Demonstration of a Verification-ready, Retrofittable Dual-loop EGR System for NO_x Reduction without Aftertreatment

Task 4 Deliverable Report

for:

New Technology Research and Development Program

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Submitted by:

QuantLogic Corporation
In collaboration with: Houston Advanced Research Center

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Abstract/Executive Summary

This project will develop a technology much needed for reducing nitrogen oxide (NO_x) and particulate matter (PM) emissions from heavy-duty trucks, especially drayage trucks used in Texas ports and rail terminals. Drayage trucks are significant emissions sources for ports and rail terminals around the nation. However, the current United States Environmental Protection Agency (EPA) or California Air Resources Board (CARB) verified technologies for NO_x reduction are mostly urea selective catalytic reduction (SCR) based. The urea-SCR technologies, no matter under retrofit or first fit, are not effective for drayage cycles because they are unable to maintain SCR light-off temperature. Exhaust gas recirculation (EGR) is the most effective way to reduce engine-out NO_x emissions through reducing engine combustion temperature which contributes to lower NO_x emissions.

Traditional high pressure loop EGR method tends to increase smoke emissions especially at high engine loads. Alternative combustion modes with high EGR rates from an advanced EGR system have shown to be being more effective in NO_x reduction.

The effectiveness of advanced Dual Loop EGR system for retrofit drayage truck application has been demonstrated by the investigators in a previous New Technology Research and Development (NTRD) grant project with 50% NO_x reduction over light to medium loads under steady-state conditions without any fuel penalty.

The benefits of this proposed project include a fully developed dual loop EGR system and demonstration over the full engine speed and load range including transient conditions with a 50% NO_x reduction goal over light to medium loads for drayage truck applications. The complete dual loop EGR system will be implemented on the target vehicle for mileage accumulation and durability demonstration for future verification purpose.

Introduction / Background

Drayage trucks are significant emission sources for Texas ports. However, urea-SCR retrofit technologies are not effective for drayage cycles because they are unable to maintain SCR light-off temperature. Exhaust gas recirculation (EGR) is the most effective way to reduce engine-out NO_x emissions through reducing engine combustion temperature which attributes to high NO_x emissions. Traditional high pressure loop EGR method tends to increase smoke emissions especially at high engine loads. Alternative combustion modes with high EGR rates from an advanced EGR system have shown to be being more effective in NO_x reduction.

The effectiveness of advanced Dual Loop EGR system for retrofit drayage truck application has been demonstrated by the grantee in a previous NTRD project with 50% NO_x reduction over light to medium loads under steady-state conditions without any fuel penalty.

In the new project, the dual loop EGR system will be fully developed and demonstrated over the full engine speed and load range including transient conditions with a 50% NO_x reduction goal over light to medium loads for drayage truck applications. The complete dual loop EGR system will be implemented on the target vehicle for mileage accumulation and durability demonstration for future verification purpose.

Project Objectives / Technical Approach

The objectives for this work are to: develop a drayage truck retrofit dual-loop EGR system resulting in at least 50% NO_x reduction under light to medium load without after-treatment, and demonstrate the prototype retrofit on a drayage truck to begin accumulating hours in preparation for verification testing.

Tasks

The following seven tasks are identified in the Grant Activities (Scope of Work):

- Task 1: Procure Components,
- Task 2: Set up engine retrofit and engine control systems,
- Task 3: Steady-state engine calibration and emissions testing,
- Task 4: Transient control strategy development and testing,
- Task 5: Transient emissions tuning and testing,
- Task 6: Vehicle installation of retrofit,
- Task 7: Reporting.

The Task 4 accomplishments are summarized below.

Task 4

From the Grant Activities (Scope of Work):

> *Task 4: Transient Control Strategy Development and Testing*
>
> *2.4. Task Statement: The PERFORMING PARTY will develop and test an engine control strategy which can smoothly adjust the EGR to the target NOx emission reduction levels during transient engine operation without noticeable impact to the engine operation.*
>
> *2.4.1. Control strategy development*
>
> *2.4.1.1. The PERFORMING PARTY will develop an engine control strategy which can smoothly adjust the high and low pressure loop EGR or a combination of both EGRs to the target NOx emission reduction levels during transient engine operation without noticeable impact to the engine operation. The control strategy will include functions to address the coupling of EGR with boost, as well as coupling of high and low pressure loop EGR. The PERFORMING PARTY will also improve the control models.*
>
> *2.4.2. Control strategy tuning*
>
> *2.4.2.2. The PERFORMING PARTY will test and tune the developed transient engine control strategy for the dual loop EGR system over various transient operation conditions, including step transients of speed and load between ESC 13-mode test points as well as over FTP test cycle.*
>
> *2.4.3. Schedule: The PERFORMING PARTY shall complete this task within 18 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.4.4. Deliverables: The PERFORMING PARTY shall submit a report to TCEQ upon completion of this task. This report will include but is not limited to the tuned transient engine control strategy ready for emissions testing and demonstration.*
>
> *2.4.5. Approval to Proceed with Further Tasks: The TCEQ will determine whether additional tasks will be approved and funded depending upon the success of completing this task. No additional funding will be provided under this Agreement unless the PERFORMING PARTY receives written approval from the TCEQ to proceed with further tasks.*

The transient control strategy development and testing have been completed and the task goal (test and tune the developed transient engine control strategy for the dual loop EGR system) were achieved.

Transient engine control strategy was developed in Matlab/Simulink which consists of the following major modules:

- sensor (smart sensor) inputs,
- fuel injection control (injection mass and timing),
- fuel pressure control (by oil rail pressure),
- boost control of variable geometry turbocharger,

- high pressure and low pressure EGR controls, and
- calibration communication,

Each module of the control strategy was first simulated and verified in Matlab/Simulink environment (software simulation) and then each module was flashed into the Open-ECU (Engine Control Unit) to be verified with real hardware. **Error! Reference source not found.** in Appendix A shows a snap shot of the engine control strategy implementation under Matlab/Simulink. Figure 1 shows the hardware setup of verifying low pressure loop EGR control.

Figure 1. Hardware setup for Open ECU and low pressure EGR valve

Low pressure loop EGR valve is controlled by H-Bridge circuitry. The algorithm of the controller of the low pressure loop EGR is based on Proportional-Integral-Differential (PID) approach. The parameters (P, I, D) were tuned to provide quick and accurate response of the low pressure loop EGR as shown in **Error! Reference source not found.** in Appendix A.

High pressure loop EGR valve is a CAN based smart actuator which means it is controlled by sending a command through CAN 2.0 communication protocol.

After the high pressure loop EGR control strategy was developed and simulated in Matlab/Simulink, it was verified in the hardware level as shown in Figure 2.

Figure 3 shows the actual command and position feedback by the EGR valve.

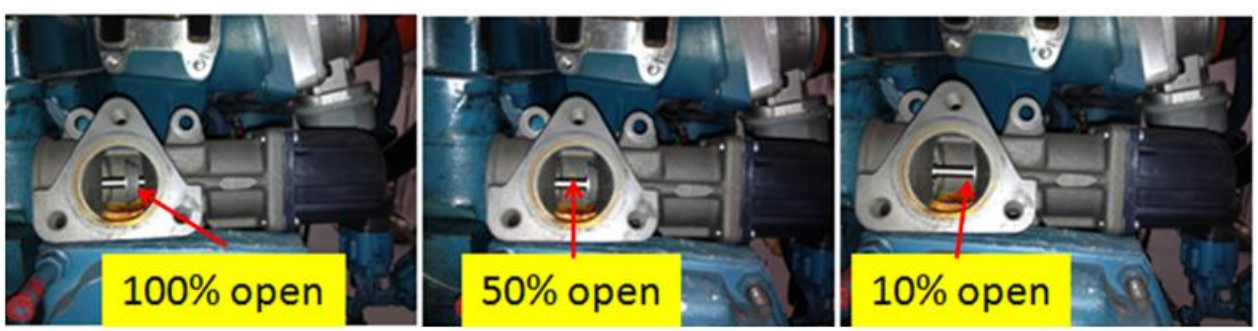

Figure 2. High pressure EGR control verification by Open-ECU

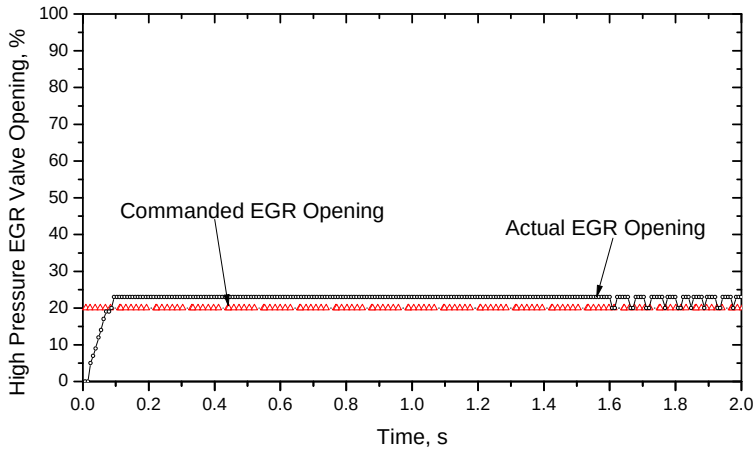

Figure 3. High pressure EGR valve commanded and actual opening

VGT is controlled by a varying duty cycle signals from the Open-ECU as shown in **Error! Reference source not found.** in Appendix A. By changing the duty cycle with PID feedback control of the boost pressure sensor, the desired boost pressure is achieved.

For fuel injection control, because the target test engine is equipped with G29 fuel injector as shown in Figure 4, two solenoids are used for each injector.

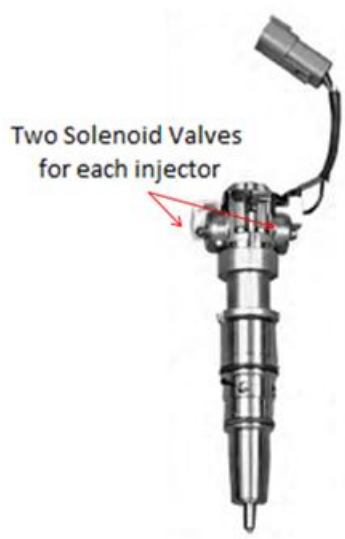

Figure 4. G2.9 fuel injector used in the International DT570 test engine

This requires twelve injector drivers for this six cylinder engine. Two six cylinder injector drivers are used to control the engine. Figure 5 shows the logic of generating two injector drive pulses from one fuel injection command which is used in rapid prototyping engine control system. As shown in Figure 5, for

each normal injection pulse (Command for fuel injection event), two injector drive pulses will be generated to open the respective solenoids as shown in

Figure 4.

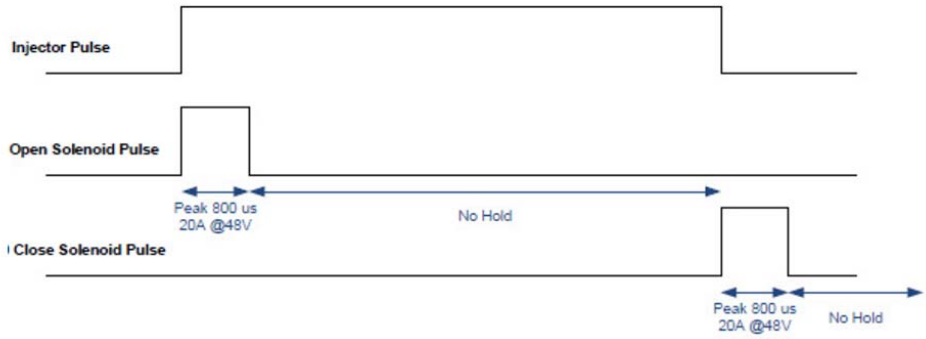

Figure 5. G29 injector driver output illustration. Line 1 shows a normal injector command from OpenECU. Line 2 and Line 3 show modification of injector drivers to provide two outputs for one injection event.

A special circuitry was designed to accomplish the driver control method as shown in Figure 5. A printed circuit board was made as shown in Figure 6.

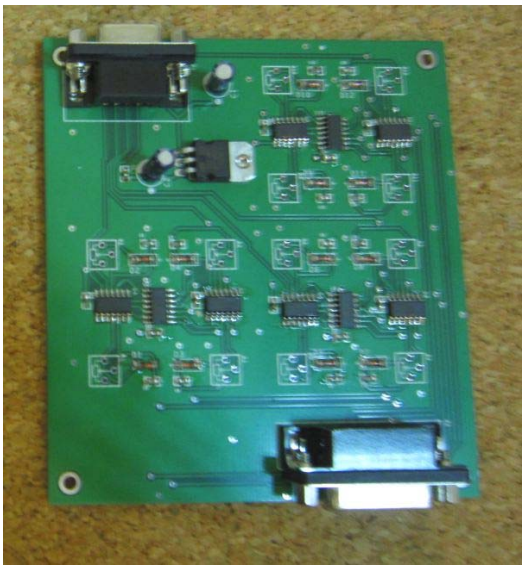

Figure 6. PCB of the circuit for generating two solenoid control signals from one fueling command pulse

Two parameter reconfigurable injector drivers (RID) were set at 20 Amp peak injection current to match the original engine manufacturer (OEM) injector driver pattern. The hardware-in-the-loop (HIL) test setup is shown in **Error! Reference source not found.** in Appendix A. And **Error! Reference source not found.** in Appendix A shows the configuration screen of the injector driver. **Error! Reference source not found.** in Appendix A shows results of the real injector control with the Open-ECU, RID and injectors. The injection command pulse was output from the Open-ECU who was synchronized with the simulated engine crank and CAM signals. The resulting injector driver current trace can be found in **Error! Reference source not found.** in Appendix A.

The test engine's crank and cam sensors are of variable reluctant (VR) type. A VR-to-Transistor-Transistor Logic (TTL) signal converter printed circuit board (PCB) as shown in Figure 7 was made to convert the mill-volt signals into TTL signals which can be used by the Open-ECU hardware.

The injector control hardware and software was verified in the test cell as shown in Figure 8. As shown in **Error! Reference source not found.** in Appendix A the resulting injector driving current trace is similar to the OEM current traces in the uprising phase and peak current phase. This demonstrated full control of the fuel injectors.

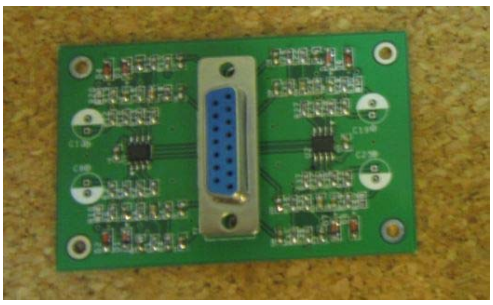

Figure 7 VR to TTL converter designed

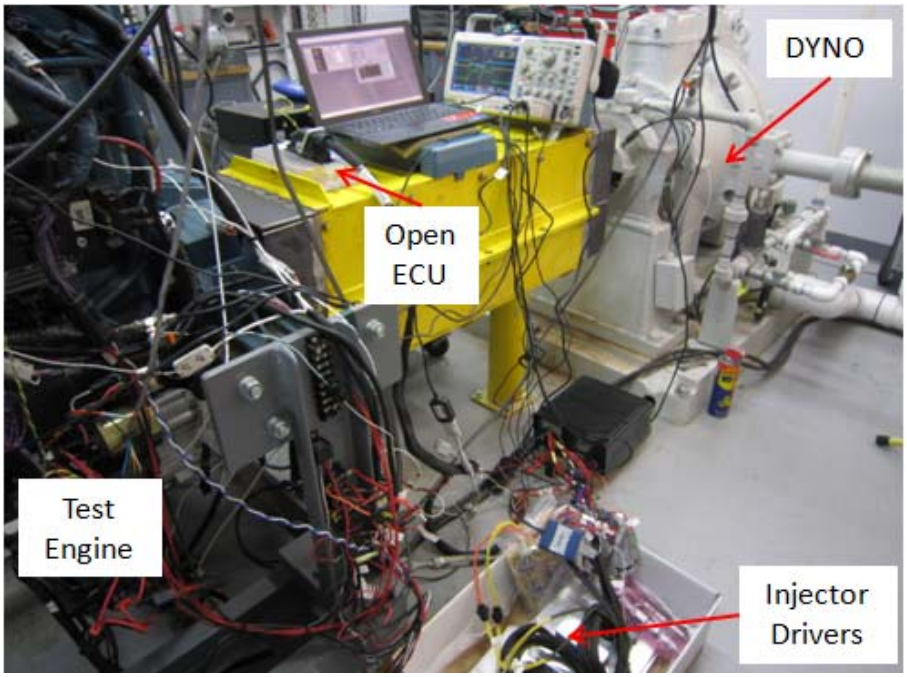

Figure 8 Injector control testing setup

The developed transient engine control strategy was tuned for the dual loop EGR system over various transient operation conditions, including step transients of speed and load between ESC 13-mode test points as well as over the FTP test cycle.

High pressure loop EGR and low pressure loop EGR controllers were tuned to be able to maintain low NO_x emissions during the transients including fast changing step transient. **Error! Reference source not found.** in Appendix A shows the high pressure loop EGR and low pressure loop EGR valve transition and **Error! Reference source not found.** in Appendix A shows the NO_x emissions during the fast step transient between A50 and B50 modes. As demonstrated in **Error! Reference source not found.** in Appendix A, low engine-out NO_x emissions were achieved by controlling both high pressure loop EGR and low pressure loop EGR properly during transients.

Discussion/Observations

Objectives vs. Results

The goal of the Task 4 is to develop and test an engine control strategy which can smoothly adjust the EGR to the target NO_x emission reduction levels during transient engine operation without noticeable impact to the engine operation. This task should be completed within 18 months of the signed Notice to Proceed, or by December 8, 2012.

The transient control strategy development and testing have been completed and the task goal (test and tune the developed transient engine control strategy for the dual loop EGR system) were achieved. Each module of the control strategy was computer simulated and verified with real hardware. Dual loop EGR

control for transient was tuned to be able to maintain low engine-out NO_x emissions during transient operations including rapid step transients. All systems developed are functioning as expected.

Summary/Conclusions

The goals of the Task 4 have been accomplished according to revised project timeline. The test engine was initially run under the dynamometer to verify the proper operation of the test engine, engine control, and instrumentation of sensors and actuators. All systems installed are functioning as expected. Currently the project team is allocating more resources to the remaining tasks and also looking into condensing the schedule of Task 5 due to test lab schedule and maintenance at UH test center currently on-going.

The project is currently under Task 5: Transient emissions tuning and testing.

The overall project progress is on the revised schedule and within budget.

Acknowledgements

The principal investigators are grateful for the support from TCEQ project management team, especially for the guidance and many helps from Ms. Katherine Williams. QuantLogic is also grateful for the diligent work conducted by the team of Houston Advanced Research Center, and the kind help from International Trucks of Houston for part procurements.

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Appendices

Appendix A: Confidential Material

The information in this appendix was claimed by the grantee as Proprietary and/or Confidential. To view this information please contact the New Technology Research and Development program at:

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Or

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