future fuel strategies

Effects of Ethanol Blends on Light-Duty Vehicle Emissions: *A Critical Review*

February 2019

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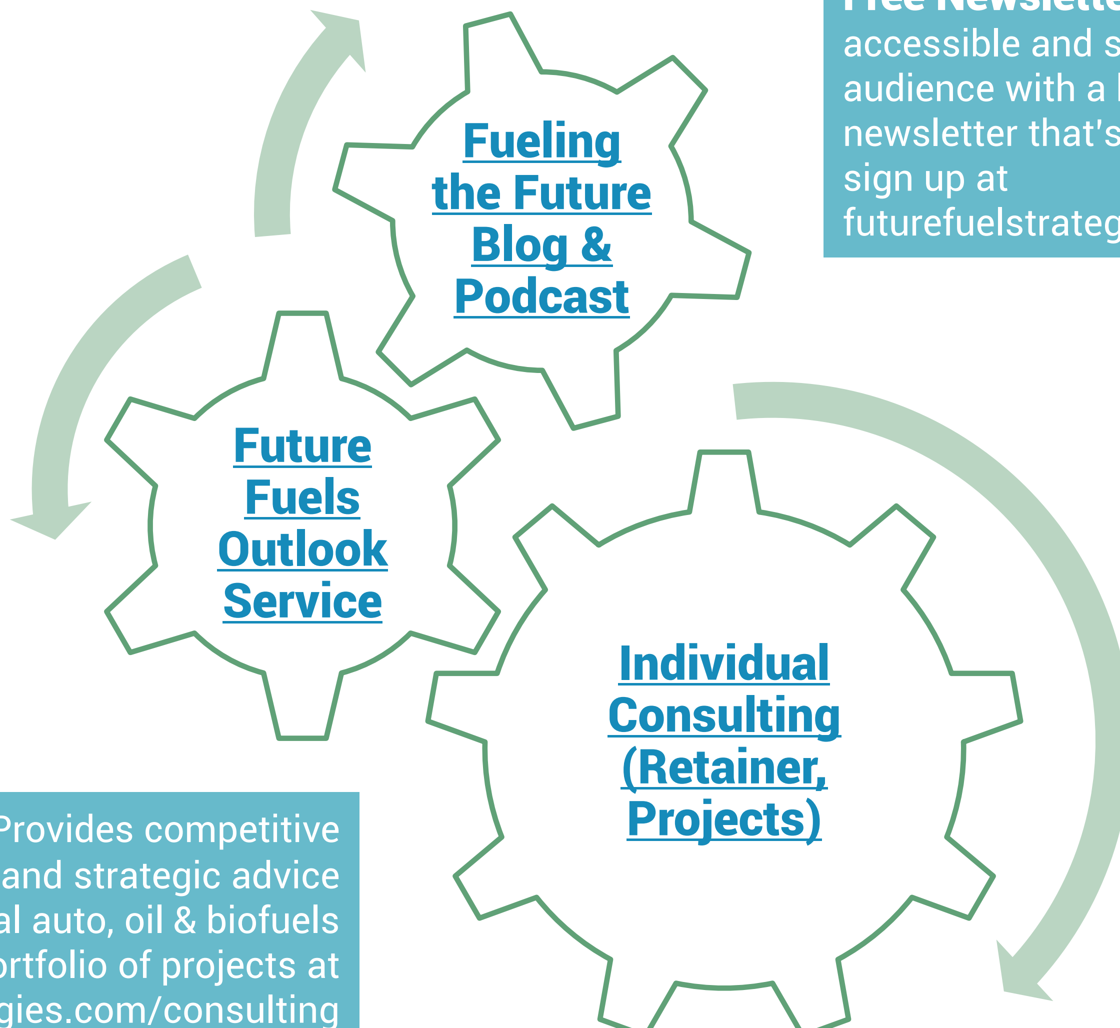

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Background & Purpose (1/2)

- Over 14 billion gallons of ethanol are sold in US gasoline annually
  - This is about 10% of total gasoline by volume
- Criteria pollutants, including NOx, PM & HC, affect atmospheric quality and are implicated in health effects
- Real-world pollutant mass will vary with fuel ethanol content
- Numerous studies have compared emissions from 10% ethanol blends and a growing body of literature addresses higher level ethanol blends.
- However, study approaches and objectives are not uniform resulting in major inconsistencies in conclusions

Background & Purpose (2/2)

- Analysis sought to determine whether current data can predict the ethanol effect
- Prior reviews have addressed inconsistencies but none have attempted a comprehensive analysis of inconsistencies across the wide range of studies that have been completed.
- The overall objective of this study was to examine prior ethanol blending studies, identify limitations/shortcomings and explain differences between study conclusions
- This study also provides for a future process whereby the effects on emissions of varying levels of ethanol in a fuel can be determined repeatably, unambiguously and realistically

Webinar Agenda

- Overview of gasoline and ethanol blending
  - Refining gasoline production, quality and economics
  - Non-linearity aspects
  - Real world ethanol blending
- The auto fleet and emissions
- Prior emission studies
- Barriers to real-world prediction from existing data
- Summaries of past studies
- Study variations and limitations
- Conclusions

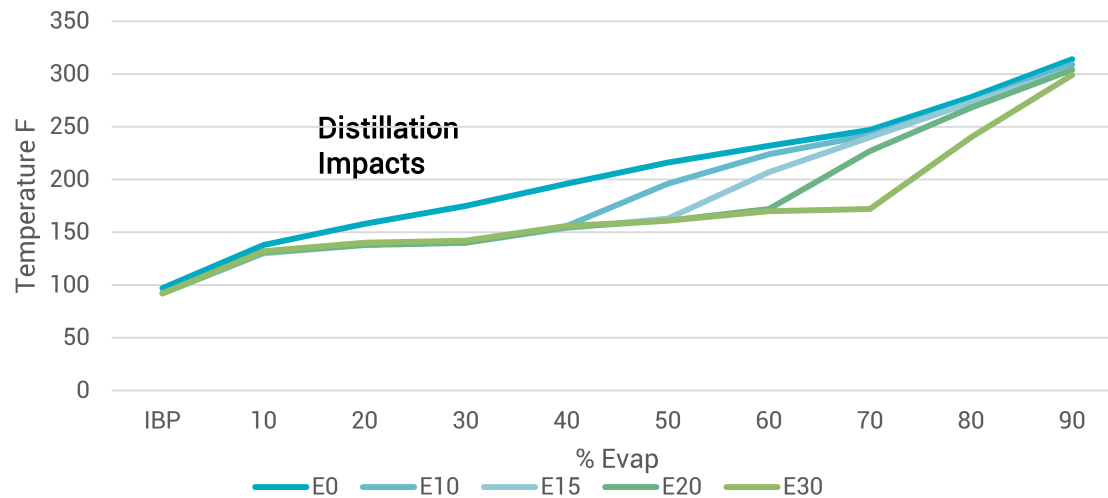
Refinery Streams: Quality & Share

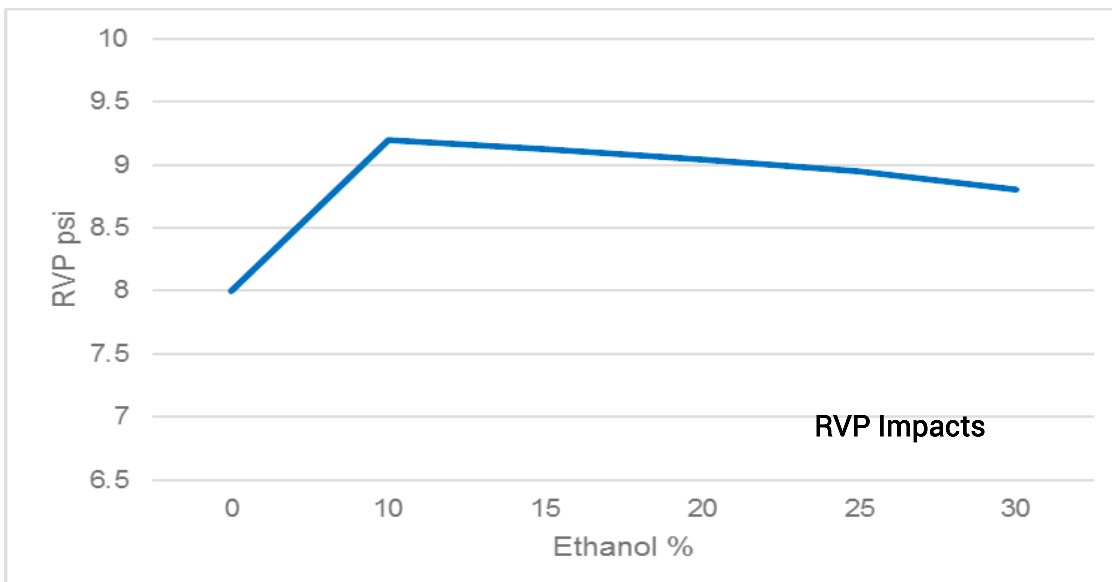
	RVP psi	Octane (R+M)/2	Aromatics Vol%	T50 °F	Share %
FCC Gasoline	5	85.0	27	225	31
Reformate	4	90.5	50	265	27
Alkylate	5	92.5	0	218	13
Isomerate	14	81.5	0	125	5
Aromatic by-product	1	105.0	95	250	1
Butane	60	92.0	0	100	3
Other	12	77.0	7	138	20

- Little component production/quality flexibility (ex reformate)
- FCC/reformate >50% of total production
- High octane characterized by high aromatics (except alkylate)
- Reformate octane and volume can be varied – higher octane increases aromatic content

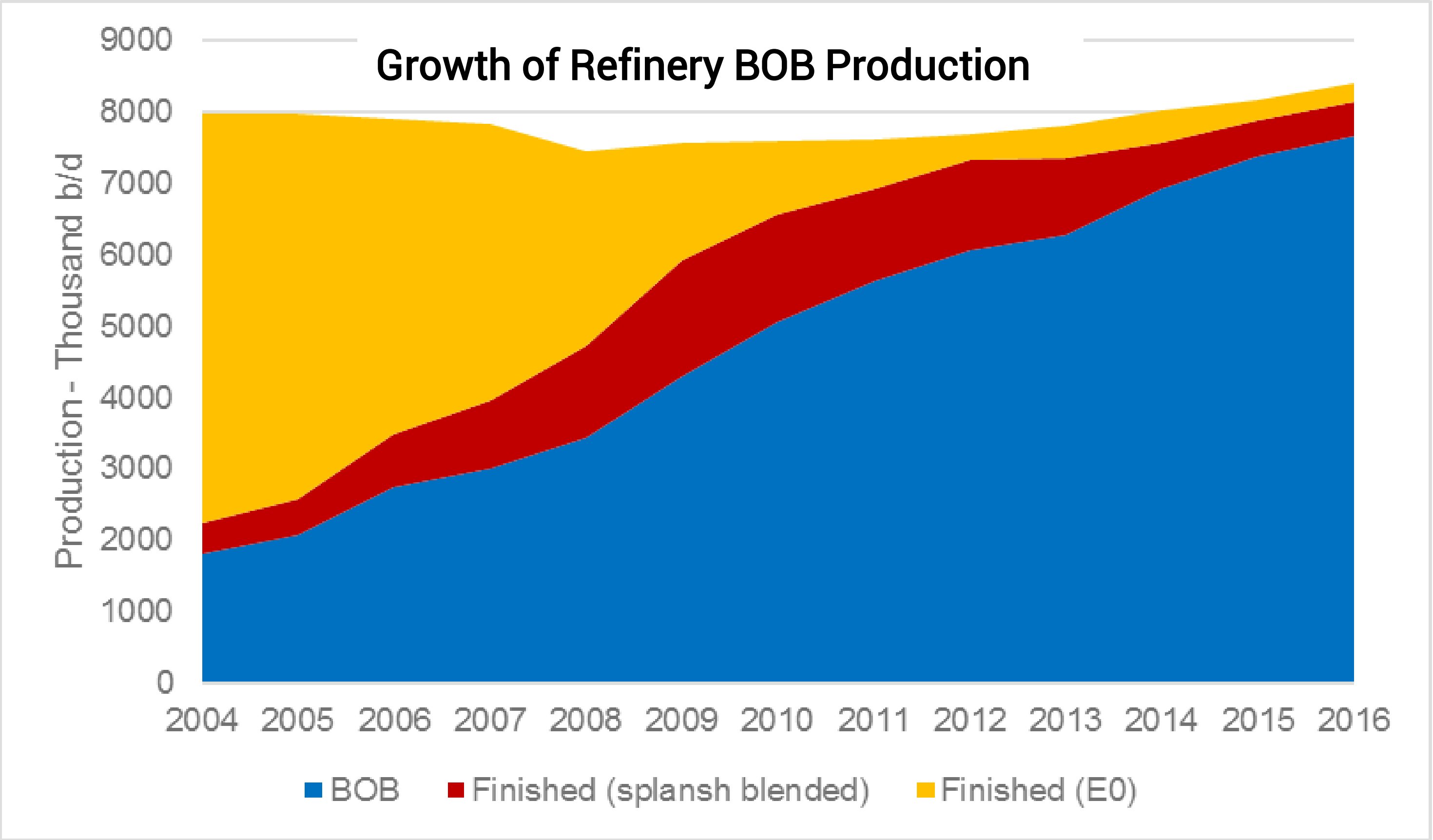
Ethanol Blending Characteristics

- Ethanol blended outside refinery @ terminals
- Ethanol high octane (~ 115 (R+M)/2 (AKI)
- Non-linear blending behavior, particularly related to volatility
- Significant shift in distillation curve with ethanol addition
- Large RVP boost, falls off at higher ethanol
- Note: Refinery HC streams exhibit non-linear blending, particularly with atypical streams





Ethanol Blending Patterns

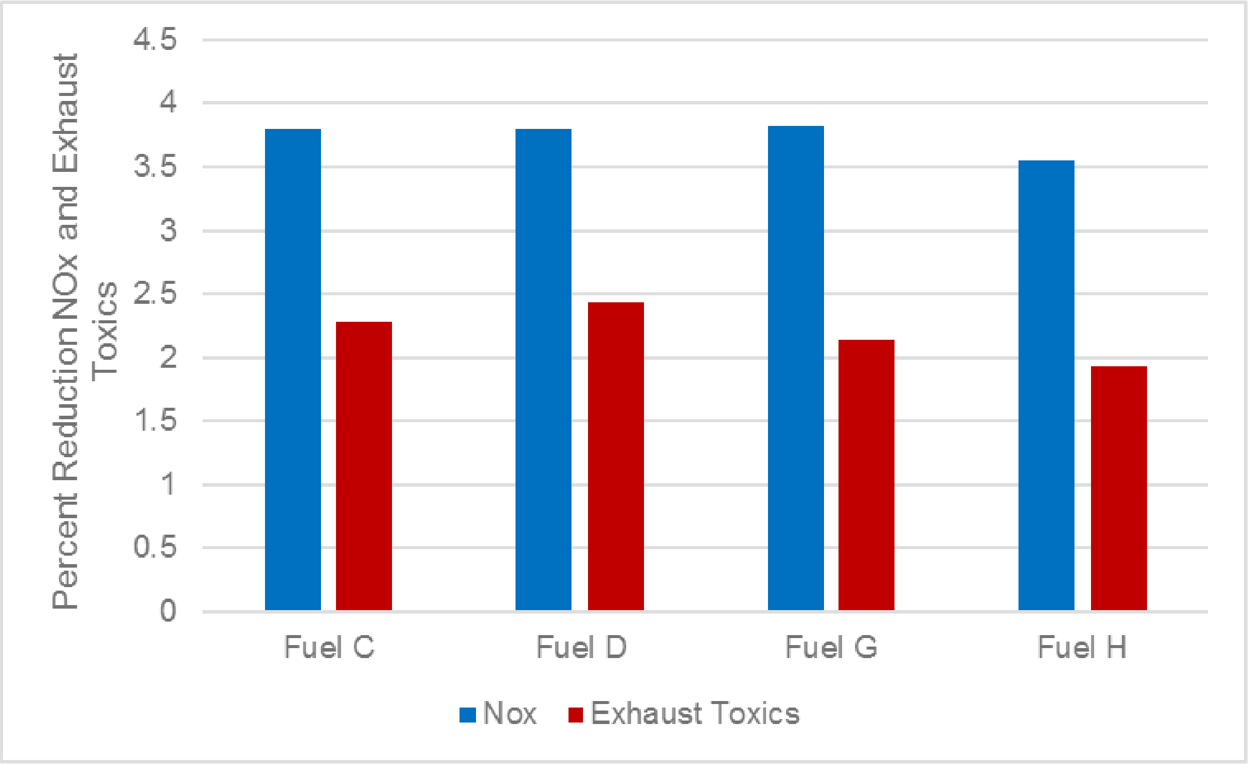


- Ethanol splash blended with finished gasoline or blended with special refinery blendstock - BOB
- BOB produced with lower octane to capture octane value of ethanol, and lower RVP where necessary to meet regulatory limits
- Octane benefits of 10% ethanol provides 9-12 cpg revenue improvement
- Industry response – only 6% of ethanol splash blended with finished gasoline

Splash Blend* Test Fuels Vs Real World

- Splash blending not consistent with real world where RVP waiver not available
- Splash blending results in octane “giveaway”
- Splash blending does not allow for emission benefits of lower final gasoline aromatic content

Comparison Splash Blending v Real World for CRC 94-3 Fuels

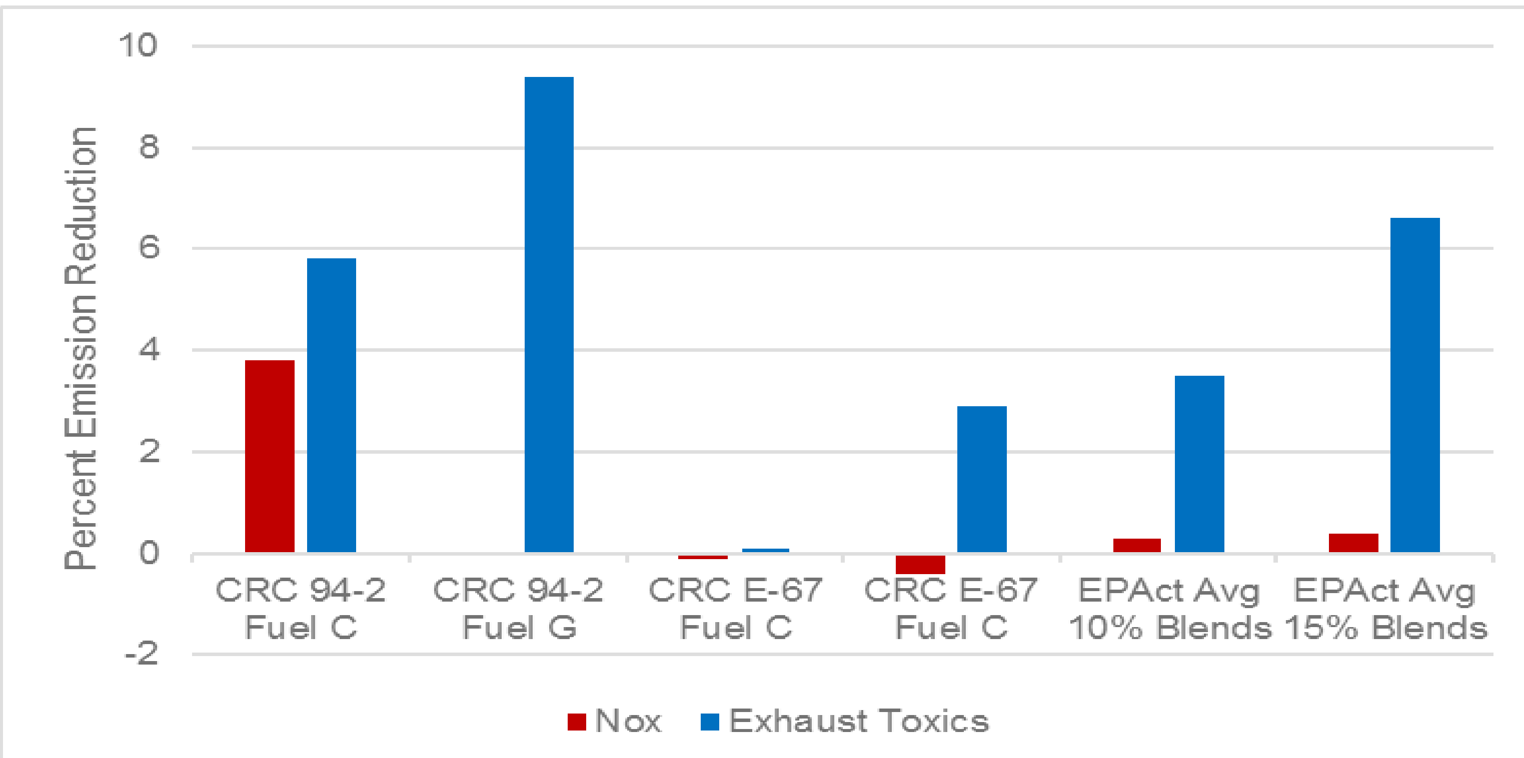


* Splash blended with finished gasoline

Match Blended Test Fuels v. Real World

- Not reasonably feasible to match all properties – studies will differ regard to parameters matched
- Matching aromatics/octane least to non-real world blends and distortion of original gasoline emission characteristics
- Matching other parameters such as distillation accomplished with unreal component shifts

Comparison Match Blending v Real World for Various Study Test Fuels



Real-World Involves the Auto Fleet

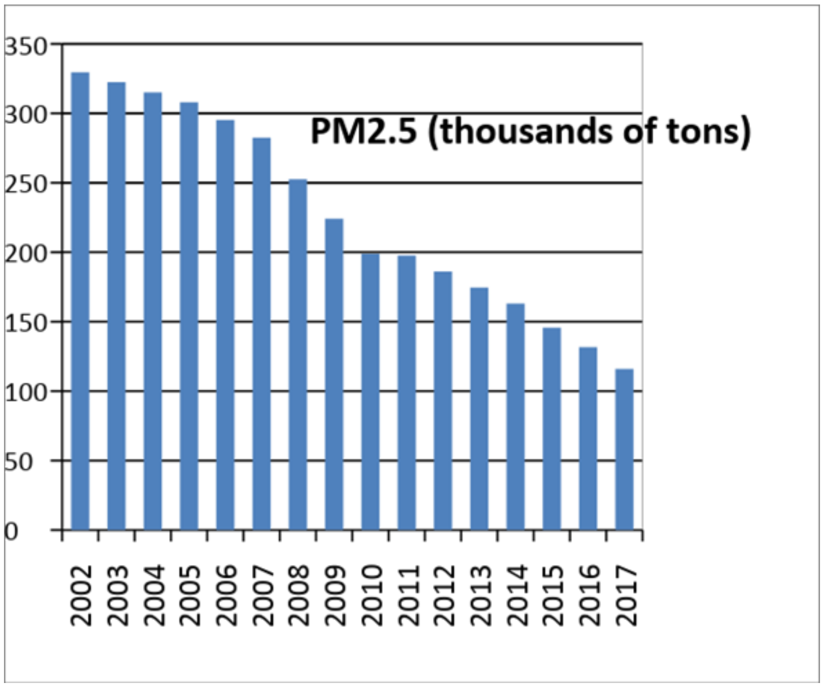
- Gasoline cars and light-duty trucks have evolved rapidly in the last decade.
- Fleet reflects many different technologies, not current sales.

	Standard	Emission Limits at 50,000 miles					Emission Limits at Full Useful Life (120,000 miles) [a]				
		NOx (g/mi)	NMOG (g/mi)	CO (g/mi)	PM (g/mi)	HCHO (g/mi)	NOx (g/mi)	NMOG (g/mi)	CO (g/mi)	PM (g/mi)	HCHO (g/mi)
Federal	Bin 1	-	-	-	-	-	0	0	0	0	0
	Bin 2	-	-	-	-	-	0.02	0.01	2.1	0.01	0.004
	Bin 3	-	-	-	-	-	0.03	0.055	2.1	0.01	0.011
	Bin 4	-	-	-	-	-	0.04	0.07	2.1	0.01	0.011
	Bin 5	0.05	0.075	3.4	-	0.015	0.07	0.09	4.2	0.01	0.018
	Bin 6	0.08	0.075	3.4	-	0.015	0.1	0.09	4.2	0.01	0.018
	Bin 7	0.11	0.075	3.4	-	0.015	0.15	0.09	4.2	0.02	0.018
	Bin 8	0.14	0.100 / 0.125 [c]	3.4	-	0.015	0.2	0.125 / 0.156	4.2	0.02	0.018
	Bin 9 [b]	0.2	0.075 / 0.140	3.4	-	0.015	0.3	0.090 / 0.180	4.2	0.06	0.018
	Bin 10 [b]	0.4	0.125 / 0.160	3.4 / 4.4	-	0.015 / 0.018	0.6	0.156 / 0.230	4.2 / 6.4	0.08	0.018 / 0.027
	Bin 11 [b]	0.6	0.195	5	-	0.022	0.9	0.28	7.3	0.12	0.032

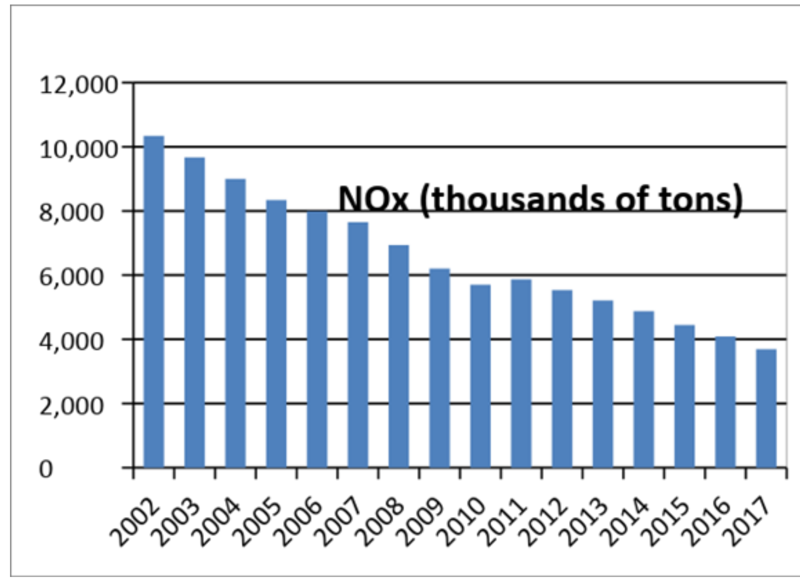
Tier 2 emissions standards, reproduced from EPA-420-B-17-028, September 2017

Emissions Are Declining Due To Fleet Replacement

- Gasoline direct injection is replacing port injection
- Catalyst technology is improving
- Controls are becoming more sophisticated

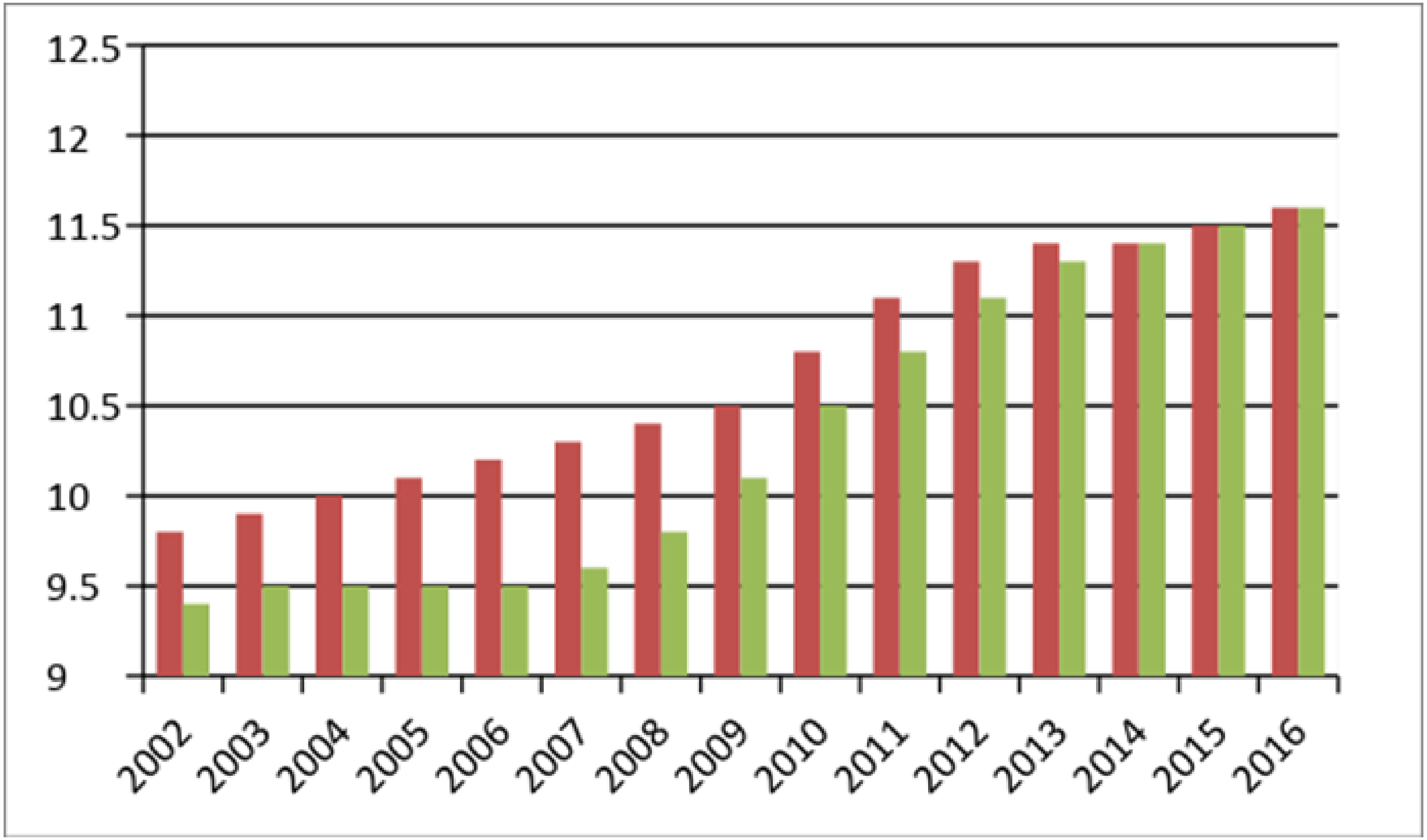


Emissions from the US highway fleet of PM less than 2.5 microns in size, over the period of this study.



NOx emissions from the US highway fleet over the period of this study.

High Fleet Diversity



- Average light-duty vehicle is 11 years old.
- Average age of the U.S. light-duty vehicle fleet has been increasing over the last two decades.

Source: US Department of Energy, Office of Vehicle Technologies.

Studies of E0 vs. Exx Emissions

Splash v. Match Blending

- Splash Blending
  - Ethanol added to a baseline gasoline
  - Hydrocarbon content changes only by dilution
  - AKI increases
  - T30-T50 lowered
- Match Blending
  - Fuels are blended with different ethanol levels but certain parameters matched between baseline and blend
  - AKI, Aromatics, T50, T90, PMI
  - Study often multivariate & seeks other composition effects
- The "Splash" and "Match" terms are not universal

Major Studies

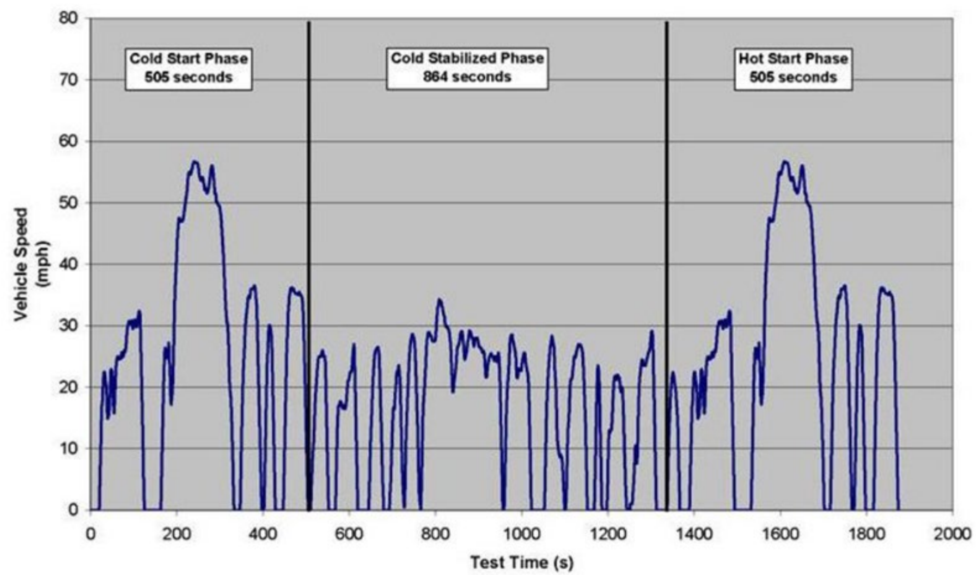
- Coordinating Research Council (CRC) E67 (Match)
- EPAct (Dept. of Energy, CRC, EPA) (Match)
- CRC E94-2 (Match) & E-94-3 (Splash)
- Oak Ridge (ORNL)

ADDITIONAL STUDIES

- Vehicle Manufacturers
- EPA (post-EPAct)
- Academia (e.g. UCR)

Barriers to Real-World Prediction from Existing Data

FTP cycle used in some studies –
others use LA-4 and LA-92



- Studies differ in conclusions, for a wide range of reasons
  - Emissions levels are low (accuracy)
  - Vehicle technology advances (MY effects)
  - Driving cycles vary
  - Engines interact with fuels
  - Experimental conditions vary
  - Statistical approaches vary
  - Blending strategies differ
- Studies do not reflect real-world fuels and operation
  - Fuels are not well described by a few parameters
  - Driving activity affects emissions
  - Study blends differ from pump fuels
- National impact would require assembly of conclusions from several studies
  - Studies configured differently

Study Summary: CRC E-67 Study

- Conducted by University of California, Riverside
- 2001-2-3 MY light trucks and automobiles
  - Certified California ULEV and SULEV
  - FTP dynamometer test
  - Port injected engine technology
- 12 fuel matrix: Match blended
  - T50 at 195°F (91°C), 215°F (102°C), or 235°F (113°C)
  - T90 at 295°F (146°C), 330°F (166°C), or 355°F (179°C)
  - Ethanol volume at 0%, 5.7%, or 10%
  - Aromatic, olefin and saturate fractions held approximately the same in the gasoline fraction
    - Composition of each group can vary

Study Summary: EPAct Study

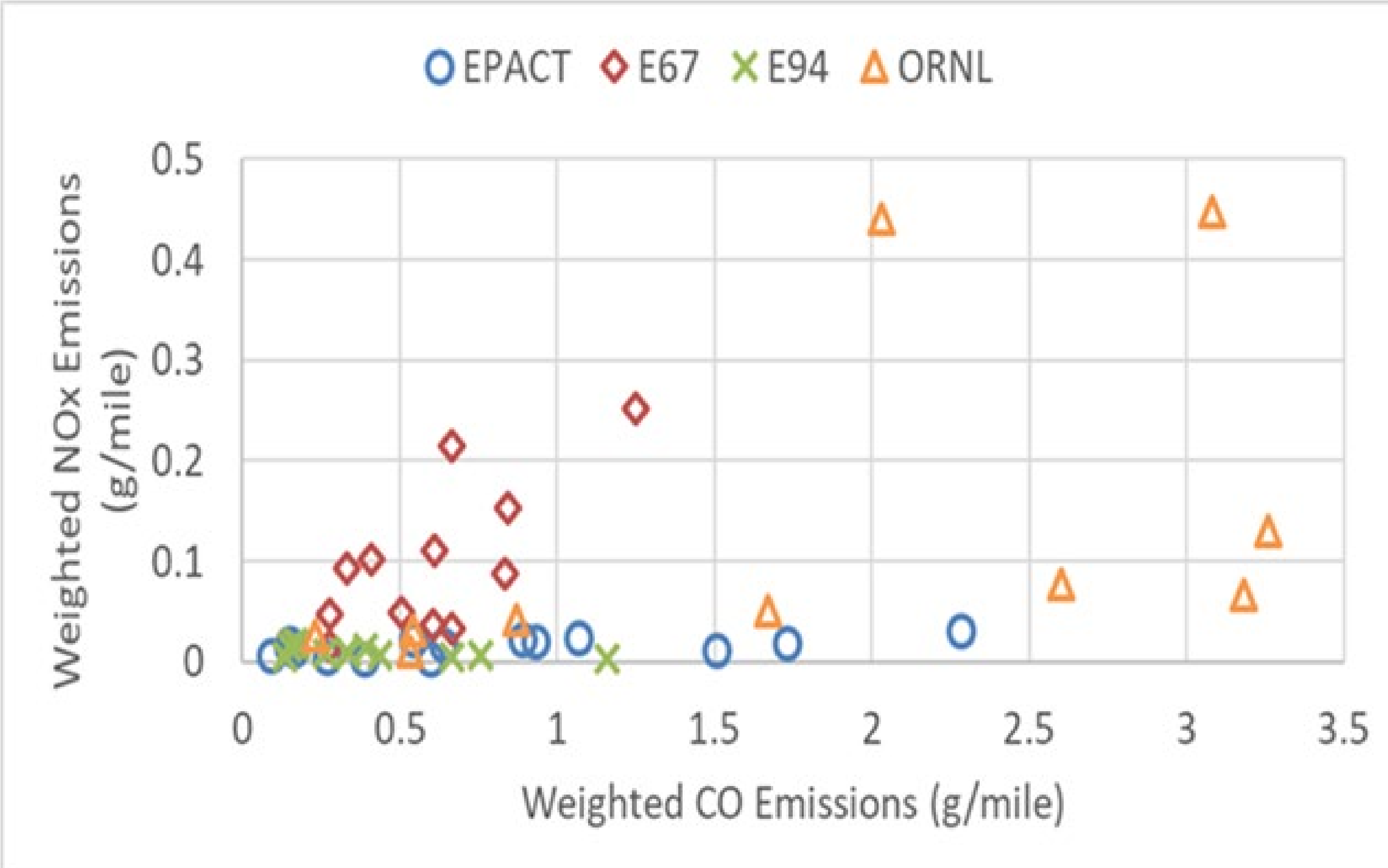
- Supported by EPA, DOE & CRC, conducted by SwRI
- 15 vehicles (all 2008 MY)
  - Port injected engine technology
  - LA92 dynamometer cycle
- 27 fuels, selected from a matrix
  - 4 ethanol levels (0, 10, 15, 20%)
  - Aromatics at 15% and 35%
  - RVP at 7 and 10 psi
  - T50 at 150, 165, 190, 220, 240 ^{o}F (limited for E15 & E20)
  - T90 at 300, 325, 340 ^{o}F
  - AKI not directly controlled

Study Summary: CRC E94-2 and E94-3

- Conducted by SwRI
- E94-2 Twelve 2011-2014 vehicles, all GDI technology
- E94-2 Eight fuels (full matrix), match blending
  - AKI 97 & 93
  - Ethanol 0 and 10%
  - PMI* 1.4 (T90 280-320 °F) and 2.4 (T90 320-350 °F)
  - Others constant: Benzene 0.6%, T50: 170-210 °F
- E94-3 Four vehicles, four fuels, splash blending

**Particulate Matter Index is calculated from weighted sum using double bond equivalency and vapor pressure*

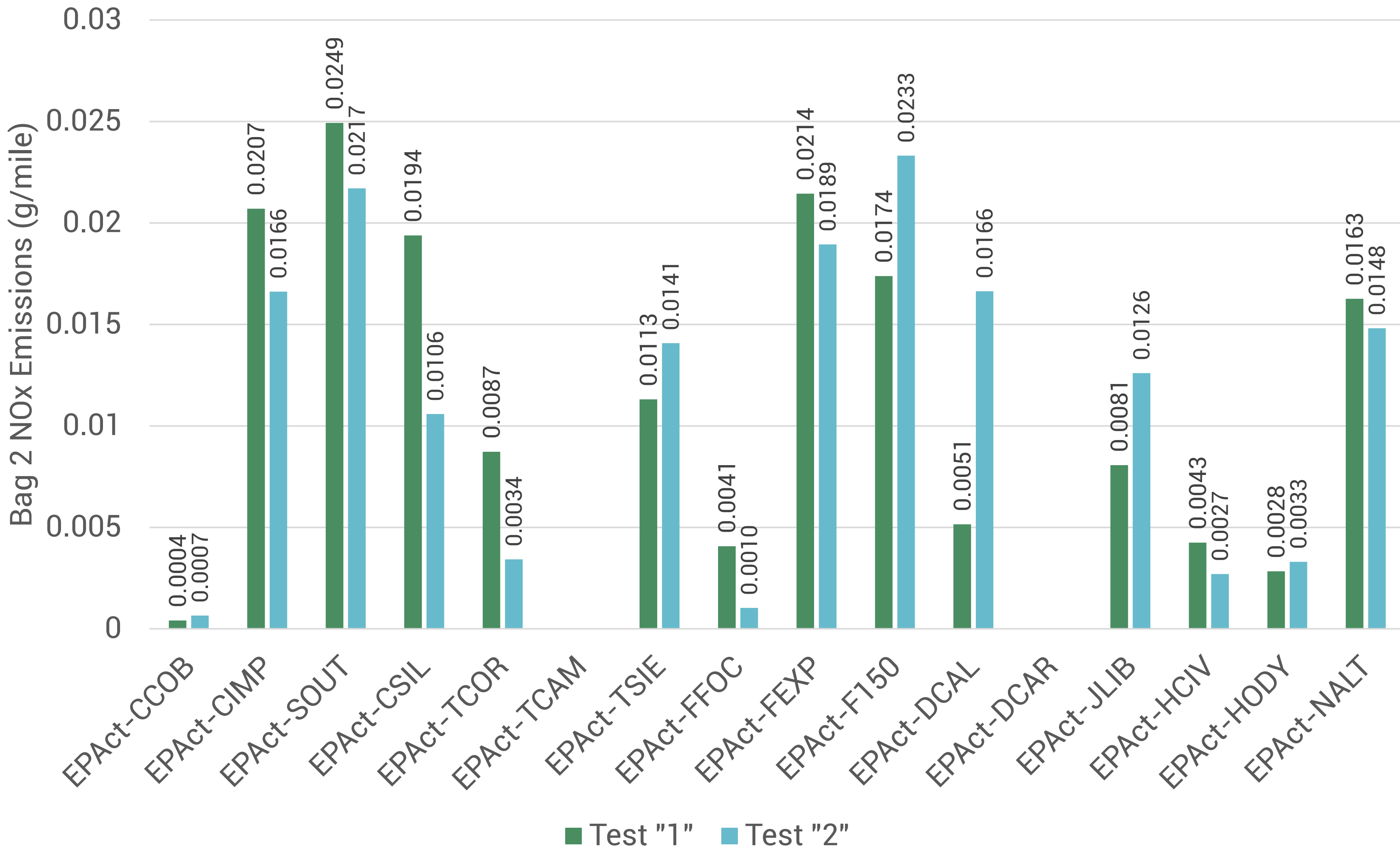
Example of Different Emissions Levels



Data for weighted NOx and Co for each vehicle in four studies:

- E-94-2 (Fuel H, LA 92 cycle) shows both low NOx and CO
- EPAct (Fuel 13, FTP schedule) includes some higher CO emitting vehicles
- West et al./ORNL (Fuel SWRI E0, LA 92 cycle) includes the highest emitters of both NOx and CO
- CRC E-67 (Fuel H, FTP schedule) has mid-level NO emitters

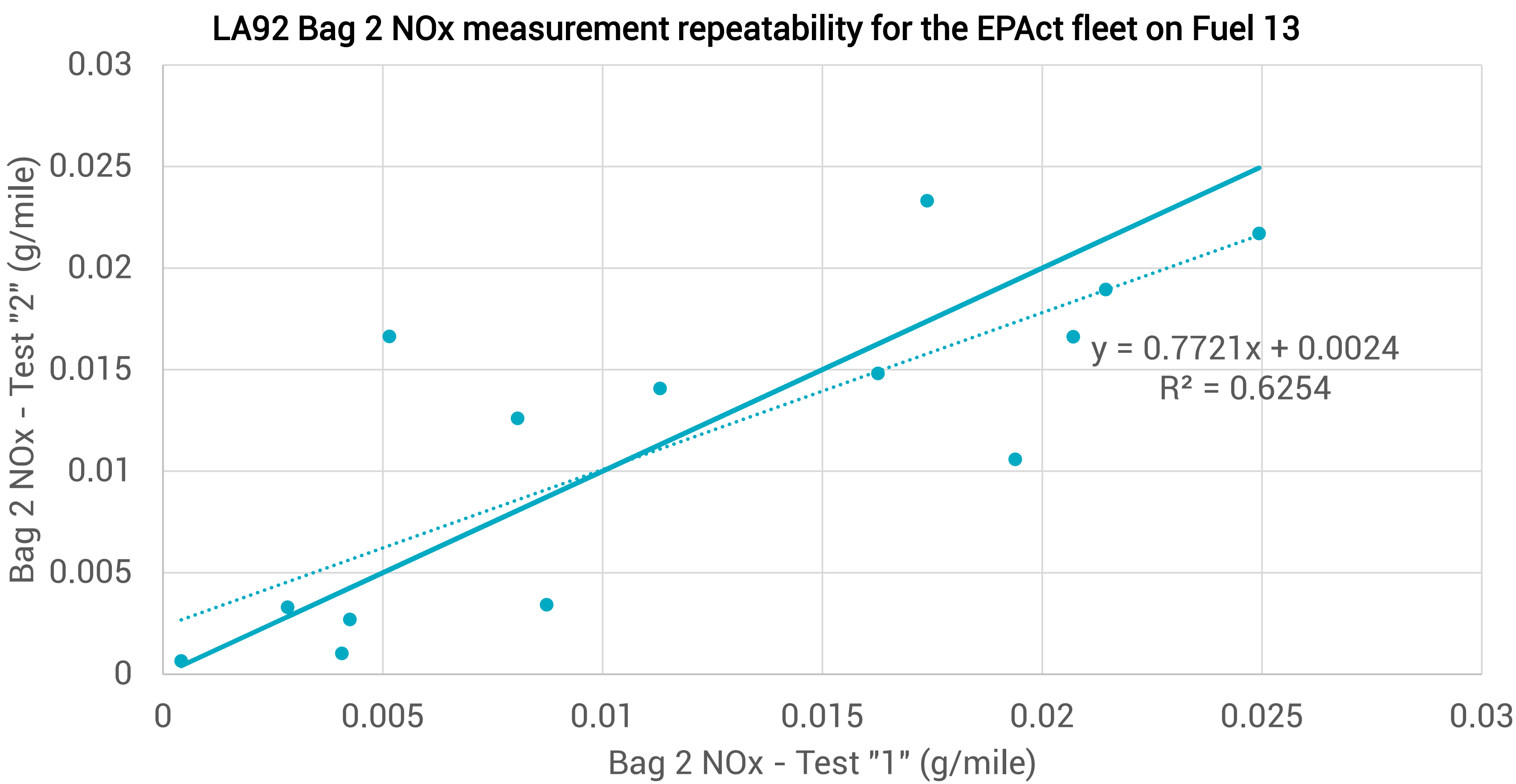
Vehicle Effects & Repeatability



Confounding Influences

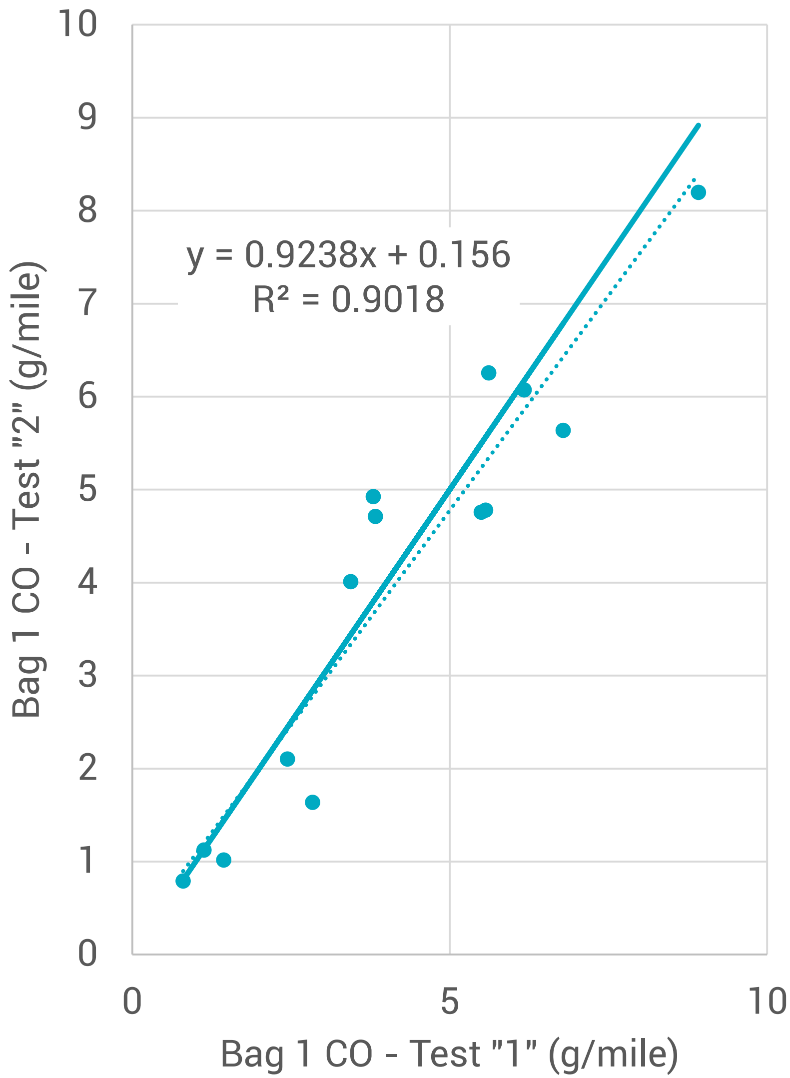
- Cycle effects
  - Vehicle conditioning
    - Timing
    - Long-term trim
  - Injection duration
  - Varying WOT strategies
  - Karavalakis et al. (SAE 2018-01-0349) discuss particle number interactions with driving cycles
  - CRC E-80 examined flex-fuel vehicles
    - NOx: FTP up (with ethanol), US06 same, UC down
- CO: FTP up, US06 down, UC up
    - THC: FTP up, US06 down, UC same
- Weighting of cold start (higher emissions) versus hot operation
- Operation in different ambient conditions
- Real-world use may be considered as a "different cycle."

Emissions Levels Are Low & Variable

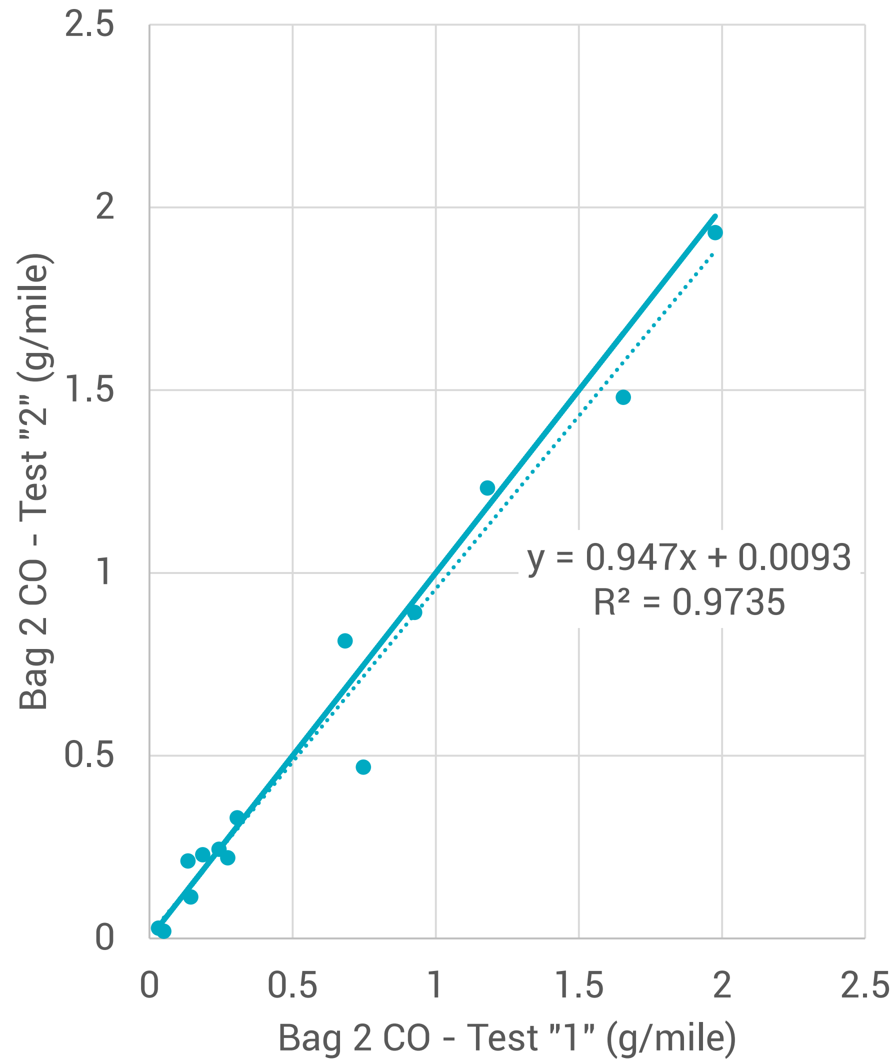


- Repeat test cycles represent high cost
- Emissions levels are low and difficult to measure accurately
- High standard deviations exist for repeat runs and between vehicles
- Gasoline and ethanol blend emissions measurements are usually similar values

Run-to-Run CO

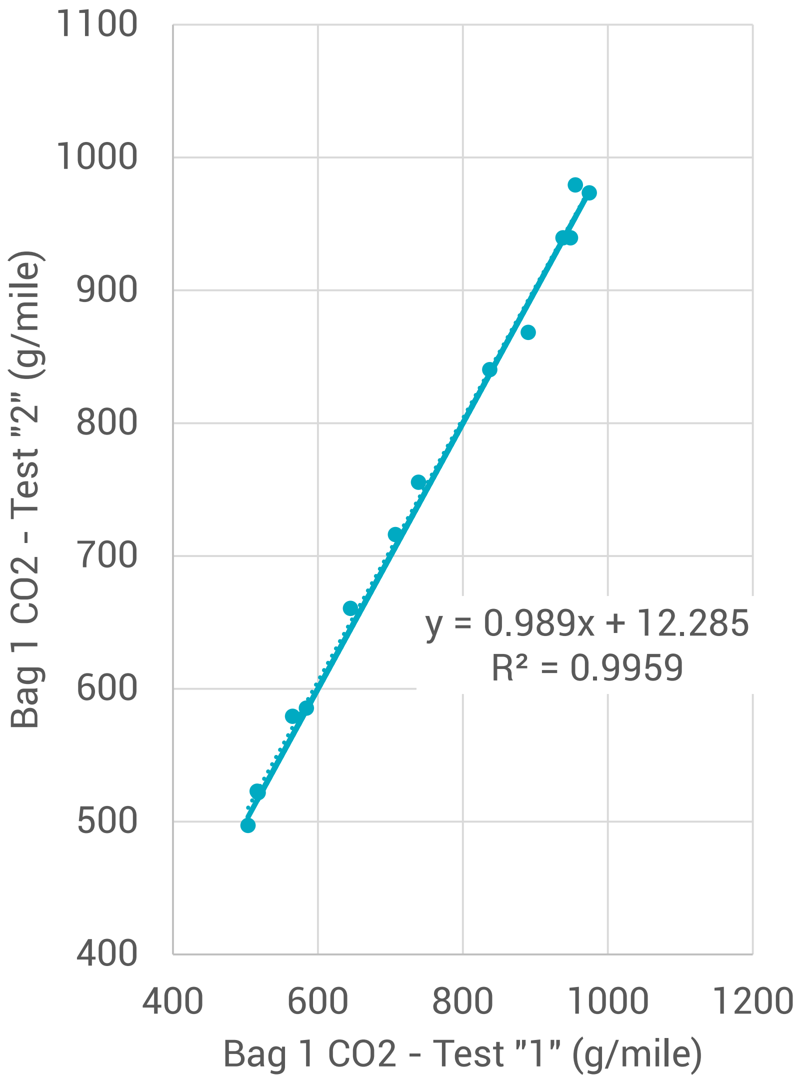


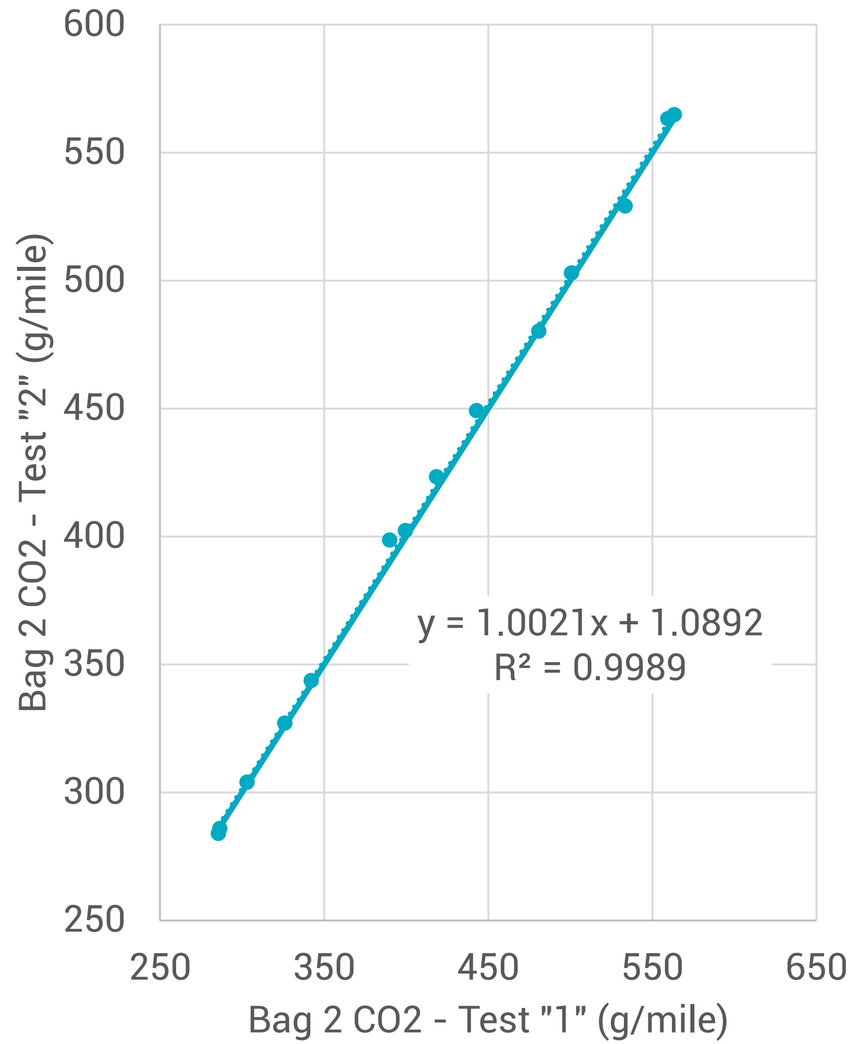
y = 0.9238x + 0.156
R² = 0.9018
Bag 1 CO - Test "2" (g/mile)
Bag 1 CO - Test "1" (g/mile)
0
1
2
3
4
5
6
7
8
9
10
0
5
10



y = 0.947x + 0.0093
R² = 0.9735
Bag 2 CO - Test "2" (g/mile)
Bag 2 CO - Test "1" (g/mile)
0
0.5
1
1.5
2
2.5
0
0.5
1
1.5
2
2.5

Fuel Consumption (as CO_2) is Repeatable between Runs





Engine Control Interaction

- Spark-ignited engines (and their controls) react to changing fuel properties
  - Fuel-air ratio
  - Long term trim
  - Knock properties (spark timing strategy)
  - Energy content (spray duration)
- Conditioning is needed
- Schulz & Clark (Jour ASTM Int. 2011) – conventional versus flex fuel differ
- Butler et al.– varying PMI responses
- Controls may not anticipate study fuel composition or properties
- Stein et al. (SAE 2013-01-1635) discuss complex interaction of fuel properties and in-cylinder pressure

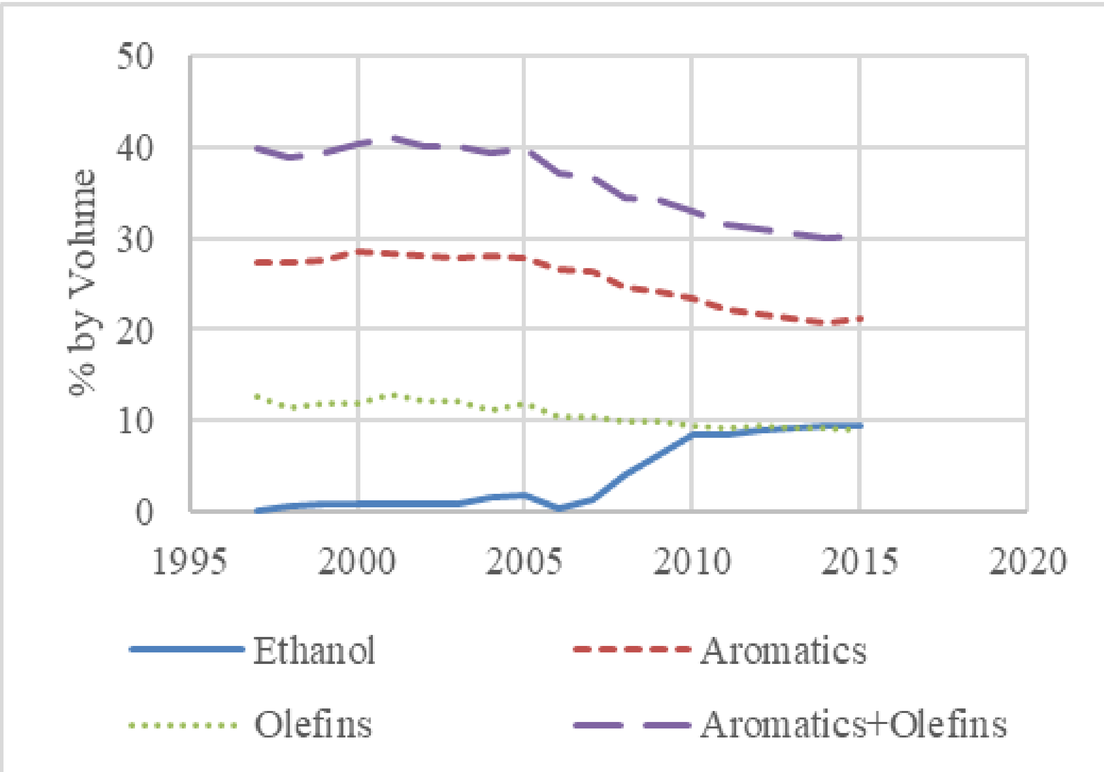
Studies Use a Variety of Plans

- Vehicles are usually treated as “black boxes”
- Most major studies seek to measure differences due to other variables (such as aromatic content) as well as ethanol content analysis
- Fuel is not fully defined by a limited number of parameters
  - Two fuels with same values for T90, T50, RVP, aromatic content may differ in RON, MON.
- Aromatics, olefins and saturates each vary widely in properties – a percent content is not fully informative
  - PMI combines aromatic content and aromatic weight
- Nonlinear properties of mixing (aromatics in paraffins, ethanol)
- Model predictions for ethanol depend on parameters used
  - Darlington et al. (SAE 2016-01-0996) on use of T70
  - Butler et al. (SAE 2015-01-1072) using PMI instead of aromatics

Blending Strategies Vary

- Splash blends are uniquely defined, but properties (e.g. AKI) vary with ethanol content
- Match blends differ because the target parameters differ from study to study
- Attitudes to blending behavior differs
  - E10 T50 could be forced to the E0 T50 value (multivariate)
  - E10 T50 could be allowed to assume a natural lower value (real world)
  - Anderson et al. (SAE 2014-01-9080) discussed T50 matching
  - T50 matching can affect T60-70-80
  - Variables are not always orthogonal
- Uncontrolled fuel properties vary due to targeting selected parameters in the blending process

Historical Changes in Fuel Composition



Data from the Fuel Trends Report, EPA-420-R-17-005

- Ethanol (mainly E10) replaced MTBE as oxygenate
- BOB reflects best economic use of streams from a specific refinery
- Ethanol blending raises AKI, allowing aromatics to be reduced
- Distillation temperatures (T30 to T50) of pump fuel are lowered by the ethanol – but not out of range
- Comparison of real world E0 and Exx must take into account fuel composition changes implied by the blend ratio

Real World Fuel Properties
(Used For Modeling Below)

	Premium Summer			Regular Summer			Premium Winter			Regular Winter		
	E10	E15	E0	E10	E15	E0	E10	E15	E0	E10	E15	E0
	Pump	Pump	Pump	Pump	Pump	Pump	Pump	Pump	Pump	Pump	Pump	Pump
PROPERTY												
API	59.35514	57.9	58.2	58.73931	57.4	57.1	62.78807	60.7	61.8	62.70807	60.6	61.7
Vap Press psi (EPA)	8.1	8.1	8.1	8.2	8.2	8.2	13.1	13.1	13.1	13.1	13.1	13.1
Distillation, Deg. F												
10 % evap.	133	133	139.59	129	129	135.63	114	114	121.39	111	111	118.405
20 % evap.	144	144	167.4894	138	138	161.3617	130	130	153.9894	124	124	147.8298
30 % evap.	152	152	197.625	146	148	191.2841	145	148	191.25	137	140	182.75
40 % evap.	166	164	217.7045	156	156	207.1364	159	159	211.4375	149	154	200.8125
50 % evap.	212	179	239.5652	192	162	218.913	182	160	209.6848	162	162	188.9239
60 % evap.	230	213	240.4792	224	208	234.4167	223	207	234.6094	204	198	215.3125
70 % evap.	246	244	248.49	249	247	251.46	241	239	244.77	237	235	240.79
80 % evap.	268	268	271.635	279	279	282.58	264	264	269	268	268	273
90 % evap.	310	310	315	320	320	325	306	306	311	312	312	317
E200	47.8	35.7	47.8	52.5	58.3	52.5	54.4	58.3	54.4	59	60.5	59
E300	87.6	87.6	87.6	85.1	85.1	85.1	88.6	88.6	88.6	87.3	87.3	87.3
Aromatics, V %	20.5	17	29.2	21.8	17.425	32	22	18.36	30.8	22.5	18.105	32.7
Olefins, V %	5.7	5.355	5.7	8.1	7.65	9	4.6	4.335	4.6	6.5	6.12	6.5
Saturates, V %	63.8	62.6	65.1	60.1	59.9	59	63.4	62.305	64.6	61	60.775	60.8
Ethanol	10	15	0	10	15	0	10	15	0	10	15	0
RON	97.5	98.035	97.4	92.2	92.425	92.1	97.7	97.865	97.6	92.5	92.935	92.5
MON	87.2	86.7	87.3	83.3	83.085	83.4	87.4	87.25	87.5	83.6	83.17	83.6
AKI	92.35	92.3675	92.35	87.75	87.755	87.75	92.55	92.5575	92.55	88.05	88.0525	88.05

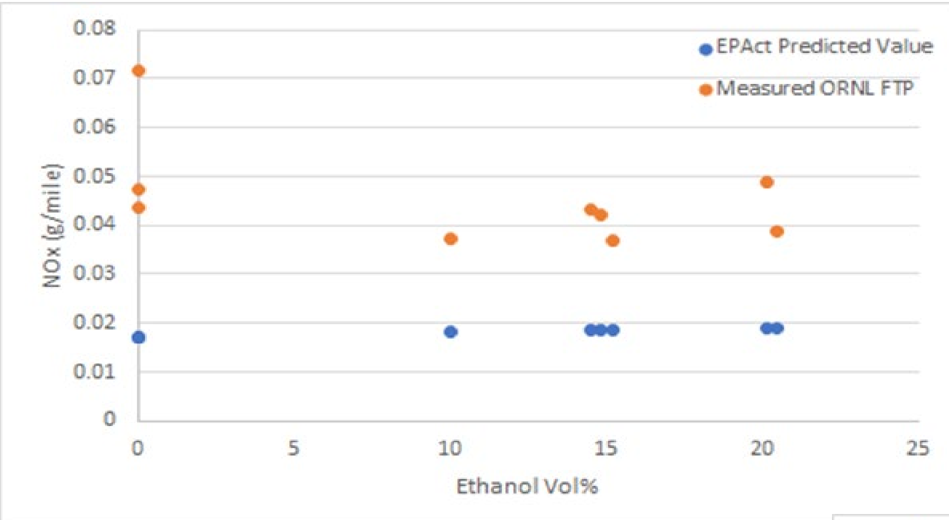
E67 Data Compared with EPAct model

In E-67 Aromatics were held constant - fuels do not reflect real world ethanol vs. aromatics tradeoff

	E67 D	D67 E	E67 K	E67 L
Ethanol (% vol.)	0	10.26	0	10.49
Aromatics (% vol.)	25.1	26.7	26	26.4
T50 (F)	199.5	197.7	236.0	232.7
T90 (F)	355.0	351.7	355.5	349.1
EPAct Bag 1 NOx (pred) g/mile	0.0765	0.0852	0.0826	0.0902
Bag 1 NOx (meas) g/mile	0.278	0.300	0.284	0.293
EPAct Bag 2 NOx (pred) g/mile	0.0132	0.0144	0.0133	0.0145
Bag 2 NOx (meas) g/mile	0.0363	0.0358	0.0284	0.0284

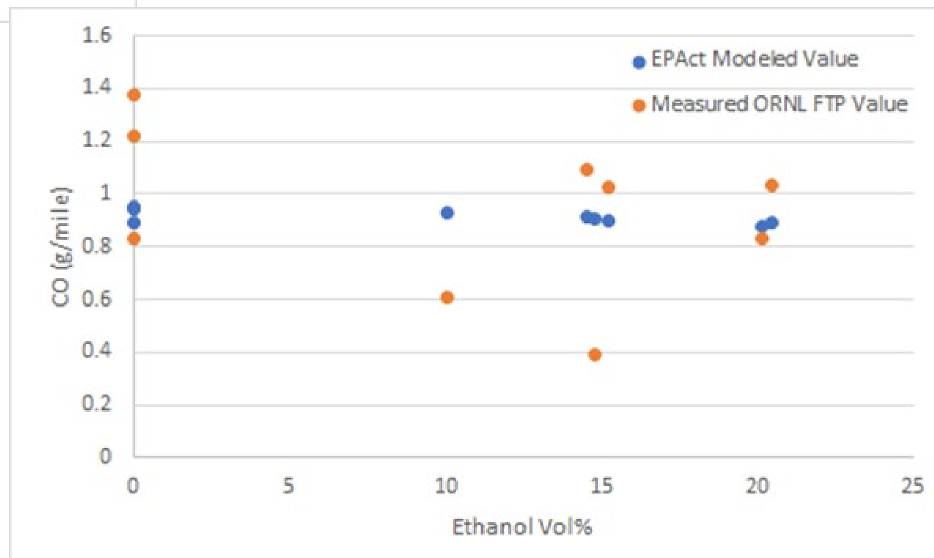
- CRC E-67 emissions of PM and NOx are far higher than EPAct predictions due to vehicle model year differences
- Ratios of PM and NOx between E0 and E10 differ between E67 data and EPAct model predictions
- Model predicts E10 has 11.4% higher Bag 1 NOx and 9.1% increase for Bag 2: the E-67 measured differences were 7.9% and -1.4%.

ORNL Tier 2 Data & EPact Model Prediction

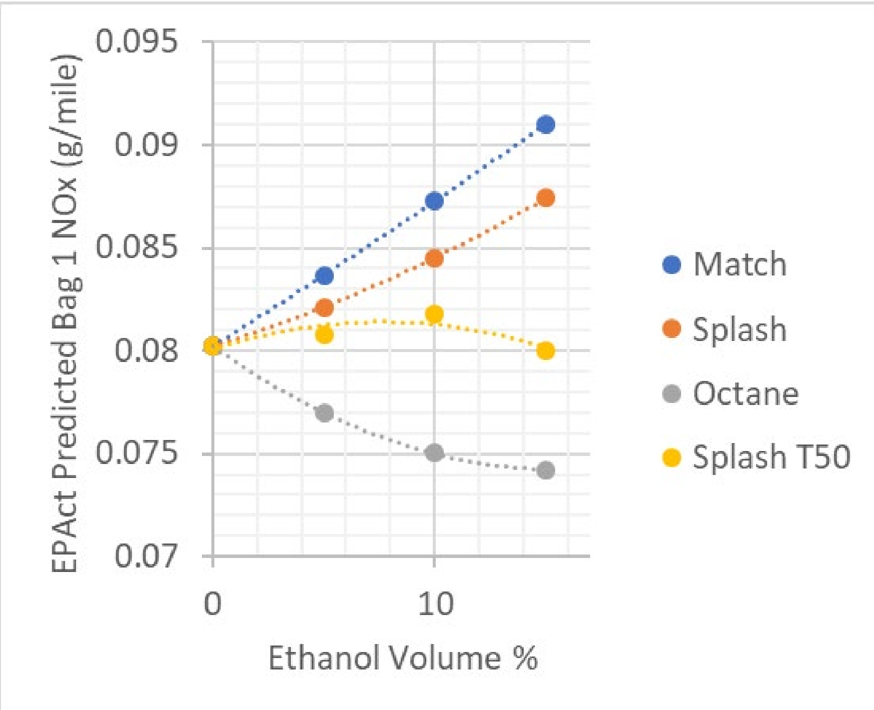


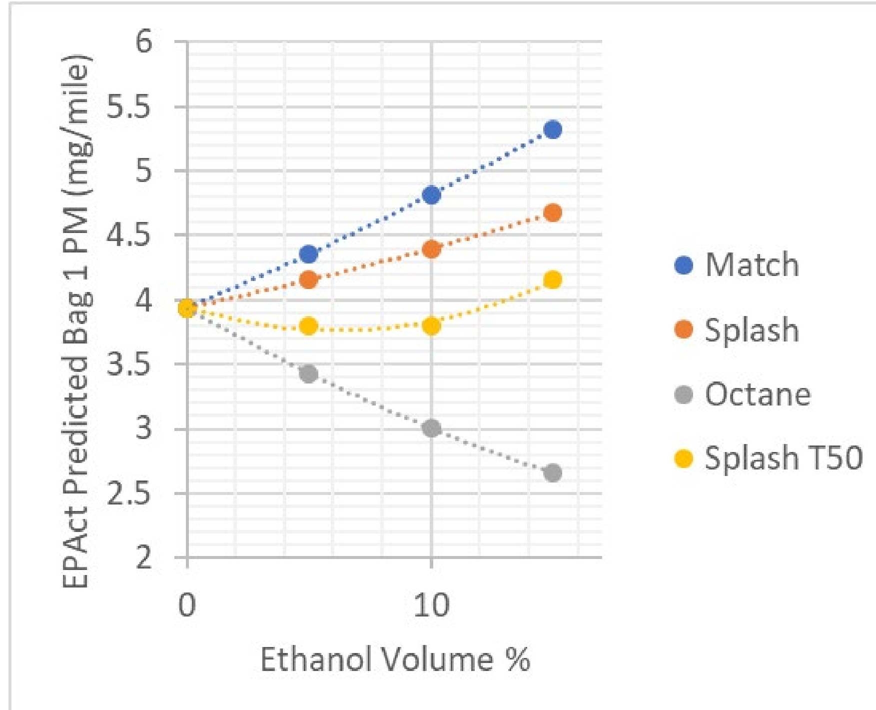
- Cycles differed between the two studies
- Good faith effort made to model the ORNL emissions

- Predicting bag 1 and bag 2, by taking the average bag 3 from EPAct, and applying the weighting function to obtain a composite value.



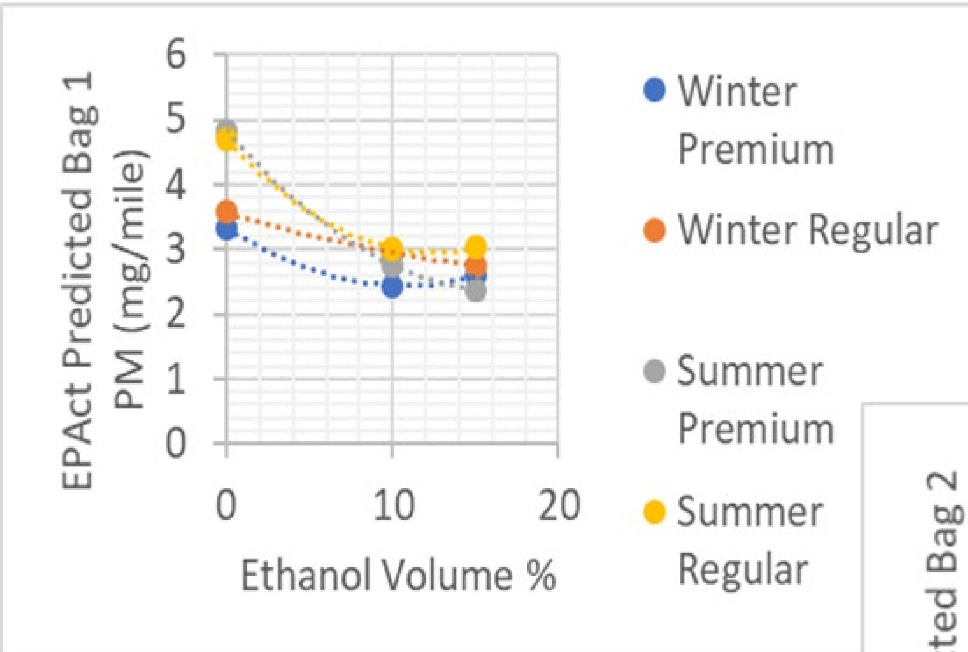
Ethanol Blend Emissions Predictions



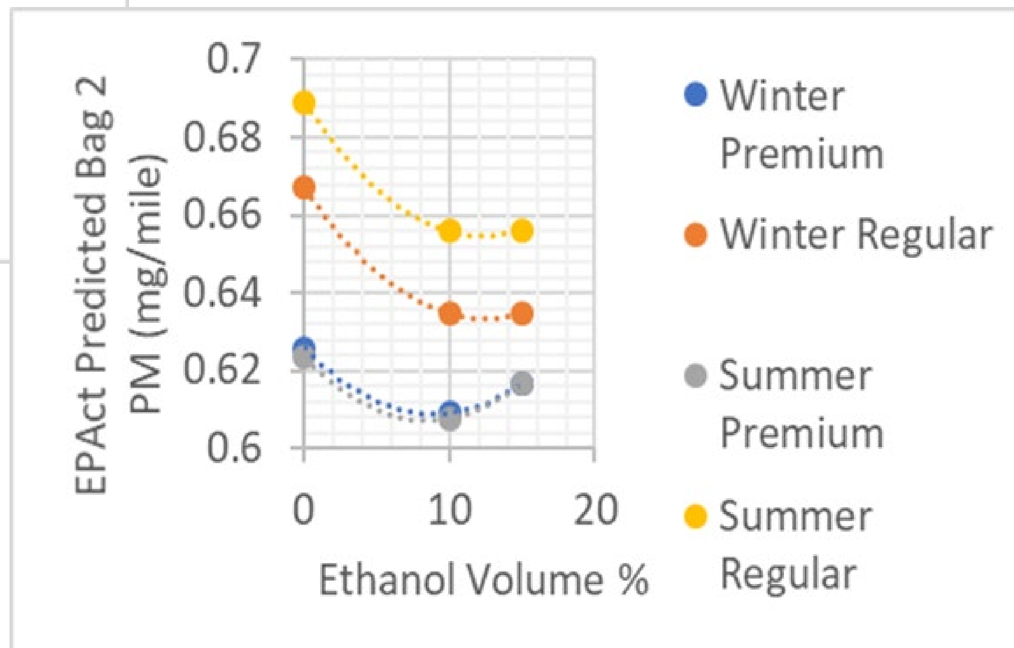


- Predictions of Bag 1 NOx emissions from a MOVES baseline E0 using the EPAct model
- Match = aromatics & T50 held constant
- Splash = dilution of aromatics only
- Octane = same AKI / reduction of aromatics and T50 (real world)
- Splash T50 = dilution of aromatics and T50 lowered

Example From Report: EPact Model with Anticipated Real World Compositions



- E0 to E10 step differs from E10 to E15 step
- Difficult to capture nonlinearities of blending faithfully



Conclusions on Differences

- Results for effects of ethanol blending on gaseous and particulate emissions have varied widely between studies – models follow
- Vehicle-to-vehicle variation is high, emissions are low, and ethanol effects are relatively small
- Run to run variation lowers statistical certainty
- Vehicles interact with specific fuels and test cycles in different ways
- In match blending, the strategies in studies have varied widely
- It is not possible to add ethanol to a BOB and hold all other properties constant, nor is this representative of real world blending practice
- Limited property sets and broad descriptors do not define a fuel
  - e.g. alkyl chain length on a benzene ring

Conclusions – Real World Comments

- Raising T50 alone in an ethanol blend by adding higher boiling point components does not reflect a real world fuel & alters the differences between T50 and neighboring distillation points
- Real world predictions must account for composition and properties that vary in sympathy with ethanol addition
  - As ethanol % rises, aromatics are reduced for constant AKI (refinery)
  - As ethanol % rises, real world T50 is reduced (property of mixing)
- Vehicle technologies affect real world emissions and emissions differences, and the fleet includes a broad mix of technologies
  - Weighting by emissions or vehicle count for global effect
- Test cycles should explore real world operation
- E15 or E20 emissions should not be predicted from E0 to E10 trends

A Final Word

- Full reference list appears in the report
- Study is available on the UAI website at fixourfuel.com
- Also available on the FFS website under “Blog” along with a brief summary
- Podcast with Nigel is also posted on the podcast page

Questions?

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