NOx detector: ______ lpm
To NDIR detector: ______ lpm

Additional Comments:

____
____
____
____
____
____
____

Signatures: Tech: ____________________ Engineer: ____________________

ATTACHMENT 5

Field Log and Custody Record
S-HDDE Phase III

Operator(s): ______________________ Date: ______________
____
____
____

Instrument: ______________________
Instrument Manufacturer/Model Number: ______________________
Instrument Serial Number: ______________________
Instrument ID (assigned by the testing agency) ______________________

Test	Vehicle#	Route	Date	Time		Output Data File Name	Remarks
				Start	End		

1 Start-up check
(Was there an indication of instrument malfunction prior to tests?) ❐Yes ❐No

2 Instrument performance
(Was there an indication of instrument malfunction prior to tests?) ❐Yes ❐No

3 Shutdown check
(Was there an indication of instrument malfunction prior to tests?) ❐Yes ❐No

Relinquished by: (Signature)	Received by: (Signature)	Date/Time
Relinquished by: (Signature)	Received by: (Signature)	Date/Time
Relinquished by: (Signature)	Received by: (Signature)	Date/Time

ATTACHMENT 6

Quality Assurance/Quality Control and Emissions Data Report

Testing Agency

Project: In –Use Emissions Testing of Heavy-Duty Diesel Engine Vehicles

Submitted to:

Principal Investigator (PI):

Co-Principal Investigators:

Project Fund/Area/Org:

Funding Agency:

Approvals:

Technician: ______________________________
Signature/Date

Test Engineer: ______________________________
Signature/Date

QC/QA Officer: ______________________________
Signature/Date

PI ______________________________
Signature/Date