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A comparison of a mini-PEMS and a 1065 compliant PEMS for on-road gaseous and particulate emissions from a light duty diesel truck

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HIGHLIGHTS

- Emissions Measurement Comparison between a fully 1065- PEMS and a mini-PEMS capable of measuring NOx, PM, and solid PN.
- NOx measurements for the compact PEMS were within approximately ±10% of those the full 1065 compliance PEMS system.
- The mini-PEMS showed larger absolute differences for PM but differences were 3% to +30% of 1 mg/mi certification level.
- Larger differences were seen for PN, which was attributed to a zero current offset for this older model mini-PEMS.
- Mini-PEMS could be used for regulatory and manufacturer compliance evaluation and validation, and I/M programs.

GRAPHICAL ABSTRACT

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ABSTRACT

The primary goal of this study was to compare emissions measurements between a 1065 compliant PEMS, and the NTK Compact Emissions Meter (NCEM) capable of measuring NOx, PM, and solid PN. Both units were equipped on a light-duty diesel truck and tested over local, highway, and downtown driving routes. The results indicate that the NOx measurements for the NCEM were within approximately ±10% of those the 1065 compliant PEMS, which suggests that the NCEM could be used as a screening tool for NOx emissions. The NCEM showed larger differences for PM emissions on an absolute level, but this was at PM levels well below the 1 mg/mi level. The NCEM differences ranged from −2% to +26% if the comparisons are based on a percentage of the 1.0 mg/mi standard. Larger differences were also seen for PN emissions, with the NCEM measuring higher PN emissions, which can primarily be attributed to a zero current offset that we observed for the NCEM, which has been subsequently improved in the latest generation of the NCEM system. The comparisons between the 1065 compliant PEMS and the NCEM suggest that there could be applications for the NCEM or other mini-PEMS for applications such as identification of potential issues by regulatory agencies, manufacturer evaluation and validation of emissions under in-use conditions, and potential use in inspection and maintenance (I/M) programs, especially for heavy-duty vehicles.

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1. Introduction

Portable Emissions Measurement Systems (PEMS) are tools that are designed to measure vehicle/truck emissions while operating on the road. The application and technology of PEMS has evolved considerably over the past 20 years. PEMS serve an important role in helping to better understand and characterize the differences between laboratory certification and other testing and real-world emissions. PEMS were incorporated into the regulatory process as part of the 1998 consent decree in the United States (U.S.) and the regulations for in-use compliance testing of heavy-duty vehicles within the Not-to-Exceed (NTE) areas of operation that were created as part of these proceedings (Federal Register 2003, 2005; US EPA, 2008). This provided an impetus for the development of more commercial PEMS. PEMS have also been used extensively for measurements of emissions from heavy-duty trucks, light-duty vehicles, and construction equipment (Johnson, 2002; Gautam et al., 2001; Kishan et al., 2011; Frey et al. 2010; Cao et al., 2016a, b). More recently, PEMS have been incorporated into regulations for Real Driving Emissions (RDE) testing in Europe (Vlachos et al., 2014).

In the development of specifications for in-use compliance testing, there has been an emphasis on PEMS that can replicate the performance of laboratory grade equipment to the greatest extent possible. In the U.S., the Code of Federal Regulations (CFR, 2000) under Title 40 Part 1065 has regulated the design and measurement techniques that can be used for such instrumentation, as well as the methods and verification processes to determine the PEMS unit is valid for the in-use compliance purposes, such as linearity verification, dew point calibration, etc. (40 CFR 1065). An extensive Measurement Allowance program and other associated studies were also conducted to evaluate the potential variance of such PEMS in comparison to more traditional laboratory equipment, and to provide an allowance for such deviations in the regulations (Boucher et al., 2012; Durbin et al., 2007; Fiest et al., 2008; Johnson et al., 2008, 2009, 2011a, 2011b; Khalek et al., 2010; Khan et al., 2012; Miller et al., 2006). PEMS that are 1065 compliant and have been verified include systems by such major manufacturers as AVL, Horiba, and Sensors Inc. While such PEMS provide a traceable level of accuracy for regulatory purposes, 1065 compliant PEMS units are still somewhat large in size, relatively expensive, and can be complex to use in terms of setup and operation.

As in-use emissions testing has advanced, emissions data has continued to show the importance of measuring emissions in-use to fully understand the range of emissions emitted by vehicles under different operating conditions. The complexity of in-use emissions has been put in the spotlight with some high profile cases where excess emissions have been identified for vehicles operating differently under in-use vs. laboratory conditions (Federal Register 2003; Thompson et al., 2014). It is also known that it is difficult to fully characterize and control emissions under all conditions as part of laboratory based certification testing, given the expense of laboratory testing. These issues have put greater emphasis on the need to collect in-use emissions measurements from a wider range of vehicles and operating conditions.

Given the complexity and cost of 1065 compliant PEMS, there is a growing interest in the development of mini-PEMS that are not targeted at compliance with 1065 specifications, but still provide reliable emissions measurements, and are easy to deploy and less expensive. Mini-PEMS are simplified versions of the 1065 compliant PEMS discussed above. Such PEMS could have a number of applications in that they could be used to screen larger numbers of vehicles to identify and characterize potential emissions issues. This could be of use to both engine and vehicle manufacturers to identify potential issues under real-world, or to government agencies looking for issues that might require more extensive investigation as part of enforcement programs. Such PEMS could also be used for enforcement in applications such as Inspection and Maintenance (I/M) programs. Some simpler instruments designed to target only a single emissions component are already being applied in I/M type of applications. Opacity has been used extensively as a surrogate for particulate matter (PM) emissions in a number of different areas. More recently, the Swiss SR941.242 Regulation in Europe is requiring biannual testing of off-road diesel machinery equipped with DPFs for compliance with a particle number (PN) mini-PEMS.

The development of non-1065 compliant mini-PEMS type of systems that can provide measurements of multiple pollutants has also expanded recently. Maha has developed a PEMS that can measure NOx, CO_2, and PM. The company 3DATX has developed their 2nd generation parSYNC PEMS that includes the real-time measurement of NOx, CO_2, and PM mass (Ropkins et al., 2016). Pegasor (Saukko et al., 2016), TSI Incorporated (2015), Testo, and Emisense (Steppan et al., 2011) have also developed small measurement systems or sensors for PEMS for PM/PN. NGK Spark Plug has also developed a mini-PEMS called the NTK Compact Emissions Meter (NCEM) (Jiang et al., 2016). The system can be used to measure particulate matter (PM) and particle number (PN), nitrogen oxides (NOx), oxygen (O_2), and air/fuel ratio. While such low cost mini-PEMS could provide considerably utility in measuring a large number of vehicles under many different operating conditions, it is important to better characterize the accuracy, repeatability, and robustness of such systems.

The goal of this study was to compare emissions measurements between a 1065 compliant PEMS, and one of the current generation mini-PEMS. This included a 1065 compliant AVL M.O.V.E system and a NTK NCEM system. Both PEMS units were equipped on a light-duty truck over local, highway, and downtown driving over 2 days. The results indicate that the NOx measurements between a 1065 compliant PEMS and the mini-PEMS were within approximately $\pm 10\%$, suggesting the NTK PEMS could be used as a screening tool for NOx emissions. Larger differences were found for PM and solid PN measurements that suggest that additional development of these measurement methods could be beneficial.

2. Materials and methods

2.1. Test vehicle, engine, and fuel

The test vehicle is a model year 2012 Chevrolet Silverado 2500HD Duramax light duty diesel pickup truck, which is widely available and used in the U.S. market. This vehicle has 43,140 mi at the start of the test and GVWR is in the range of 8501–10,000 lbs. The vehicle is equipped with advanced after-treatment technologies that have been implemented in the diesel fleet, such as DOC, DPF, and SCR. The vehicle is certified to U.S. EPA Tier 2 HDV/HD8510 (NOx at 0.8 g/mi and PM at 0.06 g/mi [U.S. EPA, 2016]) and CARB MDV/ULEV (NOx at 0.2 g/mi and PM at 0.06 g/mi [CARB, 2016]) emissions standards.

This vehicle is equipped with an engine family CGMXD06.6355 diesel engine. The engine is 6.6-liter, eight cylinders, turbocharged, direct injection, and common-rail engine configuration with a six-speed automatic transmission. The engine can deliver 397 hp at 3000 rpm and 765 lb-ft torque at 1600 rpm and has a compression ratio of 16.8:1.

The test fuel of this study was commercially available No. 2 diesel fuel from a local retail fueling station. It should be noted that the vehicle

Table 1
Summary of trips statistics for different routes and cycles.

Test routes/cycles	Distance (mi)	Average speed (mph)	Maximum speed (mph)	Number of stops	Cycle duration (s)
FTP	11.04	21.2	56.7	23	1874
LA4	7.50	19.6	56.7	18	1372
Local	6.80	16.3	53.6	11	1402
Highway	63.10	34.8	81.4	22	6545
LA downtown	15.80	15.8	65.6	45	3617
Idle and creep	1.80	2.5	32.9	18	2624

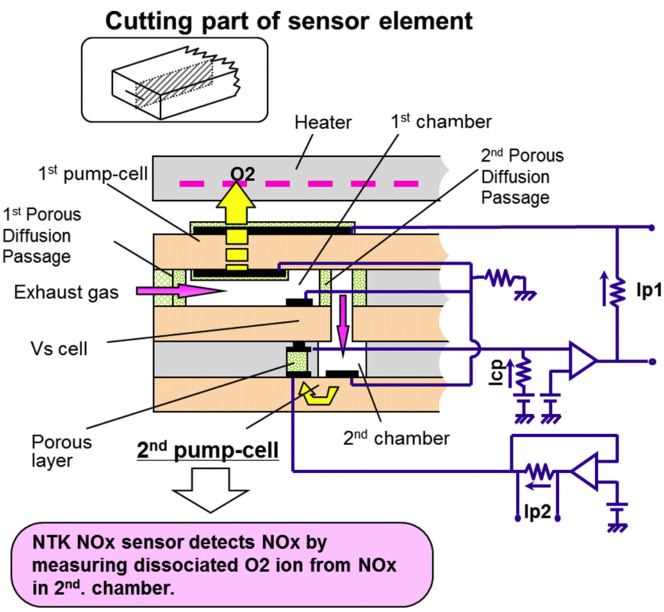

Fig. 1. NCEM NOx measurement design schematic.

Fig. 3. Instrument setup and power supply for on-road PEMS testing.

was filled up several times at the same retail fueling station. Since the properties of in-use California ultralow sulfur diesel are tightly controlled to provide comparable emissions, the use of diesel fuel from different fill ups is expected to have minimal impact on the emissions results.

2.2. Test cycles

The vehicle was tested over a period of 2 days using three different driving routes designed to represent local, highway, and LA downtown driving conditions. The characteristics of these three different cycles are shown in Table 1, along with the details for the FTP test for comparison.

The local route started and ended at the UCR CE-CERT facility in Riverside, and covered a distance of 6.8 mi. The local route was performed triplicate in order to get repeatable results. The local route is used to simulate the local driving and has a similar driving pattern to FTP driving cycle.

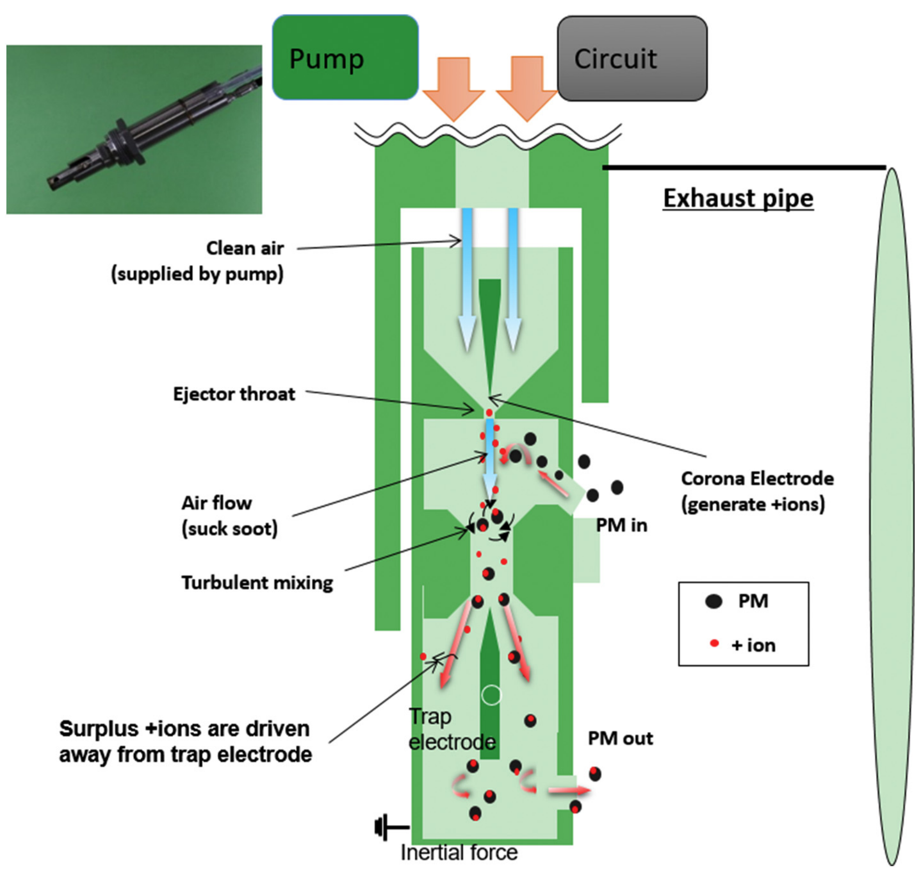

Fig. 2. NCEM PM and PN measurement design schematic.

Table 2
Summary of NOx emissions.

Results	Start location	End location	Mini-PEMS	1065 compliance PEMS			Mini-PEMS	1065 compliance PEMS			
			NOx	NOx	NO	NO_2	NOx	NOx	NO	NO_2	NO/NO_2
			g/cycle				g/mi				
Local_1	UCR CECERT	UCR CECERT	23.26	25.14	13.39	4.63	3.44	3.72	1.98	0.69	2.89
Local_2	UCR CECERT	UCR CECERT	33.19	31.06	14.64	8.64	4.82	4.51	2.12	1.25	1.7
Local_3	UCR CECERT	UCR CECERT	34.22	26.85	12.79	7.25	5.06	3.97	1.89	1.07	1.76
Average							4.44	4.07			
% difference							9.20%				
Highway_1	UCR CECERT	USC main campus	137.21	142.99	68.51	38.06	2.17	2.26	1.08	0.6	1.8
Highway_2	USC main campus	UCR CECERT	144.14	146.72	69.4	40.43	2.29	2.33	1.1	0.64	1.72
Average							2.23	2.3			
% difference							−2.90%				
LA Downtown_1	USC main campus	USC main campus	36.39	35.75	15.39	12.18	2.3	2.26	0.97	0.77	1.26
LA Downtown_2	USC main campus	USC main campus	39.03	37.71	16.07	13.1	2.47	2.39	1.02	0.83	1.23
Average							2.39	2.32			
% difference							2.70%				
Idle and Creep	USC main campus	USC main campus	10.38	11.45	6.23	1.91	5.76	6.36	3.46	1.06	3.26
% difference							−9.40%				
Total			457.84	457.68	216.42	126.2	3.54	3.47	1.7	0.86	1.97

These values are the average of all the NOx emissions over all different cycles in g/mi basis.

The highway route started at UCR and went to the main campus of the University of Southern California. The total distance of this route was 63.6 mi. The highway route includes over 95% highway driving along Highways I-60, I-10, I-710, and I-110. This route was conducted as a round trip, going first from UCR to USC and then back to UCR.

The LA downtown route started and ended at USC main campus on Jefferson Boulevard. It covered a distance of 15.7 mi. This route is used to simulate urban driving conditions in downtown LA. This route essentially represents the route that was used to develop the original FTP cycle. Additional idle and creep driving was also incorporated into this route. This route was performed twice.

2.3. Instruments

For this study, a commercial available 1065 compliant AVL M.O.V.E system was utilized (Cao et al., 2016b). The AVL M.O.V.E system includes gas-phase analyzers for nitrogen oxide (NO) and nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbon (THC), non-methane hydrocarbon (NMHC), and methane (CH_4) and also particulate phase emissions of PM mass, solid PM mass, and also solid particle number (PN). The AVL M.O.V.E system measures oxides of nitrogen (NO and NO_2) by non-dispersive ultraviolet radiation (NDUV), and then calculates the NOx value based on the reported NO and NO_2 emissions. The AVL PM PEMS measurement system selected is AVL's 483 micro soot sensor (MSS) in conjunction with their gravimetric filter module (GFM) option. The combined system is called the AVL 494 PM system. The MSS instrument measures the modulated laser light absorbed by particles from an acoustical microphone. Since the MSS only detects elemental carbon, the GFM is included along with a post processor to allow the soluble organic fraction (SOF) and sulfate fraction to be estimated, based on a comparison of the MSS and GFM measurements. The combined MSS + GFM system recently received type approval by EPA as a total PM measurement solution for in-use testing, thus making it one of the few 1065 compliant

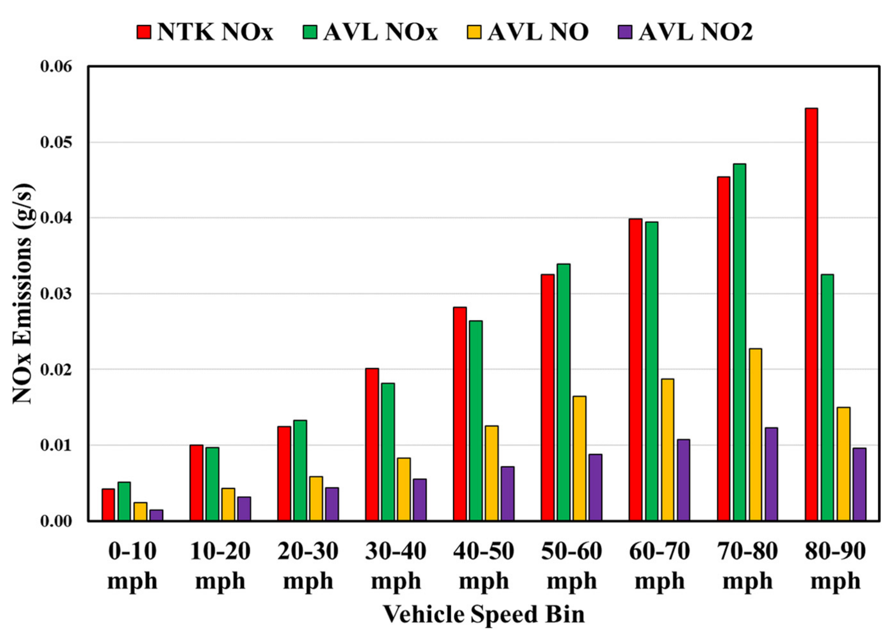

Fig. 4. Vehicle speed based comparisons for NOx emissions for 1 day of testing.

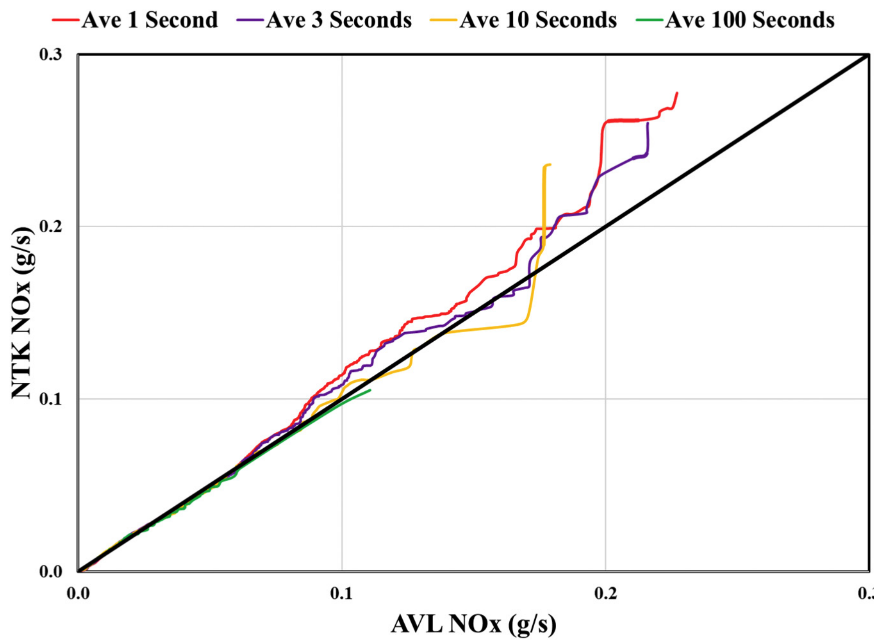

Fig. 5. Q-Q plot analysis on NOx emissions for 1 day of testing.

PM PEMS. For this study, both total PM using the MSS + GFM and soot PM using only the MSS are reported. In additional to the AVL 494 PM system, an AVL PN PEMS iEMS was also utilized. The PN PEMS measures solid particle number concentrations using diffusion charger principles consistent with the European RDE compliant program.

The mini-PEMS evaluated in this study was an NTK NCEM. The system can be used to measure PM mass, PN, NOx, and oxygen (O_2). Air/fuel ratio is also available on the latest generation NCEM, but this feature was not available for the version utilized for this study. The NCEM uses direct measurement sensors rather than dilution sampling. As the result, there is no delay time and measurements can be performed with good responsiveness in real-time. The system weights about 12 kg and measures 340 mm by 280 mm by 270 mm. It can be set up in approximately 10 min. It can be powered by a DC12/24 V vehicle battery and draws <10 Amp to operate.

The NOx sensor is based on an original equipment manufacturer (OEM) product used for engine control and on-board diagnostic (OBD) of SCR systems The NOx sensor detects NOx by measuring O_2 ions created by the dissociation of NOx into N_2 and O_2 in the detection chamber, as shown in Fig. 1. The design used for this specific sensor dissociates NO_2 to NO and O_2 in a trap layer before the gases reach the detection portion of the element. Therefore, the sensitivity to NO and NO_2 is essentially the same. Only under conditions where there is a very high gas flow rate or very cold gas that the element heater cannot overcome, would the ratio start to diverge from 1:1. In these cases the sensitivity to NO_2 could be slightly lower than the sensitivity to NO.

Table 3
Summary of 25th and 75th percentile Q-Q plot values for NOx, PM, and PN emissions.

Routes	Percentile	NOx (g/s)		PM and soot (mg/s)			PN (#/s)	
		NTK	AVL	NTK	AVL MSS	AVL PM	NTK	AVL
Local_1	25%	0.0035	0.0081	0.0000	0.0002	0.0005	0.00E+00	0.00E+00
	75%	0.0087	0.0190	0.0000	0.0008	0.0012	0.00E+00	1.47E+08
Local_2	25%	0.0043	0.0075	0.0000	0.0002	0.0005	0.00E+00	1.67E+07
	75%	0.0166	0.0223	0.0000	0.0009	0.0013	0.00E+00	1.82E+08
Local_3	25%	0.0043	0.0074	0.0000	0.0002	0.0005	0.00E+00	1.78E+03
	75%	0.0184	0.0182	0.0002	0.0009	0.0014	8.24E+08	1.80E+08
Local_Average	25%	0.0040	0.0077	0.0000	0.0002	0.0005	0.00E+00	5.58E+06
	75%	0.0146	0.0198	0.0001	0.0009	0.0013	2.75E+08	1.70E+08
Highway_1	25%	0.0042	0.0046	0.0000	0.0004	0.0005	0.00E+00	0.00E+00
	75%	0.0312	0.0339	0.0000	0.0015	0.0015	0.00E+00	2.14E+08
Highway_2	25%	0.0040	0.0056	0.0000	0.0004	0.0006	0.00E+00	2.77E+07
	75%	0.0200	0.0192	0.0001	0.0012	0.0014	3.87E+08	2.49E+08
Highway_Average	25%	0.0041	0.0051	0.0000	0.0004	0.0006	0.00E+00	1.39E+07
	75%	0.0256	0.0265	0.0000	0.0014	0.0015	1.93E+08	2.31E+08
LA Downtown_1	25%	0.0037	0.0046	0.0004	0.0003	0.0004	1.83E+09	0.00E+00
	75%	0.0083	0.0082	0.0013	0.0007	0.0010	6.28E+09	8.93E+07
LA Downtown_2	25%	0.0035	0.0047	0.0008	0.0003	0.0005	3.64E+09	1.91E+07
	75%	0.0089	0.0089	0.0019	0.0008	0.0011	9.25E+09	1.48E+08
LA Downtown_Average	25%	0.0036	0.0047	0.0006	0.0003	0.0004	2.74E+09	9.56E+06
	75%	0.0086	0.0085	0.0016	0.0008	0.0010	7.77E+09	1.19E+08
Idle and Creep	25%	0.0030	0.0036	0.0002	0.0002	0.0006	9.68E+08	0.00E+00
	75%	0.0034	0.0040	0.0003	0.0002	0.0006	1.64E+09	4.23E+07

The PM/PN sensor is based on the Pegasor PPS-M technology, where particles are charged in a corona discharge, such that the total measured charge is proportional to the particle surface area, as shown in Fig. 2 (Lanki et al., 2011; Ntziachristos et al., 2011; Ntziachristos et al., 2013; Rostedt et al. 2017). PM/PN can then be determined via calibrations that are used to establish calibration constants (Ntziachristos et al., 2013; Rostedt et al., 2014). To determine PM mass, the signal is calibrated against an AVL MSS 483, which is in turn calibrated against a gravimetric filter where the filter face temperature is not controlled to the 47 °C ± 5 °C specifications in 40 CFR 1065. To determine PN, the sensor is calibrated against a TSI scanning mobility particle sizer (SMPS). Both the PM and PN calibrations are performed with a soot generator that provides soot particles with a unimodal distribution with peak concentration around 75 nm. The calibration does have some sensitivity to the particle size distribution, which has been discussed in detail elsewhere (Ntziachristos et al., 2011; Rostedt et al., 2014; Rostedt et al., 2017). Simulations using a range of possible diesel particle size distributions, however, have shown that the maximum theoretical error is 23% when using surface area as a proxy for number and 39% when using surface area as a proxy for soot mass, although the actual error is expected to be much less than these values (Ntziachristos et al., 2012). For the test vehicle itself, our own internal data indicates that its size distribution is bimodal with a minor peak at 15 nm and a larger peak at 75 nm, which should be relatively well represented by the distribution used for the calibration. Also, since the sensor measures PM in the raw exhaust, with only a small amount of dilution, the total PM and total PN measured by the NCEM is primarily solid PM.

A Semtech 4-inch Exhaust Flow Measurement (EFM) system was used by both systems for the measurement of the exhaust flow to provide integrated mass emissions as well as second by second data for each pollutant.

2.4. Measurement protocols

The experimental set up for study is shown in the Fig. 3. This includes the NCEM, AVL gaseous M.O.V.E. system, AVL PM system, and the AVL PN PEMS iS. The power system for the set up included a Yamaha gasoline generator model EF2800i, which has two 120 V AC plugs with 20A maximum current each, a CHARGEMASTER 12 V power converter to power the AVL Gas M.O.V.E system, and a Xantrex sine wave inverter powered through a twin 12 V battery pack to power the EFM and the computers. The purpose of the 12 V batteries were to support as a backup power source, which was necessary when switching from building power to the generator power, or when powering down the generator to add more fuel.

For the AVL Gas M.O.V.E system, the tests were performed using the certification test protocol provided with Concerto software (1065 compliant), including pre- and post-test calibrations and drift corrections of the gaseous data. The NCEM was controlled through the screen of the unit with the data logged to a flash drive.

3. Results and discussion

3.1. NOx emissions

The NOx emissions results for all the testing routes are shown below in Table 2. The range of NOx emissions are in the range of 2.76 to 5.76 g/mi for NCEM unit and in the range 2.26 to 6.36 g/mi for AVL M.O.V.E. system, as shown in Table 2 below.

Overall, the NOx emissions show reasonably good agreement between NCEM unit and AVL M.O.V.E system. The average NCEM emissions were within 3% of those for the AVL M.O.V.E for both the highway and the LA downtown routes. The average differences for the local routes and the idle and creep were somewhat higher, but were still within 10% for both cycles. The NCEM did not show a consistent bias compared to the AVL M.O.V.E system, with the NCEM reading higher for some test routes and lower for others. In fact, the total grams of NOx emissions measured over 2 days of testing with variety of routes, resulting in 457.84 g for NECM and 457.68 g for AVL M.O.V.E system. This represents a difference of only 0.03% for total emissions, indicating that the NCEM read higher or lower than the AVL M.O.V.E with roughly equal frequency. The potential impacts of different NO/NO_2 ratios in the exhaust were also examined, as shown in Table 2. Although larger differences between the NTK and AVL were found for the idle/creep conditions, where the NO/NO_2 ratios were higher, and smaller differences were seen for the LA Downtown route where the NO/NO_2 were lower, the local and highway cycles also showed higher and lower differences, respectively, even though the NO/NO_2 ratios were fairly similar for these routes. As such, there were no definitive trends in terms of analyzer performance as a function of NO/NO_2 ratios.

Table 4
Summary of correlation slope and regression statistics for NOx emissions NOx (g/s).

Routes		Ave 1 s			Ave 3 s		
		NTK vs AVL NOx	NTK vs AVL NO	NTK vs AVL NO2	NTK vs AVL NOx	NTK vs AVL NO	NTK vs AVL NO2
Local_1	Slope	1.137	2.142	3.468	1.135	2.147	3.409
	R2	0.450	0.421	0.328	0.491	0.461	0.354
Local_2	Slope	1.089	2.190	4.195	1.131	2.284	4.310
	R2	0.534	0.509	0.563	0.586	0.562	0.610
Local_3	Slope	0.884	1.634	3.825	0.917	1.719	3.880
	R2	0.335	0.287	0.421	0.372	0.324	0.455
Local_Average	Slope	1.037	1.988	3.829	1.061	2.050	3.866
	R2	0.440	0.406	0.438	0.483	0.449	0.473
Highway_1	Slope	0.790	1.528	3.012	0.805	1.562	3.055
	R2	0.573	0.542	0.549	0.622	0.591	0.593
Highway_2	Slope	0.799	1.540	3.204	0.818	1.584	3.267
	R2	0.535	0.501	0.548	0.594	0.561	0.601
Highway_Average	Slope	0.795	1.534	3.108	0.811	1.573	3.161
	R2	0.554	0.522	0.549	0.608	0.576	0.597
LA Downtown_1	Slope	0.776	1.491	2.687	0.812	1.582	2.767
	R2	0.340	0.279	0.406	0.402	0.337	0.465
LA Downtown_2	Slope	0.749	1.494	2.611	0.769	1.540	2.662
	R2	0.373	0.327	0.423	0.436	0.384	0.491
LA Downtown_Average	Slope	0.763	1.492	2.649	0.790	1.561	2.714
	R2	0.356	0.303	0.414	0.419	0.361	0.478
Idle and Creep	Slope	0.724	1.124	1.599	0.767	1.198	1.553
	R2	0.202	0.128	0.168	0.257	0.160	0.202

Routes		Ave 10 s			Ave 100 s		
		NTK vs AVL NOx	NTK vs AVL NO	NTK vs AVL NO2	NTK vs AVL NOx	NTK vs AVL NO	NTK vs AVL NO2
Local_1	Slope	1.090	2.051	3.083	0.942	1.921	1.864
	R2	0.529	0.489	0.371	0.435	0.416	0.242
Local_2	Slope	1.203	2.475	4.387	0.988	1.994	3.747
	R2	0.684	0.666	0.685	0.646	0.621	0.663
Local_3	Slope	0.921	1.718	3.982	0.896	1.756	3.481
	R2	0.395	0.342	0.489	0.346	0.294	0.454
Local_Average	Slope	1.072	2.081	3.817	0.942	1.890	3.030
	R2	0.536	0.499	0.515	0.476	0.444	0.453
Highway_1	Slope	0.869	1.712	3.202	0.914	1.869	3.315
	R2	0.801	0.774	0.730	0.988	0.979	0.925
Highway_2	Slope	0.898	1.772	3.423	0.948	1.918	3.609
	R2	0.785	0.761	0.741	0.979	0.973	0.925
Highway_Average	Slope	0.884	1.742	3.312	0.931	1.893	3.462
	R2	0.793	0.767	0.736	0.984	0.976	0.925
LA Downtown_1	Slope	0.948	1.949	2.920	1.020	2.139	2.838
	R2	0.635	0.581	0.623	0.924	0.885	0.771
LA Downtown_2	Slope	0.893	1.830	2.971	1.025	2.212	2.837
	R2	0.665	0.614	0.687	0.936	0.894	0.835
LA Downtown_Average	Slope	0.920	1.889	2.946	1.023	2.175	2.838
	R2	0.650	0.597	0.655	0.930	0.889	0.803
Idle and Creep	Slope	0.974	1.680	1.494	1.206	2.193	1.234
	R2	0.513	0.356	0.302	0.950	0.504	0.538

Some additional analyses were also conducted to evaluate the NOx data in different ways. Comparisons between NOx emissions for different speed bins are provided in Fig. 4 for 1 day of testing that included two highway routes, two LA downtown routes, and an idle and creep route. The data showed relatively good comparisons throughout the full range of vehicle operation, with the exception of some bigger discrepancies seen at speeds between 80 and 90 mph. The data also show a general trend of increasing NOx emissions as a function of speed, with the exception of the 80 to 90 mph measurements with the AVL M.O.V.E. It should be noted that only 19 data points were found in the 80 to 90 mph category, considerably smaller than the number of data points in the other speed. While the NCEM measurements were higher than those for the AVL M.O.V.E. for most of these data points, this represents a relatively small data set in comparison with the data available for the other speeds.

Additional analyses were also conducted using quantile-quantile (Q-Q) plots for 1 s, 3 s, 10 s, and 100 s averaged data, as shown in Fig. 5 for the same routes used for the speed bin plot. For this analysis, the data are sorted from the lowest to highest value for each instrument. Overall, the Q-Q plots showed relatively good agreement between the instruments, with the lines being only slightly higher than the 1:1 line. The 25 and 75 percentile points are provided in Table 3, which are the points below which 25% and 75% of the measurements fall for both instruments. These points define the highest and lowest quantiles for the Q-Q plots. Regression analyses were also performed for the real-time data for 1 s, 3 s, 10 s, and 100 s averaged data. A range of different averaging intervals were used since such a comparison could be very sensitive to time alignment in addition to the actual precision of the measurement itself. The results of these analyses are presented in Table 4 for total NOx. The results show that the correlation R^2 improves and the slope gets closer to 1 as the time interval for the averaging increases, which is a measure of how this comparison can be impacted by time alignment. The local cycle showed a slope near 1 for the NTK vs. AVL NOx, but the correlation for the local cycle was relatively poor, even for the 100 s average.

The differences in integrated NOx emissions between the NTK and the AVL PEMS over various routes are comparable to those found in previous studies. In a previous study, comparisons were made between an earlier version of NTK's NCEM system, a AVL 1065 compliant gaseous portable emission measurement system (PEMS), and UCR's 1065 compliant mobile emissions laboratory (MEL) for engine dynamometer tests under transient and steady state conditions (Jiang et al., 2016) and for chassis dynamometer measurements for a truck equipped with a 2014 on-highway engine equipped with a properly functioning DPF/SCR system (Johnson and Jiang, 2015). For this previous study, the NTK NO_x measurements were lower than the MEL reference method and ranged from −16.3% for the FTP to −4.7% for an engine dynamometer version of the UDDS (Jiang et al., 2016). The AVL PEMS, on the other hand, was higher than the MEL reference method by +7.9% for the FTP and +16.7% for the UDDS. For the chassis dynamometer testing for the DPF/SCR equipped vehicle, the NTK NOx measurements were lower than the MEL reference method for the UDDS, Creep, and Transient cycles, ranging from −13% for the UDDS to −30% for the Creep, while they were higher than those for the MEL reference method for two cruise cycles with lower NOx emissions rates, with differences of +120% or greater.

The NOx emissions can also be compared back to early comparisons between 1065 compliant PEMS and CVS reference methods conducted as part of the Measurement Allowance program (Johnson et al., 2009, 2011a). For the on-road comparisons done as part of the Measurement Allowance program, bsNOx emissions for the PEMS measurements were consistently higher than those for the MEL. The deviations were 8% ± 4%, 4% ± 5%, and 3% ± 5%, for different calculation methods, relative to the NTE NOx standard 2.68 g kW^{-1} h^{-1} (2.0 g $hp.^{-1}$ h^{-1}). In another study that was done as part of the initial validation tests for the AVL's M.O.V.E GAS PEMS 493 system testing included in-lab and on-road emission comparisons between the AVL PEMS and the UCR MEL for three different heavy-duty engines with NOx emission certification levels ranging from 0.27 g/kWh (0.2 g/hp-hr) to 5.4 g/kWh (4.0 g/hp-hr) (Cao et al., 2016b). The relative error for the AVL PEMS brake-specific NOx (bsNOx) measurements was within +5 to −10% relative error over the 1.0 to 7.0-g/kWh range, ranged from a +15 to −15% over the lower 0.1 to 1-g/kWh range, and increased sharply below 0.1 g/kWh from 15% to >50% at 0.02 g/kWh. The larger relative error below 0.10 g/kWh was due to the very low NOx emission rates that approached the detection limits of both the raw PEMS and dilute MEL measurement methods. It is worth adding that in all of these previous studies the PEMS measured exhaust flow independently of the MEL,

Table 5
Summary of PM emissions.

Results	Start location	End location	Mini- PEMS	1065 compliance PEMS		Mini-PEMS	1065 Compliance PEMS	
			Total PM	Total PM	Soot PM	Total PM	Total PM	Soot PM
			mg/cycle			mg/mi		
Local_1	UCR CECERT	UCR CECERT	0.98	1.67	1.15	0.14	0.25	0.17
Local_2	UCR CECERT	UCR CECERT	1	1.77	1.43	0.15	0.26	0.21
Local_3	UCR CECERT	UCR CECERT	1.61	1.76	1.39	0.24	0.26	0.21
Average			1.19	1.73	1.32	0.18	0.25	0.19
% difference NCEM Total PM to AVL Total PM						−31.10%		
% difference NCEM Total PM to AVL Soot PM						−9.70%		
Highway_1	UCR CECERT	USC main campus	5.42	6.94	6.82	0.09	0.11	0.11
Highway_2	USC main campus	UCR CECERT	7.15	8.24	6.87	0.11	0.13	0.11
Average			6.29	7.59	6.85	0.1	0.12	0.11
% difference NCEM Total PM to AVL Total PM						−17.20%		
% difference NCEM Total PM to AVL Soot PM						−8.10%		
LA Downtown_1	USC main campus	USC main campus	6.34	3.23	2.34	0.4	0.2	0.15
LA Downtown_2	USC main campus	USC main campus	7.43	3.36	2.63	0.47	0.21	0.17
Average			6.88	3.29	2.49	0.44	0.21	0.16
% difference NCEM Total PM to AVL Total PM						109.00%		
% difference NCEM Total PM to AVL Soot PM						177.00%		
Idle and Creep	USC main campus	USC main campus	1.44	1.9	0.66	0.8	1.06	0.37
% difference NCEM Total PM to AVL Total PM						−24.30%		
% difference NCEM Total PM to AVL Soot PM						117.70%		
Total			31.36	28.87	23.29	0.3	0.31	0.19

These values are the average of all the PM emissions over all different cycles in g/mi basis.

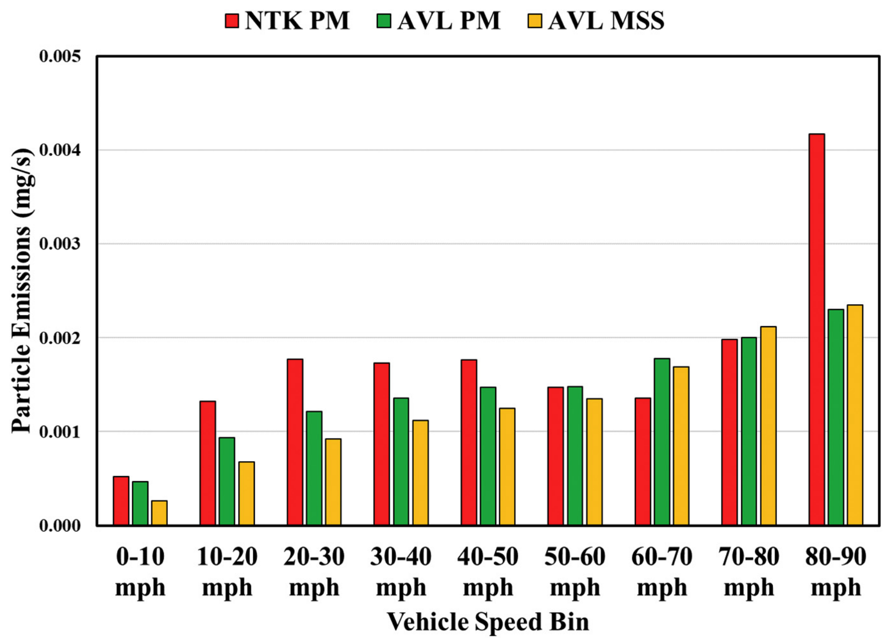

Fig. 6. Vehicle speed based comparisons for particle emissions for 1 day of testing.

which represents an important source of error that was not characterized in the current study, as the AVL PEMS and NCEM used exhaust flow measurements from the same EFM.

Overall, the differences between the instruments seem reasonable given the measurement methodologies, and are well within the ranges that would be acceptable for screening tests or tests designed to identify high emitting vehicles or off-cycle emissions events. It is worth noting that the NCEM did show a higher coefficient of variation (COV) for the local tests.

It is also worth noting that the NOx emission levels of this vehicle were considerably higher than what might be expected based on its certification level. The vehicle's FTP certification level (CARB MDV/ULEV) is 0.2 g/mi, and previous laboratory chassis dynamometer test results for this same vehicle have shown NOx emission levels below 0.2 g/mi. However, the average on-road NOx emissions results for this study were 3.5 g/mi, which suggests a potential malfunction of the SCR system. Although the malfunction indicator light (MIL) was not on during testing, subsequent to testing, the MIL did turn on with several codes indicative of a DEF coolant, DPF, and reduced power issues. The dealership performed three regenerations for the DPF, replaced the reductant temperature sensor/reservoir, and replaced the coolant reservoir/low coolant assembly. Following the repairs, the vehicle was tested again over the FTP cycle on a chassis dynamometer, and NOx emission levels were found to be below the 0.2 g/mi NOx emission standard. It should be noted that the primary purpose of this testing was a comparison between the NTK and AVL system, as such the vehicle only served as an

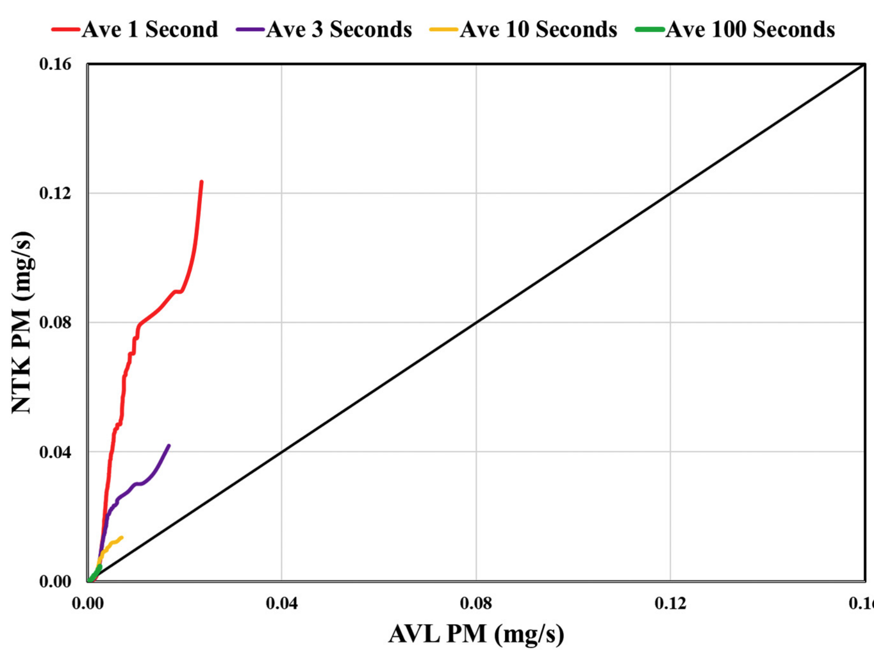

Fig. 7. Q-Q plot analysis on PM emissions for 1 day of testing.

emissions source, so the results still provide a valid comparison between the two systems independent of the condition of the vehicle.

3.2. PM emissions

The test vehicle was equipped with a DPF, so the PM emissions levels were generally low. The PM emissions results for all the testing routes are shown below in Table 5. PM emissions were in the range of 0.09 to 0.80 mg/mi for the total PM for the NCEM unit, in the range 0.11 to 1.06 mg/mi for the total PM for the AVL MSS + GFM measurements, and in the range of 0.11 to 0.37 mg/mi for soot PM for the AVL MSS. For the AVL MSS + GFM measurements, the PM emission rates were typically around 25% of the 2025 ARB 1.0 mg/mi standard or less, with the exception of the idle and creep cycle. To get PM mass, the AVL MSS + GFM system multiplies the measured PM-soot by the calculated filter correction factor. The PM filter correction factor averaged from 1.02 to 1.38 for the non-idle tests, which suggests a fairly low organic carbon (OC) fraction of <38% of the total PM mass. It should be noted that since the AVL measures dilute PM, its PM value would include any PM that may have been formed in the dilution system, which would not be measured by the NCEM system since NCEM primarily measures solid PM in the hot raw exhaust.

In general, the PM NCEM system behaved well and showed a reasonable comparison to a 1065 compliant MSS + GFM PM measurements and the AVL MSS soot measurements given the low levels of the PM emissions. The relative differences between the NCEM and AVL MSS + GFM PM mass [RelDif_% = (NCEM-[MSS + GFM])/NCEM] ranged from −31% to +109%. The relative differences between the NCEM and the AVL MSS soot measurements ranged from −8.1% to +177%. The NCEM total PM measurements showed a better comparison with AVL MSS soot measurements than the AVL total PM measurements for the local and highway driving, which is consistent with the fact that the NCEM and AVL MSS characterize primarily solid/soot PM. However, the NCEM showed greater differences for the AVL MSS than the AVL total PM for the LA downtown route and the idle and creep testing. In comparison with previous studies, Ntziachristos et al. (2013) found that the PPS measured 8% lower PM than a MSS for a diesel vehicle and approximately 40% lower PM than an MSS for a lower emitting direct injection spark ignition engine-equipped vehicle. It should be noted that NTK has improved the offset current variation for its PM measurement by 81% in its more recent version of the system, which is expected to improve the accuracy of the system at low PM levels (Tange, 2017).

It is also worthwhile to evaluate the PM differences in the context of the future 2025 California LEVIII PM emissions standard of 1 mg/mi, as there is considerable interest in how effective gravimetric and other methodologies are in quantifying PM emissions at levels below 1 mg/mi (Xue et al., 2018; Sardar et al., 2015; Swanson et al., 2018). If the comparisons were based on the future 1.0 mg/mi PM standard, the average differences reduce to −2% to +26% for the AVL total PM mass measurements [StdDif_% = (NCEM-[MSS + GFM])/1.0] and to −1% to 43% for the AVL MSS soot measurements. The lower difference relative to the emission standard suggests the NCEM system is capable of quantifying PM at and below the 1 mg/mi standard with fairly good confidence. The NCEM system showed a lower PM emission level for the FTP-like and highway routes, but a higher emission level for the LA downtown routes compared to both the MSS + GFM and MSS alone systems. This suggests a possible PM physical characteristic change between in-town driving and cruise conditions that may have caused the NCEM to report differently. Overall, the total PM emissions showed good agreement between NCEM unit and AVL MSS + GFM and MSS alone systems. The total mass of PM emissions measured over the 2 days of testing over a variety of routes was 31.36 mg for NECM and 28.87 mg for AVL MSS + GFM system. The difference between the NCEM and the 1065 compliant PEMS is 8.62%.

Additional analyses of the PM data included speed bin plots, Q-Q plots, and regression analyses. Comparisons between PM emissions for different speed bins are provided in Fig. 6 for day of testing that included two highway routes, two LA downtown routes, and an idle and creep route. The results showed that the largest PM discrepancies were seen in the 10 to 30 mph range, and for speed from 80 to 90 mph. For the 80 to 90 mph speed bin, it should be noted that only 19 data points are available, so this is a very small data set for comparison. For these 19 data points, the NCEM measured no PM emissions for all but two points, which appear to be outliers, that lead to the higher average emissions for the NCEM. The Q-Q plots for the same day of testing for the different data averaging times show the NCEM PM measurements are biased high relative to the AVL PM, particularly for the 1 s averaging, as shown in Fig. 7. The 25 and 75 percentile values from the Q-Q plots for the NCEM, AVL MSS, and AVL PM are provided in Table 3. Regression analyses were performed for the PM real-time data for 1 s, 3 s, 10 s, and 100 s averaged data, as shown in Table 6. The results show a relatively

Table 6
Summary of correlation slope and regression statistics for PM and soot emissions.

PM and MSS (mg/s)		Ave 1 s			Ave 3 s		
		NTK vs AVL MSS	NTK vs AVL PM	AVL MSS vs AVL PM	NTK vs AVL MSS	NTK vs AVL PM	AVL MSS vs AVL PM
Local_1	Slope	0.729	0.841	0.926	0.781	0.876	0.931
	R2	0.017	0.024	0.920	0.052	0.071	0.931
Local_2	Slope	0.401	0.522	1.100	0.428	0.565	1.105
	R2	0.024	0.031	0.940	0.067	0.091	0.947
Local_3	Slope	1.170	1.261	1.041	1.199	1.291	1.046
	R2	0.083	0.083	0.937	0.220	0.220	0.945
Local_Average	Slope	0.767	0.875	1.022	0.803	0.911	1.027
	R2	0.041	0.046	0.932	0.113	0.127	0.941
Highway_1	Slope	0.697	0.806	1.126	0.700	0.812	1.132
	R2	0.017	0.016	0.926	0.048	0.047	0.937
Highway_2	Slope	0.833	0.454	0.578	0.830	0.513	0.630
	R2	0.019	0.009	0.548	0.053	0.030	0.590
Highway_Average	Slope	0.765	0.630	0.852	0.765	0.663	0.881
	R2	0.018	0.013	0.737	0.050	0.039	0.763
LA Downtown_1	Slope	2.177	2.038	0.862	2.175	2.081	0.892
	R2	0.113	0.117	0.874	0.242	0.249	0.896
LA Downtown_2	Slope	2.269	2.043	0.874	2.294	2.133	0.892
	R2	0.155	0.153	0.933	0.337	0.346	0.946
LA Downtown_Average	Slope	2.223	2.040	0.868	2.235	2.107	0.892
	R2	0.134	0.135	0.904	0.290	0.298	0.921
Idle and Creep	Slope	2.154	0.935	0.430	2.208	1.011	0.447
	R2	0.102	0.095	0.917	0.262	0.260	0.948

PM and MSS (mg/s)		Ave 10 s			Ave 100 s		
		NTK vs AVL MSS	NTK vs AVL PM	AVL MSS vs AVL PM	NTK vs AVL MSS	NTK vs AVL PM	AVL MSS vs AVL PM
Local_1	Slope	0.716	0.787	0.938	0.358	0.380	0.894
	R2	0.112	0.144	0.940	0.110	0.148	0.952
Local_2	Slope	0.353	0.471	1.102	0.281	0.502	1.029
	R2	0.094	0.131	0.953	0.076	0.215	0.936
Local_3	Slope	1.213	1.256	1.034	1.174	1.197	0.941
	R2	0.319	0.303	0.946	0.433	0.480	0.944
Local_Average	Slope	0.760	0.838	1.024	0.604	0.693	0.955
	R2	0.175	0.193	0.946	0.206	0.281	0.944
Highway_1	Slope	0.716	0.821	1.139	0.713	0.831	1.154
	R2	0.142	0.136	0.946	0.607	0.596	0.964
Highway_2	Slope	0.763	0.597	0.784	0.946	0.973	0.951
	R2	0.112	0.077	0.688	0.460	0.431	0.802
Highway_Average	Slope	0.739	0.709	0.962	0.830	0.902	1.052
	R2	0.127	0.106	0.817	0.533	0.514	0.883
LA Downtown_1	Slope	2.104	2.096	0.904	2.927	2.838	0.809
	R2	0.340	0.374	0.905	0.426	0.537	0.877
LA Downtown_2	Slope	2.283	2.155	0.907	1.975	2.085	0.940
	R2	0.504	0.519	0.950	0.503	0.597	0.940
LA Downtown_Average	Slope	2.194	2.126	0.905	2.451	2.461	0.874
	R2	0.422	0.446	0.927	0.465	0.567	0.909
Idle and Creep	Slope	2.098	1.005	0.464	1.853	0.936	0.494
	R2	0.487	0.496	0.957	0.874	0.877	0.957

Table 7
Summary of total and Solid PN emissions.

Results	Start location	End location	Mini-PEMS	PN PEMS	Mini-PEMS	PN PEMS
			Total PN	Solid PN	Total PN	Solid PN
			#/cycle		#/mi	
Local_1	UCR CECERT	UCR CECERT	4.72E+12	2.96E+11	6.98E+11	4.38E+10
Local_2	UCR CECERT	UCR CECERT	4.83E+12	3.48E+11	7.02E+11	5.05E+10
Local_3	UCR CECERT	UCR CECERT	7.76E+12	3.38E+11	1.15E+12	4.99E+10
Average					8.49E+11	4.81E+10
Highway_1	UCR CECERT	USC main campus	2.62E+13	1.40E+12	4.15E+11	2.22E+10
Highway_2	USC main campus	UCR CECERT	3.46E+13	2.09E+12	5.49E+11	3.32E+10
Average					4.82E+11	2.77E+10
LA Downtown_1	USC main campus	USC main campus	3.07E+13	4.84E+11	1.94E+12	3.07E+10
LA Downtown_2	USC main campus	USC main campus	3.59E+13	7.05E+11	2.27E+12	4.46E+10
Average					2.11E+12	3.76E+10
Idle and Creep	USC main campus	USC main campus	6.97E+12	1.37E+11	3.87E+12	7.62E+10
Total			1.52E+14	5.80E+12	1.45E+12	4.22E+10

These values are the average of all total or solid PN emissions over all different cycles in g/mi basis.

poor correlation for the regression analyses between the NTK and AVL PM measurements for most of the test cycles and averaging intervals.

These results can be compared to a previous engine dynamometer study with an older NTK NCEM PM instrument compared against a 1065 compliant AVL PM PEMS and the MEL reference laboratory (Jiang et al., 2016). In this previous study, the NCEM PM emissions were lower compared to the MEL PM method for all the cycles except for an engine dynamometer version of the UDDS cycle, with differences ranging from −60% for the FTP to −23% for two steady state supplementary emission test (SET) cycles to +50% for the UDDS cycle. The soot emissions for the 1065 compliant AVL PM PEMS were also lower than the MEL PM values, and varied from −23% to −83% for the FTP and UDDS cycles and from −50% to −87% for the two steady state ramp modal cycles. Some of the higher differences for the AVL PM PEMS were attributed to PM with a higher fraction of organic carbon for the more lightly loaded cycles. Earlier testing of the photoacoustic part of the AVL PM PEMS without a filter, as part of the measurement allowance program, also showed a good correlation for a truck with high soot emissions (R^2 = 0.91, slope = 0.95), but much lower PM mass levels than the MEL PM filters for trucks with little soot emissions (R^2 = 0.18 to 0.75, slope = 0.04 to 0.11) (Johnson et al., 2011a, b). A second study as part of this measurement allowance work that included tests on a DPF equipped truck with an AVL PM PEMS with and without a prototype gravimetric filter system showed good slopes and correlations for both systems for tests where there were no regenerations (R^2 = 0.87 to 0.88, slope = 0.90 to 1.1), but essentially no correlation for tests under regeneration conditions (Khan et al., 2012).

Another point of consideration is that it is unclear how the sensor accuracy might change over long term usage. The AVL PM system has a more robust principle that includes a reference to the NIOSH thermal optical calibration method and a gravimetric filter correction. This suggests PM from the AVL PM system can be managed over time with some level of confidence. Additional studies are needed to understand the long term accuracy of the NCEM PM system.

3.3. PN emissions

PN emissions varied from 2.6×10^{10} #/mi to 5.4×10^{10} #/mi for the AVL PN PEMS system and from 5.0×10^{11} and 2.7×10^{12} #/mi for the NCEM system, as shown in Table 7. AVL PN PEMS emissions can be

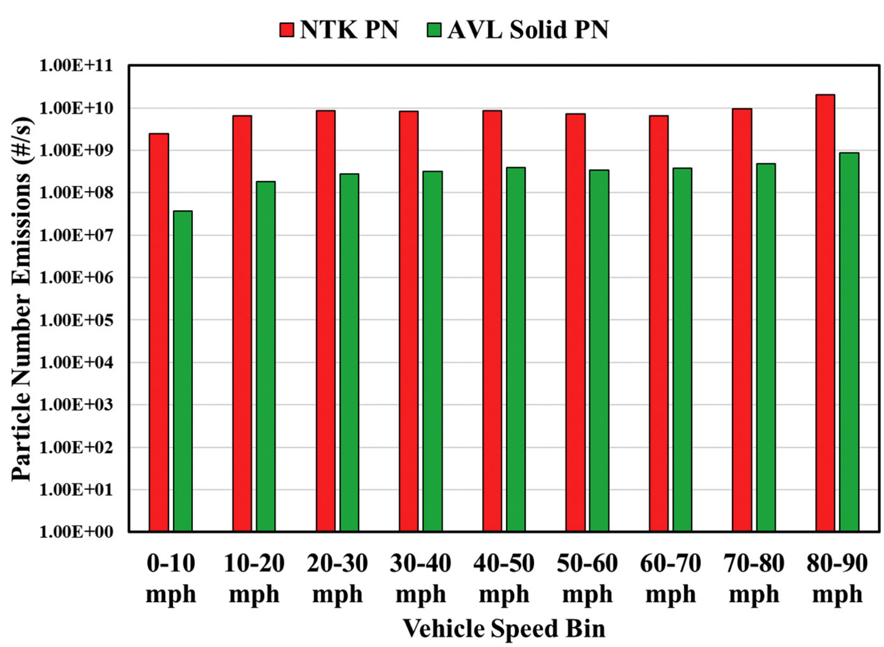

Fig. 8. Vehicle speed based comparisons for particle number emissions for 1 day of testing.

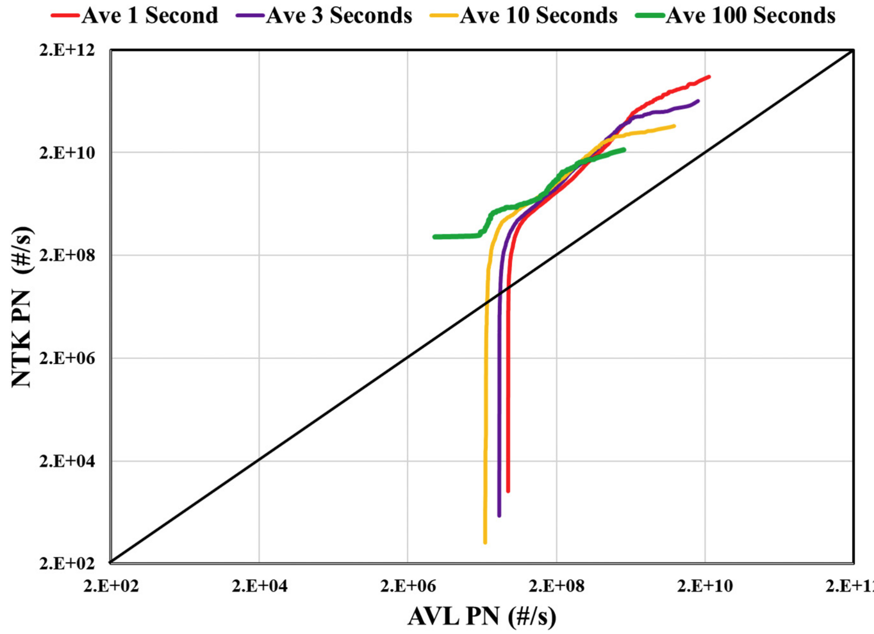

Fig. 9. Q-Q plot analysis for PN emissions for 1 day of testing.

compared to the European standard on PN emissions for light-duty trucks of 6.0×10^{11}. For the AVL PN PEMS, the PN emissions were typically 93% below the PN standard. The NCEM system, on the other hand, showed the vehicle's PN emissions were 142% higher than the standard. The differences between the NCEM and the PN PEMS ranged from 16 times higher (down town LA route) to ~35 times higher (freeway and FTP-like routes).

The high bias for the NTK PN measurements relative to the AVL PN PEMS measurements is also seen in both the speed bin and the Q-Q plots in Fig. 8 and Fig. 9, respectively, for 1 day of testing that included two highway routes, two LA downtown routes, and an idle and creep route, and the 25 and 75 percentile results from the Q-Q plots for PN in Table 3. Regression analyses for the real-time data for 1 s, 3 s, 10 s, and 100 s averaged data also showed a relatively poor correlation between the NTK PN and AVL PN PEMS results for almost all of the test cycles and averaging intervals, as shown in Table 8.

Table 8
Summary of correlation slope and regression statistics for PN emissions.

PN (#/s)		Ave 1 s	Ave 3 s	Ave 10 s	Ave 100 s
		NTK vs AVL PN	NTK vs AVL PN	NTK vs AVL PN	NTK vs AVL PN
Local_1	Slope	2.323	6.279	6.730	3.036
	R2	0.002	0.018	0.040	0.027
Local_2	Slope	3.041	6.447	7.802	7.153
	R2	0.008	0.056	0.130	0.138
Local_3	Slope	7.551	17.830	21.131	23.144
	R2	0.024	0.199	0.290	0.390
Local_Average	Slope	4.305	10.185	11.888	11.111
	R2	0.011	0.091	0.154	0.185
Highway_1	Slope	2.320	3.040	5.926	13.913
	R2	0.002	0.007	0.049	0.535
Highway_2	Slope	3.152	3.975	4.090	6.929
	R2	0.009	0.032	0.061	0.212
Highway_Average	Slope	2.736	3.507	5.008	10.421
	R2	0.006	0.019	0.055	0.373
LA Downtown_1	Slope	13.573	21.184	28.236	41.409
	R2	0.037	0.114	0.217	0.260
LA Downtown_2	Slope	10.555	16.472	21.769	23.304
	R2	0.053	0.171	0.342	0.399
LA Downtown_Average	Slope	12.064	18.828	25.003	32.357
	R2	0.045	0.143	0.279	0.329
Idle and Creep	Slope	9.366	12.399	18.542	19.197
	R2	0.051	0.125	0.405	0.716

The discrepancy between the NCEM and PN PEMS measurements can be attributed to a zero current offset. This has been seen in other tests conducted by NTK. NTK has subsequently improved the PM/PN circuit and has shown a reduction of 81% in the zero offset variation, which should reduce these PN discrepancies (Tange, 2017). Other factors that could contribute to PN differences between the PN measurements include the nature of the particles. Both the PN PEMS and NCEM PN sensor measuring in the raw exhaust would be measuring particles that are primarily solid in nature, so discrepancies due to the nature of the particles should not be significant. The NCEM also measures particles down to ~10 nm (Amanatidis et al., 2017), as opposed to the PN PEMS that has a 23 nm size cut off, which could contribute to higher PN measurements for the NCEM. Our internal particle size distribution data for this vehicle shows a primary peak at ~75 nm, however, with only a minor peak at ~15 nm, so this would only represent a small portion of the differences seen between the instruments. It should be noted that it is possible to adjust the trap voltage on the NCEM PN sensor in order to simulate higher particle cut-points (such as particles > 23 nm), which could allow for a more direct comparison with a PMP compliant PEMS.

In comparison with previous studies, an older NTK PM instrument was compared to dilution tunnel PN measurements using the UCR MEL for engine dynamometer emissions measurements (Jiang et al., 2016). In this study, the NTK PM was measured raw, while the MEL PN measurements were measured dilute (>100 − 1) without a catalytic stripper. In this previous study, the NTK PN measurements were 45% and 69% lower than the CPC PN for the FTP and UDDS, respectively. The steady state SET cycles showed a larger bias, where the NTK PN system was about −90% of the EEPS measurement. In other work, Tikkanen et al. (2013) found the PPS reported 80% higher PN than an APC for a heavy-duty engine and somewhat higher PN emissions for a passenger car, but lower PN emissions than an APC during a regeneration due to desorption from the CVS and for a Euro 4 diesel vehicle during high speed portions of the testing.

4. Conclusions

The primary goal of this study was to compare emissions measurements between a 1065 compliant AVL M.O.V.E.S. PEMS, and a current generation mini-PEMS capable of measuring NOx, PM, and solid PN. Both PEMS units were equipped on a light-duty diesel truck and tested over local, highway, and downtown driving routes over 2 days. The results indicate that the NOx measurements for the mini-PEMS were within approximately $\pm 10\%$ of those the 1065 compliance PEMS, which suggests that the mini-PEMS could be used as a screening tool for NOx emissions. The NCEM showed larger differences for PM emissions on an absolute level, but this was at PM levels well below the 1 mg/mi level. The NCEM differences ranged from -2% to $+26\%$ if the comparisons are based on a percentage of the 1.0 mg/mi standard. Larger differences were also seen for PN emissions, with the NCEM measuring higher PN emissions. This can be attributed to a zero current offset that was found for the NCEM system, which has been subsequently improved in the latest generation of the NCEM system. One other important consideration is that an external EFM was utilized to obtain the exhaust flow for these measurements, which is a part of the AVL PEMS set-up but is not typically utilized in conjunction with the NCEM. While the ECM data was not collected with the NCEM used in this study, the current version of the NCEM does collect ECM data that could be utilized for determining the exhaust flow rate. This would represent an additional source of differences between the NCEM and the AVL PEMS that was not quantified in this study.

The comparisons between the 1065 compliant PEMS and the NCEM suggest that there could be applications for the NCEM or other mini-PEMS in areas where larger data sets of emissions data, or where the cost of full laboratory or 1065 compliant PEMS testing is prohibitive. As recent findings have suggested that it is important to monitor vehicle emissions under a much wider range of conditions than can be duplicated in the laboratory, the NCEM could play a role in allowing for the testing of more vehicles under a broader range of conditions. As in-use testing becomes increasing more prevalent as part of regulatory compliance procedures, this might also suggest potential uses for the NCEM. This could include testing by government agencies to identify potential emissions issues that could subsequently be more extensively investigated in the laboratory or with 1065 compliant PEMS. Similarly, the NCEM could be utilized by vehicle/engine manufacturers to ensure are not specific environmental or operational regimes that could trigger emissions issues with their products. Finally, there is increased interest in the regulatory community to expand inspection and maintenance programs to heavy-duty vehicles, which to data have only been subject to testing with opacity or other methods that do not capture a full breadth of emissions. For the NCEM in particular, the good comparison for NOx emissions suggests that the NCEM could be applied in all of these areas where characterization of NOx is considered to be important, which could include in-use or I/M testing of light-duty or heavy-duty diesel vehicles. The PM emissions comparisons with the NCEM suggest that the NCEM could be effective in identifying potential situations where high PM emissions might be found for either gasoline direct injection vehicles or diesel vehicles with DPFs in various stages of failure. Additional testing of PM emissions over a wider range of PM emissions levels would be needed to better understand this possibility.

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