Assessment of PEMS Datasets from Modern Diesel Passenger Cars

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Introduction

Standard emissions certification tests are carried out in chassis dynamometer laboratories as part of regulated vehicle type-approval processes. Ideally, the driving cycle and other aspects of the test procedure will have been laid out in such a way that they provide a realistic approximation of the actual conditions that vehicles encounter when they are driven on the road. However, this is not always possible because the testing conditions need to have narrow boundary conditions to ensure that results from different vehicles can be directly compared, and that all vehicles sold in a given market are held to the same standards. This situation has lead to vehicle emissions being certified through laboratory procedures that cannot capture the whole range of operating conditions that vehicles encounter during real use. At the same time, the increased levels of stringency (e.g., NO_X emission limits for Diesel passenger cars on the basis of the NEDC driving cycle were reduced by

68% from Euro 4 to Euro 6) and the lack of updates to the type-approval procedures in some jurisdictions have steered vehicle manufacturers towards engineering strategies that ensure good fuel efficiency and compliance with the relevant emission limits as long as the vehicles are operated within the narrow boundary conditions of the standardized test, but not necessarily during normal use.

This paper presents the assessment of the on-road emission behavior of several different modern Diesel passenger cars tested in Europe and in the US with portable emissions measurement systems (PEMS). The data for US vehicles come from a measurement campaign sponsored by the ICCT, whereas the European vehicle data were provided by several third-party research organizations. On-road testing with PEMS is expected to play an increasingly important role in the control of regulated emissions. PEMS have experienced a remarkable technological development, with improved gas measurement principles and significant reductions in size, weight and overall complexity. They are relatively simple and inexpensive, and they have thus become a popular tool for scientific studies. In recent years, they have also been applied for regulatory purposes. US authorities have introduced additional emissions requirements based PEMS testing and the ‘not to exceed' (NTE) concept, whereby emissions averaged over a time window must not exceed specified values for regulated pollutants while the engine is operating within a control area under the torque curve (USEPA, 2005). In Europe, PEMS are being used to verify the in-service conformity of EURO V and EURO VI heavy-duty engines with the applicable emissions standards (EC 2011, 2012) and the European Commission is currently working with stakeholders to include PEMS testing as part of the type-approval process of Euro 6 passenger cars (Weiss *et al.*, 2013).

Materials and methods

The measurement campaigns that produced the experimental data were carried out in the EU and in the US by order of the ICCT and other research partners who generously shared their data to support our study. Over 130 hours worth of second-by-second data from several sources covering a combined total of more than 5900 km driven for 13 test vehicles were collected.

The emissions data were collected during several measurement campaigns carried out by different institutions.

- One of these campaigns—which was commissioned to West Virginia University (WVU) by the ICCT—was carried out in the US with US-spec vehicles certified to the US Tier 2 Bin 5/California LEV II standard. The technical details of this campaign (which covered vehicles B, F and G in table 1) have been reported in detail elsewhere (Thompson *et al*, 2014).
- The PEMS trip data for vehicles C, I, J, K, L and M (one trip each, all following the same route) were purchased by the ICCT from Emissions Analytics, a UK-based emissions consultancy with vast experience in PEMS testing.
- The rest of the datasets (covering vehicles A, D, E, G and H) were gathered from stakeholders of the RDE group that generously contributed to this work, and were carried out on Euro 6 passenger cars.

In total, vehicles from six different manufacturers were tested. Most of the trips were from vehicles equipped with SCR technology for the aftertreatment of NO_X emissions. Three vehicles (all from the same manufacturer) had no specific NO_X aftertreatment system and one was equipped with a lean NO_X trap (see Table 1).

Table 1: Overview of test vehicles

ID	Body type	NO_X aftertreatment	Emission standard	# of trips	Manufacturer
A	SUV	SCR+LNT	Euro 6	6	m1
B	SUV	SCR	Tier 2 Bin 5/ ULEV II	8	
C	Sedan	SCR	Euro 6	1	
D	Station wagon	SCR	Euro 6	25	m2
E	Sedan	SCR	Euro 6	9	
F	Sedan	SCR	Tier 2 Bin 5/ ULEV II	15	
G	Sedan	LNT	Tier 2 Bin 5/ ULEV II	13	
H	Sedan	EGR + in-cylinder control	Euro 6	4	m3
I	Station wagon	EGR + in-cylinder control	Euro 6	1	
J	Sedan	EGR + in-cylinder control	Euro 6	1	
K	Luxury sedan	SCR	Euro 6	1	m4
L	Minivan	SCR	Euro 6	1	m5
M	Sedan	SCR	Euro 6	1	m6

Due to the heterogeneous origin of the data, and in order to facilitate the comparisons across different measurement campaigns, vehicles and testing conditions, we developed a consistent framework to analyze and report the results. This allowed us to characterize the general behavior of the vehicles and to identify the operating conditions that lead to high emissions. The most significant product of this framework is a series of ‘standard PEMS charts’ which are produced for individual PEMS trips or collections of trips, and which allow us to compare the on-road emissions of regulated pollutants of the test cars to the relevant legal emission limits and corresponding type-approval results, and to visualize the operating conditions that lead to elevated instantaneous emissions.

The raw experimental results were processed using a consistent data preprocessing, analysis and reporting framework. This framework allows for a clear visualization of the general behavior of individual vehicles over single trips or collection of trips, as well as a detailed assessment of the operating conditions that lead to high emission events. The emissions data are reported as ‘raw’ values (i.e., as trip averages, with no data exclusions) and also filtered by *driving situation*. The driving situations are defined using the measured velocity, altitude and exhaust or coolant temperature[1] (see Table 2).

[1] Depending on the availability of the measured signal.

Table 2: Summary of data binning/filtering criteria for the development of the situation-specific emission factors

Criterion	Calculation	Set points for the bins	Bin descriptor (short form)
Velocity [km/h]	GPS velocity	Velocity <2 km/h	Idling (Idle)
		2 ≤ Velocity < 50 km/h	Urban (Urb.)
		50 ≤ Velocity < 90 km/h	Rural (Rur.)
		Velocity ≥ 90 km/h	Motorway (Mwy.)
Velocity* acceleration (v*a) $[m^2/s^3]^{(1)}$	From GPS velocity	Acceleration*velocity <-9.2 m^2/s^3	Strong negative v*a
		-9.2 ≤ Acceleration < 0 m^2/s^3	Mild negative v*a (MN)
		0 ≤ Acceleration < 9.2 m^2/s^3	Zero or mild positive v*a (MP)
		Acceleration ≥ 9.2 m^2/s^3	Strong positive v*a (SP)
Road gradient [%]	From GPS velocity and GPS altitude	Gradient < -4 %	Strong downhill (SD)
		-4 ≤ Gradient < -1 %	Mild downhill (MD)
		-1 ≤ Gradient < 1 %	Pretty flat (PF)
		1 ≤ Gradient < 4 %	Mild uphill (MU)
		Gradient ≥ 4 %	Strong uphill (SU)
Exhaust gas/ coolant temperature [ºC]	From tailpipe measurement / ECU readout	Temperature < 10th percentile value for the trip	Cold temperature (Cold)
		10th ≤ Temperature < 90^{th} percentile value for the trip	Medium temperature (Med.)
		Temperature ≥ 90^{th} percentile value for the trip	Hot temperature (Hot)
Combination	**Filtering**		**Descriptor**
Undemanding driving (1)	Data are binned by velocity, but points with motorway speed above 120 km/h are excluded. Likewise, only the points in the 'Pretty flat', 'Medium temperature' and 'Mild negative v*a' or 'Zero or mild positive' v*a are included.		Undemanding Urban 1
			Undemanding Rural 1
			Undemanding Motorway 1
Undemanding driving (2)	Same as undemanding (1), but including 'Mild uphill' and 'Mild downhill'.		Undemanding Urban 2
			Undemanding Rural 2
			Undemanding Motorway 2

(1) $9.2 m^2/s^3$ is the highest v*a value calculated from the NEDC speed trace.

(2)

Results and discussion

The average 'raw' emission factors of CO_2, NO_X and CO are listed for all vehicles in Table 3, along with the shares of the total distance (in %) that each some of the driving situations represented for all of the vehicles. Note that the 'raw' averages are derived from a different number of trips (sometimes from a single trip; see Table 1), and that they only apply to the particular set of driving conditions under which each vehicle was tested.

Table 3: Average raw emission factors and distance shares spent in the driving situations, by test vehicle

	Raw EF			Trip distance shares [%]													
	[g/km]	[mg/km]		Velocity				Acceleration*velocity				Gradient					
	CO_2	NO_X	CO	Idle	Urb.	Rur.	Mwy.	SN	MN	MP	SP	SD	MD	PF	MP	SP
Vehicle A	288	482	388	0.0	33.1	24.3	42.6	7.0	29.9	57.1	5.9	2.4	25.4	44.3	26.4	1.5
Vehicle B	286	248	224	0.1	17.8	52.5	29.7	14.6	22.5	49.8	13.1	12.3	18.6	41.7	15.7	11.7
Vehicle C	160	72	129	0.0	35.9	16.7	47.4	6.2	30.3	58.8	4.8	0.0	6.4	88.4	5.2	0.0
Vehicle D	184	171	159	0.0	37.9	38.7	23.4	7.8	36.6	49.8	5.7	4.1	16.9	57.9	17.6	3.4
Vehicle E	197	819	145	0.0	37.0	30.6	32.3	6.7	27.8	60.0	5.4	2.6	25.0	43.4	24.0	5.0
Vehicle F	270	908	67	0.1	18.9	27.9	53.1	11.7	33.0	44.7	10.6	5.6	19.5	45.8	21.6	7.4
Vehicle G	254	1809	86	0.1	19.2	28.0	52.7	9.0	33.3	50.3	7.4	5.8	20.4	50.9	17.4	5.5
Vehicle H	175	438	130	0.0	39.5	29.2	31.3	8.8	21.1	62.9	7.2	4.3	22.7	45.8	21.6	5.6
Vehicle I	143	279	113	0.0	37.3	14.2	48.4	4.9	24.9	66.0	4.3	0.0	6.5	87.4	6.1	0.0
Vehicle J	165	289	98	0.1	29.8	18.6	51.5	7.0	27.5	60.1	5.4	0.0	6.9	87.3	5.8	0.0
Vehicle K	210	1783	147	0.1	24.5	23.8	51.7	9.4	32.5	50.1	8.0	0.0	11.0	79.9	9.1	0.0
Vehicle L	151	758	316	0.0	37.2	13.0	49.8	4.5	29.4	62.5	3.5	0.0	6.5	88.6	4.9	0.0
Vehicle M	194	388	2	0.0	36.4	14.4	49.2	6.1	25.1	63.6	5.2	0.0	6.4	85.7	8.0	0.0

On the other hand, the situation-specific PEMS emission factors for NO_X are also listed for all vehicles in tables 4 and 5.

Table 4: Average emission factors of NOX [mg/km] (by driving situation, binning by velocity)

			All driving conditions			Undemanding			Undemanding 2		
	Raw	Idle	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.
Vehicle A	482	-	234	177	841	127	73	58	157	76	53
Vehicle B	248	-	237	340	82	79	27	37	86	46	29
Vehicle C	72	-	93	79	47	82	82	30	82	71	29
Vehicle D	171	-	253	130	82	237	101	58	221	115	58
Vehicle E	819	-	860	521	982	796	382	612	756	351	518
Vehicle F	908	-	1522	1083	533	1302	592	227	1333	767	297
Vehicle G	1809	-	2166	1906	1471	1775	1245	1372	2089	1648	1400
Vehicle H	438	-	561	373	332	337	241	148	364	248	145
Vehicle I	279	-	362	317	199	322	264	137	329	265	127
Vehicle J	289	-	533	236	147	495	152	60	476	163	81
Vehicle K	1783	-	2350	1478	1544	2346	1165	1339	2209	1157	1325
Vehicle L	758	-	884	716	653	896	636	628	896	694	589
Vehicle M	388	-	558	297	271	526	241	162	536	251	164

Table 5: Average emission factors of NOX [mg/km] (by driving situation, binning by velocity)

	Acceleration* velocity				Gradient					Temperature		
	SN	MN	MP	SP	SD	MD	PF	MU	SU	Cold	Med.	Hot
Vehicle A	153	289	496	1709	49	132	186	1344	703	548	159	1468
Vehicle B	155	198	191	655	54	86	112	225	1228	381	89	1165
Vehicle C	32	48	74	257	-	85	71	81	-	204	68	65
Vehicle D	36	83	220	502	184	128	154	230	358	310	160	180
Vehicle E	221	404	854	3286	211	485	714	1247	1654	849	686	1422
Vehicle F	455	590	1004	1992	195	468	668	1332	2844	696	779	1663
Vehicle G	1111	1539	2010	2516	225	912	1520	3117	5373	1001	1657	3147
Vehicle H	275	284	436	1105	156	197	354	586	1739	224	388	807
Vehicle I	99	181	265	1257	-	218	277	373	-	129	281	279
Vehicle J	84	158	284	1292	-	249	282	444	-	503	306	231
Vehicle K	488	995	2075	4674	-	1475	1760	2367	-	3013	1672	2105
Vehicle L	349	494	855	1768	-	548	764	936	-	717	766	739
Vehicle M	125	245	413	1087	-	291	368	684	-	2790	375	436

The main findings of the assessment are consistent with the existing body of evidence indicating that modern Diesel passenger cars have low on-road emissions of carbon monoxide (CO) and total hydrocarbons (THC[2]), but have an unsatisfactory real-world emission profile of nitrogen oxides (NO_X), thus raising air quality concerns. The results also suggest that real-world CO_2 emissions consistently exceed type-approval values by a value of about 30% (see Mock et al., 2013 for a specific discussion of this issue based on larger datasets for both gasoline and Diesel passenger cars).

This paper presents a large amount of additional evidence of a real-world NO_X compliance issue for recent technology Diesel passenger cars (Weiss *et al., 2012;* Ligterink *et al.* 2013), both for EU and US vehicles. The high temporal and spatial resolution of PEMS datasets was used to link the elevated NO_X mass emission rates to the driving conditions that cause them. It was found that a sizeable share of NO_X emissions over individual test trips (typically lasting about one hour) were concentrated over a number of discrete emission spikes spanning a few seconds. These emission events were relatively infrequent, but in most cases they could not be attributed to 'extreme' or 'untypical' driving. Instead, they were due to transient increases in engine load that constitute real-world driving (*e.g.*, uphill driving on a ramp or sustained positive accelerations from a standstill), or to regeneration events that are part of the normal operation of Diesel exhaust aftertreatment systems. In some cases, the NO_X performance of the vehicles was poor even in the 'undemanding' situations; *i.e.* after the exclusion of the situations that would *a priori* lead to high NO_X emission rates.

There were some remarkable differences among the performance of all the vehicles tested, with a few vehicles performing substantially better than others. This supports the notion that the technology for clean Diesels (*i.e.*, vehicles whose average emission levels lie below Euro 6 emission limits under real-world driving) already exists, and that the right policies could incentivize manufacturers to apply them across the board.

Unless the appropriate technical measures are adopted, the high on-road emissions of NO_X from the new Diesel technology classes of passenger cars could have serious adverse health effects in the exposed population, including asthma onset in children, impaired lung function, cardiovascular disease and premature death (HEI, 2010). Regulatory action is especially required in Europe, where all new Diesel passenger cars sold from September 2014 belong to the Euro 6 class and the regional share of Diesel vehicles is large. In this sense, the European RDE-LDV initiative (Weiss *et al.*, 2013)– whereby on-road testing with PEMS will be included as part of the passenger car type approval process in the EU—is a step in the right direction, but only so long as the existence of the real-world Diesel NO_X issue is acknowledged by regulators in its full extent and subsequently addressed in collaboration with vehicle manufacturers.

[2] THC results not listed in the tables. The measured emission values were consistently below the Euro 6 values. The complete dataset will be extensively analyzed in an upcoming ICCT report.

References

EC. Commission Regulation (EU) No 582/2011of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council; 2011.

EC. Commission Regulation (EU) No 64/2012 of 23 January 2012 amending Regulation (EU) No 582/2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI); 2012.

HEI Panel on the Health Effects of Traffic-Related Air Pollution 2010). Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. HEI Special Report no. 17. Health Effects Institute. January 12. Available online at http://pubs.healtheffects.org/view.php?id=334

Ligterink, N., Kadijk, G., van Mensch, P., Hausberger, S., Rexeis, M. Investigations and real world emission performance of Euro 6 light-duty vehicles. TNO report 2013 R11891, 2013, pp. 1–53.

Mock, P., German, J., Bandivadekar, A., Riemersma, I., Ligterink, N., Lambrecht, U. From laboratory to road, The International Council on Clean Transportation. White Paper, 2013, pp. 1–88.

Thompson, G. J.; Carder, D. K.; Besch, M. C.; Thiruvengadam, A.; Kappana, H. K. In-Use Emissions Testing of Light-Duty Diesel Vehicles in the United States; Posada, F., Ed.; West Virginia University. Center for Alternative Fuels, Engines and Emissions (CAFEE): Morgantown (WV) USA, 2014; pp. 1–133.

USEPA. United States Environmental Protection Agency. Engine-Testing Procedures, Title 40 Code of Federal Regulations 1065, subpart J; 2005.

Weiss, M., Bonnel, P., Kühlwein, J., Provenza, A., Lambrecht, U., Alessandrini, S., Carriero, M., Colombo, R., Forni, F., Lanappe, G., et al (2012). Will Euro 6 reduce the NO_X emissions of new diesel cars?–Insights from on-road tests with Portable Emissions Measurement Systems (PEMS). *Atmos. Environ.* 62, 657–665.

Weiss, M.; Bonnel, P.; Hummel, R.; Steininger, N. A complementary emissions test for light-duty vehicles: Assessing the technical feasibility of candidate procedures; EUR 25572 EN; European Commission. JRC scientific and policy reports, 2013; pp. 1–56.