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The Use of Exhaust Gas Recirculation to Optimize Fuel Economy and Minimize Emissions in Engines Operating on E85 Fuel

Final Report

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EXECUTIVE SUMMARY

This report summarizes activities conducted for the project “The Use of Exhaust Gas Recirculation to Optimized Fuel Economy and Minimize Emissions in Engines Operating on E85 Fuel” under COOPERATIVE AGREEMENT NUMBER DE-FC26-07NT43271, which are as outlined in the STATEMENT OF PROJECT OBJECTIVES (SOPO) dated March 2007 and in the supplemental SOPO dated October 2010.

The project objective was to develop and demonstrate an internal combustion engine that is optimized for E85 (85% ethanol and 15% gasoline) fuel operation to achieve substantially improved fuel economy while operating with E85 fuel and that is also production viable in the near- to medium-term. The key engine technology selected for research and development was turbocharging, which is known to improve fuel economy thru downsizing and is in particular capable of exploiting ethanol fuel’s characteristics of high octane number and high latent heat of vaporization. The engine further integrated synergistic efficiency improving technologies of cooled exhaust gas recirculation (EGR), direct fuel injection and dual continuously variable intake and exhaust cam phasers. On the vehicle level, fuel economy was furthered thru powertrain system optimization by mating a state-of-the-art six-speed automatic transmission to the engine. In order to achieve the project’s objective of near- to medium-term production viability, it was essential to develop the engine to be flex-fuel capable of operating with fuels ranging from E0 (0% ethanol and 100% gasoline) to E85 and to use three-way type of catalyst technology for exhaust aftertreatment. Within these scopes, various technologies were developed through systems approach to focus on ways to help accelerate catalyst light-off.

Significant amount of development took place during the course of the project within General Motors, LLC. Many prototype flex-fuel engines were designed, built and developed with various hardware configurations selected to achieve the project goals. Several flex-fuel demonstration vehicles were designed and built for carrying out calibration development and final testing to quantify the technology merits.

Based on the extensive test results collected from dynamometer and vehicle testing, the fuel economy benefits of cooled EGR from the intended level of turbocharger technology were quantified. When combined with turbo downsizing, the FE benefits are considered large enough for E0 fuel as well as for E85 fuel to warrant further development of the technology beyond the current proof-of-concept level to a level that can meet production driveability quality and durability requirements in order to meet customers’ expectations.

Cold-start cart test results from the emissions segment of the project were positive, confirming the assumption of faster thermal response of turbo exhaust system for emissions reductions for both E0 and E85 fuels. Vehicle emissions test results directionally correlated to the cold-start cart findings. The limited number of test runs did demonstrate the potentials of meeting stringent emission standards, however, they did not comprehend the factors such as hardware variability and long-term durability,

which are essential for mass production to satisfy customers' expectations. It is therefore recommended, moving forward, durability concerns over turbocharger, EGR system and aftertreatment system, which would likely impact production viability, should be addressed.

The data moreover suggested that further FE increase is likely with turbocharger technology advancement.

ACCOMPLISHMENTS vs. OBJECTIVES

The main objective of this project is to demonstrate the capabilities of a flex-fuel turbocharged engine that utilizes EGR to achieve significant fuel economy benefit relative to a conventional naturally aspirated gasoline engine and thereby to develop a highly optimized flex-fuel engine solution that is capable of introduction in the US in the near- to medium-term. The engine and control strategies developed must be consistent with current and future emissions legislation and competitive with alternate technologies. The project embodies two main segments: assessment of the fuel economy benefits of EGR and the effects of turbocharging on emissions compliance. These efforts were aimed at maximizing the probability that propulsion systems designed to optimize the use of E85 fuel will be capable of meeting impending Super Ultra Low Emissions Vehicle (SULEV) requirements that will be necessary to enable broad commercialization.

The following is a list of accomplishments resulted from the development course of the project, for comparison to the project objectives.

Accomplishments:

- Developed simulation capabilities in modeling various steady-state and transient flow and heat transfer processes in turbocharged engines.
- Executed a vehicle simulation model to identify key fuel economy relevant engine operating conditions under various vehicle driving cycles.
- Down-selected the promising EGR architecture for downsized application for fuel economy, within the project scope of single-turbocharger architecture.
- Developed cooled low-pressure EGR system specifications.
- Designed, constructed and assembled prototype turbocharged engines featuring flex-fuel capability, cooled EGR, air-to-liquid charge cooling, integrated single- and twin-scroll turbo manifolds, and secondary air injection capability.
- Designed and integrated flex-fuel capable turbocharged demonstration vehicles featuring six-speed automatic transmissions.
- Investigated manufacturing processes for prototyping integrated turbo manifolds.
- Demonstrated cooled EGR operation in steady-state dynamometer and transient vehicle operation.
- Developed controls algorithms and calibrations required for managing cooled EGR for improving fuel economy and minimizing cold start emissions.

- Demonstrated fuel economy advantages of cooled EGR on the flex-fuel vehicle for both gasoline and E85 fuels for various driving cycles.
- Quantified fuel economy improvement potentials of the flex-fuel turbocharged powertrain:
  - Measured 11.3% improvement in US EPA certification composite fuel economy test cycles relative a powertrain option of nearly equal engine performance available in production for the same vehicle.
  - Predicted 13% improvement in US EPA certification composite fuel economy from dynamometer steady-state tests when the turbocharged engine was compared to a baseline engine of comparable engine performance.
- Demonstrated calibration refinement to achieve EGR vehicle driveability quality acceptable for development purpose, however, further refinement would be needed to become production viable to satisfy customers expectations
- Quantified cold start engine-out emissions reduction potentials of the aftertreatment technologies and turbocharger systems for E0 and E85 fuels on cold-start cart.
- Quantified tailpipe emissions of the flex-fuel turbocharged vehicles, although further reductions from the demonstrated levels would be needed to become viable for production to meet the required durability:
  - Demonstrated the potential of meeting the impending LEV III SULEV30 standard for E0 fuel
  - Demonstrated the potential of meeting the impending LEV III ULEV50 standard for E85 fuel
- Although not included in the SOPOs as a deliverable for this project, determined through analysis the required technologies to extend EGR usage beyond the engine operating ranges which were demonstrated in this project. These technologies will serve as the basis for future projects.

Based on this list of accomplishments, the deliverables of the original as well as the supplemental SOPOs were met by developing production-viable flex-fuel powertrain technologies required to improve vehicle fuel economy and emissions characteristics when operated on E85 fuel by demonstrating such technologies on engine dynamometer and cold-start cart and further in vehicles with transient operation.

DETAILED ACTIVITIES AND RESULTS SUMMARY

The following is a more detailed summary of the activities, approaches used in executing the tasks and results for each of the four project phases

Phase 1 – Applied Research

In this first phase, several simulation and analysis tools were used to determine the component and system requirements of the engine systems, which included specifications for EGR valve, EGR cooler, exhaust turbocharger and aftertreatment system. The tools used included one-dimensional engine performance simulation GT-Power, an in-house vehicle simulation model, CFD (computational fluid dynamics), conjugate heat transfer analysis, and MS Excel spreadsheet.

Some of the analyses performed for the EGR segment included EGR valve and cooler sizing for high- and low-pressure EGR system for a single-turbocharger architecture, EGR flow ranges for high- and low-pressure EGR system, EGR architecture down-selection for downsized application, transient behaviors of EGR flow under a step change in engine throttle, and turbocharger matching in order to extend EGR usage to the entire engine operating ranges.

Some of the analyses performed for the SULEV segment were exhaust flow passage optimization to minimize cylinder-to-cylinder flow variability, turbocharger wastegate passages and housing design optimization to even flow distribution at the catalyst inlet, heat losses in turbocharger exhaust system, system design optimization for meeting air fuel ratio imbalance diagnostics requirements and EGR architecture down-selection for engine cold start conditions.

The analyses conducted in this initial phase of the project generated results which served as a comprehensive knowledge base for further execution of the tasks in the subsequent phases required to complete the project successfully.

Phase 2 – Exploratory Development

In the exploratory development phase of the project, technology variants evaluated in the first phase of applied research were first reviewed and down-selected and then prototype engines were designed and built to the specifications to allow initial evaluation of the concepts.

For cooled EGR implementation, the analysis results clearly identified, for the intended single twin-scroll turbocharger architecture, a low-pressure EGR system as the primary development focus because of its capabilities in providing EGR flow over a broader engine operating range than a high-pressure system. Once the EGR architecture down-selection was accomplished, efforts were spent to develop specifications for the low-pressure EGR system, with emphasis on system optimization to also address EGR transient concerns commonly associated with a low-pressure system. Specifically, an air-to-liquid charge cooling system was favored since it could be packaged in close proximity to the engine, which resulted in a compact system that not only could enable better EGR transient response, compared to a frequently used air-to-air system, but also packaged well in the engine compartment.

A turbocharger system, along with relevant exhaust and intake components, was designed to integrate all the preferred EGR attributes into a compact engine. The engine was further mated to a state-of-the-art six-speed automatic transmission by designing all the necessary changes for powertrain integration. The turbocharged powertrain was then packaged in a 2011 Chevrolet Equinox, which was also updated to incorporate the required attribute of flex-fuel.

The turbochcarger exhaust system design was further expanded into three discrete emissions enabling systems. The first emissions enabled turbocharger was similar to the baseline design with the exception that the wastegate passage diameter was significantly increased to approximately twice of that of the baseline unit to facilitate higher exhaust mass flow bypassing the turbine wheel thus eliminating thermal loss into the turbine wheel and conserving energy to flow downstream to the exhaust aftertreatment system. For this particular unit, the design of the flow passage through the turbine wheel had to be compromised, which was considered as acceptable for this proof-of-concept work. The other two emissions enabled turbocharger designs each had its turbine housing integrated to the respective bifurcated exhaust manifold with the goal to conserve thermal energy downstream to the directly mounted catalyst by reducing the thermal sink capacity of the turbocharger and exhaust manifold assembly. These two turbocharger manifolds were different mainly in the turbine scroll design in that one had a more widely used single scroll style while the other maintained the baseline turbocharger’s twin scroll design to preserve the higher performance potential but still yield, thru integration, opportunities for efficient exhaust gas transport and thermal management downstream to the aftertreatment system.

The aftertreatment system included a secondary air injection (SAI) system, two close-coupled catalysts arranged in series, and an under-floor catalyst. SAI was implemented by designing supply air passages in the cylinder head to feed air to the selected individual exhaust ports at locations as close to the exhaust valves as possible to provide sufficient mixing time between air and unburned hydrocarbons for proper reactions prior to arrival at the catalyst inlet. The SAI system further comprised air pump, control solenoid valve and air supply ducts. The arrangement of the two close-coupled catalysts had the first one mounted directly to the integrated turbo manifold at the turbine housing exit and the second one positioned in series downstream of the directly mounted catalyst to meet packaging requirements in the vehicle. This arrangement of the catalysts provided much of the flexibilities for testing different catalyst sizes, substrate configurations and precious group metal loadings. The integrated turbocharger manifolds, along with the aftertreatment system, were designed to package in the demonstration vehicle of 2011 flex-fuel Buick Regal.

Change parts were procured and prototype engines built to allow initial development of both segments of cooled EGR and SULEV of the project. The tests conducted in this phase included evaluation of cooled EGR benefits to engine thermal efficiency on a dynamometer under steady-state conditions and evaluation of impacts of different turbocharger design elements, catalyst configurations and calibration strategy to engine-out emissions during the cold start portion of the EPA FTP (Federal Test Procedure) cycles on a cold-start cart.

The SULEV portion of the project required significant development in this phase to prototype turbocharger hardware. In addition to the attributes which had been identified for integration of turbine housing and exhaust manifold by the analyses carried out in the previous phase and tests conducted in this phase, it was determined to reduce wall thickness to further reduce mass and, potentially, cost beyond what could be achieved just through integration. This portion of development of casting exhaust components was conducted by leveraging the expertise of Metal Casting Technology, Inc., a joint venture between General Motors and Hitchiner Manufacturing Co.

Extensive tests were conducted with both E0 and E85 fuels on a dynamometer under steady-state conditions. The steady-state dynamometer testing focused on engine efficiency improvement in the engine operating ranges covering different driving conditions. The measured results were used, in combination with vehicle simulation results, to project fuel economy potentials of cooled EGR when implemented on this downsized turbocharged powertrain.

Extensive tests were also conducted with both E0 and E85 fuels on a cold-start cart which emulated the transient warm up process of the engine. Cold-start cart testing focused on the cold start region of the FTP-75 driving cycle only – approximately the first 20 seconds of the cycle. The measured results were used to project hydrocarbons reduction potentials of the turbocharger designs as well as the aftertreatment configurations.

Cold-start cart testing of the enhanced base system with the larger wastegate valve size showed higher temperatures at the catalyst inlet and lower tailpipe hydrocarbons. This result was very encouraging because it demonstrated directionally correct thermal benefits for aftertreatment catalyst operation.

In spite of its promising thermal benefits for aftertreatment catalyst operation, the large wastegate passages design poses several implementation challenges. First, it can affect turbine housing design by compromising the flow through the main passage consisting of the turbine wheel and, consequently, engine performance and engine downsizing potential. Second, the overall turbine housing becomes larger and heavier compared to the base unit, which can reduce the thermal benefit potentials of the concept and have negative impacts to cost and packaging. Third, the large wastegate valve poses challenges to available actuation technology to achieve desired function of the valve, which can further impact cost and vehicle packaging. Since the objective of this proof-of-concept work was to facilitate a "big picture" evaluation of the system concept thereby no further development was carried out along this path. Instead, the focus was on the development of integrated systems.

During the course of the preliminary testing conducted in this phase to establish the potentials of the various efficiency and emissions improvement technologies, engine control systems with required capabilities were developed and preliminary calibrations required for the later phase of vehicle development were also established for both cooled EGR and SULEV segments.

Phase 3 – Advanced Development

Following review of the encouraging steady-state dynamometer results suggesting substantial fuel economy benefits by combining cooled EGR to the downsized turbocharging application, the powertrain design was further refined to package in a 2010 Chevrolet Equinox so the vehicle could be used in the subsequent phase of engineering development of vehicle calibration and vehicle testing to confirm the projected fuel economy benefits. The final design also incorporated any recommendations generated from the dynamometer testing. In addition, flex-fuel capability was finalized for the demonstration vehicle to allow the engine to operate from E0 to E85.

Similarly, the designs of emissions enabled turbocharger and aftertreatment systems went through refinement by incorporating cold-start cart test recommendations and were updated for the SULEV demonstration vehicle of 2011 flex-fuel Buick Regal.

It was decided to build two separate SULEV demonstration vehicles, with GM internally funding one of them, in order to expedite the development. The two SULEV vehicles each featured a separate integrated turbocharger exhaust system, but were otherwise identically equipped.

After the design freeze, a set of computer-aided design models and drawings were created for all modified engine, transmission, and vehicle components. A list of all change parts was created to facilitate procurement of these components and later engine, transmission and, vehicle builds. Multiples engines of identical contents were built – typically one for each vehicle and the others for dynamometer or cold-start cart for initial calibration development and later calibration verification.

Controls integration was further developed for the turbocharger system equipped with the cooled low-pressure EGR system to provide the capabilities of accurate estimations of EGR flow and engine torque. In addition, capabilities were developed to properly address dynamic interactions between boost scheduling and EGR effects during engine transient maneuvers.

Further SULEV cold-start cart development tests were conducted using E0 fuel with the integrated turbocharger manifolds. In summary, the tailpipe hydrocarbon emissions accumulated during the first 20 seconds from engine start correlated with the catalyst inlet temperatures. Consequently, among the turbocharger configurations studied, good correlations were observed between the accumulated tailpipe hydrocarbon emissions and the wetted surface area of each of the turbocharger exhaust systems. The dependency of the accumulated tailpipe hydrocarbon emission to the wetted surface area was found to be also a function of the secondary air injection strategy, with reduced sensitivities when secondary air was turned on during cold start.

Testing was further conducted on the cold start cart with E85 fuel. In general the accumulated tailpipe hydrocarbon emission was about twice of that of E0 fuel. This is due to the fact that disproportionally more enrichment was required for E85 than for E0 during cold start in order to produce ignitable mixtures in the vicinity of spark plug gap due to the following differences in the properties between the two fuels

- Lower stoichiometric air fuel ratio of 9.8 for E85, as opposed to 14.3 for E0
- E85 fuel's higher latent heat of vaporization

This was further complicated by E85 fuel's lower LHV (lower heating value). The net result was 50-100 degree C lower temperatures at the catalyst inlet at 20 seconds from engine start with E85 compared to E0 fuel.

Normally, secondary air is a strategy that can be used to increase the catalyst temperature during cold start. However, this was not always achievable with E85 fuel because the colder exhaust gas temperature from E85 cold start resulted in minimum gas phase oxidation reaction in the exhaust stream so the catalyst temperature could get colder due to the dilution effect of the extra air from the secondary air pump. This challenge was clearly illustrated by the cold-start cart data.

Cold-start cart testing was then progressed to evaluation of the potentials of EGR for cold-start emissions control. As determined in the earlier phase, a low-pressure EGR architecture was selected for the cold-start conditions for its flexibility in supplying expected EGR rates at such conditions than a high-pressure system. The cold-start cart was further set up with an exhaust backpressure valve to provide the needed flexibility in EGR flow control.

Since the engine was generally operated near combustion stability limits during cold start even without EGR as the cylinder charge was diluted by internal residuals, the maximum amount of EGR that could be added to the engine was only 15%. The EGR sweep test indicated it would take about 10 seconds for the EGR level in the intake manifold to reach 90% of the target EGR rate of 15%. This transport time is considered relatively long compared to the catalyst light-off time target of 20 seconds.

The measured engine-out and tailpipe hydrocarbons at 20 seconds from engine start did not show significant variations with EGR for EGR rates up to about 12%. At 17% EGR, both engine-out and tailpipe hydrocarbons more than doubled, suggesting the total dilution in the cylinders had exceeded the levels the combustion system could tolerate. This set of cold-start cart tests did not identify EGR advantages for cold start.

Phase 4 – Engineering Development

In this phase of development, cooled EGR and SULEV demonstration vehicles were developed and tested under various driving conditions. For fuel economy comparison, the cooled EGR vehicle was tested for FTP-75, Highway, and US06 cycles and, for tailpipe emissions comparison, the SULEV vehicles were tested for the standard FTP-75 cycles. For each test cycle, each vehicle was tested with both E0 and E85 fuels so the vehicle results could be compared to, at least in trends, to the dynamometer or cold-start cart results obtained in the earlier phases of the porject.

To quantify the effects of cooled EGR alone, the same vehicle was tested with and without EGR. The limited number of tests showed improvements of 1.5% for FTP-75, -0.6% for Highway and 3.4% for US06 cycles for E0 fuel and 1.2% for FTP-75, 1.8% for Highway and 2.6% for US06 cycles for E85 fuel. All tests except for Highway with E0 fuel showed FE improvements with EGR, which is consistent with the dynamometer measurements in the earlier phase of the project. The fuel economy improvements from cooled EGR were larger for more aggressive driving conditions like US06. The vehicle results further confirmed the finding from earlier dynamometer testing that E85 fuel, in spite of its high latent heat of vaporization, can also benefit from cooled EGR as does E0 fuel.

The marginal decrease in FE with EGR for Highway with E0 was the only outlier and was probably due to the premature nature of the calibration. It is expected that with further calibration development, the FE improvement would be more in line with that measured for E85 fuel. Therefore, it would be appropriate to conclude a FE gain of 1.5% for the composite cycles for the cooled EGR technology.

Quantification of the overall FE gain was first made in the second phase of the project by following the semi-analytical procedure of using steady-state dynamometer data collected at selected engine conditions to project the vehicle fuel economy. This procedure predicted a composite FE gain of about 13% when compared to a naturally aspirated engine of comparable engine technology contents but with its displacement sized to produce similar performance as the turbocharged engine. Such comparison could not be made for the demonstration vehicle due to the lack of such baseline naturally aspirated engine for this class of vehicle. Therefore, the comparison was made to a production naturally aspirated powertrain option that had slightly lower peak torque than the turbocharged engine. As expected, the composite FE gain became 11.3%, mainly due to the slightly undersized baseline engine.

At the current level of calibration, the overall driveability rating of the cooled EGR demonstration vehicle was judged to be slightly inferior to the production quality that GM would consider as acceptable in meeting customers’ expectations. However, the FE benefits are considered large enough for E0 fuel as well as for E85 fuel to warrant further development of the technology beyond the current proof-of-concept level to a level that can meet production driveability quality and durability requirements.

The SULEV demonstration vehicle test results were very positive as well, in spite of the project scope of stoichiometric three-way catalyst technologies only. To illustrate the benefits of the integrated turbocharger exhaust concept, the combined emissions of NMOG and NOx with E0 fuel from the integrated twin-scroll turbocharger vehicle were reduced, as expected from the cold-start cart experience, by 17% compared to the production vehicle using a similar turbine scroll design. The measured tailpipe emissions with E0 fuel met the impending LEV III SULEV30 standard, although the margins are considered still insufficient as the required for long-term durability of the aftertreatment system is factored into consideration.

With E85 fuel, tailpipe hydrocarbon emissions became higher relative to E0 fuel. The NOx trend depended on the calibration strategy. Overall, the combined emissions of NMOG and NOx became higher by 40-60% relative to E0 fuel. Therefore, at the current level of development, the measured tailpipe emissions with E85 fuel can be concluded as only meeting the impending LEV III ULEV50 standard.

PROJECT PRODUCTS

Properties resulted from the development during the course of the project include computer-aided design data, analysis data, engine test data, vehicle test data, engine and vehicle hardware, and intellectual properties as listed below.

<u>Intellectual Properties</u>

1. “An Exhaust Gas Recirculation System and Its Operation,” Ko-Jen Wu, DOE S-119,971
2. “Integrated Exhaust Gas Recirculation and Charge Cooling System and Its Operation,” Ko-Jen Wu, DOE S-119,972
3. “Boosting Devices with Integral Features for Recirculating Exhaust Gas,” Ko-Jen Wu, DOE S-122,151
4. “Integrated Cooling System for Boosted Engines Employing Recirculated Exhaust Gas,” Ko-Jen Wu, DOE S-122,668
5. “Secondary Air Injection System for Twin-Scroll Turbocharged Engines,” Ko-Jen Wu and Darrel Walter, DOE S-122,866
6. “Boosting Devices with Integral Features for Recirculating Exhaust Gas,” Ko-Jen Wu, DOE S-126,059
7. “Integral Twin-Scroll Turbine Housing and Manifold,” Ko-Jen Wu, Rodney Baker and Darrel Walter, DOE 126-277
8. “Exhaust Valve Control Method for Accelerating Catalyst Light-off,” Ko-Jen Wu and Judy Jin, DOE S-126,840