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

Task 5 Deliverable Report

for:

New Technology Research and Development Program

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Submitted by:

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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 5 accomplishments are summarized below.

Task 5

From the Grant Activities (Scope of Work):

> *Task 5: Transient Emissions Tuning and Testing*
>
> *2.5. Task Statement: The PERFORMING PARTY will finalize the engine control parameters to achieve targeted emissions goal and emissions test the retrofitted engine.*
>
> *2.5.1. Transient Emissions Tuning*
>
> *2.5.1.1. The PERFORMING PARTY will tune the engine control parameters with dual loop EGR to achieve targeted emissions goal. The PERFORMING PARTY will finalize the engine control parameters such as fueling command, dual loop EGR settings, and boost to provide targeted NOx emissions reduction over the transient FTP test cycle.*
>
> *2.5.2. Transient Emissions Testing*
>
> *2.5.2.1. The PERFORMING PARTY will emissions test the dual loop EGR retrofitted engine on an engine dynamometer at the Houston Advanced Research Center's engine lab over the EPA Heavy-duty FTP test cycle.*
>
> *2.5.3. Schedule: The PERFORMING PARTY shall complete this task within 22 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.5.4. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task. This report will include but is not limited to the final set of engine calibration maps and control parameters for the control strategy and results of the transient emissions testing on the engine dynamometer.*

The transient emissions tuning and testing have been completed and the task goal (emissions tuning and testing for 50% NO_x reduction target) were achieved.

In this task, the EPA Federal Test Procedures (FTP) transient test cycle profile was implemented into the dynamometer controller. The ramp rate from test point to test point was tuned. A engine pedal proportional-integral-differential (PID) controller was designed and tuned.

The total EPA FTP test cycle consists of 1200 seconds with varying speed and torque profile specified in terms of the percent speed and percent torque of the rated engine speed and torque. This profile with the maximum engine speed and torque were used to generate a engine speed and torque profile respectively in terms of revolutions per minute (rpm) and foot-pound (ft-lb) which then can be used by the dynamometer controller and engine pedal controller.

Figure 1 shows that the tuned dynamometer controller and pedal controller were able to control the dynamometer speed and engine pedal (engine torque) in order to meet the EPA FTP test cycle profiles.

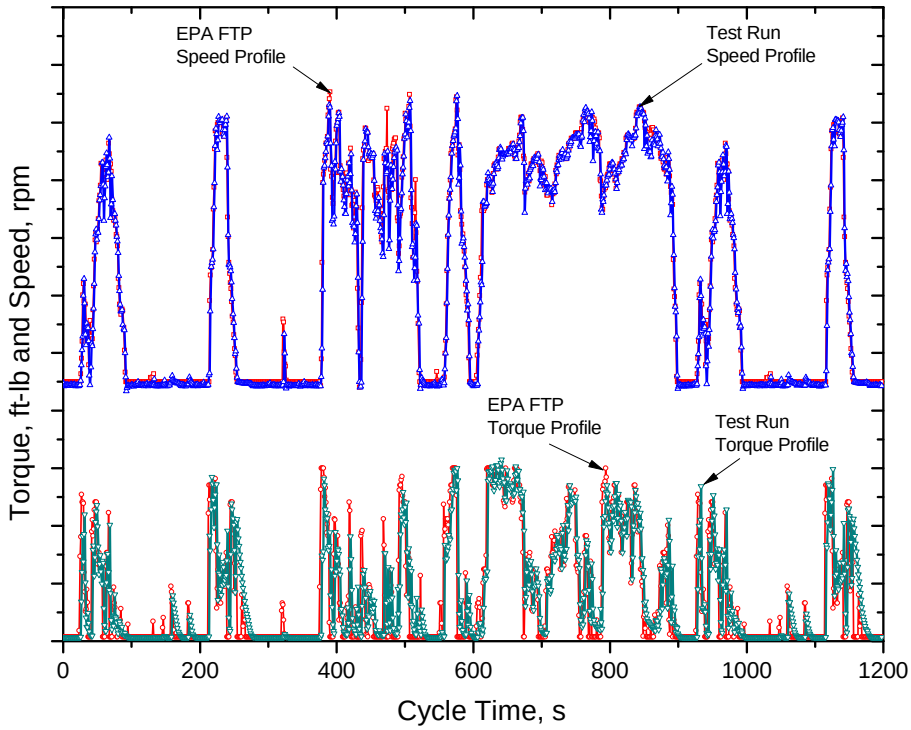

Figure 1. Comparison of EPA FTP test cycle speed/torque profiles and tuned dynamometer/engine speed/torque profiles

Before and during emissions testing, Navistar diagnosis software "ServiceMaxx" was used to make sure no error codes from the stock engine control unit exists. This is necessary to make sure the baseline and low pressure EGR retrofitted engine would run at normal conditions.

The emissions benefit of dual loop EGR system over transient FTP test cycle was demonstrated by results in Figure 2, Figure 3, and Figure 4. Figure 2 shows the engine out NO_x emissions reduction in parts per million (ppm) units with dual loop EGR and Figure 3 shows the intake fresh air flow rate reduction by introduced the low pressure loop EGR. Figure 4 shows that the fuel flow rates from the baseline and with low pressure loop EGR were very similar which explained the no fuel penalty result.

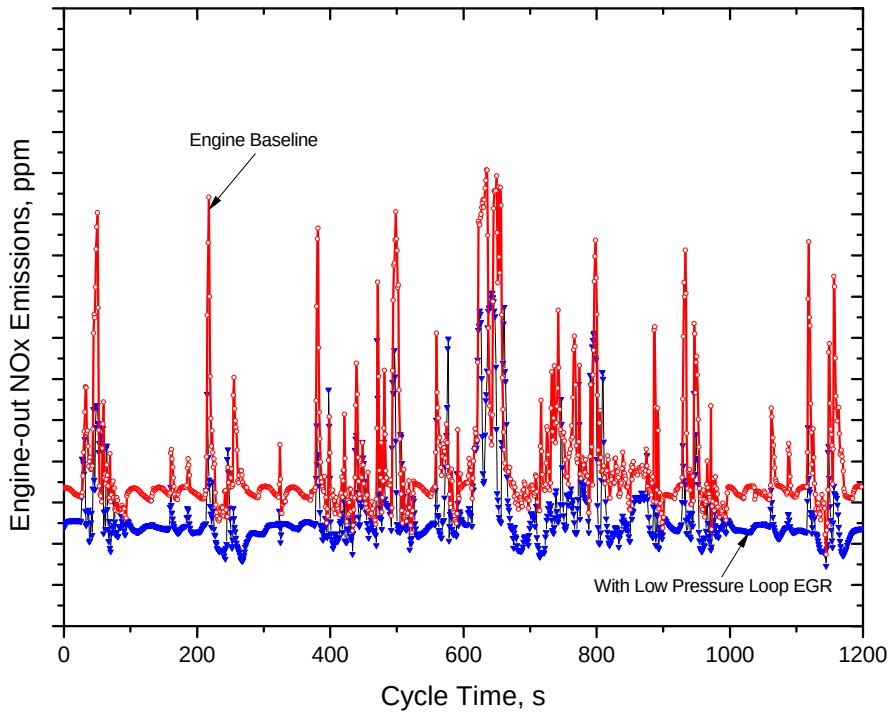

Figure 2. Engine-out NO_x emissions reduction with low pressure loop EGR over EPA FTP test cycle

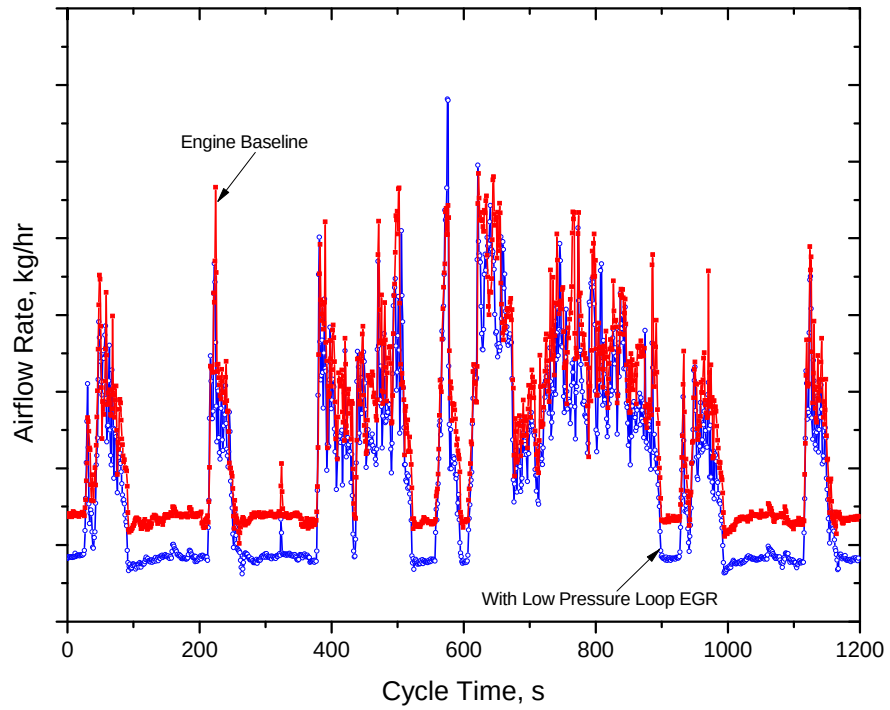

Figure 3. Intake fresh air reduction by low pressure loop EGR over EPA FTP test cycle

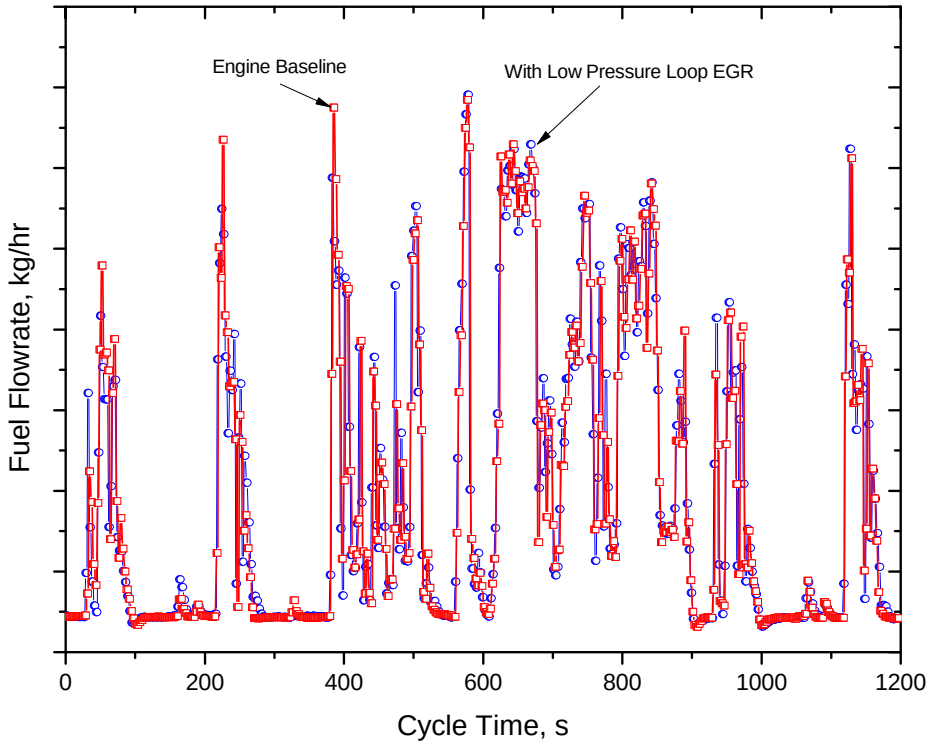

Figure 4. Fuel flow rate comparison between baseline engine and with low pressure loop EGR over EPA FTP test cycle

The compounded effects of exhaust flow rate reduction (due to air flow rate reduction by low pressure loop EGR) and the engine-out NO_x concentration reduction led to the final near 50% significant tailpipe NO_x reduction. \

Multiple transient emissions FTP test cycles for the baseline and the retrofitted system were conducted. The control parameters were tuned to achieve the project goal of 50% NO_x reduction without fuel penalty compared with baseline engine configuration. Figure 5 and Figure 6 show the cycle speed and torque traces of the FTP tests conducted.

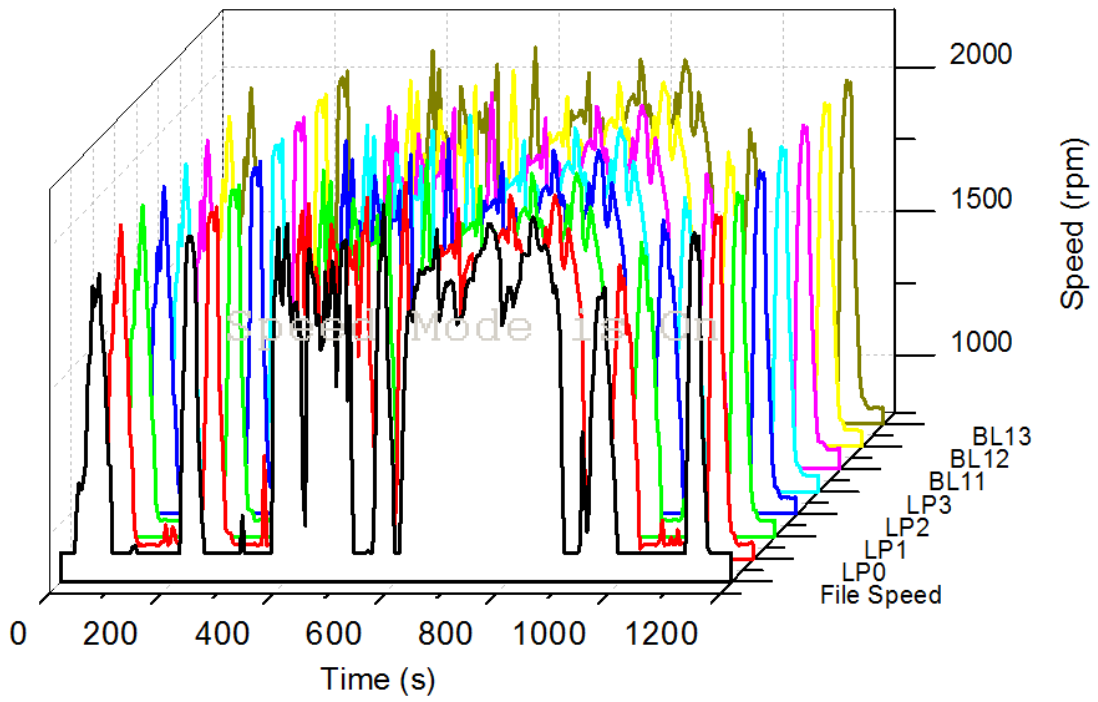

Figure 5. Illustration of speed profiles for multiple EPA FTP test cycle for the retrofit system and baseline

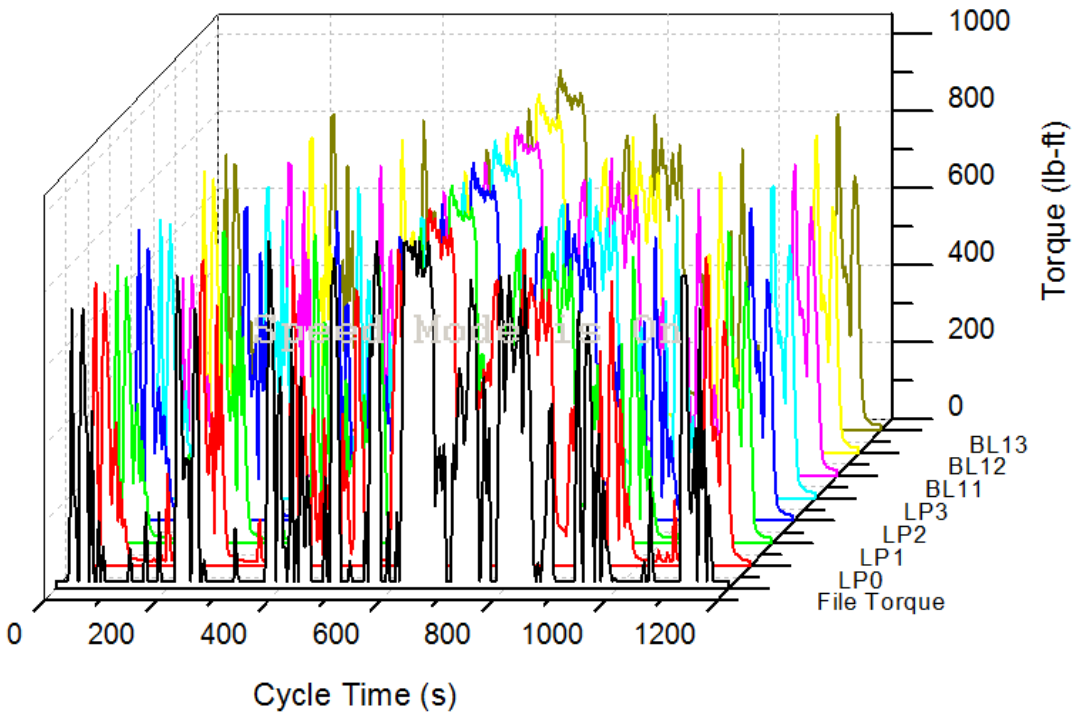

Figure 6. Illustration torque profiles for multiple EPA FTP test cycle for the retrofit system and baseline

Near 50% (48.8%) NO_x emissions reduction over transient FTP cycles was achieved by dual loop EGR configuration with improved "Calibration 2" as indicated by Figure 7. With dual loop "Calibration 1" in which less low pressure EGR was applied, 40% NO_x reduction was achieved over the transient FTP test cycle compared with baseline configuration as shown in Figure 7.

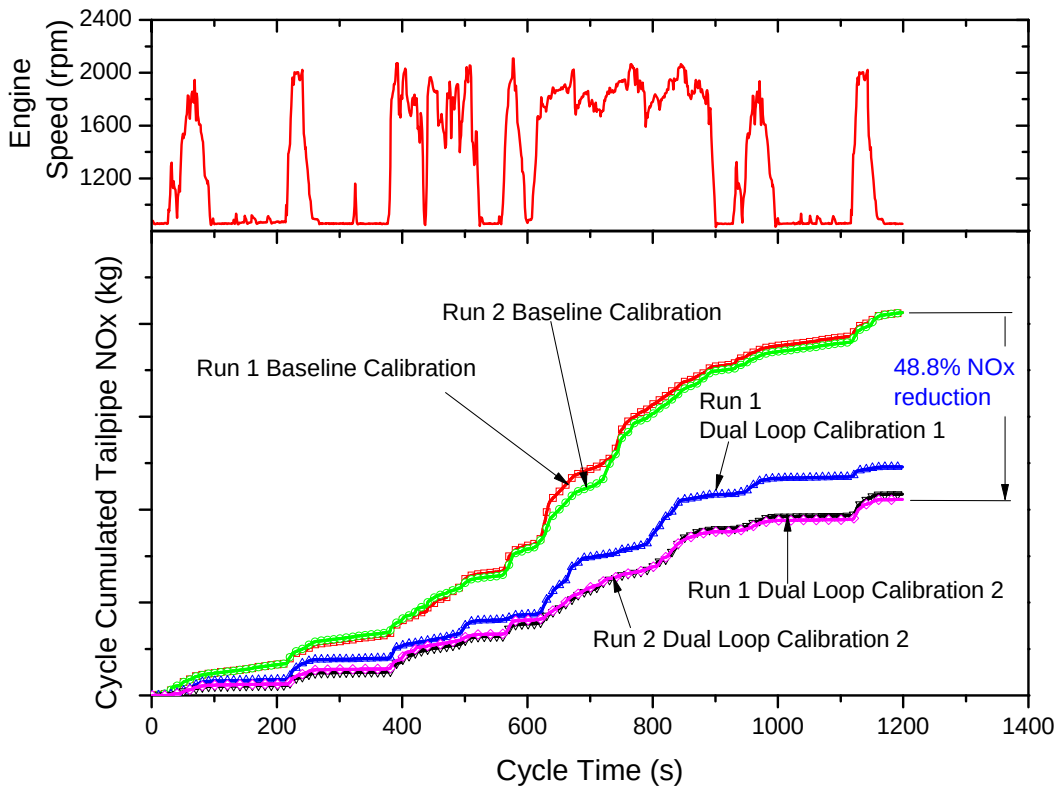

Figure 7. Results of NOx emissions reduction from dual loop EGR engine compared with baseline engine configuration over transient FTP test cycle

Figure 8 shows the cycle cumulative fuel consumption over transient FTP test cycle where different engine configurations and calibrations were applied. As indicated by the results in

Figure 8, the fuel consumptions were the same for all test runs, which means the fuel economy was unchanged or no fuel economy impact by the dual loop EGR system and associated dual loop EGR calibration.

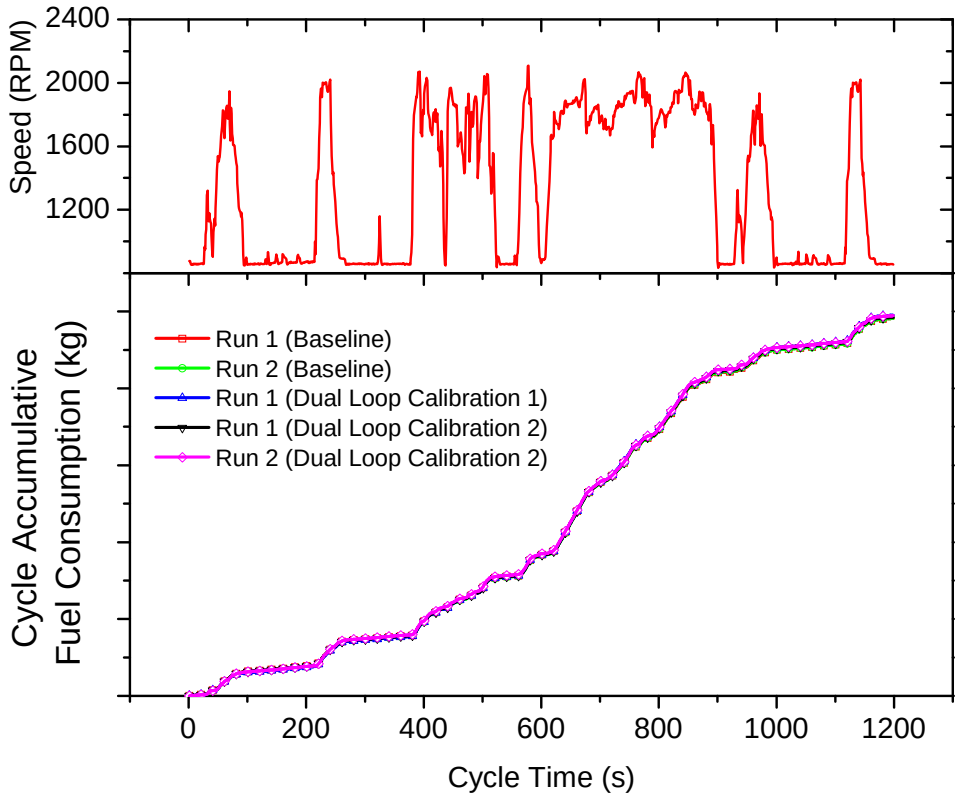

Figure 8. Cycle cumulative fuel consumption over transient FTP test cycles from different engine configurations and calibrations

Discussion/Observations

Objectives vs. Results

The goal of the Task 5 is to finalize the engine control parameters to achieve targeted emissions goal and emissions test the retrofitted engine over transient FTP test cycle. This task was to be completed within 22 months of the signed Notice to Proceed.

Different control parameters were tuned, and two different calibrations were tested to achieve the project emissions goal of 50% NO_x reduction over baseline.

The transient control parameters tuning and FTP testing have been completed and the task goals of finalizing the engine control parameters to achieve targeted emissions goal and emissions testing the retrofitted engine over transient FTP test cycle were achieved.

No fuel economy penalty was achieved for the dual loop EGR system calibration developed and 50% emissions reduction level targeted. The Task 5 goal was achieved.

Summary/Conclusions

The goals of the Task 5 have been accomplished. The test engine was run under the transient FTP test cycle on the engine dynamometer to verify the emissions reduction and fuel economy impact. All systems installed are functioning as expected. The 50% NO_x reduction goal was achieved without fuel economy penalty.

Currently the project team is working on *Task 6: Vehicle installation of retrofit* which has been lab demonstrated in engine dynamometer lab.

The overall project progress is on schedule and within budget.

Acknowledgements

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