PM Fuel Effects Results from EPAct/V2/E-89 Study and Related Work Since

Presented by Aron Butler
US EPA Office of Transportation & Air Quality
December 8, 2016

Brief Outline

Three analyses of two test programs:

- Original design analysis of EPAct test program
- PM Index analysis of EPAct test program
- PM Pilot Study and results

Background on EPAct Study

Energy Policy Act of 2005 gave statutory direction for EPA to produce updated models of fuel property effects on emissions

- These models drive inventory and air quality assessments
- No data on fuel effects from Tier 2 vehicles with which to assess validity of existing models

Useful model requires a statistically-designed fuel matrix covering relevant properties across the range of in-use fuels

- Need ability to compare present and past years, multiple localities, and varying regulatory scenarios
- Splash blending studies are unable to discern the effects of ethanol’s presence from changes in other fuel properties, and therefore do not meet EPA’s modeling needs (or the statutory directive)
- Performed literature review to select most relevant parameters and interactions

Overview of EPAct Study Design

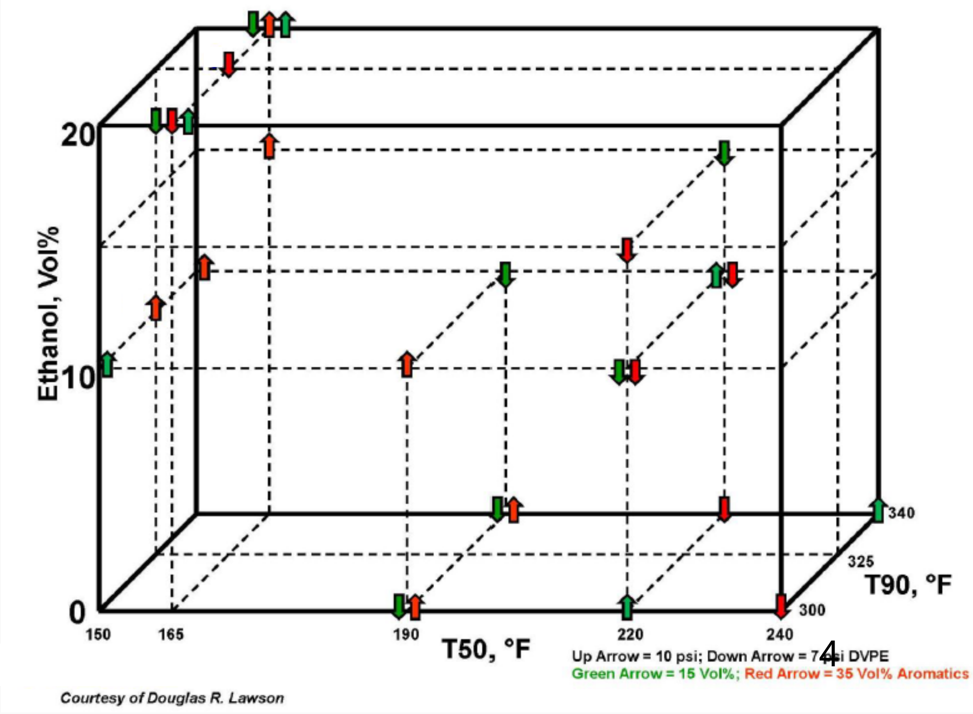
Design and data collection spanned ~4 years 2006-10

- 27 test fuels carefully blended from refinery streams to represent the range of in-use fuels
- 15 high-sales MY 2008 LD vehicles, Tier 2 compliant (all PFI)
- LA92 cycle at 75F, 2+ test replicates per vehicle/fuel combination (956 tests)
- Detailed procedures for vehicle and fuel handling
- Measured several gaseous emissions plus particulate matter (PM)

Brand	Model	Engine Size
Chevrolet	Cobalt	2.2L I4
Chevrolet	Impala FFV	3.5L V6
Saturn	Outlook	3.6L V6
Chevrolet	Silverado FFV	5.3L V8
Toyota	Corolla	1.8L I4
Toyota	Camry	2.4L I4
Toyota	Sienna	3.5L V6
Ford	Focus	2.0L I4
Ford	Explorer	4.0L V6
Ford	F150 FFV	5.4L V8
Dodge	Caliber	2.4L I4
Jeep	Liberty	3.7L V6
Honda	Civic	1.8L I4
Honda	Odyssey	3.5L V6
Nissan	Altima	2.5L I4

ETOH, ARO, T50, T90, RVP

$T50^2$, $ETOH^2$, ETOH*ARO, ETOH*T50, ETOH*T90, ETOH*RVP



Model Fitting Procedures

Key steps:

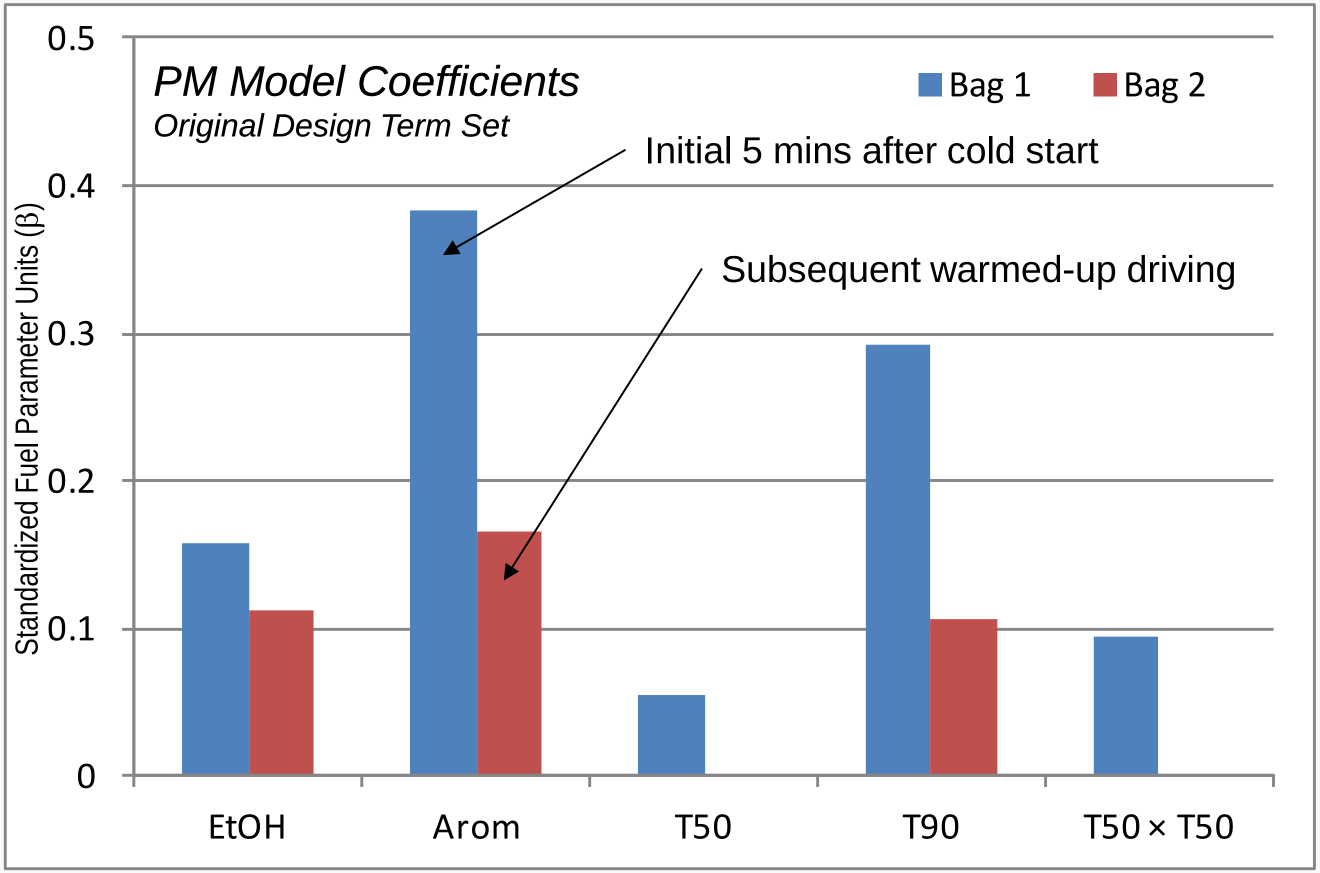
- Fuel property values were standardized into z-scores
- Emission data were transformed using natural logarithm
- Models were fit using maximum likelihood estimation
  - Allows inclusion of all tests including those producing "censored" measurements (i.e., below detection limits)
  - Bag 1 PM data contains 45 zeros, bag 2 has 47 zeros (out of 955 obs.)
  - Omission of tests containing zeros from the analysis could bias the model results
- Reduced via backwards elimination based on goodness of fit using likelihood ratio tests

Detailed analysis report and peer review comments available on EPA website (search for "epact study")

Original Findings on PM

First comprehensive look at gasoline PM fuel effects

- Positive correlation with aromatics, T90, T50, and ethanol



Example Model Application

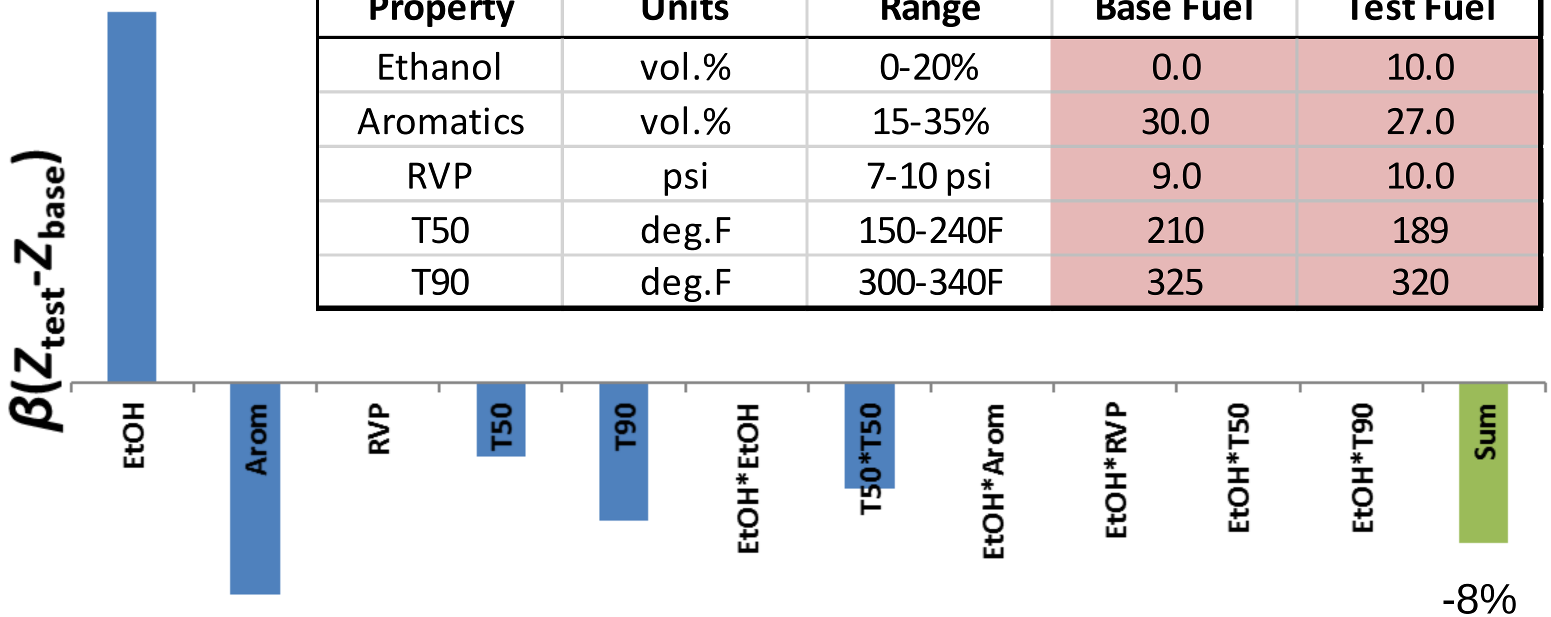
Positive coefficient doesn't necessarily mean PM goes up for ethanol blends; depends on other fuel properties

- Example shows reduced cold-start PM for E10 splash blend

Contribution of Model Terms to Emission Effect as Δln(Emission)

(*Green bar is sum of blue bars and indicates net effect*)

Fuel Properties				
Property	**Units**	**Range**	**Base Fuel**	**Test Fuel**
Ethanol	vol.%	0-20%	0.0	10.0
Aromatics	vol.%	15-35%	30.0	27.0
RVP	psi	7-10 psi	9.0	10.0
T50	deg.F	150-240F	210	189
T90	deg.F	300-340F	325	320



From model calculator at https://www.epa.gov/moves/epactv2e-89-tier-2-gasoline-fuel-effects-study

PM Index Fuel Parameter

Contemporary to EPAct data collection and analysis, researchers at Honda published the PM index (or PMI)

- Correlates PM emissions to molecular structure and volatility using fuel speciation data

$$PM\ Index = \sum_{i=1}^{n} \frac{DBE_i + 1}{VP_i} \times Wt\%_i$$

i = fuel component from speciation analysis
DBE_i = double bond equivalent of component i
VP_i = vapor pressure in kPa of component i at 443K
$Wt\%_i$ = weight percent of component i in fuel

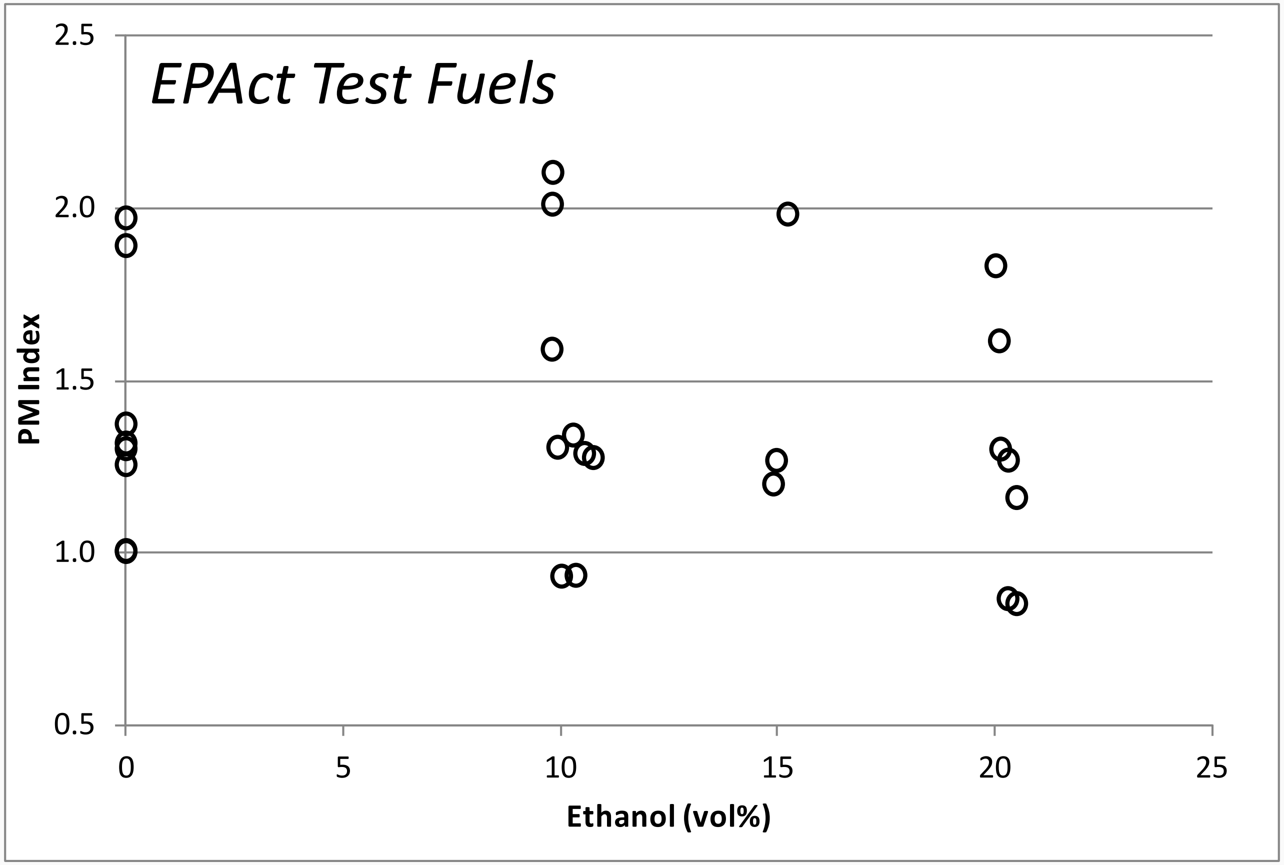
HC Species	DBE
Paraffins	0
Monocycloparaffins	1
Monoaromatics	4
Naphthalenes	7
Ethanol	0

- Suggested total aromatics as modeled in EPAct study may have been too broad a parameter for trying to understand and predict PM emissions

PM Index of EPAct Fuels

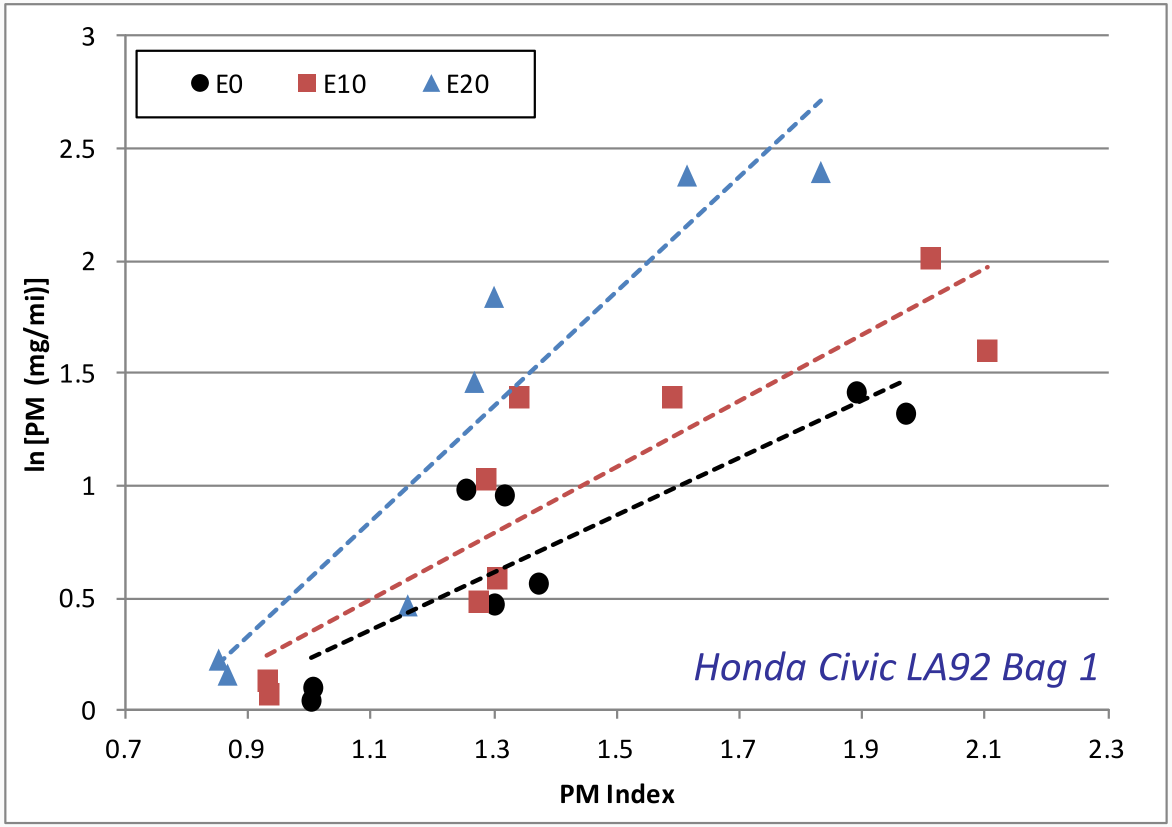
Low correlation between PMI and ethanol allowed further analysis

- Aromatic content of EPAct test fuels was specified by carbon number to reflect proportions typical in market fuels



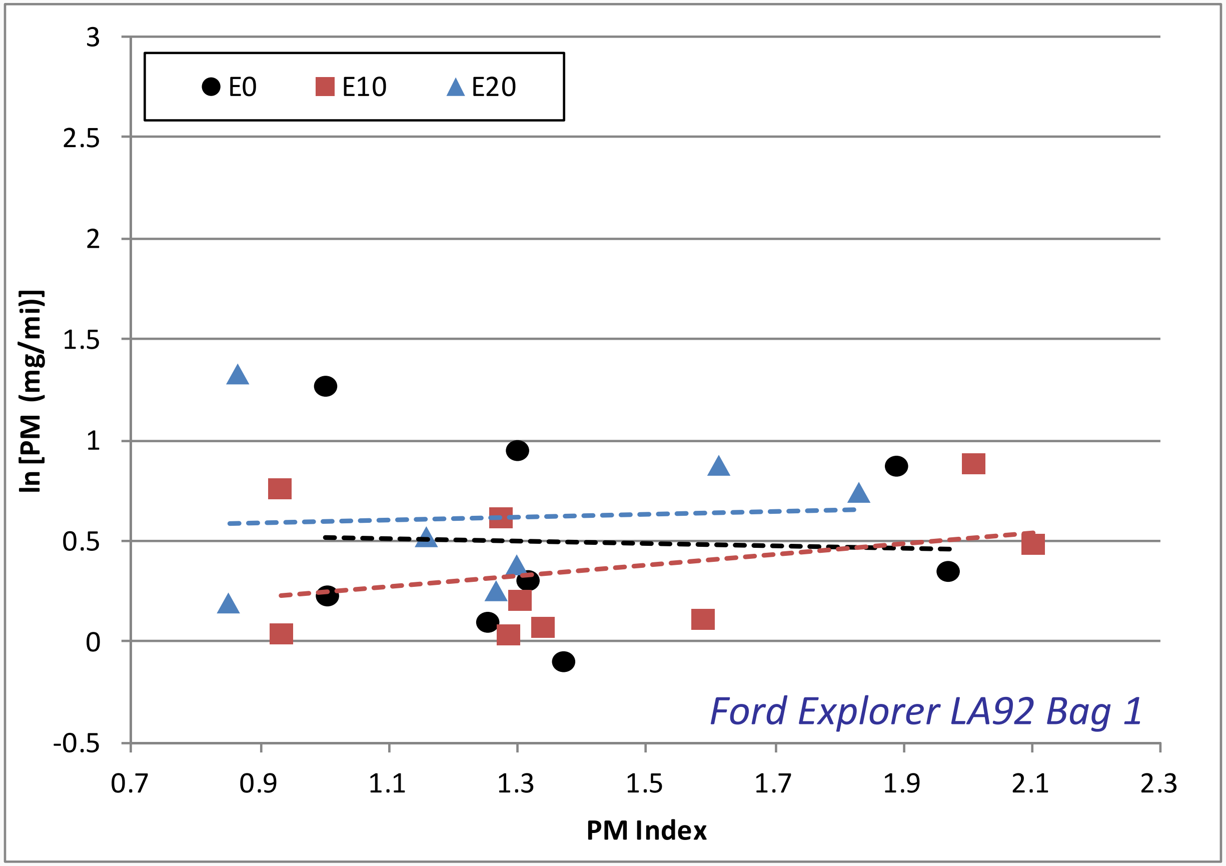
PM Index and Ethanol – More Sensitive Vehicles

10 of 15 vehicles showed a strong correlation between PM emissions and PM Index, and ethanol having a reinforcing effect



PM Index and Ethanol – Less Sensitive Vehicles

5 of 15 vehicles showed no clear effect of PM Index or ethanol on emissions



Model Term Sets

Before fitting models, needed to consider whether PMI is correlated with other terms

- Pearson coefficients:
  - Total aromatics (0.71)
  - T90 (0.64)
  - T50 (-0.07)

Used the same procedures as outlined earlier

Original Design	PMI Term Set
EtOH	EtOH
~~Arom~~	RVP
RVP	T50
T50	PMI
~~T90~~	T50 × T50
T50 × T50	EtOH × EtOH
EtOH × EtOH	EtOH × T50
~~EtOH × Arom~~	EtOH × RVP
EtOH × T50	PMI × EtOH
~~EtOH × T90~~	PMI × RVP
EtOH × RVP	PMI × PMI
	PMI × T50

Models with PM Index

Table shows reduced model coefficients (statistically significant)

	Original Design		PMI Term Set	
Model Term	**Bag 1**	**Bag 2**	**Bag 1**	**Bag 2**
Arom	0.3833	0.1662		
T90	0.2923	0.1072		
PMI			0.4815	0.2133
EtOH	0.1582	0.1126	0.2287	0.1300
T50	0.0550		0.1063	
T50 × T50	0.0935			
PMI × EtOH			0.0836	

PMI terms larger than Aro or T90

Ethanol terms persist

Ethanol interaction term

Published these results in an SAE paper (2015-01-1072)

PM Pilot Study

Conducted a pilot study to examine PM fuel effects in more detail

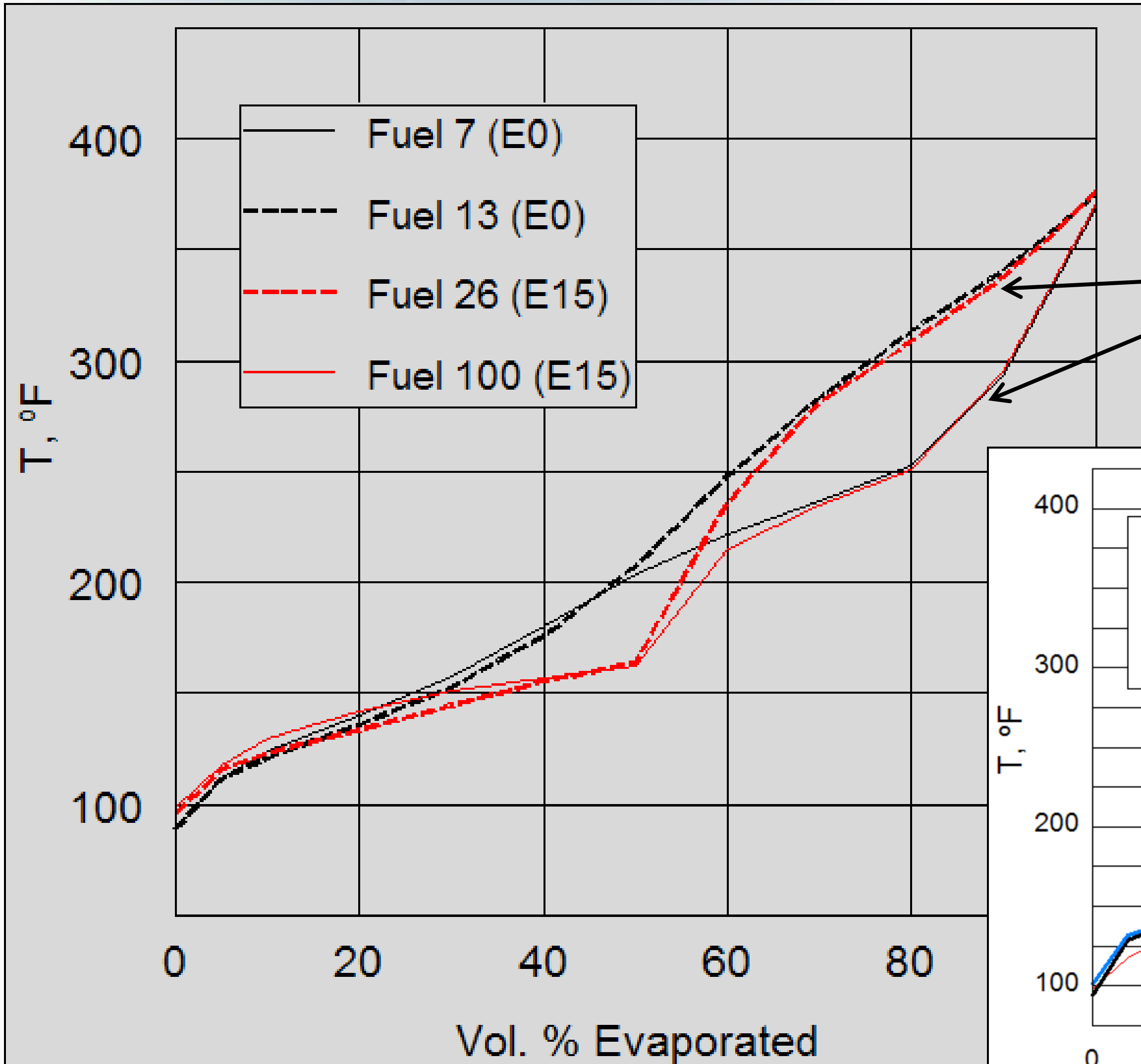
Design goals:

- Confirm published results on PM Index and aromatic carbon number with vehicles from EPAct fleet
  - 3 PFIs with range of sensitivity to fuel properties + 1 GDI
- Create new fuel blends specifically designed to examine ethanol-PM Index interaction
  - Use well-characterized refinery streams to produce test fuels representative of what is in the market

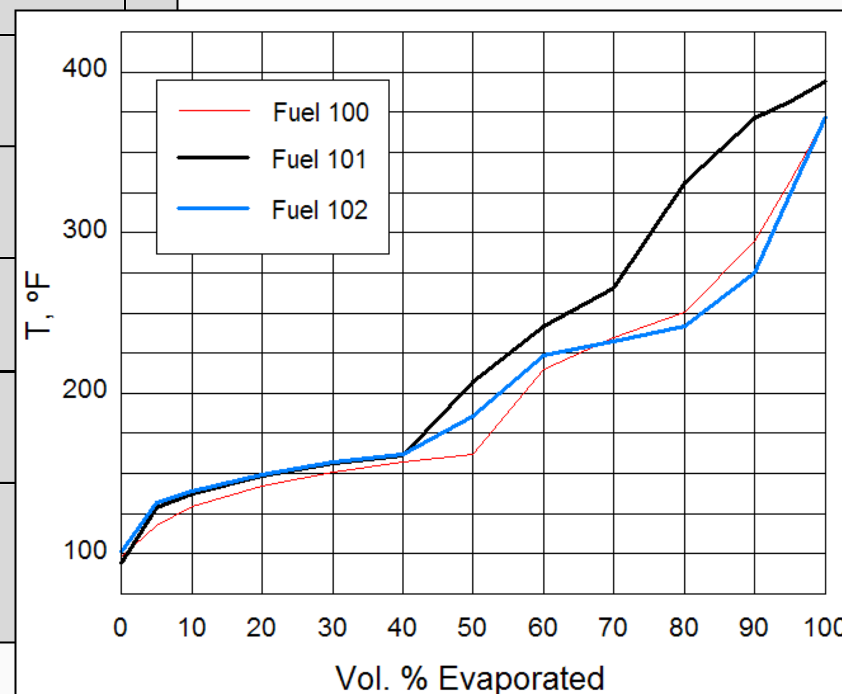
PM Pilot Fuels

Parameter		
DVPE	Fuels 101 and 102 assess the effect of the adding light and heavy aromatic components to a low-PMI fuel	Fuel pairs 7-100 and 13-26 designed to examine interaction between PMI and ethanol
T50		
T60		
T70		
T80		
T90		
T95		
Ethanol	Certification fuel fills in the gap in the PMI range of the fuel set and provides a recognizable reference	
Toluene		
C8 Aromatics		
C9 Aromatics		
C10+ Aromatics		
Total Aromatics		
PM Index		

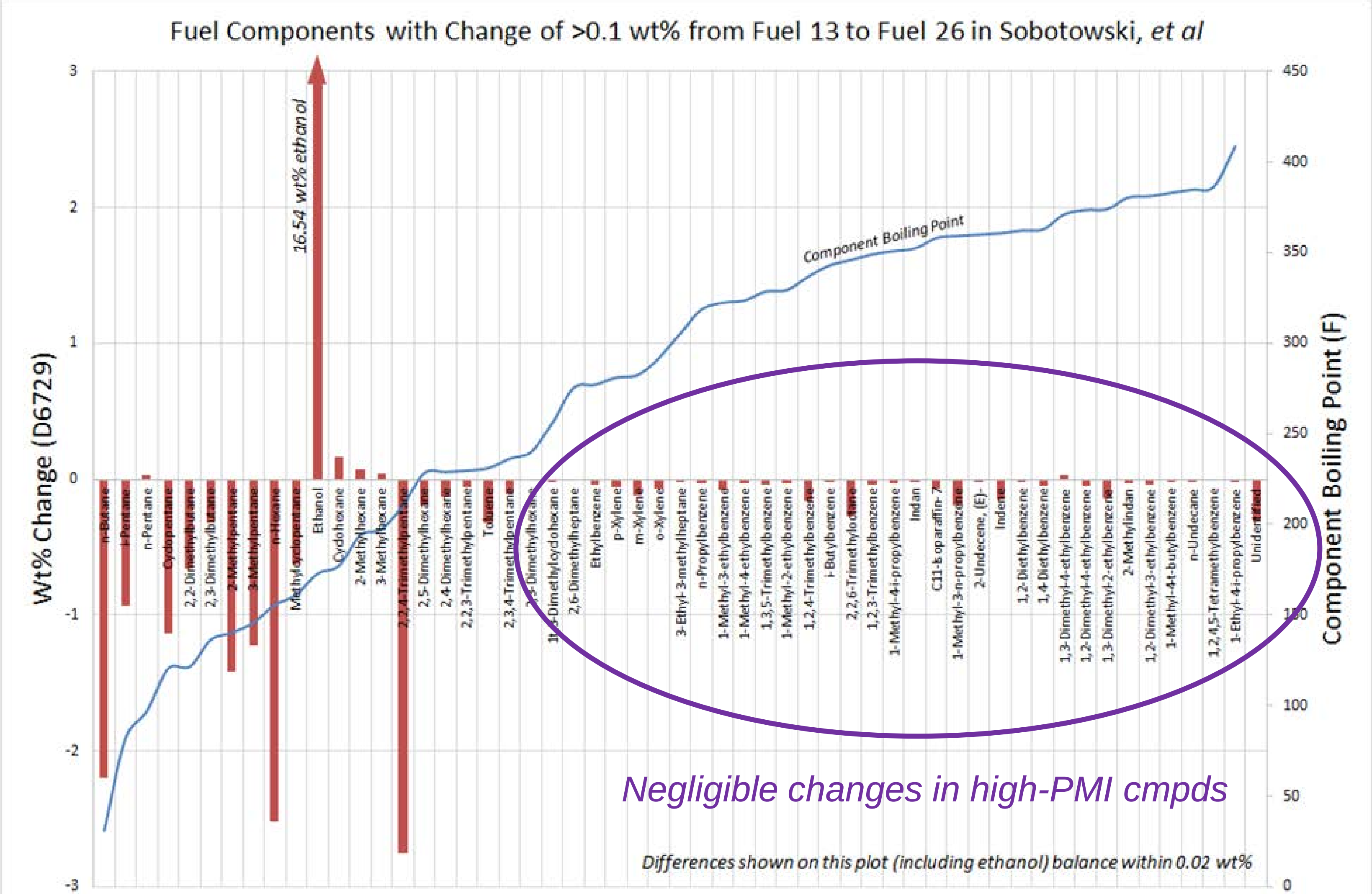
PM Pilot Fuel Distillation Curves



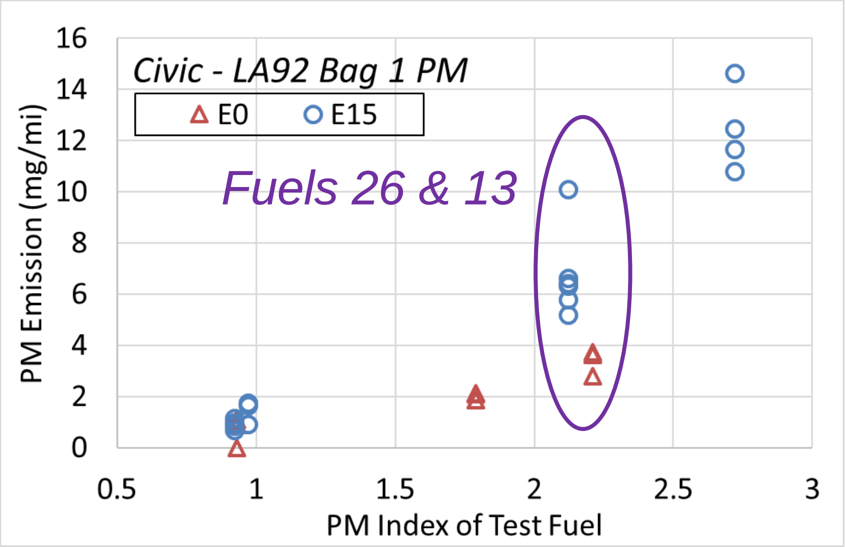
Very tightly matched distillation curves above T60 between E0 & E15 test fuels



Detailed Fuel Comparison Between Ethanol Levels

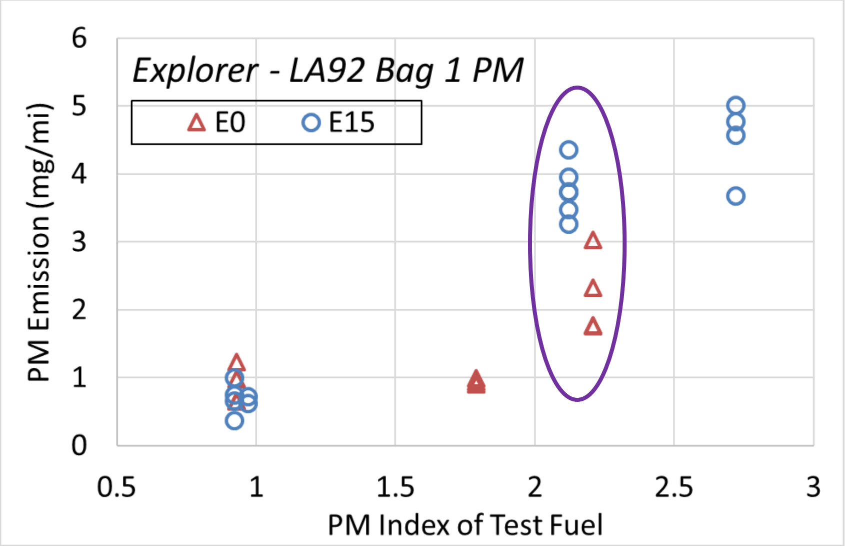


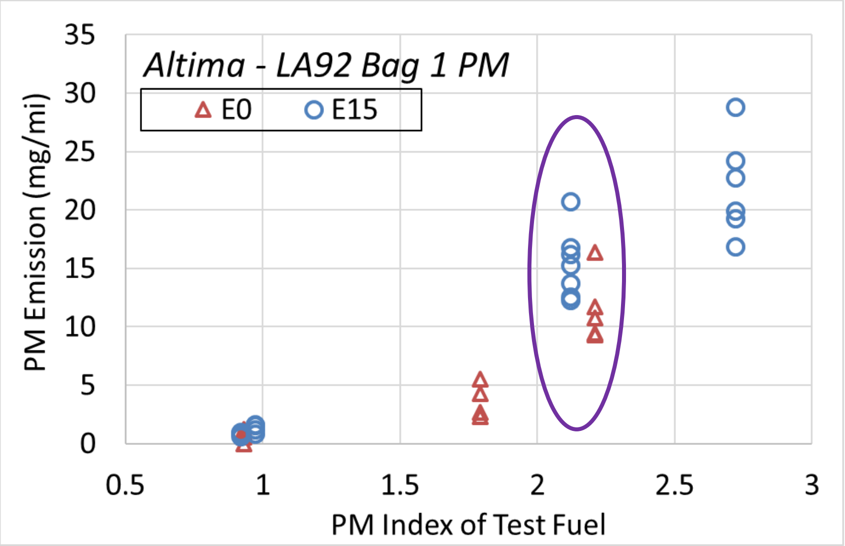
PM Pilot Study Results



Confirms the conclusions of PMI analysis of EPAct/V2/E-89 data:

- PM index is strongly correlated with PM emissions
- Ethanol has a reinforcing interaction with PM Index





Cooling as Potential Mechanism

Interaction of ethanol with PMI suggests it exacerbates the propensity of low-volatility fuel components to form PM

Support in recent literature:

- Association of ethanol's higher heat of vaporization with a cooling effect, with potential to hinder fuel vaporization and lead to increased PM emissions (Stone, *et al.* 2012; Vuk, *et al.* 2013)
- Experimental and computational studies of droplet behavior showing slower evaporation when ethanol is added to a hydrocarbon base (Kobashi, *et al.* 2014)

PM Pilot study published as SAE 2015-01-9071

Take-Aways for PM Study Design

Range of PM sensitivity to fuel properties suggests important interaction with vehicle-specific characteristics including:

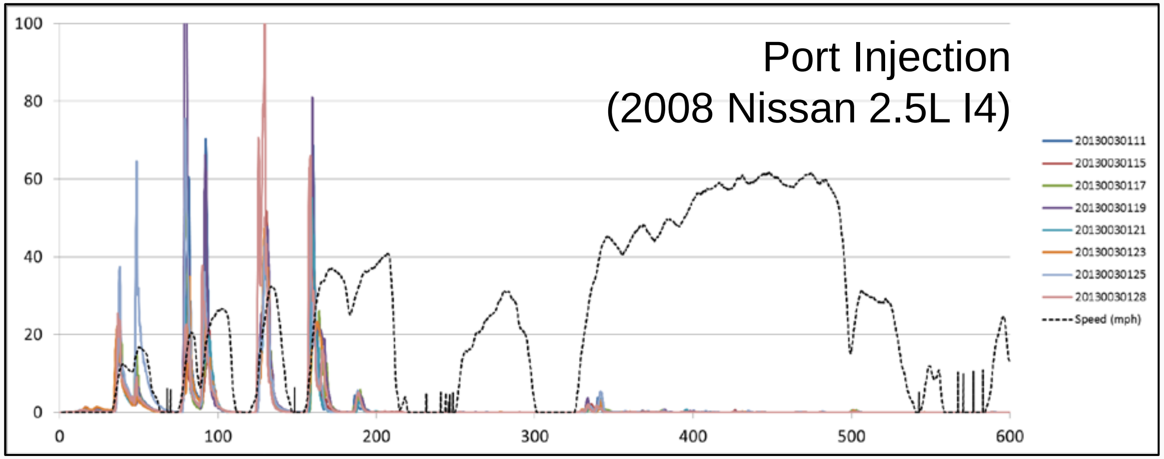
- Engine and intake system design
- Control algorithms and calibrations

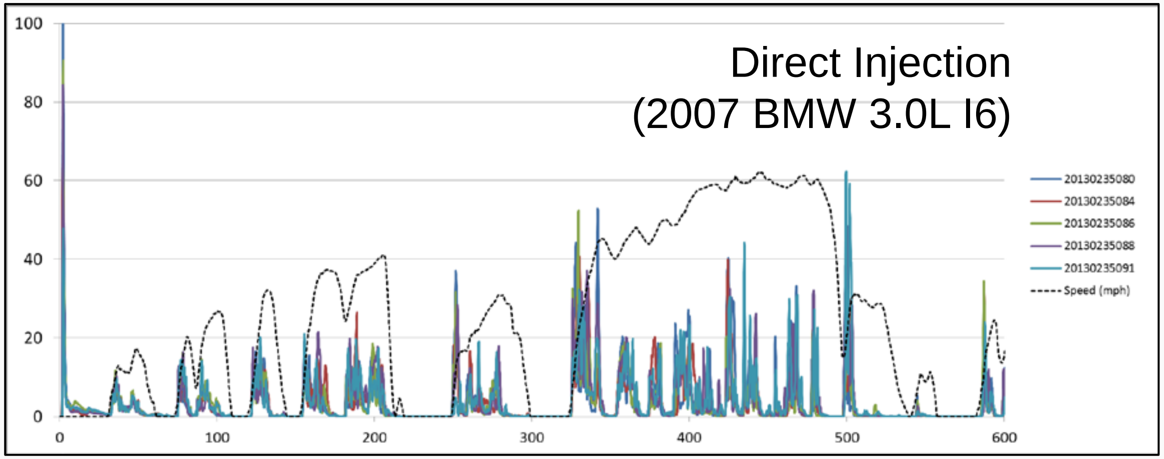
Ethanol blending can show different results depending on PM Index of base fuel and other details of the blending process

Small studies of a few splash blends using one or two vehicles are very difficult to interpret

What about GDIs?

Fuel property effects on PM likely to continue





Additional Work

General areas

- How fuel effects may differ in GDIs
- Effect of gasoline components on PM and precursors

Goal of larger collaborative PM study (2018+) building on other recent work:

- CRC E-94-2 GDI PM study
- CRC AVFL-29 development of improved gasoline speciation method
- Environment Canada GDI study
- EPA HEARO Pilot with Environment Canada (launching early 2017) will use GDIs and include SVOC speciation

Acknowledgements & Further Reading

Results presented here include the work of many colleagues at EPA including Rafal Sobotowski, James Warila, George Hoffman, Paul Machiele, Zuimdie Guerra, Nick Bies, Dave Bochenek, Bill Courtois, Steve George, Bruce Kolowich, Chris Laroo, John Spieth, Nancy Tschirhart, and Rick Zurel.

The EPAct/V2/E-89 study reports and data are available on the web:

https://www.epa.gov/moves/epactv2e-89-tier-2-gasoline-fuel-effects-study

For more information on the PM Pilot study data and publications send me an email (butler.aron@epa.gov)