REAL-WORLD EMISSIONS FROM HEAVY-DUTY IN-USE TESTING PROGRAM

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NTE VS WORK-BASED WINDOW, SENSITIVY AND LIMITATIONS OF THESE METHODS

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Presentation Content

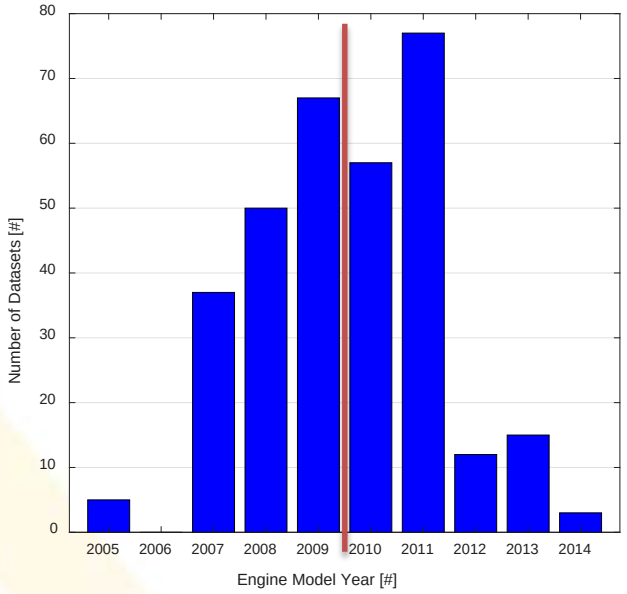
- Background
  - Heavy-duty in-use testing (HDIUT) program
- Description of HDIUT dataset
  - Type of vehicles/engines
  - Characteristic vehicle (speed) and engine (power) operation of datasets
- Methodology of Analysis
  - Design of Experiment Matrix
- Results
  - NTE Analysis and parametric study
  - WBW Analysis and parametric study
- Conclusion

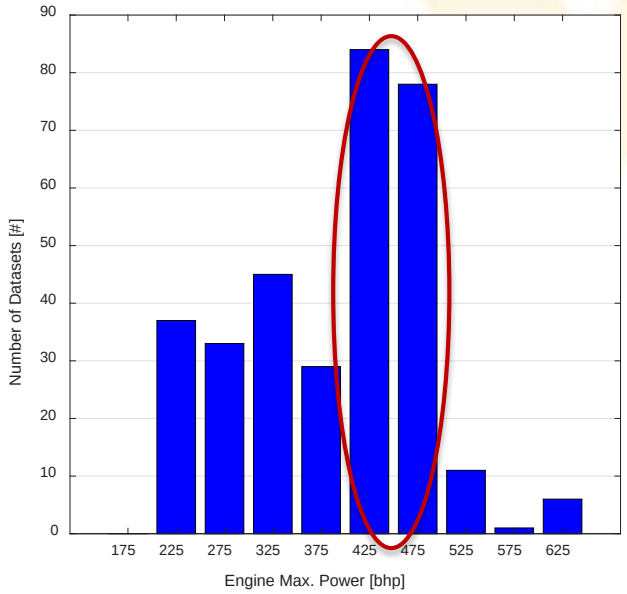
Background and Motivation

- Engine manufacturer driven heavy-duty in-use testing program
  - Collection of real-world emissions data using PEMS instrument
    - Over duration of at least 3 hours of non-idle operation.
    - Analysis based on NTE method => calculation of Vehicle-Pass-Ratio (40 CFR, Part 86).
    - Analysis based on WBW method => calculation of 90th percentile
- NTE and work-based window analysis of all HDIUT dataset
  - Quantify impact of exclusion criteria onto number of NTE events or work windows.
  - Can extending the NTE control area boundaries result in significantly increased amount of data being included for analysis? Which parameter are dominant?
  - Comparison of NTE to WBW method results.

Description of Data - *Type of Vehicles*

- Total of **324** HDIUT dataset (159 pre-2010, 165 post-2010)
- Engine displacement in range of 6.7 to 16L
- Engine model year (MY) 2005 to 2014

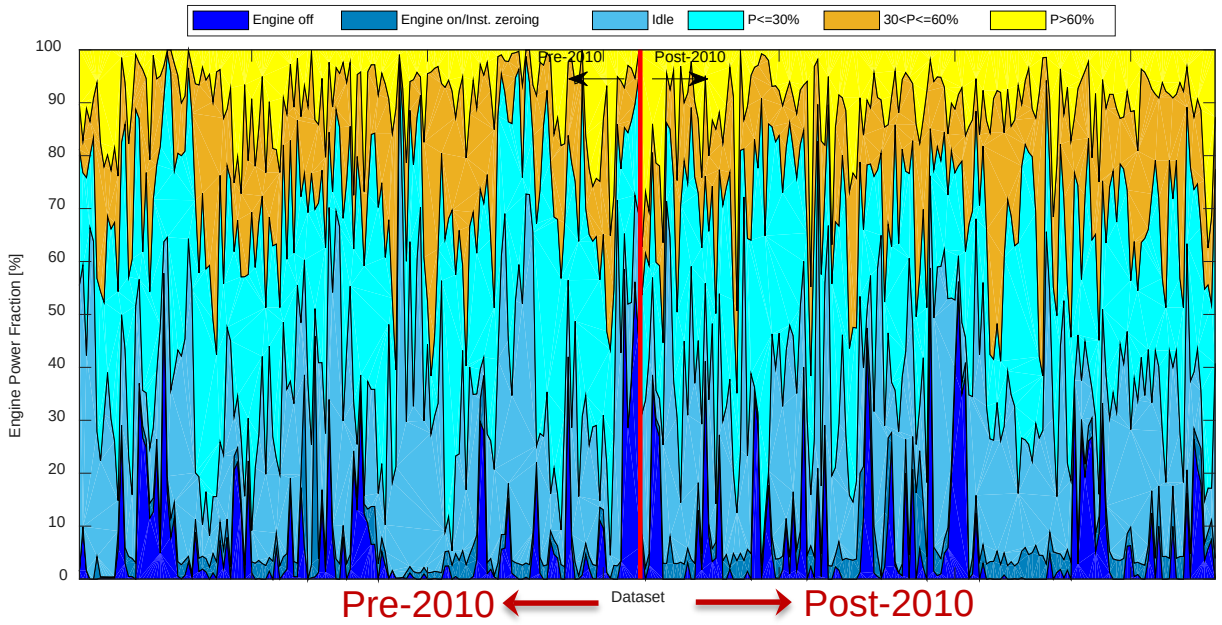




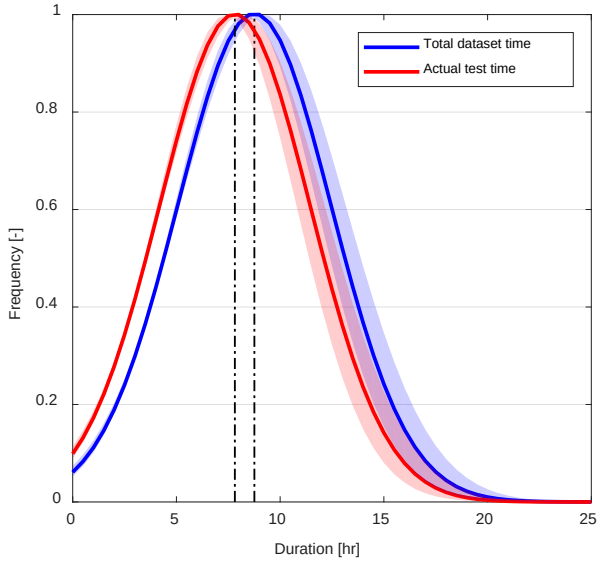
	Pre-2010 All	Post-2010 All	Post-2010 Non-Credit	Post-2010 Credit w/o SCR	Post-2010 Credit w/ SCR	Post-2010 CNG
Line-Haul	60	68	50		18	
Delivery	37	63	28	28	7	
Utility and Construction	21	8	6		2	
Dump Truck	2	1	1			
Transit Bus		15	10			5
School Bus	2	0				
Refuse	3					
Motorhome	5					
Other	5	3			3	
Not specified	24	7	5	2		
Total	**159**	**165**	**100**	**30**	**30**	**5**

Description of Data - *Characteristics of datasets*

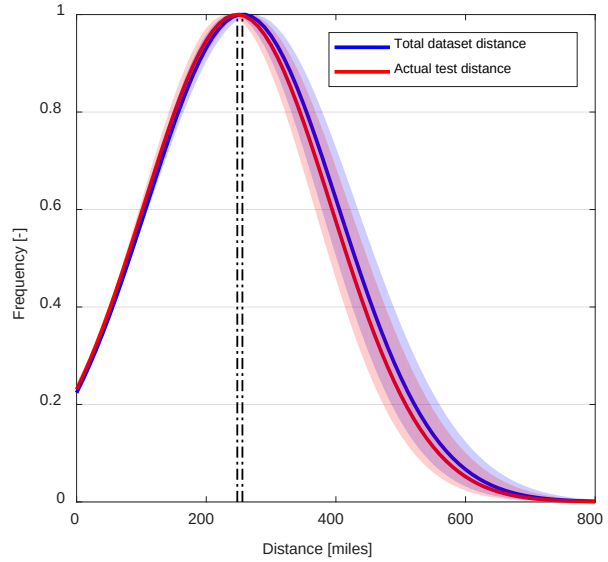
Engine Power Distribution => *time-based fractions*



Duration [hr]



Distance [mile]



- Emissions limits based on 40 CFR, Part 86, §86.007-11
  - 0.20 g/bhp-hr NO_x for post-2010 engines
  - 1.3 g/bhp-hr NO_x+NMHC for pre-2010 engines
- Engine-off events removed from analysis => no emissions production
- PEMS zero/span (Z/S) events removed from analysis => no valid data
- DPF exclusion for NTE => Exclude event if regeneration at any point

Parameter	μ	σ	Δ [%]
	Test duration [hr]		
Total dataset duration	8.76	3.70	
Actual test duration	7.82	3.63	*10.7*
	Test distance [miles]		
Total dataset distance	255.8	147.9	
Actual test distance	247.9	144.7	*3.1*

Methodology - *Design of Experiments NTE*

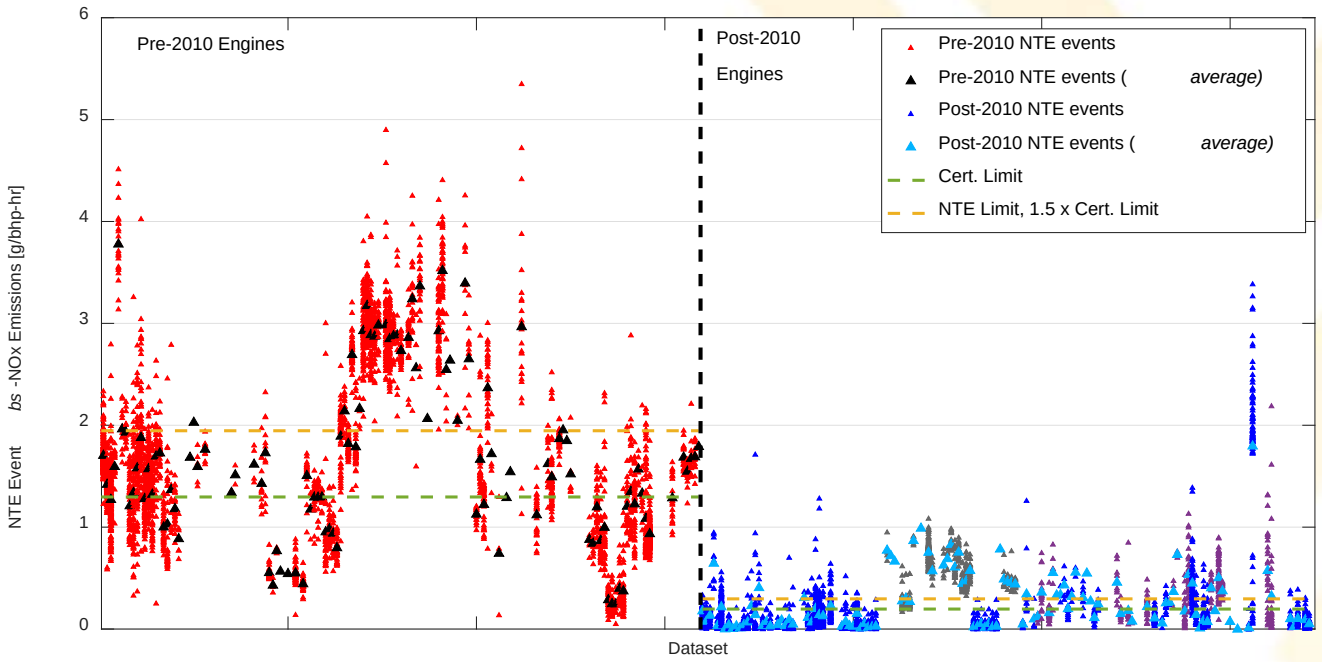
Control Parameter

Boundary Parameter	Range
Torque threshold [ft-lb]	5% to 30% of peak torque
Engine power threshold [hp]	5% to 30% of rated power
$T_{exhaust}$ exclusion threshold [ºC]	110ºC to 250ºC

- Other NTE boundary parameters
  - Engine speed threshold
  - Minimum event duration

Experiment [#]	Thresholds			
	Peak Torque [ft-lb]	Rate Power [hp]	Exh. Temp. [ºC]	
1	30%	30%	250	orig.
2	15%	15%	250	mod.
3	5%	5%	110	
4	5%	5%	200	
5	5%	15%	250	
6	5%	30%	150	
7	15%	5%	150	
8	15%	15%	200	
9	15%	30%	110	
10	15%	30%	250	
11	30%	5%	250	
12	30%	15%	110	
13	30%	15%	150	
14	30%	30%	200	

Results - *NTE bsNO$_x$ Emissions, pre- vs. post-2010*



Percentage of dataset operating in NTE control area

Time-Weighted Fraction [%]	Pre-2010	Post-2010 All	Post-2010 Non-Credit
Total fraction spent in NTE control area	28.2 ± 12.8	29.7 ± 13.2	31.9 ± 14.2
Total fraction spent in NTE control area w/ Excl. applied	17.3 ± 14.0	14.2 ± 12.6	15.5 ± 13.2
Total fraction spent in valid NTE events	**5.3** ± 7.4	**5.1** ± 7.7	**6.6** ± 8.8

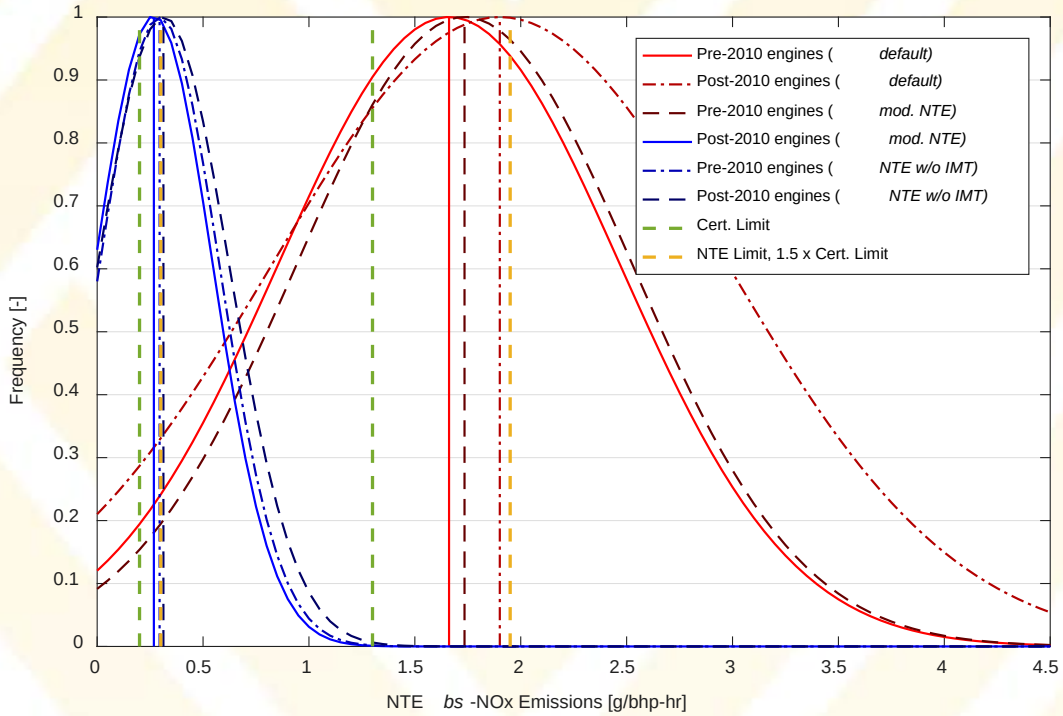
Parameter	Pre-2010	Post-2010 All	Post-2010 Non-Credit
# of dataset	159	165	100
# dataset with NTE events; w/o exclusions applied	155 (Δ 2.5%)	163 (Δ 1.2%)	100 (Δ 0%)
# dataset with NTE events; w/ exclusions other than AT temperature exclusion applied	132 (Δ 17.0%)	129 (Δ 21.8%)	82 (Δ 18.0%)
# dataset with NTE events; all exclusions applied	117 (Δ 26.4%)	124 (Δ 24.8%)	80 (Δ 20.0%)
Averages and Standard Deviation (μ ± 1σ)			
# of total NTE events	67.8 ± 51.3	80.2 ± 60.1	89.7 ± 66.1
# of NTE events w/ exclusions other than AT temperature exclusion applied	37.2 ± 42.1 (Δ 45.2%)	36.0 ± 48.4 (Δ 55.1%)	41.8 ± 52.3 (Δ 53.4%)
# of NTE events w/ all exclusions applied	25.7 ± 37.5 (Δ 62.1%)	28.7 ± 43.6 (Δ 64.2%)	37.1 ± 50.3 (Δ 58.6%)
Overall event-averaged bsNO$_x$ emissions[5] [g/bhp-hr]	1.6615 ± 0.8038	0.2676 ± 0.2768	0.1596 ± 0.2326

Results - *Impact of Extending Control Area and IMT*

- Scenario 1 => Default NTE
  - ➢All default NTE control area and exclusion limits
- Scenario 2 => Modified NTE
  - ➢Torque limit: 15%Tmax; Power limit: 15%Pmax, AT limit: 200ºC
- Scenario 3 => Default NTE w/o IMT exclusion
  - ➢All default NTE control area and excl. limits w/o IMT exclusion

Percentage of dataset operating in NTE control area

Time-Weighted Fraction [%]	Default NTE	Mod. NTE	NTE w/o IMT
	Pre-2010		
Total fraction spent in NTE control area	28.2 ± 12.8	39.7 ± 15.9	28.2 ± 12.8
Total fraction spent in NTE control area w/ Excl. applied	17.3 ± 14.0	25.2 ± 18.8	26.7 ± 13.3
Total fraction spent in valid NTE events	**5.3** ± 7.4	**13.4** ± 14.4	**8.3** ± 8.0
	Post-2010 (all)		
Total fraction spent in NTE control area	29.7 ± 13.2	38.4 ± 14.7	29.7 ± 13.2
Total fraction spent in NTE control area w/ Excl. applied	14.2 ± 12.6	19.9 ± 16.4	28.1 ± 13.2
Total fraction spent in valid NTE events	**5.1** ± 7.7	**11.0** ± 13.3	**12.8** ± 12.2



Results - *Impact of Extending Control Area and IMT*

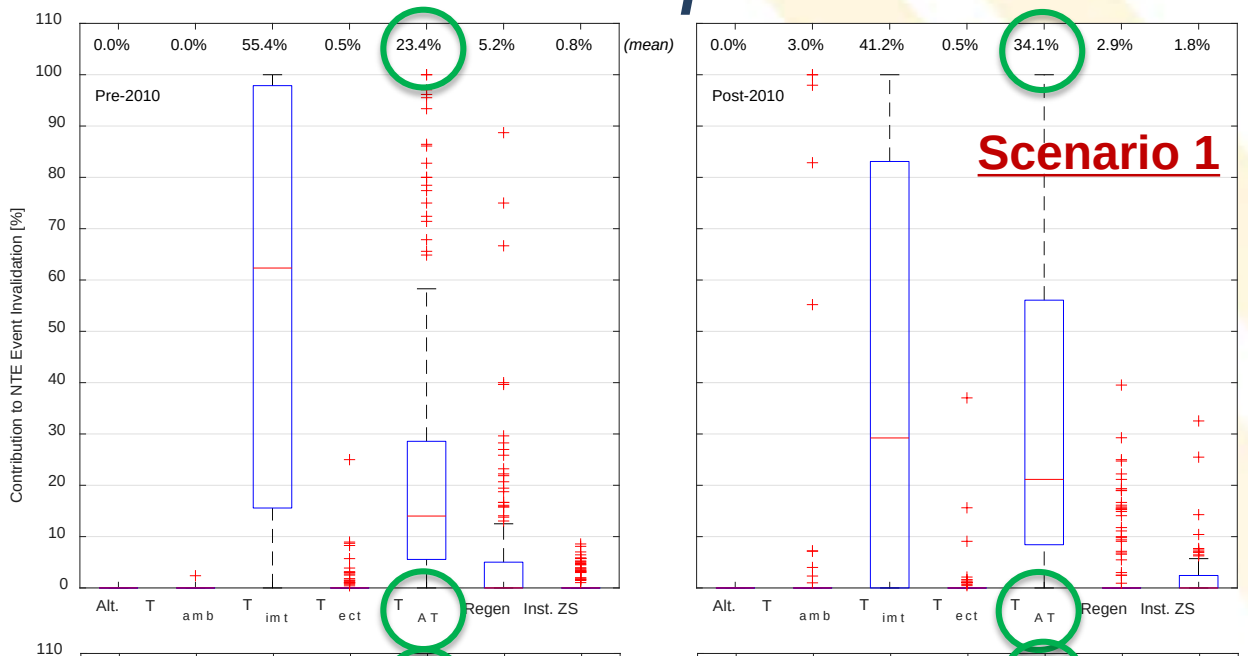
Pre-2010

Parameter	Default NTE	Mod. NTE	NTE w/o IMT
# of dataset	159	159	159
# dataset with NTE events; w/o exclusions applied	155 (Δ 2.5%)	158 (Δ 0.6%)	155 (Δ 2.5%)
# dataset with NTE events; w/ exclusions other than AT temperature exclusion applied	132 (Δ 17.0%)	138 (Δ 13.2%)	153 (Δ 3.8%)
# dataset with NTE events; all exclusions applied	117 (Δ 26.4%)	129 (Δ 18.9%)	141 (Δ11.3%)
Averages and Standard Deviation (μ ± 1σ)			
# of total NTE events	67.8 ± 51.3	92.0 ± 62.6	67.8 ± 51.3
# of NTE events w/ exclusions other than AT temperature exclusion applied	37.2 ± 42.1 (Δ 45.2%)[4]	53.6 ± 51.0 (Δ 41.8%)	61.0 ± 47.8 (Δ 10.0%)
# of NTE events w/ all exclusions applied	25.7 ± 37.5 (Δ 62.1%)[4]	47.6 ± 50.1 (Δ 48.3%)	39.3 ± 41.4 (Δ 42.0%)
Overall event-averaged $bsNO_x$ emissions[5] [g/bhp-hr]	1.6615 ± 0.8038	1.7345 ± 0.7899	1.9011 ± 1.0724

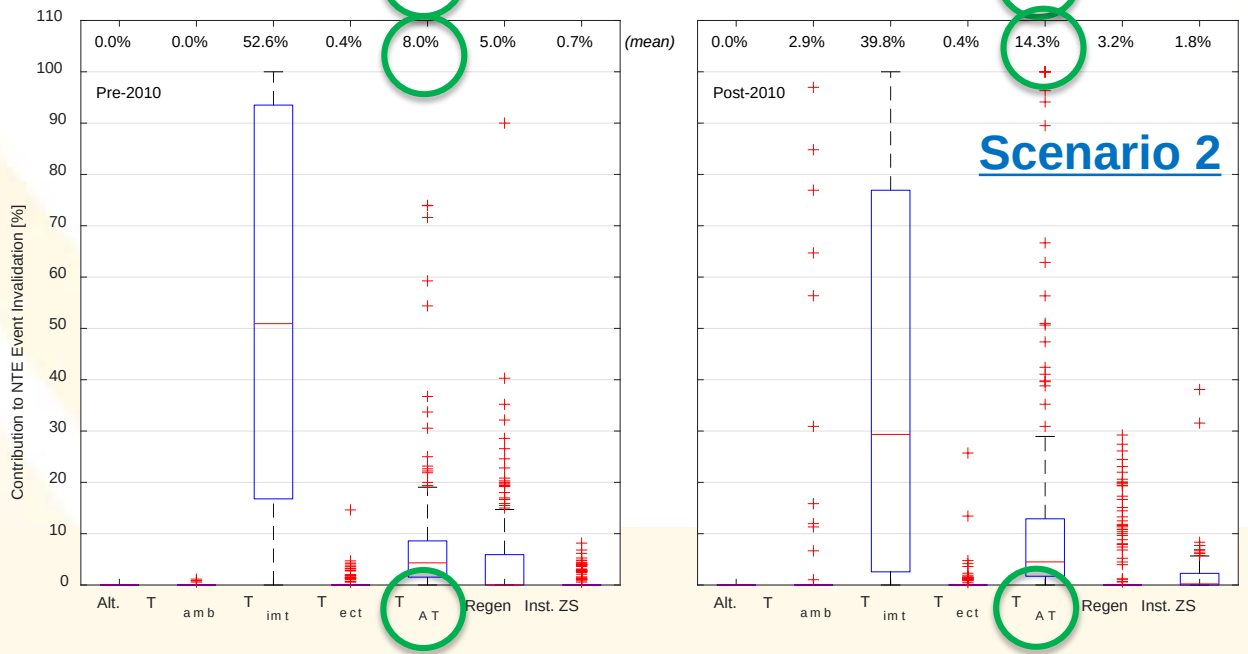
Post-2010

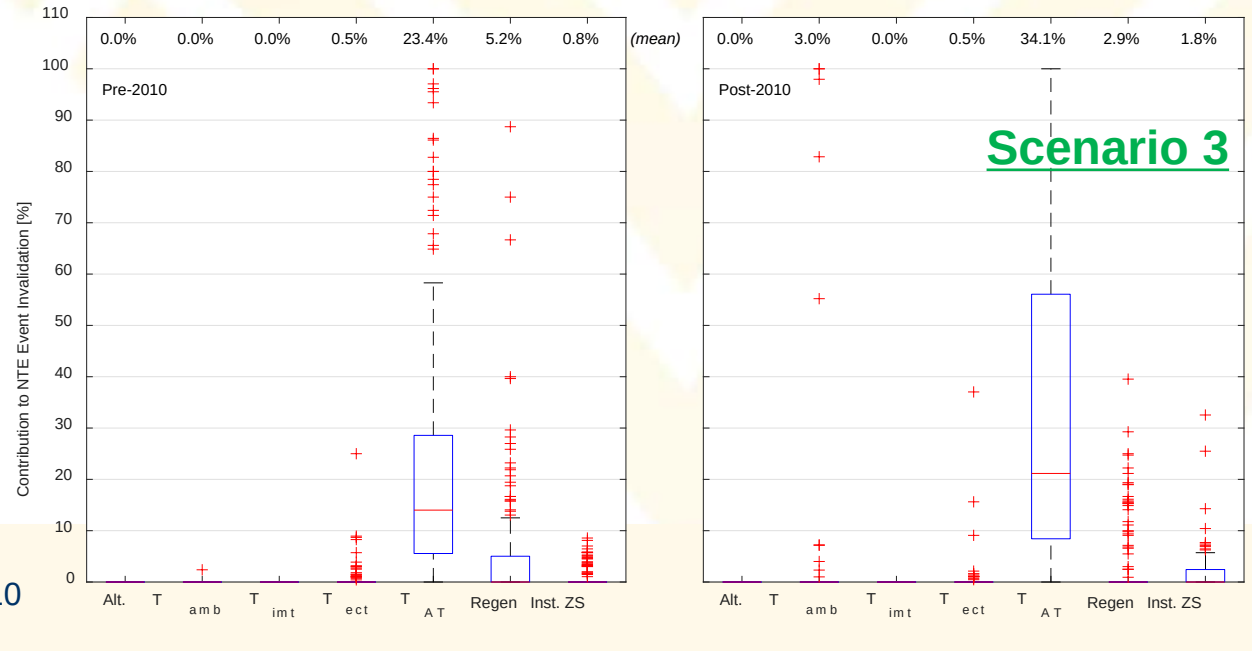
Parameter	Default NTE	Mod. NTE	NTE w/o IMT
# of dataset	165	165	165
# dataset with NTE events; w/o exclusions applied	163 (Δ 1.2%)	165 (Δ 0%)	163 (Δ 1.2%)
# dataset with NTE events; w/ exclusions other than AT temperature exclusion applied	129 (Δ 21.8%)	141 (Δ 14.5%)	163 (Δ 1.2%)
# dataset with NTE events; all exclusions applied	124 (Δ 24.8%)	140 (Δ 15.2%)	157 (Δ 4.8%)
Averages and Standard Deviation (μ ± 1σ)			
# of total NTE events	80.2 ± 60.1	94.5 ± 51.8	80.2 ± 60.1
# of NTE events w/ exclusions other than AT temperature exclusion applied	36.0 ± 48.4 (Δ 55.1%)[4]	48.7 ± 51.9 (Δ 48.5%)	74.7 ± 58.4 (Δ 6.8%)
# of NTE events w/ all exclusions applied	28.7 ± 43.6 (Δ 64.2%)[4]	45.9 ± 50.6 (Δ 51.4%)	60.2 ± 56.5 (Δ 24.9%)
Overall event-averaged $bsNO_x$ emissions[5] [g/bhp-hr]	0.2676 ± 0.2768	0.3127 ± 0.3090	0.2947 ± 0.2814

Results - *Impact of Extending Control Area and IMT*



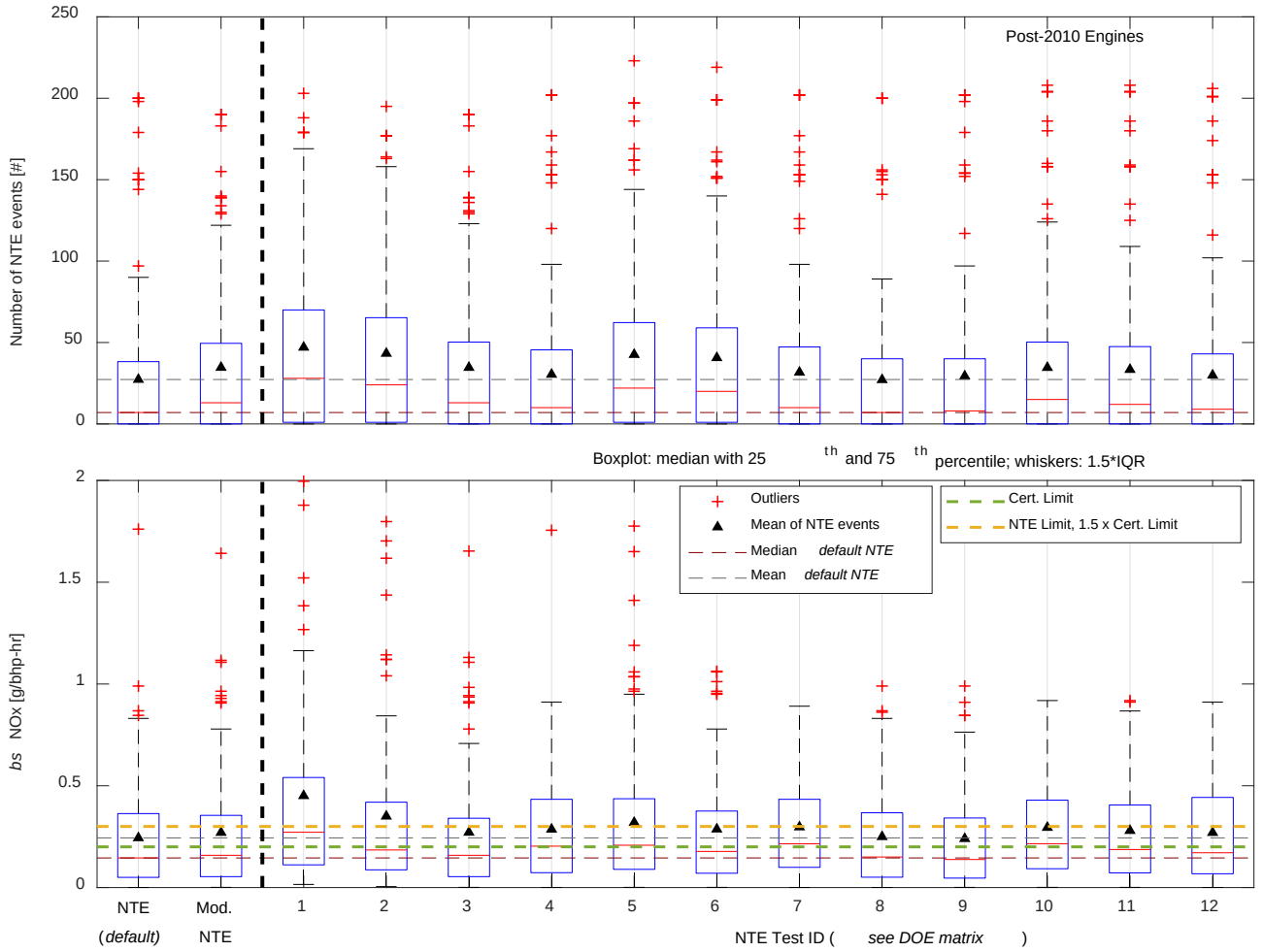
Engine	Altitude	T_{amb}	T_{imt}	T_{ect}	T_{AT}	DPF Regen	Inst. ZS
	Default NTE definition						
Pre-2010	0.00	0.01	55.39	0.53	23.40	5.23	0.84
Post-2010	0.00	2.95	41.18	0.48	34.08	2.93	1.78
	Modified NTE definition						
Pre-2010	0.00	0.02	52.59	0.43	8.00	4.96	0.72
Post-2010	0.00	2.90	39.80	0.44	14.30	3.19	1.79
	Default NTE definition w/o IMT exclusion applied						
Pre-2010	0.00	0.01	NA	0.53	23.40	5.23	0.84
Post-2010	0.00	2.95	NA	0.48	34.08	2.93	1.78





Results - *Parametric Analysis*

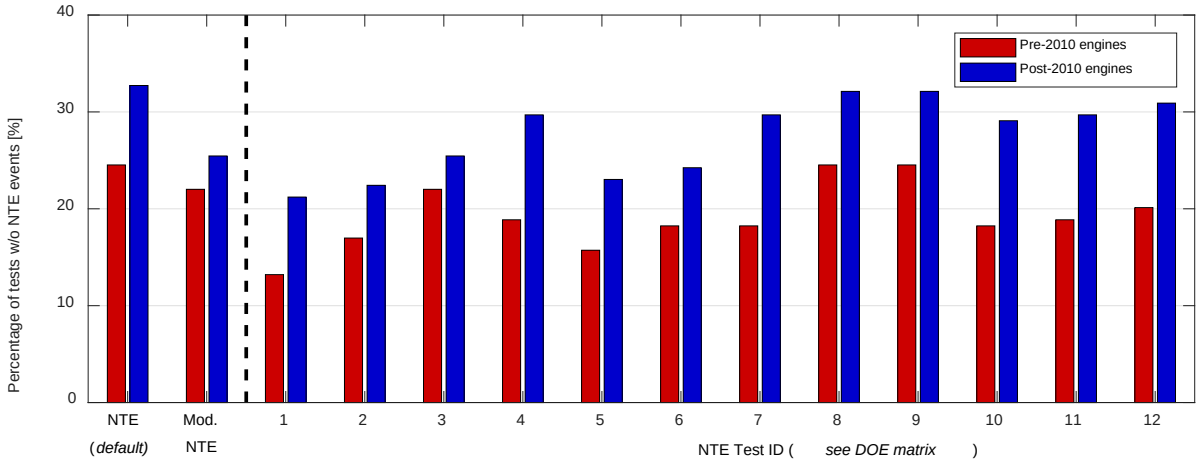
Post-2010 engine datasets



Exp.	Thresholds			NO_x Emissions	NTE Events	
[#]	Peak Torque	Rated Power	Exh. Temp.	[g/bhp-hr]	μ [#]	σ [#]
	30%	30%	250	0.2440	27	44
	15%	15%	250	0.2703	35	46
1	5%	5%	110	0.4508	47	52
2	5%	5%	200	0.3502	43	50
3	5%	15%	250	0.2710	35	46
4	5%	30%	150	0.2861	30	45
5	15%	5%	150	0.3191	43	52
6	15%	15%	200	0.2868	41	51
7	15%	30%	110	0.2972	32	46
8	15%	30%	250	0.2495	27	43
9	30%	5%	250	0.2398	29	46
10	30%	15%	110	0.2947	35	49
11	30%	15%	150	0.2796	33	48
12	30%	30%	200	0.2699	30	46

=> Including all post-2010 datasets

Results - *Parametric Analysis, ANOVA*



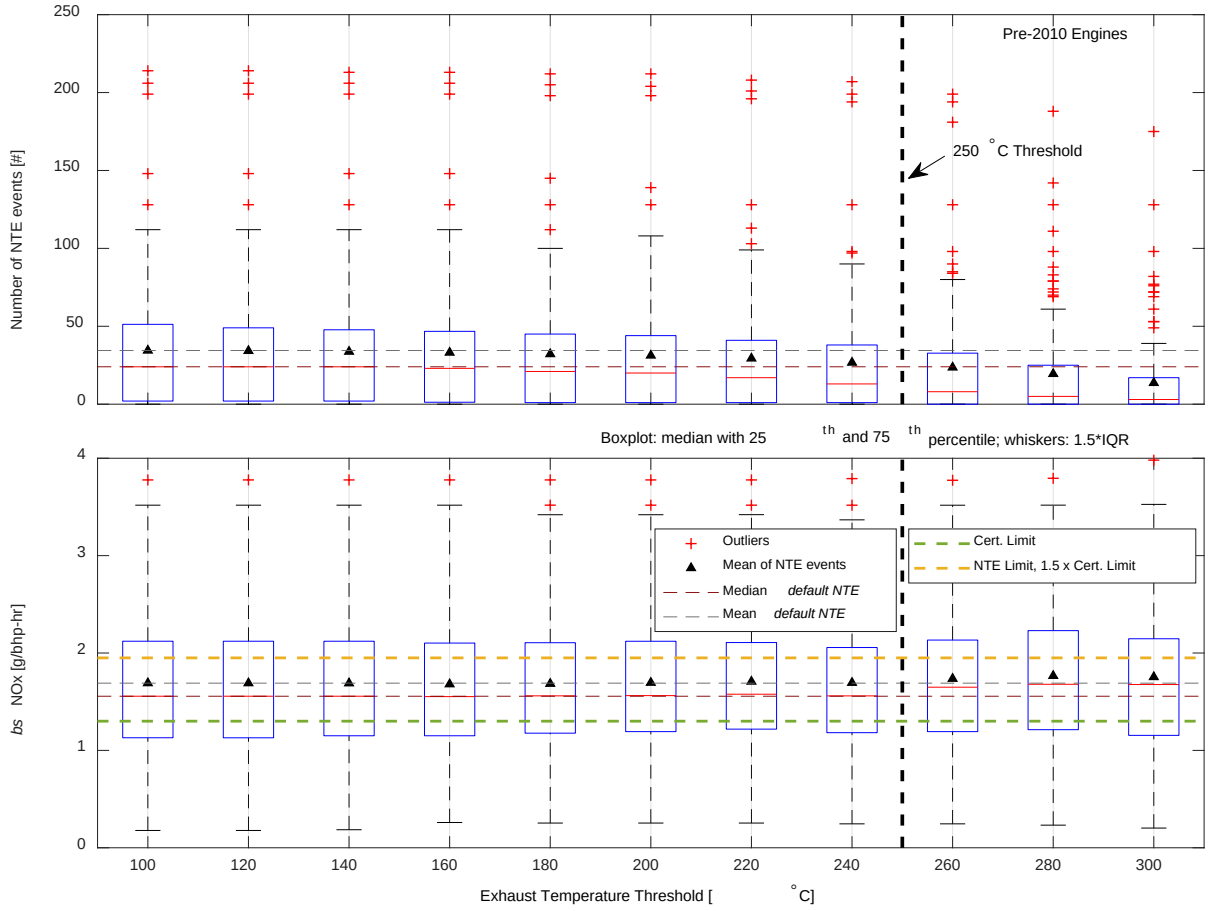
Effect Contribution of Parameters

Control Parameter	Effect Contribution			
	$bsNO_x$ Emission		NTE Events	
	Pre-2010	Post-2010	Pre-2010	Post-2010
Engine torque threshold	35.3%	26.8%	19.4%	20.5%
Engine power threshold	**52.6%**	26.1%	36.5%	**48.6%**
$T_{exhaust}$ exclusion threshold	12.1%	**47.0%**	**44.0%**	30.9%

Exp.	Thresholds			Test w/o NTE Events					
[#]	Peak Torque	Rated Power	Exh. Temp.	Pre 2010 [#]	% of total [%]	Δ rel. to default [%]	Post 2010 [#]	% of total [%]	Δ rel. to default [%]
1	30%	30%	250	39	24.5		54	32.7	
2	15%	15%	250	35	22.0	10.3	42	25.5	22.2
3	5%	5%	110	21	13.2	46.2	35	21.2	35.2
4	5%	5%	200	27	17.0	30.8	37	22.4	31.5
5	5%	15%	250	35	22.0	10.3	42	25.5	22.2
6	5%	30%	150	30	18.9	23.1	49	29.7	9.3
7	15%	5%	150	25	15.7	35.9	38	23.0	29.6
8	15%	15%	200	29	18.2	25.6	40	24.2	25.9
9	15%	30%	110	29	18.2	25.6	49	29.7	9.3
10	15%	30%	250	39	24.5	0.0	53	32.1	1.9
11	30%	5%	250	39	24.5	0.0	53	32.1	1.9
12	30%	15%	110	29	18.2	25.6	48	29.1	11.1
13	30%	15%	150	30	18.9	23.1	49	29.7	9.3
14	30%	30%	200	32	20.1	17.9	51	30.9	5.6

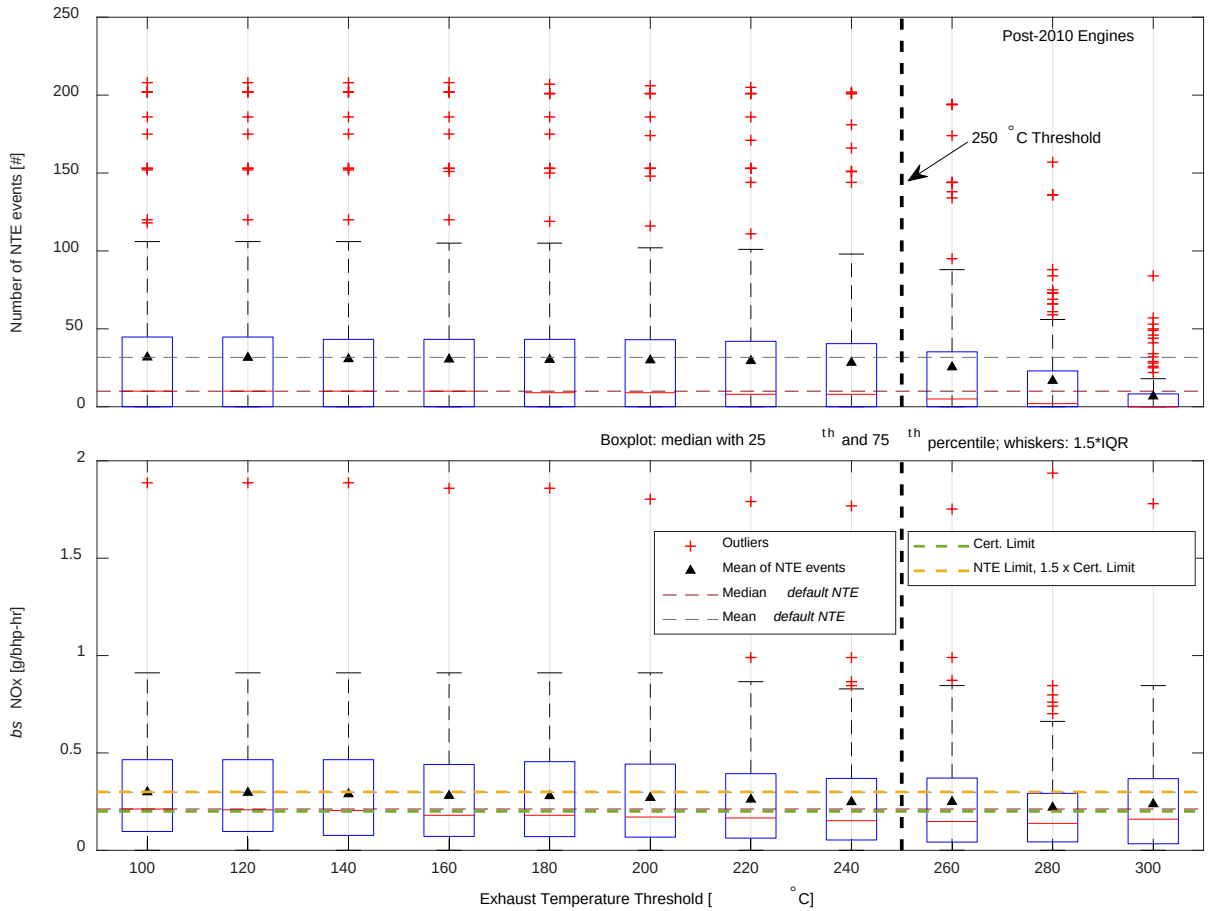
Results - *Impact of AT-Temperature Threshold on NTE*

Pre-2010 engine datasets



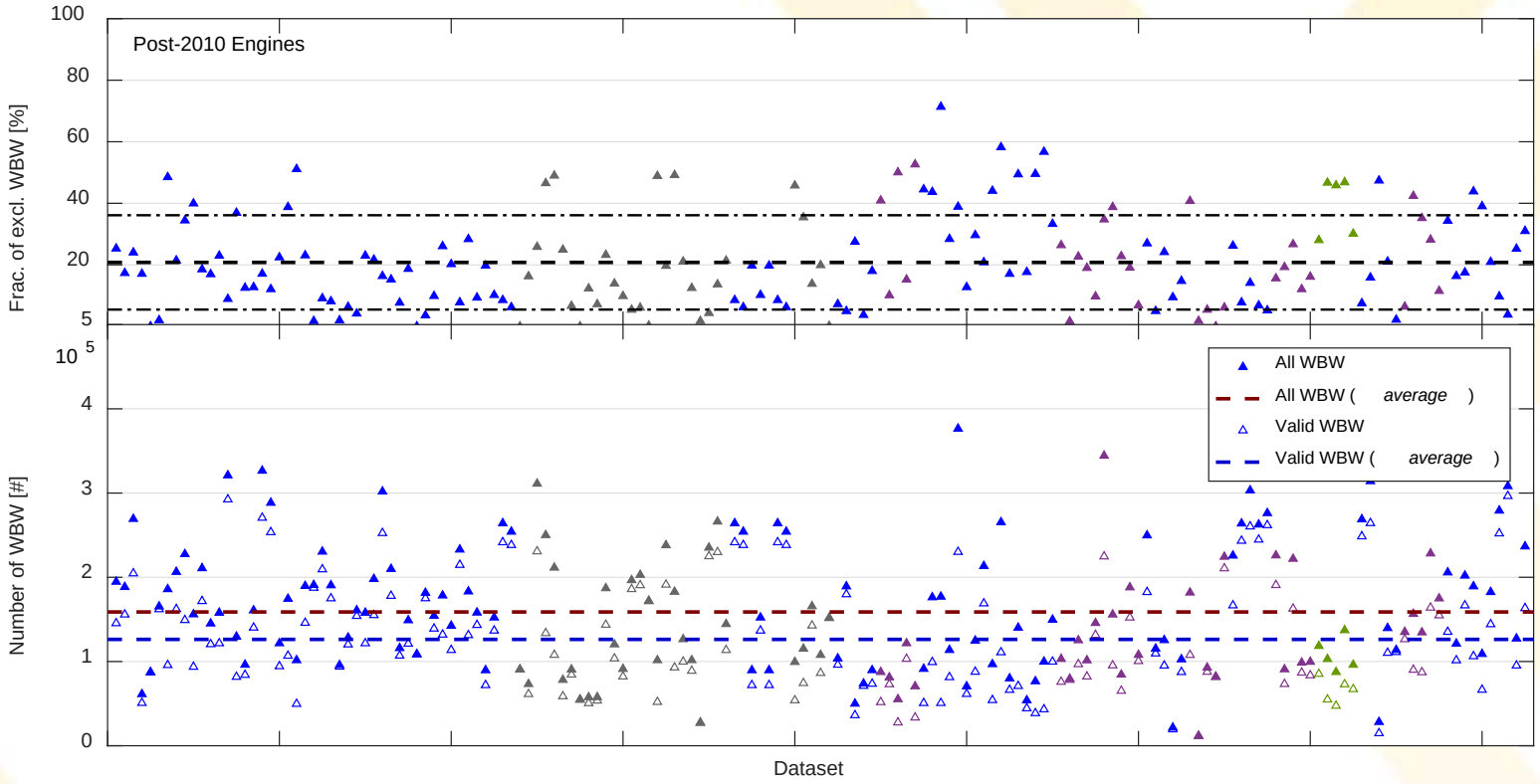
- 36.6% more NTE events on average
- 1.5% reduction in event-averaged NO_x => 1.72 vs. 1.69g/bhp-hr

Post-2010 engine datasets



- 16.3% more NTE events on average
- 22.4% increase in event-averaged NO_x => 0.24 vs. 0.29g/bhp-hr

Results - *Work-based Window Analysis*

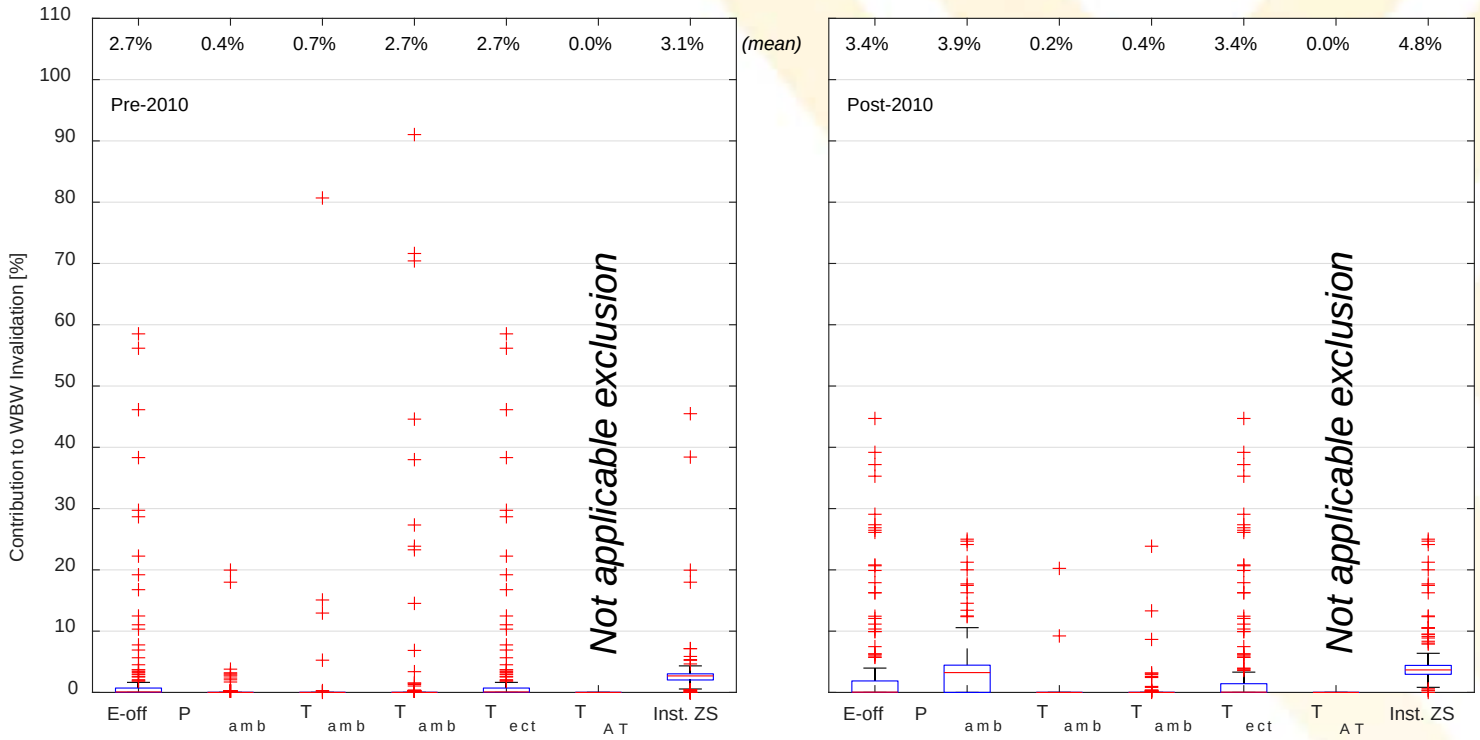


Parameter	Pre-2010	Post-2010	$\Delta_{pre\ vs\ post}$ [%]
Number of total windows	14299 ± 9972	15880 ± 7418	*-11.1*
Number of valid windows	10942 ± 7054	12625 ± 6583	*-15.4*
$\Delta_{total\ vs\ valid}$ [%]	***23.5***	***20.5***	

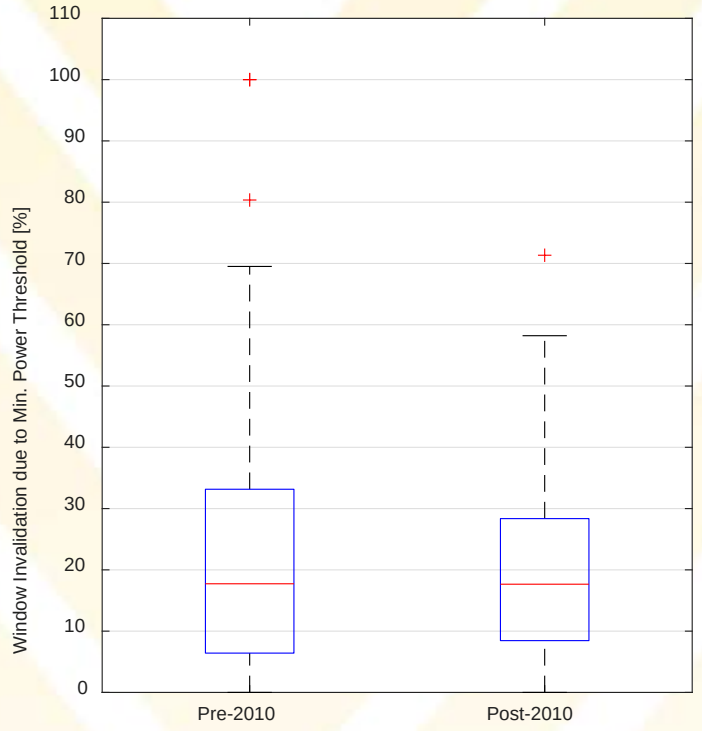
- Number of work-based windows
  - post-2010 non-credit engines (▲)
  - post-2010 credit w/o SCR engines (▲)
  - post-2010 credit w/ SCR engines (▲)
  - post-2010 CNG engines (▲)
- Data exclusions EU Reg. EC No. 582-2011
  - Barometric pressure => altitude
  - Ambient temperature
  - Engine coolant temperature
  - Minimum average window power
- Additional data exclusions
  - Engine off
  - PEMS Z/S
- Only 5 pre-2010 dataset result in '*zero*' valid windows.

Results - *Work-based Window Exclusions*

Exclusions applied to data domain => *removing data for windowing*



Invalidation of windows



Time-Weighted Fraction [%]	Pre-2010	Post-2010	Pre-2010	Post-2010
Total fraction spent in NTE control area	28.2 ± 12.8	29.7 ± 13.2		
Total fraction spent in NTE control area w/ Excl. applied	17.3 ± 14.0	14.2 ± 12.6		
Total fraction spent in valid NTE events or WBW	**5.3** ± 7.4	**5.1** ± 7.7	**91.1** ± 16.0	**91.7** ± 8.9

Results - Event/window-averaged *bs*NO_x Emissions

NTE-event work-window averaged *bs*NO_x Emissions

Parameter	Pre-2010	Post-2010 All	Post-2010 Non-Credit
Overall NTE event-averaged bsNO_x emissions [g/bhp-hr]	1.662 ± 0.804	0.268 ± 0.277	0.160 ± 0.233
Overall WBW-averaged bsNO_x emissions [g/bhp-hr]	2.019 ± 0.983	0.475 ± 0.393	

- Based on NTE-event-averaged emissions rates
  - 83.9% reduction between pre/post-2010 (=> all post-2010)
  - 90.4% reduction between pre/post-2010 (only non-credit)
- Based on WB-window-averaged emissions rates
  - 76.5% reduction between pre/post-2010 (=> all)

Daily-averaged *bs*NO_x Emissions

Parameter	Pre-2010	Post-2010				
	All	All	Non-credit	Credit w/o SCR	Credit w/ SCR	CNG
Daily-averaged *bs*NO_x [g/bhp-hr]						
μ [g/bhp-hr]	2.413	0.622	0.446	1.080	0.779	0.178
σ [g/bhp-hr]	1.173	0.514	0.433	0.487	0.459	0.123
$\Delta_{pre\text{-}post}$ [%]		***74.20***	***81.51***	***55.25***	***67.71***	***92.63***
"Sum-over-sum" *bs*NO_x [g/bhp-hr]						
bsNO_x	2.146	0.535	0.365	1.074	0.706	0.186
$\Delta_{pre\text{-}post}$ [%]		***75.07***	***83.00***	***49.95***	***67.10***	***91.34***

Conclusions

- NTE exclusion analysis showed IMT (55 and 41%) to be most dominant exclusion followed by T_{AT} (23 and 34%).
- Parametric study indicates engine power threshold and T_{AT} exclusion level to have strongest impact on # of events and event-averaged *bs*NO_x
  - For pre-2010 => power threshold strongest factor for *bs*NO_x, T_{AT} level strongest factor for # of events.
  - For post-2010 => power threshold strongest factor for # of events, T_{AT} level strongest factor for *bs*NO_x.
  - A combination of reducing power threshold, lowering T_{AT} and changing IMT exclusion can lead to increase in # of events while maintaining representativeness of event emissions.
- Changing boundaries/exclusions alone can only lead to moderate increase in # of events => challenge to stay inside NTE area.
- Lowering T_{AT} threshold to 100C leads to 16% increase in event-#, with increase in *bs*NO_x by 22.4% (0.24 vs. 0.29g/bhp-hr).
- Time-weighted data utilization for analysis is lower for NTE as opposed to WBW
  - 5.3% vs. 91.1% for pre-2010, and 5.1% vs. 91.7% for post-2010

THANK YOU FOR YOUR ATTENTION

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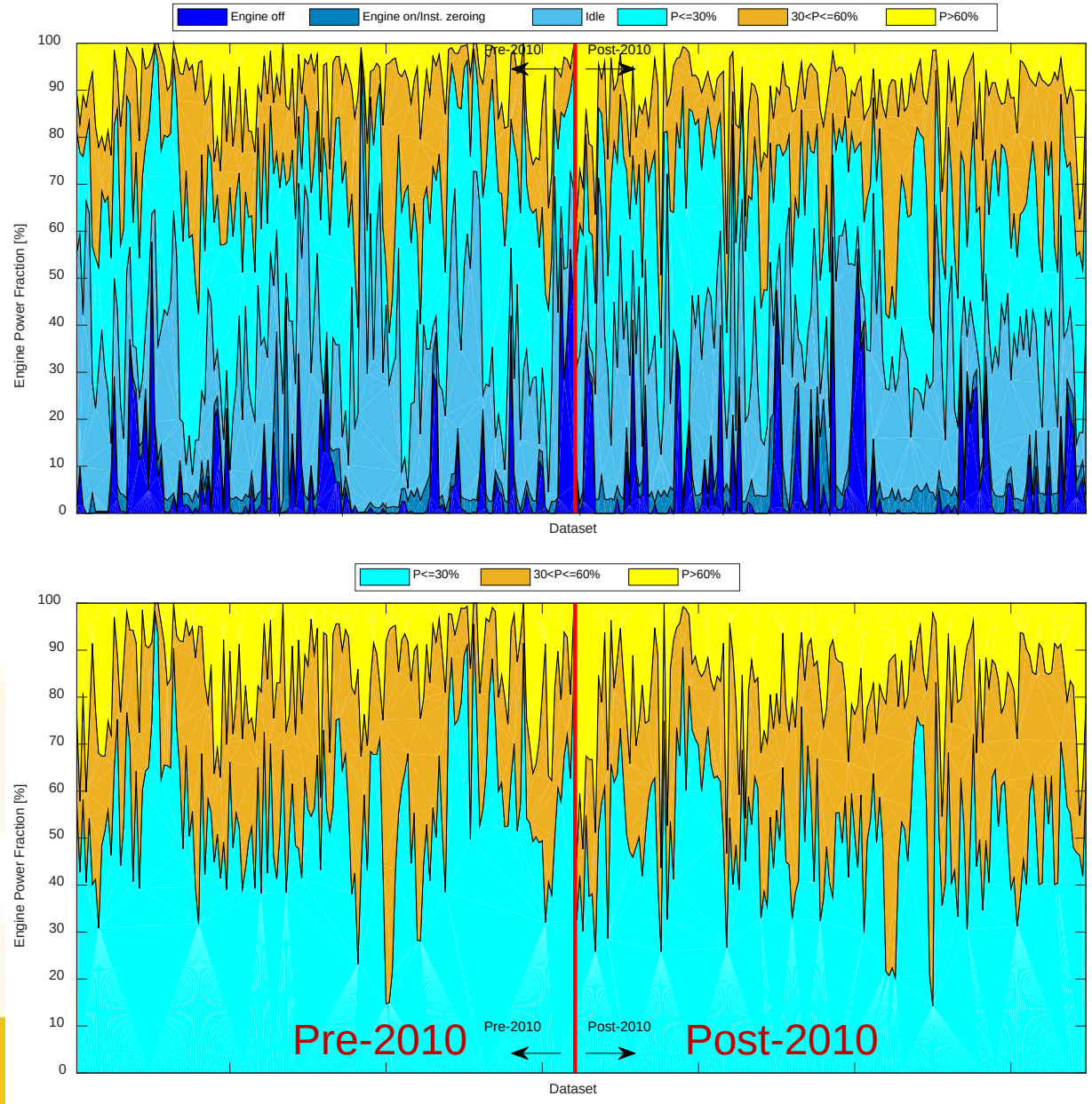
Backup Slides

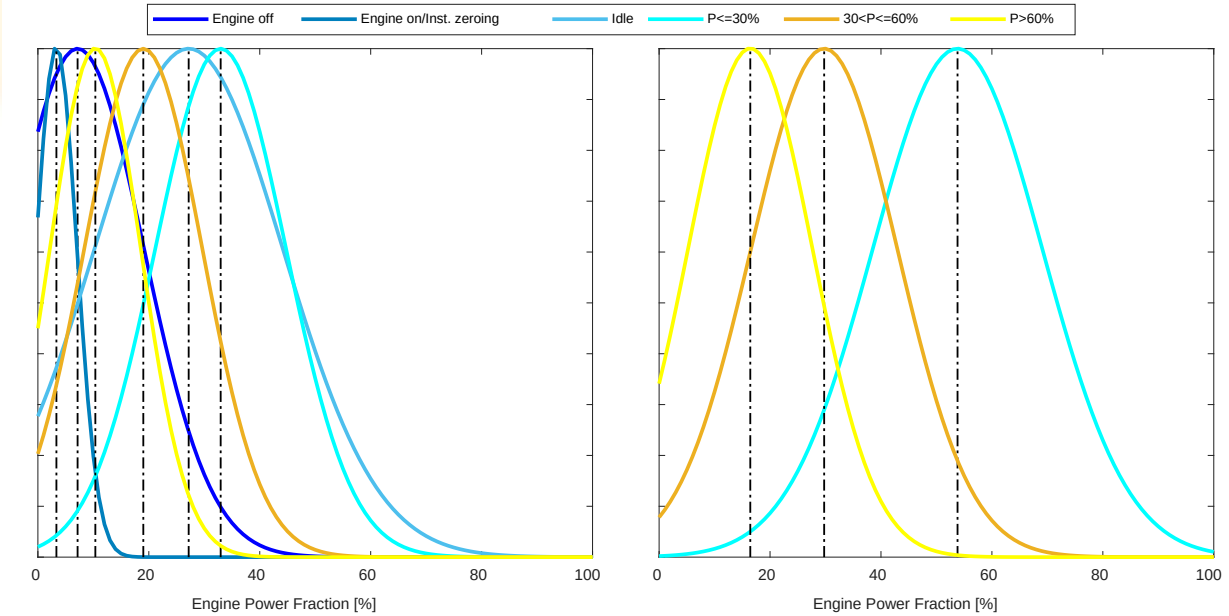
Description of Data - *Characteristic engine power*



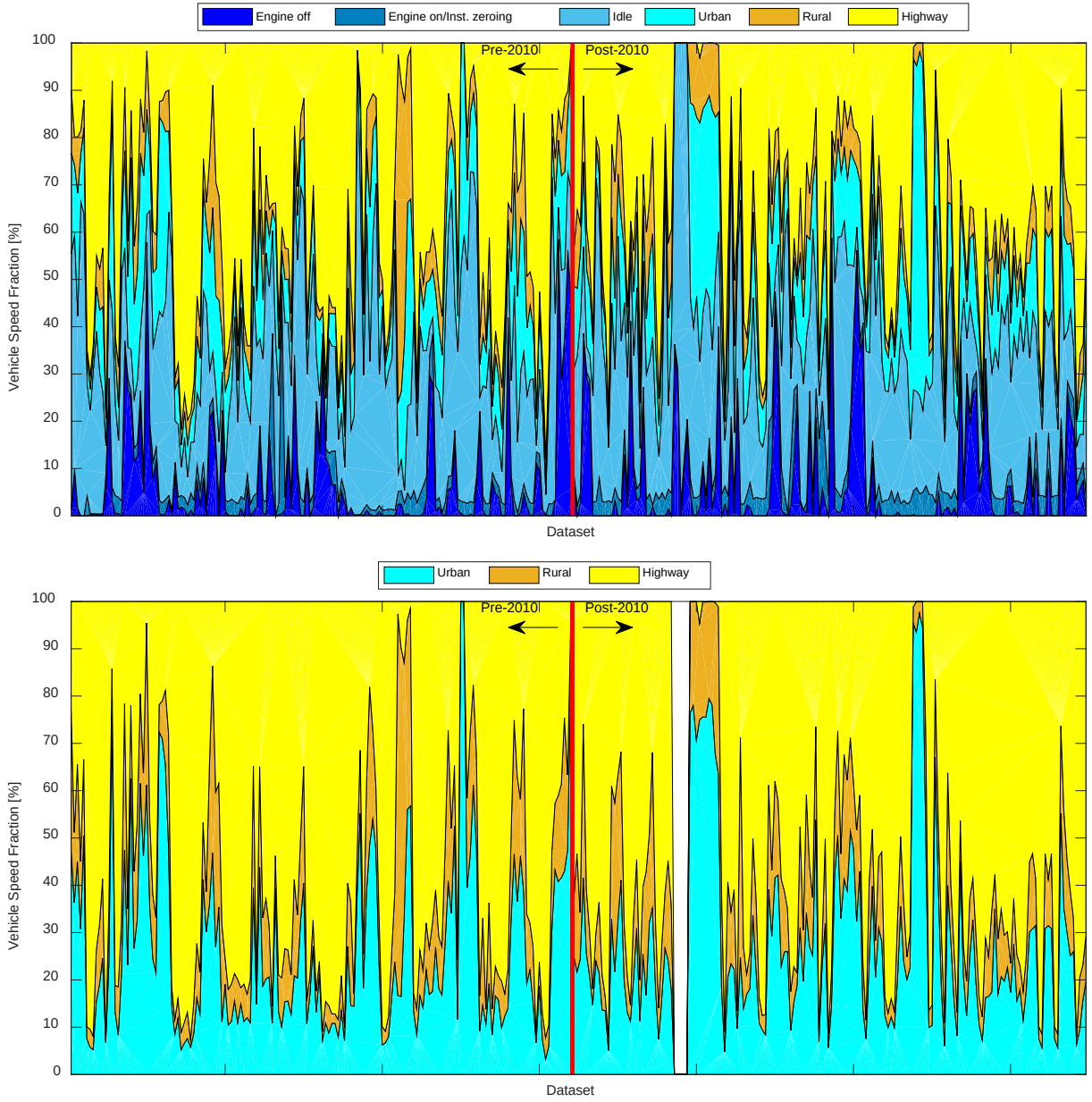
Time-weighted engine power distribution

	Pre-2010		Post-2010	
	All	Only TW	All	Only TW
Engine off	6.8 ± 11.7		7.5 ± 12.2	
Engine on/Inst. Z/S	2.8 ± 4.4		3.9 ± 2.7	
Engine Idle	27.9 ± 18.5		26.5 ± 15.3	
Power ≤ 30%	34.5 ± 12.0	56.5 ± 15.8	31.4 ± 11.4	51.1 ± 14.3
30% < Power ≤ 60%	18.8 ± 10.8	29.0 ± 13.1	19.2 ± 10.5	30.5 ± 13.2
Power > 60%	9.2 ± 7.7	14.4 ± 10.7	11.5 ± 8.5	18.4 ± 11.3

TW - engine performing tractive work



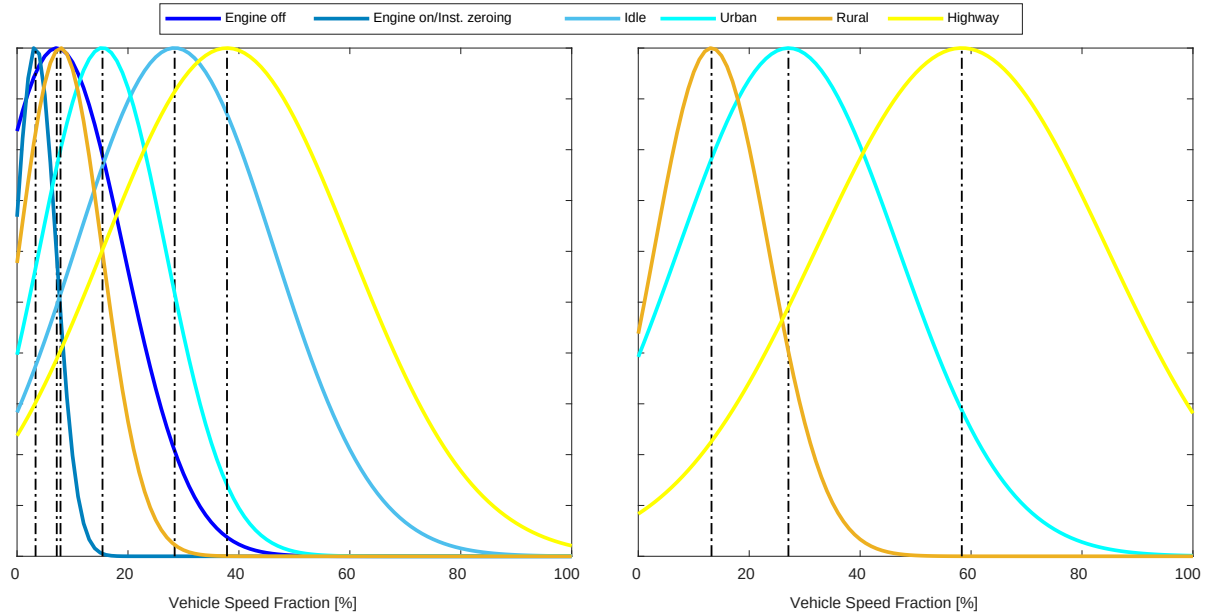
Description of Data - *Type of Vehicles*



Time-weighted engine power distribution

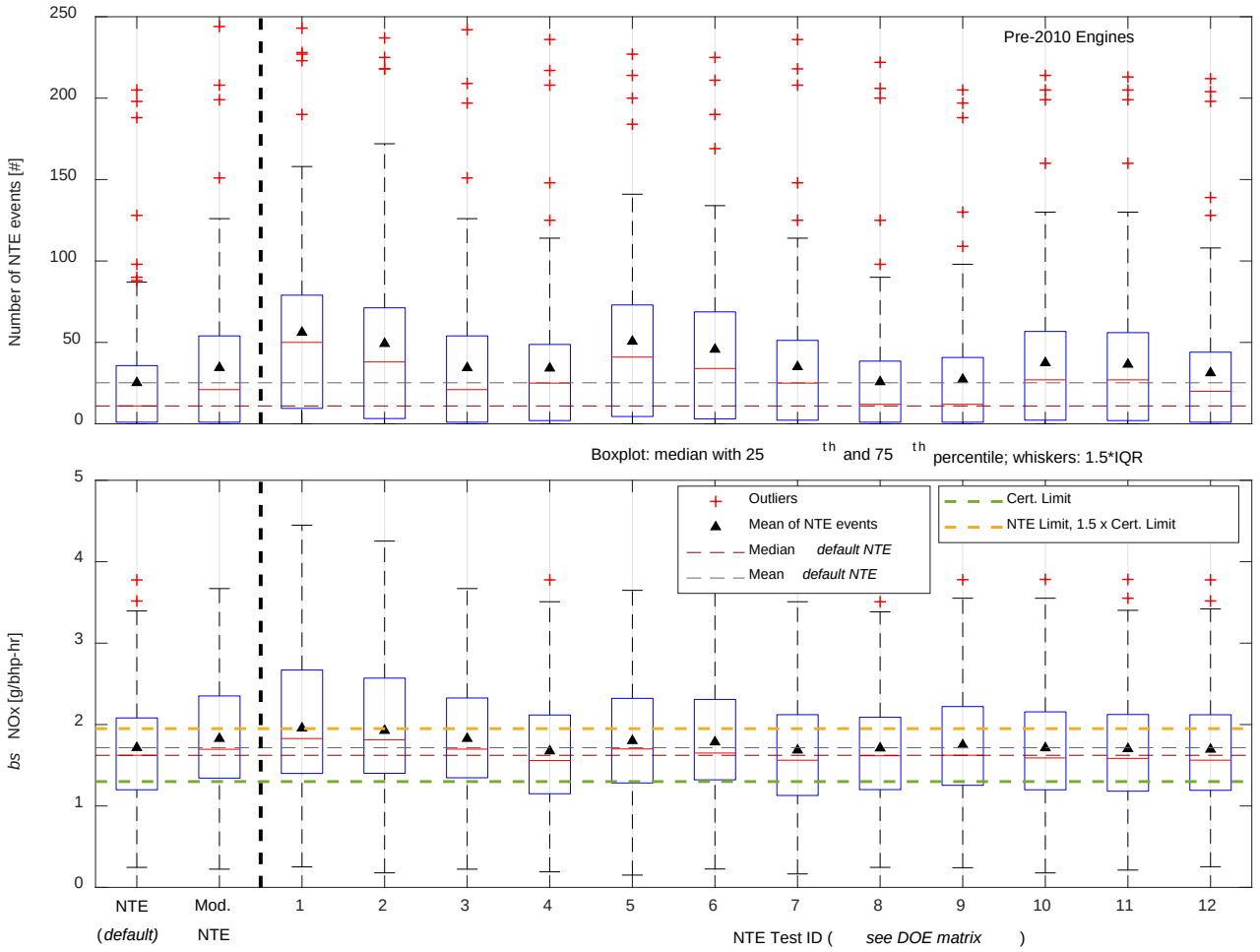
	Pre-2010		Post-2010	
	All	Only URH	All	Only URH
Engine off	6.8 ± 11.7		7.5 ± 12.2	
Engine on/Inst. Z/S	2.8 ± 4.4		3.9 ± 2.7	
Engine Idle	27.9 ± 18.5		28.9 ± 17.3	
Urban Driving	14.7 ± 9.7	26.5 ± 19.3	16.1 ± 12.7	28.4 ± 20.1
Rural Driving	8.4 ± 9.5	13.7 ± 12.0	7.3 ± 4.6	13.1 ± 8.3
Highway Driving	39.4 ± 23.0	59.8 ± 25.9	36.3 ± 21.6	58.6 ± 25.0

URH - urban, rural and highway operation (i.e. without idle => V = 0mph)



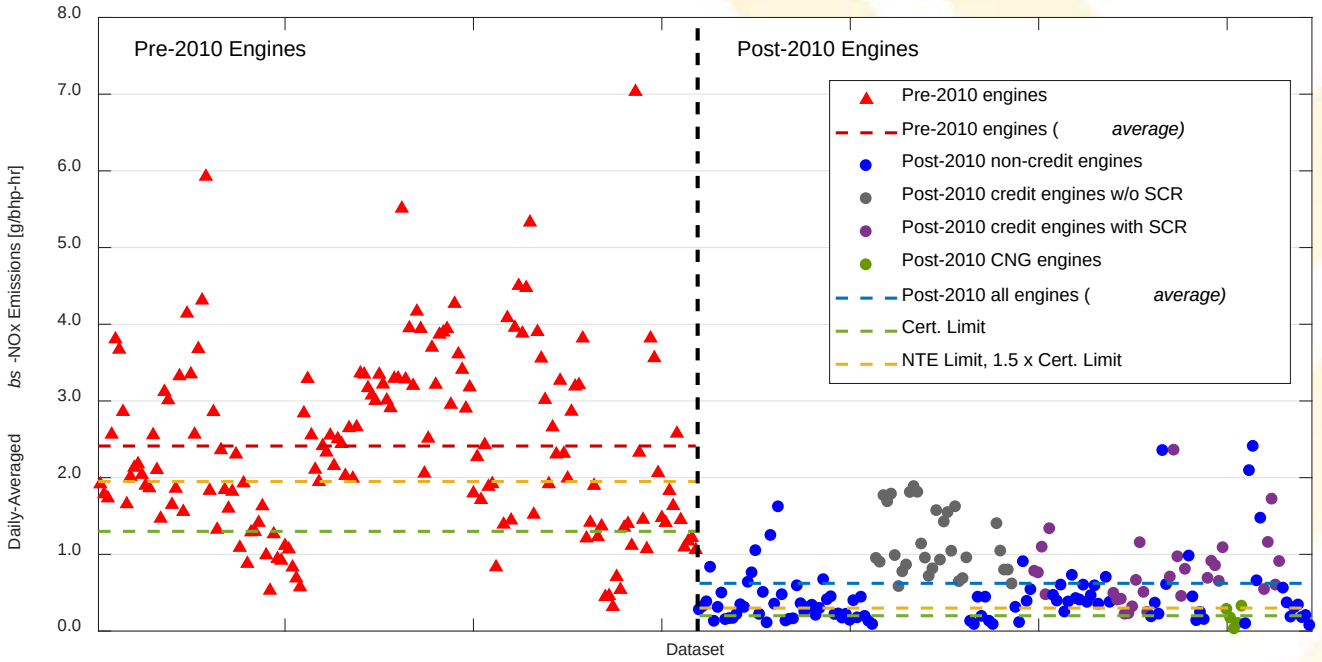
Results - *Parametric Analysis*

Pre-2010 engine datasets



Exp.	Thresholds			NO_x Emissions	NTE Events	
[#]	Peak Torque	Rated Power	Exh. Temp.	[g/bhp-hr]	μ [#]	σ [#]
1	30%	30%	250	1.7157	25	36
2	15%	15%	250	1.8274	34	43
3	5%	5%	110	1.9555	56	52
4	5%	5%	200	1.9261	49	50
5	5%	15%	250	1.8279	34	43
6	5%	30%	150	1.6744	34	41
7	15%	5%	150	1.8010	51	50
8	15%	15%	200	1.7848	46	49
9	15%	30%	110	1.6851	35	41
10	15%	30%	250	1.7105	26	37
11	30%	5%	250	1.7486	27	37
12	30%	15%	110	1.7125	37	41
13	30%	15%	150	1.7020	36	41
14	30%	30%	200	1.6952	31	39

Results - *Daily-averaged work-specific NO_x Emissions*



- Data during engine-off & PEMS Z/S states excluded.
- Including data during DPF regeneration.

NO_x Emission Standard

Parameter	NO_x Standard		FEL	
	Pre-2010	Post-2010	Pre-2010	Post-2010
μ	1.3	0.2	1.50	0.30
σ			0.61	0.11
COV [%]			40.72	38.09
$\Delta_{pre\text{-}post}$ [%]		*84.6*		*79.9*

Real-World Emissions

Parameter	Pre-2010	Post-2010				
	All	All	Non-credit	Credit w/o SCR	Credit w/ SCR	CNG
Daily-averaged *bs*NO_x [g/bhp-hr]						
μ [g/bhp-hr]	2.413	0.622	0.446	1.080	0.779	0.178
σ [g/bhp-hr]	1.173	0.514	0.433	0.487	0.459	0.123
$\Delta_{pre\text{-}post}$ [%]		*74.20*	*81.51*	***55.25***	***67.71***	***92.63***

Parameter	*ds*NO_x [g/mile]			*ts*NO_x [g/hr]		
	Pre-2010	Post-2010		Pre-2010	Post-2010	
	All	All	Non-credit	All	All	Non-credit
μ	6.83	1.78	1.38	188.05	51.38	36.89
σ	5.03	1.52	1.36	108.55	41.42	37.35
$\Delta_{pre\text{-}post}$ [%]		*73.92*	*79.76*		*72.68*	*80.38*

CARB EMFAC => distance-based emissions factors

EPA MOVES => times-based EF assoc. with set of speed/power bins