Growth Energy Ethanol and Aromatics Testing Program

Presented at: EPA MOVES Meeting

March 7, 2018

AIR, Inc.

Overview

- Test Program
- Emission trends vs ethanol and aromatics
- Modeling the data
- Comparison to EPAct

Motivation for Testing

- Concern with EPAct test fuels and results for ethanol
  - EPAct results used in MOVES for all 2001+ vehicles
- Also, EPAct focused only on PFI vehicles
- GDI vehicles are becoming the predominant fuel delivery technology because of the GHG standards
- Compare ethanol and aromatics using Environmental Chamber

EPAct Bag 1 Modeling Results

Figure ES-1. Qualitative Summary of the Sign and Magnitude of Linear-Effects Coefficients for "Cold-Start" (Bag 1) Reduced Models, based on the 11-term Design Model (NOTE: This figure does not attempt to represent interaction terms).

Fuel Property	THC	NMOG	NMHC	CH_4	NO_x	PM	CO
Ethanol	↑	↑	↑	↑	↑	↑	↓
Aromatics	↑	↑	↑	↓	↑	↑	↓
RVP	↓	↓	↓	↓	---	---	↓
T50	↑	↑	↑	↑	↑	↑	↓
T90	↑	---	↑	---	---	↑	↓

↑ = positive coefficient

↓ = negative coefficient

--- = no effect

EPAct Bag 2 Modeling Results

Figure ES-2. Qualitative Summary of the Sign and Magnitude of Linear-Effects Coefficients for "Hot-running" (Bag 2) Reduced Models, based on the 11-term Design Model (Note: This figure does not attempt to represent interaction terms).

Fuel Property	THC	NMOG	NMHC	CH_4	NO_x	PM	CO
Ethanol	↑	↑	---	↑	↑	↑	---
Aromatics	↓	↑	↑	↓	↑	↑	↑
RVP	↓	↓	↓	↓	---	---	↑
T50	↑	↑	↑	↑	---	---	↑
T90	↑	↑	↑	↑	---	↑	↑

↑ = positive coefficient

↓ = negative coefficient

--- = no effect

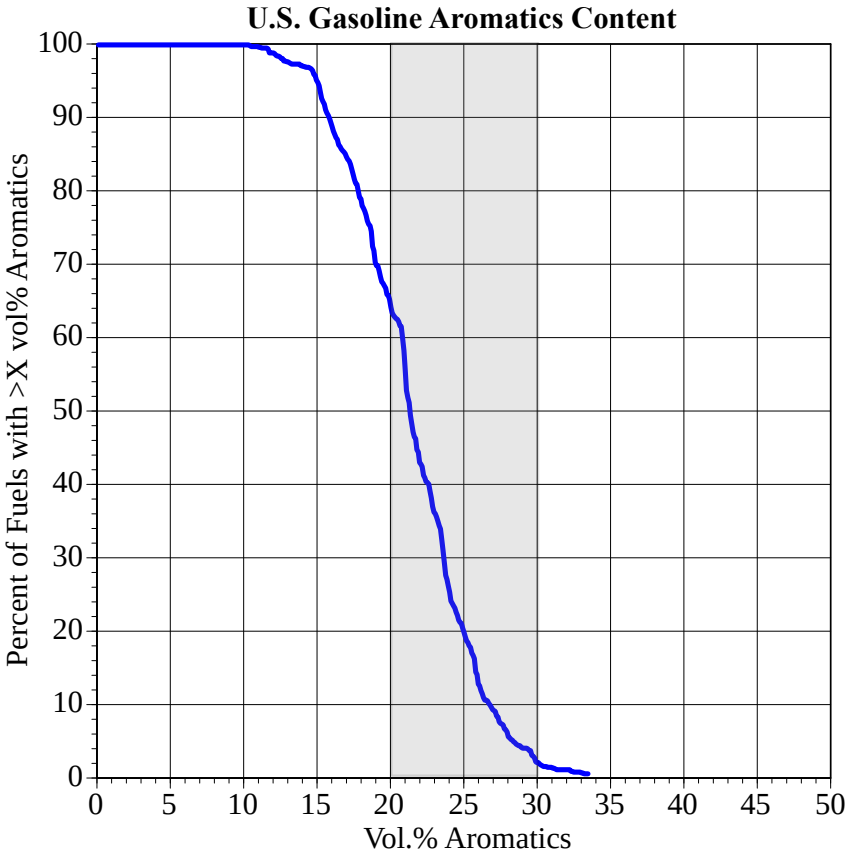
Overview of Test Program

- 5 gasoline direct injection (GDI) vehicles (2016 and 2017)
- 8 fuels, 0-20% ethanol, 20-30% aromatics, 2 splash blends
  - Tested ethanol and aromatics because these are the primary components for octane
- LA92 exhaust testing (no evap), min 2x
- THC, NMHC, CO, NOx, PM (speciated), toxics
- 1 vehicle had environmental chamber testing on all 8 fuels to evaluate impacts on aerosols

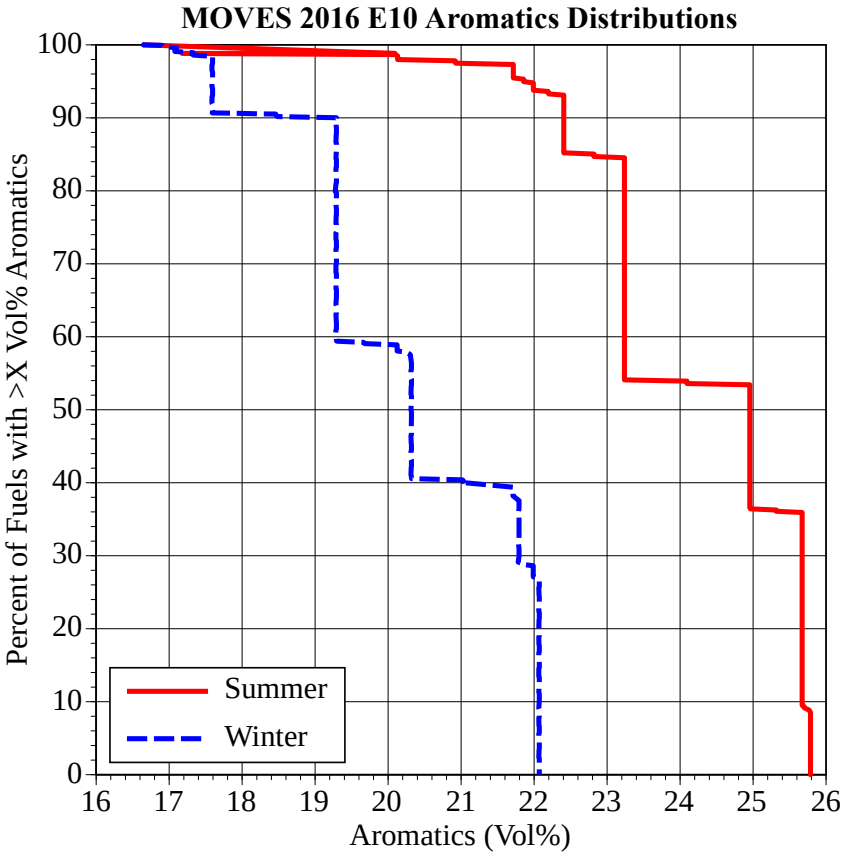
Fuels

#	1	2	3	4	5	6	7	8
Type	E0 low	E0 high	E10 low (T3)	E10 high	E15 splash	E15 low	E15 high	E20 splash
Ethanol	0.0	0.0	9.98	9.62	14.72	14.77	14.74	19.61
Aromatics (D5769)	21.2	29.4	21.4	29.1	20.3	21.8	29.3	19.1
Octane	88.1	87.2	87.8	87.0	89.8	88.6	87.4	91.5
RVP	8.9	8.8	9.0	9.2	8.8	9.1	9.1	8.6
Sulfur	8.6	8.0	8.2	8.5	8.9	8.7	8.9	8.3
Olefins	7.9	6.5	7.0	8.1	6.5	7.3	8.6	6.0
T50	212.7	234.7	188.6	207.3	159.6	157.6	163.2	161.2
T90	320.4	342.3	317.5	336.9	316.0	324.7	337.5	311.0
PMI	1.80	2.39	1.95	2.21	1.78	1.82	2.16	1.67

Why Aromatics Range of 20-30%?



Source: Alliance of Automobile Manufacturers North American Fuel Survey - 2014 Summer Excluding Fairbanks, AK

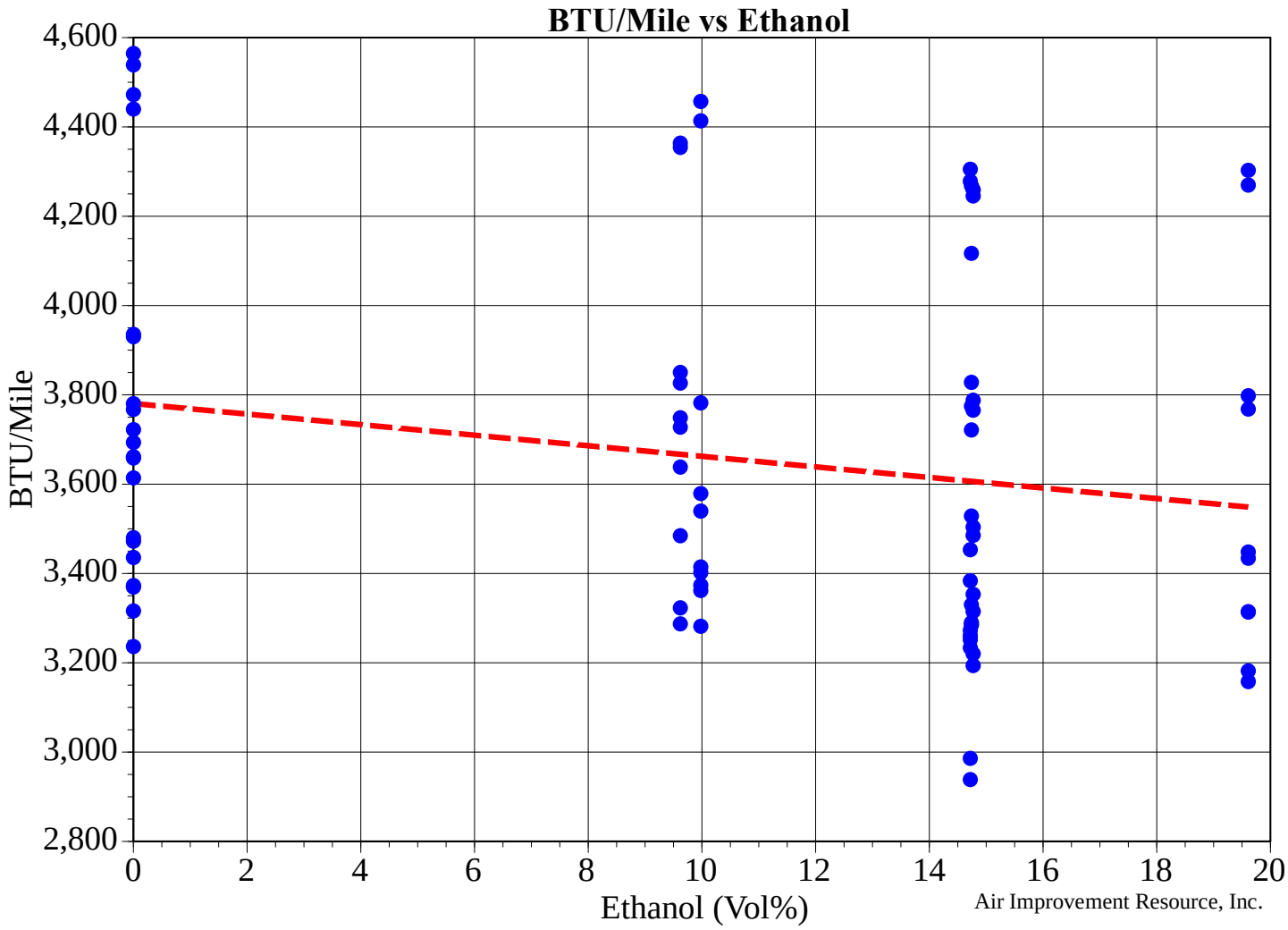


Vehicles

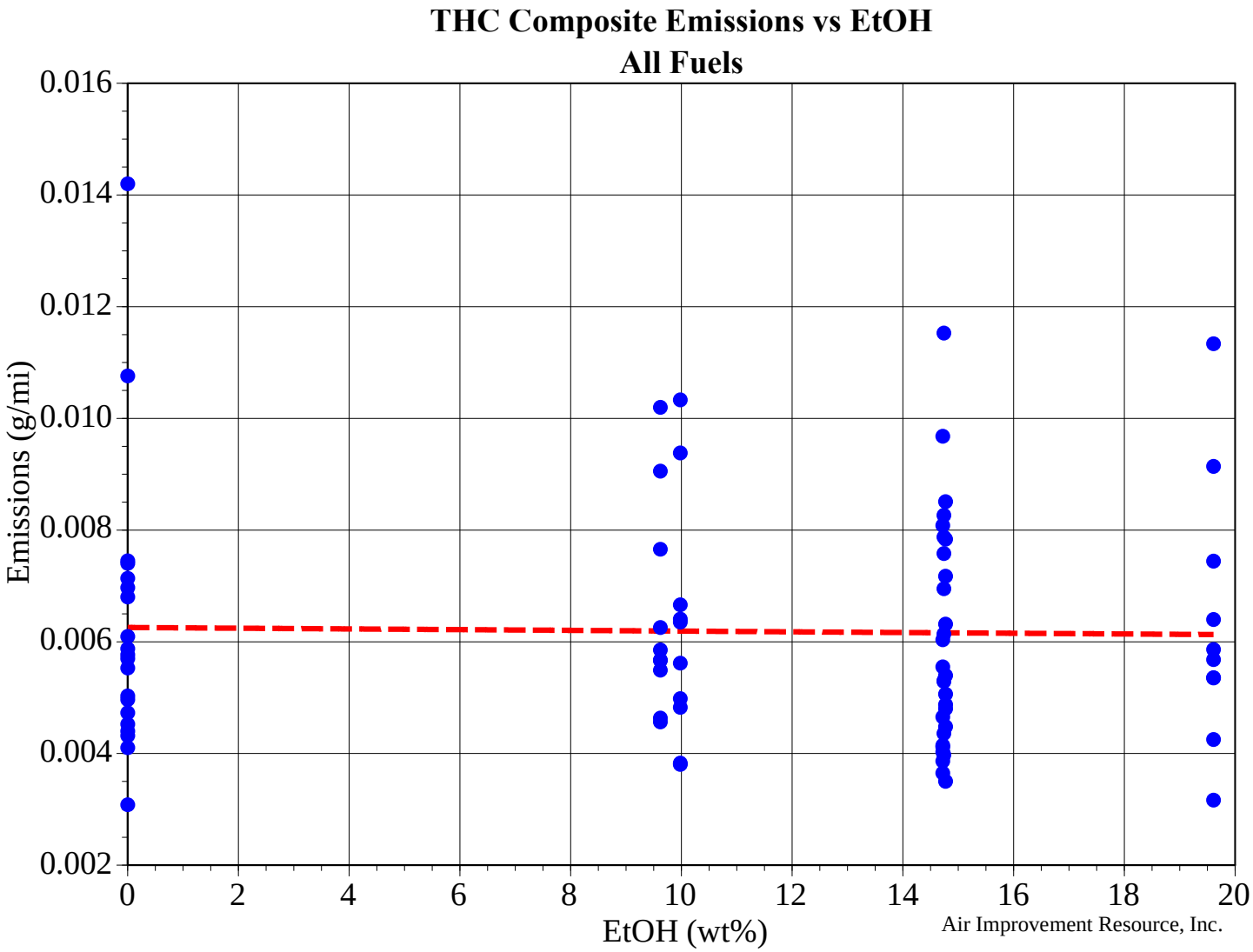
#	1	2	3	4	5
Year	2016	2017	2017	2017	2017
Make	Honda	Chevrolet	VW	Kia	Ford
Model	Accord	Impala	Jetta	Optima	Fusion
Miles at start (mi)	17,795	17,483	7,858	33,285	24,491
Engine Size (L)	2.4	3.6	1.4	2.4	1.5
Transmission	Continuously Variable Transmission (CVT)	6-speed automatic transmission	6-speed DSG transmission	6-speed automatic transmission	6-Speed Automatic with Paddle Shifters
GDI Type	Wall-guided DI	Wall-guided DI	Wall-guided DI	Wall-guided DI	Spray-guided DI
AIR System	Naturally Aspirated	Naturally Aspirated	Turbocharged	Naturally Aspirated	Turbocharged
Emission Standard	USEPA:T3B30 ,California: SULEV30/ PZEV	USEPA: T 3B? California: PC/PZEV	USEPA: T3 B70 California: LEV3/ULEV70	USEPA: T3B70	USEPA: T3B30 California: SULEV30/PZEV

Scatter Plots

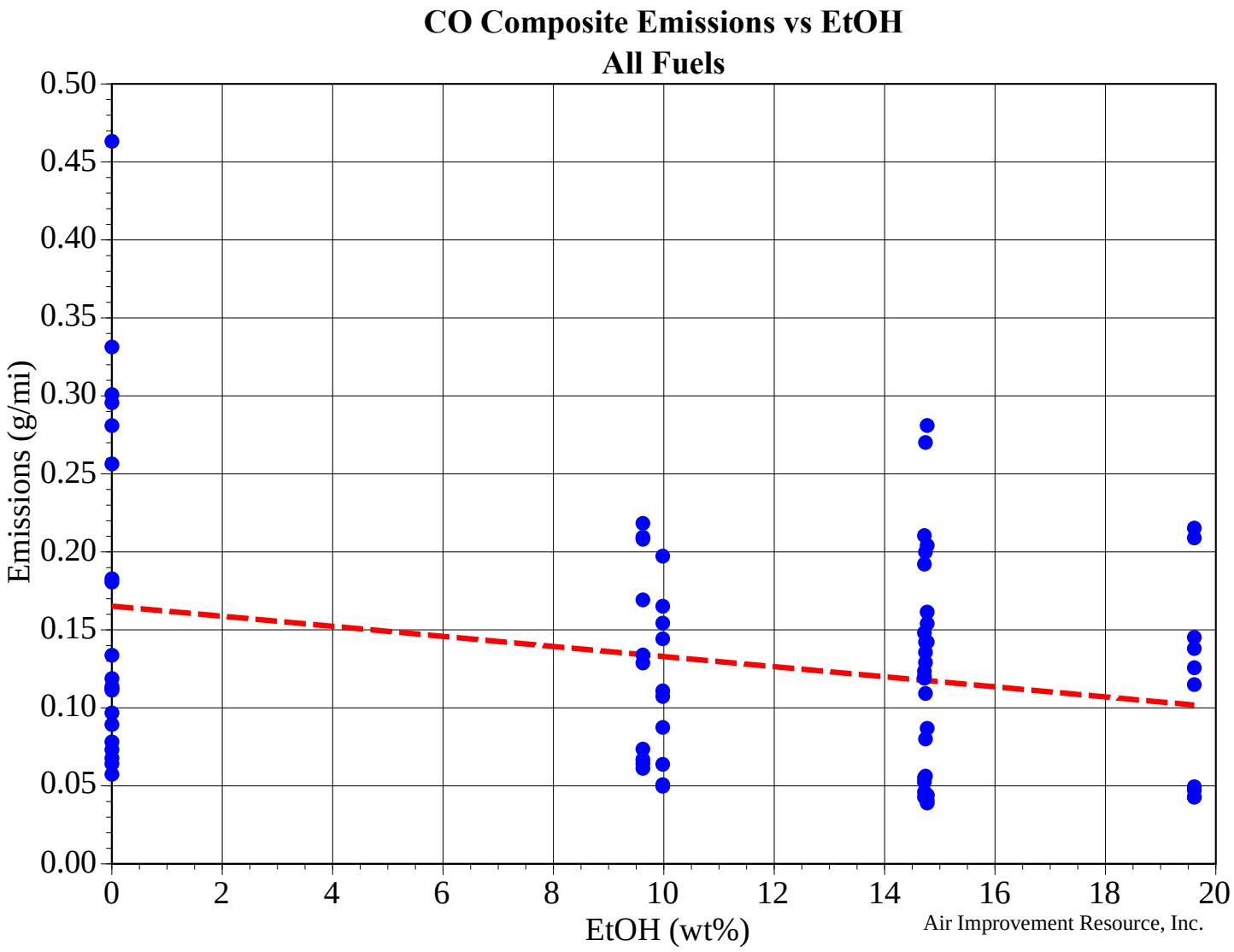
Energy/mile vs Ethanol



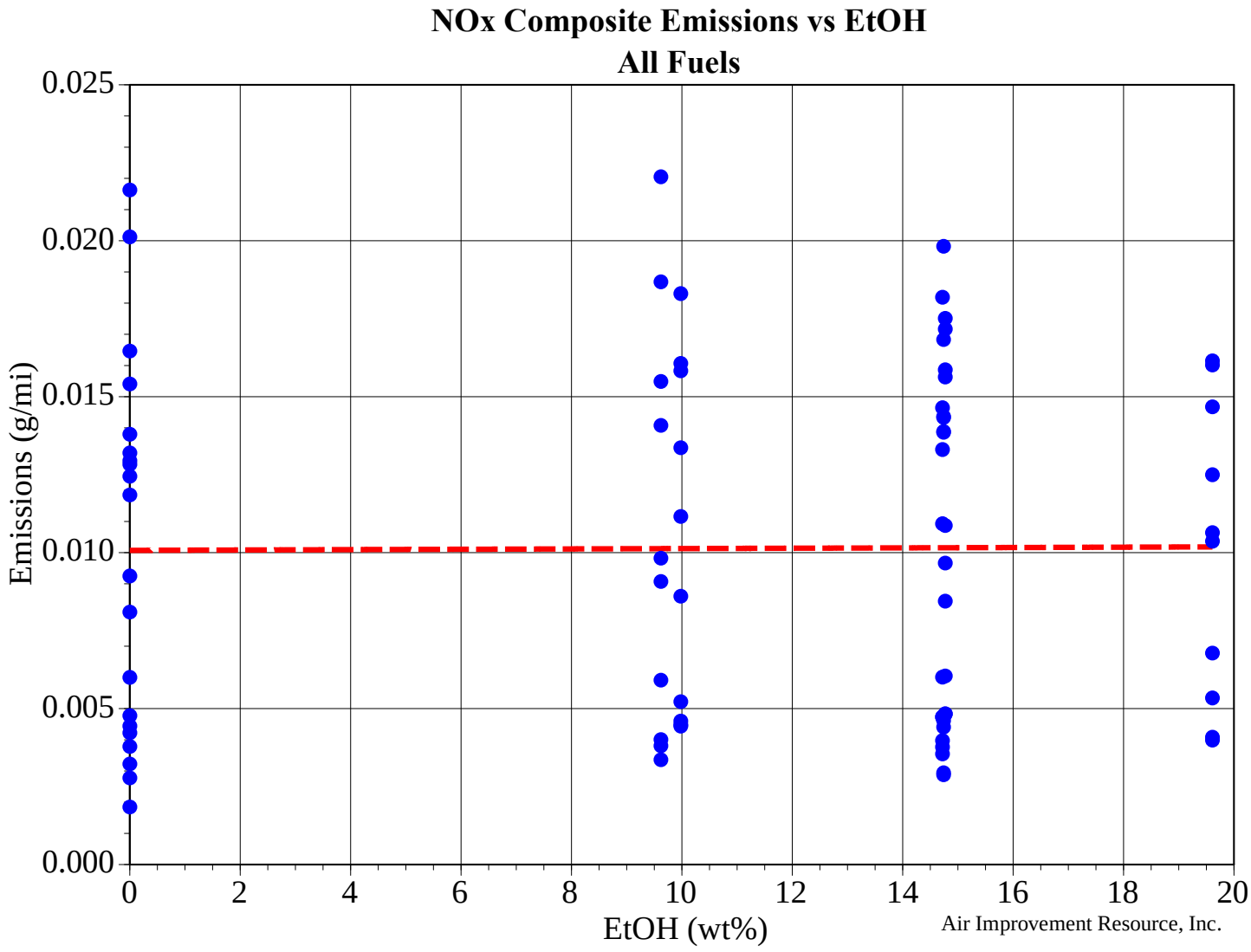
THC vs Ethanol



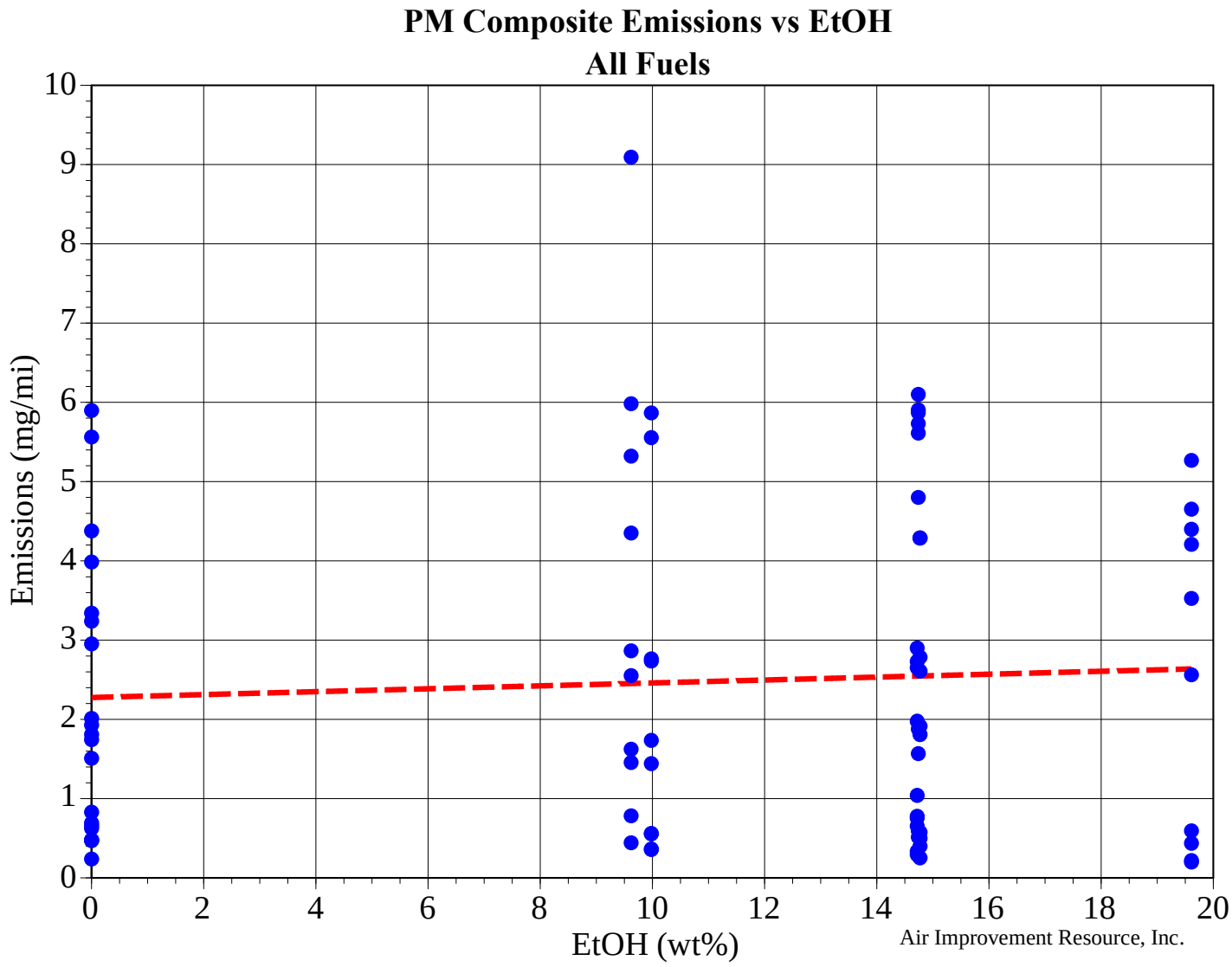
CO vs Ethanol



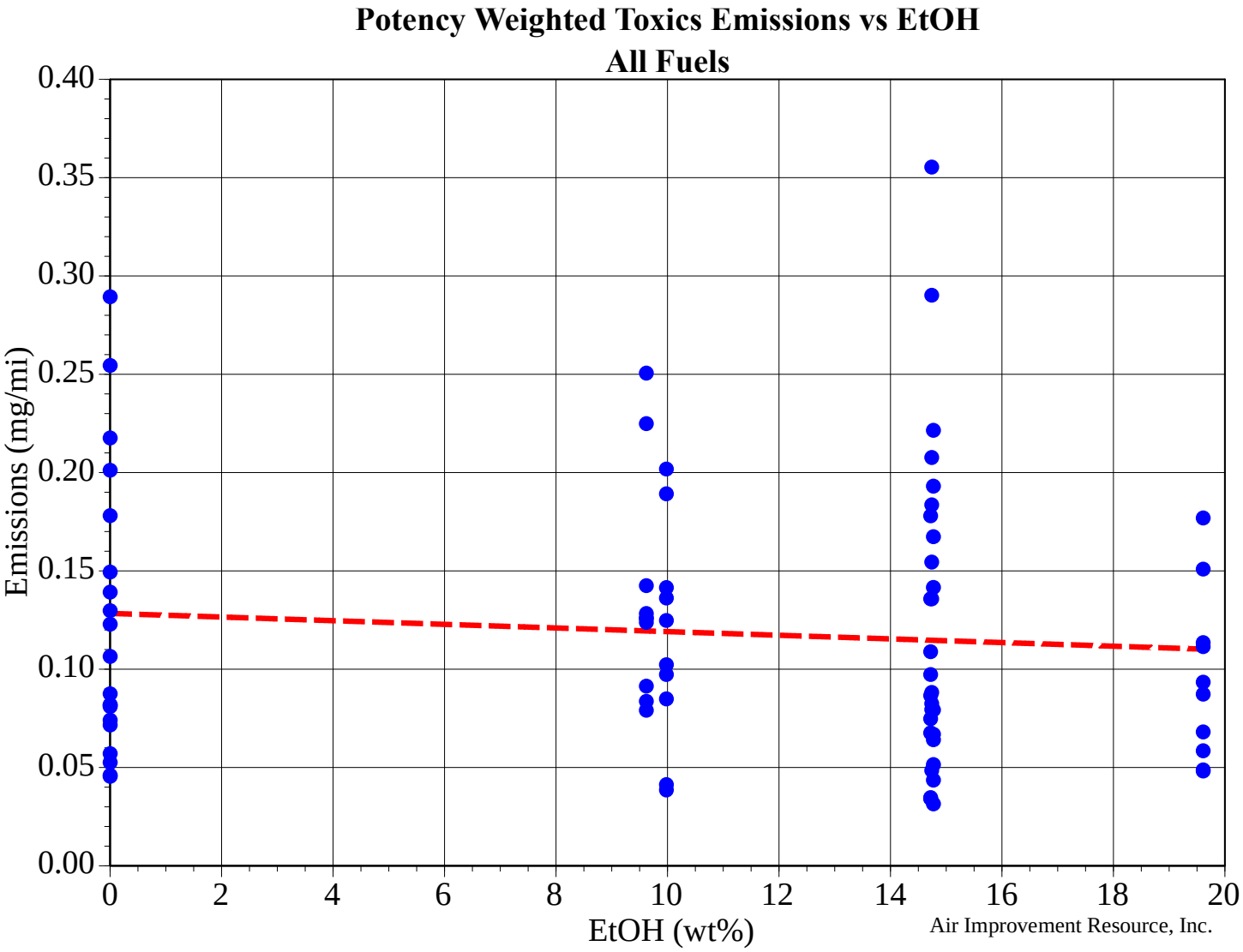
NOx vs Ethanol



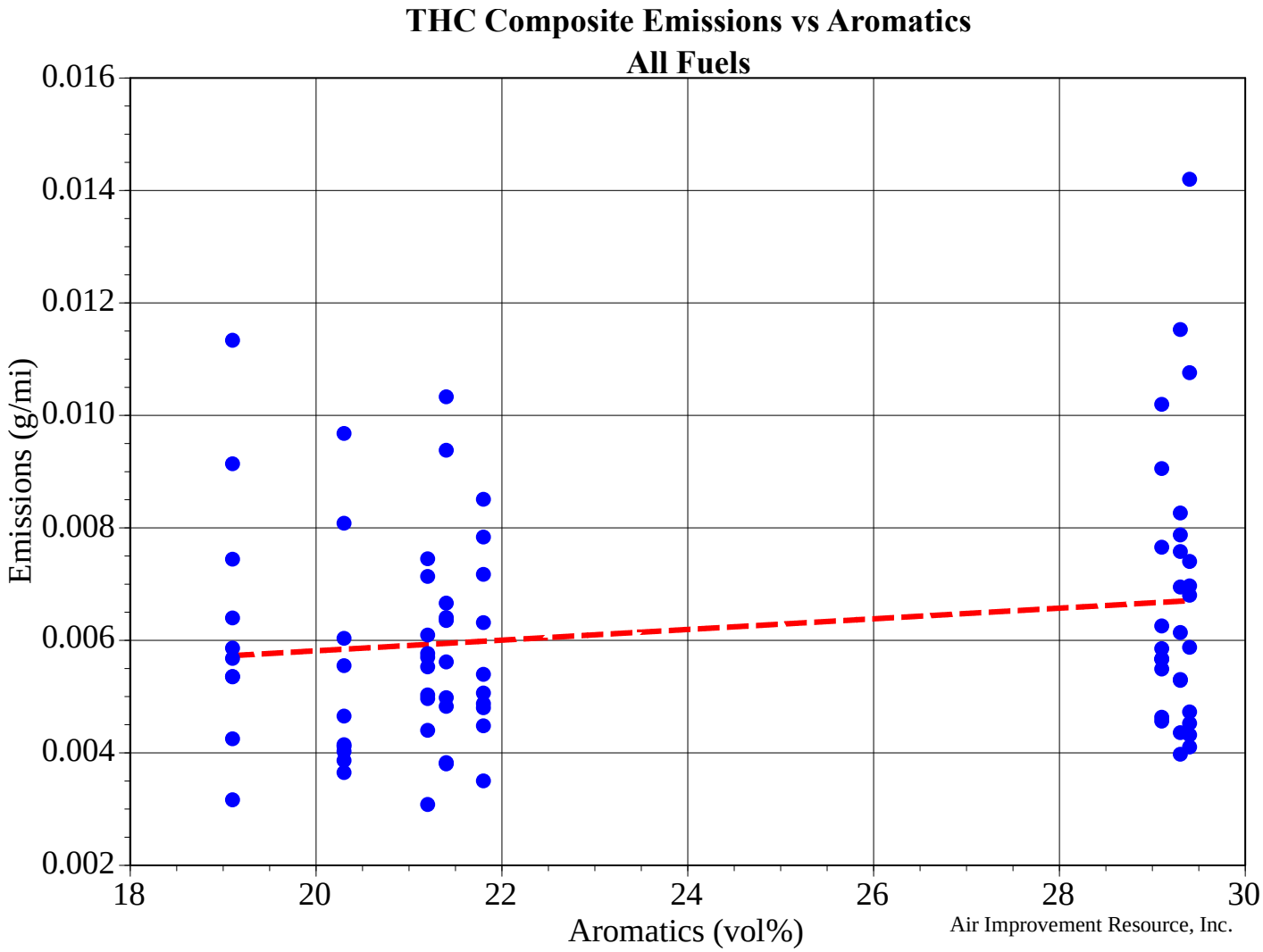
PM vs Ethanol



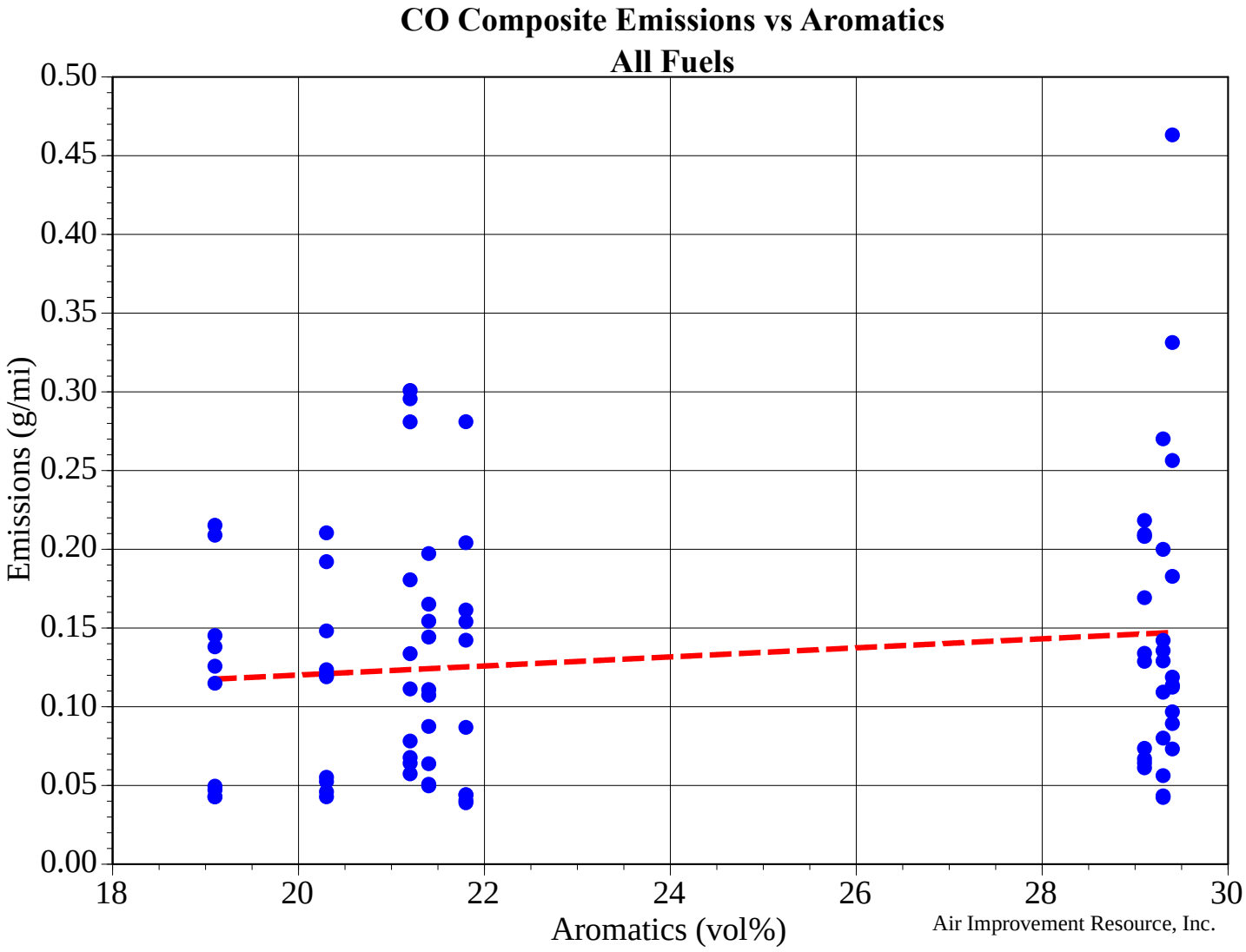
PWToxics vs Ethanol



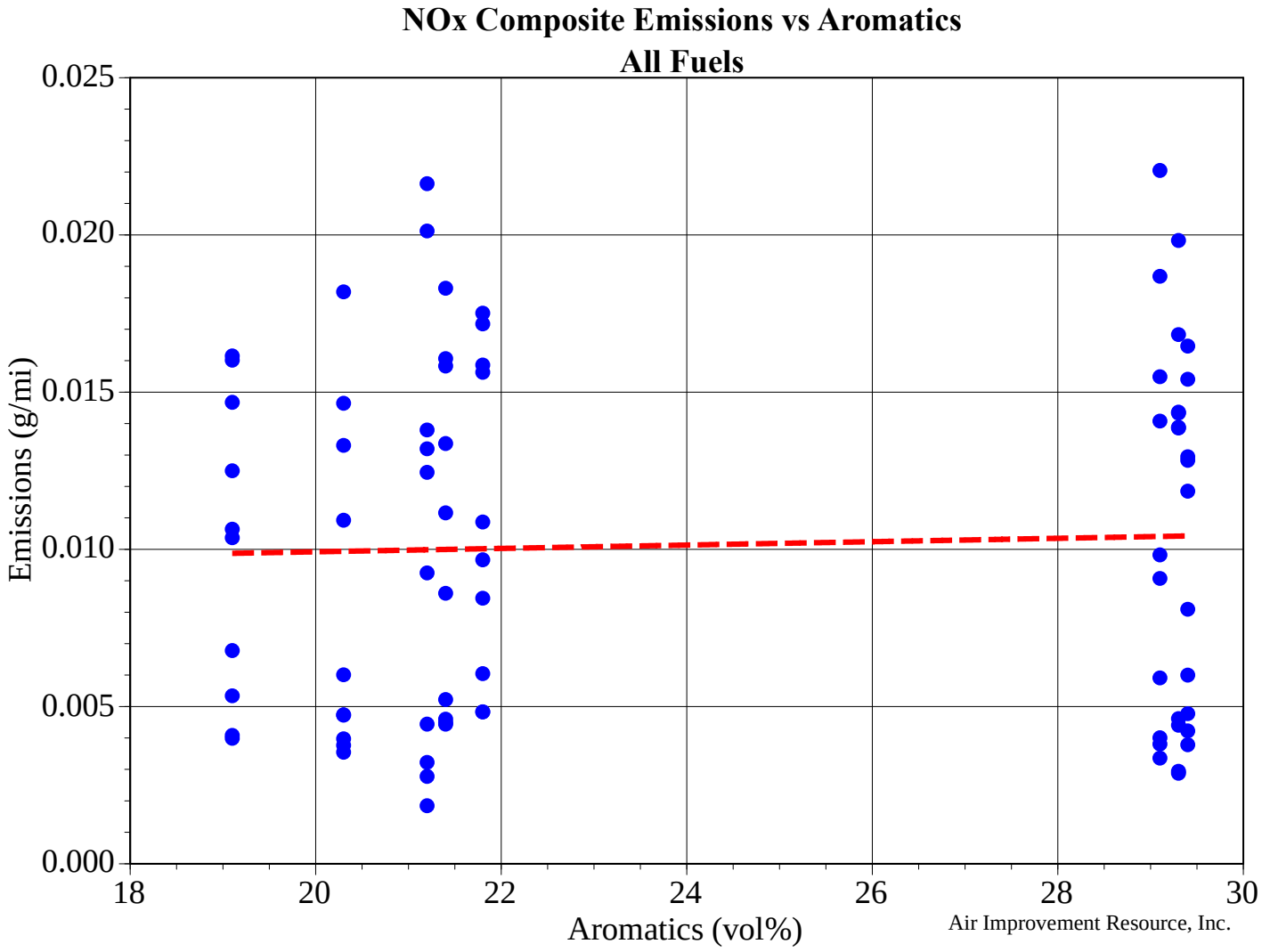
THC vs Aromatics



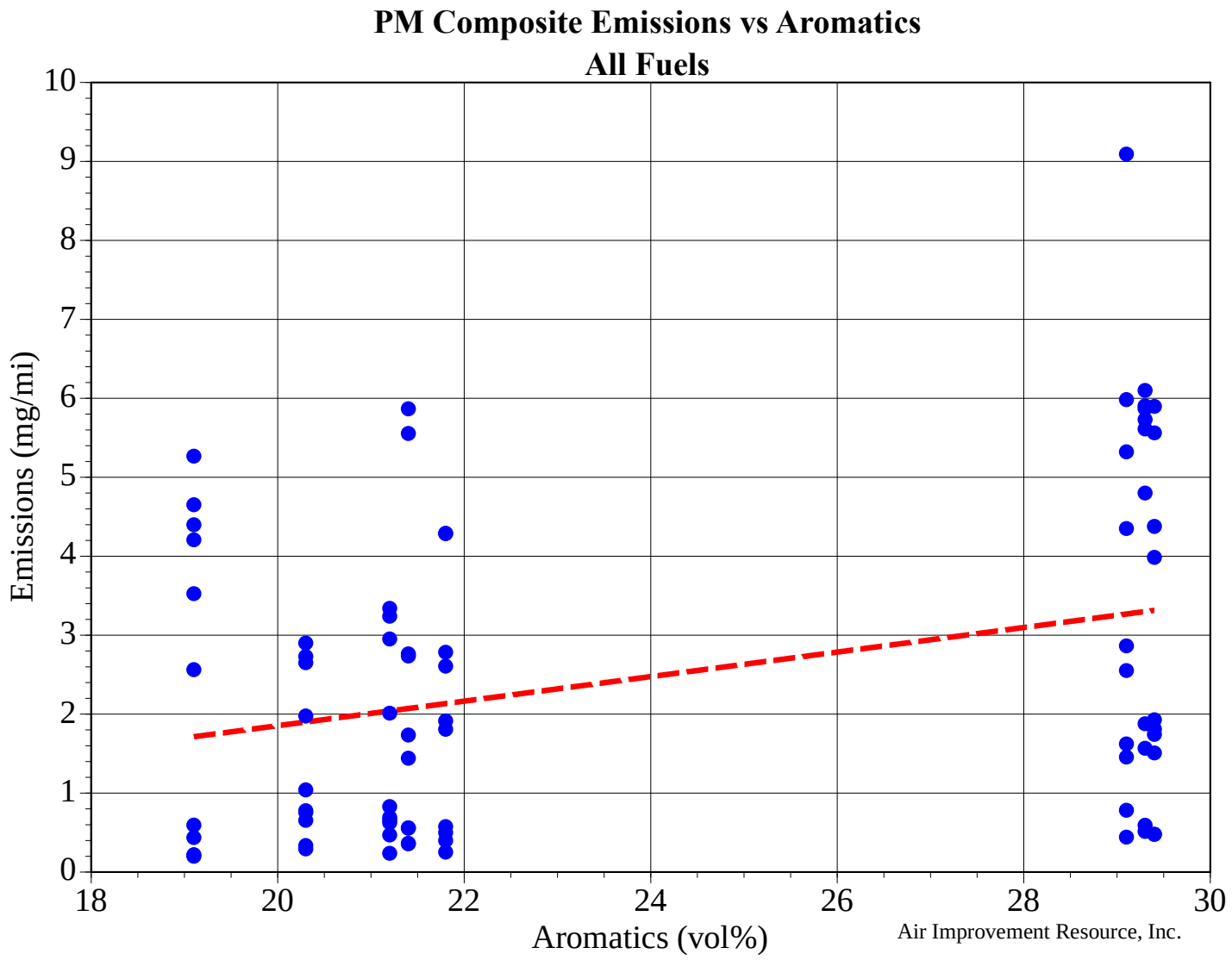
CO vs Aromatics



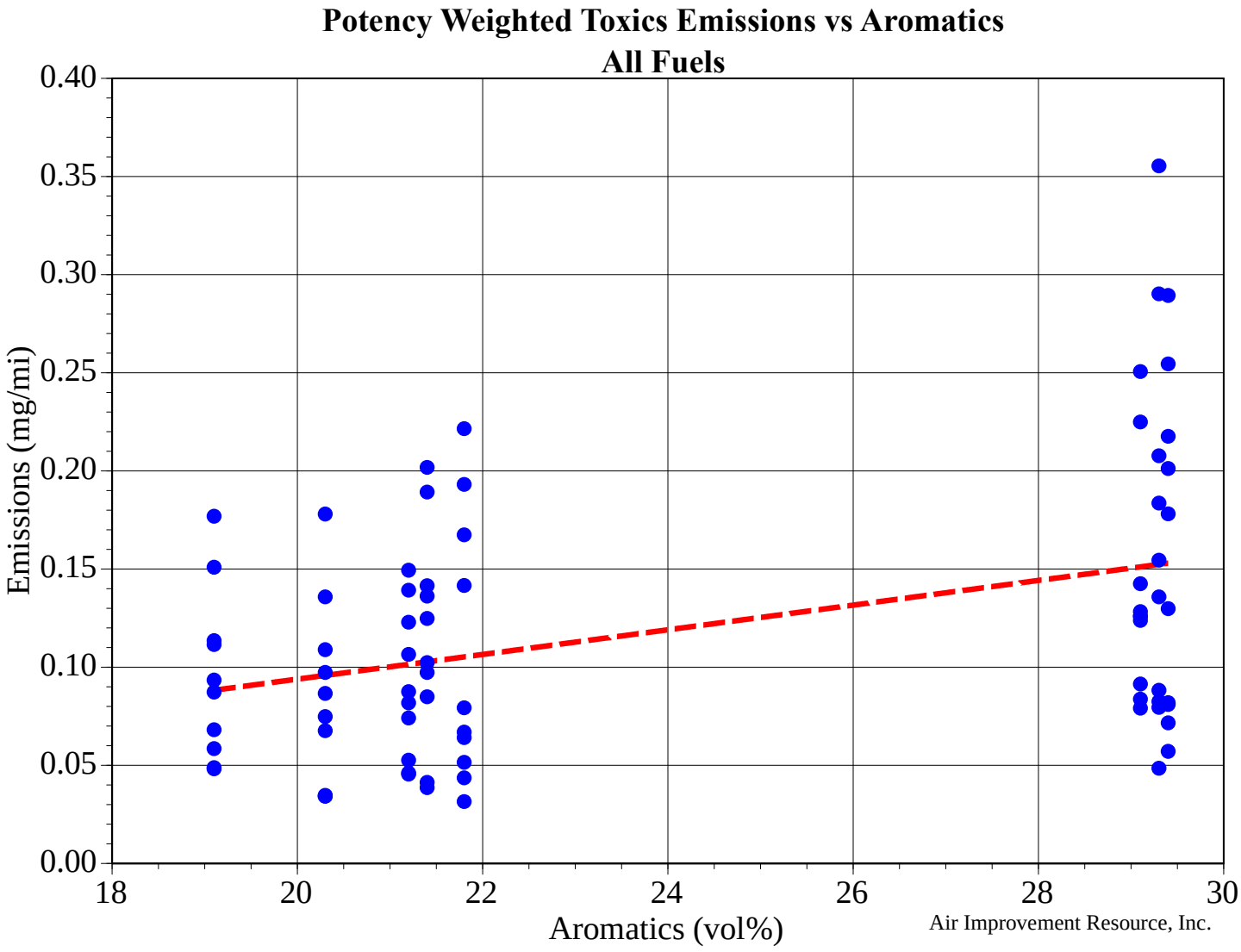
NOx vs Aromatics



PM vs Aromatics



PWToxics vs Aromatics



Modeling of Data

Data Revisions

- Take the Natural Log of the Emissions
  - Transforms the emissions into a normal distribution
- Standardize the Fuel Properties
  - Standardized = (Actual-Average)/Standard Deviation
- Replace Zero or Missing Emissions Data
  - If zero, replace with one-half of the lowest detectable emissions for all tests
  - If missing, use the other test value for that vehicle

Fuel Property Selection

- Due to the fuel creation methodology, several of the fuel properties are highly co-related (red highlighted).

Pearson Product-Moment Correlation								
Property	Aromatics	Ethanol	Olefins	RVP	Sulfur	T50	T70	T90
Aromatics	1.000							
Ethanol	-0.346	1.000						
Olefins	0.531	-0.181	1.000					
RVP	0.509	-0.015	**0.817**	1.000				
Sulfur	-0.099	0.414	0.491	0.354	1.000			
T50	0.484	**-0.918**	0.090	0.003	**-0.629**	1.000		
T70	**0.952**	-0.567	0.383	0.377	-0.282	**0.701**	1.000	
T90	**0.975**	-0.435	0.506	0.507	-0.105	0.523	**0.953**	1.000

- To avoid regression and confounding issues, highly co-related terms must be avoided.

Fuel Property Selection (cont.)

- Since the primary purpose of this study was to determine the impact of Aromatics and Ethanol on emissions, these two properties were included, even though somewhat correlated.
- Since T50, T70, and T90 are highly correlated with Aromatics, Ethanol, Olefins, and often with each other, these temperature values were eliminated from consideration.
- As for RVP and sulfur: These properties were held nearly constant during the preparation of the fuels. Therefore, they were also eliminated.
- Thus, Olefins, Aromatics, and Ethanol were selected for the analysis, and regressed “in conjunction”.
- Although attempted, no “interactive” terms could be included due to regression issues.

Regression Method

- All of the regressions performed in the analysis were linear-mixed via the R statistical software and the “nlme” and “lme4” packages. To ensure agreement with the linear-mixed modeling in SAS (the program used in the EPA’s EPAct study), the diagonal covariance matrix and contrast options were employed.
- Following EPAct, the fuel properties included in the fixed effects were also included in the random effects. In addition, the vehicle field (make and model) was included in the random effects.

Multiple Variable Regression Results

- Linear-mixed regressions were applied to the Composite emissions for all the pollutants and fuel economy.
- Coefficients with P-Values at/below 0.10 (10%) were considered significant.
- Following EPAct, non-significant primary terms were kept in the regressions.

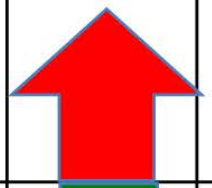
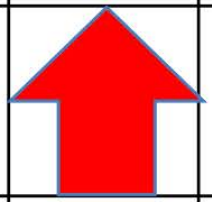
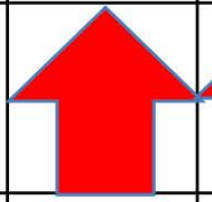
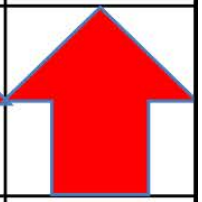
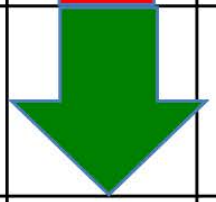
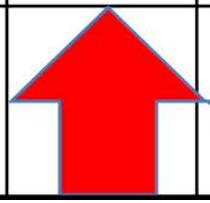
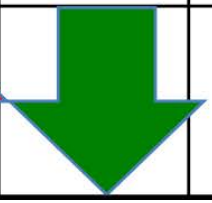
Regression Results (cont.)

Composite Coefficients, Mixed Regressions, 3 Properties in Conjunction								
Fuel Property	**CH4**	**CO**	**CO2**	**Fuel Economy**	**NMHC**	**NOx**	**PM**	**THC**
Aromatics	-0.0355	**0.0732**	0.0010	0.0092	**0.1029**	0.0090	**0.3735**	**0.0794**
Ethanol	0.0087	**-0.1291**	-0.0034	-0.0022	0.0243	0.0311	0.1379	0.0224
Olefins	-0.0225	-0.0474	**0.0118**	**-0.0134**	-0.0204	0.0340	-0.0266	-0.0205

Composite Coefficients, Mixed Regressions, 3 Properties in Conjunction							
Fuel Property	**Acetal-dehyde**	**Black Carbon**	**1,3-Buta-diene**	**Ethyl-benzene**	**Formal-dehyde**	**Organic Carbon**	**Toluene**
Aromatics	**0.2050**	**0.3852**	**0.2101**	**0.3492**	**0.1763**	0.1448	**0.2758**
Ethanol	**0.5969**	0.1432	-0.0036	0.0546	0.0911	0.0056	0.0189
Olefins	0.0589	-0.0095	-0.0410	0.0464	-0.0698	0.0299	0.0048

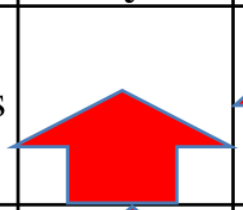
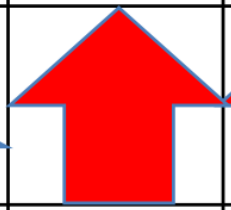
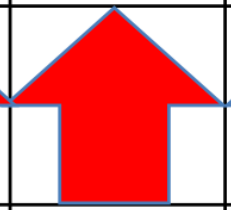
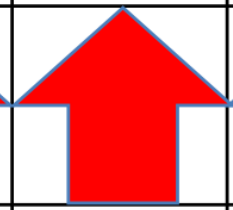
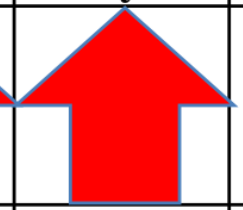
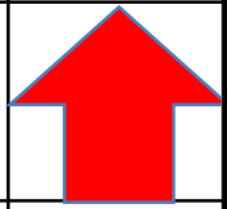
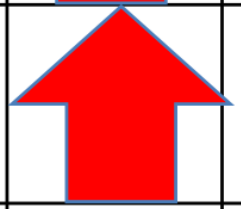
Significant terms are highlighted in red.

Regression Results (cont.)

Composite Coefficients, Mixed Regressions, 3 Properties in Conjunction								
Fuel Property	**CH4**	**CO**	**CO2**	**Fuel Economy**	**NMHC**	**NOx**	**PM**	**THC**
Aromatics								
Ethanol								
Olefins								

Red up arrow indicates a positive coefficient.
Green down arrow indicates a negative coefficient.

Regression Results (cont.)

Composite Coefficients, Mixed Regressions, 3 Properties in Conjunction							
Fuel Property	**Acetal-dehyde**	**Black Carbon**	**1,3-Buta-diene**	**Ethyl-benzene**	**Formal-dehyde**	**Organic Carbon**	**Toluene**
Aromatics							
Ethanol							
Olefins							

Red up arrow indicates a positive coefficient.

E10 to E15 Comparison with EPAct – County Average Properties in MOVES2014

Property	Units	E10	E15
Aromatics	vol%	23.5	22.0
Benzene	vol%	0.64	0.65
Ethanol	vol%	10	15
Olefins	vol%	9.58	8.62
RVP	psi	8.33	7.13
Sulfur	ppm	29	30
T50	°F	203.8	191.0
T90	°F	328.3	327.2

E10 to E15 Comparison

Pollutant	EPAct % Change (E10 to E15)		UCR % Change (E10 to E15)	
	Bag 1	Bag 2	Bag 1	Bag 2
THC	-0.07%	1.52%	-1.71%	1.80%
CO	-2.78%	-4.89%	-8.73%	-12.57%
NOx	0.68%	3.39%	3.60%	-0.16%
PM	-2.47%	4.13%	-14.06%	3.45%

Conclusions

- Higher levels of ethanol reduce per mile energy consumption in GDI vehicles
- Emission results (+ modeling) indicate quite different results for GDI vehicles than EPAct results for PFI vehicles

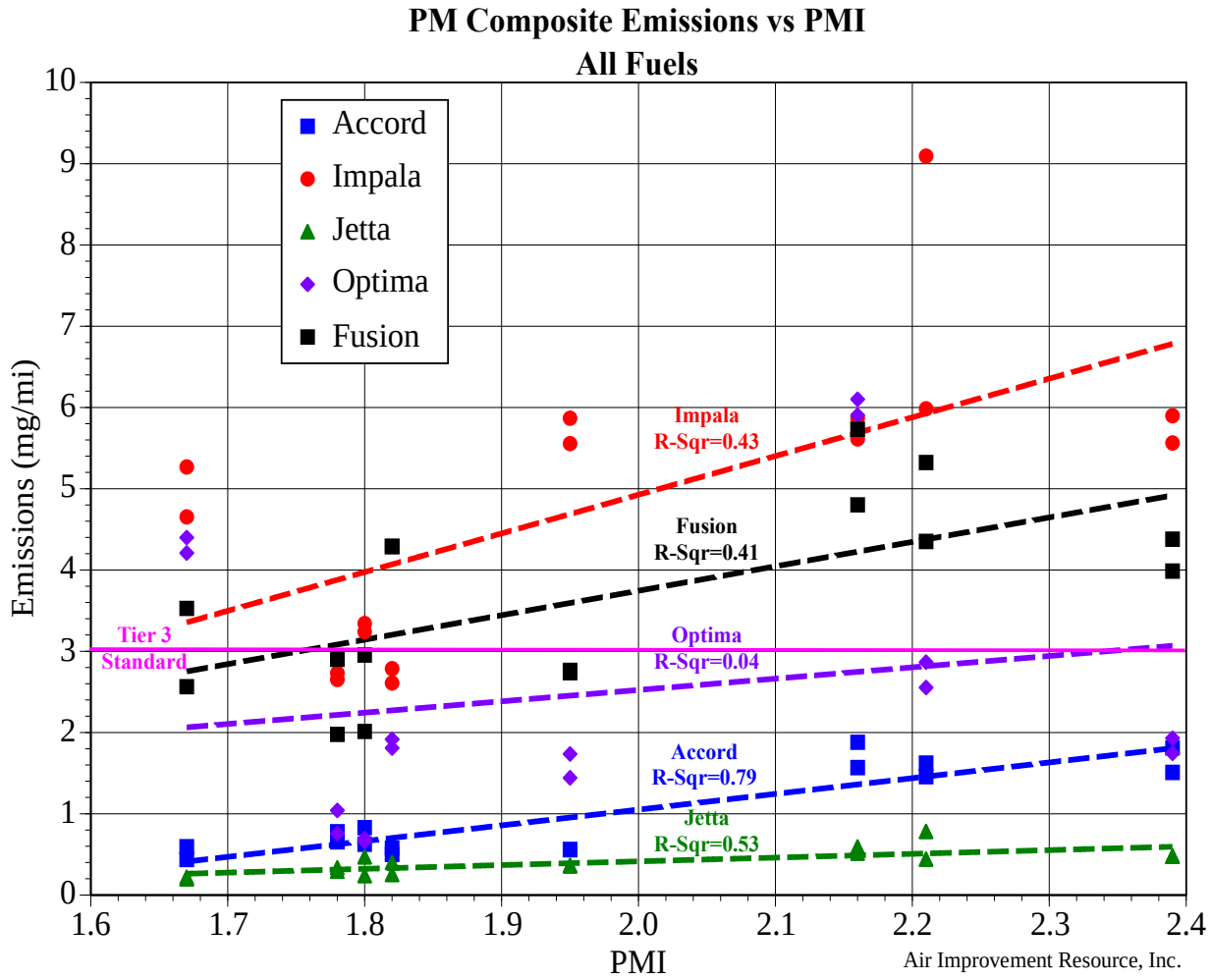
Bag 1 and 2 Regression Results

Bag 1 Coefficients, Mixed Regressions, 3 Properties in Conjunction								
Fuel Property	**CH4**	**CO**	**CO2**	**Fuel Economy**	**NMHC**	**NOx**	**PM**	**THC**
Aromatics	0.0028	-0.0204	0.0018	0.0076	**0.0930**	0.1027	0.4786	**0.0786**
Ethanol	-0.0082	**-0.1326**	-0.0012	-0.0046	0.0104	**0.0885**	0.0324	0.0106
Olefins	-0.0024	0.0010	0.0115	**-0.0117**	-0.0155	-0.0332	0.0283	-0.0151

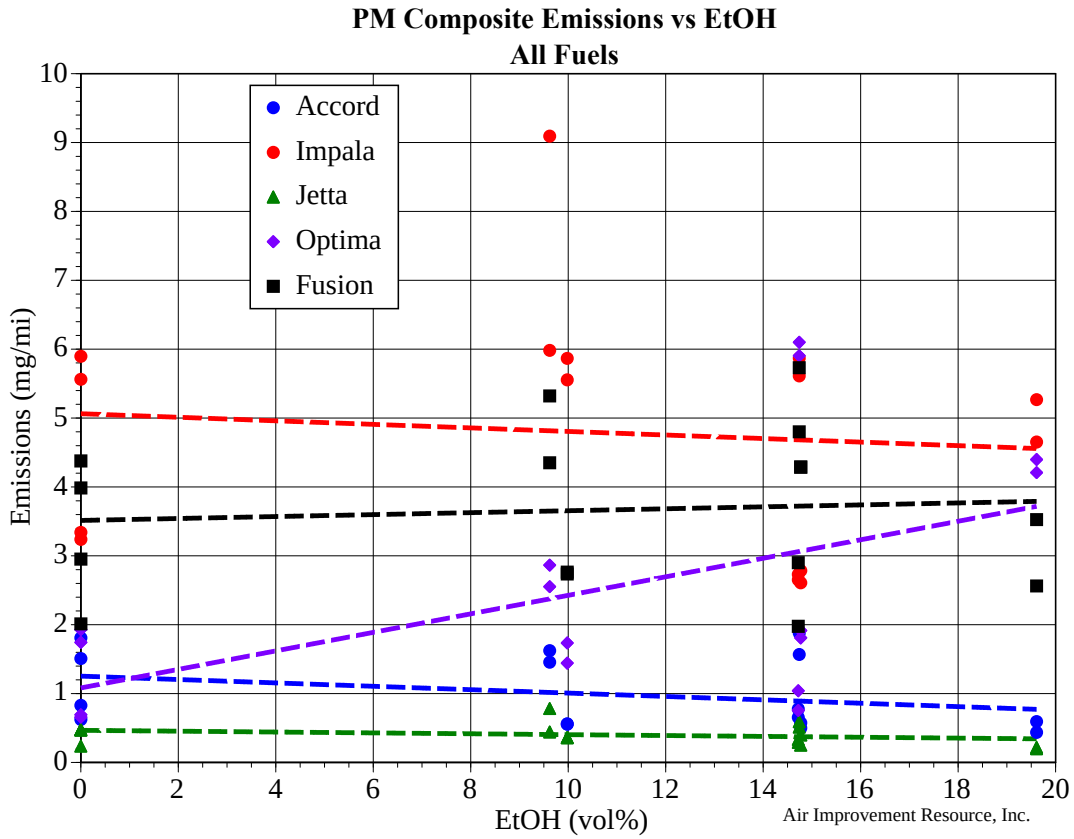
Bag 2 Coefficients, Mixed Regressions, 3 Properties in Conjunction							
Fuel Property	**CH4**	**CO**	**CO2**	**Fuel Economy**	**NMHC**	**NOx**	**PM**
Aromatics	-0.1488	**0.1090**	-0.0014	**0.0107**	0.0700	0.0174	**0.3558**
Ethanol	0.1861	**-0.1512**	-0.0008	-0.0051	0.1027	0.0132	**0.2096**
Olefins	-0.0778	-0.0891	**0.0188**	**-0.0188**	0.0103	0.0282	-0.0266

Significant terms are highlighted in red.

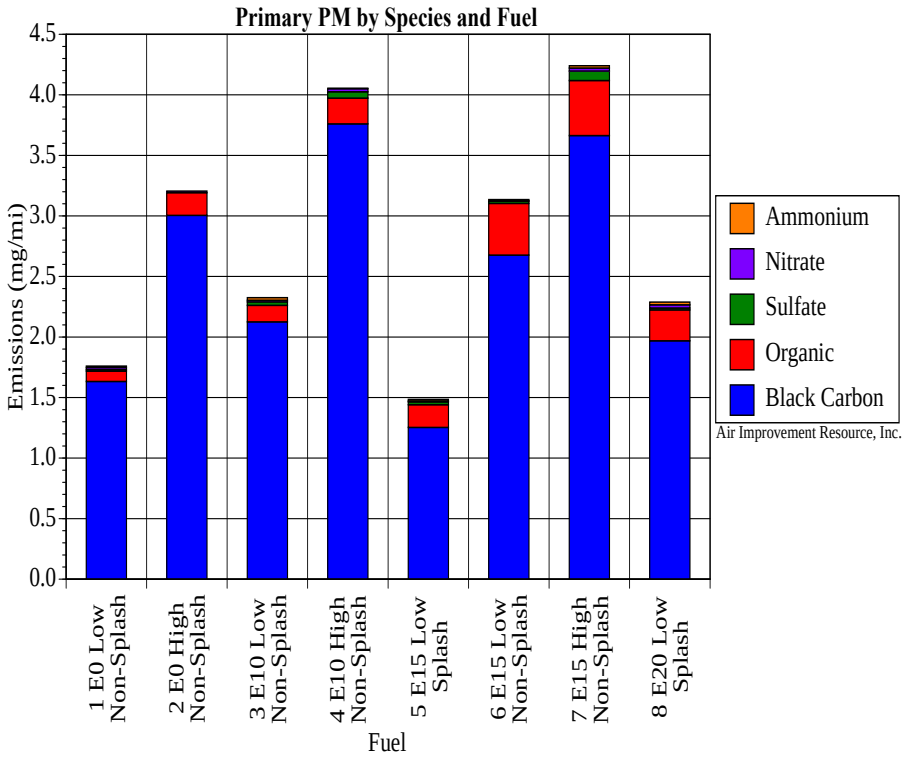
PM vs PMI

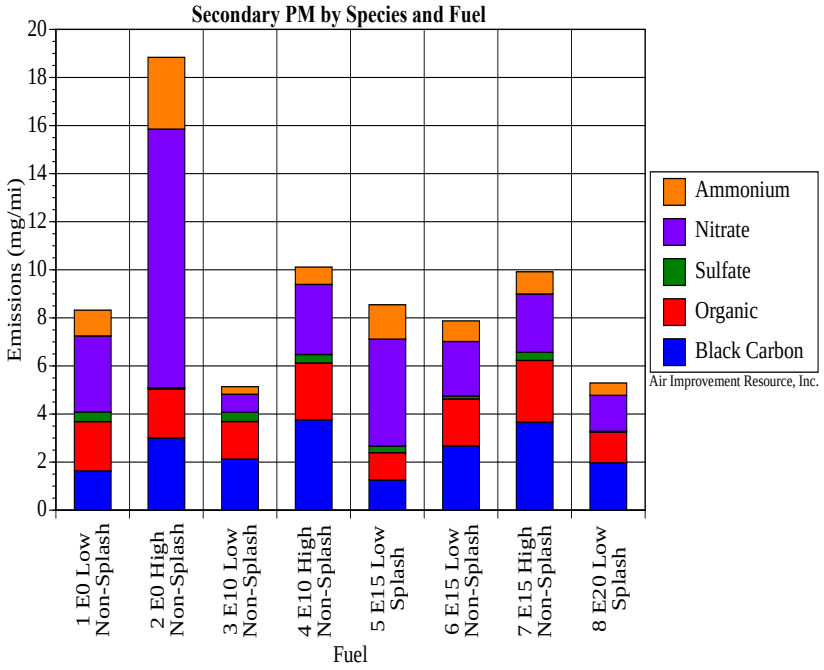

PM Composite Emissions vs PMI
All Fuels
Accord
Impala
Jetta
Optima
Fusion
Impala
R-Sqr=0.43
Fusion
R-Sqr=0.41
Optima
R-Sqr=0.04
Accord
R-Sqr=0.79
Jetta
R-Sqr=0.53
Tier 3
Standard
Emissions (mg/mi)
PMI
Air Improvement Resource, Inc.

PM Emissions vs Ethanol – Individual Vehicles



SMOG Chamber Fuel Effects for Ford Fusion





SMOG Chamber Fuel Effects for Ford Fusion