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FINAL REPORT

Lean Gasoline System Development for Fuel Efficient Small Cars

Period Covered: May 1, 2010 through September 30, 2013

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National Energy Technology Laboratory

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1. EXECUTIVE SUMMARY

The General Motors and DOE cooperative agreement program DE-EE0003379 is completed. The program has integrated and demonstrated a lean-stratified gasoline engine, a lean aftertreatment system, a 12V Stop/Start system and an Active Thermal Management system along with the necessary controls that significantly improves fuel efficiency for small cars. The fuel economy objective of an increase of 25% over a 2010 Chevrolet Malibu and the emission objective of EPA T2B2 compliance have been accomplished.

A brief review of the program, summarized from the narrative is:

> *The program accelerates development and synergistic integration of four cost competitive technologies to improve fuel economy of a light-duty vehicle by at least 25% while meeting Tier 2 Bin 2 emissions standards. These technologies can be broadly implemented across the U.S. light-duty vehicle product line between 2015 and 2025 and are compatible with future and renewable biofuels. The technologies in this program are: lean combustion, innovative passive selective catalyst reduction lean aftertreatment, 12V stop/start and active thermal management. The technologies will be calibrated in a 2010 Chevrolet Malibu mid-size sedan for final fuel economy demonstration.*

The program had been operated in three phases from 2010 to 2013 and supported between 4.5 to 24 full-time-equivalent development staff based on workload. During all phases the technologies had been initially developed on engine dynamometers, integrated in to development vehicles and subsequently demonstrated to compare to the production baseline vehicle. To support the performance evolution throughout the phases, two entirely new unique engines had been designed and developed as well as four entirely new unique lean aftertreatment systems, with demonstration in five Chevrolet Malibu vehicles.

The program phases constituted; applied research, exploratory development and advanced development. Phase 1 consisted of research activities to define the lean combustion system and passive lean aftertreatment hardware as well as the initial controls. Phase 2 included developing the refined 2.2L SG5 lean combustion engine, exploring the G1 passive lean aftertreatment system, development transition to the G4 passive + active lean aftertreatment system, integration in to a vehicle and demonstrating the available fuel economy and emissions performance. Phase 2 additionally incorporated development and bench demonstration of the 12V Stop/Start and ATM systems fuel economy performance enhancement capability. Phase 3 focused on generating an optimized 1.4L Lean Downsize Boost combustion engine and G4 passive + active lean aftertreatment system which demonstrated the extended fuel economy potential and the full emissions performance capability under all vehicle operating conditions.

2. INTRODUCTION

General Motors (GM) and the Department of Energy (DOE) initiated a cooperative agreement program to develop new vehicle technologies, DE-EE0003379. The program scope had been initiated to support the targeted development and synergistic integration of four cost competitive technologies to improve fuel economy of a light-duty vehicle by at least 25% while meeting US EPA Tier 2 Bin 2 (T2B2) emissions standards. Ideally the technologies could be broadly implemented across the U.S. light-duty vehicle product line between 2015 and 2025 and are to be compatible with future and renewable biofuels. The technologies initially targeted in this program are: lean gasoline combustion, innovative passive Selective Catalyst Reduction (SCR) lean aftertreatment, 12 Volt Stop/Start (12V S/S) and Active Thermal Management (ATM). The technologies had been initially developed on engine dynamometers, integrated in to development vehicles and subsequently demonstrated to compare to the production baseline vehicle. Figure 1 details the comparative baseline and demonstration vehicles along with the advanced technologies targeted for integration.

VEHICLE			
Phase	**Production Baseline**	**2 Exploratory Development**	**3 Advanced Development**
Model	Chevrolet Malibu 1LT 	Chevrolet Malibu 1LT-SG5 	Chevrolet Malibu 1LT-LDB 
Model Year	2010	Experimental	2018+ feasibility target
Engine	Ecotec 2.4L PFI (LE5)	2.2L SG5 (Spray-Guided version 5)	1.4L LDB (Lean Downsize Boost)
12v Stop/Start	none	investigate	12v S/S Integrated
Active Thermal Mgmt	none	investigate	Pump Integrated
Lean NOx Conversion	none	G1→G4 Passive + Active SCR	G4 Passive + Active SCR

Figure 1: Comparative Baseline and Technology Demonstration Vehicles

The program schedule constituted development in three phases from 2010 to 2013; Phase 1 – Applied Research, Phase 2 – Exploratory Development and Phase 3 – Advanced Development. Phase 1 consisted of research activities to define the lean combustion system and lean aftertreatment hardware as well as the initial controls. Phase 2 included developing a refined lean combustion engine, an initial lean aftertreatment system, integration in to a vehicle and demonstrating the available fuel economy and emissions performance. Phase 2 additionally incorporated development and bench demonstration of the 12V S/S and the ATM systems fuel economy performance enhancement capability. Phase 3 focused on generating an optimized lean combustion engine and lean aftertreatment system which demonstrated the extended fuel economy potential and the full emissions performance capability under all vehicle operating conditions. The top-level tasks of the program are highlighted in Figure 2 and the evaluation milestone goals in Figure 3.

Figure 2: Schedule

Timeline	Evaluation Milestone (1)	Evaluation Milestone (2)
12/22/10	SG Engine Installed	12V S/S Ready
6/24/11	Hwy FE > 13%	NOx Eff. > 60% on H18
12/23/11	Cold ftp & Hwy FE > 13%	Gen 2 A/T dyno results
6/22/12	ATM FE >1.5%	Emissions < 200% w/o PM
12/21/12	C & H FE > 20%	Emissions < 150%
7/24/13	C & H FE > 25%	Emissions T2B2
8/28/13	Demo Drives	Final Report

Figure 3: Milestones Goals

The initial approved budget represents the total initial project funding of $15,411,724, equally shared between the DOE and GM. The cumulative budgets along with the monthly spends are depicted in Figure 4. The Forecasted Cumulative budget was $17,192,787 and the actual Spent Cumulative budget was $18,041,707. The Spent Cumulative budget expense finalized at a greater level that the initial program funding with the offset covered by GM. The greater budget expense had been due to the additional risk mitigation activities incurred during phase 3 with additional engine and aftertreatment development hardware as well as additional supplier support for engine calibration and vehicle installation. The complete development vehicle fleet is detailed in Figure 5.

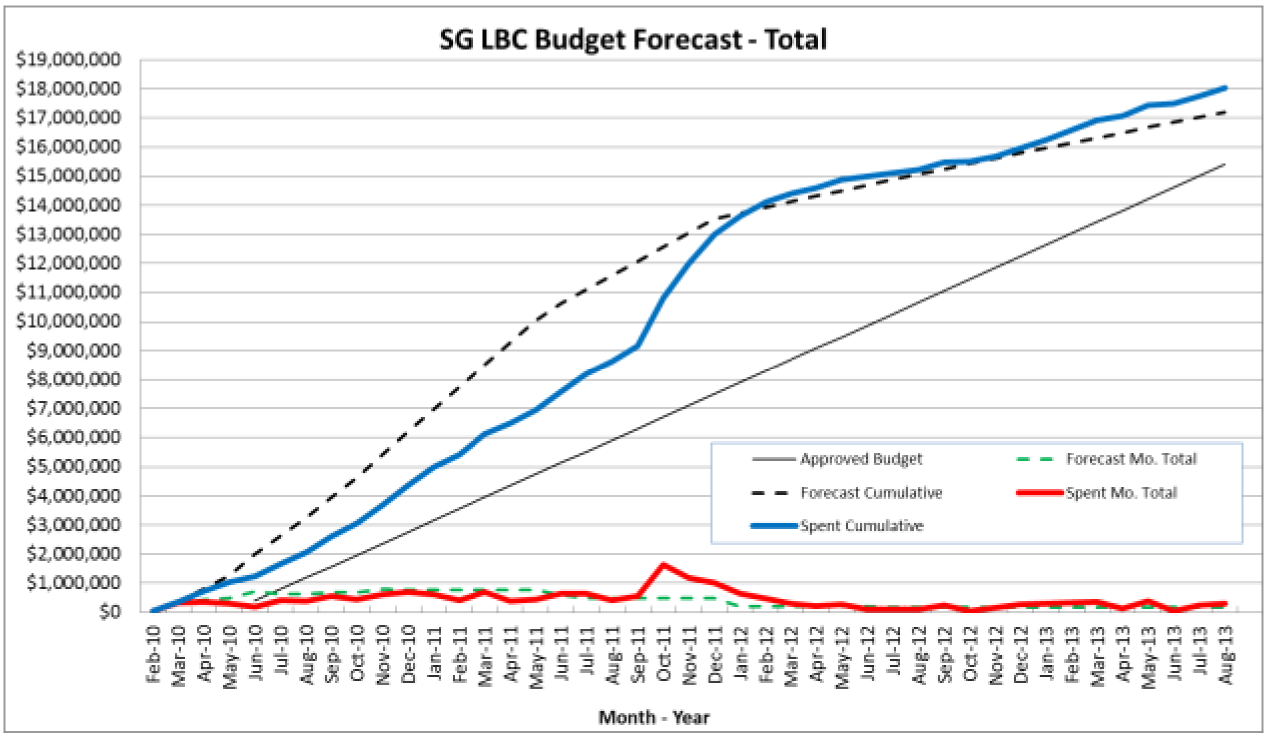

Figure 4: Budget

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VEHICLE #	ENGINE	AFTERTREATEMENT SYSTEM	ADDED FE SYSTEMS
10Z32573	LE5	Baseline FE Vehicle	-
10Z32571	SG5	G1 → G2 → G3 Passive SCR	-
10Z32572	SG5	Active SCR → G4 Passive + Active SCR	-
10Z63988	LDB Beta	G3 Passive SCR	ATM
10Z28286	LDB Gamma	G4 Passive + Active SCR	12V S/S

Figure 5: Development Vehicle Fleet

The program had collaborated with the following suppliers in order to develop a common understanding of the integration challenges to implement lean gasoline combustion and lean aftereatment systems in to production:

- Ricardo - Calibration and combustion performance evaluation of lean gasoline combustion technology enablers
- Bosch - Fuel injector to enable multiple close-spaced injection capability
- Umicore - Aftertreatment hardware formulations supporting passive + active ammonia systems integration

The development staff that had supported the program directly at GM and at the collaborative development suppliers is detailed in Figure 6. The number of directly attributed jobs either retained or created for this program peaked at approximately 24 Full-Time-Equivalent (FTE) during Phase 2 and reduced down to approximately 4.5 FTE during the final Phase 3 of the program.

Responsibility	Department	FTE
Leadership		30.1
Engineering Group Manager	I&E	0.5
Lab Group Manager	Controls	0.3
Lab Group Manager	R&D	0.5
Engingeering Group Manager	AE Gas Engine	0.3
Program Manager	I&E/Contract	1
Engine Design & Build		
Project Engineer	AE Gas Engine	1
Designer	AE Gas Engine	2
Build Technician	AE Gas Engine	1
Build Coordinator	AE Gas Engine	0.5
Lean Aftertreatment		
Sr. Staff Researcher	R&D	3
Sr. Staff Engineer	I&E AdvEng	2
Dyno Technician	R&D dev	3
Controls		
Staff Engineer	Controls	2

Responsibility	Department	FTE
Combustion		
Sr. Staff Researcher	R&D	2
Dyno Technician	R&D Dev	1
Calibration		
Sr. Staff Engineer	I&E AdvEng	1
Staff Researcher	I&E AdvEng	1
Staff Engineer	AE Gas Engine	1
Build Technician	I&E AdvEng	0.5
Supplier Development		
Calibration Engineer	Engine Dev.	1
Dyno Technician	Engine Dev.	2
Calibration Engineer	After. Dev.	1
Dyno Technician	After. Dev.	1
Vehicle Technician	Veh. Installation	1
Program Manager	Veh. Installation	0.5

Figure 6: Development Staff Throughout Program

3. *ACCOMPLISHMENTS vs. OBJECTIVES*

INTEGRATION OBJECTIVE: Lean Combustion, Lean Aftertreatment, 12V S/S, ATM

VEHICLE			
Phase	**Production Baseline**	**2 Exploratory Development**	**3 Advanced Development**
Model	Chevrolet Malibu 1LT 	Chevrolet Malibu 1LT-SG5 	Chevrolet Malibu 1LT-LDB 
Model Year	2010	Experimental	2018+ feasibility target
Test Weight (lbs)	3875 (3436 curb)	3875	3875
Transaxle Type	6T70 A FWD	6T40 A FWD (MH8)	6T40 A FWD 12v S/S (MHH)
ENGINE			
Engine	Ecotec 2.4L PFI (LE5)	2.2L SG5 (Spray-Guided version 5)	1.4L LDB (Lean Downsize Boost)
Engine Base	---	L850 2.0L DI Turbo (LNF)	SGE 1.4L DI Turbo (LE2)
Compression Ratio	10.4 : 1	12.0 : 1	10.5 : 1
Bore x Stroke	88 x 98 mm	86 x 94.6 mm	74 x 81.3 mm
Bore / Stroke Ratio	0.90	0.91	0.91
Peak Power (hp)	169 @ 6400	162 @ 6500	
Peak Torque (lb-ft)	160 @ 4500	155 @ 3700	
Aspiration	Naturally Aspirated	Naturally Aspirated	Turbo w/ A→W CAC
Cyl Block / Cyl Head Material	Aluminum / Aluminum	Aluminum / Aluminum	Aluminum / Aluminum
Valvetrain	VVT, roller follower, 4v/cyl	VVT, roller follower, 4v/cyl	
Intake Port Arrangement	Bifurcated port	Split port w/PDA	Split port w/PDA
Fuel Injection System	Seq. Port Injection	Central Direct Injection	Central Direct Injection
Fuel Injection Pressure	4 bar	200 bar	200 bar
Fuel Injector Type		HDEV 5.2, 6-hole solenoid	
Multiple Fuel Injection		No	yes
Ignition System		Bosch 100 mJ high energy	
Controller		E39A+WRAF	
EGR System		post-TWC, long, non-cooled	post-TWC, short, cooled
12v Stop/Start	none	investigate	12v S/S Integrated
Active Thermal Mgmt	none	investigate	Pump Integrated
LEAN AFTERTREATMENT			
HC/CO/NOx Abatement	CC TWC	CC + UF TWC	CC + CC TWC
Lean NOx Conversion	none	G1→G4 Passive + Active SCR	G4 Passive + Active SCR
PM Refinement	none	none	none
PROCURED QUNATITY			
Development Vehicles	1	2	2
Lean Combustion Engines	1	10	4
Lean Aftertreatment Systems	1	5	4

Figure 7: Product Design Specification and Hardware Integration

EMISSION OBJECTIVE: T2B2 COMPLIANCE

T2B2 emission is a challenge for stoichiometric engines. It requires extremely fast TWC light-off in order to meet the NMHC requirement. The direct central injection cylinder head and combustion system integrated in both the SG5 and LDB engines, demonstrated good TWC light-off by enabling very aggressive spark retard while maintaining acceptable engine combustion stability.

T2B2 also has a challenging NOx standard, which combined with the relatively high engine-out NOx at lean air fuel ratios, required development of a new aftertreatment architecture. The initial focus of this project had been to develop a passive SCR system in which NH3 is generated across a TWC upstream of the SCR. Due to the high engine-out NOx, the passive system had to be supplemented by an active urea dosing system. This combined aftertreatment system is referred to as PAASS (Passive + Active Ammonia SCR System). The G4 PAASS lean aftertreatment architecture schematic is shown in Figure 8.

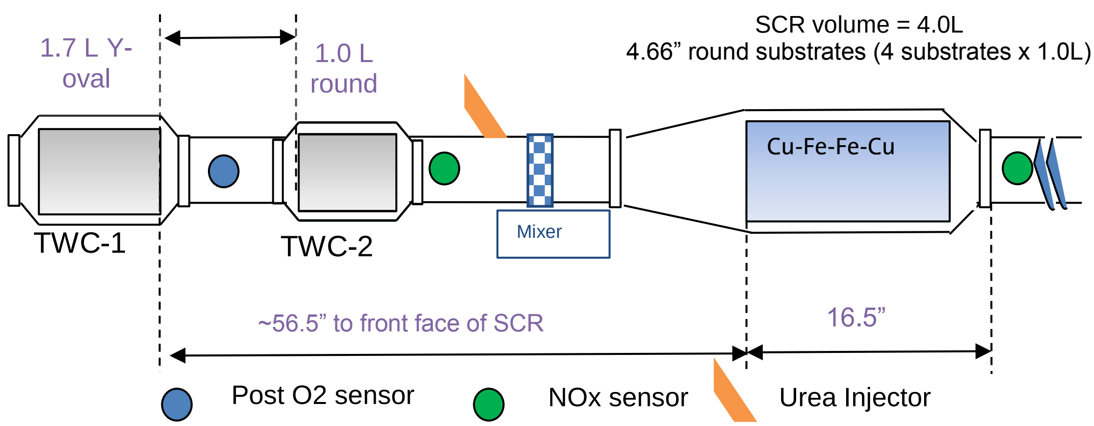


Figure 8: G4 PAASS Lean Aftertreatment System Schematic

The continued incorporation of the passive SCR system has demonstrated the ability to significantly reduce the amount of urea consumed as shown in Figure 9. This combined G4 PAASS lean aftertreatment system proved very capable and enabled demonstration of T2B2 compliance in an SG5 engine equipped development vehicle, Figures 10, 11, 12.

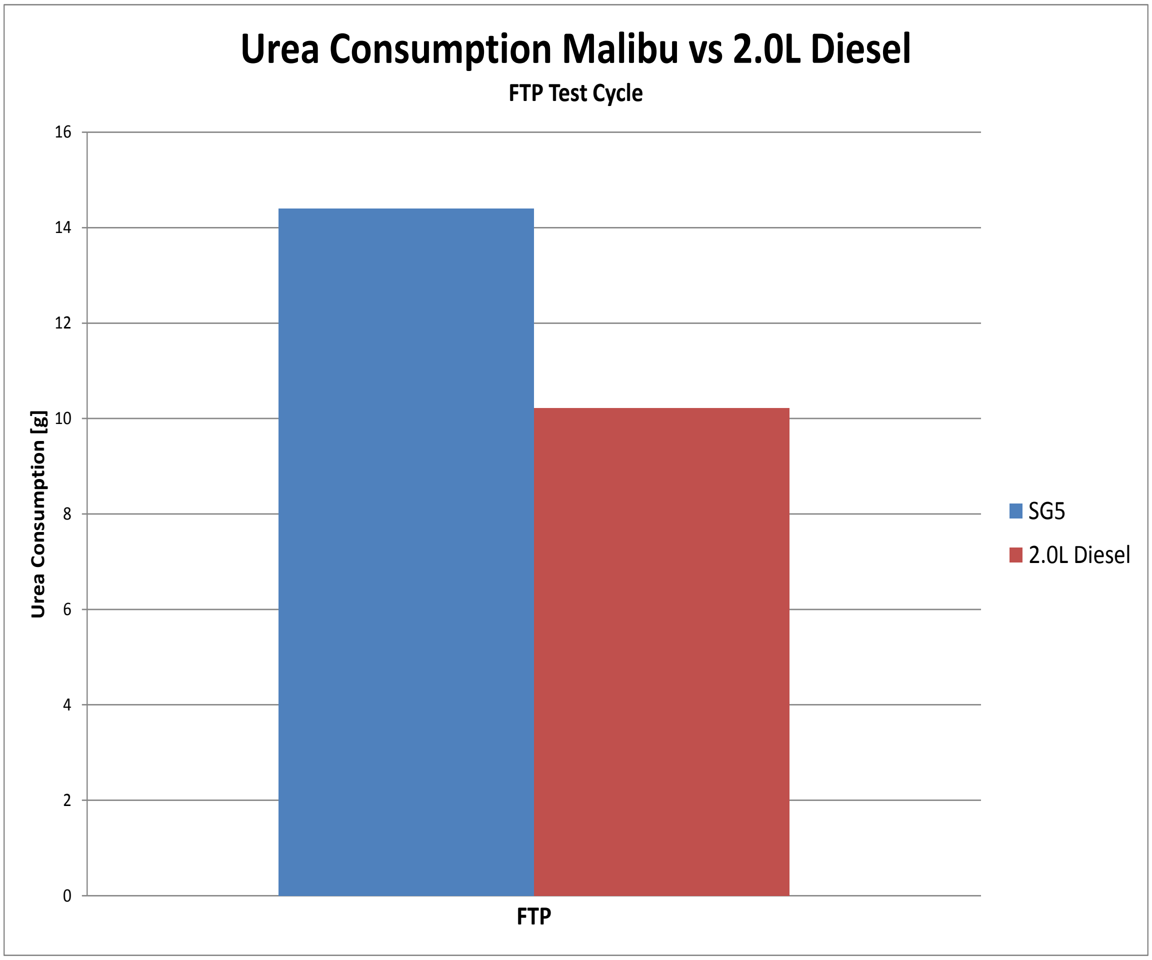


Figure 9: Comparative Urea Consumption for 2.2L SG5 Gasoline vs. 2.0L Diesel

T2B2 Standard	NMHC (gm/mi) .010	CO (gm/mi) 2.1	NOX (gm/mi) .020	Demonstration Method
SG5 Naturally Aspirated Lean-Stratified Operation	.008	0.31	.015	Chevrolet Malibu with 2.2L NA SG5 Engine and G4 PAASS Lean Aftertreatment System

Figure 10: Emissions Compliance Objective Achievement

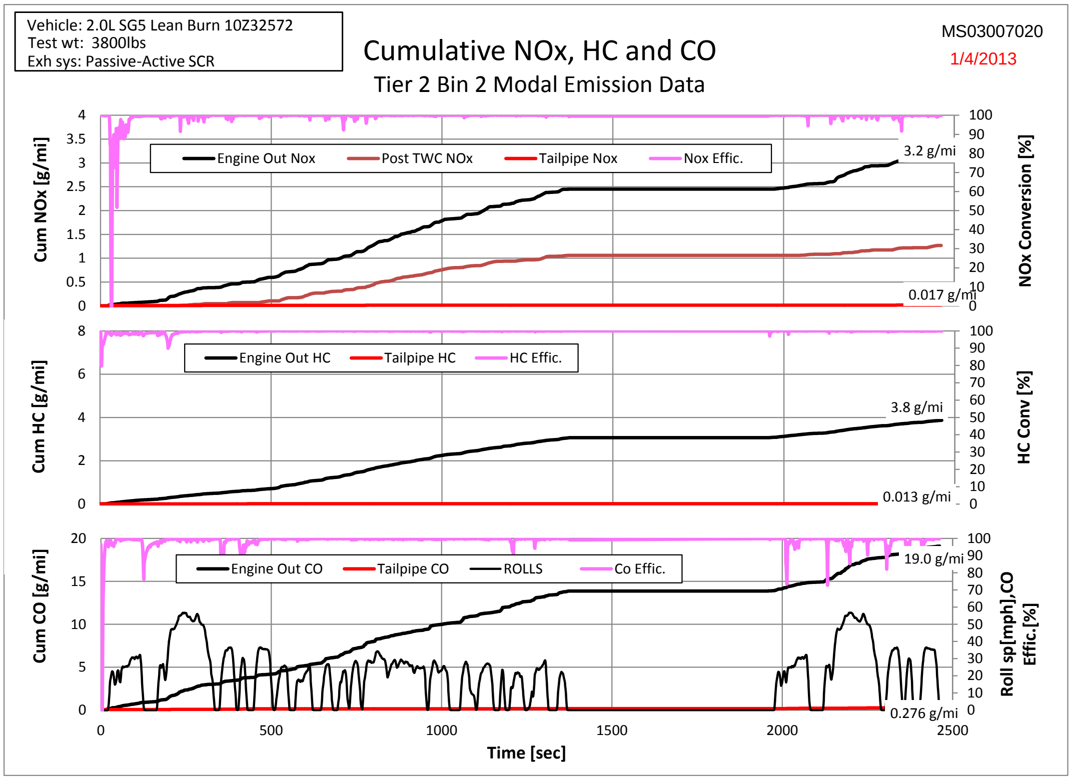


Figure 11: FTP Cold-start Cumulative Emissions of the G4 PAASS Lean Aftertreatment

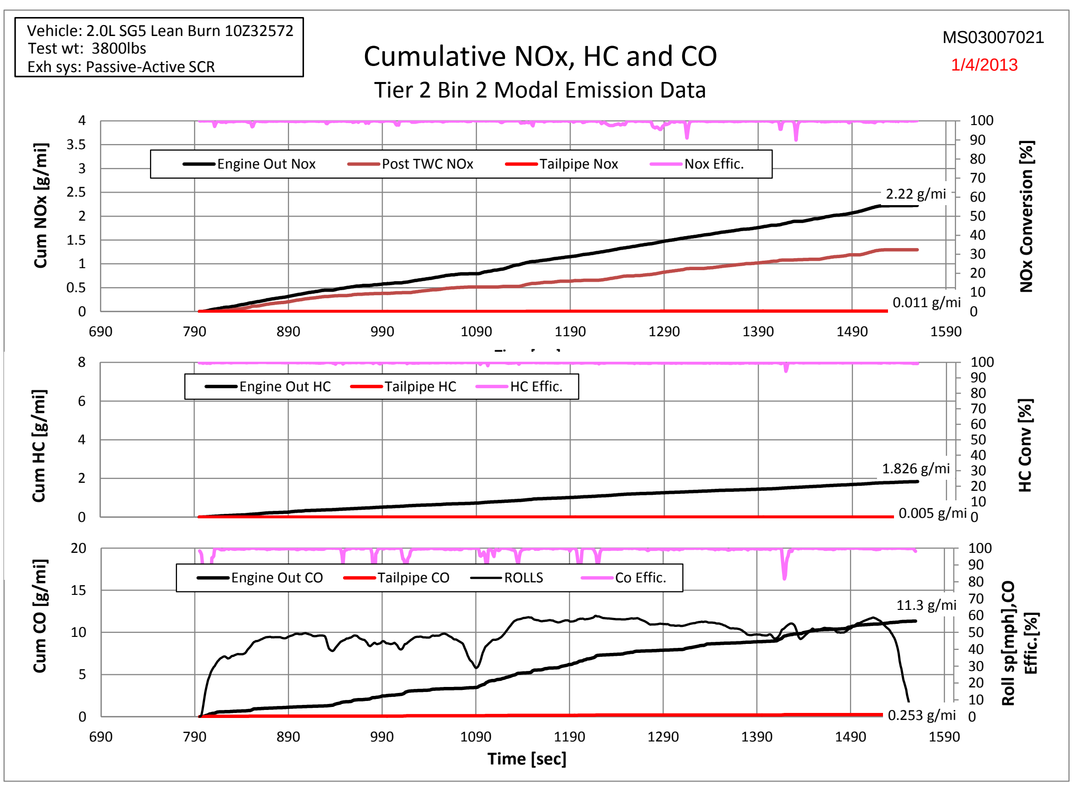


Figure 12: Highway Cumulative Emissions of the G4 PAASS Lean Aftertreatment

FUEL ECONOMY OBJECTIVE: Increase of 25% over a 2010 Chevrolet Malibu

PHASE 2 – SG5 COMBUSTION SYSTEM OPTIMIZATION

The SG5 engine combustion system was developed through CFD analysis and single cylinder engine development at GM R&D. This evolved through compromises when designing the multi-cylinder engine at GM Advanced Engineering. After engine design, procurement and assembly of the multi-cylinder engine, the SG5 engine was developed on a dynamometer. This development included optimization for EGR, port deactivation, injection strategies, and ignition system requirements. These results were run through a vehicle simulation which required steady state BSFC information from 11 steady-state points. The steady-state data is weighted based on vehicle and powertrain characteristics. The steady-state dynamometer results are shown in Figure 13.

		Speed (RPM)	Load (n-m)	BSFC Improvement PFI to Lean NA
Urban	Idle	700	19	0%
	Zone 2	1335	27	17%
	Zone 3	1565	28	19%
	Zone 4	1805	29	18%
	Zone 5	1530	95	-1%
	Zone 6	1821	80	3%
	Zone 7	2250	101	0%
Highway	Zone 8	1410	51	18%
	Zone 9	1669	60	9%
	Zone 10	1461	114	0%
	Zone 11	1692	100	0%

	Projected FE Improvement
City	12%
Hiway	8%
Combined	10%

Figure 13: SG5 Dynamometer Results & Projected Fuel Economy Improvement

This vehicle model fuel economy projection was confirmed in the exploratory development vehicle. This required focus on integration, controls and calibration work in-vehicle that spanned approximately 18 months. This activity has been a significant accomplishment that consumed considerable effort as well as drove significant hardware, controls and integration comprehension. This extended activity with the SG5 engine equipped vehicles had been required to demonstrate confidence in the vehicle model capability as demonstrated in Figure 14.

	Projected FE Improvement	Measured FE Improvement
City	12%	12%
Hiway	8%	7%
Combined	10%	10%

Figure 14: SG5 Projected vs. Measured Fuel Economy Improvement

PHASE 2 - SG5 FUEL ECONOMY IMPROVEMENT

Technology	City Schedule % FE Improvement	Demonstration Method
SG5 Combustion System	12	Engine Dynamometer Confirmed with Vehicle Chassis FE tests
12V Stop/Start	6	Engine Dynamometer Confirmed with Vehicle Chassis FE test on a SIDI Stoichiometric Engine
Advance Thermal Mgmt.	3	Engine Dynamometer Tests
SG5 City % FE Increase	***21***	

Technology	Highway Schedule % FE Improvement	Demonstration Method
SG5 Combustion System	7	Engine Dynamometer Confirmed with Vehicle Chassis FE Tests
12V Stop/Start	0	No Idles
Advanced Thermal Mgmt.	0	Hot Test
SG5 Highway % FE Increase	***7***	

Figure 15: SG5 Combined City and Highway CAFÉ Improvement of 15%

SG5 engine development resulted in an integrated vehicle that demonstrated a high level of transient drivability as well as met T2B2 emissions. However, it did not sufficiently meet the fuel economy objective, Figure 15. Due to the limited fuel economy performance, a lean-stratified downsize boosted engine project was initiated, as detailed in the submission as a potential risk mitigation.

PHASE 3 – LDB COMBUSTION SYSTEM OPTIMIZATION

The LDB engine combustion system optimization followed a path similar to the SG5 engine combustion system development. Early analysis with some simple modeling that was confirmed by engine dynamometer testing with a mechanical boost cart. After this initial combustion system definition was established, a 1.4L turbo charged spray-guided lean-stratified SIDI engine was designed, procured and assembled. This is the second complete unique engine designed, procured and built by this team in just over 24 months.

After the engine design, procurement and assembly the multi-cylinder engine was developed on an engine dynamometer. This development included optimization for EGR, port deactivation, injection strategies, and ignition system requirements. These results had been run through a vehicle simulation that required steady state BSFC information from 11 steady-state points. The steady-state data had been weighted based on vehicle and powertrain characteristics. The steady-state dynamometer results for just the combustion system are shown in Figure 16.

				BSFC Improvement	
		Speed (RPM)	Load (n-m)	PFI to Lean NA	PFI to LDB
Urban	Idle	700	19	0%	0%
	Zone 2	1335	27	17%	30%
	Zone 3	1565	28	19%	31%
	Zone 4	1805	29	18%	35%
	Zone 5	1530	95	-1%	7%
	Zone 6	1821	80	3%	9%
	Zone 7	2250	101	0%	7%
Highway	Zone 8	1410	51	18%	16%
	Zone 9	1669	60	9%	14%
	Zone 10	1461	114	0%	3%
	Zone 11	1692	100	0%	6%

	Projected FE Improvement	
City	12%	26%
Highway	8%	12%
Combined	10%	21%

Figure 16: LDB vs. SG5 BSFC Improvement and Projected FE Improvement

PHASE 3 – LDB FUEL ECONOMY IMPROVEMENT

The results shown in Figure 17, for the LDB engine combined with the earlier SG5 engine fuel enhancing technologies of 12V S/S and ATM results in achieving the 25% FE improvement:

Technology	City Schedule % FE Improvement	Demonstration Method
LDB Combustion System	26	Engine Dynamometer
12V S/S	6	Carryover from SG5 Demonstration
Advanced Thermal Mgmt.	3	Carryover from SG5 Demonstration
LDB City % FE Increase	***35***	

Technology	Highway Schedule % FE Improvement	Demonstration Method
LDB Combustion System	12	Engine dynamometer
12V S/S	0	No Idles
Advanced Thermal Mgmt.	0	Hot test
LDB Highway % FE Increase	***12***	

Figure 17: LDB Combined City and Highway CAFÉ Improvement of 25%

4. DETAILED ACTIVITIES and RESULTS

4.1. PHASE 1 – APPLIED RESEARCH

4.1.1. PASSIVE AMMONIA TWC / SCR HARDWARE

The initial investigations on lean aftertreatment fundamentals started at GM Research & Development Laboratories (GM R&D) with experiments on TWC and SCR component hardware using reactors and transferring to systems development on engine dynamometers. The research activities had been initiated as the currently available production lean aftertreatment systems had functional implementation limitations (i.e. performance, cost, packaging, etc.), Figure 18.

Figure 18: Fuel Efficiency vs. Emission Control Functional Limitations

Early passive ammonia TWC and SCR hardware investigations evaluated various lean-stratified gasoline engine exhaust aftertreatment system strategies prior to converging on the Passive Ammonia SCR System (PASS) lean aftertreatment, Figure 19. The convergence to the PASS lean aftertreatment had been due to the theorization that the system provides excellent conversion efficiencies, is mechanically simple, and catalyst cost low. The system operates by using Hydrogen (H2) and Carbon Monoxide (CO) to generate Ammonia (NH3) over the TWC and store NH3 in multiple SCRs and subsequently utilizes the stored NH3 for lean Nitrogen Oxides (NOx) conversion.

Figure 19: PASS Lean Aftertreatment for Extended High Speed Lean Operation

To support the initial component level investigations, lab reactors provided efficient screening of TWC Precious Group Metal (PGM) formulations and SCR configurations prior to dynamometer test-cell evaluation. Experimental lab reactor TWC investigations involved using supplied gas at 550 ppm Nitric Oxide (NO), 700 ppm Hydrocarbon (HC), where lean operation was simulated by 10% Oxygen (O2) and rich operation simulated by 1.5%CO / 0.5%H2 / 0.5%O2. The TWC experiments yielded an optimum PGM formulation to support maximum NH3 production under representative rich operating conditions, Figure 20.

Experimental lab reactor SCR investigations involved using Cu-Zeolite monolith (HTA, 72h) / 30,000 h-1 and a supplied gas at 200 ppm NO and 180 ppm NH3, where lean operation simulated with 10% O2 / 5% H2O / 8% CO2. The SCR experiments yielded an optimum configuration to support maximum NOx reduction under representative lean operating conditions over the greatest temperature range, Figure 21.

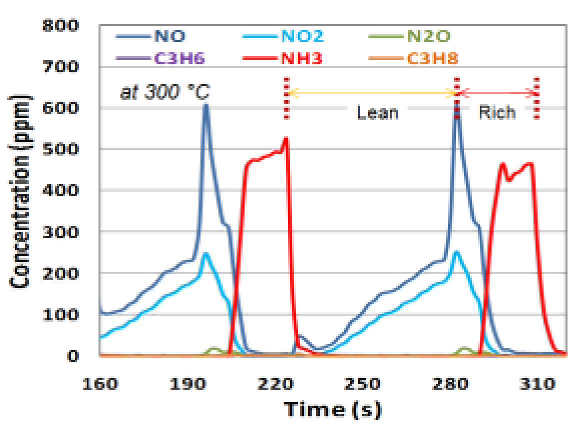


Figure 20: TWC for Efficient NH3 Generation

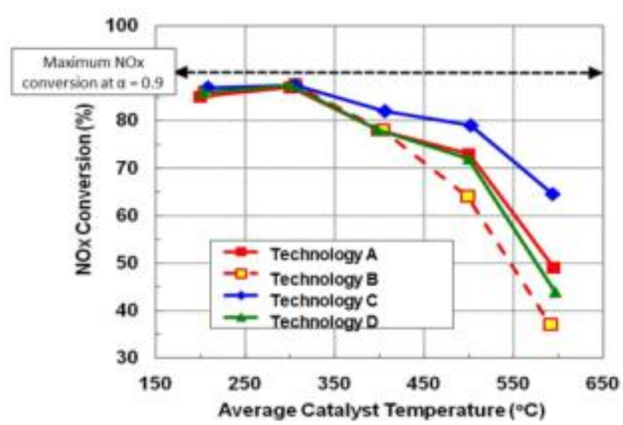


Figure 21: SCR for Efficient NOx Conversion

To support the initial system level investigations, a dynamometer test-cell had been equipped with an early generation 2.2L wall-guided lean-stratified direct-injection gasoline engine controlled by a full authority engine controller (dSPACE). The engine combustion hardware, calibration and control algorithms had been developed internally. The engine dynamometer ran both steady-state and full transient conditions. A dynamometer engine control program had been developed from vehicle data to simulate a New European Drive Cycle (NEDC) emissions test cycle. The test-cell had been instrumented with 2 dual analyzer Horiba emissions benches to monitor the exhaust gases; CO2, CO, NOx, O2, and total HC. This enabled the analysis of exhaust emissions at 4 different points in the exhaust system. Additionally, the test-cell had been equipped with 2 fast response Fourier Transform Infra-Red (FTIR) spectrometers to monitor NH3 and N2O. Finally, a mass selective spectrophotometer had been installed for monitoring H2.

Because of the low SCR convertor cost, a second SCR catalyst set had been added towards the rear of the PASS lean aftertreatment. The second SCR convertor set had been envisioned to enable lean operation at conditions where the front SCR temperature is above the operating range for passive NH3 SCR's. During the high speed portion of the NEDC the front SCR convertor reaches temperatures above the operating range of the system, Figure 22. During this portion the rear convertor stays within the targeted operating range of the convertor (shown in green on Figure 22) and converts the lean NOx to N2.

The NH3 necessary to reduce the lean NOx is generated by operating the engine slightly rich of the stoichiometric A/F ratio in a stoichiometric homogenous mode to produce H2 and NOx which then reacts across the TWC to form NH3. Initially, NH3 generation cycles had been initiated through commands in the engine dynamometer control schedule file. Figure 23, demonstrates the NH3 production at different A/F ratio operating conditions.

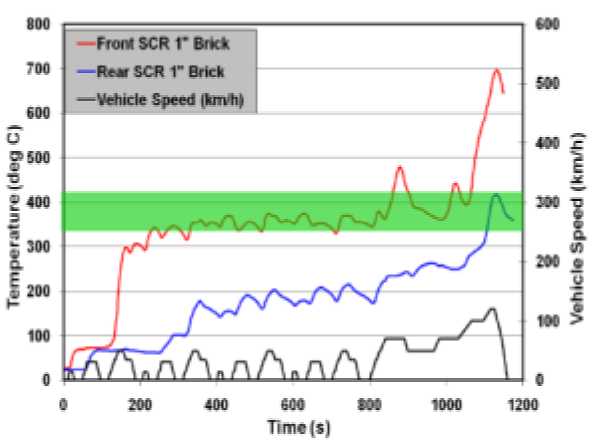


Figure 22: TWC Brick Temperature

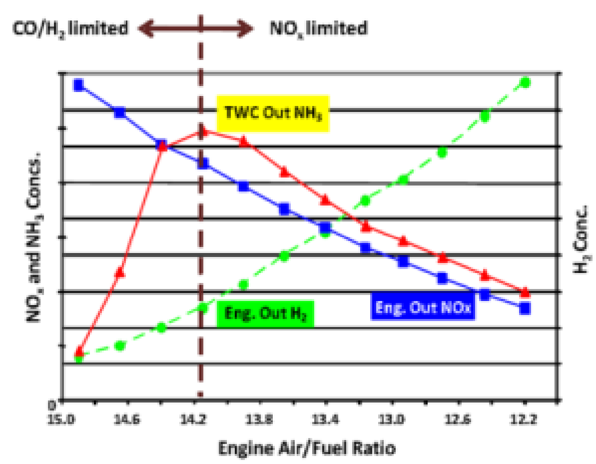


Figure 23: A/F Ratio Effect on NH3 Formation

The TWC had been verified to ensure the formulation had adequate Oxygen Storage Capacity (OSC) after the TWC had been aged. OSC reduces the loss of TWC conversion efficiency caused by short shifts of the engine A/F ratio. The effects had been analyzed of the TWC out A/F ratio during an NH3 generation event in the NEDC. Testing results indicated that the development had washcoats selected that contained sufficient OSC.

Conventional stoichiometric gasoline engine TWC catalysts are formulated to minimize NH3 production across the TWC while the lean-stratified engine PASS lean aftertreatment uses the NH3 produced on the TWC. The passive NH3 development consisted of optimizing a TWC formulation that maximizes the conversion of NOx to NH3 during rich engine operation. This new formulation must efficiently convert the engine out NOx to NH3 without compromising the oxidation of CO and unburned HCs.

A standard test cycle with extended lean and rich engine operation had been utilized for evaluating new formulations. Each new formulation ran on the exact same cycle to determine catalyst operating ranges and conversion efficiencies, Figure 24. The red/green arrows denote the ranges of acceptable and unacceptable performance. This series had been the first to identify a TWC formulation, the blue columns, which could meet the engineering development performance targets.

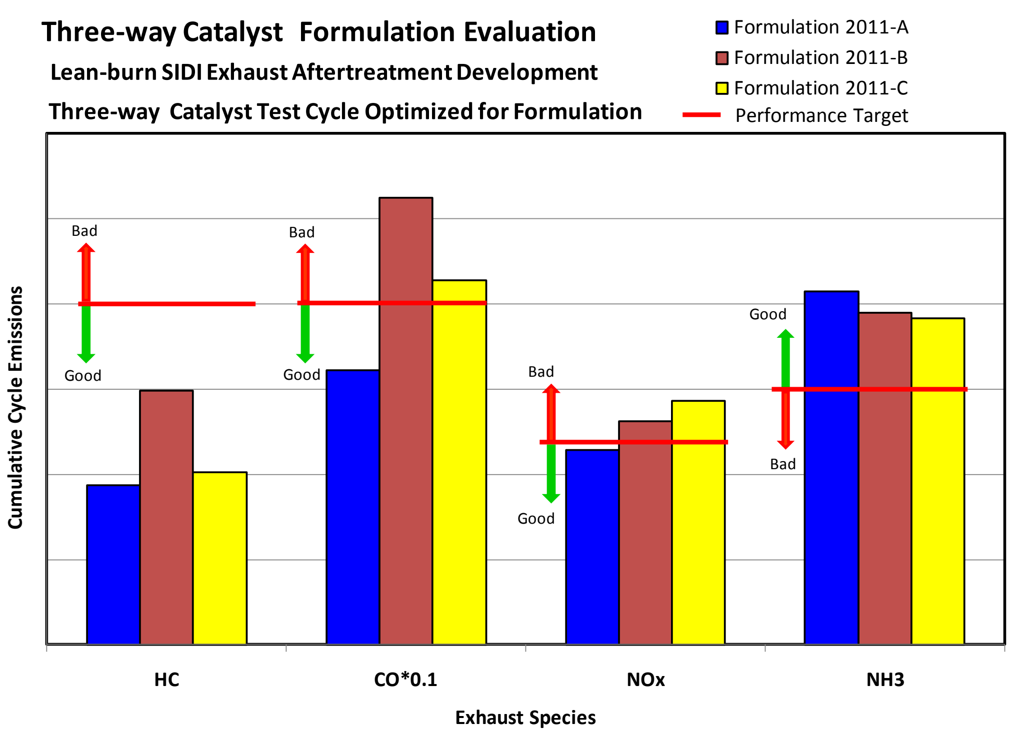


Figure 24: TWC Formulation Comparisons

Aftertreatment hardware development continued with evaluating TWCs which had been aged to simulate different points in the catalyst useful life. This is necessary because the catalyzing performance changes as the TWC ages. Normally, CO and HC oxidation efficiency declines along with the stoichiometric NOx reduction, Figure 25. The reductions in conversion efficiency for the red, yellow, and blue columns demonstrate this trend. Testing of aged TWCs provided the information required to verify the TWC performs adequately to meet the emissions standards for the full useful life of the system targeted at 120k miles.

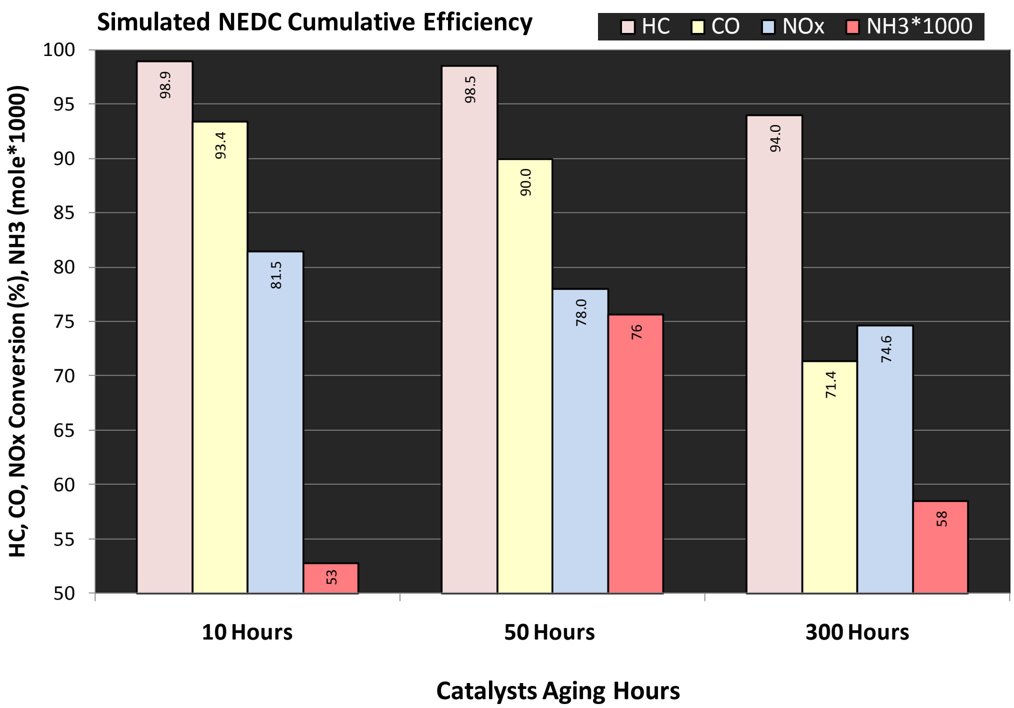


Figure 25: TWC Aging Performance Comparison

As highlighted, the PASS lean aftertreatment produces the NH3 used to reduce the lean NOx by biasing the A/F ratio slightly rich during high load, high rpm engine operation. Figure 25, indicated the mildly aged TWCs (10 hours) produced less NH3 over the NEDC (salmon colored column) than the more severely aged TWCs using the engine control strategy. Further, there had been a decline in the NH3 production as the TWC had been further aged (300 hours). The “smart” engine control intended for the PASS lean aftertreatment application must be able to detect these changes and adjust accordingly to assure sufficient NH3 is stored on the SCR for reducing the lean NOx.

To confirm the optimal TWC PGM formulation and SCR configuration, steady-state system level tests had been conducted. The steady-state test had been operated at 2000 RPM, 2.0bar load and cycled between lean and rich conditions. Figure 26 demonstrates the TWC generates sufficient NH3 to reduce engine out NOx during lean operation as the TWC out NOx concentration of 0.022% is reduced to yield a tailpipe out NOx concentration of 0.002%.

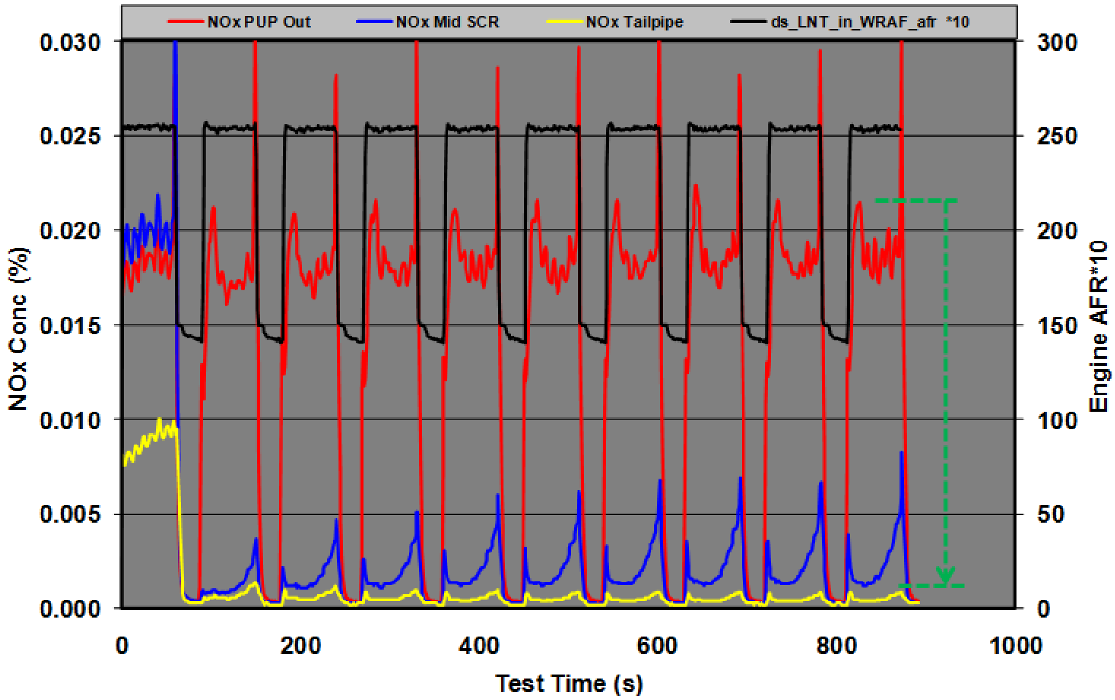


Figure 26: TWC Out NOx and Tailpipe Out NOx

The initial PASS TWC and SCR hardware investigations demonstrated limitations of excess CO from the TWC and SCR temperatures outside the required temperature range. To address the limitations, further exploratory research activities commenced to potentially resolve the limitations and drive the optimal hardware specifications for the next generation vehicle level passive lean aftertreatment system.

The initial PASS system relied on the production of NH3 from the reaction of NOx with H2 during rich engine operation. Unfortunately, the initial PASS lean aftertreatment presented the challenge of simultaneously producing a significant level of CO emission. Investigations had been conducted on the lean aftertreatment hardware focusing on innovating a close-coupled TWC formulation that minimizes these CO emissions while producing the greatest amount of NH3. Limited improvements had been realized in the CO oxidation along with NH3 formation chemistry with the follow-on TWC formulations, therefore risk mitigation investigations of alternate system architectures had been initiated and to potentially incorporate in to the next generation vehicle level PASS lean aftertreatment.

The initial PASS lean aftertreatment architecture focused on splitting the TWC volume into a close-coupled catalyst and an underfloor catalyst. The desire had been to enable the use of formulations in the underfloor catalyst that would not tolerate the high temperatures associated with close-coupling. Additionally, there had been differences in reaction kinetics due to the lower temperatures that may have promoted CO oxidation with less NH3 oxidation. Figure 27 demonstrates that good CO oxidation (blue bars) can be obtained without the loss of significant amounts of the NH3 (red bars).

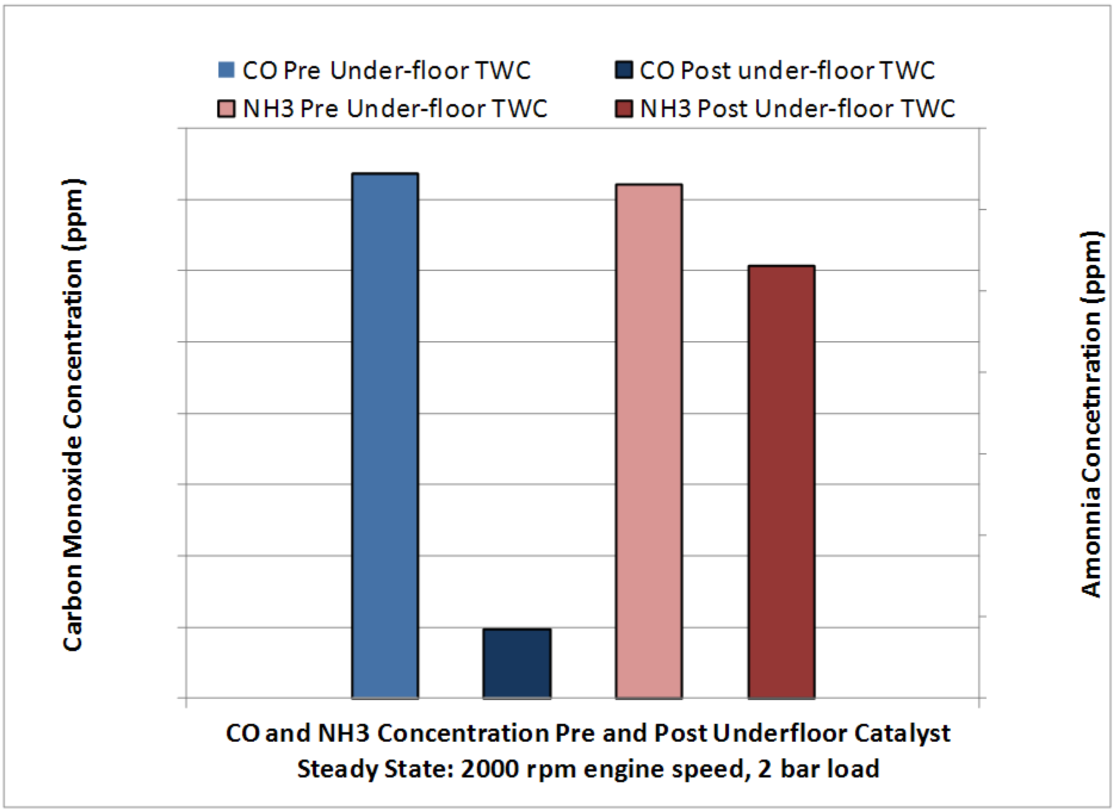


Figure 27: TWC CO and NH3 Concentrations

The next generation PASS lean aftertreatment hardware development investigated potential low CO passive NH3 system architectures. A CO clean-up catalyst formulated for very low temperature (~120C) conversion of CO had been the first system evaluated. An un-aged CO clean-up catalyst had been installed behind the rear SCRs then tested using transient NEDC and steady-state engine conditions. Figure 28, highlights the CO concentration of the clean-up catalyst out (red line) dropping, relative to the CO concentration in (blue line), as the catalyst temperature (black line) increases. The CO light-off temperature as defined by a 50% conversion is about 110C. By the time the catalyst temperature reached 140C, the CO conversion had been greater than 90%. During the NEDC the CO clean-up catalyst temperature reached 110C at about 750 seconds into the run and reduced the cumulative CO for the run by about 50%. Subsequently, this explored alternative approach had been discarded.

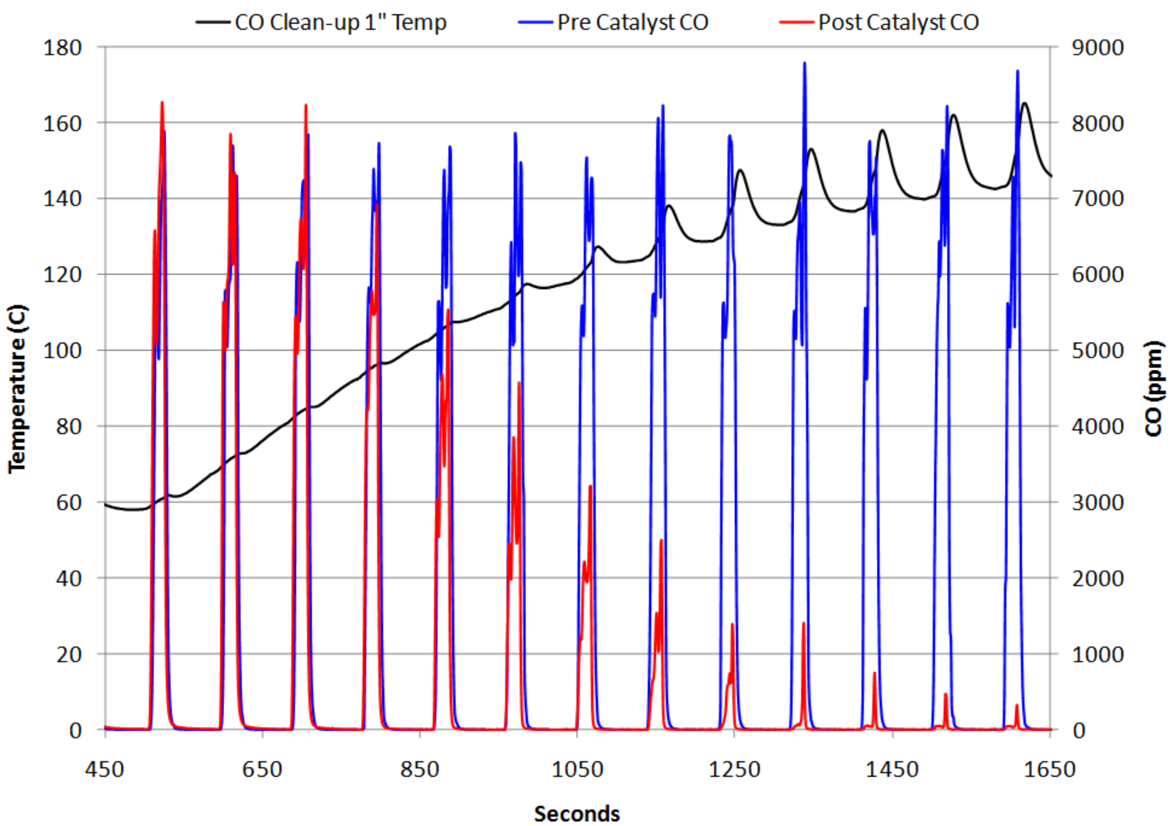


Figure 28: CO Concentration of the Investigated Clean-up Catalyst

A second potential next generation technology explored to reduce the CO emissions had been a small (0.66 & 1.0 L) lean-NOx trap. These catalysts had been tested in the close-coupled position with a Pd only front brick and the underfloor position, with the same Pd only brick close-coupled. The intention had been to determine the potential of new NOx storage technology, to adhere to the program goals. Each configuration had been tested on an NEDC cycle. The data indicated that the Pd Only-LNT PASS system did reduce our cumulative NOx emissions by about 50%, but also reduced the cumulative CO by more than 50% from our baseline system. Similarly, this explored alternative approach as well had been discarded.

4.1.2. PASSIVE AMMONIA CONTROLS

For the initial passive ammonia generation control, an initial kinetics-based control-oriented TWC model had been created. The model predicted TWC outlet species concentration which includes NH3 generated in TWC. The inputs parameters include A/F ratio, exhaust mass flow rate, TWC inlet temperature, TWC inlet pressure, engine outlet O2, NO, CO, H2 and HC concentration. For onboard application, the engine outlet species concentration had been targeted to be determined from a set of tables with engine speed, fueling rate and A/F ratio as input parameters. The tables had been targeted to be populated with engine test data. The model had been planned to be integrated with a kinetics-based control-oriented SCR model to predict SCR NH3 storage onboard for lean-stratified engine A/F ratio control. The model considered 11 kinetics reactions including CO, H2, HC and NH3 oxidation, NO reaction with CO and H2, steam reforming and water gas shift (two directions), and O2 absorption and desorption. To determine TWC outlet NO and O2 concentrations, onboard solvers required employment due to high order nonlinear feature of the problem.

GT-SUITE aftertreatment model had been utilized to calibrate the SCR control model kinetics reaction efficiency. There are multiple kinetics reaction efficiency tables in the SCR control model to be calibrated. Each of the tables corresponds to a kinetics reaction considered in the SCR control model. Using GT-SUITE aftertreatment model to populate these tables significantly reduced calibration time and engine tests.

The SCR control model uses a multi-brick method to simulate one-dimensional SCR flow phenomenon, in which gas species are considered to be uniformly distributed in each individual brick. In order to correctly populate the reaction efficiency tables, a proper GT-SUITE model solution method should be used. There are three solution methods available in GT-SUITE model, that is, explicit, implicit and quasi-steady. In this study, the explicit and quasi-steady methods had been investigated and applied to SCR NH3 absorption efficiency determination. The NH3 absorption efficiency is formulated as a two-dimensional table with SCR substrate temperature as one of the table inputs. The second input of the table is formulated as a function of NH3 storage and resident time.

Figures 29 and 30 show the correlation between SCR NH3 absorption efficiency with the second input at a constant substrate temperature, but varied gases flow rate (resident time) and SCR inlet NH3 concentration. The correlation shown in Figure 29 is determined by the explicit solver of the GT-SUITE model, while the correlation shown in Figure 30 is determined by the quasi-steady solver. It can be found that NH3 absorption efficiency correlations fall into one curve in Figure 29, which means that the NH3 efficiency can be mapped with the second table input as axis at the given temperature. Figure 30 doesn't show such correlation. The data suggests that explicit solution method of GT-SUITE aftertreatment model should be used to calibrate SCR control.

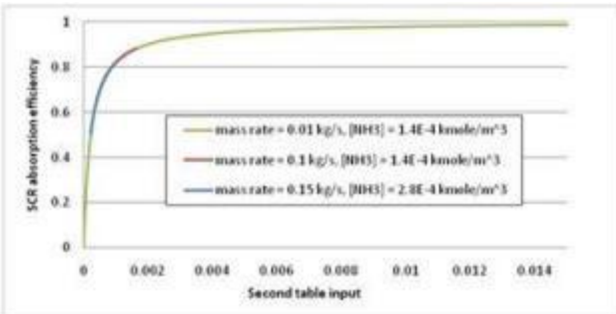


Figure 29: A/T Model Explicit Solver

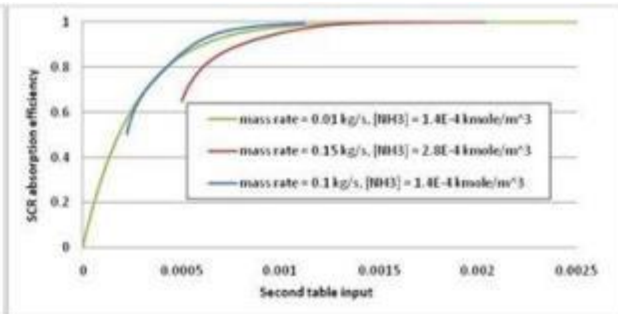


Figure 30: A/T Model Quasi-Steady Solver

A prototype control system had been set up for passive SCR system control development in an engine dynamometer test cell. The engine is a lean-stratified engine equipped with the initial PASS lean aftertreatment, capable of running at lean-stratified, stoichiometric and rich conditions. The initial PASS system includes a TWC and front and rear SCRs. The passive SCR control software includes a kinetics-based SCR model and a NH3 generation controller. The kinetics-based SCR model is capable of predicting NH3 storages in both front and rear SCRs. The NH3 generation controller planned to be developed determines whether NH3 generation is needed based on NH3 storages in front and rear SCRs and other engine operation parameters and sends a request signal to the engine control system if needed. The signals transmitted from passive SCR control system to engine control system include NH3 generation request signal and NH3 generation A/F ratio. The system had been configured and had demonstrated desired functional operation. Figure 31, illustrates the set-up of the system.

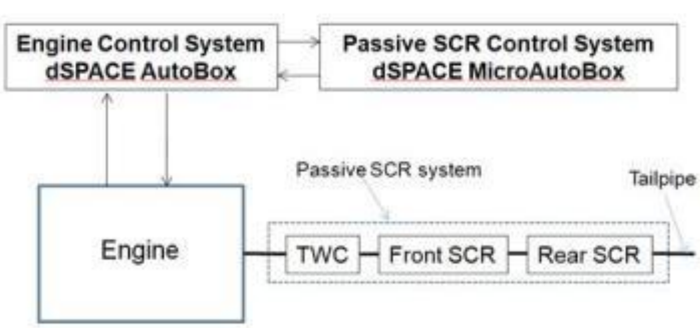


Figure 31: Initial PASS Lean Aftertreatment Controls

The initial passive SCR control system had been tested in a dynamometer test cell at steady-state engine operation condition. The control system automatically controls engine combustion mode (lean or rich) to maintain a desired NH3 storage level in the front and rear SCR.

In Figure 32, the blue curve is SCR NH3 storage. The storage increases during engine rich condition when NH3 is generated in TWC and stored in SCR and decreases during engine lean condition when NOx passes through TWC and consumed in SCR. The red curve of Figure 32 is NOx sensor signal at TWC outlet. The signal represents NH3 concentration during rich condition and NOx concentration during lean condition. When the engine switches to rich mode, the red curve reaches a significant high level which indicated that NH3 is generated. When engine switches to lean condition, the red curve drops to relative low level which indicated the NOx comes out from TWC. Based on the NH3 or NOx concentration from the NOx sensor and other engine parameters, a kinetics-based SCR storage model determines current SCR NH3 storage (the blue curve), which is used to control engine combustion modes.

Figure 33 indicated the NOx concentrations at the front SCR outlet and tailpipe. During rich condition, NOx concentrations at both front SCR outlet and tailpipe are near zero because TWC consumes almost all NOx from the engine. During lean condition, the NOx passing through TWC is reduced by the front and rear SCR in steps and reaches to a desired level at tailpipe when the system gets to stable condition.

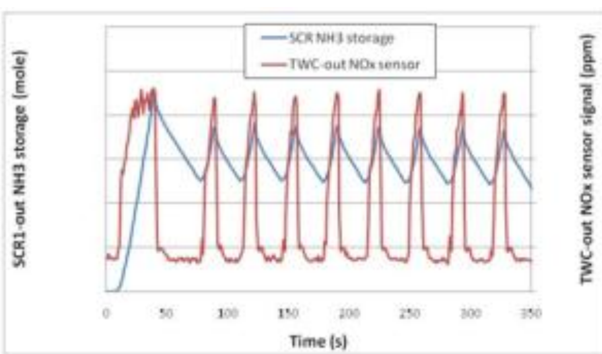


Figure 32: SCR NH3 Storage

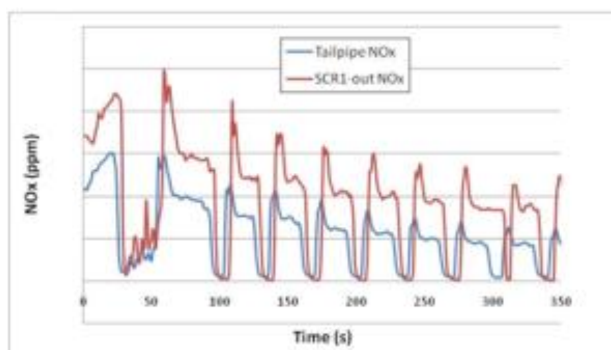


Figure 33: NOx at Front SCR and Tailpipe

4.1.3. PARTICULATE FILTER HARDWARE

Particulate filter hardware investigated aftertreatment solutions for possible control of particulate emissions from the lean-stratified engine applications. The focus had been to determine how to optimally integrate a particle filter into the PASS lean aftertreatment system if the need arose due to final system integration yielding excessive particulate emissions. The type of filter technology, size of the filter, possible coatings and position in the aftertreatment system, close-coupled or underfloor, had been addressed. The possibility of integrating particle and gaseous emissions control in a single device had additionally been investigated.

The dynamometer test cell had been equipped with an earlier generation 2.2L wall-guided lean-stratified direct-injection gasoline engine controlled by a full authority engine controller (dSPACE). The test protocol adopted for these investigations had been with a preparatory NEDC followed by a high temperature (700° C) clean-up on the day prior to an actual test sequence. The test sequence includes cold start and hot start NEDCs, with and without regeneration between tests, a steady-state test, and a final clean-up in prep for a repeat sequence the following day.

The test cell had been instrumented with a dual-leg Horiba Mexa 7000 emissions bench and two AVL SESAM benches. This provides redundant CO2, CO, NOx, O2 and Total Hydrocarbons at both the engine out and post aftertreatment device locations. The SESAM benches also provide the capability to measure various unregulated emissions via their onboard FTIR. Particle measurements are made at the same locations using two Cambustion DMS500 Fast Particle Spectrometers. The DMS500s make real-time measurements of particle number size distributions in the particle diameter range from 5 to 1000 nanometers. From this measurement particle mass distributions are calculated. Thus, measures of both mass and number emissions are obtained to assess compliance with emissions regulations.

During initial testing, various low mean pore size and membrane coated filters from two suppliers had been benchmarked. This testing showed that Rapid Aging Test H (RAT-H) catalyst aging resulted in improved filtration efficiency compared to green parts. Significantly lower soot loadings had been necessary to achieve the target filtration efficiency compared to the standard diesel filter technologies previously evaluated in this test cell. In the close-coupled position no significant back-pressure had been observed during the NEDC test cycle. However, since this drive cycle is a relatively low speed and low load cycle, further evaluations had been conducted to comprehend back-pressure under conditions experienced at Wide Open Throttle

(WOT). The cordierite substrate filters achieved the 250° C target temperature earlier in the cycle and reached a maximum temperature approximately 100° C higher than the SiC substrate filters. These observations would translate to more passive regeneration on cordierite filters and the potential to transfer more heat to downstream aftertreatment devices.

A fundamental study to understand the impacts of the placement of PGM on gaseous emissions and downstream temperatures within a close-coupled system had been conducted. Four basic systems had been compared. The systems all had equivalent PGM loading and the PGM ratios had been maintained. The baseline system had been a dual brick monolith. The second system consisted of a monolith coupled to a membrane filter, each containing ½ of the total PGM. The third had been a coated membrane filter alone and the fourth had been the baseline dual monolith coupled with an uncoated membrane filter (all the PGM had been on the monolith). The data indicated that the baseline monolith alone and the baseline followed by the uncoated filter gave the best and equivalent conversion efficiency performance. However, when the uncoated filter had been placed upstream of the monolith the light-off time increased significantly, resulting in 15% lower HC conversion. The monolith + coated filter system had somewhat lower HC efficiency (5%), but equivalent CO and NOx conversions relative to the baseline dual monolith. The coated membrane filter only system conversion efficiencies had been all lower than the baseline: HC (25%), CO (10%) and NOx (8%).

For PGM coated filters it appears that membrane technology filters demonstrated lower conversion activity relative to a non-membrane filter. It is believed that this arises from poorer dispersion of the PGM when the coating volume is limited to the non-membrane half of the filter. In the close-coupled position uncoated cordierite filter/monolith systems reach temperature sooner than uncoated SiC filter/monolith systems on cycle and obtain higher temperatures. This performance had impacts on passive regeneration of the filter and on thermal management of downstream aftertreatment devices. Filters tested on the NEDC cycle produce in the range of 2-6 kPa additional back-pressure compared to a monolith. At exhaust flows comparable to WOT conditions clean coated membrane filters produced an additional 20kPa back-pressure.

Figure 34, a series of relatively poor filtration efficiency filters aged for 50 hours using the RAT H schedule had been evaluated to assess the role of ash accumulation and filter temperature achieved upon filter performance. The secondary goal had been to determine if filtration efficiency enhancement would potentially be adequate to make an initially inadequate substrate capable of meeting a particle number based standard. Three test filters and a blank filter (not aged) had been aged. The filters had been 1.5L, 200 cells-per-square-inch (cpsi), 50% porosity substrates with a mean pore size of 19 microns. The engine out filter then had been exposed to the maximum exhaust ash concentration. The filtered/exotherm filter experiences the maximum temperature but the exhaust ash concentration already had been reduced after going through the engine-out part. The exotherm filter then had received the maximum ash exposure and the maximum temperature. This is the typical exposure that all non-coated filters had received in all previous testing.

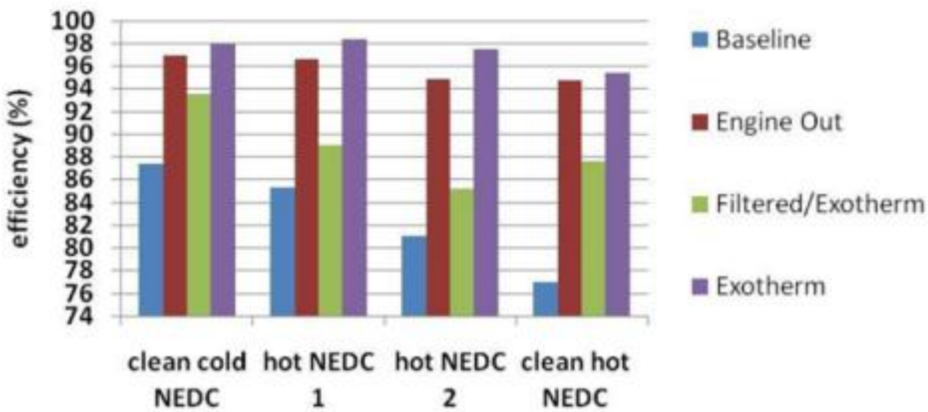


Figure 34: Ash Exposure Particle Number Collection Efficiency

The testing demonstrated that the ash effect alone (engine out filter) could improve the filtration efficiency by 10% relative to the baseline part. In the case of the exotherm filter the improvement had been even greater, with the hot NEDC tests reaching 98% efficiency. At this efficiency level the exotherm part would meet the proposed European particle number standard of 6 x 10E11 #/km. Under steady-state test conditions the exotherm filter required less than 50% of the trapped mass to meet the target filtration efficiency relative to the baseline filter.

Down-selected particulate filters had been canned and aged per the recommended schedules determined to be representative of 4K service. The TWC had been coated parts had been aged for 10 hours on the GMAC875 schedule. SCR coated substrates had been aged for 17 hours on the GMAC750 schedule. The performance of the monolith/filter systems in terms of filtration efficiency, back-pressure, gaseous conversion efficiency, and light-off had been determined for architectures utilizing filters in both the close-coupled and underfloor locations.

Initially only green SCR coated filters in the underfloor location had been evaluated. Aged parts had yet to be evaluated. The SCR coated parts had been prepared at two different coat loadings, high and low (1/2 the loading of high). Filtration performance of the green parts had been poor as shown in Figure 35. Maximum back-pressure observed during the EUDC portion of the NEDC cycle for these filters had been comparable to that observed to date with 2.5L filters.

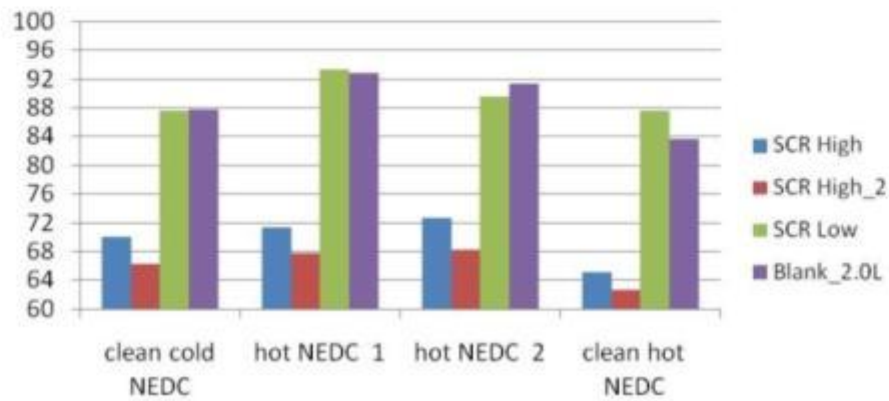


Figure 35: Particle Number Collection Efficiency

Fifteen TWC coated filter and/or TWC monolith configurations had been tested in support of the program. Two TWC coatings (A and B), based upon the optimized formulation for the initial PASS lean aftertreatment application, had been used to coat varying filter volumes and cell densities. Parts PA and PB are the A coated and B coated monoliths, respectively.

Of the 15 configurations tested, three met the filtration target collection efficiency necessary to meet the particle #/km engineering target. These had been systems 6, 10, and 12. The filtration efficiencies, HC and CO conversion efficiencies are plotted in Figure 36 for these systems. It is obvious that HC conversion efficiency for each of these does not meet the engineering target. This is largely due to much longer light-off times in the particulate filter test cell as compared to the aftertreatment hardware and integration test cells which use a different warm-up strategy, and to the greater thermal mass of a coated filter versus a monolith. If modifying the warm-up strategy improves the HC conversions sufficiently for systems 10 and 12 to meet the target, they would provide possible solutions for a close-coupled system (#10) and a split close-coupled underfloor architecture (#12).

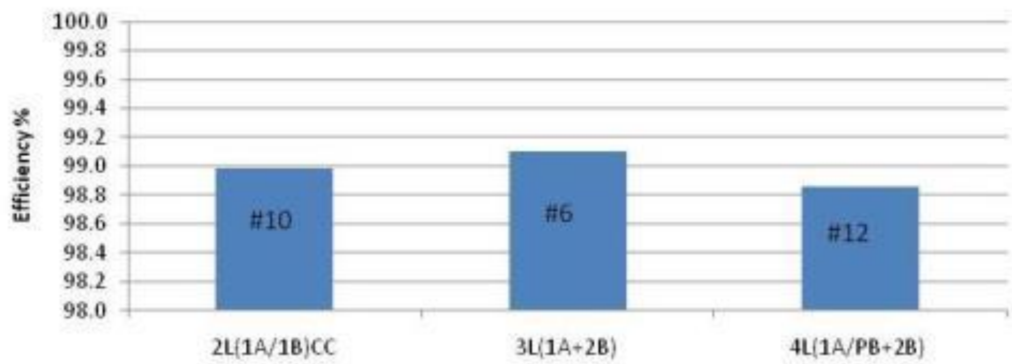


Figure 36: Various TWC Size Particle Number Efficiency Evaluation

An additional SCR coated filter system had been identified that would be a candidate system for particle emissions mitigation. The three systems identified had been:

1. 2L of TWC had washcoated filter close-coupled
2. 5L of TWC had washcoated, 2L monolith close-coupled and 3L filter underfloor
3. 4.5L of TWC, 2L TWC had washcoated monolith close-coupled, 1L SCR monolith + 2.5L SCR had been coated filter underfloor

Figure 37 demonstrates particle number filtration efficiency levels for the optimized hardware evaluated. A similar set of downsized parts had been provided by an alternate supplier.

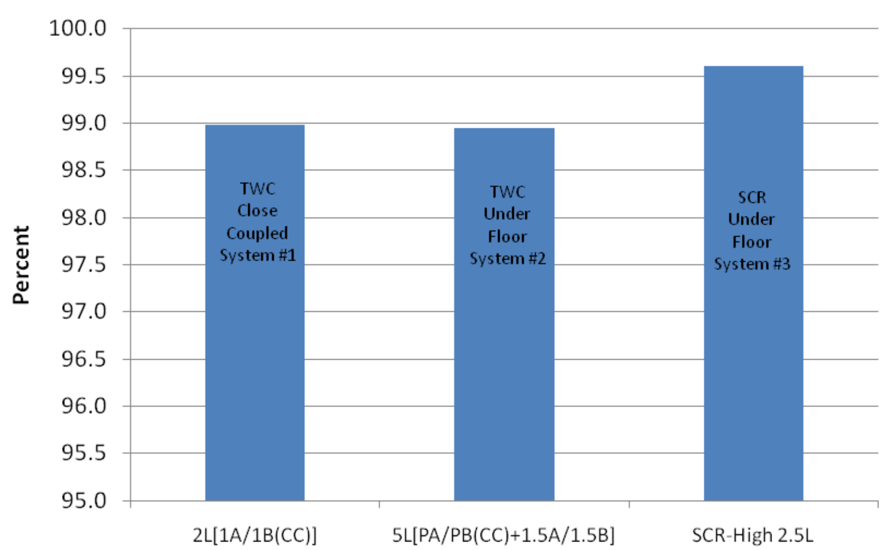


Figure 37: Particle Number Filtration Efficiency

Of the downsized parts received from our second supplier (B), we had been able to test a configuration identical to one furnished by supplier (A) that had been previously identified as a candidate system for particle emissions mitigation. Both of these systems consisted of 5L of TWC had been coated parts (2L monolith close coupled and 3L filter underfloor). Particle number filtration efficiency for both systems had been virtually identical. The data indicated that filters provided by both suppliers provide the targeted filtration efficiency required, Figure 38.

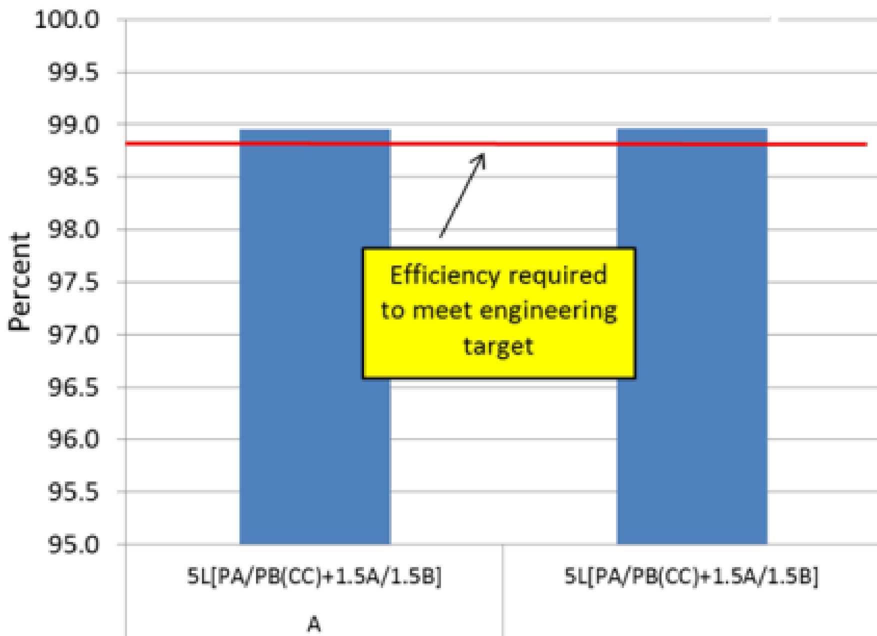


Figure 38: Particle Number Filtration Efficiency

4.1.4. LEAN COMBUSTION RESEARCH

The initial program investigations on lean gasoline combustion fundamentals started at GM R&D with experiments on a fuel spray chamber, single cylinder test engine as well as simulations using Computational Fluid Dynamics (CFD). Fundamental naturally aspirated lean gasoline combustion research had been conducted in the areas of; fuel spray, spray-guided combustion, single-pulse fuel injection, multiple-pulse/double-pulse fuel injection, alternative injection supplier systems impacts, spark plugs.

Fuel spray investigations had been conducted in the fuel spray chamber to obtain a detailed understanding of vaporization process for different spray configurations and engine operating conditions. The fuel spray data, Figure 39, was further leveraged as fundamental input in to the CFD model to assist in validating the baseline model. Initial investigations generated Schlieren images to obtain liquid and vapor envelopes, where follow-on investigations acquired MIE images (white contours) to obtain liquid only envelope. Subsequently, overlaying the MIE image over Schlieren image obtains the vapor only envelope. A key data point which assists in comparing performance results of typical spark ignited engine operation is 5bar 600k. These investigations had been the fundamental enabler to obtain a detailed understanding of vaporization process for different spray configurations and engine operating conditions. Additionally, the fuel spray lab capability reduces combustion system optimization time through improved accuracy of the CFD modeling.

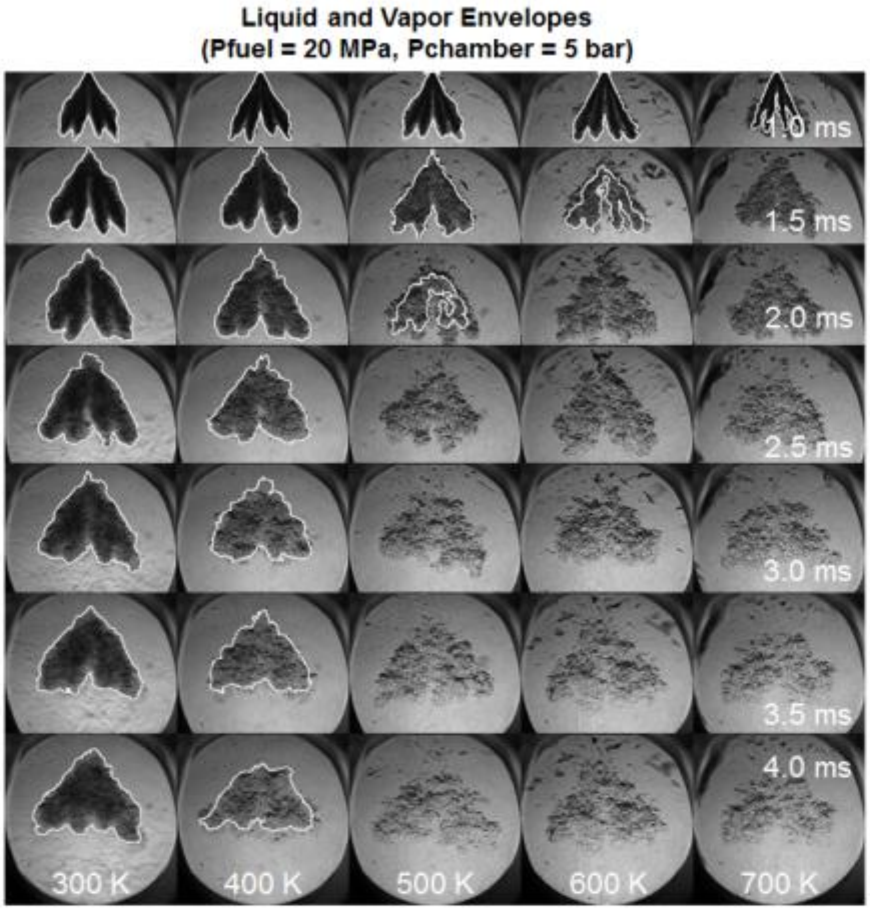


Figure 39: Vaporization Process for Different Spray Configurations and Operating Conditions

Multiple-pulse fuel injection experimentations had been explored to quantify the improvements to lean gasoline combustion. The initial mainstream fuel injection system (injector, pump, driver system) for the initial SG4 engine had been based on single-pulse injection from the initial collaborative Injection Supplier #1. The Injection Supplier #1 injection system had been previously tested with multi-pulse injection technology on the single cylinder engine. Those tests revealed erratic flow behavior when the Injection Supplier #1 injector is multiple-pulsed, causing significant risk for next phase of the program. Therefore, an alternative supplier, viz., Injection Supplier #2, had been selected for possibly mitigating the risk of erratic flow behavior.

Alternative Injection Supplier #2 injection system experimental testing demonstrated that when single-pulsed, the injector is comparable to the Injection Supplier #1 injector in all respects except for smoke emissions. The higher smoke emissions with the Injection Supplier #2 injector are a cause for concern and strategies to reduced smoke had been investigated as the evaluation and testing proceeds. Injection Supplier #2 testing demonstrated during double-pulsing, the injector exhibits far less or no erratic flow behavior at all in many cases. This stable behavior allows for better optimization of multiple pulsing parameters to obtain best engine performance. Furthermore, at light-loads the engine performance results with double pulsing are better than those with the Injection Supplier #1 injector when double-pulsed. This is particularly true for HC emissions and Coefficient of Variants (COV) of Indicated Mean Effective Pressure (IMEP). At wider engine speeds and loads, results with the Injection Supplier #2 injector indicate that this alternative injection system can mitigate the risk with the Injection Supplier #1 injection system during the next program phase incorporating multiple-pulsing.

CFD simulations on double-pulsing relating to spray and combustion of the spray-guided SG4 single cylinder engine had been carried out by using the Converge code with the 7-stream model, Figure 40. The predicted flame image can match the measured experimental data properly. However, it over-predicted the heat release rate in the early stage of combustion. To solve this problem, new ignition and G-Equation models available in the Converge code had been selected. Validation of these models for gasoline stoichiometric homogenous combustion had been carried out, and the calculations can match the measured data by tuning the model constant. The data indicated peak heat release rate is a factor of two higher with double-pulsing as well as fuel-air mixture is contained more within the bowl with double-pulsing.

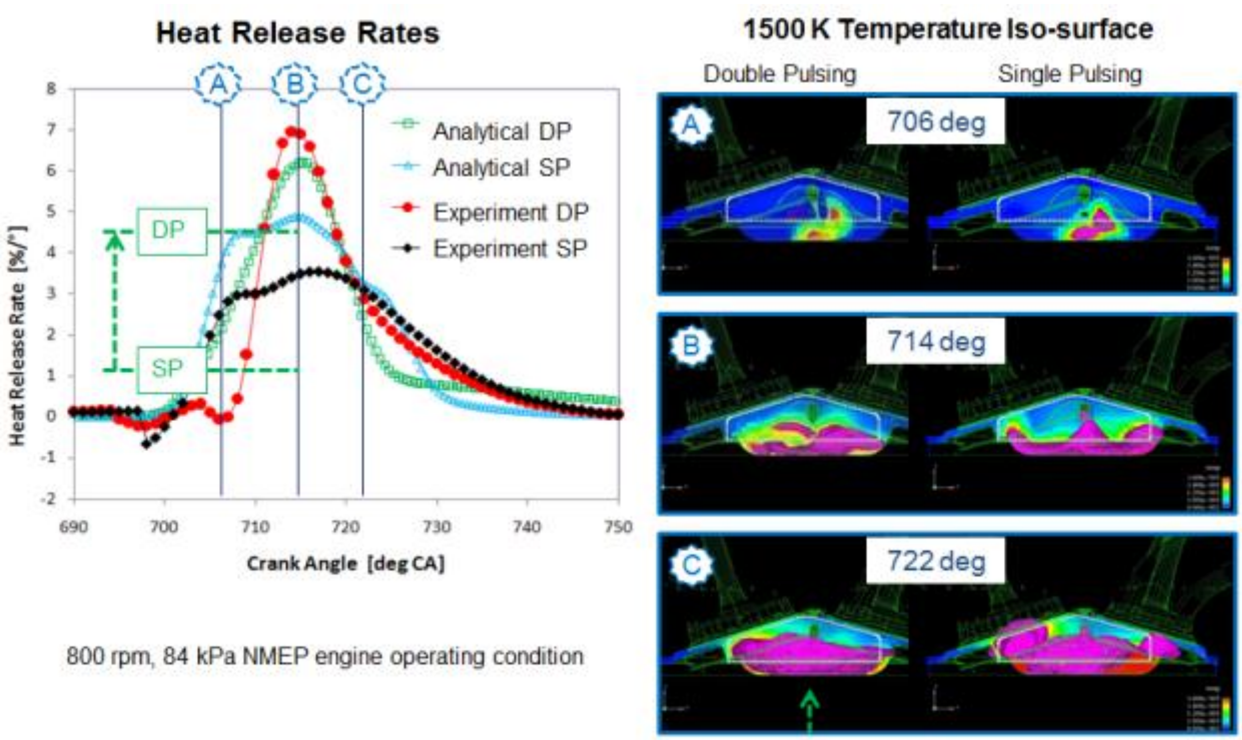


Figure 40: CFD and Experimental Heat Release and Temperature Iso-surface

CFD simulations with the G-Equation model failed to predict trends in the heat release rate because the model tries to track the flame front. However, there is no clear flame front in this complex combustion process. In order to handle this extremely difficult combustion issue, a detailed chemistry combustion model and energy deposit ignition model had been implemented. The models give very good predictions in both trend and magnitude, as seen Figure 41. The detailed chemistry combustion model uses elementary chemical reactions which can give reasonable predictions with fine mesh for high temperature reactions like conventional spark ignition combustion. The energy deposit ignition model converts the plasma energy (~30mJ) to moving ignition cells (which represent the moving plasma) and then ignites the mixture based on elementary chemical reactions. The simulations also indicated that the single-pulsing case requires more energy for ignition than double-pulsing, because injection of a single-pulse produces much higher velocity around the spark plug.

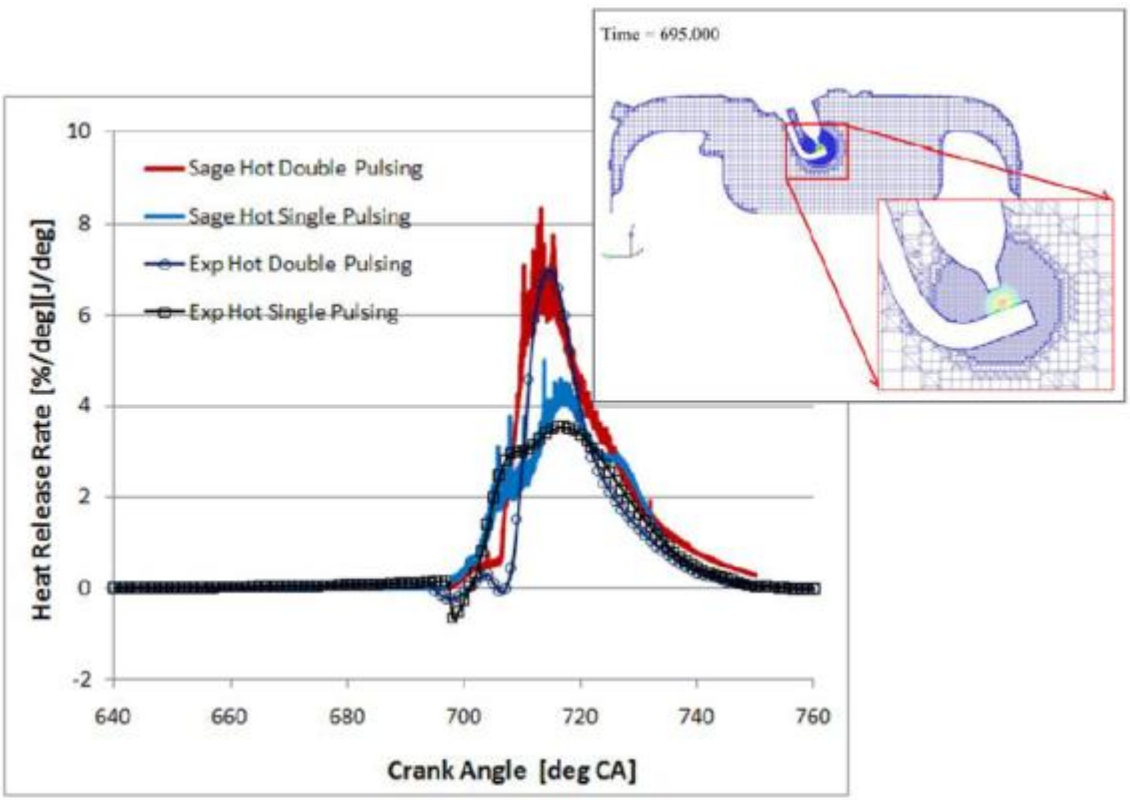


Figure 41: CFD Simulations Using Detailed Chemistry and Energy Deposit Ignition Model

CFD simulations of combustion regimes of the engine operating conditions indicated that the Damköhler number varies from 0.02 to 0.08 (Da<<1) and the Karlovitz number varies from 25 to 800 (Ka>>1), implying that ignition and combustion occur predominantly in thickened flame regimes where the chemical reactions dominate the combustion due to a slow reaction rate.

Therefore, the assumption of a well-stirred reactor is valid for the combustion simulation of the spray-guided Spark Ignited Direct Injection (SIDI) engine, permitting use of the Arrhenius combustion model which neglects the interaction between reaction and turbulence in each computational cell. Figure 42, indicated the simulation results with single-pulsing for different spark advances. The predictions generally had the correct trends, in that the burning rate increases with increasing spark advance. When spark timing occurs before injection, however, as expected no further increases in the burning rate is observed.

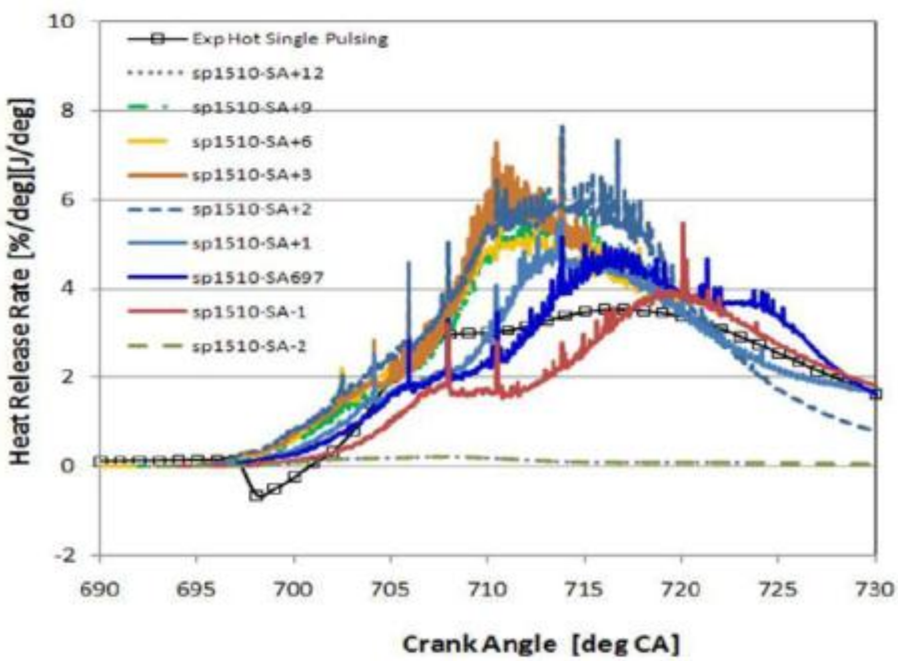


Figure 42: CFD Simulations Using Detailed Chemistry and Energy Deposit Ignition Model

Experimental evaluations further explored wider engine speeds and loads for the Injection Supplier #2 system. The additional testing continued to confirm that the flow behavior of Injection Supplier #2's injector, when double-pulsed is far more stable than from Injection Supplier #1. While Injection Supplier #2's injector is not totally free from instabilities, the extent is low enough to seriously consider their injector as risk mitigation for the next phase engine development with multiple-pulse technology. The additional testing evaluated wider speeds and loads continued to confirm that the smoke emissions are significantly high, far above the target Filter Smoke Number (FSN) of 0.1. Figure 43, compares data from both suppliers at 10 speed and load points that simulate the FTP- 75 cycle. It is suspected that the high smoke for Injection Supplier #2 is related to the Length to Diameter (L/D) ratio of the individual holes in the injector nozzle. It had been hypothesized that there is a critical injector L/D ratio, below which the individual spray plumes merge and inhibit air entrainment into the bulk spray. Resulting conclusions are that two equivalently specified injectors do not necessarily perform the same and fuel spray characteristics need to be matched to the specific unique combustion system.

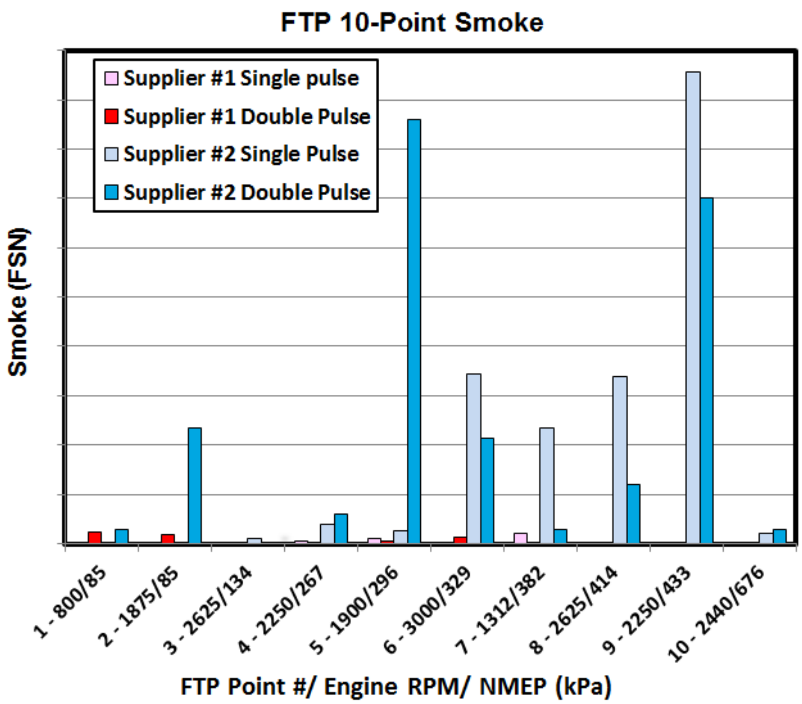


Figure 43: Experimental Comparison of Smoke Emissions

Spark plug design changes had been experimentally evaluated and targeted towards better ignition performance of fuel air mixtures. This is achieved by reducing heat loss from the early flame kernel to the electrodes. Figure 44, compares the COV of IMEP of the standard spark plug with that of the new design spark plug. A significant reduction in combustion variability is noted.

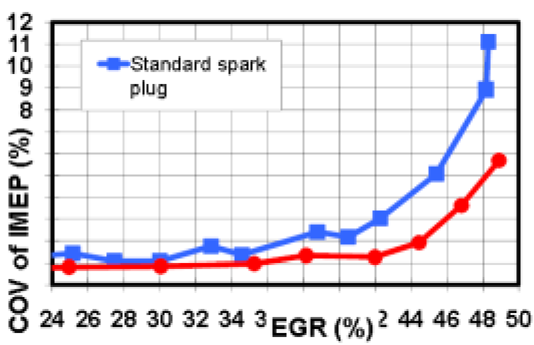


Figure 44: Experimental Comparison of Spark Plug Performance

4.1.5. LEAN COMBUSTION SYSTEM INTEGRATION

Lean combustion system integration focused on multi cylinder impacts and integration optimization with the initial lean aftertreatment system for transient drive cycle operation on an engine dynamometer. The system integration had been conducted on a four cylinder 2.2L Spray-Guided (SG4) engine with, Injection Supplier #1 controller, a 6-speed manual transmission and an initial PASS lean aftertreatment system. PASS is an integrated TWC + SCR lean aftertreatment system that relies on the intrinsic performance characteristics of the TWC and SCR to holistically address stoichiometric and oxygen-rich exhaust gas aftertreatment. The concept takes advantage of the NH3 that is naturally generated on the TWC when the feed-gas is slightly rich of stoichiometric to facilitate the control of NOx that breaks through the TWC when oxygen is present. The initial PASS system makes use of an underfloor SCR to store and use the intermittently generated NH3 to reduce the NOx breaking through the TWC.

Using the torque and engine speed for the NEDC from a model for a SG4 engine with 6-speed manual transmission, on a 3000 pound vehicle, with a 675 rpm idle speed for a fully warmed up engine, a pedal schedule had been developed for the Injection Supplier #1 engine controller to operate at the prescribe engine torque loads. The model had been then extended to be compatible with the engine idle speed temperature dependencies of the Injection Supplier #1 engine controller. 12V S/S operation and Deceleration Fuel Cut-Off (DFCO) operation also had been implemented into the model while working within the limitations of the Injection Supplier #1 engine controller.

A procedure had been developed to heat up and hold the temperature of the TWC to 600°C as rapidly as possible from a cold engine start. After the initial catalyst warm up period, the engine control is shifted into homogenous stoichiometric operation until the engine is able to run lean-stratified. Extensive studies had been performed to evaluate the fuel economy potential of transitioning from stoichiometric to lean-stratified mode as quickly as possible. These test results indicate that there is a 1% fuel economy advantage for every 100 seconds reduced time required to achieve a fully warmed up coolant temperature of 90°C. This fuel economy benefit is above any fuel economy benefit that is due to reduced friction and reduced engine idle speed associated with warming up an engine sooner. Test results indicate that the temperature of the TWC drastically drops when the combustion mode shifts from stoichiometric to lean-stratified combustion. A TWC temperature of at least 300°C is required to obtain adequate HC and CO conversion efficiencies.

Strategies that had been investigated to maintain the prescribed minimum TWC temperature included: stoichiometric homogenous idle, stoichiometric homogenous accelerations, different DFCO strategies, 12V S/S vs. normal engine idle, and throttled lean-stratified operation.

Experiments had been conducted to validate the initial PASS lean aftertreatment concept on a test schedule. The location and size of SCR catalysts had been determined to maintain an effective temperature window for maximum NH3 storage and lean NOx conversion. The following tests had been investigated:

- The SCR catalysts saturated with NH3 prior to running a cold test schedule. The test ran without triggering any NH3 generation events during the test schedule. The preconditioning of the SCR catalysts allowed to quantify the NH3 production that would be required to reduce NOx emission levels to engineering targets
- Cold tests with SCR catalysts having no NH3 reductant at the beginning of the test schedule. The test had been run without triggering any NH3 generation events during the test schedule
- Above tests repeated with partially throttled lean-stratified operation during the test cycle for thermal management of SCR catalysts

The following observations are summarized from the initial testing of initial PASS lean aftertreatment concept:

- Approximately 79% reduction in NOx emissions had been achieved when the SCR had been preconditioned with NH3 at the beginning of the test cycle, Figure 45. It should be noted that the tests had been conducted at higher engine-out NOx calibrations with no NH3 generation events during the test schedule
- 30-kPa of throttling during lean-stratified operation had been sufficient to optimize SCR convertor efficiency

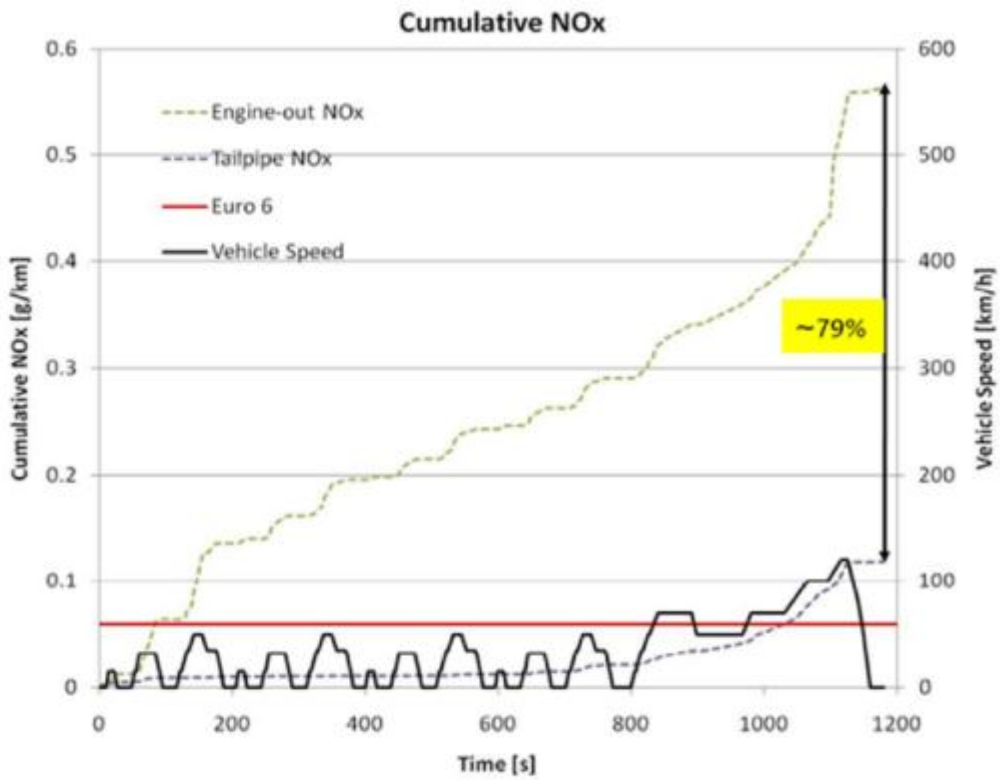


Figure 45: Cumulative NOx Emissions Reduction Using the Initial PASS Lean Aftertreatment

Enhancements had been made to the engine control software of the Bosch MED9 engine controller. The ability to input time based combustion mode through an external file, the ability to command multiple time based regeneration events through an external file, the ability to disable/delay DFCO during accelerations gear shifts and the ability to enable different types of cold-start catalyst heating strategies. In addition, the ability to dynamically control torque using a closed loop pedal command to MED9 engine controller via an external dSPACE controller had been incorporated into the testing facilities. These enhancements provided the ability to perform repeatable NEDC or U.S. Federal Test Procedure (FTP) operating schedules, test different NH3 generation strategies evaluate different NOx calibrations strategies and quantify differences in fuel consumption for the different operating strategies. Stoichiometric homogenous and lean-stratified calibration strategies had been investigated to optimize fuel economy while maintaining emission robustness.

Several strategies identifying NH3 production and the CO trade-offs had been explored for transient drive cycle operation of the lean-stratified engine and initial PASS lean aftertreatment system. To accomplish this, a steady-state operating condition that simulates the engine conditions during a typical NH3 generation condition had been selected. A comparison of the investigated engine strategies and corresponding impact on the NH3 generation to CO breakthrough are plotted in Figure 46.

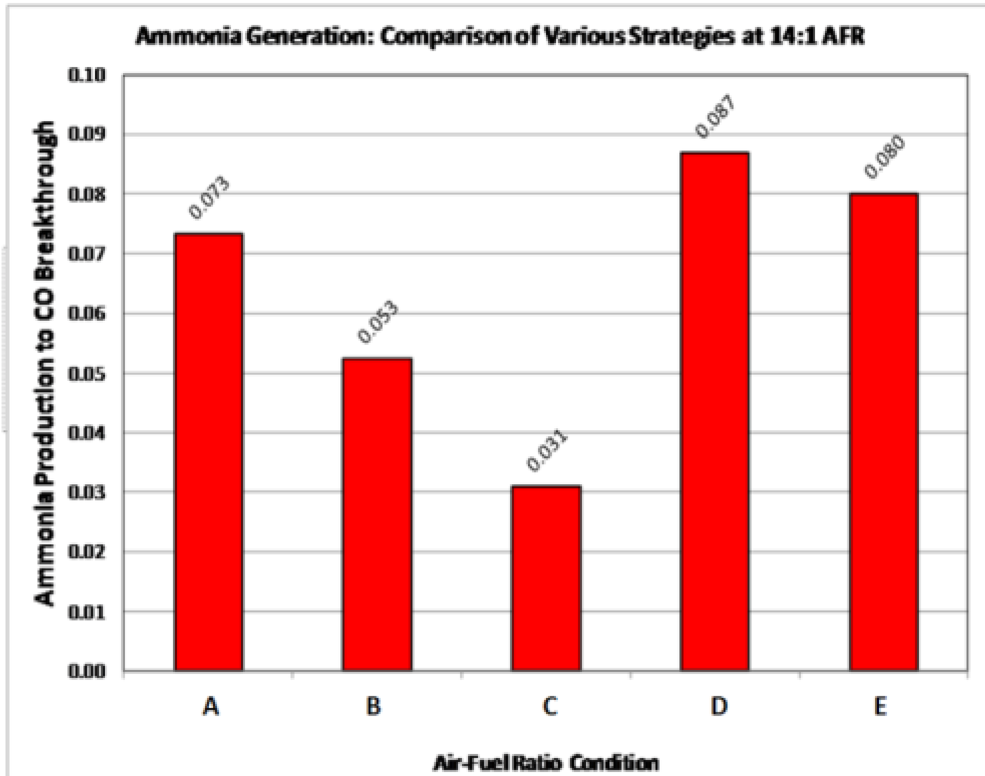


Figure 46: NH3 Generation to CO Breakthrough

Integration regarding the NOx to NH3 and the CO conversion efficiencies had been explored for several different TWCs. To accomplish this, a steady-state operating condition that simulates the engine conditions during a typical NH3 generation condition had been selected at RPM = 2000. The operating condition is equivalent to a third gear acceleration during a typical transient test schedule. Since this steady-state test condition resulted in a TWC temperature higher than experienced for NH3 generation events during a transient test cycle, a lighter load at RPM=1000 with more representative catalyst temperatures had been also tested for some of the catalysts. For each catalyst investigated, an A/F ratio sweep had been performed. For all catalysts, an A/F ratio slightly rich of stoichiometric had been the best compromise that allowed form maximum NH3 formation with minimum CO production.

The results at this optimum A/F ratio are shown in Figure 47. Catalyst A and B had been also tested at the lower-temperature lighter-load condition as well as at the higher-temperature heavy-load condition.

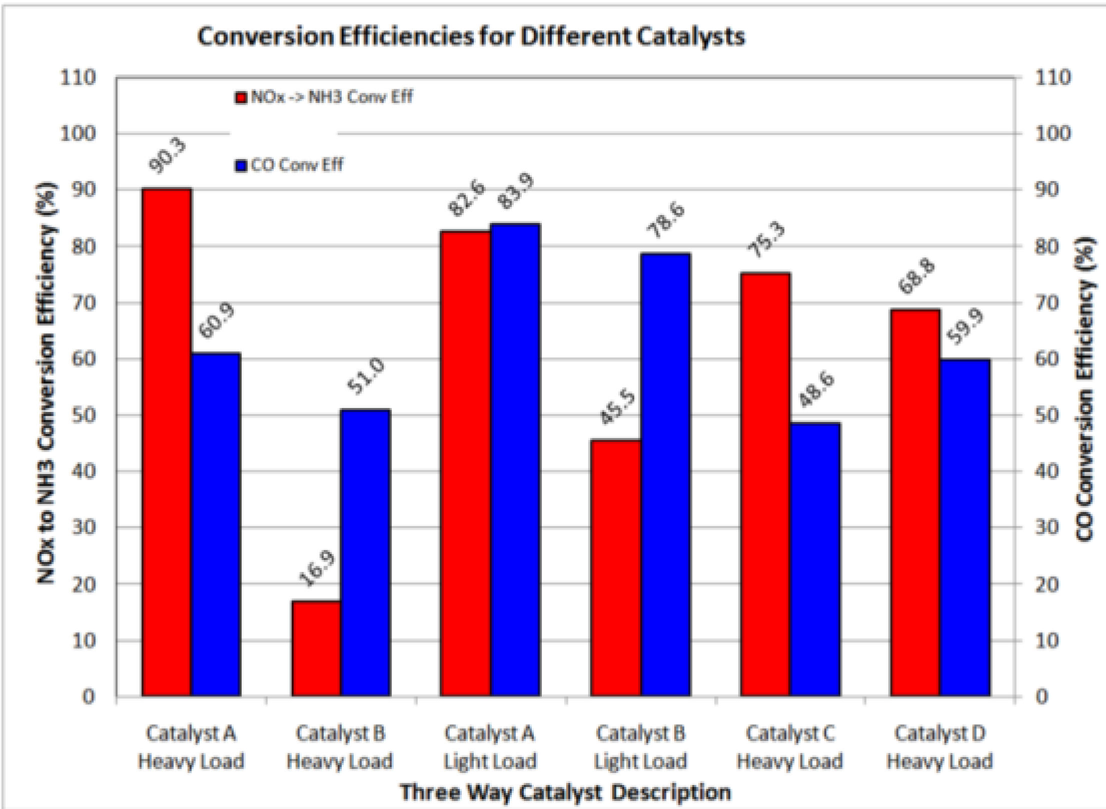


Figure 47: TWC Conversion Efficiencies

From this investigation, the following conclusions had been reached:

- At richer A/F ratios, the amount of CO generated substantially increased
- Catalyst A had the best NOx to NH3 conversion efficiency
- Catalyst A had the best CO conversion efficiency
- Catalyst A performed best not only at the high-temperature heavy-load condition, but also at the lower-temperature light-load condition

Testing transitioned from the NEDC driving schedule to the FTP driving schedule. Compared to the NEDC driving schedule, the FTP driving schedule not only had higher overall loads, but also larger transients in torque and engine speed. At present, in order to match the torque schedule for the FTP schedule, the engine switches between lean-stratified and stoichiometric homogenous combustion much too often. This frequent transition between combustion modes leads to excessively high emission levels. The pedal position was optimized to more closely match the required torque without overshoots, leading to fewer combustion mode transitions which in turn should lead to lower exhaust emissions.

Due to of the overall higher loads of the FTP driving schedule, the initial PASS system front SCR is at a too high of a temperature (near 500°C) for almost the entire cycle. The rear SCRs are at a temperature of 300°C for almost the entire test schedule and therefore any NOx to NH3 reduction that occurs, likely occurs on the rear SCRs. The initial PASS system required additional thermal optimization to account for the higher loads of the FTP driving cycle.

The second primary investigation focus had been around a TWC without OSC. Test planning for optimization sought NH3 generation events for a TWC without OSC, that a rich tip-in to deplete the stored oxygen would not be required. Thus, not only could NH3 generation begin earlier in the NH3 generation event, but also without the rich tip-in less CO and HC emissions would be generated.

A TWC formulation had been optimized for NH3 production and had been selected to determine the impact of OSC on NH3 production as well as compare it to the initial PASS system TWC.

Without the OSC, this TWC had been able to generate more NH3 during an NEDC test cycle as shown in Figure 48. The higher NH3 production did in fact lead to a reduction in the tailpipe cumulative NOx emissions as shown in Figure 49.

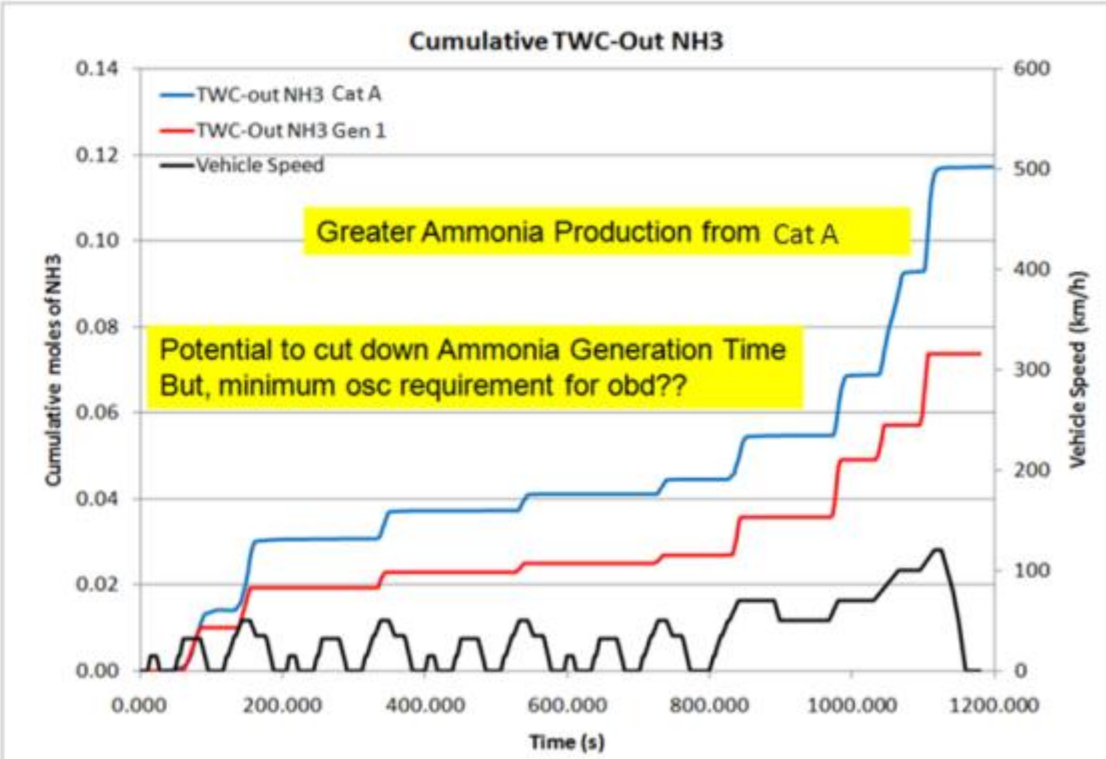


Figure 48: NH3 Generation with a TWC without OSC

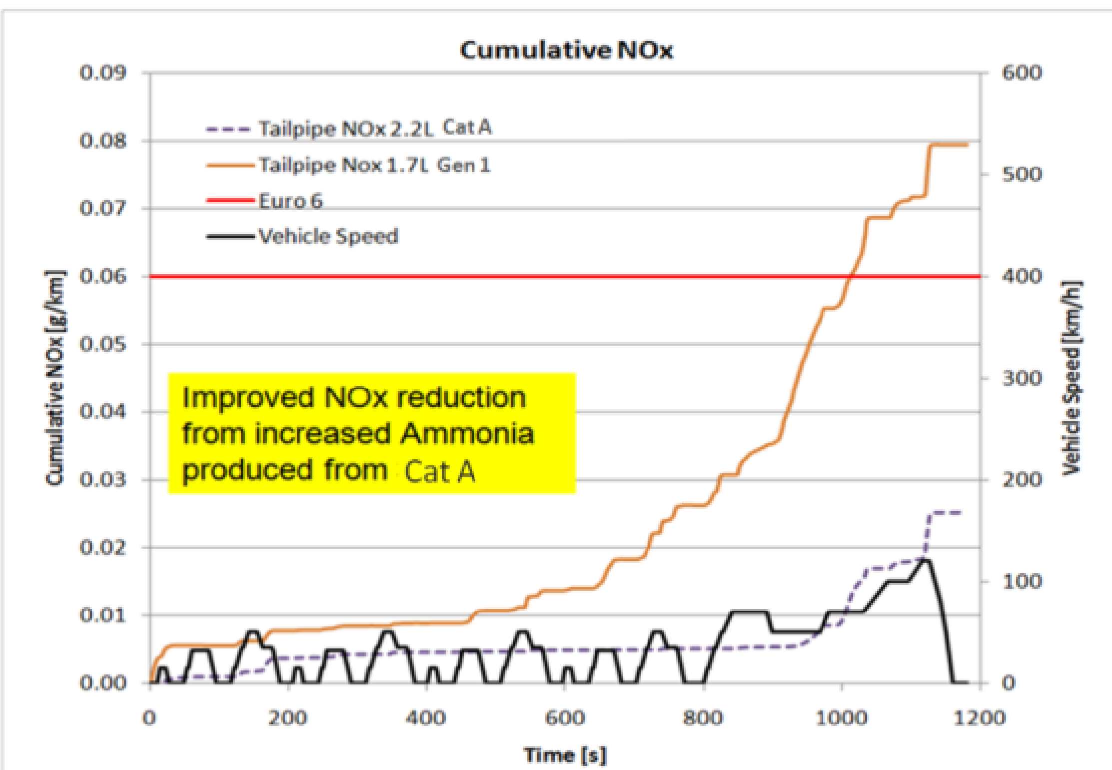


Figure 49: Cumulative Tailpipe NOx Comparisons

An optimized torque model enabled a transient FTP test to be run on an engine dynamometer while accurately reproducing the engine speeds and torques consistent with the actual vehicle operation. With these enhancements in place, several FTP test where conducted to assess the fuel economy potential of the SG4 engine compared to other operating modes and other engines. Further testing had been performed using steady-state points weighted to represent operating over the transient FTP test schedule. These points had been used to help quantify and understand the fuel economy shortfall observed for the engine when operated over an actual transient FTP test.

Several fully warmed-up FTP test where run on an engine dynamometer to assess the fuel economy potential of the spray-guided engine operated over a transient test cycle. For these tests, the baseline exhaust system architecture (consisting of a close coupled TWC, underfloor SCR & a rear SCR) had been used. In addition, no NH3 generation had been attempted for these tests. Results from these tests are shown in Figure 50. Lean idle operation had been shown to be worth approximately 1% benefit in fuel economy which is consistent with previous wall-controlled vehicle test results. 12V S/S as opposed to idle had approximately 5% fuel economy benefit, and lean operation had been only shown to be worth an additional 3% fuel economy benefit.

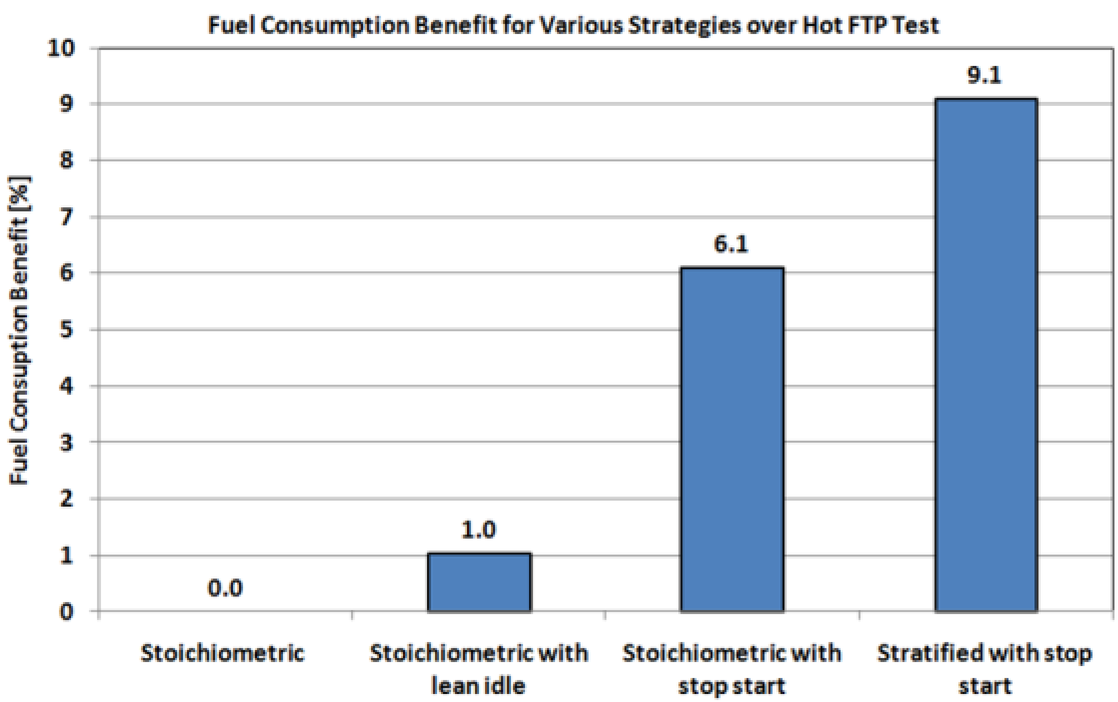


Figure 50: Fuel Consumption Strategy Optimization

To help quantify the fuel economy shortfall measured over the transient FTP test, a series of steady-state test points weighted to simulated operation of the vehicle over the transient FTP test schedule had been tested and compared to other multi-cylinder test engine data and optimized single-cylinder test engine data, Figure 51. The baseline for this comparison is the GM LCH engine which is essentially a stoichiometric L850 engine with Exhaust Gas Recirculation (EGR). The baseline for the current engine operated stoichiometrically falls 6.3% short of the fuel economy of the LCH engine, indicating that supplier provided calibration does not take advantage of production stoichiometric homogenous EGR calibration features. Based on the 10 steady-state points, the previous wall controlled engine shows a 12.6% fuel economy advantage which compares well to the 13% fuel economy advantage measure for the wall controlled engine system when run on an actual FTP test. This provides some confidence in the FTP fuel economy results predicted based on the 10 steady-state weighted points.

From these 10 steady-state weighted points, an optimized single-cylinder engine with a high energy ignition system had been shown to achieve a 21% fuel economy advantage over the LCH base engine. With an identical high energy ignition system, with cylinder load balancing and operating at the same control settings for spark, injection, cam timings, EGR, etc., the multi-cylinder engine had been able to achieve a fuel economy advantage of 20%, showing that the fuel economy advantage of the lean-stratified multi-cylinder engine is achievable. Without cylinder load balancing, the fuel economy advantage is reduced to 18.6%. And without the high energy ignition system, the combustion phasing had to be retarded to maintain combustion stability which resulted in a further reduction in the fuel economy advantage to only 14.5% compared to the baseline LCH engine. The operating conditions for the single cylinder test points had been calibrated to a NOx emission index level of 6 g/kg-fuel. If the NOx emission level is relaxed to approximately 12 g/kg-fuel as had been done for the initial calibration, the fuel economy advantage is further reduced to 14.5%. The calibration currently used by the controller had a NOx emission index level between 20 and 25 g/kg-fuel, and gave a fuel economy advantage over the LCH engine of between 8.2-9.1%. The initial C-17 calibration had more features to enable NH3 generation compared to the original E-1 calibration, but had slightly poorer fuel economy.

Thus, to achieve the maximum fuel economy potential, a revised calibration with a high energy ignition system, individual cylinder balancing, higher levels of EGR and a more advanced combustion phasing would need to be implemented. In addition, to perform better under cold operating conditions, a calibration taking advantage of double-pulse injection is required, based on single cylinder experimental results.

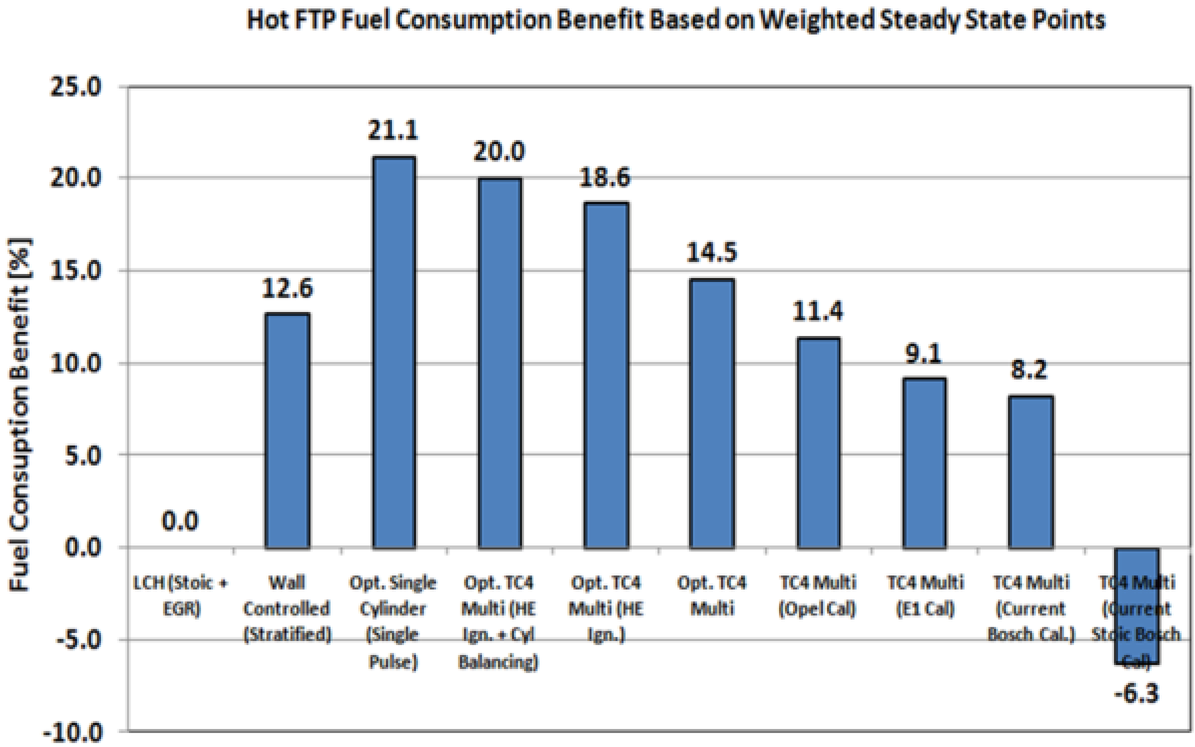


Figure 51: Hot FTP Fuel Consumption Improvement

4.2. PHASE 2 – EXPLORATORY DEVELOPMENT

4.2.1. SG5 NA ENGINE ASSEMBLY

The lean combustion research investigations had culminated in a framework of features and design application guidelines that had been applied to the refined Spray-Guided version 5 (SG5) lean combustion engine design, Figure 52. The SG5 is an inline four cylinder 2.2L naturally aspirated engine based on the 2.4L LE5 engine. A significant number of SG5 engine components had been enhanced and redesigned from the previous version SG4 lean combustion engine to support further achievement of the performance objectives:

- Direct cylinder high pressure fuel injection with upgraded fuel injectors
- Port Deactivation Actuator system with improved motor robustness and adjustment
- Intake manifold with variable length runners, Wide Ratio Air Fuel (WRAF) sensor, improved high temperature EGR inlet
- Revised cam cover and gasket design to accommodate the enhanced fuel injectors
- Cylinder head refined to accommodate refined split intake ports, fuel injection and PDA
- EGR system with reduced length and valve position for improved transient operation
- Integrated exhaust manifold to minimize exhaust gas heat loss

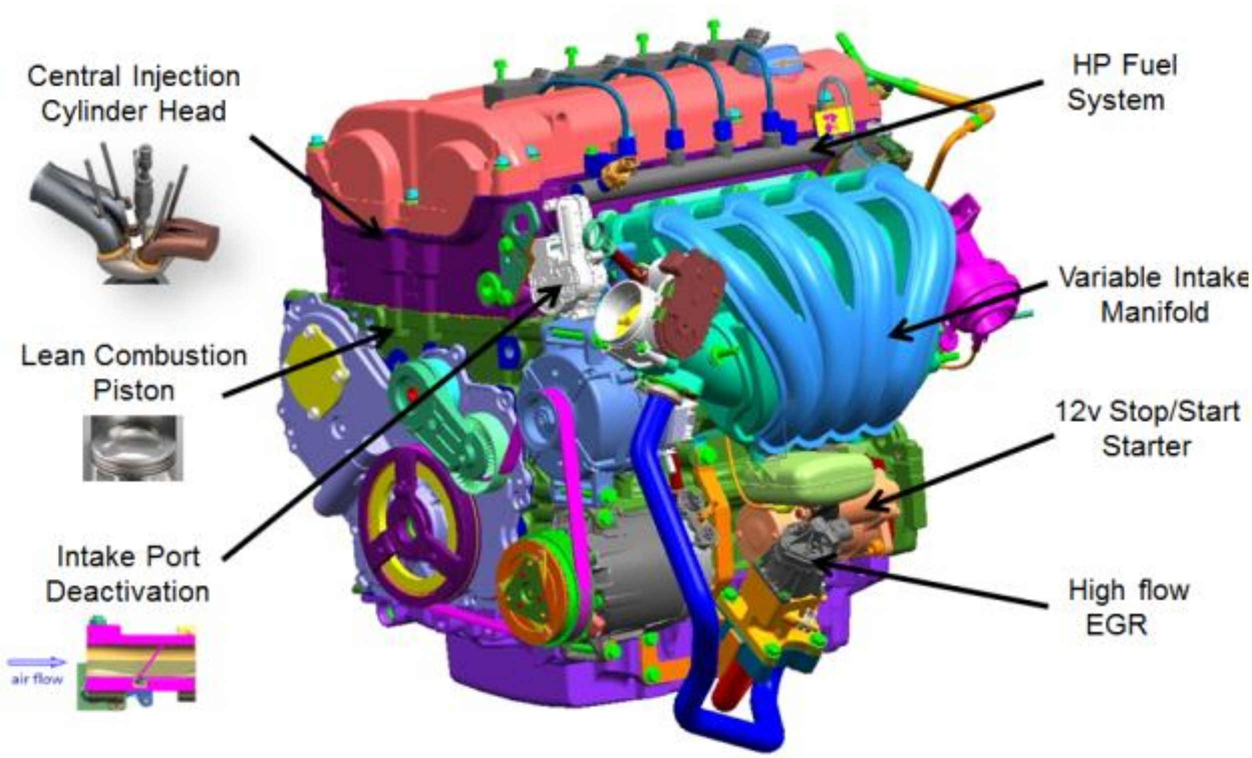


Figure 52: SG5 Engine Assembly and Refined Lean Combustion Enabling Features

Engine build commenced after part procurement, followed by start-cart electronic control verification, hot testing operation verification, engine break-in and relevant FTP test point verification. The test point verification had been to ensure similar engine out exhaust gaseous emissions to minimize test property data variation. Six SG5 engines had been built and installed in dynamometer and vehicle test properties. An additional four SG5 engine had been built to provide spare test properties to support all test facilities with uninterrupted support in case of engine failures.

4.2.2. SG5 ENGINE CONTROLS

New engine controls had been required to enable the SG5 lean combustion engine to operate in lean-stratified mode and transition to conventional stoichiometric homogenous combustion mode. A strategy had been developed to determine how the engine actuators that had to be commanded in order to achieve the desired amount of torque the driver requests via the accelerator pedal. A high level control architecture block diagram had been generated based on both the existing dynamometer controller content and anticipated vehicle controls needs as per the strategy above. Software modifications initially focused on dynamometer data to support the development of a torque estimation/control approach that enabled the overall controls strategy.

Program objectives had been to keep a torque modeling structure similar to the production structure. The development activities had focused on identifying the engine torque characteristics while varying individual control parameters. One example includes holding constant engine airflow, engine speed, valvetrain position and fuel mass while varying fuel injection timing. This process is repeated for each of the adjustable engine parameters.

Next stages of controls development targeted integrating the existing lean-stratified algorithms with the 12V S/S algorithms. The first step in this area had been identifying a compatible version of 12V S/S ECM software/calibration for the hardware being used in the lean-stratified vehicles. Subsequently, the task to identify the differences between the software sets and the necessary changes had commenced. The results of the changes had been tested in the laboratory on a simulation bench before being taken to the vehicle for further development testing.

Dynamometer calibration data generation had been completed to support the EGR valve position controls and flow characterization. Algorithms originally designed to control diesel EGR valves had been modified to work on the gasoline lean-stratified engine. Functionality, like valve position control and minimum position learning had been successfully implemented and tested on the dynamometer. These algorithms had been used on all the test properties, vehicle and dynamometer, as they became available.

Dynamometer data had been collected and processed to characterize the basic flow characteristics of the EGR valve at various A/F ratios. This data is utilized to generate an algorithm to translate the desired EGR percentage at different speed and load points to a desired EGR valve position, Figure 53. This had been combined with the above valve positioning algorithm to give a complete EGR control system.

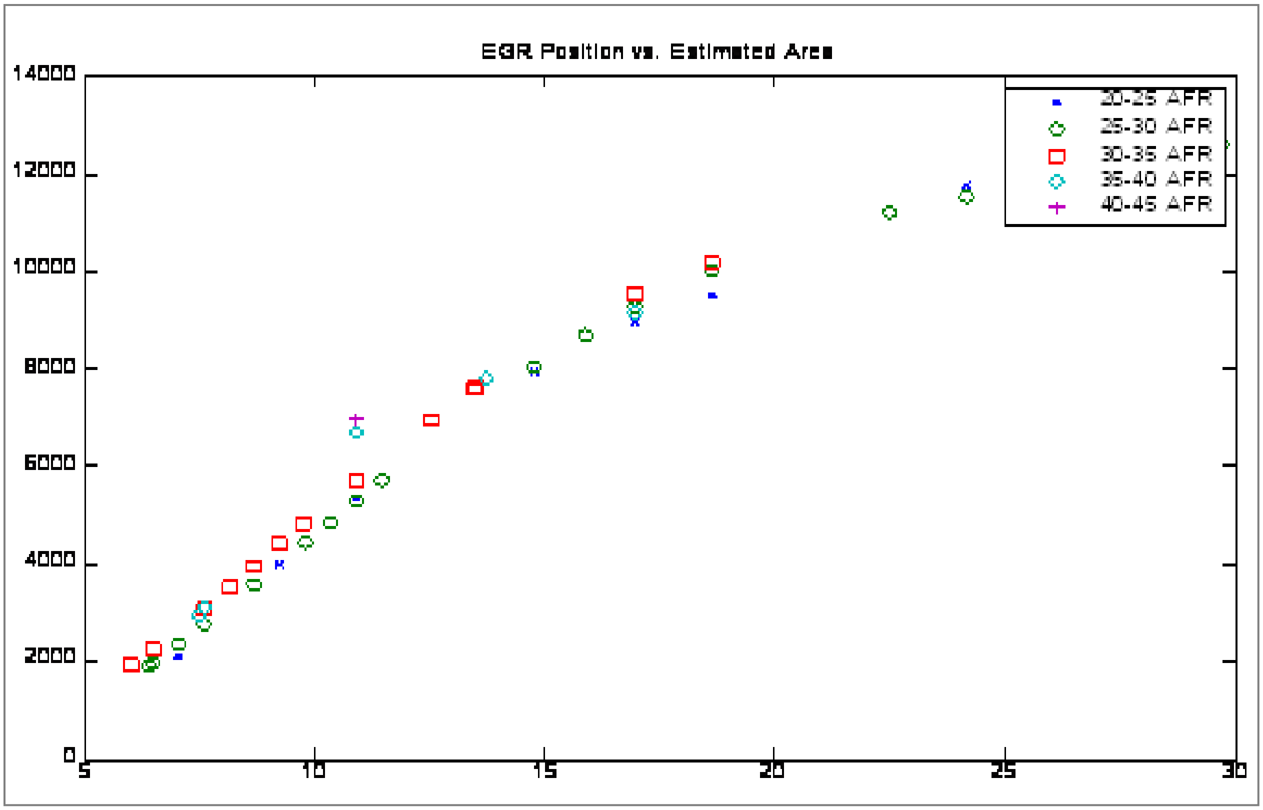


Figure 53: Flow Characteristics of the EGR Valve

Control development generated an engine torque estimation and controls strategy for lean-stratified combustion mode operation. Dynamometer data had been collected to complete characterization of lean-stratified combustion with a single injection pulse and lean-stratified combustion with dual-injection pulses at a single engine speed. Additional data had been collected at additional engine speed levels to ensure we had a complete map of engine torque output at various actuator positions and engine operating conditions. Once complete, the electronic control module's algorithms had been modified to comprehend this torque characterization.

Engine Control Module algorithm work had supported refinement of lean-stratified operation in the vehicles. Separate tables had been added, along with the necessary switching logic, for lean-stratified actuator control in both single-pulse and dual-pulse injection combustion modes. This logic had originally been designed only for steady-state engine operation. Algorithms had been added later to address the transient dynamics of switching between combustion modes as these conditions are evaluated in the dynamometer cell.

The engine calibration in the test cell had been oriented towards collecting data to support modeling the engine combustion and torque output. To accomplish this task, engine parameters had been slewed to non-optimized settings in order to determine the influence on engine power output and emissions. This data had been used to support developing control strategies when a switch between lean and stoichiometric operation is required as well as converting the driver's torque request from the pedal input to an engine operating setpoint.

The data had been used to create a model of engine torque output as a function of operating parameters of the engine. Several iterations had been completed to determine which engine parameters had the highest effect on torque output and which parameters could be excluded from the model, Figure 54. Further work is continued to determine the ability of this model to accurately calculate engine torque over all engine speeds and loads and operating modes.

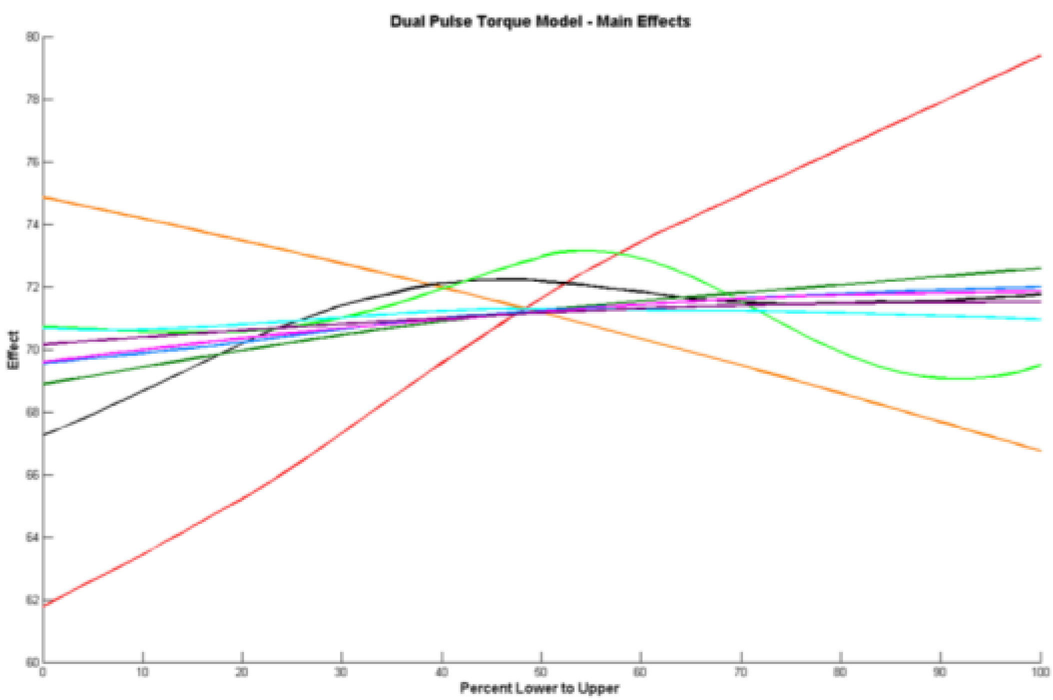


Figure 54: Dual Pulsing Engine Calibration Parameter Sensitivity Influence

The model had also been evaluated to support torque interventions which occur in normal driving such as transmission shifts, traction control events or other times when torque must be temporarily and quickly modified which may require short periods of non-optimized operation. Therefore the model had been evaluated against not only the optimized operation, but also the temporary non-optimized conditions. This activity led to strategy development to determine the best methods of torque control while minimizing fuel economy loss and emissions impacts.

Dynamometer data had been collected to characterize any differences in steady-state engine torque output between stoichiometric homogenous and lean-stratified fueling modes. Initial mode transitions in the vehicles felt as if there had been less steady-state torque being generated for an identical driver request when in lean-stratified versus stoichiometric homogenous mode. This offset had been confirmed on the dynamometer. A mapping of the torque offset over the lean-stratified speed/load operating range had been completed so compensation can be made in the current vehicles.

Dynamometer data additionally had been collected to support the creation of a lean-stratified torque estimation and control model. Data had been collected in all speed/load ranges except idle and ~4000 RPM.

Steady-state fueling mode (stoichiometric homogenous or stratified) operation had been implemented in the algorithms. These had been used extensively in the vehicles to generate fuel economy and emissions data. Basic fueling mode transition logic had been added as testing had been performed. One area of focus had been determining actuator response times so individual devices can be commanded such that they all achieve their desired positions in sync with the fueling mode change. While some actuators move between their extremes, i.e. completely open to completely closed, additional work had been performed to coordinate engine components that may had to be ramped or scheduled during transitions to maintain a constant engine torque during transitions.

Enhanced lean-stratified combustion engine control module algorithms had been added to allow engine operation which generates NH_3 across the TWC that had been subsequently stored in the SCR device. This involved adding logic to run at various air-fuel ratios at different durations.

Algorithms had been added to the engine controller to support processing an oxygen sensor installed in the intake manifold. This sensor is expected to help calibrate external EGR algorithms under transient operating conditions. Transient EGR control is critical to enabling good drivability when transitioning between lean-stratified and stoichiometric homogenous engine operation. Functionality had been added to compensate the sensor's readings relative to different manifold pressures.

Continued controls support further enabled engine dynamometer operation towards developing active NH_3 dosing SCR aftertreatment system. Controls algorithm and calibration changes had been made so the dosing system could respond to different engine operating modes, speeds and loads.

Control algorithms had been added to the engine controller as well to support the active thermal management coolant pump design. Initial controls design is based on control strategy input from the supplier that outlined the basic desired operation.

Lean-stratified fueling mode torque model algorithms had been implemented in the controls software. These algorithms allow the engine to operate at a constant torque across stoichiometric homogenous and lean-stratified fueling modes.

Continuing controls support enabled engine dynamometer operation to investigate the active NH3 dosing aftertreatment system. Calibrations had been improved to facilitate optimization of the active aftertreatment system.

EGR algorithms had been updated to more closely align with current production algorithms. This supports greater ease of potential integration of the technology within the production groups. Additionally, modifications had been incorporated that allowed for different set points and estimations when running in lean-stratified versus stratified stoichiometric homogenous modes.

In an effort to improve lean-to-stoichiometric transitions, missing and mis-timed fuel injection pulses had been addressed. Large changes in the commanded timing of the injection pulses had been determined to be the root cause of the problem. The algorithms had been modified so that each cylinder's fuel pulse is sequenced through the mode transition in order to solve the problem.

Enhancements to the NH3 generation algorithms had been implemented to support ongoing aftertreatment system optimization for NOx performance. Algorithms had been implemented so that various air-fuel ratio commands could be issued when NH3 generation events had been triggered. The ability to modify other engine actuators, like spark timing and camshaft position, had been also added to help maximize NH3 production during these events.

The original EGR algorithms had been undergoing modifications to correct anomalies and enhance functionality relative to lean-stratified operation. The algorithms originally translated into the software had been designed for stoichiometric homogenous-only engines. As lean-stratified operation specific functions had been added, portions of the original code required modification to support the new operating mode.

Controls activities further enhanced EGR algorithms and controls to enable optimal combustion calibration. The engine controls had additionally been refined by integrating the exhaust pressure and temperature sensor outputs to the algorithms rather than using production models.

To support potential introduction to the consumer market to ensure market viability, the engine torque controls had been expanded to comprehend Air Conditioner (AC) compressor transitions. During elevated ambient temperature conditions, the AC compressor is cycled more often and requires greater engine torque to operate. This added torque draw must be compensated for in order to maintain engine smoothness and to avoid engine stalls, a key customer drivability attribute.

Figure 55, provides an example of the problem and solution with AC load. In the upper graph, there is no compensation for the reduction in engine output torque when the AC compressor is engaged. Although the driver is requesting a constant torque from the engine, the actual torque output drops with AC compressor operation. In the lower graph, the torque request to the engine is offset by the estimated AC compressor torque. The AC compressor compensation allows the engine output to remain constant as per the driver's request, thereby meeting customer demands for seamless AC operation.

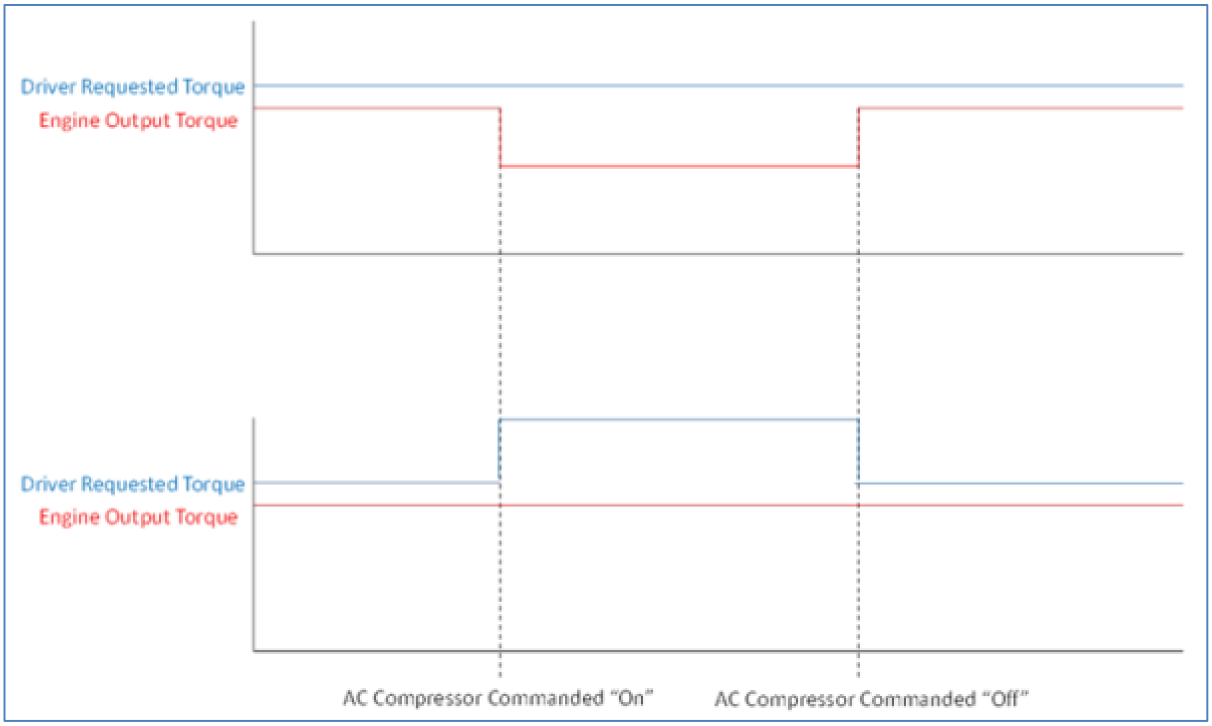


Figure 55: Engine Controls with AC Compressor Compensation

Critical to stable lean-stratified combustion, enhancement occurred to EGR algorithms and controls on the naturally aspirated lean-stratified vehicles. The recirculated exhaust gas flow control is one of the primary enablers of the lean-stratified operation with precise control critical to meeting combustion parameters targeted for seamless transition to stoichiometric operation. To support the precise control of exhaust gas flow, exhaust pressure and temperature sensors had been integrated into the ECM to allow the EGR valve to respond to changes in environmental conditions. In previous algorithms, the valve would remain at a static position based on driver input and engine speed. Enabling the ability to react to changing conditions allows the engine to run higher levels of EGR, without sacrificing drivability and therefore allowing extended lean operation.

4.2.3. SG5 ENGINE CALIBRATION

SG5 engine dynamometer calibration activities had been initiated to assist in developing a vehicle level calibration that could support transient vehicle operation and functional performance evaluations. The initial SG5 engine calibration focused on specific areas for lean-stratified operation, stoichiometric homogenous operation and the transition region between the operation modes.

The engine had been studied to find optimized set points for lean-stratified operation. The actuators (EGR, PDA, throttle, cam phasing and spark angle) had been optimized for fuel consumption, specific power output and emissions of NOx and smoke. In conjunction with developing the procedure to determine the optimized set points an automated version had been developed that can be applied to future engines using this technology. This had facilitated calibration mapping as engine design parameters are changed and optimization must be determined for these new configurations.

A method to collect engine torque data in lean-stratified mode while operating in non-optimum operating set points had also been developed. This data had been utilized to develop control algorithms to be used in vehicles during transient operation. During these transient conditions blending engine torque output improves vehicle drivability. The blending is controlled by the algorithms developed based on the data collected in this method.

Calibration data had been taken over the full range of engine speed and load in lean-stratified combustion operation. The data had been reviewed for Brake Specific Fuel Consumption (BSFC) performance along with meeting the criteria for emissions of NOx and Soot. Upon review of the data collected, analysis of the data pointed to areas of improvement. The data collection procedure had been revised several times to optimize the engine BSFC and emissions. These procedures had been coded into dynamometer control scripts that automated the subsequent data collection processes.

A fuel study had been conducted to see the impact on the calibration set points when the fuel had been changed. The initial test fuel used had been a laboratory grade gasoline fuel. The fuel study had been performed using customer intent fuel, which is a readily available gasoline blend. The study revealed very similar performance between the two test cases.

The test cell dynamometer setup had been used to generate data to develop a model structure to calculate torque based on the actuators of the engine. To generate this data the engine actuators had been swept through a range of possible operating conditions. For example, engine speed, fuel quantity delivered to the cylinder, and airflow among others had been studied for their contribution to final output torque of the engine. From this data, models to predict the engine output torque had been developed and evaluated.

Data had been collected to evaluate the proposed measurement systems for EGR. The data had been used to evaluate the correlation between laboratory grade emissions measurement equipment and the sensors that could be commercially viable. This data generated new requirements for the EGR control algorithm.

Further calibration effort supported the primary lean-stratified calibration by collecting additional data to support modeling the engine combustion and torque output. To accomplish this task, engine parameters had been slewed to non-optimized settings in order to determine the influence on engine power output and emissions. This data had been utilized to support developing control strategies when a switch between lean-stratified and stoichiometric operation is required. This data also had been used to support torque interventions which occur in normal driving such as transmission shifts, traction control or other times when torque must be temporarily and quickly modified which may require short periods of non-optimized operation.

A study of engine blow-by gasses had been conducted to determine the operating environment for proposed engine control sensors in the intake manifold of the engine. The blow-by vapors had been captured and measured to determine the rate of blow-by gases passing through the intake manifold. This information had then been used to estimate the potential reliability of the sensors being developed for this control system.

Calibration shifted towards refinement on key parameters such as; Intake & Exhaust Cam positions, Spark Advance, Start of Injection for single pulse, Fuel Rail Pressure and PDA position. All of these parameters had been optimized for fuel economy in stoichiometric homogenous operation mode for 4 FTP and 3 GM corporate test points. Fuel economy improvements between stoichiometric homogenous and lean-stratified modes had been compared for 3 of the FTP points that could be run on either mode. For the FTP points operated in stoichiometric homogenous mode, the naturally aspirated engine became marginally more fuel efficient by running the PDA in the near closed position instead of fully open. Also, adding external EGR in stoichiometric homogenous mode improved fuel economy reasonably well as compared to optimized stoichiometric homogenous operation without EGR. Figure 56 demonstrates load and fuel economy gains for the two operating modes.

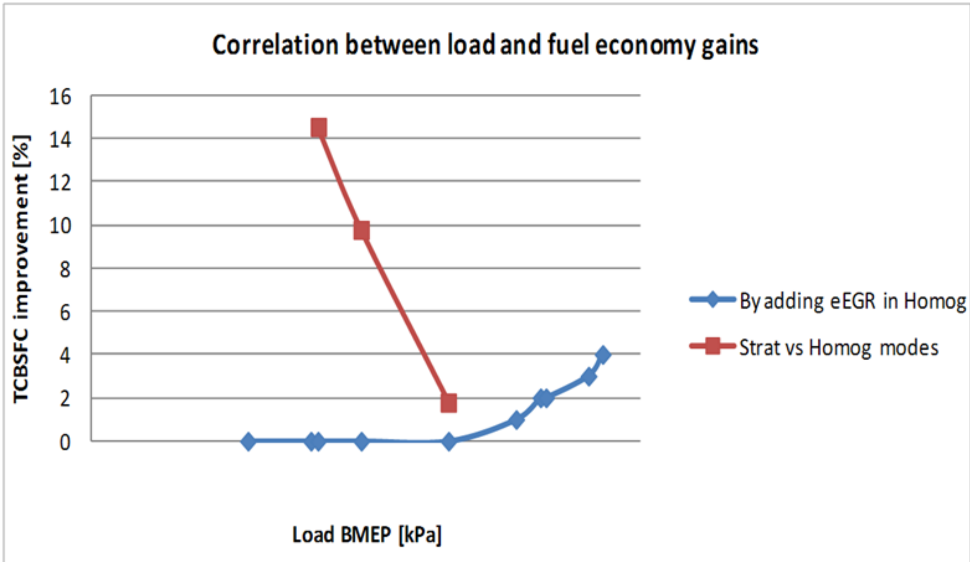


Figure 56: Stoichiometric Homogenous and Lean-stratified Load and Fuel Economy Gains

4.2.4. G1 PASSIVE LEAN AFTERTREATMENT SYSTEM

The PASS lean aftertreatment hardware research investigations had generated a fundamental understanding of the hardware and the operational capability necessary for efficient lean NOx conversion and that had been incorporated in to the Generation 1 (G1) passive aftertreatment system. The G1 passive lean aftertreatment incorporated the refined specifications in TWC and SCR arrangements that packages within the available spacial constraints of the Malibu development vehicle. The G1 passive lean aftertreatment system had been mated to the new SG5 engine with the Integrated Exhaust Manifold (IEM) cylinder head and optimized the post-TWC EGR extraction location. The system additionally incorporated the required development features; thermocouples, oxygen sensors, WRAF sensors, NOx sensors, pressure sensors and emissions sample probes, Figure 57.

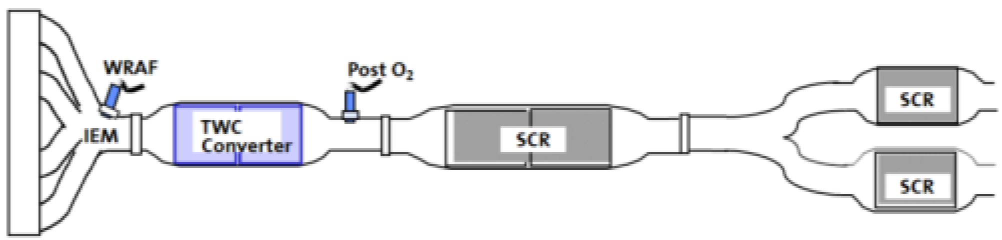


Figure 57: G1 Passive Lean Aftertreatment Schematic Layout

Three G1 passive lean aftertreatment systems had been fabricated to support vehicle level testing as well as dynamometer development of the SG5 engine. To support representative customer in-use NH3 generation and NOx conversions, prior to canning the first vehicle TWC had been dynamometer aged and the SCRs oven aged. Inert substrates had been supplied for the engine dynamometer testing as the engine calibration was at its infancy, though provided representative back-pressure. The system installed on the first vehicle is shown in Figure 58.

Figure 58: G1 Passive Lean Aftertreatment System Y-oval TWC and Rear SCRs

Tailpipe emissions engineering development targets had been developed for HC, NMHC, CO, NOx. The development targets generated ensures regulatory emissions targets are achieved when taking in to account manufacturing variably and degradation from in-use aging. Exploratory data analysis had been undertaken to fully comprehend the full useful life aging requirements for SCRs. SCR utilization in gasoline fueled vehicles is an atypical application, thereby requiring new procedures and processes to be developed which emulates expected 120,000 mile vehicle life usage.

Accelerated SCR aging schedules had been developed for the G1 passive lean aftertreatment hardware. These schedules are based on the SG5 engine operated conventional stoichiometric combustion mode. SCR temperature histograms had been developed to determine representative aging schedules, Figure 59. The accelerated aging schedules for the G1 passive lean aftertreatment SCRs take place on a burner instead of an engine dynamometer, this allows maintaining a very narrow temperature window which is critical to avoid thermal damage to the SCRs.

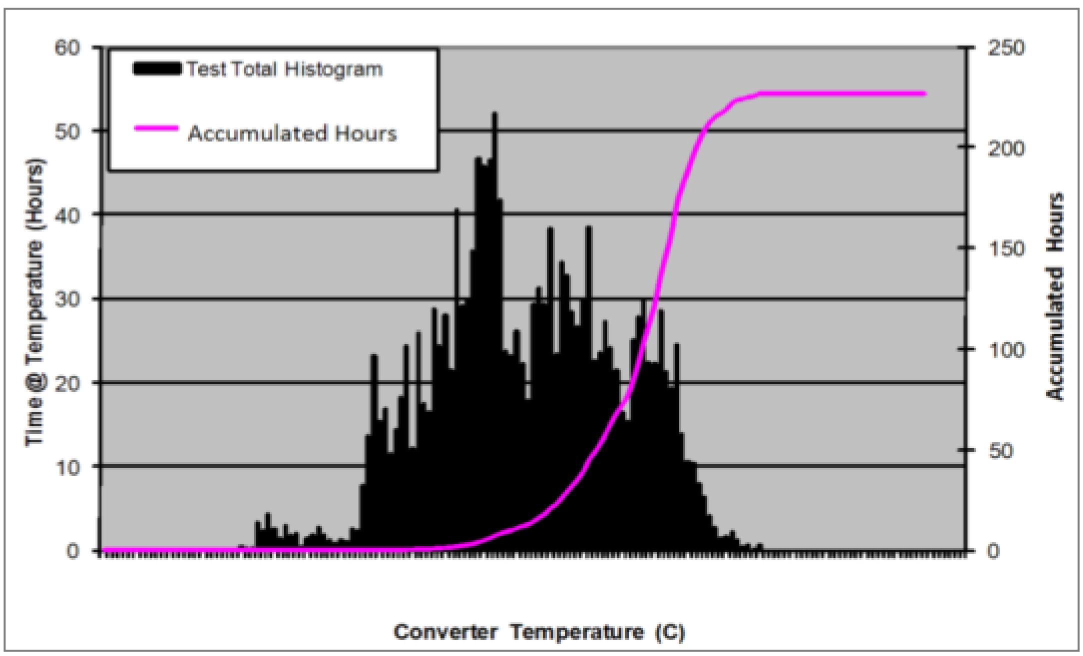


Figure 59: Production Malibu LE5 Engine Aging Histogram.

Initial vehicle results for the G1 passive lean aftertreatment system indicate that initial location for the 2.0L SCR is not optimal for NOx emissions performance, Figure 60. The optimum operating temperature for an SCR converter is in the range of 200 to 350C. The G1 passive lean aftertreatment system design targeted the underfloor SCR catalyst to be in the optimum temperature range during low to mid speed operation and the rear SCR catalysts being in the optimum temperature range during high speed operation. Steady-state data indicated that during lean-stratified operation the front SCR is in the optimum temperature range and the rear SCR's are below the optimum temperature range at speeds below 50 mph. Exhaust temperatures measured during the FTP city and highway tests indicate that during transient conditions the front SCR temperature is generally above 350C and the rear SCR temperatures are generally in the recommended SCR temperature range. This is primarily due to running stoichiometric homogenous mode during acceleration maneuvers.

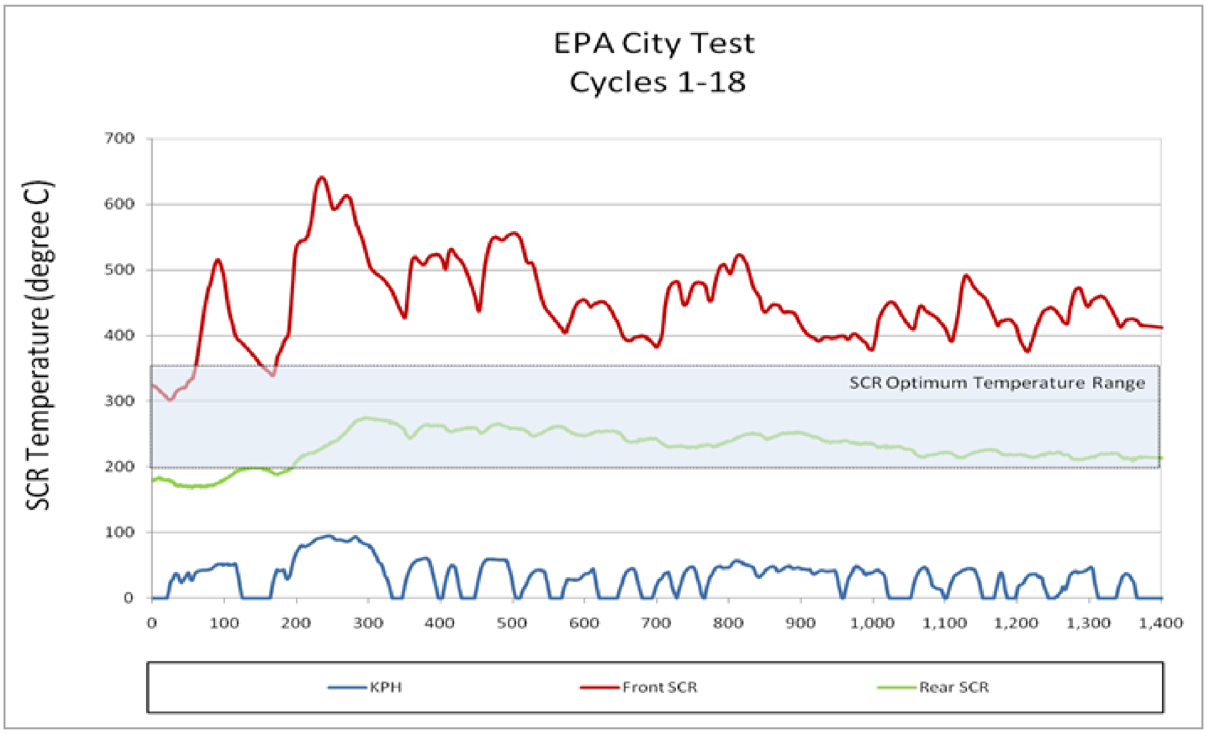


Figure 60: G1 Passive SCR Temperatures Measured During EPA FTP City Test

The temperature of the TWC needs to be above activation temperature for good conversion efficiency. Steady-state vehicle data had been run to determine the operating temperatures of the various exhaust components when operating lean. The vehicle chassis dynamometer data shows the TWC meets the temperature requirements, but again confirms the underfloor SCR temperature is excessive at 50 mph. The data is summarized in Figure 61.

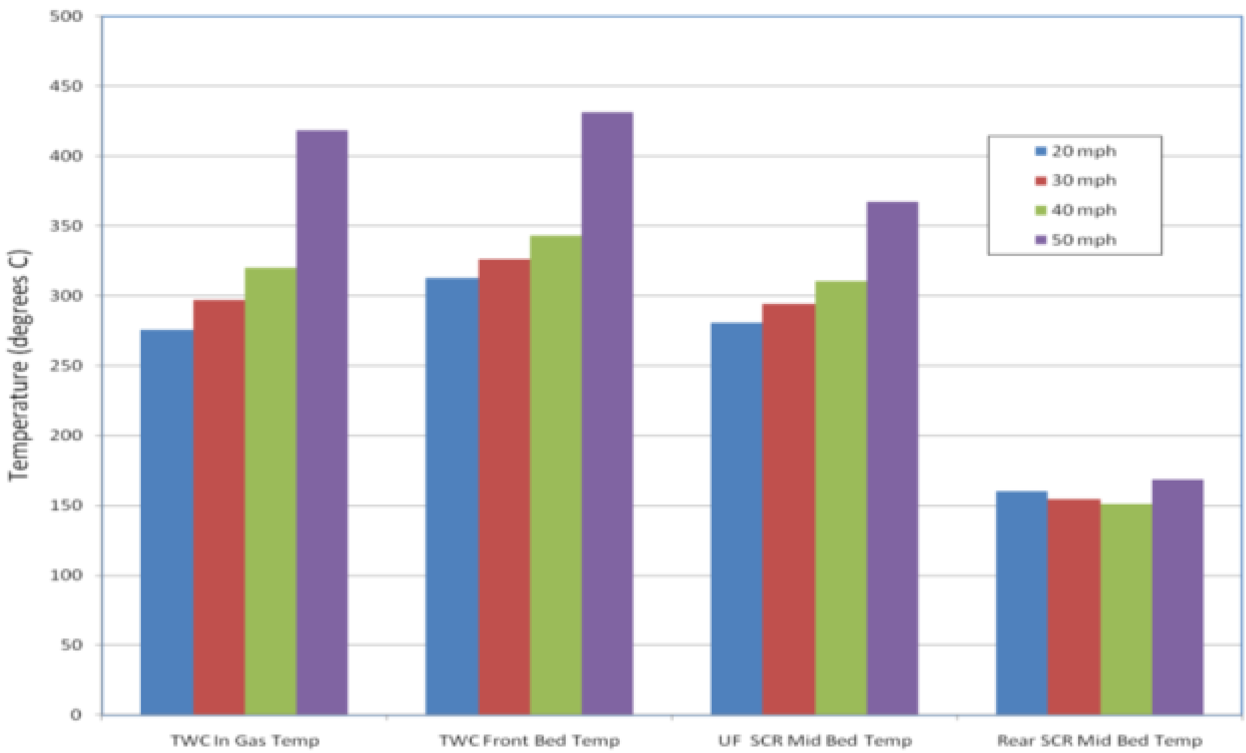


Figure 61: Malibu #1 Steady-State Exhaust Temperature Data

Figure 62 demonstrates the cumulative weighted tailpipe emissions during the FTP city test cycle. As expected, the majority of the tailpipe HC emissions occur during and immediately after initial engine start before the TWC is hot. The air fuel ratio during engine starting and after start had been modified to reduce engine out emissions and the spark and injection timing had been retarded to improve TWC light-off time. This resulted in a TWC light-off time (time to 350C) of 9-10 seconds and first cycle tailpipe emissions similar to other four cylinder direct inject engines that GM produces.

The warm-up characteristics of the TWC and SCR's are shown in Figure 63. The emissions plot also shows HC emission breakthrough after the hot restart in cycle 19. Calibration refinement in this area had focus on leaner commanded air fuel ratio during engine starting and after start.

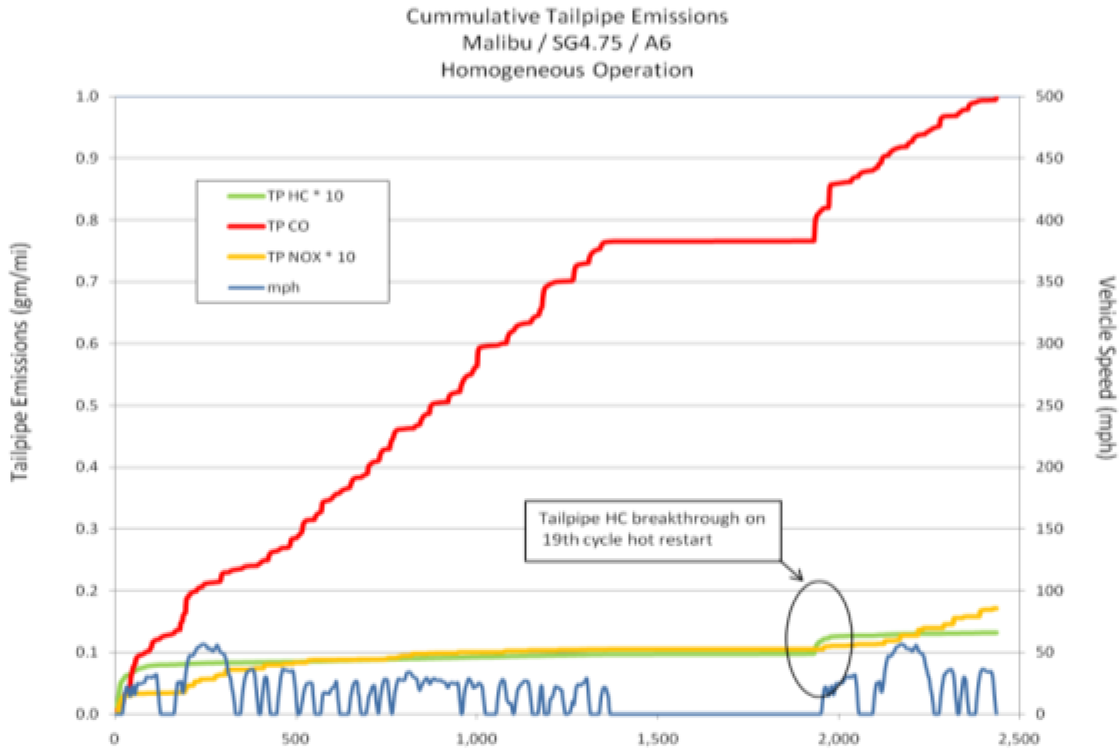


Figure 62: Malibu #1 Tail Pipe Emissions over the FTP City Test Cycle

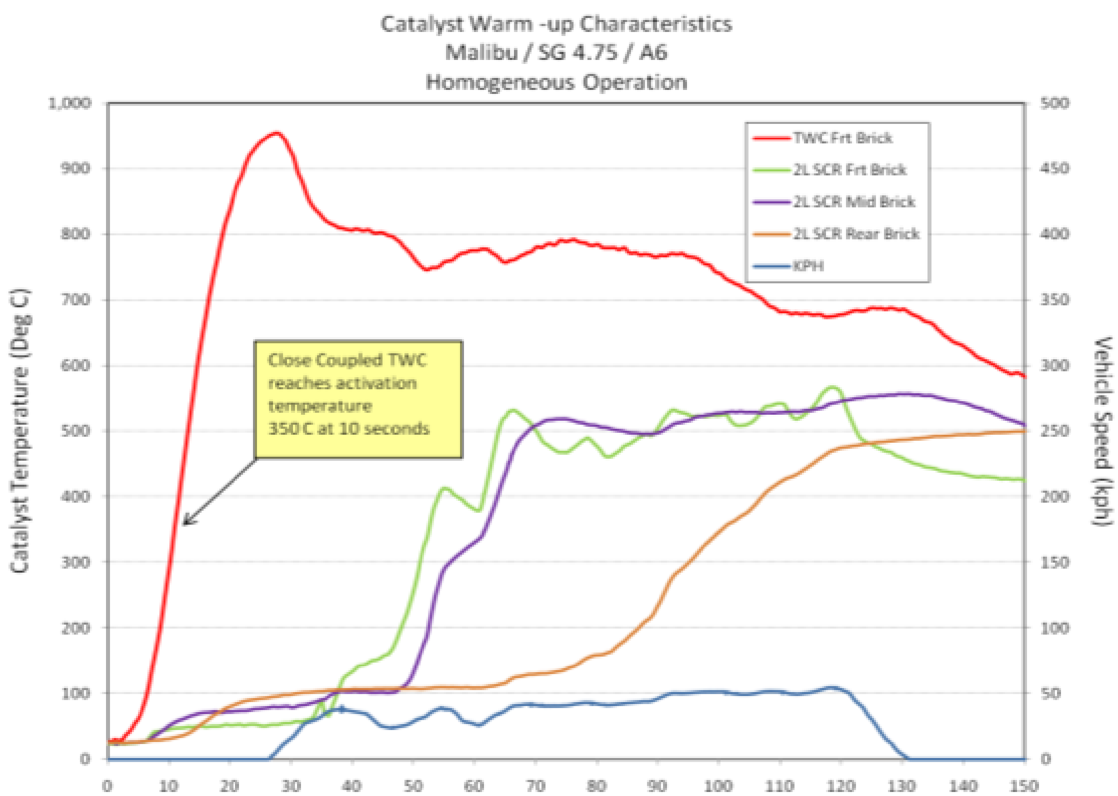


Figure 63: Malibu #1 TWC and SCR Warm-up Characteristics

A plot of cumulative NOx emissions for the FTP city test is shown in Figure 64. Overall NOx efficiency needs to be approximately 90% to meet the T2B2 NOx standard. The G1 passive lean aftertreatment system yields NOx efficiencies for the underfloor and rear SCR's that are lower than targeted. The results of the G1 passive lean aftertreatment had provided valuable insight towards the specification for the following generation of lean aftertreatment

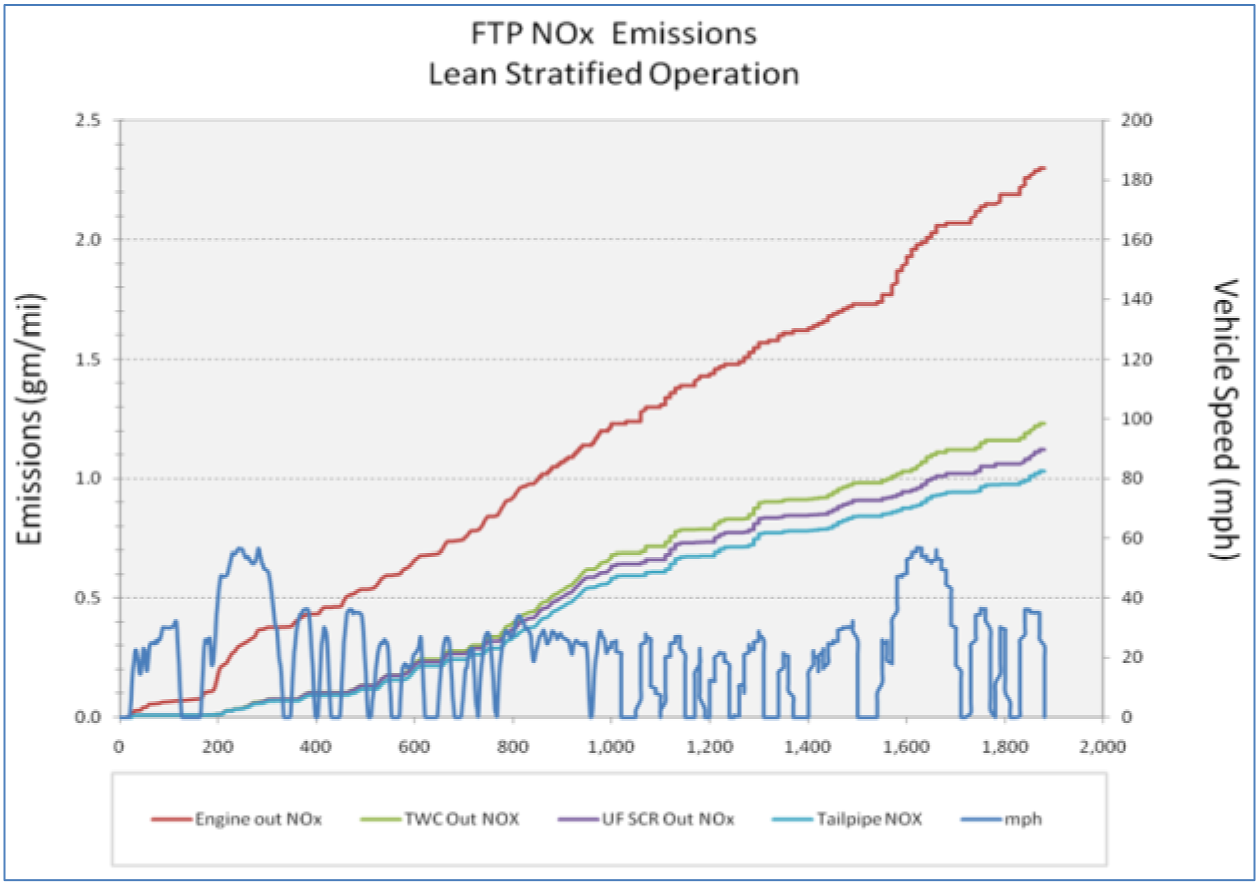


Figure 64: Cumulative NOx Emissions for the FTP City Test

4.2.5. G2 PASSIVE LEAN AFTERTREATMENT SYSTEM

From the vehicle testing of the G1 passive lean aftertreatment exposing the continued limitations of the SCR temperatures being outside of the optimal range, a revised Generation 2 (G2) passive lean aftertreatment system had been configured with new SCR locations. The system had a revised location for the front 2.0L SCR of 29" downstream from initial location. The system additionally incorporated SCRs aged to 4K miles, Figure 65.

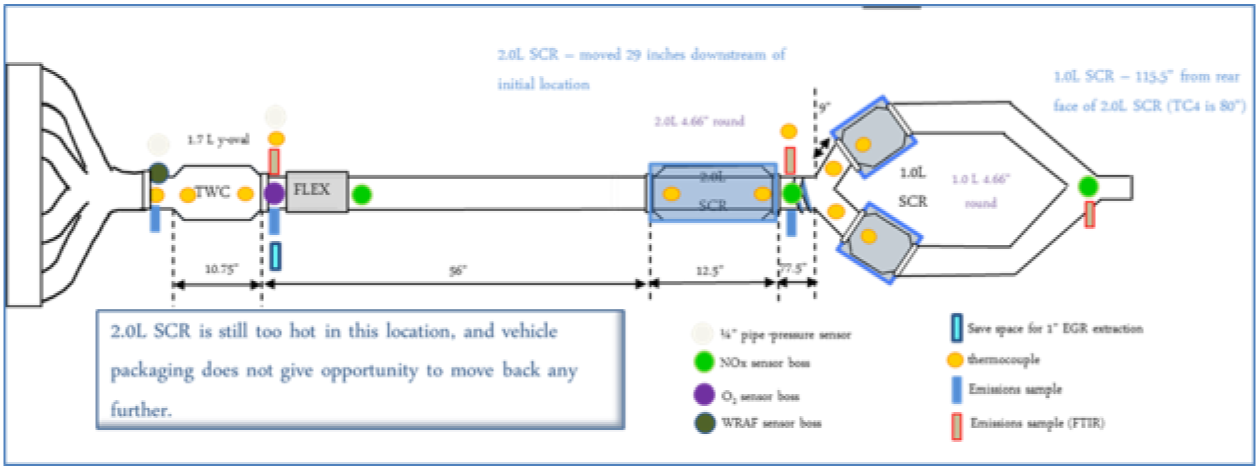


Figure 65: G2 Passive Lean Aftertreatment Revised Vehicle SCR Locations

Vehicle test results for the Gen 2 Passive lean aftertreatment indicated that the revised location of the front SCR had been improved and the temperature is approximately 75C cooler. In this revised location however, the temperatures are still excessively high for optimal SCR performance through the intended vehicle operation range of low-speed, mid-speed and high-speed, Figure 66.

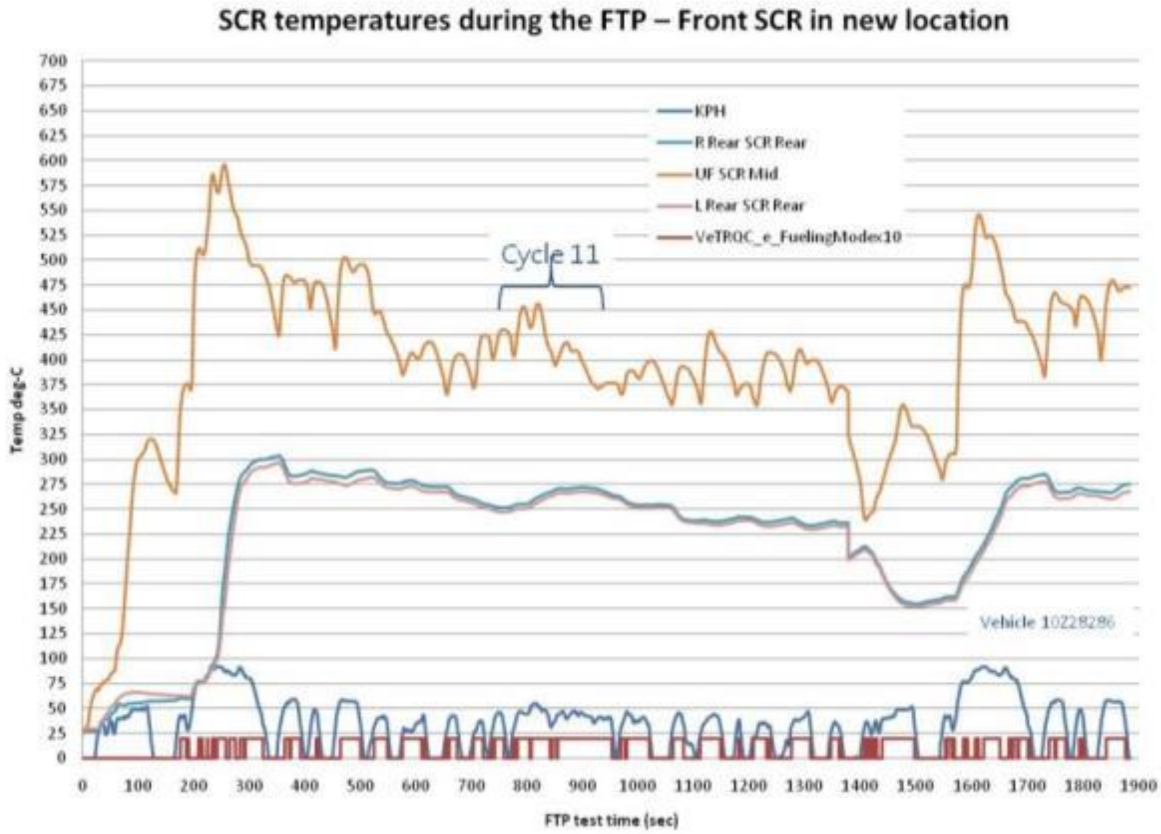
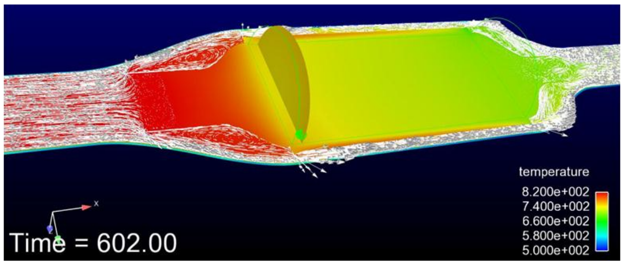


Figure 66: G2 Passive Lean Aftertreatment SCR Temperature Profiles on the FTP Cycle

To address the continued limitation of SCR temperatures, multiple lean aftertreatment risk mitigation alternatives had been conceptualized. The first alternative approach involved incorporating an exhaust gas active thermal management device. The second alternative approach involved relocating the front SCR rearward in vehicle. The third alternative solution investigated revising the calibration to reduce exhaust gas temperatures in stoichiometric homogenous mode.

The first risk mitigation approach concepted, the exhaust gas active thermal management device, incorporates the most radical aftertreatment alternative solution. Temperature simulation had been conducted on an initial concept to determine the amount of time required to bring the SCR down to the operating temperature after it is exposed to high exhaust temperature due to high speed and load conditions during EPA FTP City Test. Figure 67 indicated the rise in temperature in the SCR substrate when an active valve is closed once the SCR temperature exceeds typical ammonia storage and NOx conversion temperatures. After a designated time period, with the valve closed, the substrate temperature rises. Although this temperature increase seems minimal, Figure 68 indicated the duration to cool down the substrate once it exceeds the operating temperature. After 750 seconds, the substrate still exceeds the optimal SCR operating window.   Subsequently, the concepted approach had been discarded.



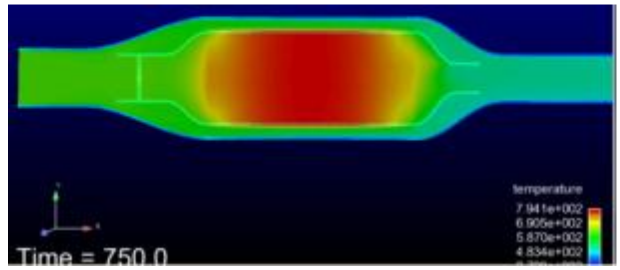


Figure 67: SCR Temperatures – Valve Closed   Figure 68; SCR Temperatures - Cool Down

From exploratory investigations, the second and third concepted approaches, relocating the front SCR rearward in vehicle and revising the calibration, had been analyzed with sufficient merit and subsequently targeted to be integrated in the next generation passive lean aftertreatment.

4.2.6. G3 PASSIVE LEAN AFTERTREATMENT SYSTEM

Vehicle development continues on the passive SCR lean aftertreatment system to generate an optimal lean aftertreatment package for NOx emissions performance. The updated Generation 3 (G3) passive lean aftertreatment is installed on vehicle with three design changes incorporated to improve emissions performance, Figure 69 and Figure 70. Firstly, the front SCR location had been positioned axially rearward by 29 inches to lower temperatures and improve NH3 storage. Secondly, the rear SCR configuration had been modified to a single 2.0L SCR with a revised torpedo inlet cone. Finally, a TWC had been generated with a different washcoat, targeted to generate increased NH3 and reduced CO emissions.

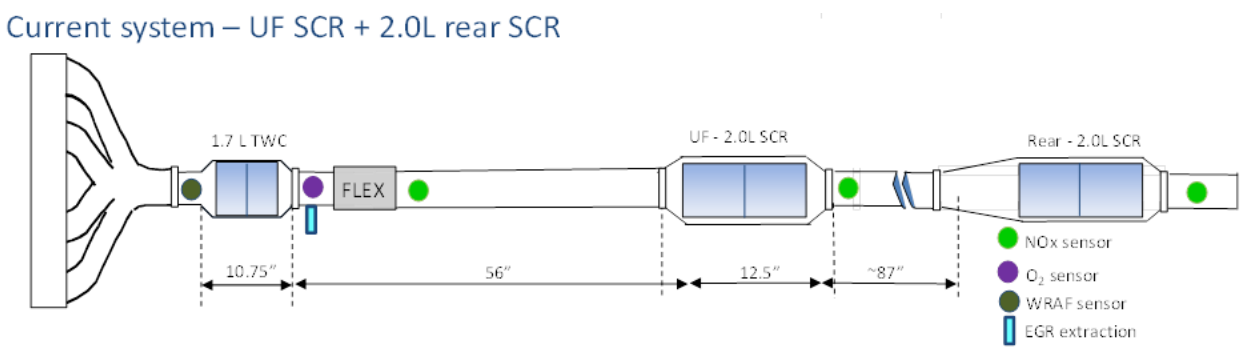


Figure 69: G3 Passive Lean Aftertreatment with Revised SCRs

	Front	Rear	Front	Rear	Front	Rear
Total PGM (g)	Pd Rh		Pt Pd Rh		Pt Pd Rh	
Substrate volume (L)	.73	.96	.45	1.55	.45	1.55
Substrate geometry	Y-oval 3.74"x5.79"		Round 3.15"dia x 3.54"long	Round 3.82"dia x 8.27"long	Round 3.15"dia x 3.54"long	Round 3.82"dia x 8.27"long
Cell density, wall thickness	900/2.5 and 600 cpsi/ 4.3 mil		900/2.5 and 600 cpsi/ 2.5 mil		900/2.5 and 600 cpsi/ 4.3 mil	

Figure 70: G3 Passive Lean Aftertreatment TWC Configurations

In support of further optimizing NOx performance, SCR NOx efficiency engineering targets had been developed based on the expected engine-out NOx levels. For the targeted NOx index range of 10 – 12 gr NOx/kg fuel, greater than 97% NOx efficiency is required to meet the T2B2 regulatory targets. Steady-state and transient testing had been conducted to determine NOx efficiency across the SCR system given different NOx inlet concentrations (100 – 300 ppm) and Ammonia Generation Event (AGE) times (12 – 60 sec), Figure 18. In each case, an AGE took place, followed by a 32 MPH steady state lean condition. The equivalence ratio during the AGE had been 1.035 for all test points. As shown in Figure 71, even with AGE time = 60 seconds, the G3 passive lean aftertreatment system falls short of the 97% NOx efficiency target.

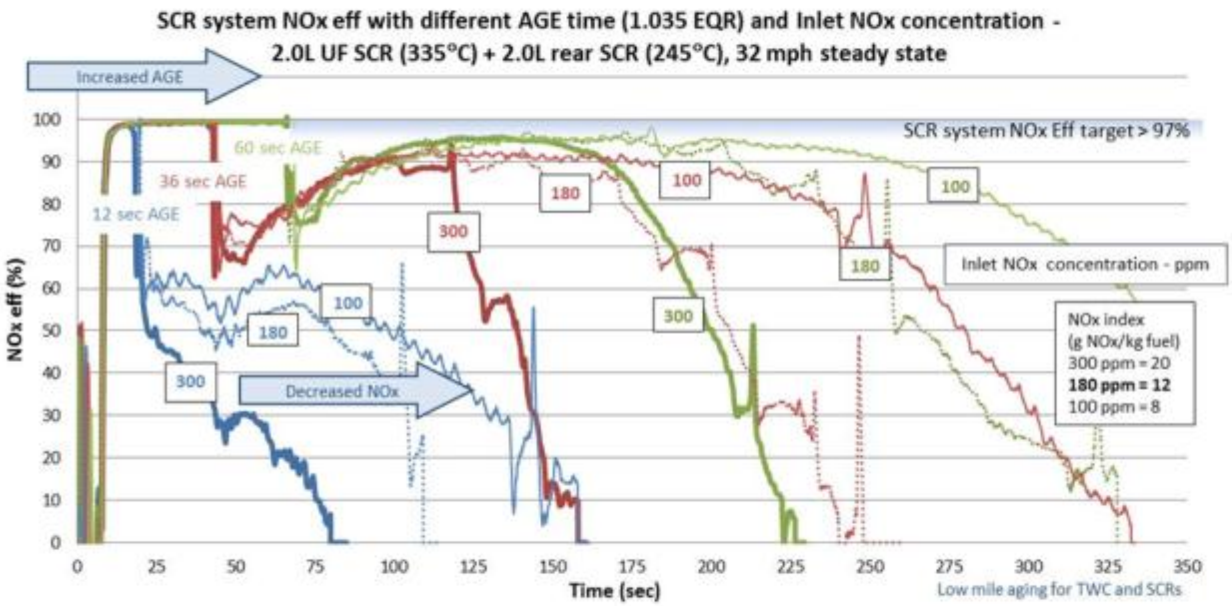


Figure 71: G3 Passive Lean Aftertreatment NOx Efficiency

When the engine is operated rich to generate NH3, it is not surprising that CO breakthrough occurs. Figure 72, highlights the concentration of CO that breaks through when 1500 ppm of NH3 is generated for 36 seconds. Based on this CO rate, the FTP CO target would be exceeded with 142 seconds of AGE during an FTP. This does not include any cold start CO emission that would occur during the engine warm up phase. Two options to resolve the CO tailpipe issue are using a CO clean-0up catalyst post SCR volume or utilize an additional/alternative source of NH3.

The steady-state testing also revealed that the underfloor SCR is storing NH3 effectively and that no NH3 is supplied to the rear SCRs, even with AGE up to 100 seconds. Thus, there is essentially no NOx conversion over the rear SCRs. The results are shown in Figure 73.

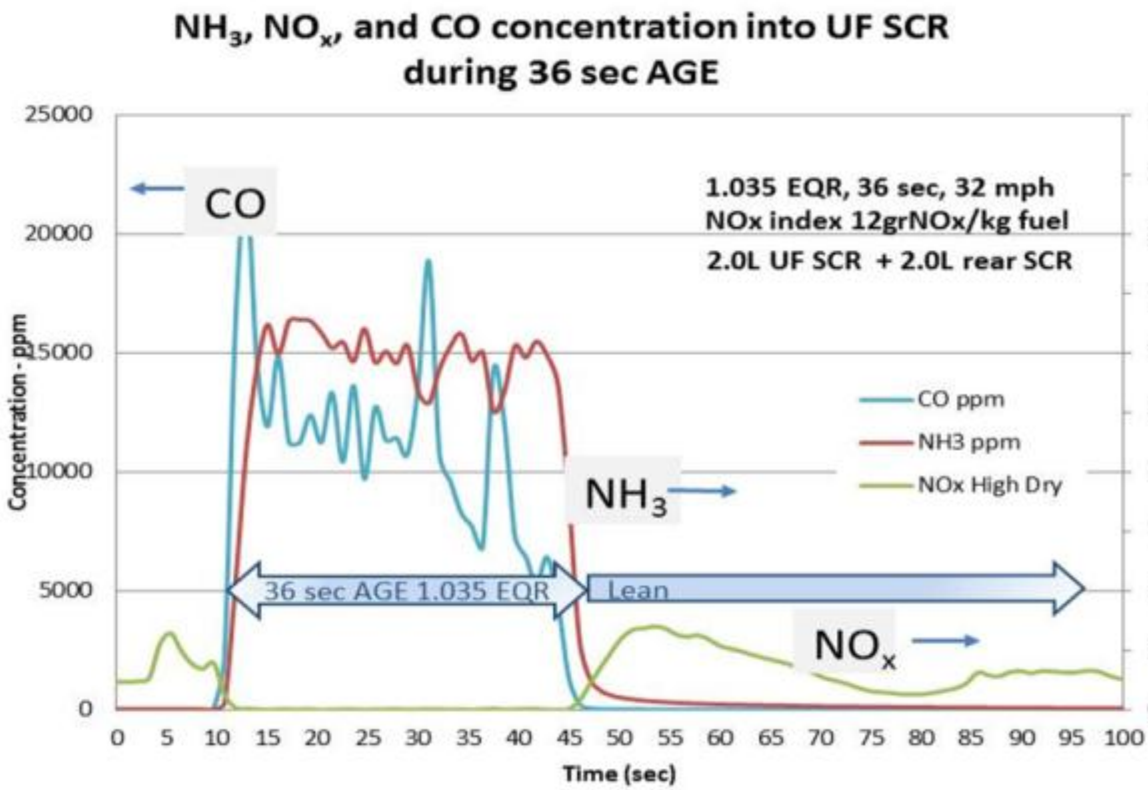


Figure 72: G3 Passive Lean Aftertreatment CO Breakthrough

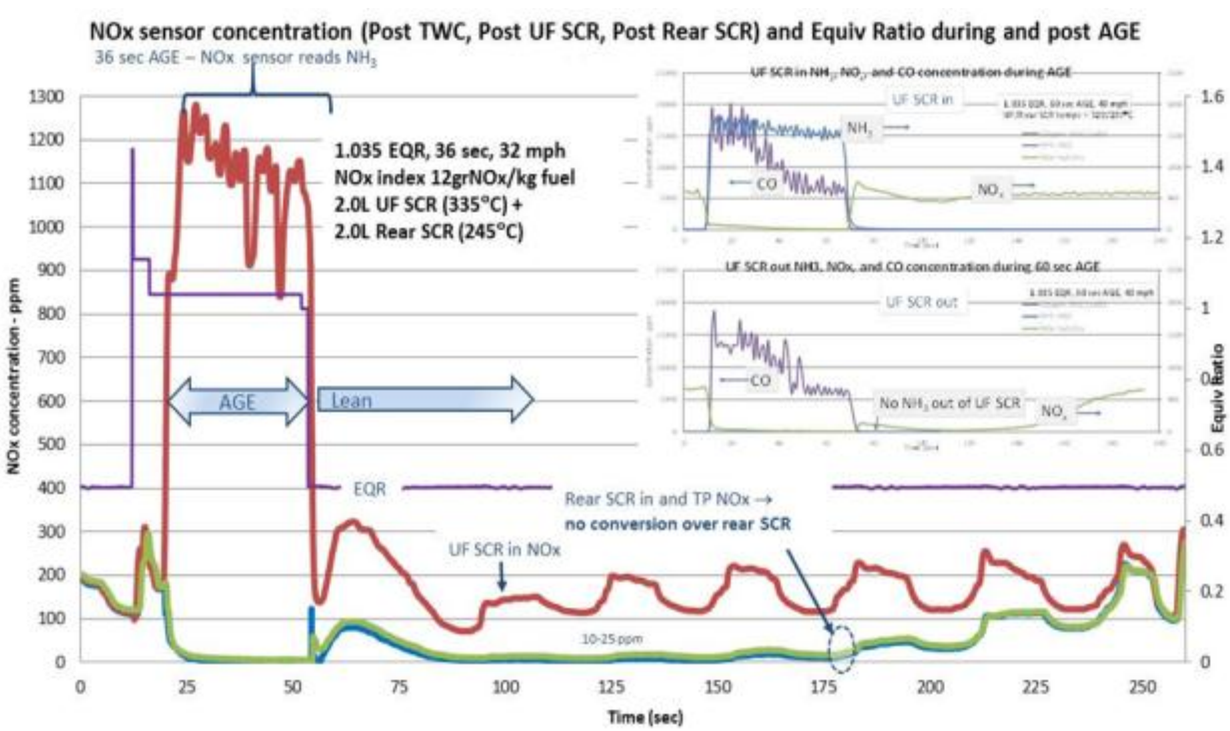


Figure 73: G3 Passive Lean Aftertreatment SCR NH3 Storage

Tailpipe emissions for the G3 passive lean aftertreatment system are shown in Figure 74. The stoichiometric homogenous closed loop control calibration has been refined to shift the control leaner to reduce the NMHC and CO emissions. The latest passive SCR lean aftertreatment results support the conclusion that the passive system is not capable on its own merit of meeting the T2B2 emissions requirements.

T2B2 Standard	**NMHC (gm/mi)** **.010**	**CO (gm/mi)** **2.1**	**NOX (gm/mi)** **.020**
Stoichiometric homogenous	.014	2.4	.008
Lean-stratified (Passive SCR control)	.017	5.5	.643

Figure 74: G3 Passive SCR Lean Aftertreatment Tailpipe Emission Results

Due to the insufficient NH3 generation for high NOx performance with the G3 passive lean aftertreatment system, the active urea dosing system had been further developed to provide a supplemental source of NH3. A fourth generation, Generation 4 (G4) passive lean aftertreatment system had been created with combined passive + active SCR lean aftertreatment technologies with a designation of Passive + Active Ammonia SCR System (PAASS). A strategic benefit to the G4 system is that it reduces the amount of actively dosed liquid urea that would be required for a solely active lean aftertreatment system.

4.2.7. ACTIVE UREA LEAN AFTERTREATMENT SYSTEM

The initial G1 passive lean aftertreatment system demonstrated some significant performance potential during the initial evaluations as well as indicated that there may be some structural performance limitations. Risk analysis of the limitations signaled that additional lean aftertreatment technologies needed to be implored to achieve the required T2B2 functional performance. Correspondingly a risk mitigation project to develop an active urea dosing system had been initiated.

To engage on an active urea dosing system development project, a SG5 engine and production aftertreatment system had been installed on an engine dynamometer. Packaging studies had been conducted to optimize the urea injector location and mixing to ensure an efficient active urea dosing system is developed before installation on to the development vehicle, Figure 75.

Figure 75: Active Urea Lean Aftertreatment Hardware

Controls methodologies had been generated, incorporated in to a controller, as well as subsequently demonstrated on a hardware-in-the-loop bench. The system strategies covered all lean-stratified speed/load points currently generated on the FTP and highway test cycles. In addition, the system had been targeted to perform at all temperatures encountered regarding these test cycles and not slip excessive NH3 at the tailpipe. In Figure 76, the blue line represents data generated from the optimized exhaust configuration demonstrating improved system performance for NOx conversion efficiency over initial active urea configurations.

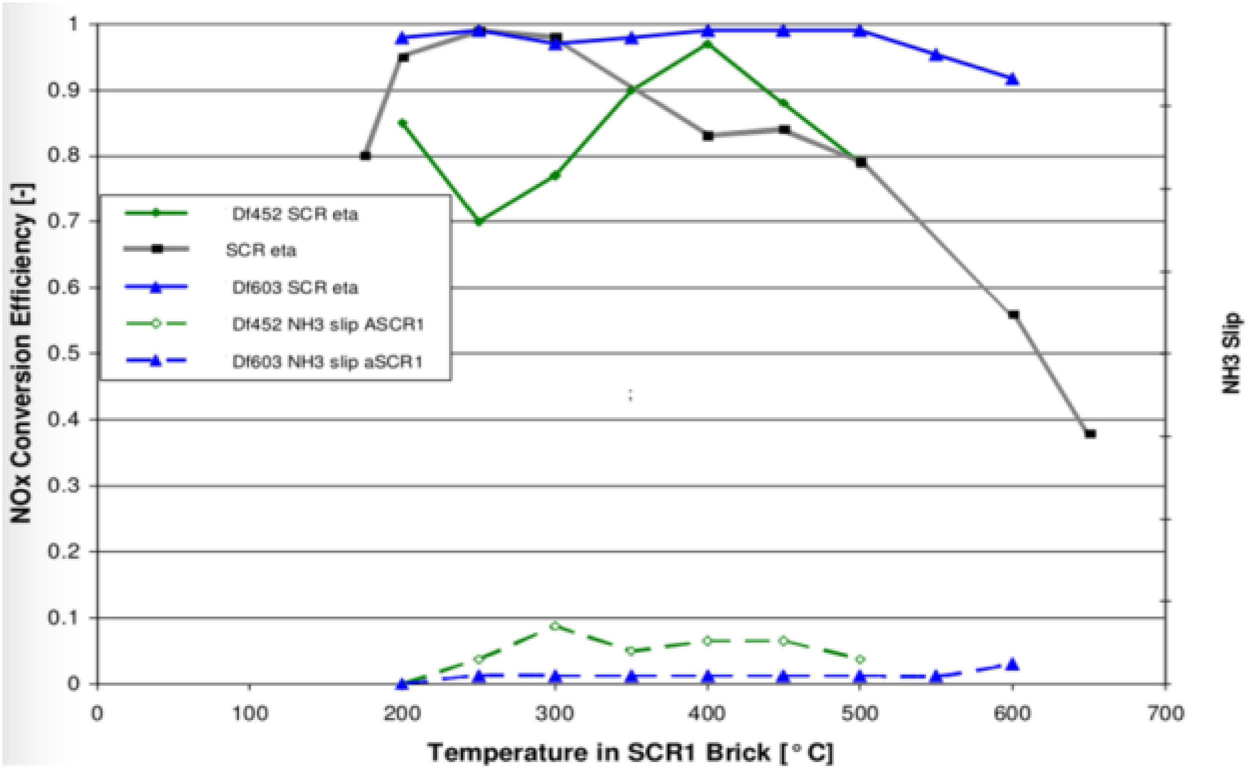


Figure 76: NOx Conversion Efficiency for Experimental Active Dosing System Configurations

The active urea architecture had been run on the engine dynamometer and had been used to calibrate the aqueous urea SCR dosing system. The system focused on covering all speed/load points currently generated on the FTP City and Highway test cycles, Figure 77. In addition, the system must perform for all temperatures encountered regarding these test cycles, handle the transients while not slipping NH3 of more than 10 ppm at the tailpipe. To accomplish the transient testing the Highway fuel economy test cycle had been adapted for the dynamometer. This test cycle had been not optimal but proved valuable providing good calibration adjustments before integrating the active urea system to the vehicle.

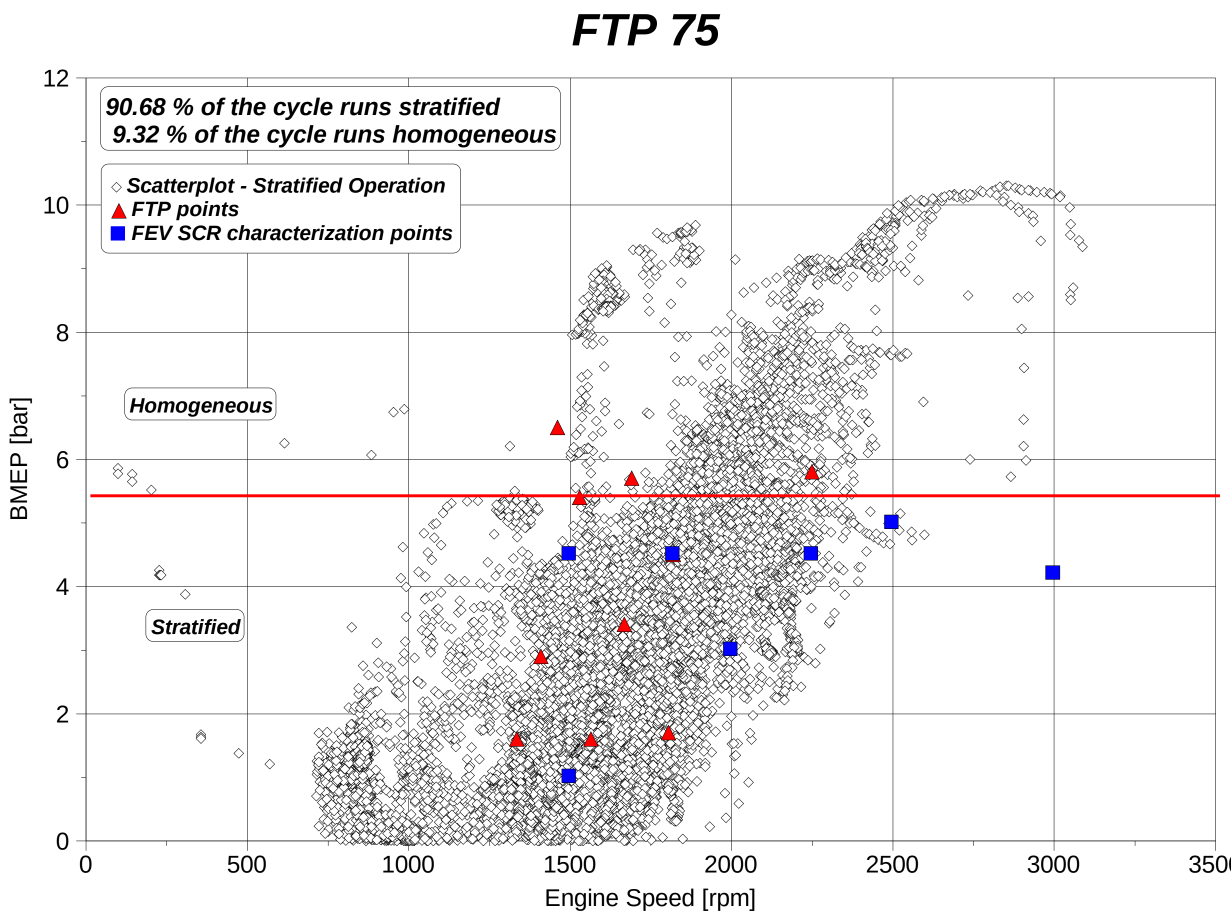


Figure 77: Speed/Load Points on FTP City and Highway Test Cycles

To accomplish the active dosing system calibration the dynamometer had been operated at approximately 7 speed/loads points that cover an acceptable range of the above test cycles. The testing protocol had been to saturate the front SCR brick with NH3 and allow it to slip to the rear SCR bricks but not exceeding the tailpipe target of 10 ppm NH3 slip. The data had been collected for each test point at steady state conditions and analyzed for best NOX conversion efficiency. This test had been done for the fresh and aged SCR converter.

The data indicated the fresh SCR catalyst achieves very good NOx conversion efficiency with the current SCR catalyst technology. The aged SCR catalyst clearly demonstrates poor NOx conversion efficiency at the lower temperatures as well as falling off at very high temperatures. The NOX conversion efficiency performance of the tested system is best for the temperature range of 275 to 525°C.

HWFET cycle had been adopted for the dynamometer and the 4k aged SCR “torpedo” architecture had been used to support the evaluation. Although this cycle does not represent the HWFET to the fullest extent, this had been a good starting step to dial in an SCR calibration before moving into the vehicle level calibration. Sixteen tests had been run consecutively to validate calibration and performance of the exhaust system. The fresh "torpedo" SCR had been used for this testing (4K aged). This had been done because the aged SCR converter had been not received in time when testing commenced. The results can be seen in Figures 78 and 79.

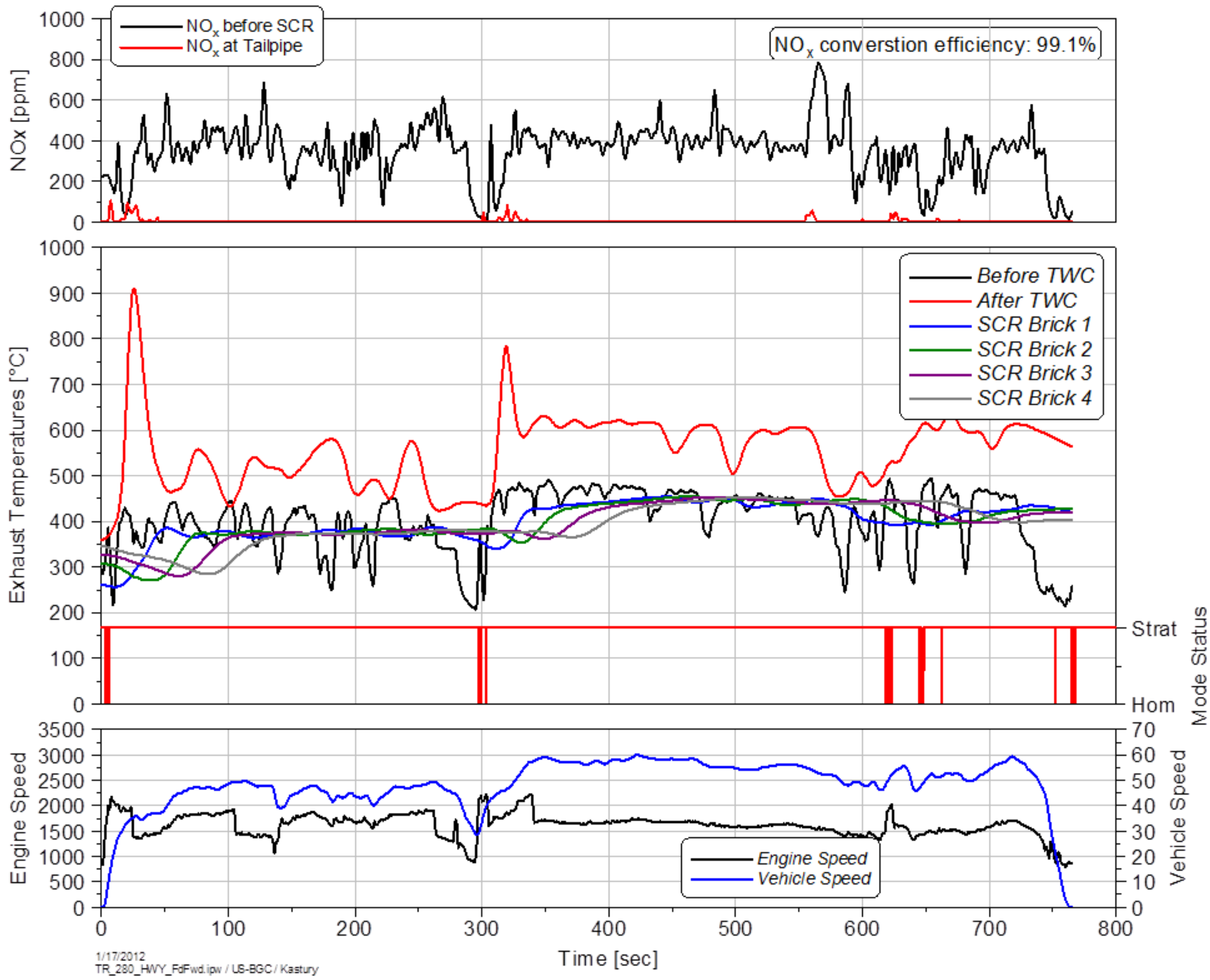


Figure 78: Emission Data for the HWFET Test Cycle

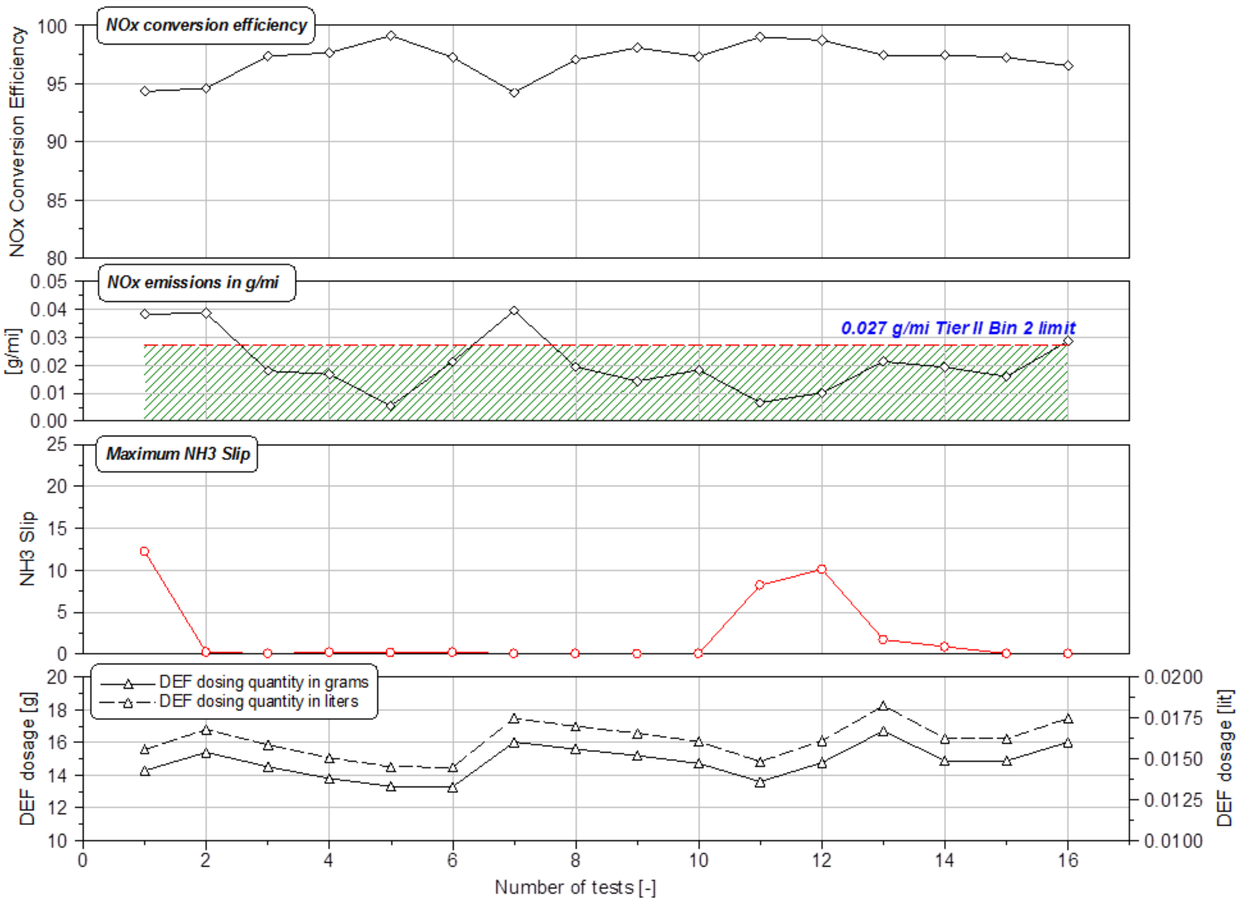


Figure 79: NOX efficiency, NH3 Slip and Urea Usage for 16 Consecutive Tests

The summation of the dynamometer testing phase follows:

- The steady state mapped aged "torpedo" SCR NOx conversion efficiency shows that at low and high temperatures, the efficiency is lower. In the 275-525C range, the NOx conversion efficiency is still approximately 99%
- A dosing system calibration had been developed and verified for the HWFET test cycle and the NOx conversion efficiencies had been ranging between 97 and 99% with slip lower than 10 ppm over a range of 16 tests

Figure 80 illustrates the installation with the SG5 engine in the front and the close coupled TWC in the back near the flex joint. Following is the dosing valve, SCR catalyst and then the tailpipe. The dosing reservoir, pump and all data acquisition equipment are located in the trunk of the vehicle.

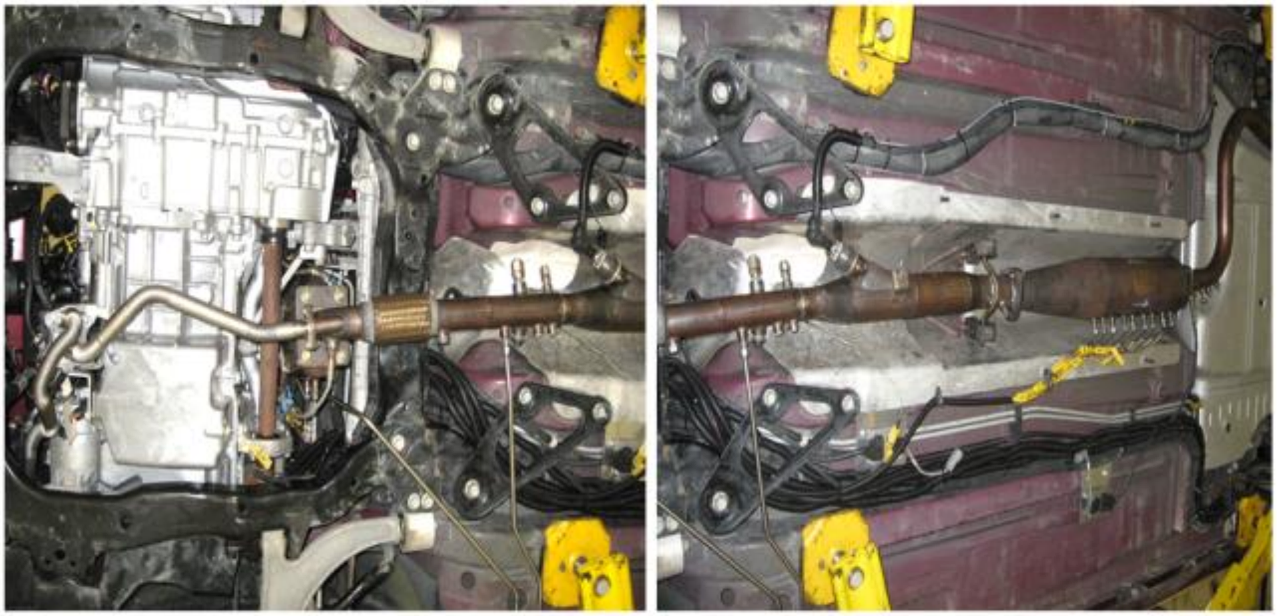


Figure 80: Initial Active Urea System Installed in the Development Vehicle

Vehicle level transient operation emission testing consisted of the FTP and HWFET test cycles. The active urea dosing system utilized separate bricks of Copper/Iron/Iron/Copper SCR technology. The FTP test cycle emission results are detailed in Figure 81 and the HWFET cycle emission results are detailed in Figure 82.

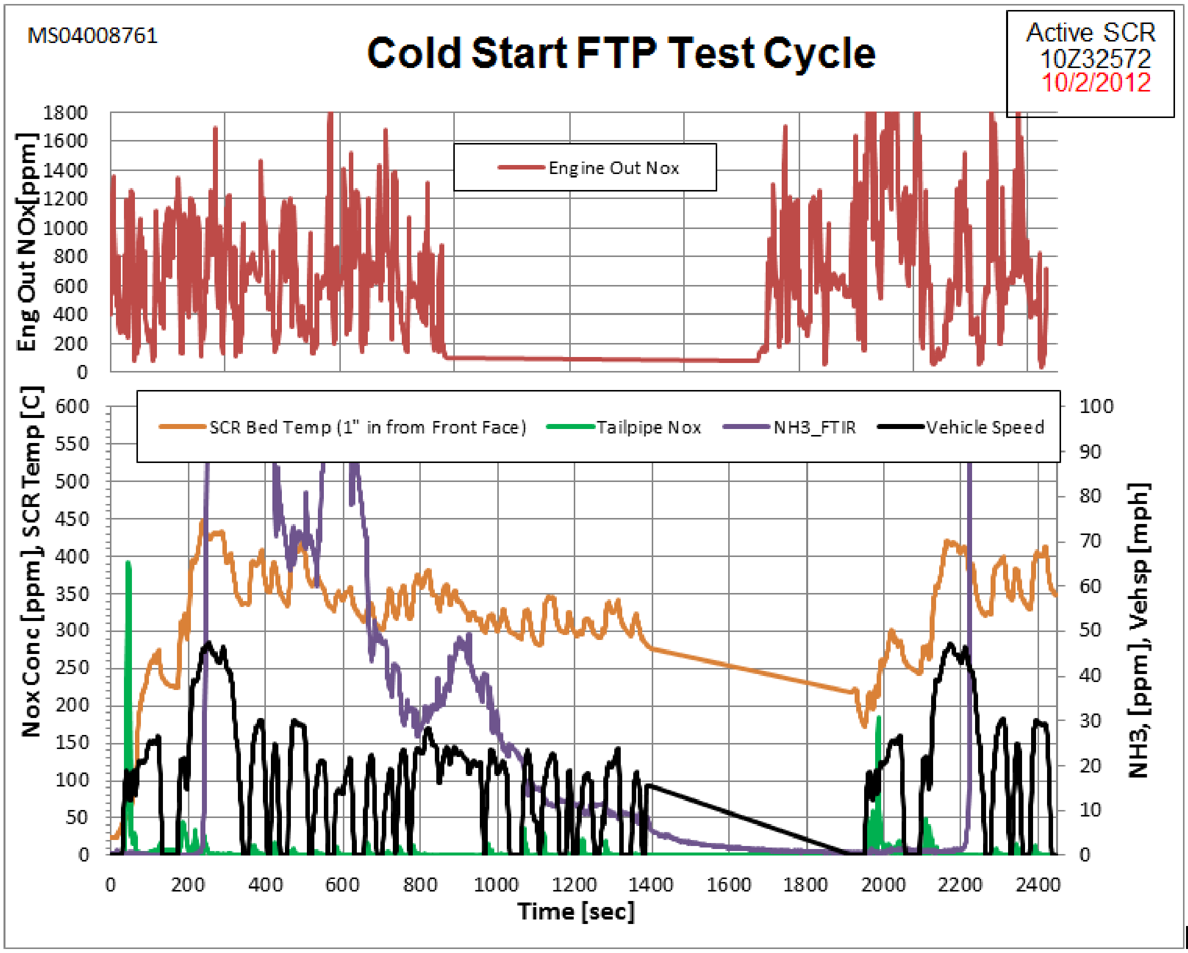


Figure 81: Active Urea Lean Aftertreatment System FTP Vehicle Emissions

Key observations of the FTP test cycle emission performance results, Figure 81, include:

- The emission totals are 0.033g/mi HC (0.010 std), 3.8g/mi CO (2.1 std), and 0.019g/mi NOx (0.020std)
- The combustion is very sensitive to calibration and richer calibrations can meet the standards for HC and NOx but at the expense of fuel economy
- There is sufficient data available which supports that with a short cold start strategy, the engineering target for NOx can be achieved
- Increased TWC volume is needed for complete reduction of CO and HC
- NH3 is still higher than expected, but is due to new catalyst formulation and an immature dosing calibration. Outside of the high temperature release the NH3 slip is very good

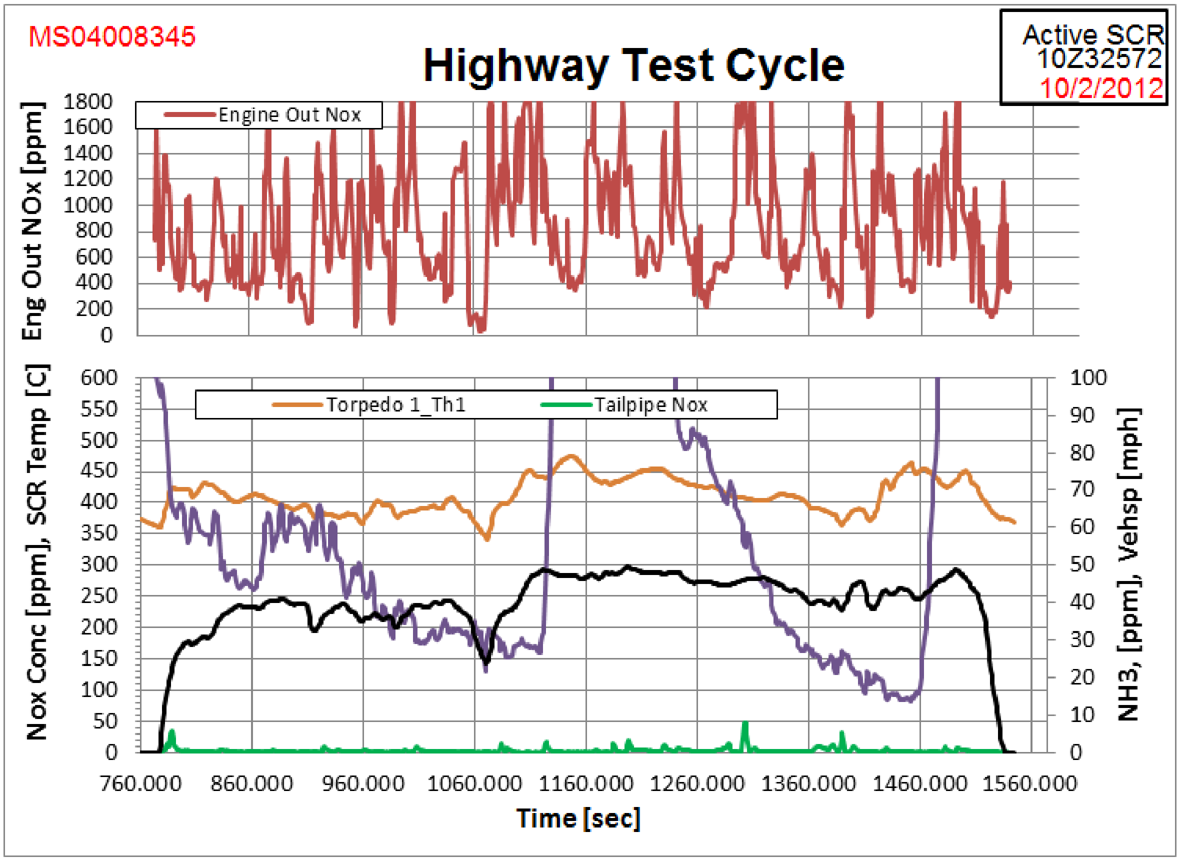


Figure 82: Active Urea Lean Aftertreatment System HWFET Vehicle Emissions

Key observations of the HWFET test cycle emission performance results, Figure 82, include:

- Emission 0.014g/mi HC (.010 std), 3.8g/mi CO (2.1 std), and 0.007g/mi NOx (0.02 std)
- HC and NOx are very good for the highway fuel economy but CO is still excessive (extra catalyst volume needed)
- NH3 slip can be improved with an optimized storage model calibration

Subsequent development focus had transitioned to minimizing HC and CO emissions during engine start / warm-up as well as calibrating the active urea dosing aftertreatment system to minimize NOx emissions. Tailpipe emissions results to date are shown in Figure 83.

	NMHC (gm/mi)	CO (gm/mi)	NOX (gm/mi)
T2B2 Standard	.010	2.1	.020
Stoichiometric Homogenous	.009	2.1	.008
Lean-stratified w/ Active Urea Dosing System	.033	3.9	.019

Figure 83: Active Urea Dosing Lean Aftertreatment Tailpipe Emission Results

4.2.8. SG5 G4 PASSIVE + ACTIVE LEAN AFTERTREATMENT

The Generation 4 (G4) passive lean aftertreatment system combines the optimized G3 passive lean aftertreatment TWC washcoat formulations, an additional underfloor TWC along with the optimized active urea SCR system that provides a supplemental source of NH3. This G4 system has converged the passive + active SCR lean aftertreatment technologies and is defined as Passive + Active Ammonia SCR System (PAASS) lean aftertreatment. The dual approach towards NH3 supply had assisted in minimizing urea storage tank size and urea consumption rate required for a solely active lean aftertreatment system.

The incorporation of the G3 TWC formulation technology provides NOx storage and release effect off of deceleration and idle as well as a contributing quantity of NH3 exiting the TWC. The incorporation of a second 1L underfloor TWC results from the initial active urea SCR system exceeding the NOX reduction engineering target, though deemed necessary to complete the achievement of meeting T2B2 emissions. This additional 1L TWC further reduced the NMHC and CO which enables achievement of T2B2 emissions targets. The a second 1L underfloor TWC had been added just after the flex joint, followed by the urea dosing injector, and the updated torpedo SCR catalyst and then tailpipe, Figure 84

Figure 84: G4 SG5 Passive + Active Lean Aftertreatment Vehicle Installation

The final vehicle level emission testing of the G4 passive + active lean aftertreatment was mated to the SG5 engine and consisted of the FTP cold-start as well as Highway test cycles. The FTP cold-start testing had been conducted to comprehend the level of passive NH3 generated. NH3 is generated at high loads when the engine is operating in stoichiometric homogenous mode, which assists the active SCR system with the reduction of NOx emissions,

Figure 85. This passive NH3 feature is targeted to assist in minimizing the overall urea consumption level.

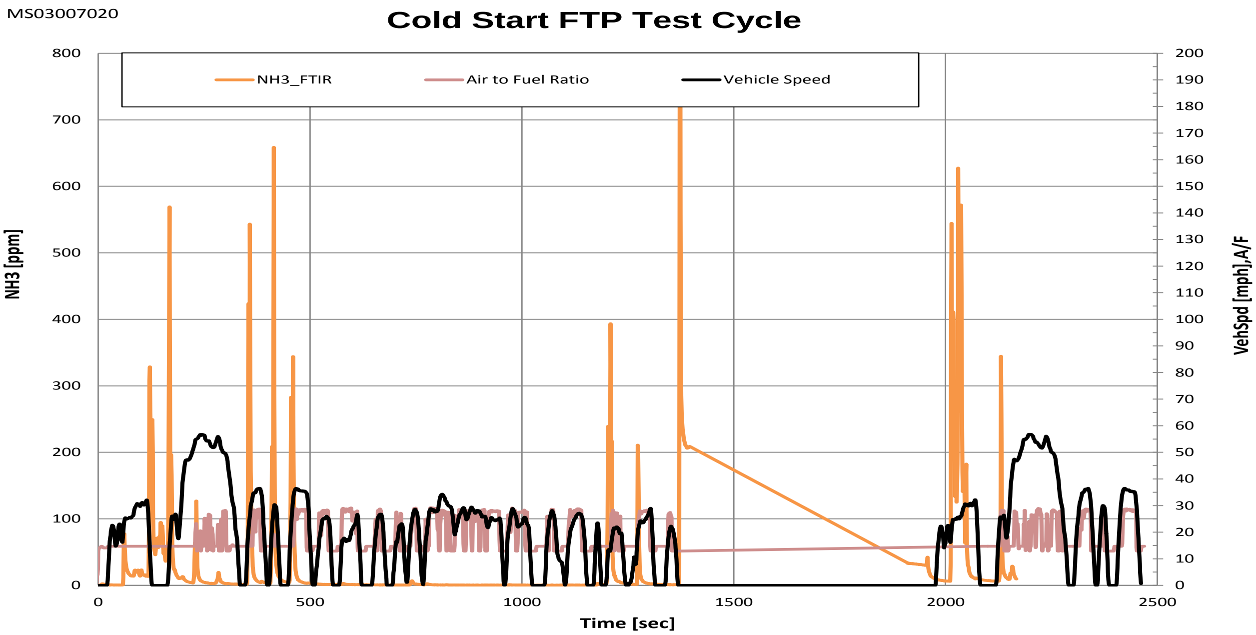


Figure 85: G4 SG5 Lean Aftertreatment FTP Cold-start Passive NH3 Generation

The FTP cold-start HC, CO and NOx concentration levels are detailed in Figure 86 and the weighted cumulative vehicle emission results are detailed in Figure 87. The cumulative emission totals for the FTP cold-start is 0.0083g/mi NMHC (0.010 std), 0.31g/mi CO (2.1 std), and 0.015g/mi NOx (0.020 std).

The Highway HC, CO and NOx concentration levels are detailed in Figure 88 and the weighted cumulative vehicle emission results are detailed in Figure 89. The cumulative emission totals for the Highway is 0.00178g/mi NMHC (0.010 std), 0.262g/mi CO (2.1 std), and 0.010g/mi NOx (0.020 std).

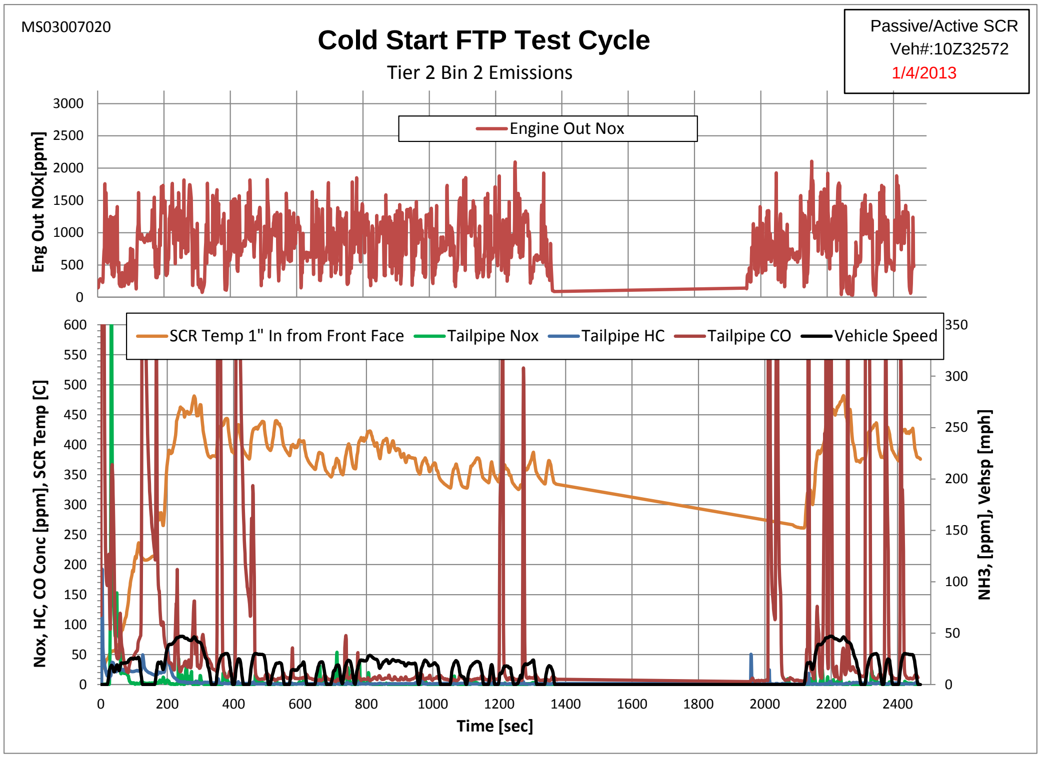


Figure 86: G4 Lean Aftertreatment FTP Cold-start Concentration Levels

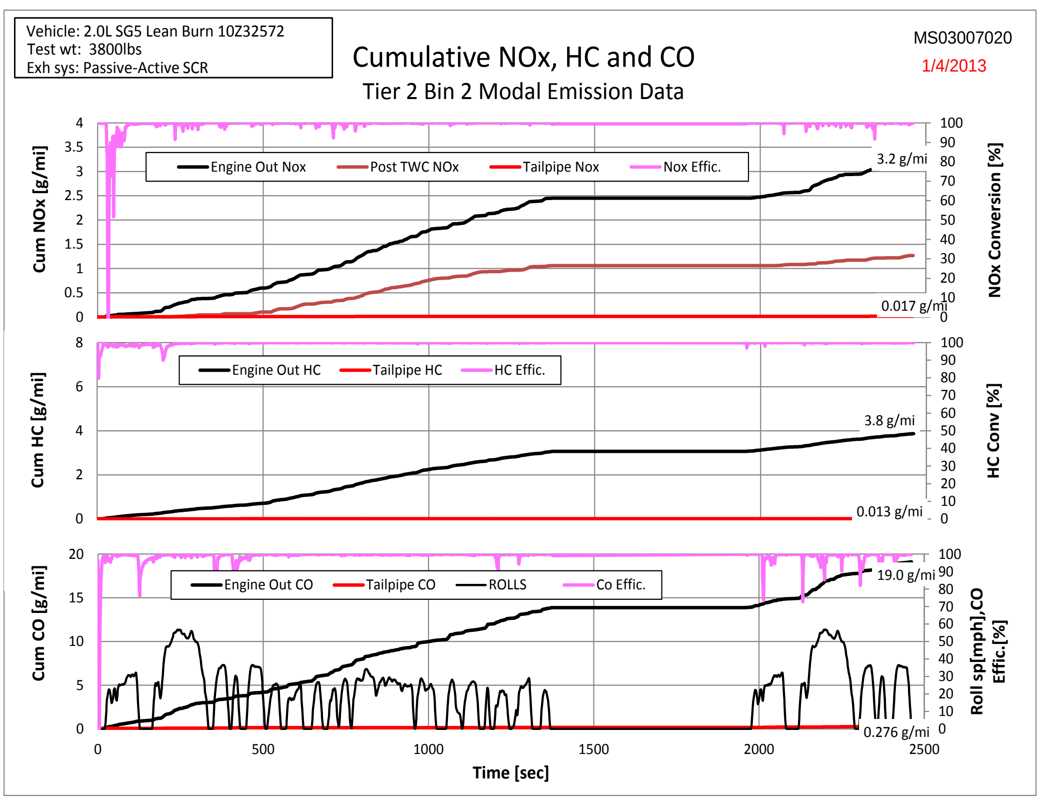


Figure 87: G4 Lean Aftertreatment FTP Cold-start Cumulative Emissions

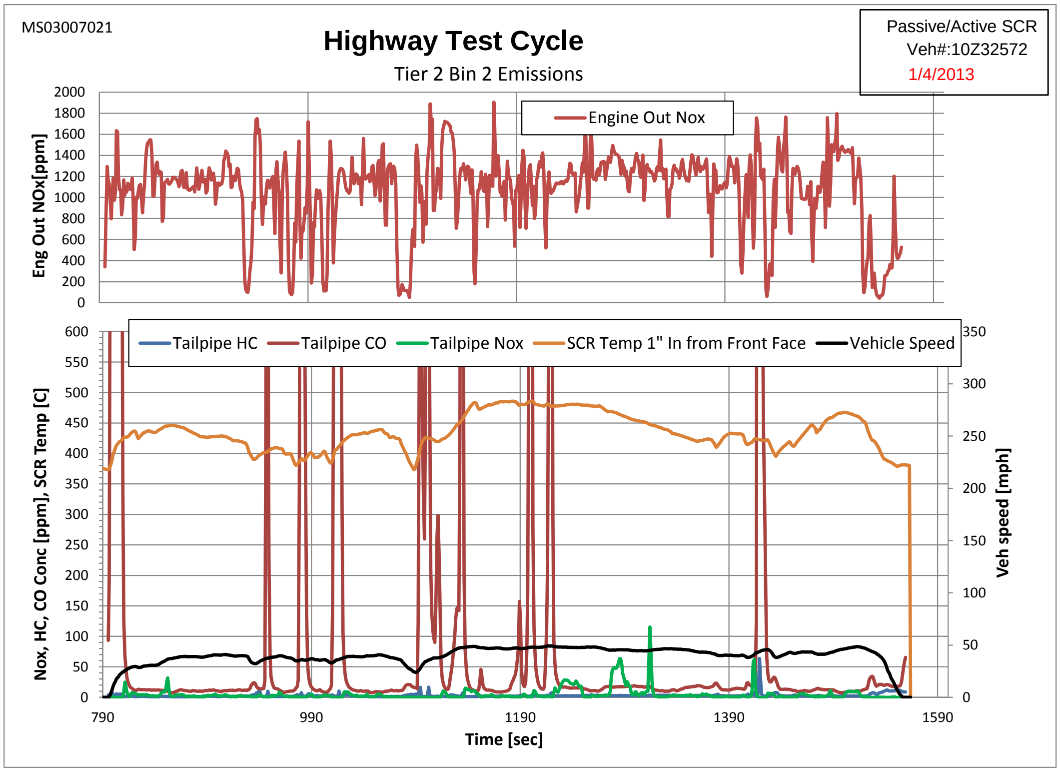


Figure 88: G4 Lean Aftertreatment Highway Concentration Levels

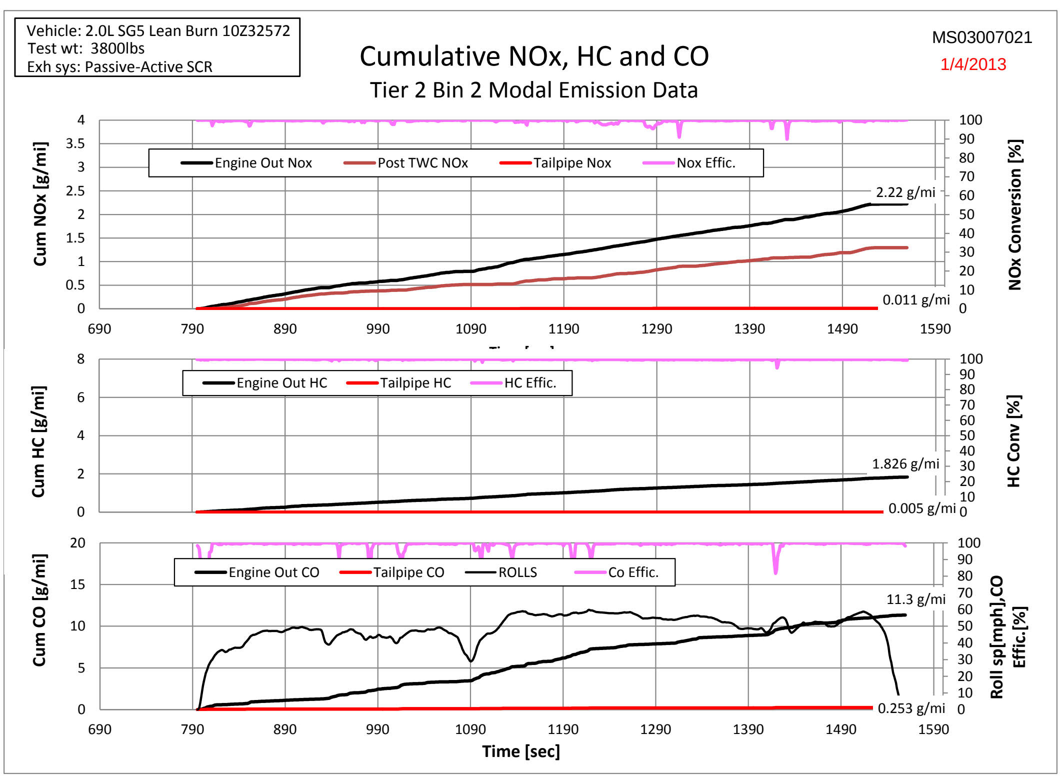


Figure 89: G4 Lean Aftertreatment Highway Cumulative Emissions

4.2.9. 12V STOP / START SYSTEM

The 12V Stop/Start (12V S/S) operating in conjunction with the 6-speed automatic transmission provided substantial fuel economy improvement when coupled to the SG5 engine. Several strategies were investigated to minimize fuel consumption at idle. These initial studies were done on an engine dynamometer. The final options studied were lean idle vs. 12V S/S. 12V S/S was selected as a result of the significant fuel economy improvement and production potential, Figure 90.

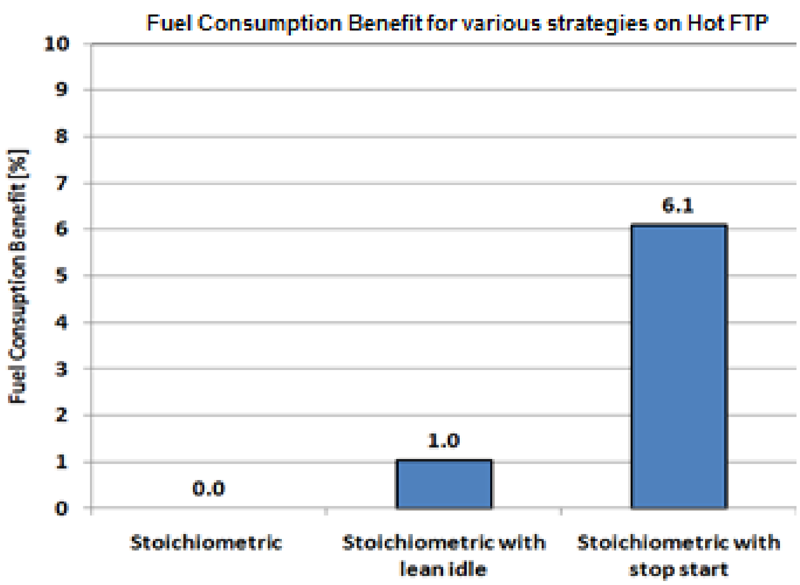


Figure 90: 12V S/S Fuel Economy Improvement Potential

Unique components used with 12V S/S system include:

- A tandem-solenoid starter that enables the engine to restart quicker and more smoothly
- An electrically driven transmission auxiliary hydraulic pressure pump that keeps the fluid in the six-speed automatic circulating and primed
- Larger primary 12-volt and an rear mounted accessory battery
- Dual-battery isolation module that ensures both batteries are properly charged
- Torque-reaction engine mounts that dampen the vibrations associated with a restart

12V S/S is a balance between smooth starts and launch delay. This is much more difficult than hybrid applications, as the conventional starter motor has limited capability and the combustion event needs to be carefully managed on the first several events. There is a significant fuel economy advantage as once the catalyst is hot, the engine can be shut-down during idle events. The catalyst light-off strategies required for T2B2 emission performance ensures that the catalyst is fully functional by the first acceleration on the city FTP test. This allows the engine to be shut-down for maximum fuel economy gain without negatively impacting emission performance. The engine dynamometer studies were confirmed by multiple chassis tests on a 4-cylinder SIDI engines equipped with a 6-speed automatic transmission as demonstrated in Figure 91.

	A/S Enabled	A/S Disabled	Benefit	Benefit	Comment
Schedule	mpg	mpg	mpg	%	
City (Hot18)	28.19	26.52	1.66	6.28%	Baseline: A/S Disabled
Hwy (est)	34.49	34.49	0.00	0.00%	2010 LAF Lacrosse: 29.6 unadjusted composite CAFE
Composite	30.71	29.60	1.11	~3.76%	1/((0.55xCity)+(0.45xHwy))

Notes:
4 test average.
Target: +3.5 – +4.5% unadjusted composite.

Figure 91: 12V S/S Fuel Economy Improvement on a 2.4L SIDI NA Engine

4.2.10. ACTIVE THERMAL MANAGEMENT SYSTEM

The main focus of Active Thermal Management (ATM) is to reduce CO2. The primary mechanism is to reduce friction at piston ring-pack to liner contact ATM systems included in this investigation include switchable waterpump, thermos bottles, electric thermostat and the necessary controls.

As engines become more efficient such as lean-stratified, it had been proven they take more time to reach steady state operating temperatures after cold start. Lean-stratified engine have a lower fuel consumption reduction at cold start when compared to stoichiometric homogenous engines. Not only does this cause a lower fuel conversion efficiency which produces a higher increase of HC and CO at cold temps, it also had additional fuel consumption reduction at MVEG test cycle due to the load increase due to engine friction, slower increase of oil and coolant temp at lean-stratified operation. An evaluation of warm-up behavior on a lean-stratified L850 engine vs. a stoichiometric homogenous gasoline engine had been conducted by GMPTE Advance Engineering Group and shown in Figure 92. The results confirm its warm-up behavior is similar to that of a diesel engine where both engines take up to 900-1000 sec. to reach steady state operating temps (approx. 75-90C). The transition between homogenous operations and lean-stratified occurs at approx. 45C. In theory, if the engine warm-up increases, this had also decreased the time it takes the engine to run lean-stratified, which helps decrease fuel consumption.

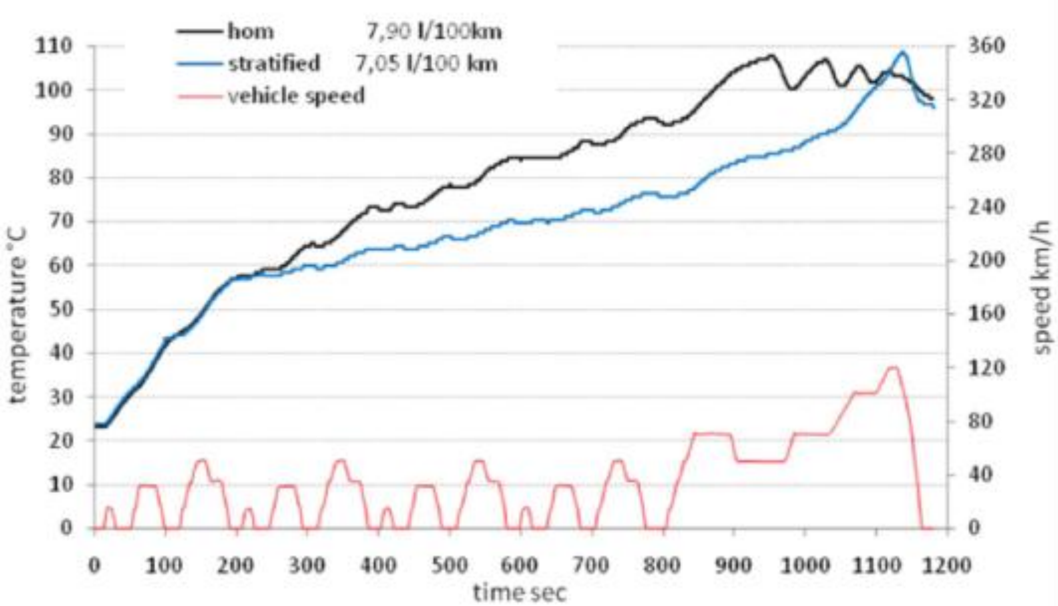


Figure 92: Warm-up Behavior

GMPTE had concluded the best results for CO2 emissions and fuel economy gains on a diesel engine had been found by using a switchable water pump that shuts off the coolant at cold start. Therefore a similar coolant strategy had been targeted to be applied to the lean-stratified engine to achieve similar results. An evaluation of warm-up behavior for gasoline lean-stratified and stoichiometric homogenous operating modes on a FTP cycle is shown below for a manual transmission vehicle. The results confirm lean-stratified combustion delays warm-up, and is similar to that of a diesel engine, Figure 93.

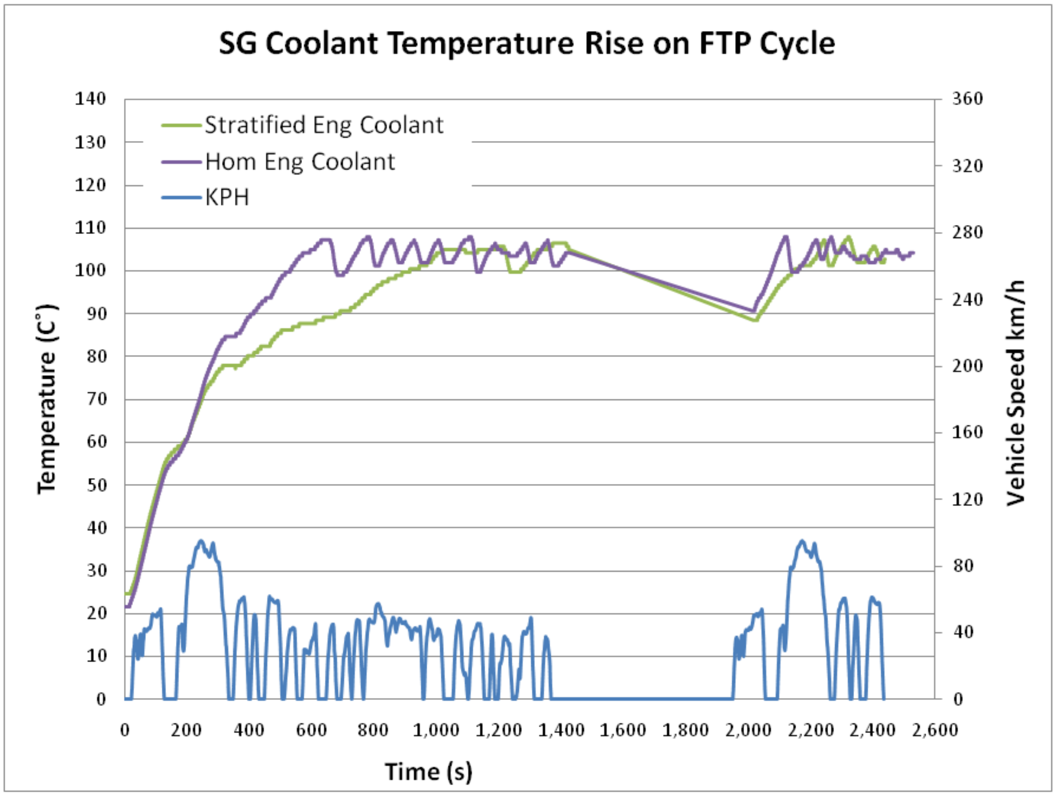


Figure 93: Coolant Temperature Rise, Gasoline Lean-stratified and Homogeneous Operation

An investigation into "zero-flow" concept was undertaken in the engine dynamometer. This concept focuses on rapid warming of the top of the block were the piston ring-pack has the highest friction. The limitation is the point at which localized boiling occurs in the cylinder head.

The engine dynamometer study determined that for this engine architecture that flow was required before the acceleration of the second cycle. Although there was the potential for significant fuel economy advantage if cooling was delayed beyond that acceleration, the concerns for long term engine stability limited zero flow to 180 seconds. Testing on multiple 4 cylinder engines indicate that a coolant of 90C is typically achieved at this time, Figure 94. The testing had demonstrated the significant fuel economy improvement when ATM is integrated in to an engine and vehicle system, Figure 95.

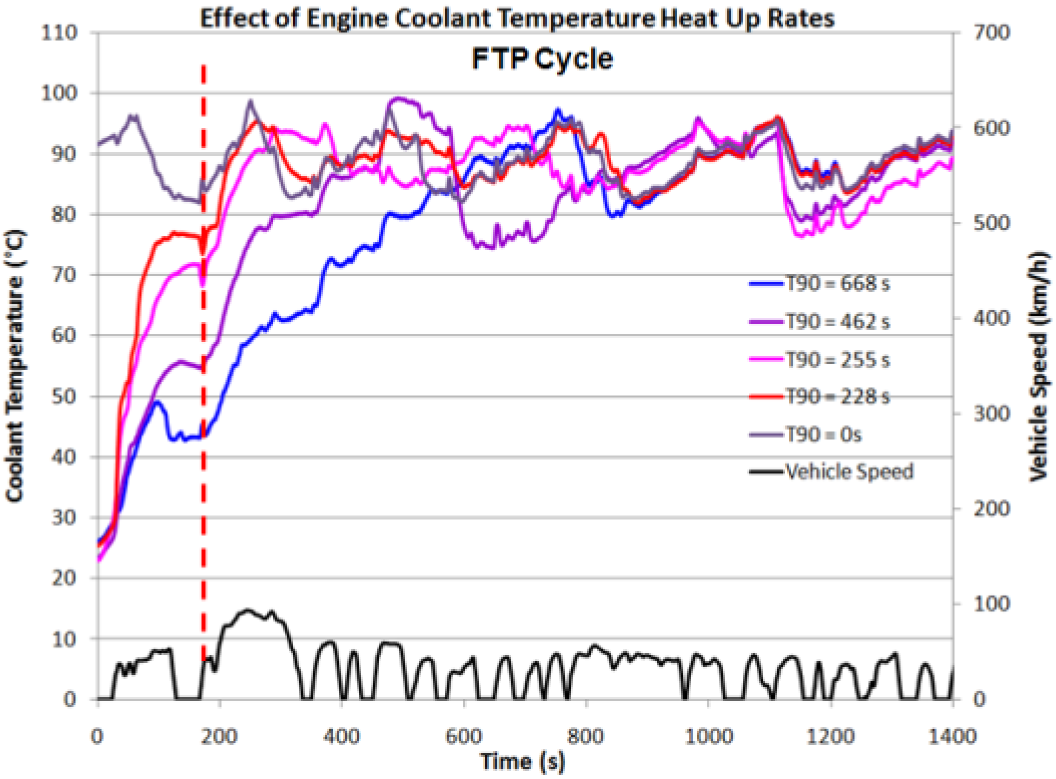


Figure 94: ATM Effects on Coolant Heat-up Rates

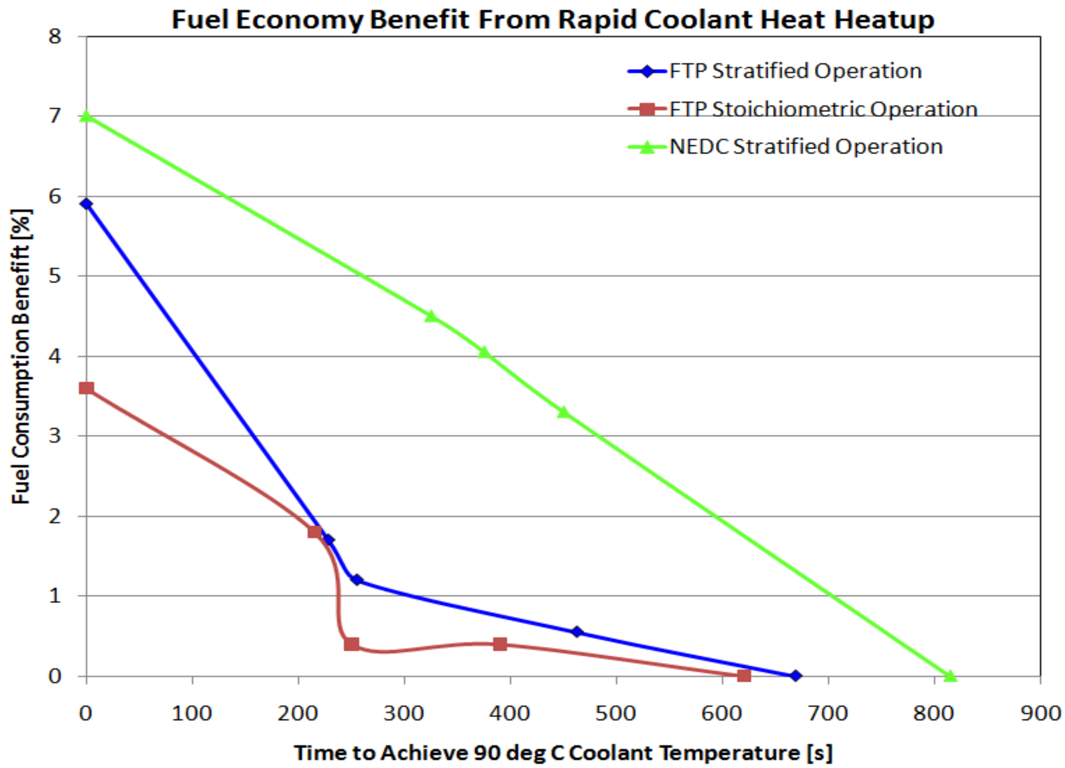


Figure 95: Engine Dynamometer Studies Indicated a 3% FE Advantage when 90C coolant reached at 180sec on FTP City Test

4.2.11. *SG5 VEHICLE INTEGRATION*

The support the fuel economy performance with lean-stratified operation, the SG5 engine had been installed in a Malibu development vehicle. The vehicle had then been and compared to the control Malibu vehicle with the production LE5 engine. Two Malibu development vehicles had been integrated with the SG5 engine and had been used to optimize the transmission shift calibrations, fuel economy development, and emissions development.

Four of the development vehicles had been instrumented to support chassis dynamometer testing. The instrumentation includes ETAS instrumentation to monitor and record engine control parameters as well as thermocouples and pressure transducers. Thermocouples had been installed to measure engine and exhaust temperatures including;

- Engine oil, coolant, inlet air, and fuel temperatures,
- Exhaust gas temperature at catalyst inlet and outlet
- Catalyst bed temperatures
- Transducers had been added to measure fuel pressure and engine air fuel ratio.

Modifications had been made to the vehicle wiring harness to accommodate the SG5 engine components and the E39 engine controller, Figure 96 and Figure 97. The G1 lean aftertreatment had been initially installed including the thermocouples, pressure taps, and NOx sensors. An initial engine calibration that had been initially developed allowed operating the engine in stoichiometric homogenous mode.

Figure 96: SG5 Engine Installed

Figure 97: E39 Engine Controller Monitoring

An auxiliary battery had been added to power the instrumentation and probes had been installed in the exhaust to facilitate measuring exhaust emissions in and out of the close-coupled and underfloor TWC. Figure 98 show the instrumentation installation.

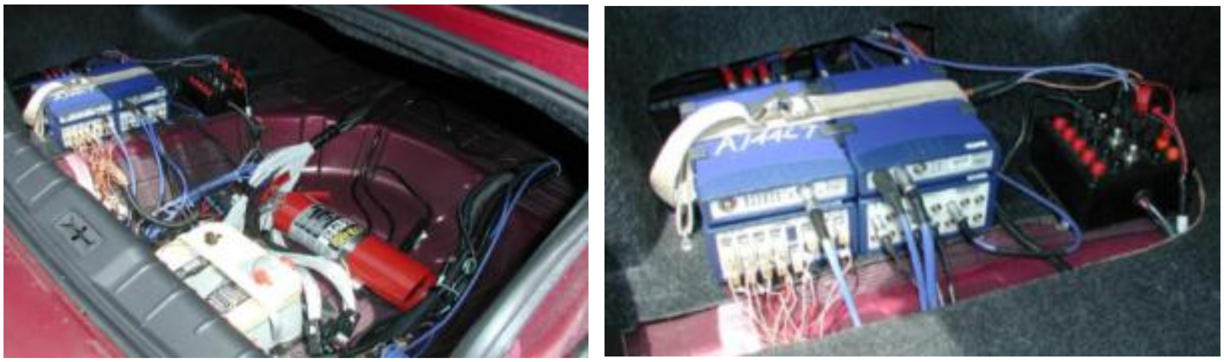


Figure 98: Instrumentation Installation and ETAS Interface Modules

Three of the Malibu development vehicles had been modified with SG5 engines and G1 passive lean aftertreatment installed to support vehicle level controls and calibration development.

4.2.12. SG5 VEHICLE FUEL ECONOMY

Baseline fuel economy testing had been completed on the control vehicle with the LE5 engine and the development vehicle with the SG5 engine. EPA city and highway tests had been run on each vehicle using the same emission test site and the same driver to minimize variability. The data had been analyzed using the "t" distribution to determine the number of tests required to quantify the fuel economy difference between the vehicles with 90% confidence. Based on the preceding analysis, ten city and ten highway tests had been performed on each vehicle. The data shows the demonstration vehicle delivered 1.06% lower composite fuel economy when compared to the control vehicle. The average unadjusted average fuel economy data and vehicle to vehicle fuel economy deltas are shown in Figure 99. The control vehicle had been used throughout this project to gauge the fuel economy improvements that are observed on the development vehicle.

	City	Highway	Composite
Control Vehicle Average (MPG)	22.56	37.46	27.48
Demo Vehicle Average (MPG)	22.32	37.06	27.19
Fuel Economy Difference (MPG)	-0.24	-0.40	-.29
Fuel Economy Difference (%)	-1.06%	-1.07%	-1.06%

Figure 99: Baseline Fuel Economy Data

Fuel economy assessment testing had been conducted on with the first Malibu development vehicle with a SG5 representative engine. An initial stoichiometric homogenous engine calibration had been developed that provided acceptable drivability and reasonable emission performance. The calibration effort had been primarily focused on base combustion parameters (spark timing, intake and exhaust camshaft positions, injection timing, fuel pressure and spark advance), idle speed control, open and closed loop fueling, and powertrain to vehicle interface items. The FTP city and highway fuel economy results are shown in Figure 100. Also included for reference are the fuel economy results for the same vehicle with the production baseline control vehicle with the 2.4L PFI engine (LE5) and automatic 6 speed transmission.

	Homogeneous Fuel Economy (mpg)	
	City	Highway
SG 4.75	24.2	40.9
LE5 (2.4L PFI)	24.0	41.0

Figure 100: Malibu #1 Stoichiometric Homogenous Fuel Economy

Controls and calibration refinements had been made to improve the drivability of the vehicle to the level that would allow running FTP tests. The calibration had been set up to run lean at part throttle conditions. During closed throttle and idle the engine had been initially forced to run stoichiometric homogenous. This had been done due to not having implemented a lean idle control strategy at the initial stages of testing. When in sixth gear at 55 and 60 mph the engine load had been above the current operational BMEP limit for lean operation. By shifting to 5th gear the engine load had been low enough to allow lean operation. When running lean in fifth gear, the fuel economy result had been similar at 55 mph and declined at 60 mph when compared to stoichiometric homogenous in sixth gear.

Further calibration enhancements had improved vehicle drivability which resulted in increased lean-stratified operation during FTP city and highway tests. Lean-stratified operation is enabled at part throttle when vehicle speed is above 28 kph and driver requested torque is below the BMEP threshold. For this testing the idle and low rpm deceleration maneuvers had been in stoichiometric homogenous mode because the lean idle control algorithm had been under development. Figure 101 demonstrates when lean-stratified operation is enabled during cycles 1-18 of the FTP city test.

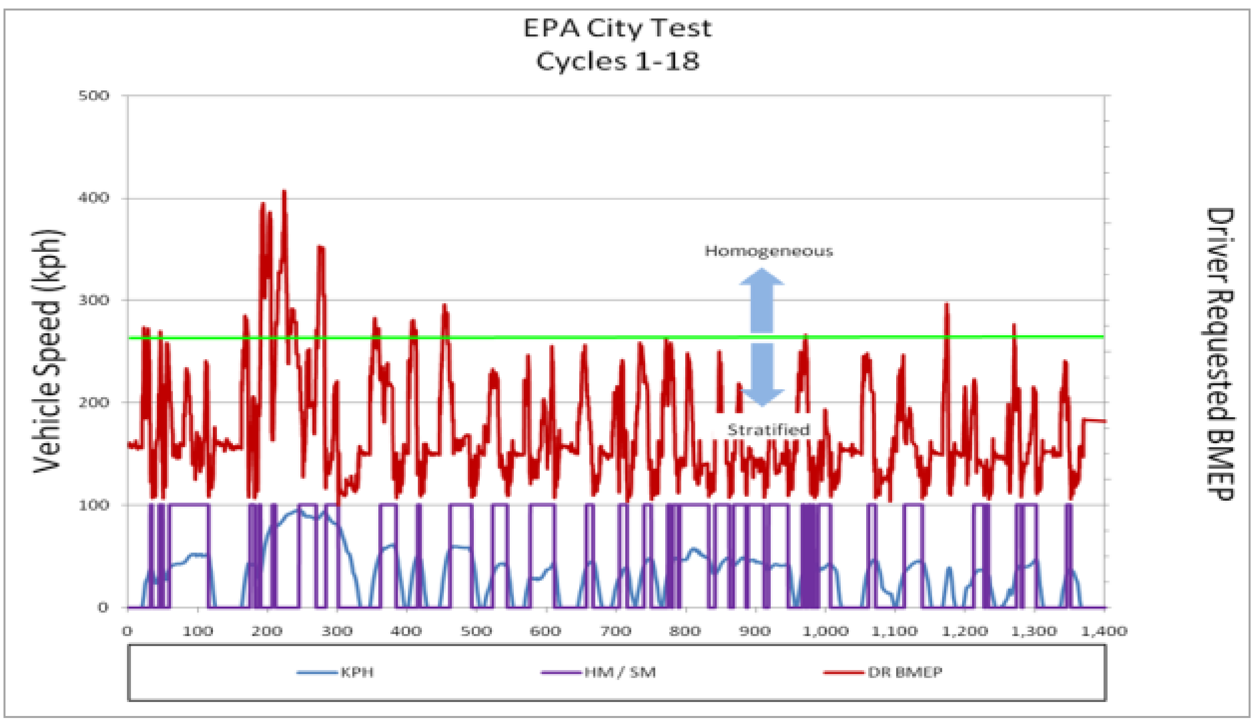


Figure 101: Stratified Operation During the EPA City Test – Cycles 1-18

Calibration refinement had continued with the continued integration of enhanced engine control features. FTP city and highway testing had been completed on the Malibu #1 (demo vehicle) to determine the emissions and fuel economy performance of the naturally aspirated 2.2L SG5 engine and G1 lean aftertreatment system. The vehicle runs 43% of the city test and 68% of the highway test in lean-stratified mode. The majority of time spent in stoichiometric homogenous mode had been during idle and acceleration maneuvers. Some acceleration maneuvers are stoichiometric homogenous due to the torque required to accelerate the vehicle being greater than the maximum torque available in lean-stratified mode. Refinements to the mode transition software and calibration had been determined to allow lean-stratified operation during lighter load accelerations.

Steady state vehicle testing had been done at each of the FTP speed/load points to verify the BSFC improvement that had been seen on the dynamometer. The plot in Figure 102 shows the relative improvement in fuel consumption for the lean-stratified engine when compared to the baseline LE5 engine at each of the FTP speed / load points. The dynamometer data is shown in terms of BSFC and the vehicle data is shown in terms of tailpipe CO2.

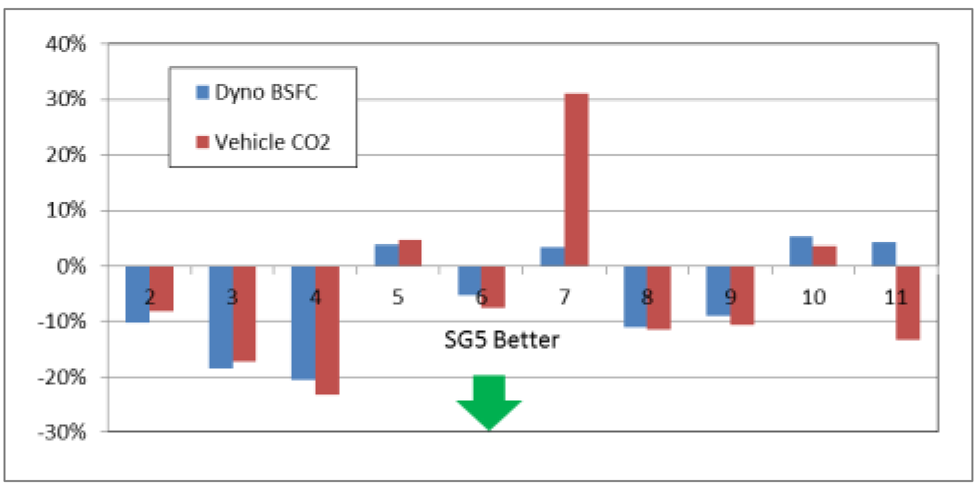


Figure 102: Fuel Consumption SG5 Stratified vs. LE5 Stoichiometric

For the points that are run in lean-stratified mode (2, 3, 4, 6, 8, and 9), fuel consumption improvements in the 5-20% range are realized. For points 5, 7, 10, and 11 the engine loads exceed the lean load capability of the SG5 engine therefore those points had to be run in stoichiometric homogenous mode. Those points generally showed a fuel consumption penalty of 3-5% for the SG5 engine. There is generally good correlation between the dynamometer BSFC data and the vehicle tailpipe CO2 data with the exception of point 7. This speed/load point represented a high flow point that had been encountered on acceleration maneuvers found on the FTP and had a significant contribution to the fuel economy short fall. Initial investigation into the cause of this fuel economy penalty indicated that the stoichiometric homogenous calibration parameters are not optimized.

Drivability enhancements had focused on fuel mode changes in and out of lean-stratified mode which had been improved significantly with software and calibration changes. The changes correct a problem with missing fuel injection pulses that had been occurring during the transitions. Additional software changes had been made to eliminate the potential for engine stalls when the engine is subjected to high air conditioning compressor loads during lean-stratified operation. This potential stall condition existed because the desired engine torque request in lean-stratified mode did not include the torque that had been required to drive the air conditioning compressor. Software development continues in the areas of torque management during lean-stratified operation and EGR scheduling and control.

Further, fuel economy improvements had been measured on an SG5 equipped Malibu when compared to the same vehicle with the baseline 2.4L PFI LE5 engine. The level of improvement correlated reasonably well with the simulation results. This simulation results had been based on BSFC data for the high density speed load points that are seen on the FTP city and highway test schedules. The fuel economy measured on Malibu #5 with the LE5 and SG5 engines as well as the measured and predicted fuel economy improvement are shown in Figure 103.

	LE5 (baseline)	**SG5 (2.2L NA)**	**Measured % Improvement**	**Simulation % Improvement**
City	23.61	26.08	10.5%	12%
Highway	41.17	43.68	6.1%	8%
Combined	29.22	31.86	9.0%	10%

Figure 103: Fuel Economy Results

The SG5 engine lean-stratified operation indicated significant fuel economy improvement at light to medium loads, however extension of the lean operating range to higher loads had been required to achieve the complete fuel economy objective, Figure 104.

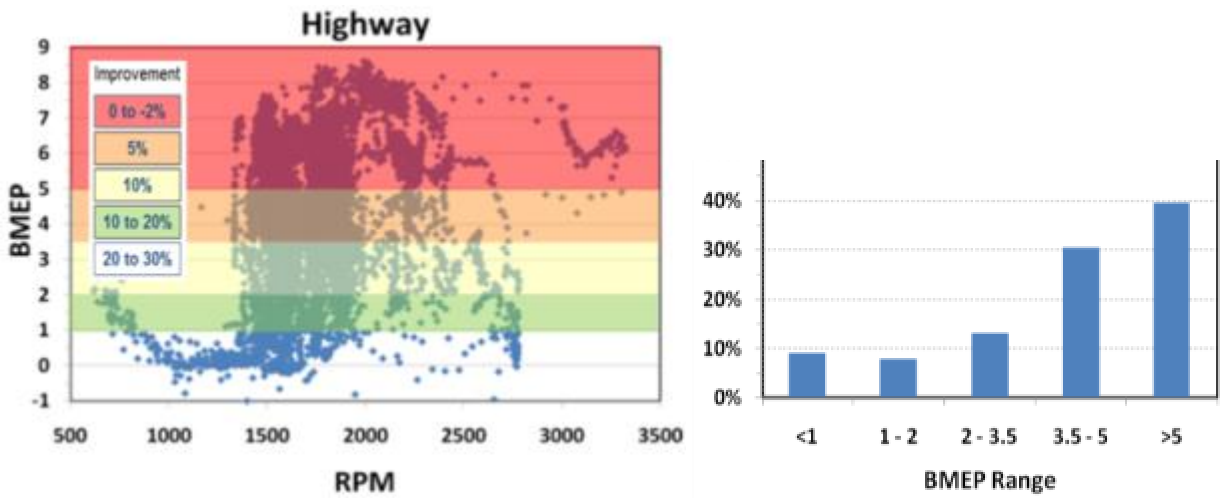


Figure 104: SG5 Fuel Economy Improvement at BMEP Loads of the FTP Cycles

Due to the fuel economy limitations demonstrated with the 2.2L SG5 naturally aspirated engine, downsize boost had been reviewed as a risk mitigation approach as it is a proven method to improve fuel consumption of a vehicle due to reduction in engine pumping and friction losses. Figure 105 indicated the NMEP requirement for a downsized and turbocharged engine in a Malibu test weight class under both FTP and highway tests. In order to get the maximum fuel economy benefit of the lean-stratified combustion system, a 90% target for residence time in lean-stratified mode had been selected.

The initial naturally aspirated SG5 engine can be operated in lean-stratified condition up to a limited NMEP level. Therefore investigations on the impact of introducing boost pressure on the lean-stratified operating range had been initiated. Investigative steady state test results indicate that the lean-stratified operating range can be extended by introducing boost pressure on the intake. This corresponds to approximately 60% of highway test and 80% of the FTP test but falls short of our 90% residence time target. Therefore, further investigations targeted upgrading the fuel injection system to support improved injection capability. This increased capability, combined with additional boosting, had been predicted to run in lean-stratified mode up to the desired load requirement.

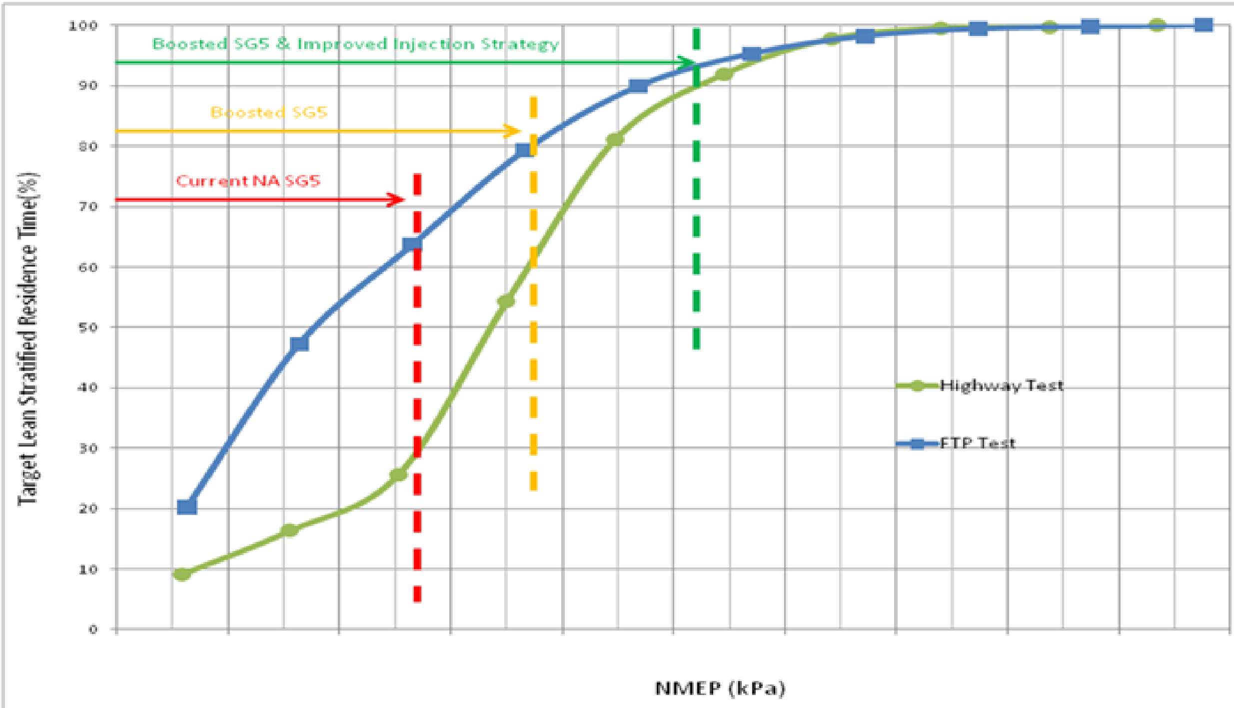


Figure 105: NMEP vs. Lean-stratified Residence Time During FTP City and Highway Test

4.3. PHASE 3 – ADVANCED DEVELOPMENT

4.3.1. SINGLE CYLINER LEAN BOOST EVALUATION

The exploratory phase SG5 naturally aspirated lean combustion engine demonstrated insufficient fuel economy performance potential during the initial vehicle evaluations. Risk analysis of the limitations signaled that a major structural engine configuration change needed to be implored to achieve the required fuel economy functional performance. Correspondingly a risk mitigation project to develop a significantly downsized and boosted engine had been initiated. Two parallel path activities had been undertaken in an effort to achieve the fundamental understanding of boosted lean combustion as the enabler for the significant fuel economy improvement; single cylinder lean boost evaluation using the 2.2L based architecture and a multi cylinder SG5 lean boost evaluation.

The single cylinder lean boost evaluation had been conducted at GM R&D and incorporated further CFD simulation to comprehend the fundamental boosted lean combustion dynamics. Single cylinder development testing at point #4 (1710 RPM, 411 kPa NMEP) of a 10-Point FTP steady-state simulation of a boosted engine had been commenced. Of the several variables that can exert a significant influence on boosted operation, two had been chosen for initial investigation. These two variables had been EGR and boost level. In these initial tests, the intake temperature, which can also had a significant effect on knock and NOx emissions, had been kept constant at 95C. Boost levels up to an intake manifold pressure of 150 kPa and varied EGR mass fraction levels had been tested. The results had been compared to the naturally aspirated baseline point.

Figure 106 demonstrates NOx emissions results as a function of EGR for these tests. The baseline naturally aspirated results at an intake manifold pressure of 95 kPa are shown by the red curve. For all levels of boost tested, EGR is effective in decreasing NOx emissions.

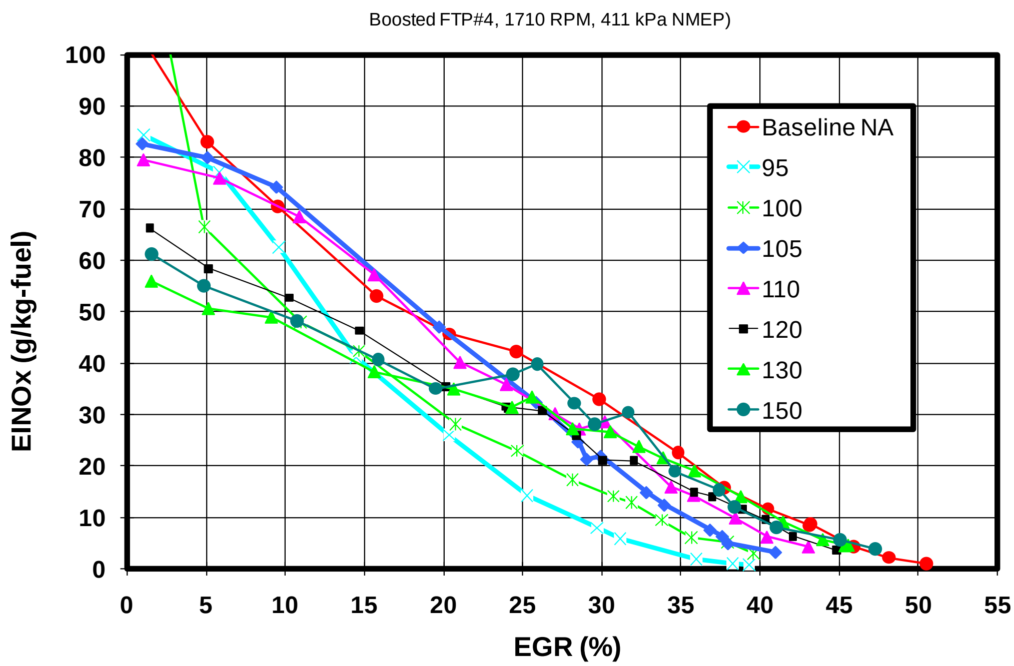


Figure 106: Experimental Effect of Boost and EGR on NOx at 1710 RPM and 411 kPa NMEP

CFD simulations of spray and combustion in the boosted spray guided single-cylinder engine with single pulsing had been carried out to study the effects of throttle opening position, boost pressure, intake air temperature, spray cone angle, spray droplet size, ignition cell size, mesh size and arrangement, etc. Converge code with an Arrhenius combustion model and energy deposit ignition model had been used to consider the interaction between spray and spark ignition. Figure 107 shows the simulation results of SG4 engine with single pulsing for different spray droplet size.

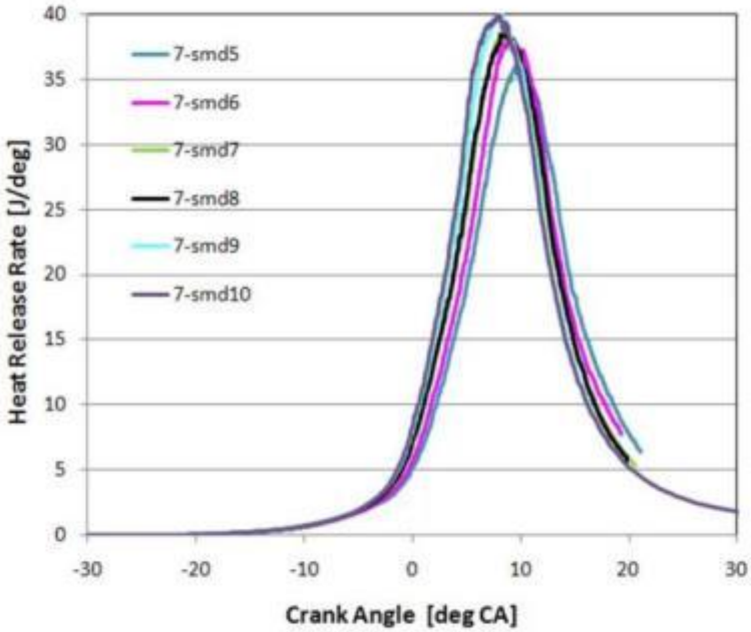


Figure 107: CFD Simulations Lean Engine with Single Pulsing for Different Spray Droplet Size

Continued testing had focused on a load hook at an engine speed of 2000 RPM. For these tests, the intake temperature, which can have a significant effect on knock and nitric-oxide emissions, had been kept constant at 30C. Boost levels up to an intake manifold pressure of 170 kPa and EGR mass fraction levels up to 45% had been tested. Additional variables like port throttle position, intake and exhaust cams, and multiple injections had been also investigated and optimized for best overall results.

The engine performed reasonably well across the load range tested. Figure 108 shows combustion stability results as a function of engine load. The target COV-of-IMEP is 3%. It is seen that the target can be achieved for engine loads in the range 350 to 750 kPa NMEP. Further work is focused on reducing COV-of-IMEP and increasing efficiency at engine loads above 750 kPa NMEP.

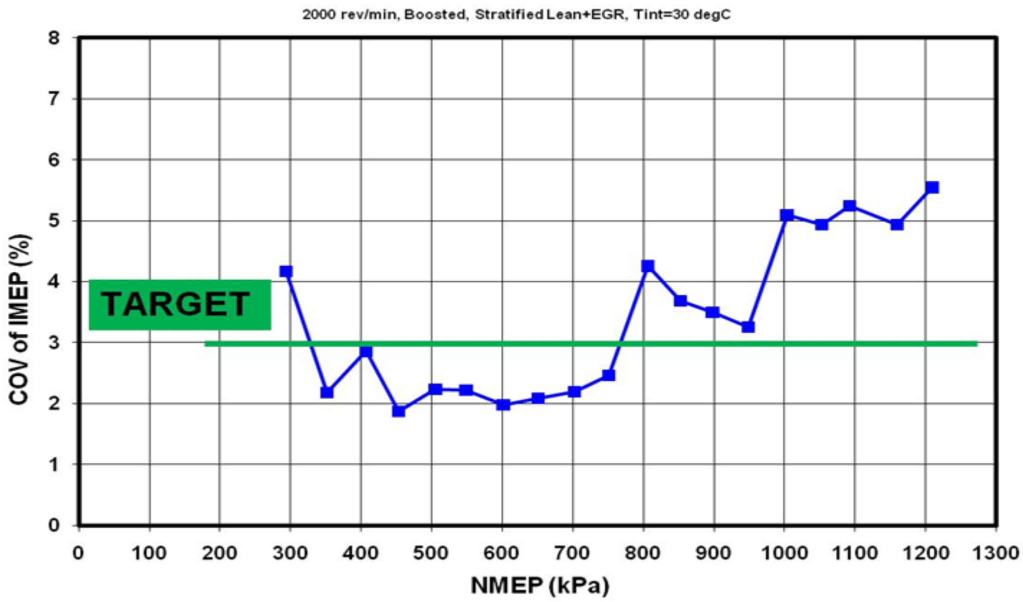


Figure 108: Experimental Combustion Stability Versus Engine Load at 2000 RPM

CFD simulations of spray and combustion with single pulsing at FTP #4 had been carried out for boost pressure of 95, 110, 120, 130 and 150 kPa and EGR rate of 10% and 35% respectively. The Converge code with an Arrhenius combustion model and energy-deposit ignition model had been used to consider the interaction between spray and spark ignition. The models can predict reasonable trends of heat release rates in the boosted SG4 engine. Preliminary Large Eddy Simulation (LES) of the SG4 engine at FTP #1 had been done for one cycle as well as more conventional CFD using Reynolds Average Navier Stokes (RANS). Figure 109 shows the comparison of experimentally measured, LES predicted and RANS predicted heat release rate of the SG4 engine at FTP #1.

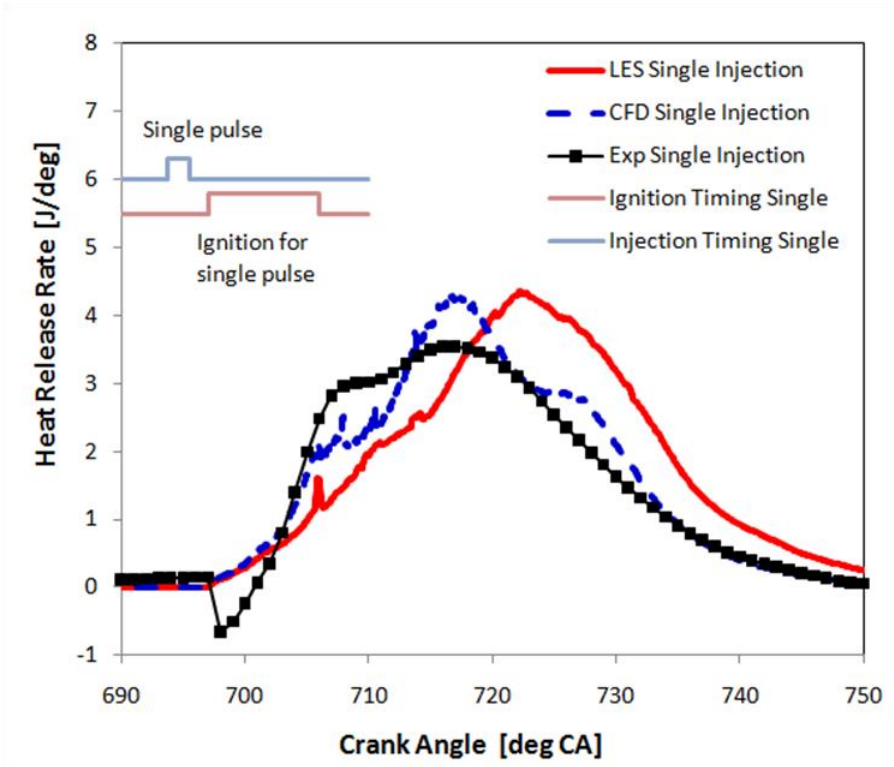


Figure 109: CFD / Predicted LES / Experimental Heat Release Rates of SG4 Engine at FTP #1

CFD simulations of spray and combustion with single and double pulsing had been carried out to study the effects of ignition advance. The Converge code with an Arrhenius combustion model and energy deposit ignition model had been used to model the interaction between spray and spark ignition. The results indicate that the ignitable ignition range is 23 degrees CA from 689 to 712 degrees CA for double pulsing, while it is 14 degrees CA from 685 to 699 degrees CA for single pulsing. The CFD simulations confirmed that the ignition and combustion of double pulsing is more robust than that of single pulsing. Figure 110 shows the simulation results of the boosted SG4 engine with double pulsing for different spark advance. It agrees well with experimental trends.

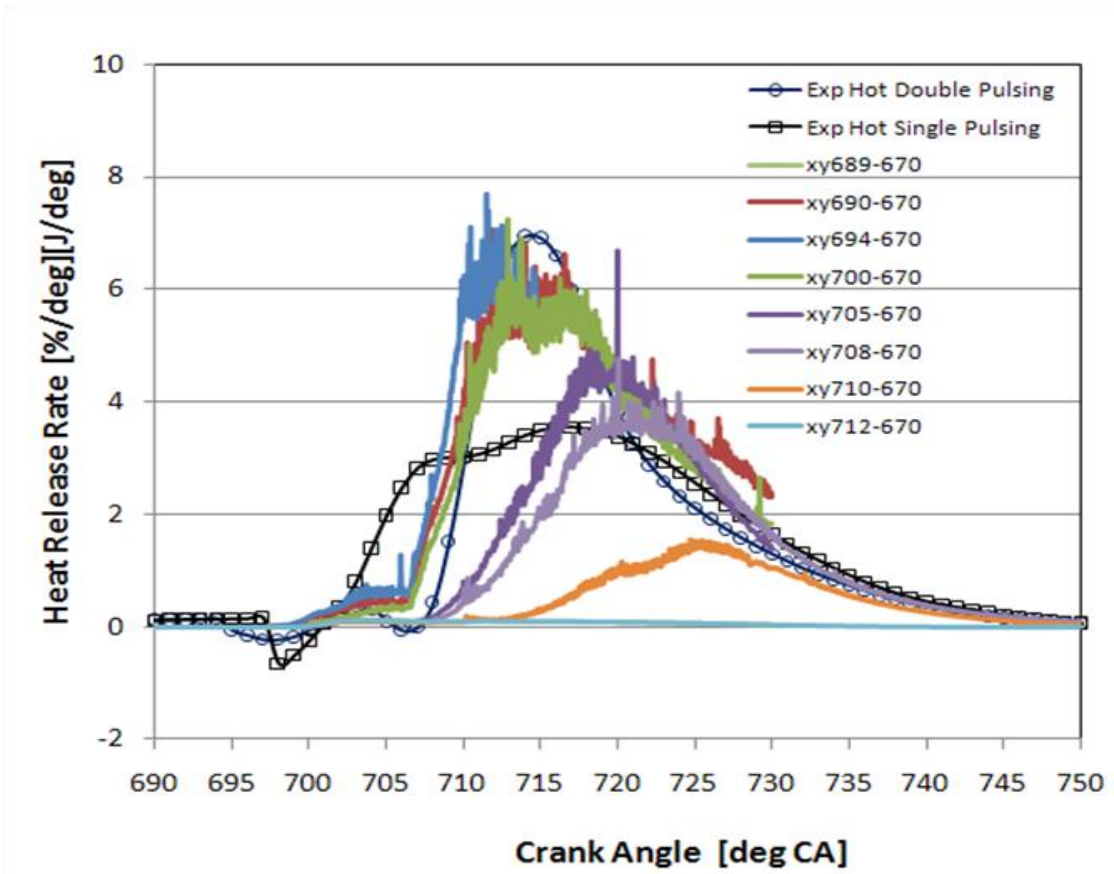


Figure 110: CFD Simulations of SG4 Engine with Double Pulsing for Varying Ignition Advance

4.3.2. MULTI CYLINDER LEAN BOOST EVALUATION

To support the fuel economy risk mitigation of developing a significantly downsized and boosted lean combustion engine, a multi cylinder SG5 lean boost evaluation had been initiated. This evaluation supported the guidance of the new boosted engine design to ensure the optimal combination of technologies is applied that provide the maximum fuel economy improvement. Multi-cylinder boosted evaluation areas focused on; multiple injection pulses, alternative multi-hole injection hardware, A-cone injection hardware, high energy ignition, increasing the air flow capacity.

Alternative injection hardware had been evaluated to further improve the fuel economy benefit of the lean-stratified combustion system. Figure 111, shows the combustion stability comparison between HDEV.1 fuel injectors and HDEV.5 injectors under closely spaced injection condition. Figure 111 indicates that HDEV.1 injectors can deliver closer spaced injection (below 1 ms spacing) compared to HDEV.5 injectors while maintaining good combustion stability.

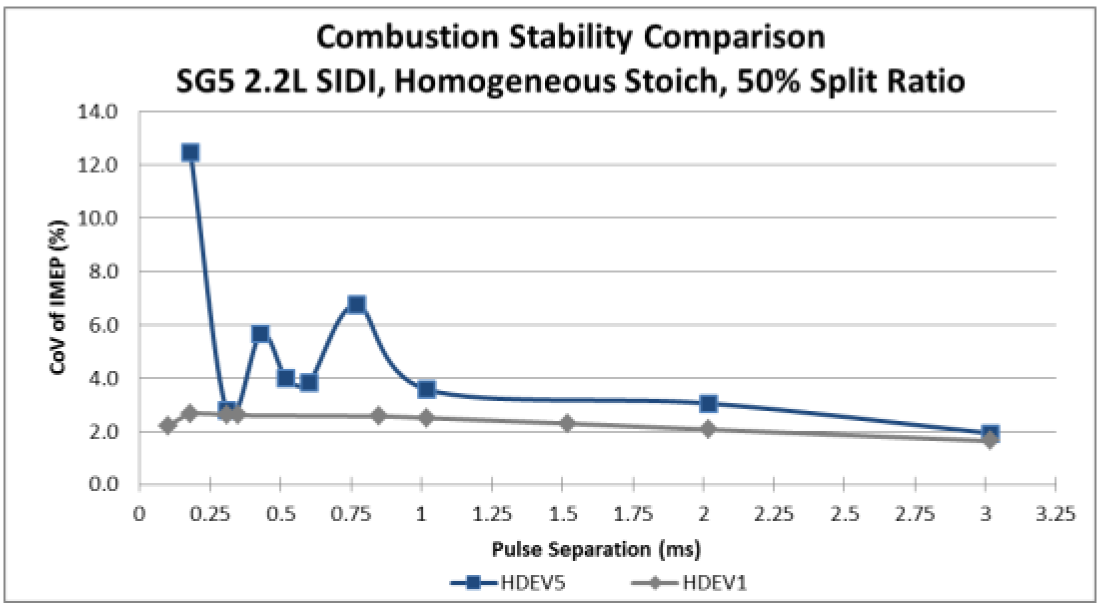


Figure 111: Fuel Injector Combustion Stability Comparison

In order to quantify the fuel economy benefit of HDEV.1 injectors, two speed and load points had been selected that represents a medium load point and a high load point. Figure 112 summarizes the findings. At the medium load point, the HDEV.1 injectors result in 5.8% fuel economy improvement over our baseline configuration with HDEV.5 injectors. However, at higher load point, this benefit is reduced to 2%.

	Speed (RPM)	Torque (Nm)	HDEV5 BSFC (g/kWh)	HDEV1 BSFC (g/kWh)	% Improvement over HDEV5
Urban	1821	79.6	249	234.5	5.8%
Highway	2000	175	245	240	2.0%

Figure 112: Fuel Injector Fuel Consumption Comparison

In addition to the new injection system, investigations had also focused on the benefits of a High Energy (HE) ignition system. The HE system is capable of delivering significantly longer spark to ignite the combustion gases. The ignition energy transferred to the combustion gases with this HE system can reach 700 mJ per combustion event, which is about 10 times higher than our conventional stock ignition system. Figure 113 summarizes the test result of the HE ignition system at the lower load condition.

The summarized data indicated that the HE ignition system can improve the combustion Coefficient of Variance (COV) at lower load points. This leads to higher EGR rate tolerance compared to stock ignition system which results in lower engine out NOx emission. The data summary also demonstrates that 1-5% fuel economy improvement can be achieved by using the higher ignition energy system. Additional exploratory tests had been conducted with this HE ignition system at the higher load condition. Undesirably, at the higher load condition the HE system does not provide additional fuel economy benefit compared to stock ignition system.

Speed (RPM)	BMEP (kPa)	AFR (-)	EGR Rate Stock (%)	EGR Rate HE (%)	COV Stock (%)	COV HE (%)	BSFC Stock (g/kW-hr)	BSFC HE (g/kW-hr)	Improvement over Stock
2000	200	29.5	21	21	3.0	2.6	318	314	1.26%
3000	300	30.9	0	5	4.9	3.1	321	303.5	5.45%
3500	200	26.5	0	5	3.8	3.5	415	397	4.34%
1500	300	27.0	10.5	31	1.3	3.3	270	261	3.33%
2500	100	36.4	0	5	4.2	3.4	492.5	487	1.12%

Figure 113: Stock Ignition to High Energy Ignition System Comparison

The next phase of evaluation had been the operation and performance potential of A-cone solenoid fuel injectors. Figure 114 illustrates the brake thermal efficiency improvement that can be achieved by boosting the engine and upgrading the injection strategy. The top curve on Figure 114 shows the estimated brake thermal efficiency of a lean-stratified engine running with a Piezo injector as advertised by one of our collaborative suppliers.

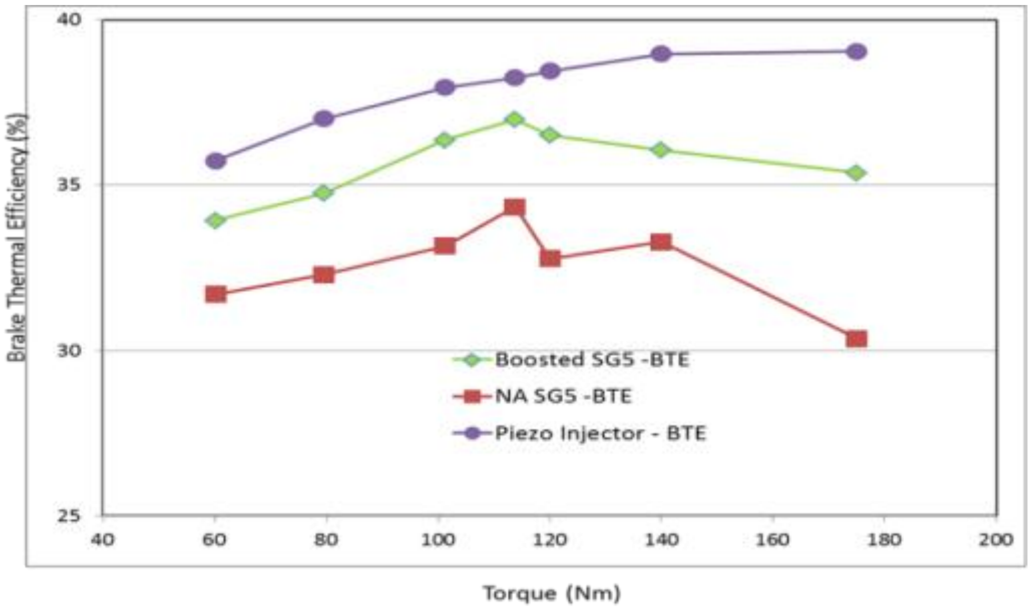


Figure 114: Brake Thermal Efficiency of Piezo versus Tested Solenoid Injection

The top curves in Figure 114, clearly indicated the fuel economy improvement potential of the piezo injection system. However, the high cost and additional control complexity requirements for the Piezo injectors are causing some in the automotive industry to move away from Piezo injectors. Recent improvement in solenoid injector technology, such as capability to deliver small and multiple injection pulses accurately, had significantly reduced the performance gap between solenoid injectors and Piezo injectors. Therefore, we had engaged our collaborative supplier to test the A-cone solenoid injection system while limiting the engine out NOx emission level to 12 g/kg fuel. This NOx emission limit had been used throughout our internal development program for the lean-stratified project. The A-cone solenoid injection system had been selected due to its spray pattern similarity with the Piezo injection system that our collaborative supplier had used in its previous investigation.

Figure 115 summarizes the test results of running the A-cone solenoid injection system on a single cylinder engine. For comparison, the brake thermal efficiency of our current boosted SG5 engine is also included. It can be seen that without the NOx emission constraint, the A-cone solenoid injection system can provide higher brake thermal efficiency compared to our current system. This is particularly true at higher engine load. However, this benefit goes away when same NOx emission constraints is applied to the engine.

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BMEP (kPa)	Brake Thermal Eff (%) Boosted SG5 with NOx Constraints	Brake Thermal Eff (%) SCE A-cone Injector w/o NOx Constraints	Brake Thermal Eff (%) SCE A-cone Injector with NOx Constraints
343	33.93	31.28	30.72
454	34.75	35.31	32.23
650	36.98	41.52	34.17
800	36.06	39.22	37.32
1000	35.38	41.31	35.16

Figure 115: A-Cone Injector Brake Thermal Efficiency Comparison

Figure 116 illustrates the fuel consumption and NOx emission trade-off observed in the single cylinder engine running with A-cone solenoid injection system. As EGR level is increased, the NOx emission decreases and the BSFC increases. There are many possible explanations, including deterioration in combustion efficiency, decrease in specific heat ratio, and combustion phasing losses that can cause this BSFC increase so further detailed investigation had been conducted at our collaborative supplier facility.

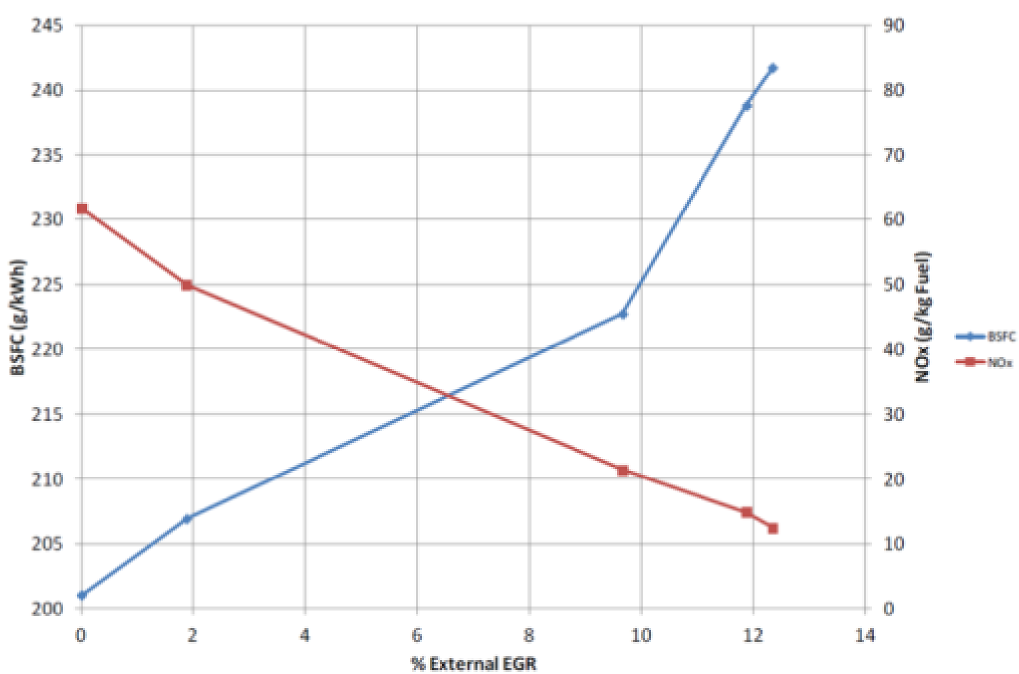

Figure 116: A-Cone Injector BSFC and NOx Emission Trade-off

4.3.3. LDB ENGINE ASSEMBLY

The single cylinder and multi cylinder SG5 lean boost combustion evaluations had formulated a new framework of features and design application guidelines that had been applied to create the new optimized Lean Downsize Boost (LDB) lean combustion engine design. The LDB is a compact inline four cylinder of 1.4L displacement, boosted with a compact turbocharger and is based on GM's next generation Small Gasoline Engine (SGE) architecture platform (RPO code LE2). Conversion of this conventional stoichiometric homogenous direct injection engine into a spray guided lean-stratified variant required redesigns of several major components along with a number components further optimized from the previous naturally aspirated SG5 lean combustion engine.

Figure 117 illustrates the relative position of the fuel injector and spark plug of the base LE2 turbo engine. It can be seen from the sectional layout that the base LE2 engine injector spray pattern misses the spark plug gap, which is a requirement for a good spray guided lean-stratified combustion. Modification to the fuel injector and spark plug locations had been incorporated so that the edge of the fuel spray reaches the spark plug gap as shown in Figure 118. As part of the combustion optimization on the initial dynamometer hardware for the 1.4L Lean Downsize Boost engine, an evaluation study had commenced that tested different injector positions to ensure the optimal injector location is selected.

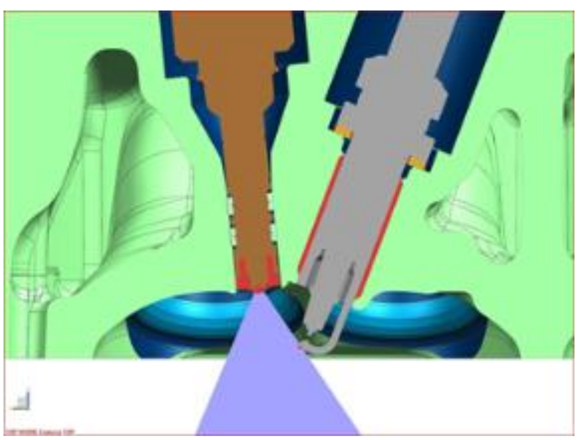

Figure 117: LE2 Injector to Spark Plug

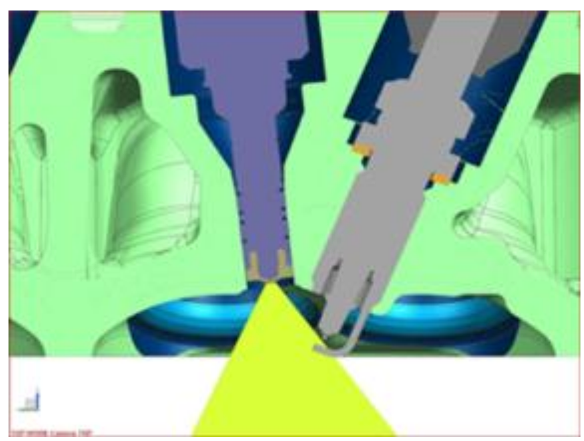

Figure 118: LDB Injector to Spark Plug

Piston bowl design is known to play a major role in ensuring good spray guided lean-stratified operation. Since the bore size and the compression ratio of the base LE2 turbo engine are different from the SG5 engine, the piston bowl had been redesigned to match our base LE2 engine geometric constraints. Figure 119 illustrates the LE2 piston and Figure 120 illustrates different piston bowl designs that had been tested on the 1.4L LDB engine. Three different piston bowl sizes at the same compression ratio (10.5) had been evaluated. Since piston bowl design could have had different impact at low and high engine load, multiple piston designs had been acquired to potentially evaluate at 3 different conditions: 2 bar (lean), 10 bar (lean), and 16 bar (stoic) to ensure good lean operation and acceptable high load stoichiometric homogenous operation. Based on initial test results, lower compression ratio piston bowls designs had been made available if engine knock at high load prevented running lean at high load condition.

Figure 119: LE2 Piston

Figure 120: LDB Piston Bowl at Various Bowl Geometries

The fuel economy improvement can be achieved by increasing the air flow capacity of the engine, executing a multiple closely spaced injection pulse strategy, and utilizing a higher ignition energy system. Therefore, the turbo system on the base 1.4L LE2 turbo engine had been redesigned to match the air flow requirement for maximizing lean-stratified operation, the fuel system and engine controller capability enhanced to deliver multiple closely spaced injection pulses (up to 4 injection pulses and less than 0.5 ms spacing between injection pulses), and a high ignition energy system selected to be installed on the new LDB engine.

In addition to the above mentioned engine enhancements, some additional combustion related features of the base 1.4L LE2 turbo engine had also been modified to replicate the original 2.2L SG5 lean-stratified engine. Figure 121 shows the tumble index of base LE2 turbo engine vs the SG5 engine. The high tumble index of the base LE2 turbo engine created concern that the LE2 turbo engine would not be able to operate in lean-stratified mode robustly. Therefore, provisions had been made to create a lower tumble version of the base LE2 turbo engine for the new LDB engine by modifying the existing cylinder head. Figure 122 demonstrates intake port tumble and swirl performance of the LDB engine cylinder head with the PDA open and closed.

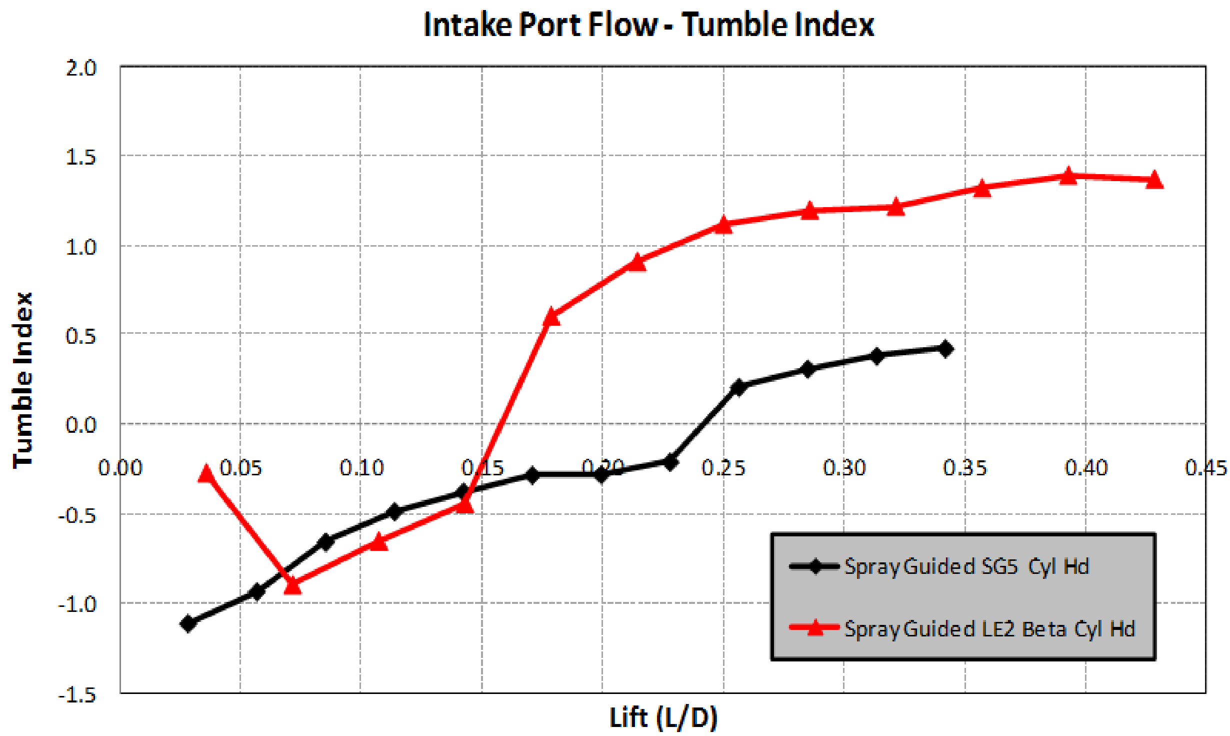

Figure 121: Intake Port Tumble Index of the Base LE2/LDB Engine vs. SG5 Engine

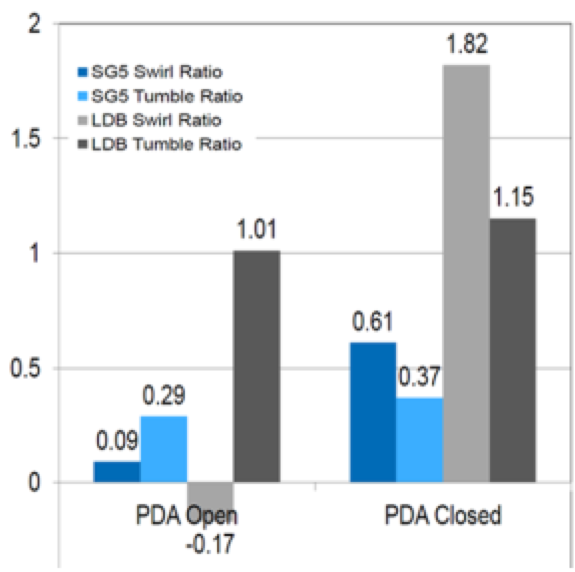

Figure 122: Intake Port Tumble / Swirl of the LDB Engine vs. SG5 Engine

This new LDB engine provides the optimum level of hardware and boosted lean-stratified combustion technology to demonstrate additional fuel efficient improvements to enable the combined achievement of the fuel economy performance objectives, Figure 123 to Figure 131:

- Intake manifold revisions to incorporate the new PDA adapter
- PDA system to provide high swirl mixture motion for increased lean dilution tolerance
- Cylinder head revisions for a split intake ports to support swirl based mixture preparation, chamber smoothing modifications and provisions for pressure transducers
- Pistons with dished style crowns to support spray-guided mixture preparation resulting in 10.5 nominal compression ratio
- Fuel system modifications to incorporate Bosch HDEV5.2 spray guided injectors with multi-hole spray patterns
- Impact of high energy ignition systems investigated
- Improved blow-by and PCV gas flow control
- Camshaft cover gasket sealing improvements
- External EGR cooler, valve and routing system revised for the compact engine
- New smaller turbocharger assembly with close-coupled TWC exhaust system
- Switchable water pump and electric thermostat on beta engines
- Front engine mount revised to mate engine to Malibu vehicle
- Rear torque converter housing revised to mate the 6T40 12V S/S transmission

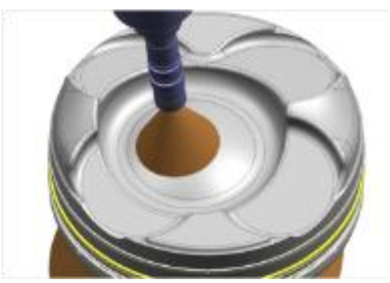

Figure 123: LDB Piston to Spray Pattern

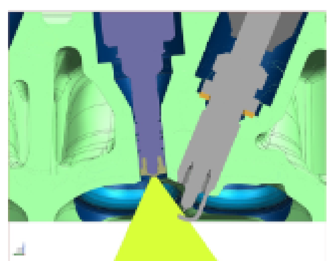

Figure 124: LDB Injector, Spray and Spark Plug

Figure 125: LDB Cylinder Head

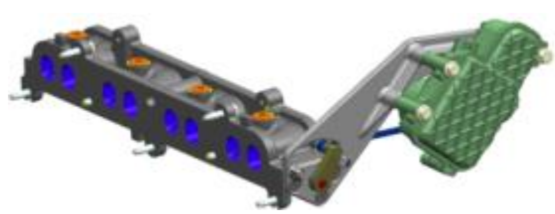

Figure 126: Port Deactivation Adapter

Figure 127: LBD Fuel Injectors, lines and Rail

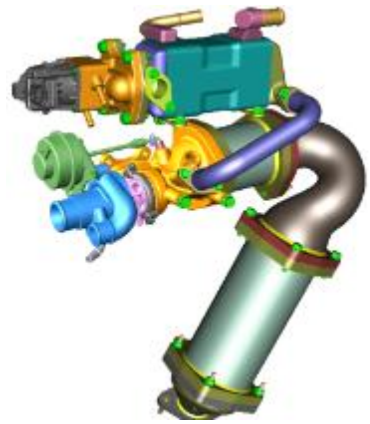

Figure 128: LDB Turbo, TWC, External EGR

Figure 129: 12V S/S Torque Converter Housing

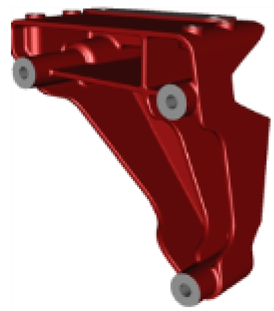

Figure 130: LDB Front Engine Mount

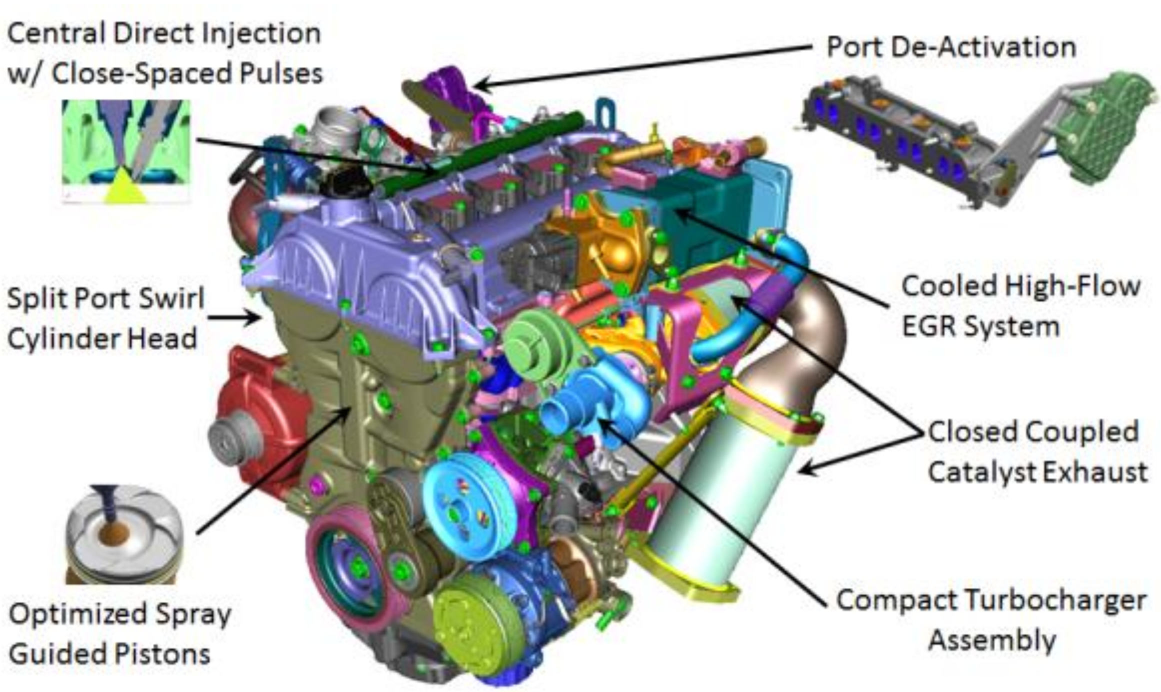

Figure 131: LDB Engine Assembly and Optimized Lean Combustion Enabling Features

Engine build commenced after part procurement, followed by start-cart electronic control verification, hot testing operation verification, engine break-in and relevant FTP test point verification. The test point verification is to ensure similar engine out exhaust gaseous emissions to minimize test property data variation. Four LDB engines had been built and installed in dynamometer and vehicle test properties, Figure 132.

Figure 132: Assembled Beta 1.4L LDB Engine

4.3.4. LDB ENGINE CALIBRATION

To ensure consistency and accuracy of the multiple dynamometer and emissions bench capabilities in the test-cells, a qualification assessment had been conducted. This had been accomplished by comparing historical data generated at GM with data generated at the supplier. For this test a production turbo charged 1.4L SGE engine (LE2), similar to the LDB engine had been utilized. The emissions bench test involved running A/F Ratio sweeps and recording the measurements of exhaust species. The results of the measurements are shown in Figure 133, where it can be seen the curves of the exhaust species follow the expected trends within normal measurement error.

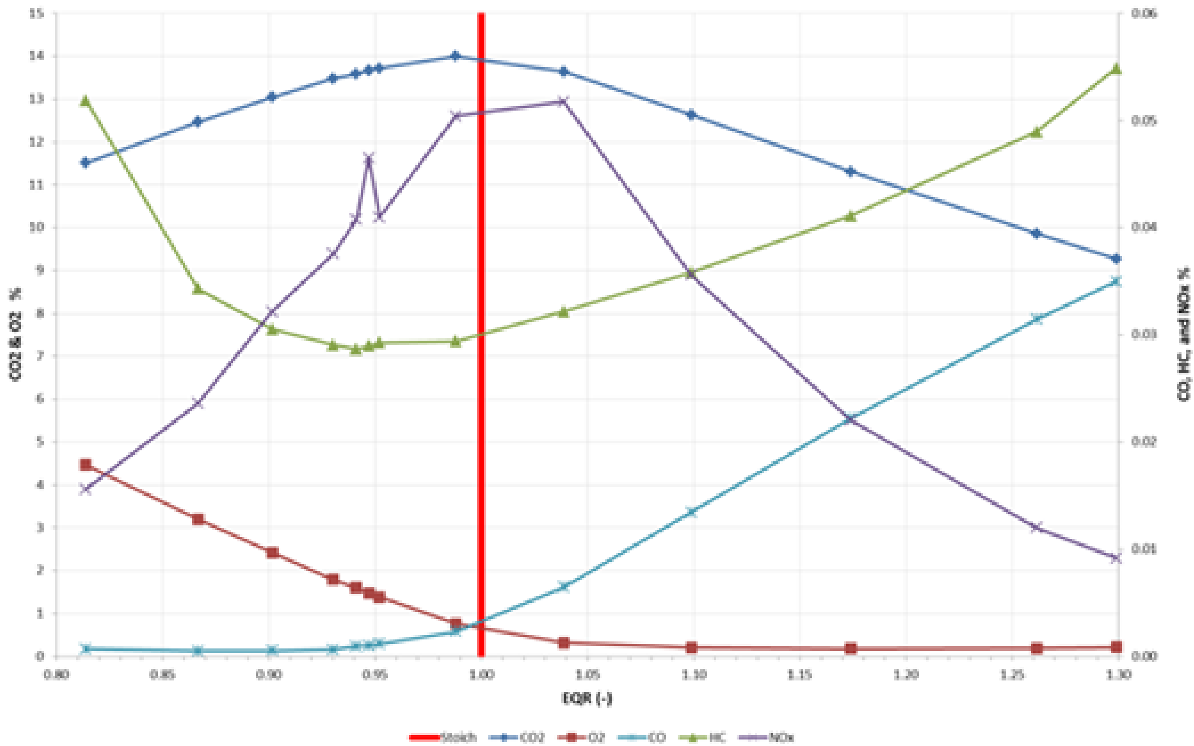

Figure 133: Exhaust Species Measurements During A/F Ratio Sweep

Figure 134, highlights an analysis of the exhaust species. The A/F Ratio sweep resulted in points of CO+O2 vs. Equivalence Ratio (EQR) that follow linear trends in both the lean and rich regions, as expected. The intersection of the linear trend lines occurred within the limit of 1% of EQR = 1 (EQR = 0.99 – 1.01) as expected. The difference between the Carbon-based and Oxygen-based A/F Ratio calculations stay below 0.1 for the lean region (limit is 0.2) and below 0.3 in the rich region (common behavior).

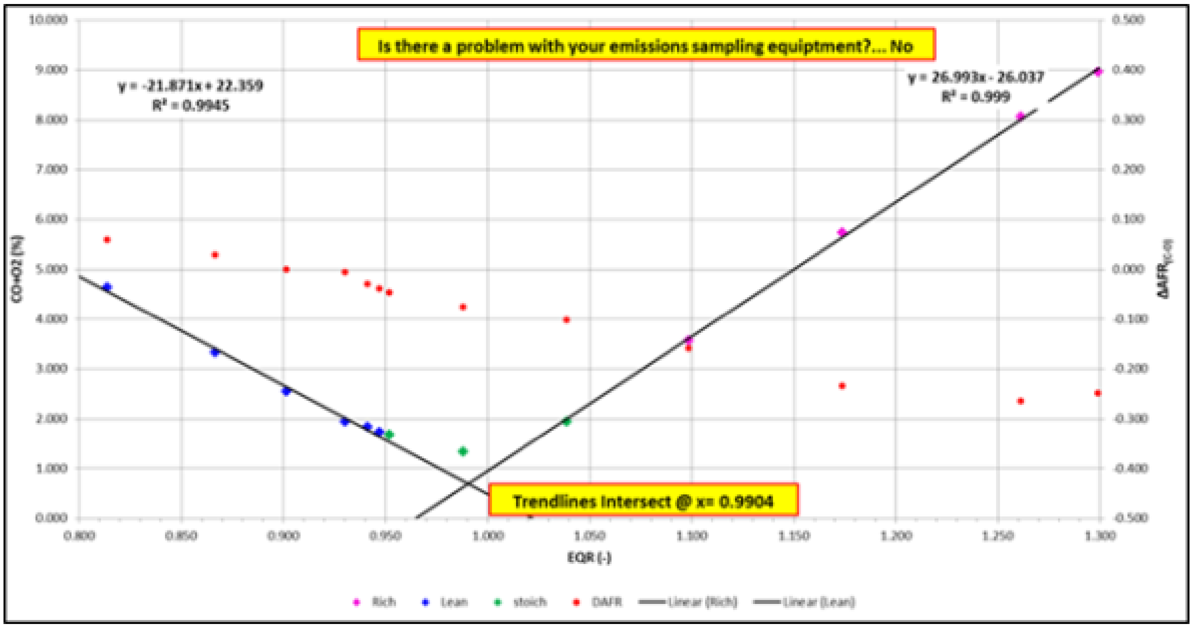

Figure 134: Analysis of A/F Ratio Sweep Measurements

Once the emissions measurement capabilities of the dynamometer test facility had been assessed and deemed to be satisfactory, the LE2 test engine had been run under conditions that reproduced those of the GM laboratory. The results had been compared and as Figure 135 shows, the correlation had been remarkably good within measurement error.

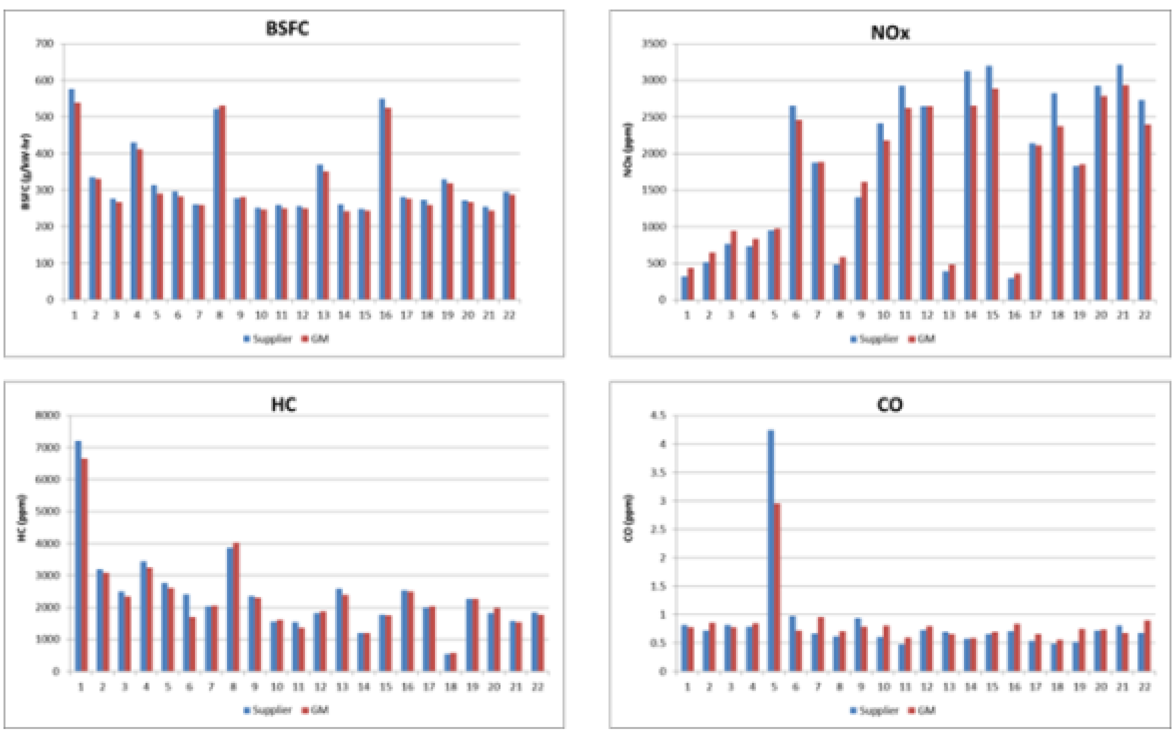

Figure 135: Comparison between GM's and Supplier's Dynamometer Test Results

An additional test facility verification area had been to run the BSFC data for the LE2 engine, at the speed/load points experienced during the FTP test cycles. This data had been utilized to compare to data from the LE5 baseline engine and establish the fuel economy benefit of downsizing the engine (stoichiometric homogenous operation). The results are reflected in Figure 136.

	Zone	Speed (rpm)	Load (Nm)	LE5 BSFC	LE2 BSFC	LE2 % BSFC Improvement
Urban	Idle	700	19.1	490	401	18.2%
	2	1335	27.4	401	333	17.0%
	3	1565	27.7	409	330	19.3%
	4	1805	29.3	405	321	20.7%
	5	1530	94.6	253	261	-3.1%
	6	1821	79.6	266	258	3.0%
	7	2250	101.3	253	254	-0.4%
Highway	8	1410	50.6	302	281	7.1%
	9	1669	60.2	290	274	5.5%
	10	1461	113.8	244	276	-13.3%
	11	1692	100.0	251	260	-3.7%

Figure 136: LE2 vs. LE5 Baseline BSFC Comparison at FTP Speed/Load Points

Considering that the LDB engine had been planned to be installed in a vehicle that also benefits from 12V S/S technology (thus making the difference in BSFC at idle irrelevant), the difference in BSFC at the FTP Speed/Load points translates to a predicted fuel economy improvement of 7.5% over the combined FTP city and highway cycles as indicated in Figure 137.

	LE2 % FE Improvement
City	+12.1%
Highway	-.4%
Combined	+7.5

Figure 137: LE2 vs. LE5 Baseline Fuel Economy Improvement Prediction

With the test facility verified to provide precise combustion data, engine calibration shifted focus on the LBD engine calibration on specific areas for lean-stratified operation, stoichiometric homogenous operation and the transition region between the operation modes. Due to number of variables in lean-stratified combustion mode, running full-factorial sweeps with the required resolution for all variables would make the required number of points literally impossible to run in a reasonable time. To optimize data collection, a Design of Experiment (DoE) approach that uses a Space-Filling algorithm with weighted randomized points had been selected. Based on previous experience of GM and the dynamometer test supplier, the engine load had been divided into two overlapping regions with different calibration approaches: Low-Load, from 1 to 6 bar of BMEP and High-Load, from 5 to 10 bar of BMEP.

An example of the space filling point generation is shown in Figure 138. The data captured had then been utilized to generate comprehensive models for the two different combustion modes for the responses of multiple combustion parameters. The final step of the DoE had been to optimize the model for BSFC with the following constraints:

- CoV of IMEP
- Fuel Specific NOx emissions
- Turbine Outlet exhaust gas Temperature
- Turbine Inlet exhaust gas Temperature

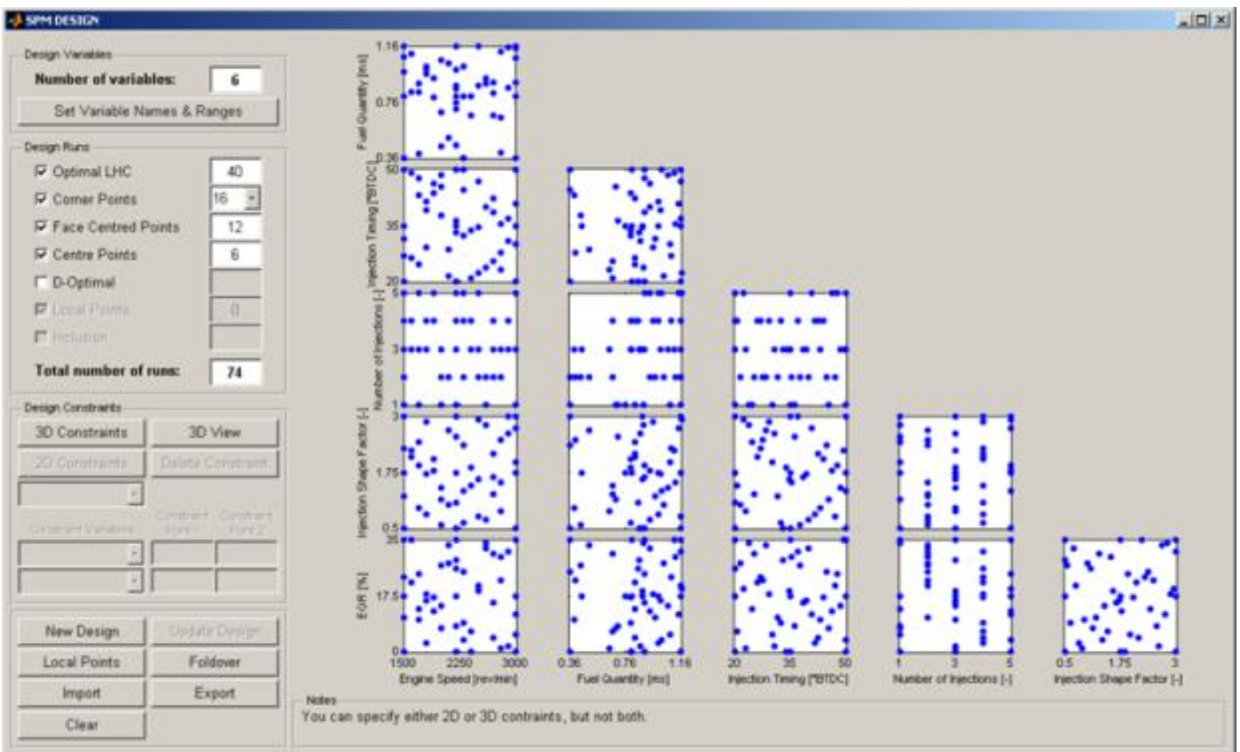

Figure 138: Percent Weighted Random Point Generation Example

Following the test-cell verification and LE2 vs. LE5 fuel economy evaluation, calibration activities transitioned towards the LDB engines. The initial step had been to complete the GM break-in procedure on the LDB engine to ensure the internal friction is stable to avoid any data noise and are focused on the calibration activities. Engine calibration activities targeted specific areas for lean-stratified operation, stoichiometric homogenous operation and the transition region between the operation modes. The initial calibration support had started on lean-stratified operation with detailed calibration in the areas of; reverse current multiple pulse fuel injection capability, initial high energy ignition impacts, fuel spray proximity to ignition electrode influences, compression ratio affects and turbocharger assembly sizing performance.

The control system of the fuel injectors had been modified to operate in "reverse current" mode. Conventional fuel injector control applies a voltage to open the injector allowing fuel to flow, then the voltage is dropped and the spring internal to the injector closes it. The reverse current system actually reverses the current applied to the injectors thus electrically forcing them shut instead of relying solely on the internal spring force. The reverse current control of the injectors allows for a better control of pulse width, making it shorter, Figure 139. The shorter pulse width subsequently enables capability for multiple injection pulses.

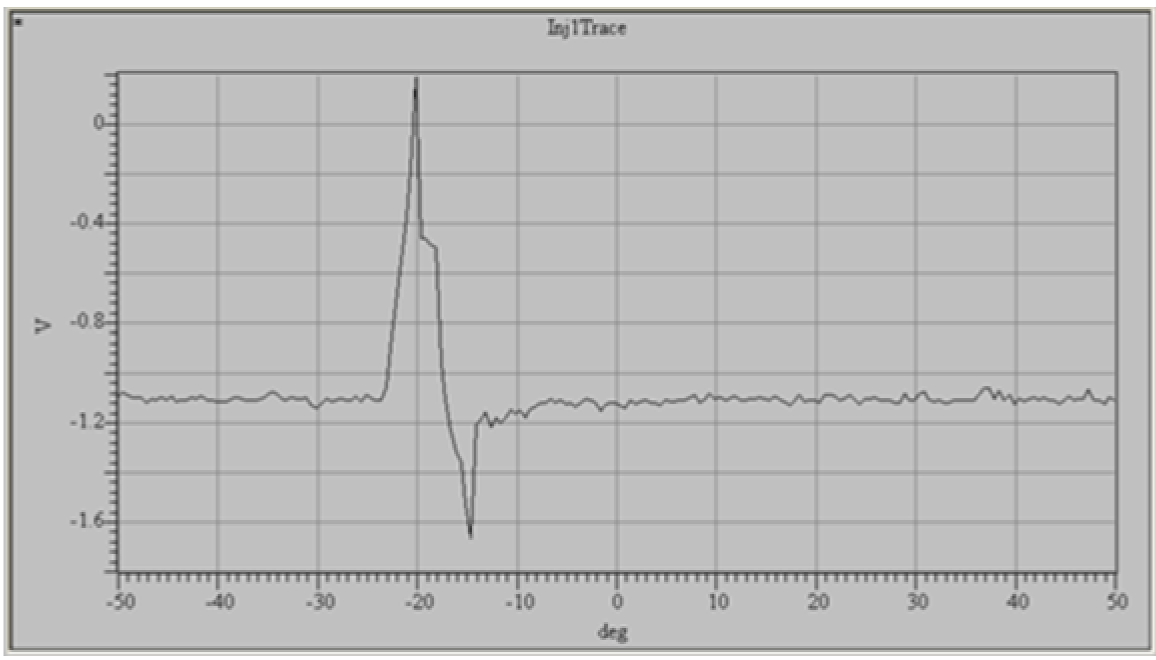

Figure 139: Reverse Current Pulse Width

Initial evaluation of a High Energy Ignition System had been performed to ascertain the performance benefit potential. This system allows for a longer and more energetic electrical discharge at the spark plug, allowing robust combustion initiation of a more dilute air-EGR-fuel mixture than a conventional system would allow. This initial test showed a marginal improvement in combustion stability. However, the gain had been accompanied by spark plug erosion at a rate of 10 to 20 times what is seen with a conventional ignition system. There had been also multiple instances of arching between the spark plug boot and grounded parts of the engine (spark plug tube, mounting harness, etc.). The resulting arching caused adjacent rubber parts to melt and the engine to function erratically. Subsequently, HE ignition as an enable to improved lean-stratified combustion performance had been discarded.

The axial location (depth) of the fuel injection spray had been tested to optimize the relative proximity of the fuel spray to the spark plug electrode. The test compared the depth from a baseline position by moving the injectors by -1.5 mm, +0.5 mm, +1.5 mm and +2 mm (where a negative number represents movement towards combustion chamber from the baseline). A position of +3.5 mm had been also attempted but the smoke generation and the COV had been outside the established constraints. The fuel injector depth tests had been run at 1565 rpm, 2.5 bar BMEP (FTP Zone 3). Injection timing and ignition timing had been swept together with constant separation, Spark Offset. The Spark Offset had been then re-optimized at each injector depth. All other calibration parameters, including AFR, PDA position, External EGR, Fuel Rail pressure and cam phasing, had been held constant. The fuel injection spray proximity evaluation results are:

- +1.5 mm injector depth had the lowest COV of IMEP, divergence in COV began at CA50 = 3 deg aTDC, Figure 140
- +1.5 mm injector depth had the lowest percent misfires (one misfire at CA50 = 0 deg), Figure 141
- +1.5 mm injector depth had the highest LNV of IMEP across the range of injection/ignition timings, Figure 142
- Smoke had been low at all injector depths. At late injection timings, smoke increased with injector movement down into the cylinder, Figure 143
- BSFC had been not affected by injector depth. +2 mm and baseline injector depth had been affected by high oil pressure at CA50 = 0 deg aTDC due a calibration setting, Figure 144

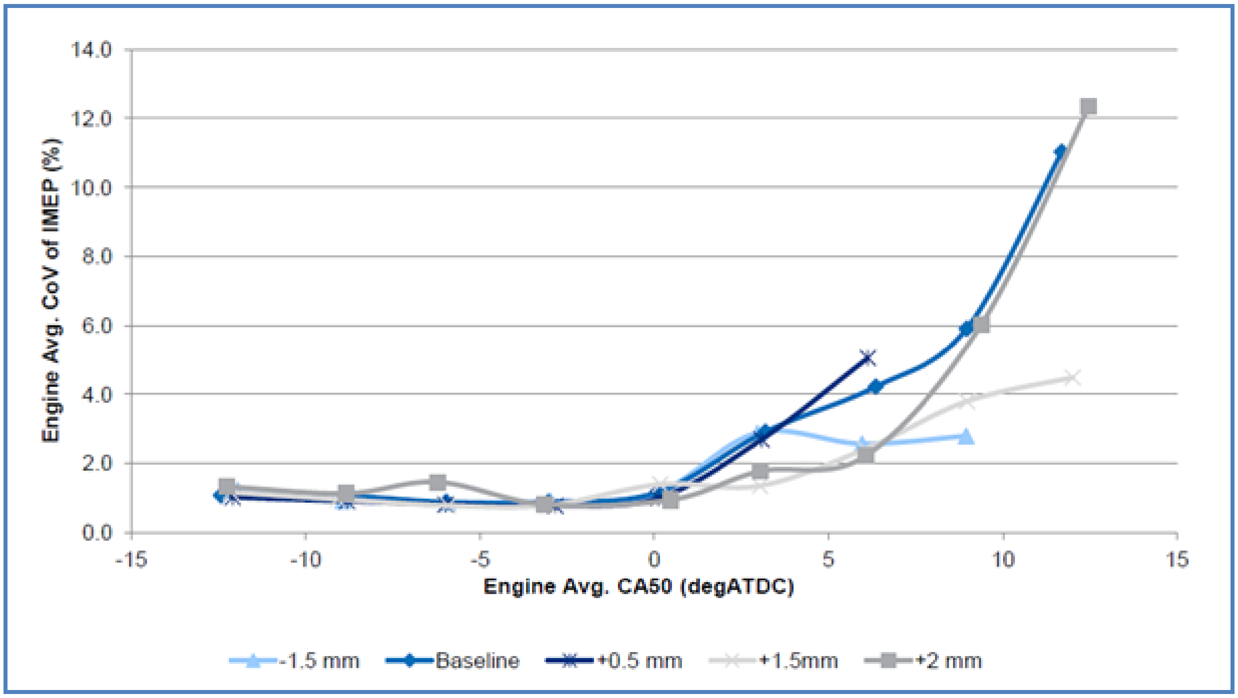

Figure 140: Injector Depth Influence on COV of IMEP

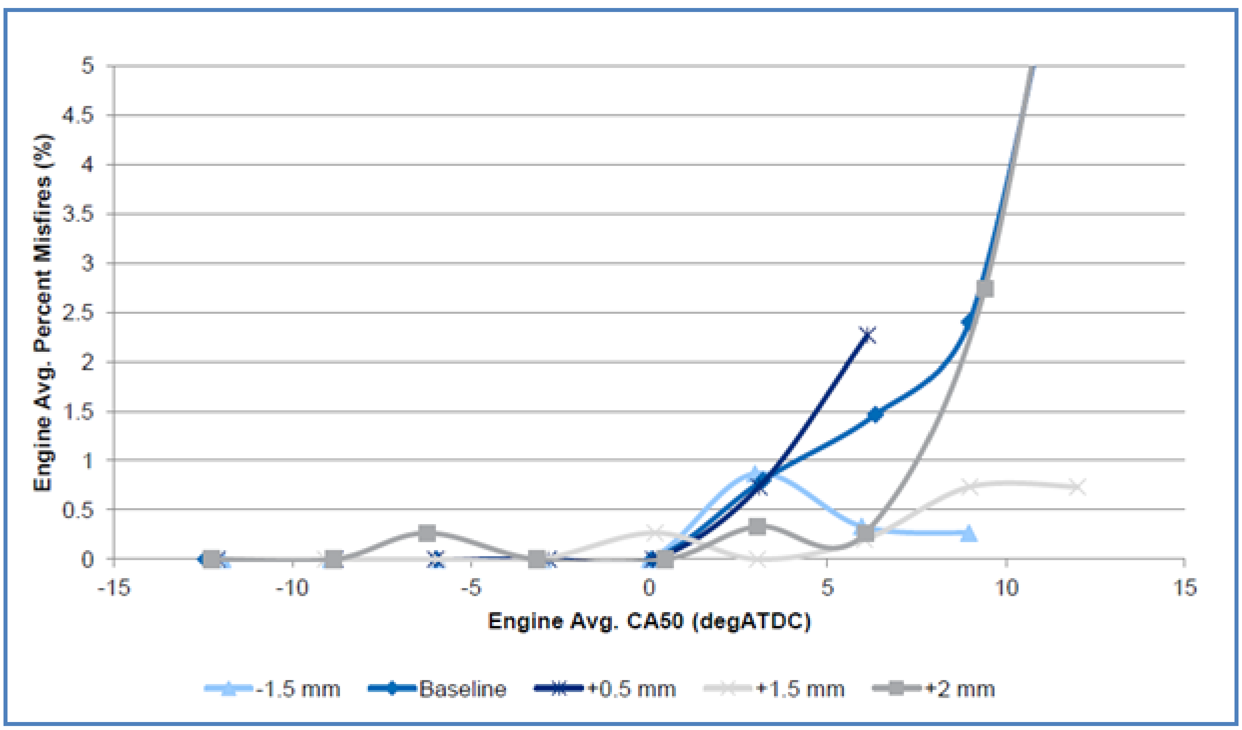

Figure 141: Injector Depth Influence on Percent Misfires

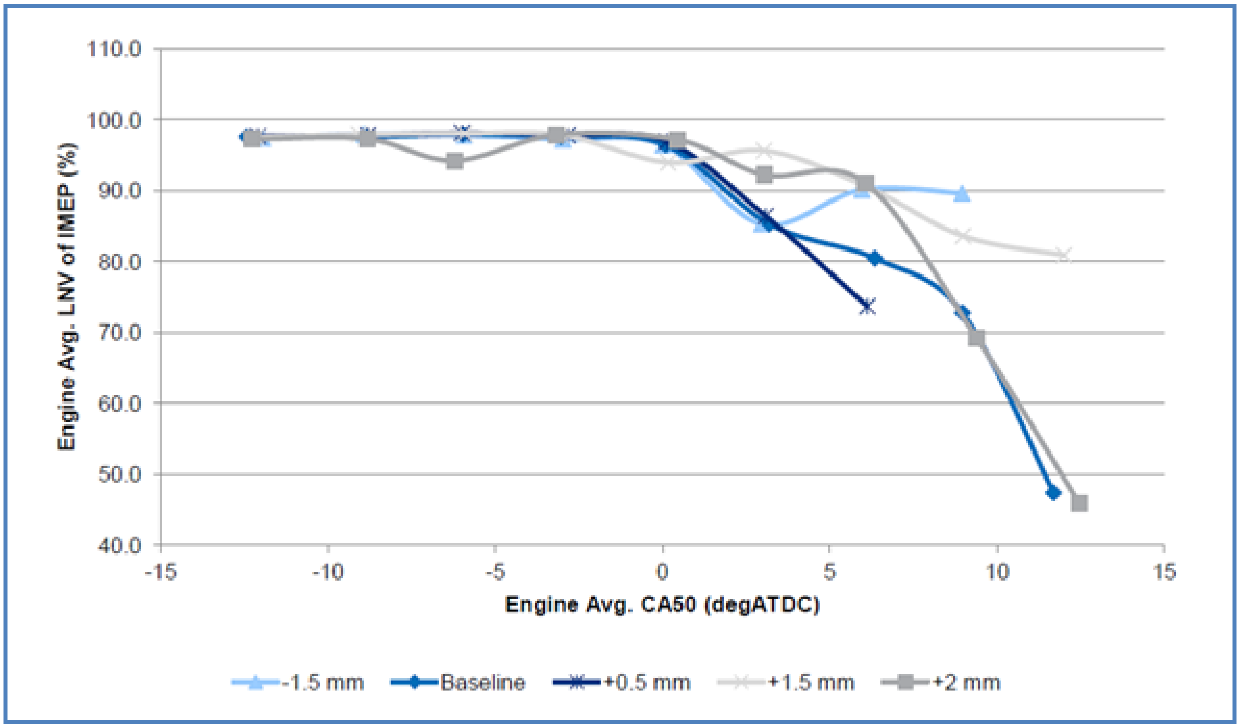

Figure 142: Injector Depth Influence on LNV of IMEP

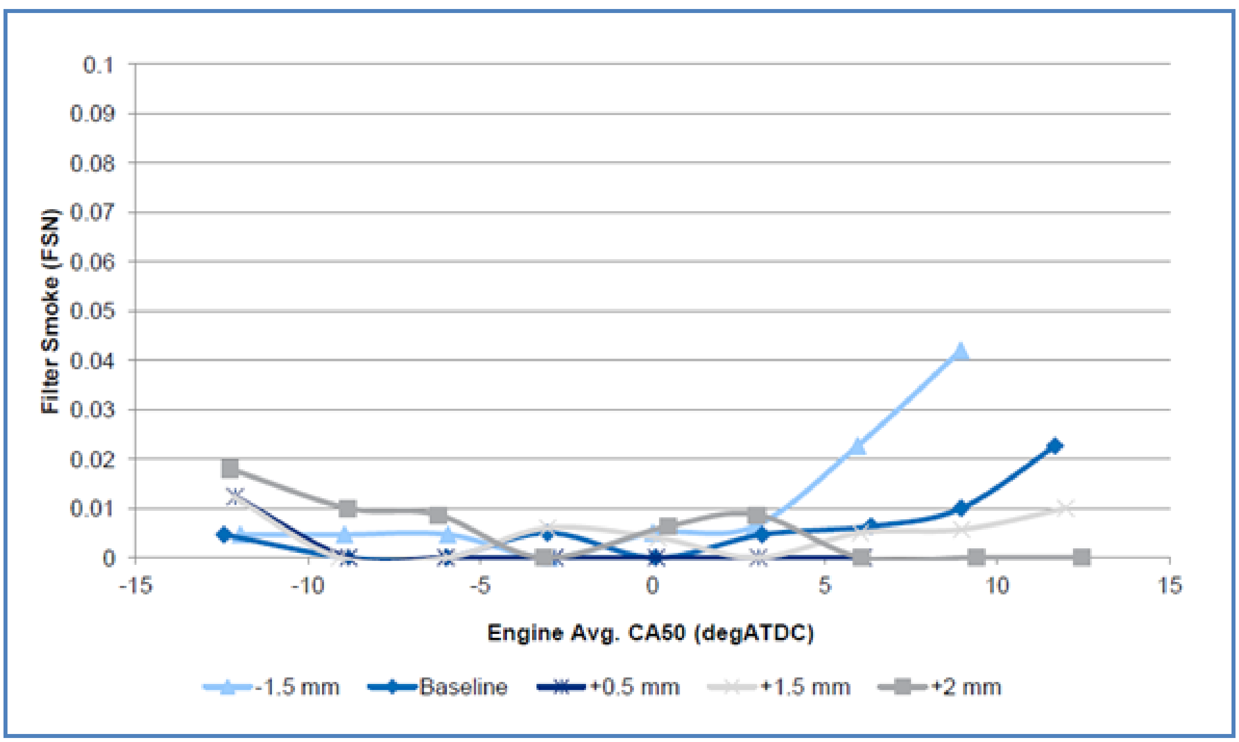

Figure 143: Injector Depth Influence on Smoke

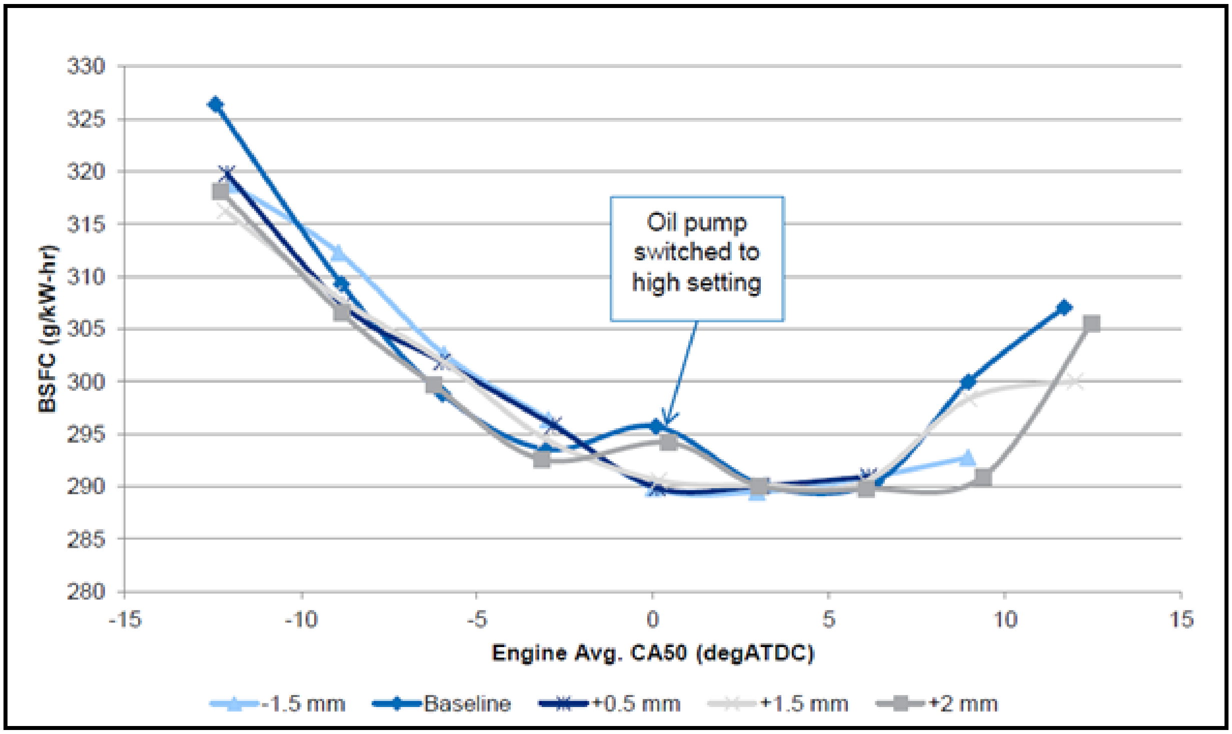

Figure 144: Injector Depth Influence on BSFC

In summary, the injector proximity evaluation showed:

- Combustion had been relatively stable at injector depths from -1.5 to +2 mm
- +3.5 mm had very high smoke and COV
- +1.5 mm injector depth had the lowest COV and percent misfires across the full range of injection timings
- Optimal BSFC had been not affected by the injector depths tested
- Optimal BSFC is flat from CA50 = 0-6 deg aTDC
- Smoke had been low at injector depths from -1.5 to +2 mm
- At late injection timings, smoke increased with movement down into the cylinder

The Compression Ratio (CR), which is in part driven by the piston dome bowl geometry, had been evaluated to address some potential concerns of knock limiting the performance of the engine. The baseline pistons of the LDB engine result in a 10.5:1 CR and had a bowl with a diameter of 44 mm. The LDB engine had been evaluated for BSFC at Zones 3, 6, 8, 9, 11 and 14 with these baseline pistons. In addition to the zones used to evaluate part load stratified performance, the high load stratified limit had been also explored. The BSFC results had been compared to the initial BSFC performance established with the baseline stoichiometric LE2 engine with the intent of evaluating the need to test a lower CR and/or a modified piston bowl. The zones that had been evaluated showed BSFC improvements with the LDB engine ranging from 6.6 to 15.2% compared to the LE2 baseline, Figure 145. These improvements met the LDB targets for the zones tested, except for Zone 6. The high load stratified limit at 2000 rpm (10.7 bar) also met the 10 bar engineering target requirement. Based on these results, the project proceeded with the baseline LDB pistons.

	Zone	Speed (RPM)	Torque (Nm)	BMEP (bar)	LE2 BSFC	LDB Target BSFC	LDB BSFC	% Improvement LDB vs. LE2	% Improvement LDB vs. Target
Urban	Idle	700	19.1	1.7	490	490			
	2	1335	27.4	2.5	333	281			
	3	1565	27.7	2.5	330	286	280	-15.2%	-2.1%
	4	1805	29.3	2.6	321	283			
	5	1530	94.6	8.5	261	240			
	6	1821	79.6	7.1	258	226	241	-6.6%	6.6%
	7	2250	101.3	9.1	254	240			
Highway	8	1410	50.6	4.5	281	257	249	-11.4%	-3.1%
	9	1669	60.2	5.4	274	247	245	-10.6%	-0.8%
	10	1461	114	10.7	276	231			
	11	1692	100	9	260	238	235	-9.6%	-1.3%
High Load	14	2000	174.7	15.7	278		256	-7.9%	
Other		2000	22.3	2	368	316	315*	-14.4%	-0.3%
		2000	119	10.7			239		

Figure 145: BSFC Improvement with Initial 10.5:1 CR Pistons

During the above testing, pumping losses had been found to be significantly higher in the LDB engine as compared to the LE2 engine. Back-pressure had been found to be the main contributor (86.1 kPa vs. 27.5 kPa @ 1750 rpm, 12 bar BMEP, EQR = 1). The difference in the back-pressure had been partly due to plugged catalytic converter, but the decision had been made to test a LE2 turbocharger assembly on the LDB engine to further reduce pumping losses and evaluate this effect on BSFC. For this purpose, 3 baseline points had been run on the LDB engine with the LDB turbocharger assembly (but a new converter):

- Zone 6: 1821 rpm; 7.1 bar BMEP
- Zone 8: 1410 rpm; 4.5 bar BMEP
- Zone 11: 1692 rpm; 9 bar BMEP

A LE2 turbocharger assembly had been then fitted and the same 3 points had been run by the same LDB engine. With the LE2 turbocharger installed on the LBD engine, BSFC improved at the 3 tested points (although, Zone 6 BSFC target still not met), Figure 146. The BSFC improvement is due to reduced pumping losses. However, boost with the LE2 turbocharger assembly is significantly lower (due to lower EGT) reducing the stratified combustion limit from 10.7 to 9 bar. Based on these results, the project proceeded with the original LDB turbocharger assembly.

	Zone	Speed (RPM)	Torque (Nm)	BMEP (bar)	LE2 BSFC	LDB Target BSFC	LDB BSFC (LDB Turbo)	LDB BSFC (LE2 Turbo)	% Improvement LE2 Turbo vs. LDB Turbo	% Improvement LE2 Turbo vs. Target
Urban	Idle	700	19.1	1.7	490	490				
	2	1335	27.4	2.5	333	281				
	3	1565	27.7	2.5	330	286	280			
	4	1805	29.3	2.6	321	283				
	5	1530	94.6	8.5	261	240				
	6	1821	79.6	7.1	258	226	240	236	1.7%	4.4%
	7	2250	101.3	9.1	254	240				
Highway	8	1410	50.6	4.5	281	257	246	239	2.8%	-7.0%
	9	1669	60.2	5.4	274	247	245			
	10	1461	114	10.7	276	231				
	11	1692	100	9	260	238	232	230	0.9%	-3.4%
High Load	14	2000	174.7	15.7	278		256			
Other		2000	22.3	2	368	316	315			
		2000	119	10.7			239			

Figure 146: LDB vs. LE2 BSFC Performance of Turbocharger Assemblies

The primary calibration activities generated two complete calibration models for lean-stratified operation mode using the DoE process. The first calibration model had been developed by minimizing BSFC regardless of engine-out NOx emissions, then introducing excess EGR to reduce engine-out NOx emissions to 31 g/kg-fuel of Fuel Specific Nitrogen Oxides (FSNOx). This first calibration model had been found to be the lowest value of FSNOx possible without deteriorating BSFC by more than 1% of the optimum. The second calibration model had been developed by adding even more EGR to reduce engine out NOx emissions to 20 g/kg-fuel of FSNOx or less. The functional performance of the two lean-stratified calibrations is detailed in Figures 147 through 150. The calibration models highlighted the sensitivity of the LDB engine to PDA actuation, the PDA effect is mostly engine speed related, with a much lower sensitivity to load, Figure 150.

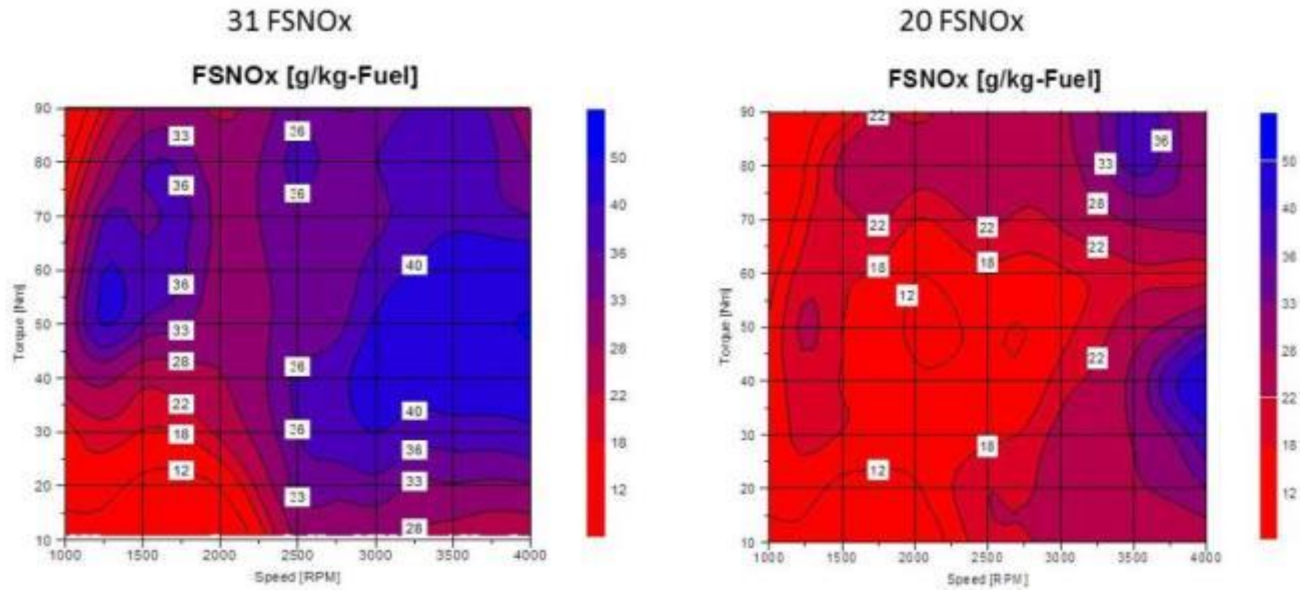

Figure 147: FSNOx speed/load map for the two calibration models

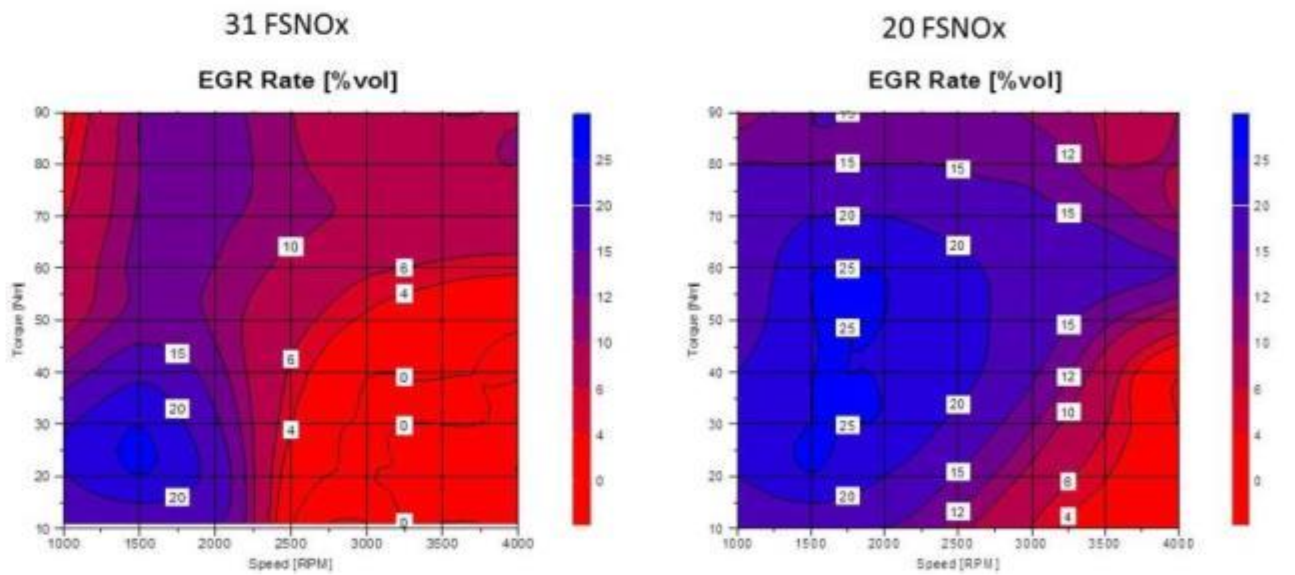

Figure 148: EGR Rate speed/load map for the two calibration models

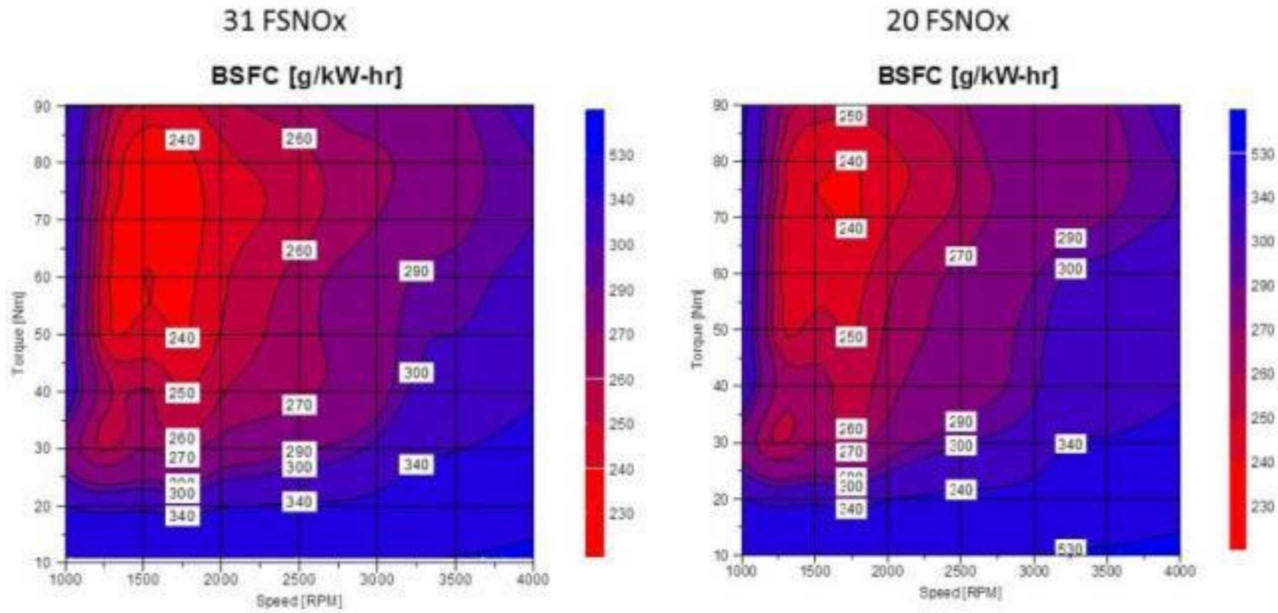

Figure 149: BSFC speed/load map for the two calibration models

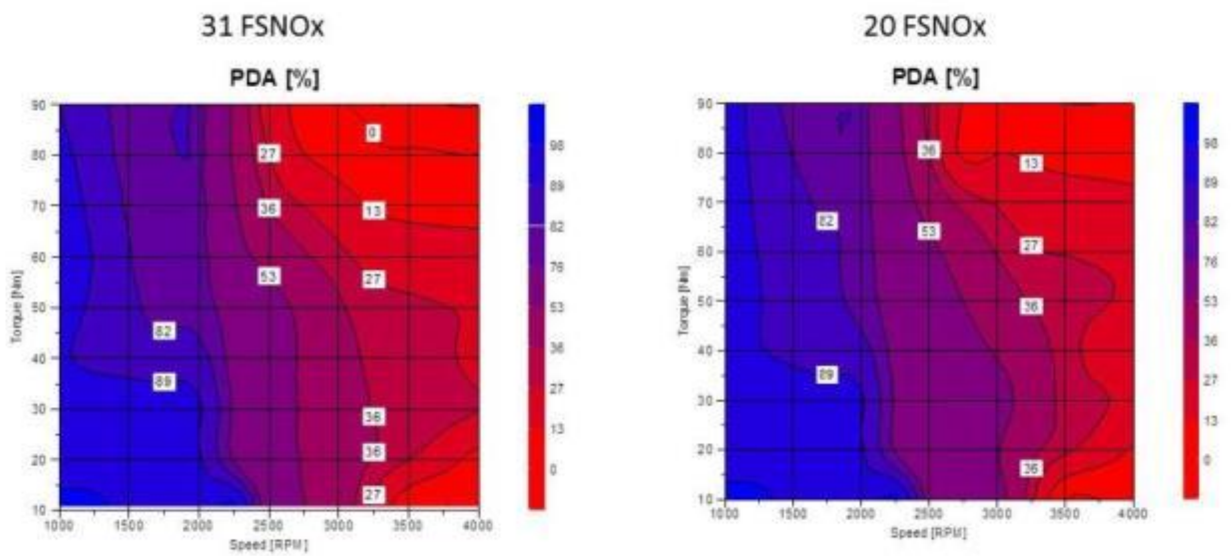

Figure 150: PDA Position speed/load map for the two calibration models

4.3.5. LDB VEHICLE INTEGRATION

The support the final fuel economy demonstration element of significant improvement through a high level of downsizing and boosted lean operation, the LDB engine had been installed in a Malibu development vehicle, Figure 151. The vehicle integrates the optimal combination of advanced powertrain technologies to maximize the fuel economy and emissions performance. Two vehicles had been integrated with the LDB engine and had been used to optimize the transmission shift calibrations, fuel economy development, and emissions development.

The engine control module and software required upgrading for the LDB engine. The engine controller used on the SG5 engine did not had sufficient memory or throughput to support controlling both the turbocharger and the 12V S/S functions. Additional features that are in the upgraded engine controller include electric thermostat, switchable water pump and two stage oil pump controls. The stratified controls which had been developed for the SG5 engine are being integrated into the new software.

A low pressure cooled external EGR system is used on the LDB engine. The EGR exhaust gas is extracted downstream of the turbo and passes through a cooler before flowing through the EGR valve and into the intake system upstream of the throttle body. The EGR valve and cooler are plumbed into the existing vehicle cooling circuit and shown in Figure 152.

Figure 151: LDB Engine Installation

Figure 152: EGR Valve and EGR Cooler

The LDB also uses an engine mounted air to coolant charge air cooler as shown in Figure 153. The cooler is plumbed into a low temperature coolant circuit independent of the standard engine cooling system. An auxiliary electric coolant pump is used to circulate the coolant. The pump and radiator installation is shown in Figure 154.

The LDB engines include the ATM system including an electric thermostat and switchable engine coolant pump that had been planned to be controlled by the engine control module. The engine warm up rate increases by disabling the coolant pump after an engine cold start until the engine coolant and cylinder head metal temperatures reach a specified temperature. Once the coolant pump is enabled, the electronic thermostat allows the engine to run at the most efficient temperature.

Figure 153: Charge Air Cooler

Figure 154: Low Temp Radiator & Aux. Pump

4.3.6. LDB G4 PASSIVE + ACTIVE LEAN AFTERTREATMENT

To support the G4 passive/active lean aftertreatment integration with the 1.4L LDB engine, a packaging design study had been conducted to determine TWC options for the new installation with the reconfigured front engine exhaust. It had been determined that 1.95L of converter volume can be packaged in two separate volumes, .45L close-coupled followed by 1.5L further downstream. The program's collaborative supplier for catalyst development provided recommendations for TWC and SCR technology for the LDB engine. In an effort to ascertain the optimal LDB passive + active lean aftertreatment system, multiple cell density substrates and washcoat technologies had been evaluated as part of the development. Cu and Fe zeolite SCRs also had been included in the evaluation for added system optimization.

The engine-out temperature profile of the LDB engine had been projected to be significantly lower that what had been demonstrated on the SG5 engine equipped vehicle. To ensure good HC light–off performance as well as T2B2 emissions performance, the close-coupled converter had been changed to a 900/2 (900 cells per sq in/2mil wall thickness) substrate. Although the higher density TWC is targeted to help with emission performance, the increase in back-pressure had a measured affect the engine power curves near peak power. The initial packaging architecture is shown in Figure 155.

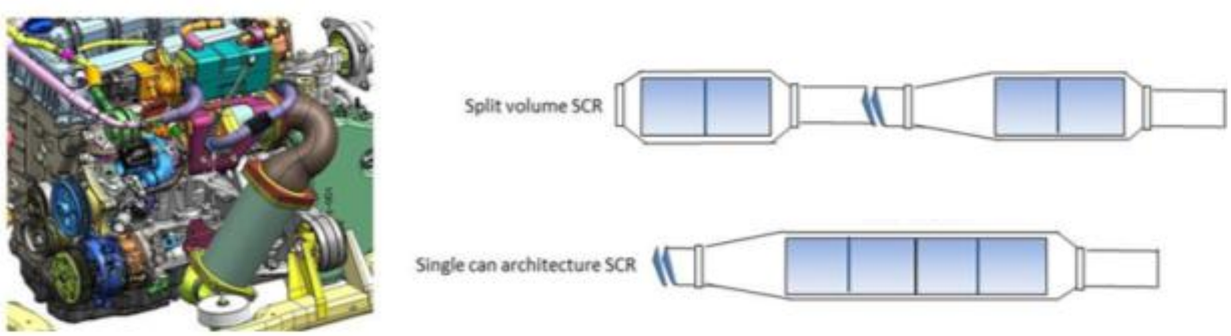

Figure 155: LDB G4 Passive + Active Lean Aftertreatment TWC and SCR Configurations

Following procurement, the optimized LDB G4 passive + active lean aftertreatment system had been fully integrated in to the Malibu development vehicle with the LDB engine. The majority of LDB lean aftertreatment system hardware is carried over from the original SG5 engine equipped vehicle with respect to the underfloor 1L TWC and urea dosing system. However, the close-coupled TWCs had been repackaged to fit the new LDB engine as it now exits from the front of the LDB engine as opposed to the rear of the SG5 engine, Figure 156

A second 1.0L underfloor TWC is moved toward the engine and is located under the driveshaft. The urea dosing injector had been relocated as far as possible from the front face of the SCR converter. The updated torpedo SCR convertor had moved forward approximately 16 inches to maintain good mixing, followed by the tailpipe section. The initial LDB G4 passive + active lean aftertreatment underbody components are depicted in Figure 157 and Figure 158. The dosing reservoir, pump and all data acquisition equipment are located in the trunk of the vehicle.

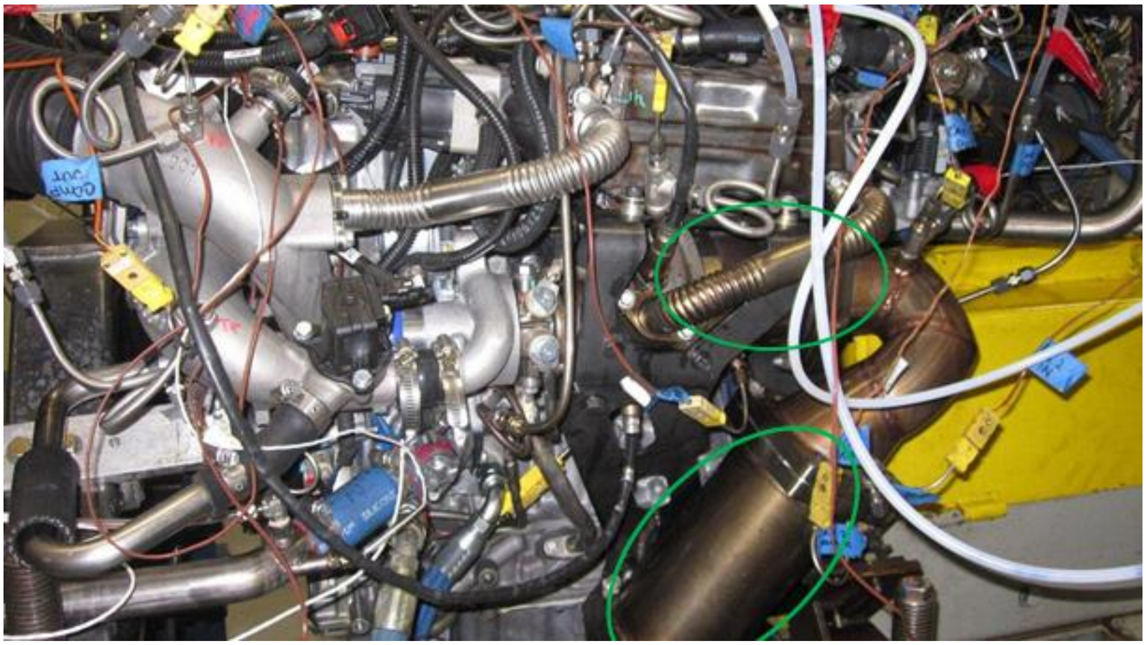

Figure 156: LDB G4 Passive + Active Lean Aftertreatment with Updated Close-coupled TWCs

Figure 157: Initial LDB G4 Passive + Active Lean Aftertreatment with Updated Underfloor TWC

Figure 158: Initial LDB G4 Passive + Active Lean Aftertreatment with Updated SCR Location

The TWC and SCR inlet temperature data proved out to be cooler than had been expected and became apparent that meeting the emission standards might be a challenge for cold starts. For the final LDB Passive + Active lean aftertreatment layout, the under-floor TWC converter in Figure 157 was moved as close to the exhaust manifold as possible to increase exhaust system temperature between 75-100C. The urea dosing valve was also moved to maximize mixing and allow more room to bring the torpedo SCR slightly closer to ensure SCR light-off by cycle 2 at cold start. This worked very well and we achieved are target temperatures at cold start while maintaining good SCR temperature for the rest of the test, Figure 159.

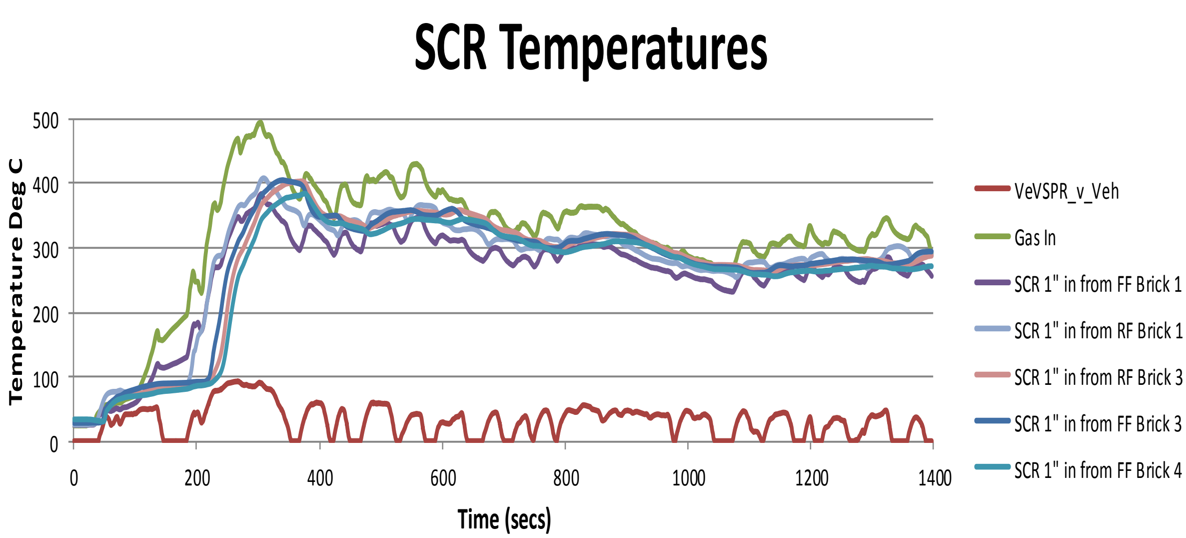

Figure 159: Increased SCR Inlet Temperature by 100C at Cold Start

4.3.7. LDB VEHICLE FUEL ECONOMY

Simulation had been used to quantify the fuel economy improvement that could be expected with the LDB engine in a Malibu vehicle. The simulation results are based on BSFC data for the high density speed and load points that are seen on the FTP city and highway test schedules. This simulation had shown good correlation to actual vehicle data with the original SG5 engine. The result of this analysis predicts that the LDB engine provides a 19.8% combined fuel economy improvement when compared to the baseline Malibu with the LE5 engine. This improvement, in combination with the projected improvement for the 12V S/SS and ATM (+4 to 6%), supports the vehicle in meeting the project objective of +25% combined fuel economy improvement. The FTP speed load points, BSFC data and the resulting projected fuel economy estimates are shown in Figure 160.

		Speed (RPM)	Load (n-m)	LE5 BSFC	LDB BSFC	% BSFC Improvement LDB to LE5
Urban	Idle	700	19.1	490	490	0.0%
	Zone 2	1335	27.4	401	283	-29.4%
	Zone 3	1565	27.7	409	280	-31.5%
	Zone 4	1805	29.3	405	273	-32.6%
	Zone 5	1530	94.6	253	243	-4.0%
	Zone 6	1821	79.6	266	241	-9.4%
	Zone 7	2250	101.3	253	236	-6.7%
Highway	Zone 8	1410	50.6	302	249	-17.5%
	Zone 9	1669	60.2	290	245	-15.5%
	Zone 10	1461	113.8	244	257	5.3%
	Zone 11	1692	100.0	251	232	-7.6%

	LE5 FE	LDB FE	Improvement
City	26.57	33.28	25.3%
Hiway	42.42	46.78	10.3%
Comb	31.94	38.25	19.8%

Figure 160: LDB vs. LE5 Baseline Vehicle BSFC and FTP Fuel Economy Projections for Combustion only (not including 12V Stop/Start or ATM)

LDB stoichiometric homogenous and lean engine calibrations had been developed on the dynamometer to support integration in to the development vehicles. Calibration focus areas relating to idle control, boost control, and transmission shift pattern. The initial part throttle vehicle drivability had been reasonable, though the vehicle had been sluggish at high load. This had been due to the characteristics of the initial turbo selection which had been chosen for the LDB engine to support extended lean-stratified operation.

The maximum engine load for lean-stratified operation for the LDB engine is 10.5 BAR BMEP. Figures 161 and 162 show the driver requested BMEP from FTP city and highway tests with the LDB Malibu development vehicle. Other than a few of the acceleration maneuvers, the majority of the test cycles can be run in lean-stratified mode which is indicated by the red lean-stratified line being in the high state. For this testing, idles and low speed decelerations had been run in stoichiometric homogenous mode but the engine will be off once the 12V S/S function is fully active.

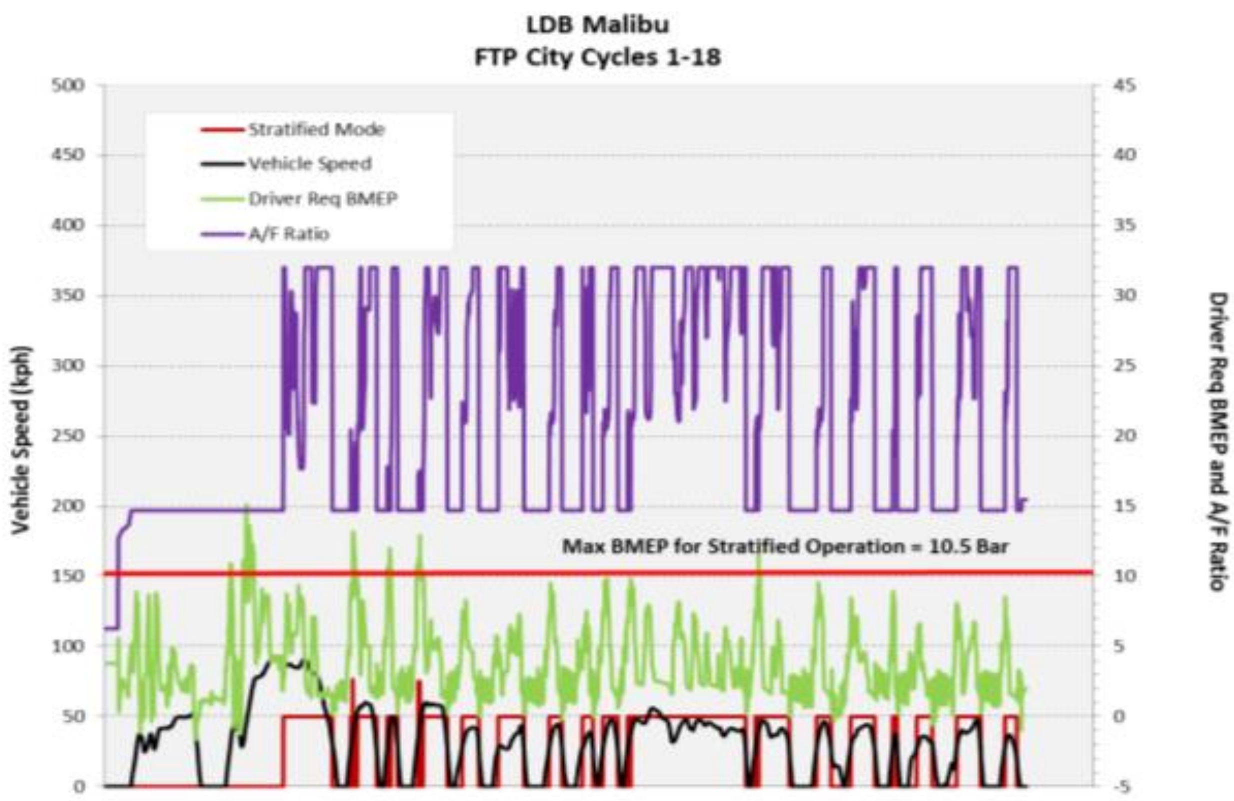

Figure 161: LDB FTP City Lean-Stratified Operation

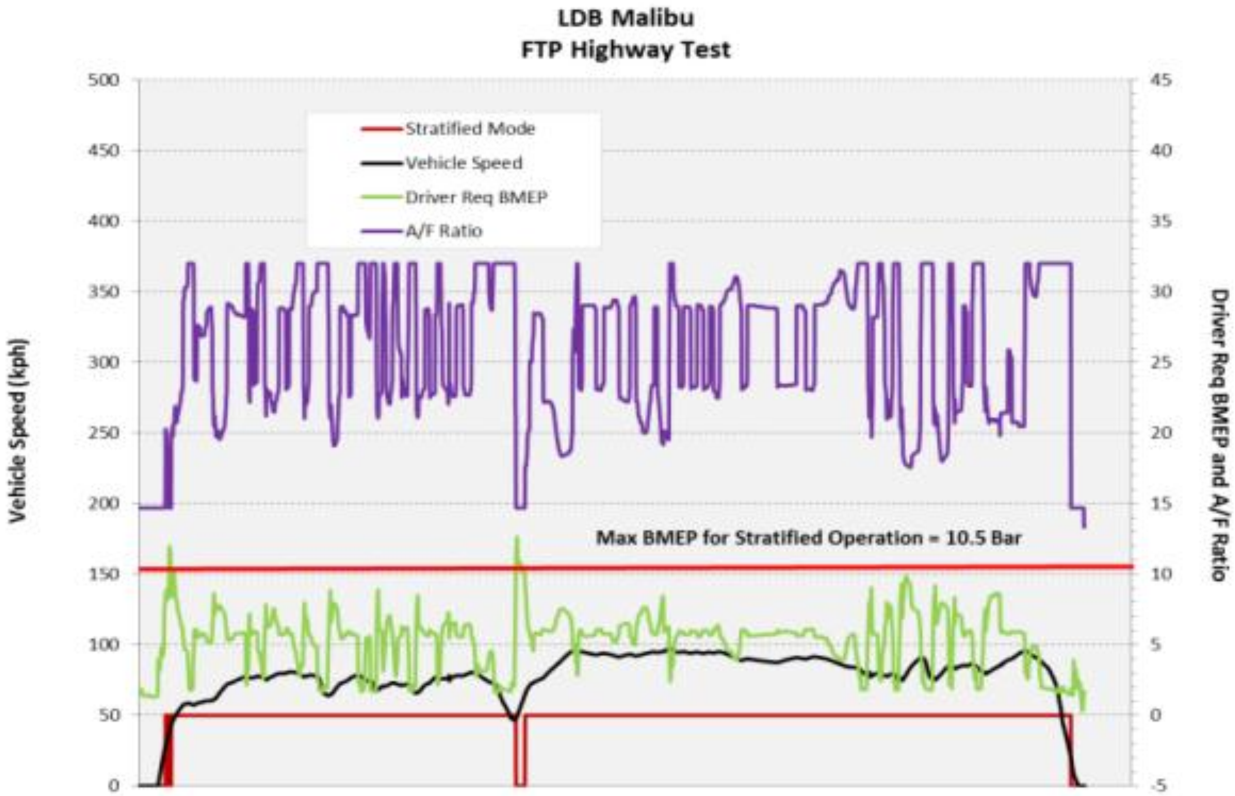

Figure 162: LDB FTP Highway Lean-Stratified Operation

For further details and discussion of the LDB fuel economy demonstration, refer to section 3.

At this point the decision was made to complete the DOE project. GM had demonstrated the fuel economy and emission potential of lean-stratified combustion and aftertreatment systems. During this project two lean-stratified combustion systems were developed, which required additional internal GM funding of nearly $3 million beyond the initial project award.

August 2013 was focused on developing vehicle calibrations to support the final vehicle demonstration with the DOE on August 28th, 2013 at GM Milford Proving Grounds in Milford, MI.

5. PRODUCTS DEVELOPED

- The 12V S/S system is now in production on the 2014 2.5L Chevrolet Malibu
- There are multiple thermal management projects within advanced engineering, all include some form of zero-flow concept
- Lean Stratified combustion system is on the GM roadmap for future engine architectures, and an analysis of CO_2 benefit vs. cost is being completed
- The Passive SCR system is being considered for alternative future combustion technologies that are capable of lean AFR with lower engine-out NOx
- A more complete understanding of control system complexity in a torque based structure is understood, and would serve as an initial point for future internal control systems
- Patents
    - Method and Apparatus For Ammonia Formation In a Catalytic Converter - US 8216521 B2
    - Catalyst Materials for NOx Oxidation in an Exhaust Aftertreatment System that uses Passive Ammonia SCR - US 8539760 B2
- Patent Applications
    - Passive Ammonia-Selective Catalytic Reduction For NOX Control In Internal Combustion Engines - US 12/576,412 - US 20100043402 A1
    - Passive Ammonia-Selective Catalytic Reduction for NOx Control in Internal Combustion Engines - US 12/430,825 - US 20100107606 A1
    - Method and apparatus for controlling operation of a spark-ignition direct-injection engine - US 12/330,587 - US 20100139248 A1
    - Technique for Production of Ammonia on Demand in a TWC for a Passive Selective Catalytic Reduction System - US 12/390,5 - US 20100212295 A1

6. ACCRONYMS

Acronym	Description
12V S/S	12 Volt Stop/Start System
A/F	Air Fuel Raito
A/T	Aftertreatment
ATM	Active Thermal Management
C & H	City & Highway
C02	Carbon Dioxide
CC	Close Coupled
COV	Coefficient of Variance
CCV	Coolant Control Valve
CO	Carbon Monoxide
Cold FTP	FTP-75 at 20C (ambient room temp)
COV	Coefficient of Variance
cpsi	cells per square inch
CR	Compression Ratio
DFCO	Deceleration Fuel Cut Off
DMS500	Cambustion Fast Particulate Spectrometer
DOE	Department of Energy
dP	delta Pressure
E39A	Continental ECM
ECE	Europe (ECE 15, urban drive cycle)
ECM	Electronic Control Module
EGR	Exhaust Gas Recirculation
EO	Engine-Out
EUDC	Extra Urban Driving Cycle (drive cycle)
Euro 6	European Union Emissions Standard
FC	Fuel Consumption (EU)
FE	Fuel Economy (US)
FELV	Fuel Economy Learning Vehicle
FTIR	Fourier-Transform Infra-Red (analyzer)
FTP-75	Federal Test Procedure 1975 (drive cycle)
G1 A/T	Generation 1 Passive Lean Aftertreatment
G2 A/T	Generation 2 Passive Lean Aftertreatment
G3 A/T	Generation 3 Passive Lean Aftertreatment
G4 A/T	Generation 4 Passive + Active Lean A/T
GMAC875	GM 875 Catalyst Aging Procedure
GM	General Motors LLC
GVRW	Gross Vehicle Weight Rating
H2	Hydrogen gas
HC	Hydrocarbons
HCHO	Formaldehyde
HDEV 5.x	Bosch Fuel Injector
HP	High Pressure
HWFET	Highway Fuel Economy Test (drive cycle)
IEM	Integrated Exhaust Manifold
IMEP	Indicated Mean Effective Pressure
LE2	GM 1.4L Stoichiometric Turbo Engine
LDV	Light Duty Vehicle
LE5	GM 2.4L NA PFI Ecotec Engine
LNT	Lean NOx Trap
LNV	Lowest Normalized Value
LVW	Loaded Vehicle Weight
MED17	Bosch ECM version 17
MED9	Bosch ECM version 9
MVEG-B	Motor **Vehicle** Emission Group Rev. B (See NEDC)
NEDC	New Euro Driving Cycle (urban/ECE at -7C + EUDC)
NA	Naturally Aspirated
NH3	Ammonia
NMEP	Net Mean Effective Pressure
NMHC	Non-Methane Hydrocarbons
NMOG	Non-Methane Organic Gases
NOx	Nitrogen Oxides
O2	Oxygen Gas
OBD	On Board Diagnostics
OSC	Oxygen Storage Capacity
PASS	Passive Ammonia SCR A/T System
PAASS	Passive + Active Ammonia SCR A/T System
PDA	Port Deactivation Assembly
PGM	Precious Group Metals
PM	Particulate Matter
R&D	Research & Development
RAT-H	GM Rapid Aging Test H (catalyst aging procedure)
RFG Tier2	Federal Reformulated Gasoline (sulfur ~<30ppm)
RPM	Revolutions Per Minute
SCR	Selective Catalyst Reduction
SESAM's	Sys. for Emission Sampling & Measurement
SG4	Spray Guided Engine version 4
SG5	Spray Guided Engine version 5
SIDI	Spark Ignited Direct Injected
SULEV	Super Ultra Low Emissions Vehicle
T2B2	EPA Tier Two Bin Two
TWC	Three Way Catalyst
UDC	Urban Driving Cycle (see ECE)
ULEV	Ultra Low Emission Vehicle
US06	Supplemental FTP (SFTP) (drive cycle)
WLTP	World Light-duty Test Procedure (drive cycle)
WOT	Wide Open Throttle
WRAF	Wide Ratio Air / Fuel Ratio