Advanced Combustion Catalyst & Aftertreatment Technologies
SOUTHWEST RESEARCH INSTITUTE

CATALYST AND AFTERTREATMENT R&D

Emissions Characterization for D-EGR® Vehicle

Cary Henry

Baseline GDI Vehicle – 2012 Buick Regal GS

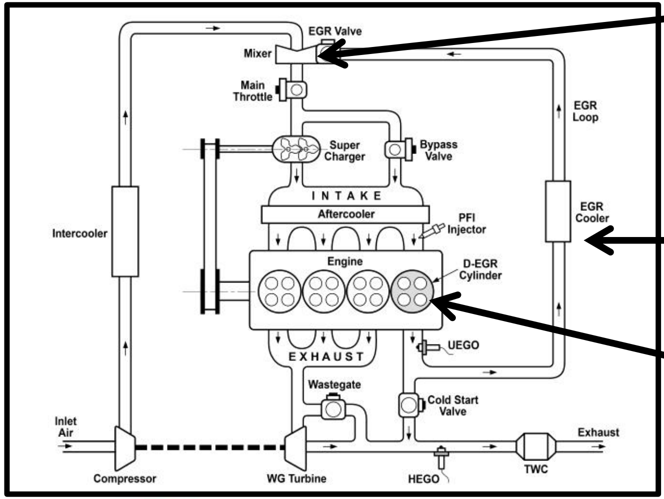
- Buick Regal GS uses state-of-the-art turbocharged, direct-injected gasoline engine
- Down-sized engine provides fuel economy improvement on regulated drive cycle
- Stoichiometric combustion system uses conventional TWC to achieve Tier 2 Bin 5 emission levels

2012 LHU GDI Turbo	
Configuration	Inline 4-cylinder
Displacement	2.0 L
Bore and Stroke	86 mm x 86 mm
Compression Ratio	9.25:1
Max. Power	220 hp @ 5300 rpm
Max. Torque	350 Nm @ 2000 - 4000 rpm
Max. Engine Speed	6350 rpm

Advanced Concept: Dedicated EGR (D-EGR®)

- **SwRI Patented Novel Engine Architecture**
  - One or more cylinders have their exhaust connected directly to the intake system
  - The EGR composition or quality is de-coupled from the exhaust composition; rich combustion in the dedicated cylinder can be used to make reformate (H_2 and CO)

A SwRI designed and patented mixer is used to improve cylinder-to-cylinder and temporal EGR imbalance.



Hydrogen enriched exhaust is routed to the intake. H_2 increases flame speed, EGR tolerance and knock tolerance while reducing fuel consumption and emissions.

The dedicated cylinder is run with up to 40% excess fuel to create H_2 and CO as well as power the crankshaft.

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D-EGR Results in Improved Fuel Economy

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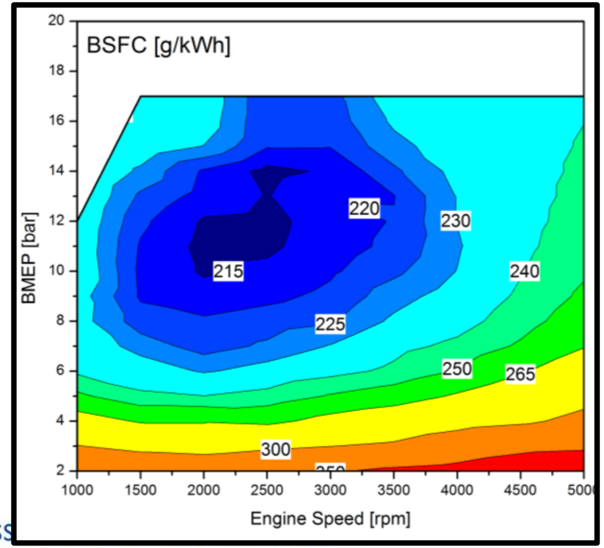
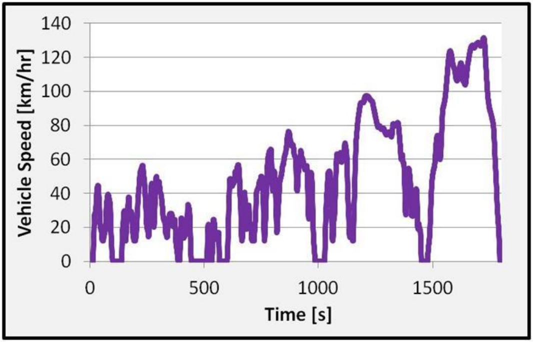
- **Three Engines Run As D-EGR Engines**
  - Chrysler 2.4L
  - Renault 2.0L
  - GM 2.0L

Stock (EPA) D-EGR % Change	Bag 1	Bag 2	Bag 3	FTP	HWFET
Fuel Economy (Test uses Regal GS dyno coefficients) [MPG]	23 24 4.6%	22.2 25.1 12.9%	26.7 28.7 7.4%	23.5 25.7 **9.5%**	37.4 43 **10.7%**
Fuel Economy (Test uses Regal Premium dyno coefficients) [MPG]	24 25.6 7%	23.1 27 17%	28.4 30.7 8%	24.5 27.6 **12.7%**	43.6 47.6 **9.2%**



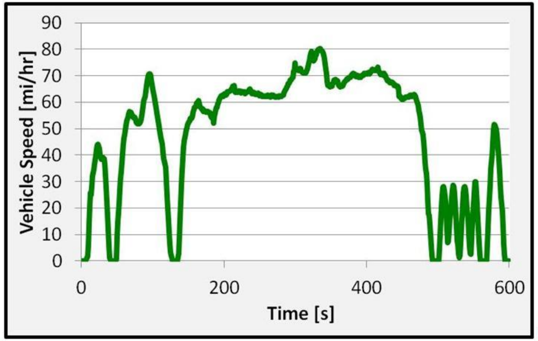
Emissions Characterization Methods – Vehicle Drive Cycles

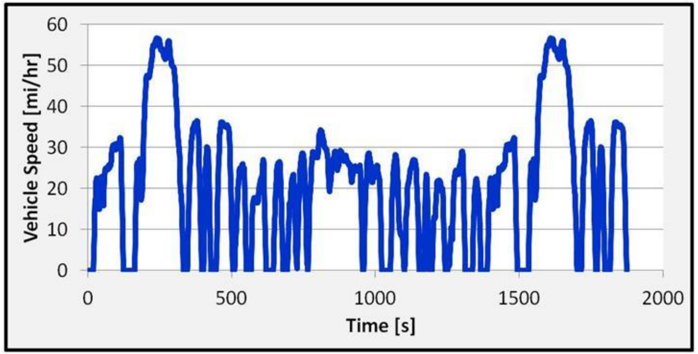
- World Light Transient Protocol (WLTP)
- Federal Test Procedure 75 (FTP-75)
- Supplemental FTP US06



WLTP

US06

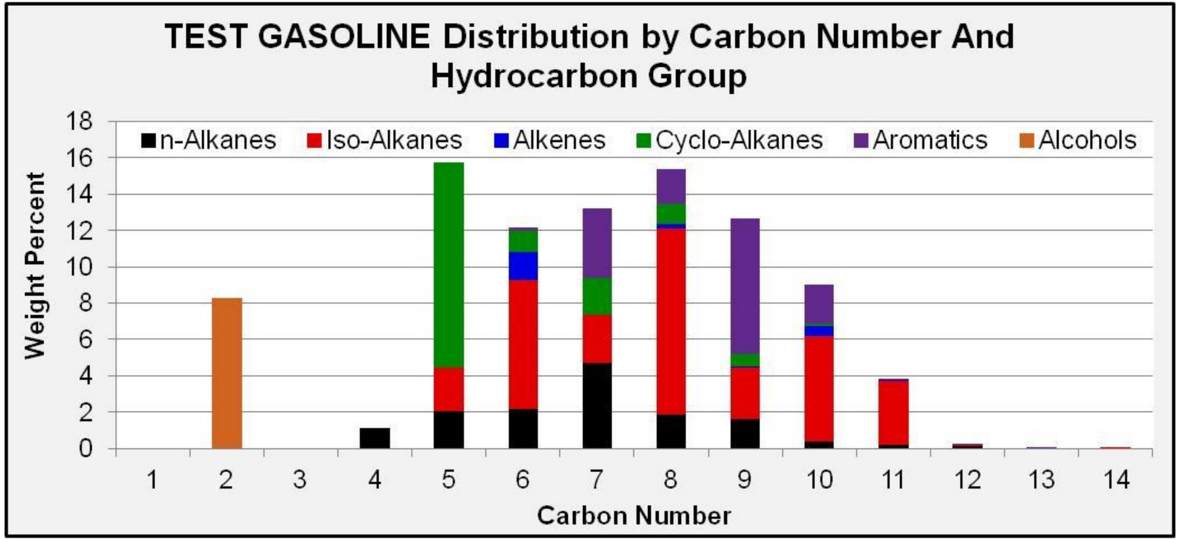




FTP-75

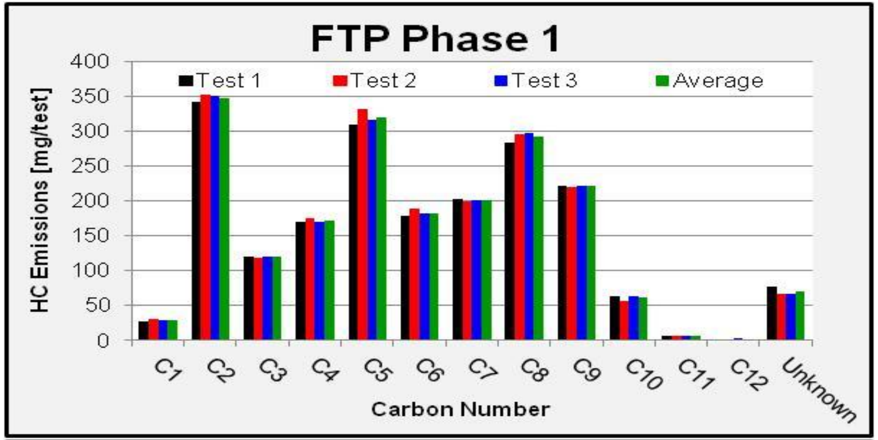
Fuel Analysis

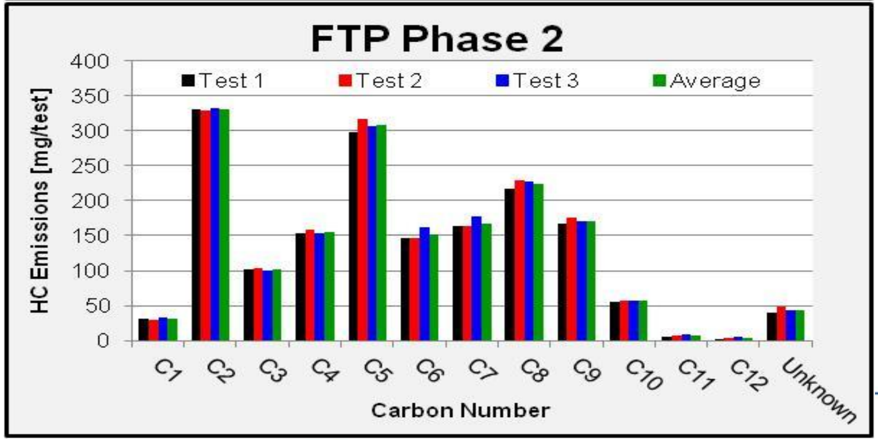
- Complete HC Breakdown of Test Fuel
- Used for Comparison with Exhaust Samples
- 10% EtOH, 87 AKI LEV-III Type Certification Fuel

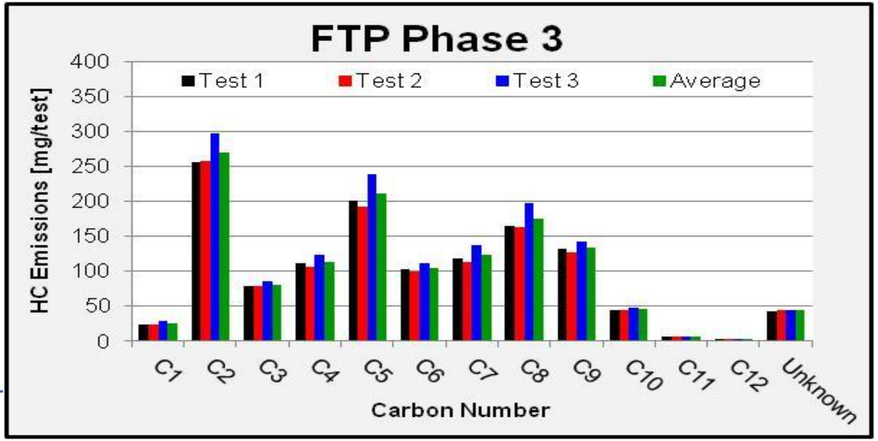


HC Speciation Test Repeatability

- Three FTP-75 Cycles Were Evaluated to Quantify Repeatability of HC Speciation
  - Repeatability was determined to be excellent over these three tests
- Future Test Cycles Were Evaluated Twice to Save Resources







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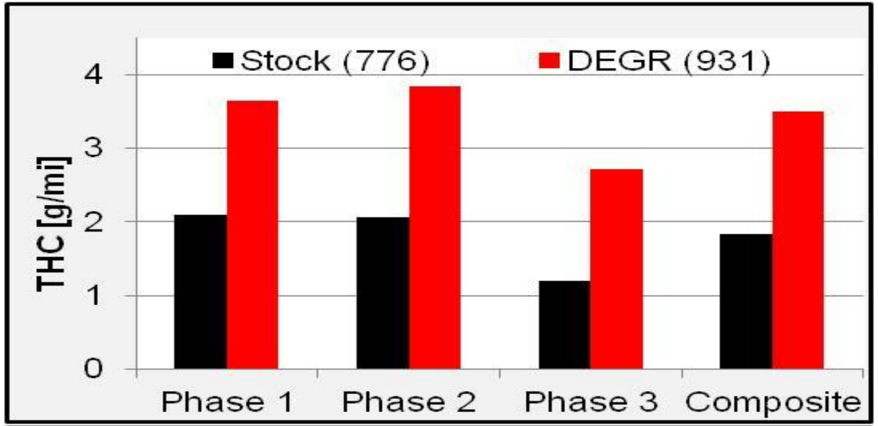
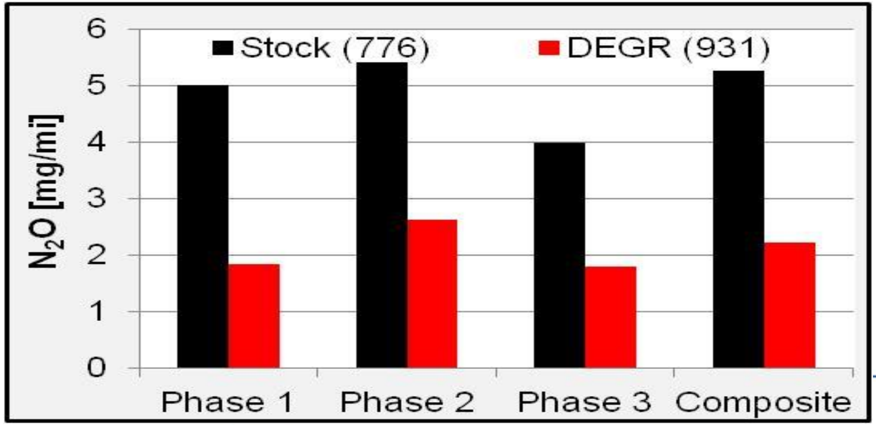
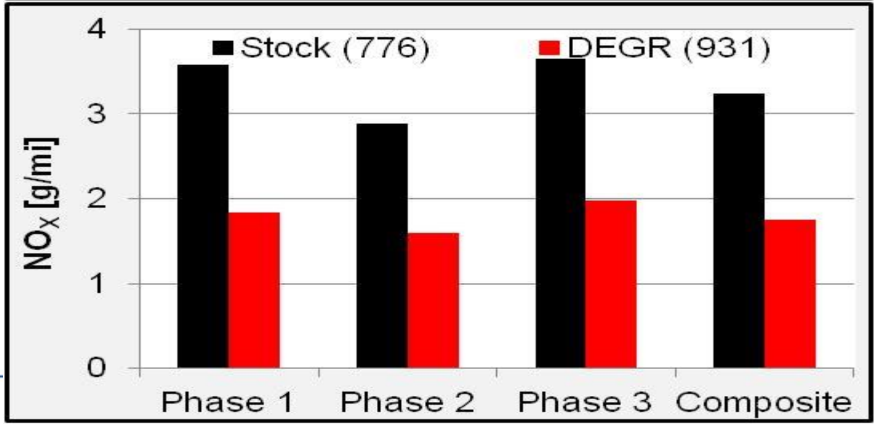
FTP-75 Emissions Summary

- HC Emissions were Observed to Increase by ~100% Over the FTP-75
- NO_X and N_2O Emissions were Reduced by ~50%
- CO was Nearly Constant Between Both Vehicles, so It is Not Shown

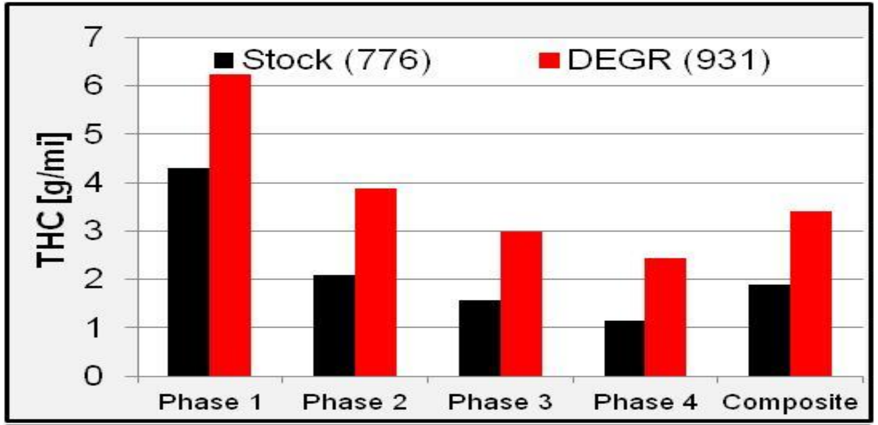


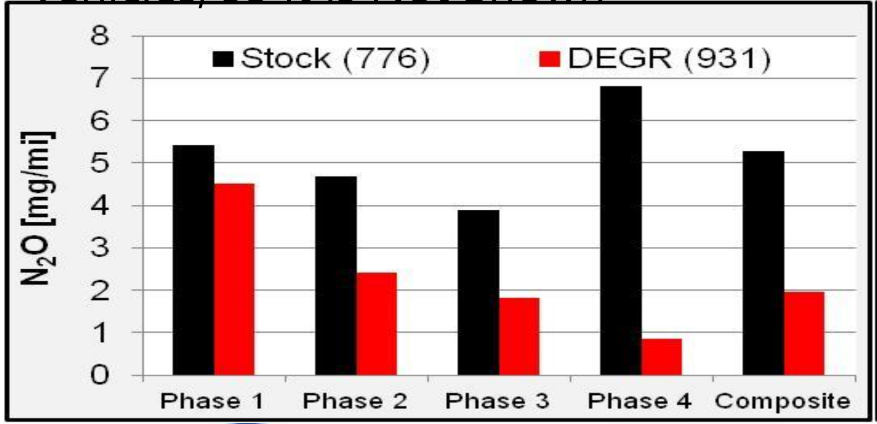


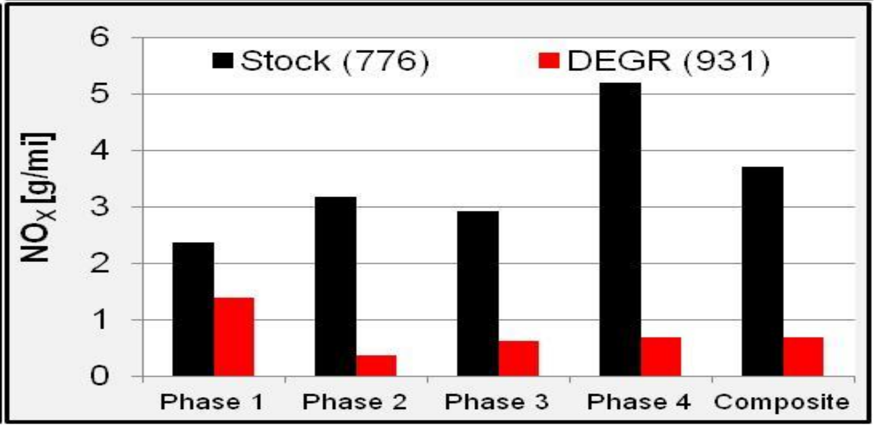


WLTP Emissions Summary

- HC Emissions were Observed to Increase by ~60% Over the WLTP
- NO_X Emissions Decreased by Nearly 80% and N_2O Emissions Decreased by ~60%
- CO was Nearly Constant Between Both Vehicles, so It is Not Shown







D-EGR
FTP-75 HC Speciation Results

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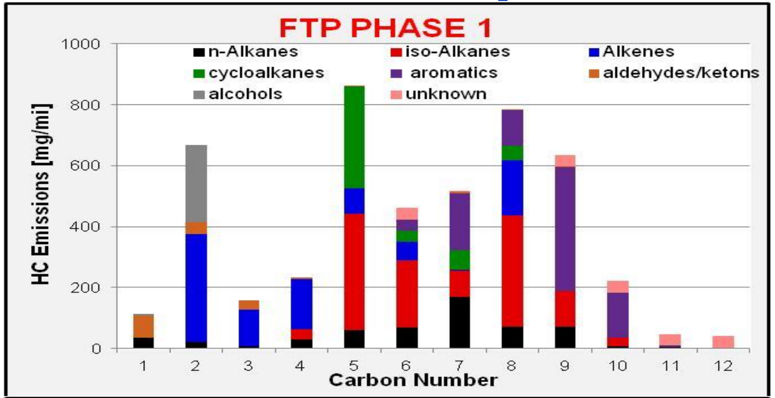
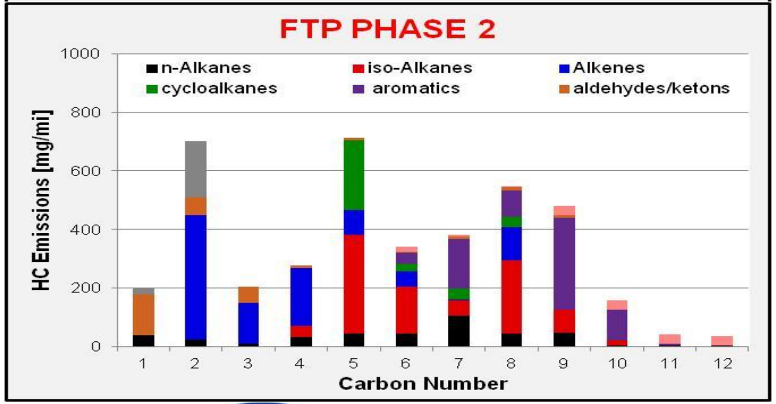
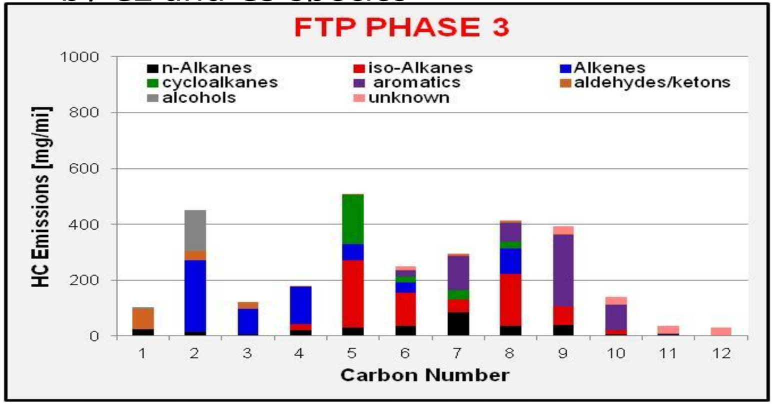
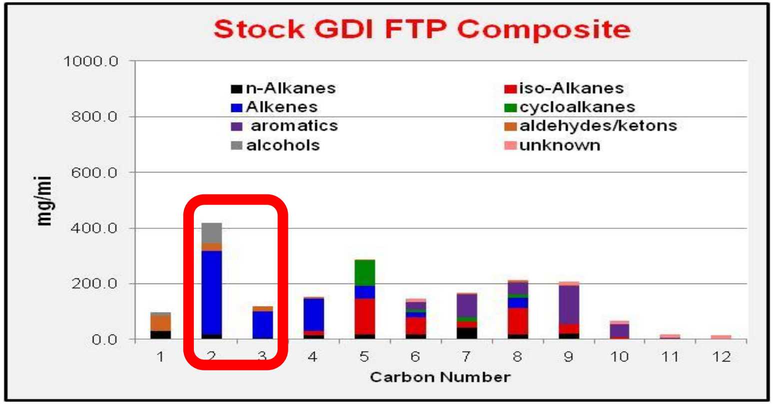


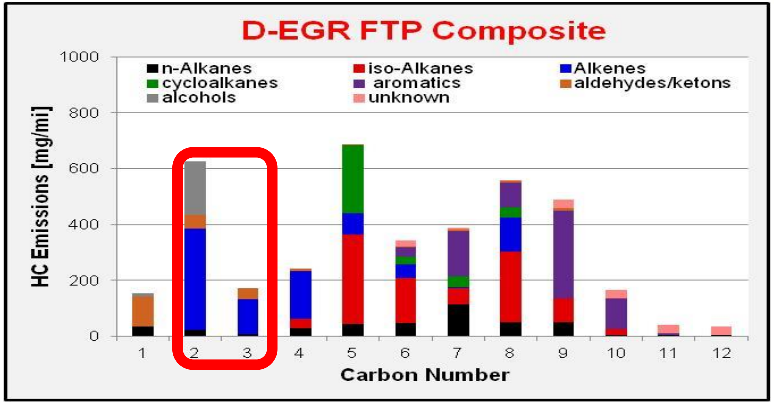
- Phase 3 of the FTP-75 Cycle Had the Lowest Total HC Emissions
- HC Distribution Varied Among the Phases
  - Phase 1: HC Emissions were dominated by C5 and C8 species
  - Phases 2 & 3: HC emissions were dominated by C2 and C5 species



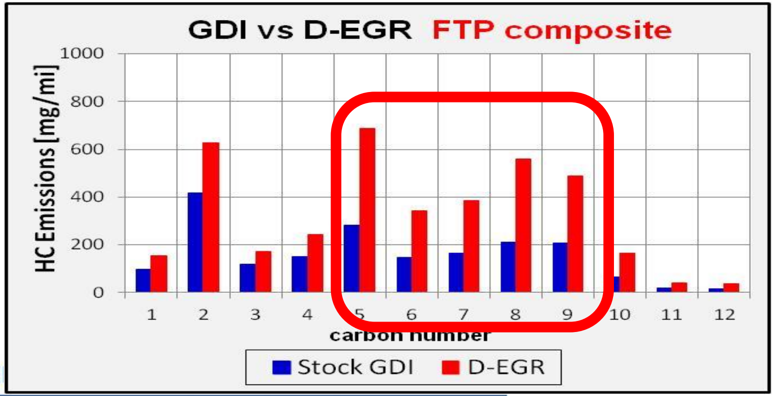


D-EGR vs Stock GDI FTP-75 HC Speciation Results





- Clear Differences in HC Emissions Between Stock GDI and D-EGR Were Observed
  - EtOH was much higher for D-EGR exhaust than stock GDI
  - Other than EtOH, C1 – C4 HC species and mass were similar to stock GDI
  - Largest difference in HC speciation was a substantial increase in C5 – C9 species present in D-EGR exhaust



D-EGR vs Stock GDI WLTP HC Speciation Results

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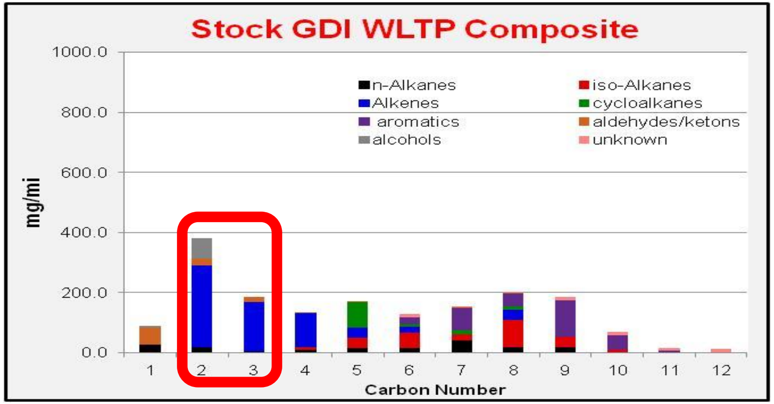

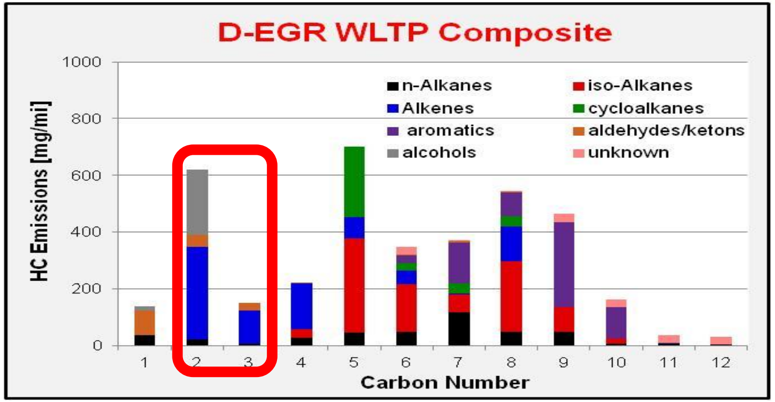

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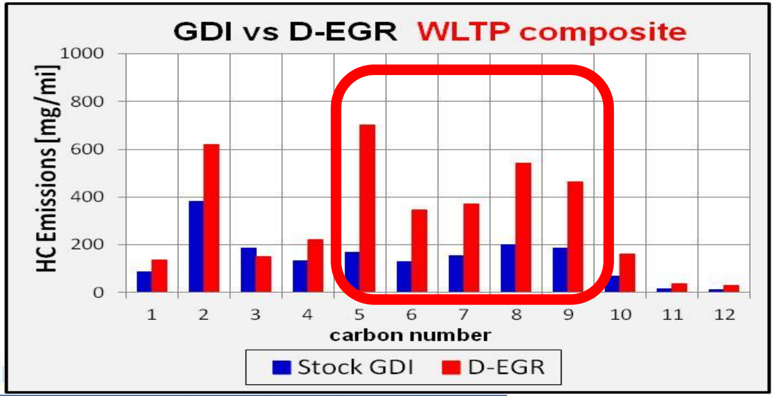

Vehicle Emissions Results – Further Hydrocarbon Speciation

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- D-EGR vs. Stock
- Total HC = 2x
- Saturated = 4.5x
- Unsaturated = 1.4x
- Aromatic = 3.4x
- Cyclic Aliphatic = 6x
- Ethanol = 6.8x

HC	Name	STOCK	D-EGR
CH4	methane	15	69
CH2O	Formaldehyde	78	102
C2H4	**Ethene**	315	**297**
C2H6	Ethane	17	18
C2H4O	Acetaldehyde	31	53
C2H5OH	**Ethanol**	38	**259**
C3H6	Propene	150	114
C3H8	Propane	2	6
C4H8	Butene	110	154
C4H10	n-Butane	6	
C4H10	iso-butane	6	
C5H10	pentene	34	86
C5H12	n-pentane	10	
C5H12	iso-pentane	27	59
C5H10	cyclopentane	52	319
C6H12	hexene	14	60
C6H14	n-hexane	9	63
C6H14	iso-hexane	36	216
C6H12	cyclohexane	5	31
C6H6	benzene	30	27

HC	Name	STOCK	D-EGR
C7H14	heptene	1	5
C7H16	n-heptane	23	145
C7H16	iso-heptane	12	77
C7H8	Toluene	58	146
C8H16	octene	13	151
C8H18	n-octane	10	59
C8H18	iso-octane	58	316
C8H10	dimethylbenzene	34	100
C9H20	n-nonane	10	59
C9H20	iso-nonane	22	92
C9H12	mesitylene	78	367
C10H14	Durene	30	142
	Total	**985**	**1933**
Total saturated		263	1179
Total unsaturated		668	920
Total aromatic		230	782
Total cyclic aliphatic		57	350

Values are concentration in ppmV

Vehicle Emissions Results – Further Hydrocarbon Speciation

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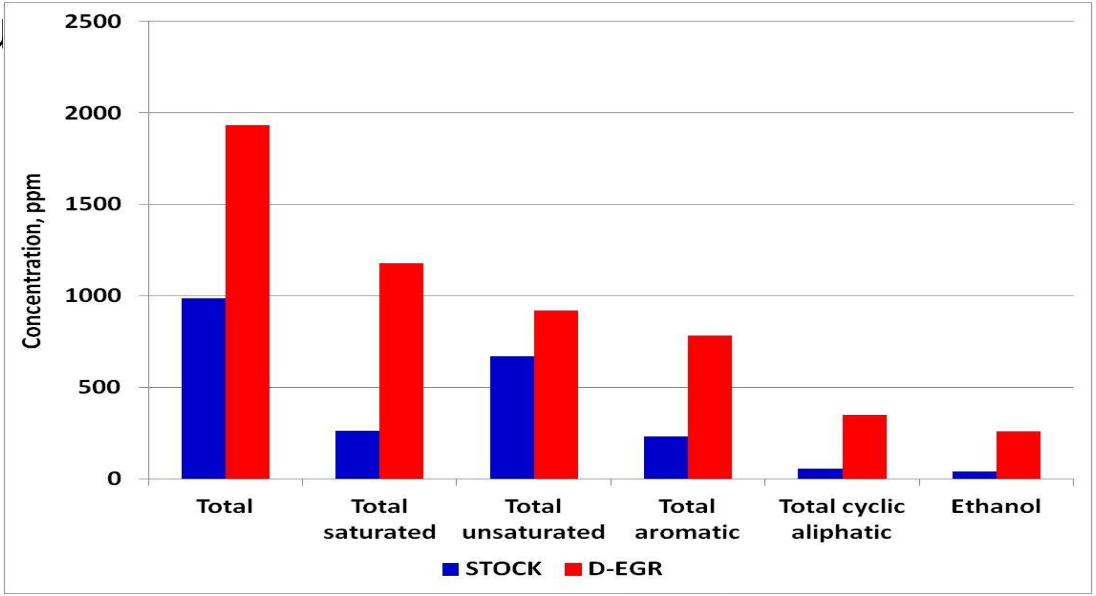
- Majority of Increased HCs are Unburned Fuel
  - Only small increase in unsaturated HCs (combustion produ



Boundary Conditions for Low Temperature Catalysis Evaluation

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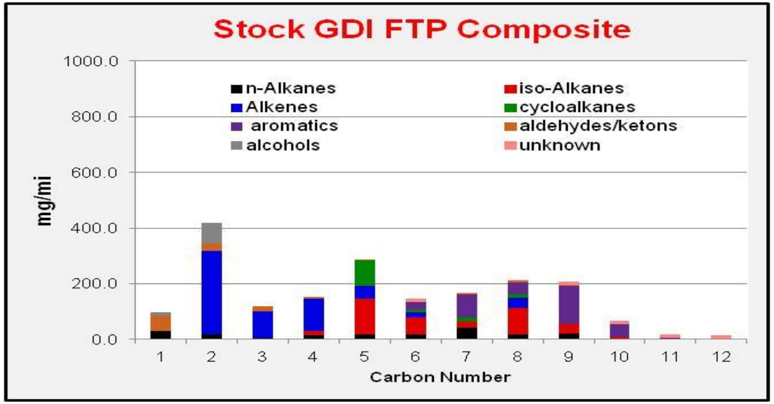
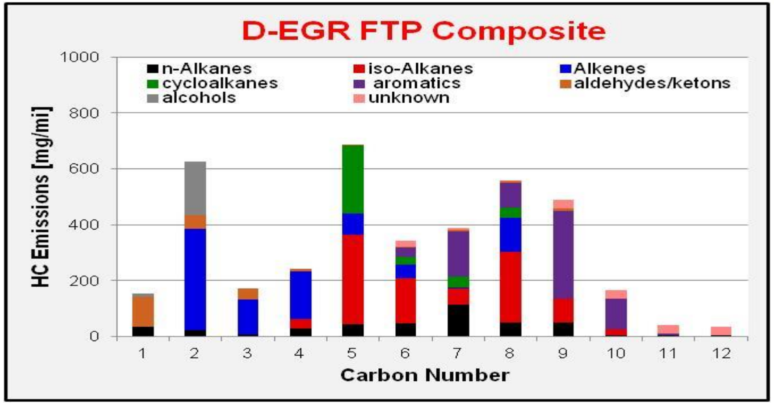




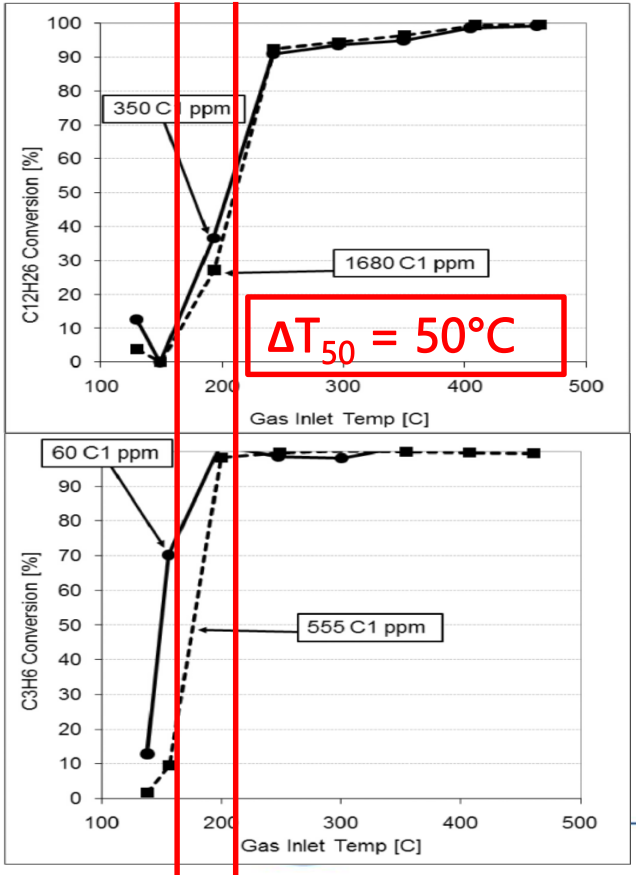
- D-EGR HC Mixture is Significantly Different from Stock GDI
- USCAR LT Oxidation Protocol Does Not Take Into Account Differences in HC Concentration or Speciation for LTC Gasoline Strategies
- Boundary Conditions Can Have a Significant Impact on the Observed Behavior of New Catalyst Strategies

USCAR LT Protocol

Constant Components	Stoichiometric GDI [S-GDI]	Clean Diesel Combustion [CDC]	Lean GDI [L-GDI]	Low Temp Combustion of Gasoline [LTC-G]	Low Temp Combustion of Diesel [LTC-D]
[O_2]	0.74%	12%	9%	12%	12%
[H_2O]	13%	6%	8%	6%	6%
[CO_2]	13%	6%	8%	6%	6%
[H_2]	1670 ppm	100 ppm	670 ppm	670 ppm	400 ppm
Variable Components	all in [ppm]				
[CO]	5000	500	2000	2000	2000
[NO]	1000	200	500	100	100
	Hydrocarbon – [ppm] on C_1 basis**				
Total [HC]	3000	1400	3000	3000	3000
[C_2H_4]	700 (1050)	500 (778)	700 (1050)	700 (1050)	500 (1667)
[C_3H_6]	1000 (1500)	300 (467)	1000 (1500)	1000 (1500)	300 (1000)
[C_3H_8]	300 (450)	100 (155)	300 (450)	300 (450)	100 (333)
[$i\text{-}C_8H_{18}$]	1000 (0)	-	1000 (0)	1000 (0)	-
[$n\text{-}C_{12}H_{26}$]	-	500 (0)	-	-	2100 (0)

HC C_1 concentrations in parenthesis to be used if the user chooses to omit the liquid HC species

Hydrocarbon Species Affect Lightoff Temperature



- The Impact of HC Species Have Been Well Documented in the Literature
- Different HC Species have Different Reactivity, and Can Affect HC Light-Off on PGM Catalysts
- Short Chain Alkenes Like Ethene and Propene are Typically More Reactive than Long Chain Alkanes
- Similarly, Oxygenated Species Like EtOH Can be Difficult to React

SAE 2011-01-1137

Advanced Concepts Require Detailed Understanding of HC Speciation

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- New Strategies, Like HC Traps are Very Selective for HC Adsorption
- Traps Can be Tuned for Different Species, but HC Composition Must be Known
- New Combustion Strategies Will Likely Need Alternative F axi

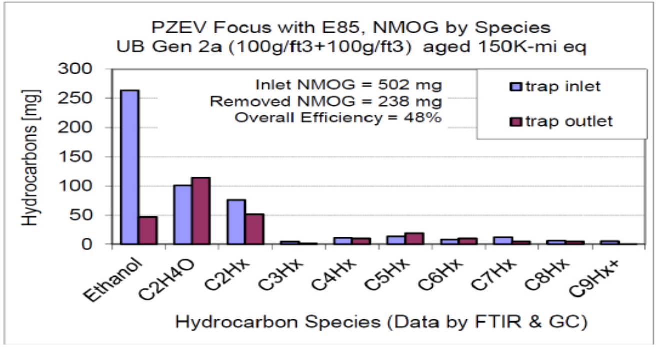

Figure 26. Inlet & Outlet HC Emissions Speciation Gen 2A

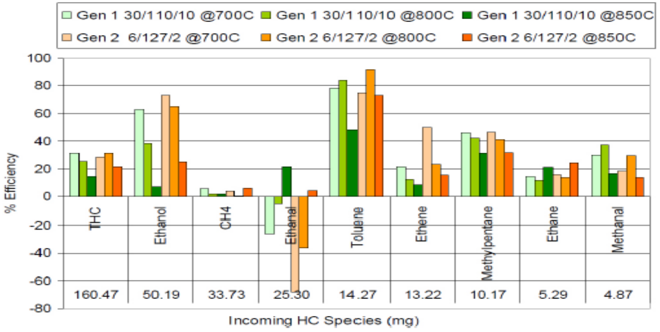

Figure 19. Durability Study - HC Speciation with E85

SAE 2013-01-1297

Project Benefits: Emission Control System Design

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- Understanding The Detailed Composition Of HC Emissions From D-EGR Combustion Technology Will Enable The Design And Development Of Optimized Aftertreatment Systems
  - Emissions characterization component of project will determine requirements for aftertreatment based HC control for LEV-III and Euro 6
  - Exhaust temperature profile will provide guidance for catalyst selection
- Development Of Novel Emission Control Solutions
  - Typical stoichiometric engines utilize three way catalysts for emissions reduction
  - Due to changing emissions chemistry and availability of H_2 reformate on-board, the D-EGR vehicle may be able to utilize alternative emission control solutions to reduce fuel consumption
  - Potential strategies include: Zeolite HC traps, passive NO_X adsorbers, HC-SCR, and H_2 SCR catalysts

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