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

## Tasks 6 & 7 Final Report

## for:

## New Technology Research and Development Program

## 582-11-13469-2019

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**In collaboration with: Houston Advanced Research Center**

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## Abstract/Executive Summary

This project was to 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 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 dual loop EGR technology was reported in several technical papers in society of automotive engineers (SAE).

The benefits of this 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 over light to medium loads for drayage truck applications. The complete dual loop EGR system has been 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 in a previous NTRD project with 50% $NO_x$ reduction over light to medium loads under steady-state conditions without any fuel penalty. The technology was sound and proven and published in several SAE technical papers by automotive industries [1-3].

In this project, the dual loop EGR system has been 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 has been implemented on the target vehicle for mileage accumulation and durability demonstration for future verification purpose.

## Project Objectives/Technical Approach

The objectives for this work were 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 were 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.

## *Task 6*

From the Grant Activities (Scope of Work):

> *Task 6: Vehicle installation of retrofit*
>
> *2.6. Task Statement: The PERFORMING PARTY will retrofit the target vehicle with the dual loop EGR system for functionality test and initial usage accumulation.*
>
> *2.6.1. The PERFORMING PARTY will uninstall the prototype retrofit dual loop EGR from the test engine and install it on the target vehicle.*
>
> *2.6.2. The PERFORMING PARTY will complete a preliminary vehicle functionality test and begin the durability demonstration and usage accumulation*
>
> *2.6.3. Schedule: The PERFORMING PARTY shall complete this task within 24 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.6.4. 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 documentation, including pictures, of the retrofit installation on the target vehicle and results of the preliminary vehicle test.*

In Task 6, vehicle retrofit of the dual loop EGR system was completed as indicated by Figure 1. The diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and low pressure loop EGR were installed under the chassis.

**Figure 1. Completed vehicle retrofit showing exhaust aftertreatment system**

Figure 2 shows the wring junction box for connecting various sensors, actuators as well as power to the control system. The wiring junction box and control system were installed under the cabin. The control system was activated by the ignition signal from the truck.

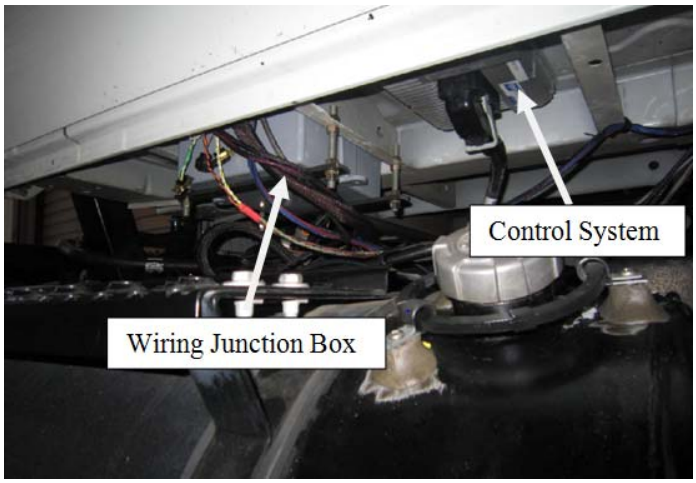


**Figure 2. Installation of wiring junction box and control system under cabin**

After the test vehicle retrofitting was complete, series of road tests were conducted on local and highway conditions. First the vehicle was tested at the garage to confirm the normal function of the retrofit system.

While the vehicle was in parked condition, the actuator of the exhaust back pressure valve performed a self-testing on ignition-on. Next, the functionality of the control system was tested by running the engine, and pushing accelerator pedal gradually while observing the movement of the exhaust back pressure valve actuator. The back pressure valve opened with the increase of pedal and started to reduce opening when the engine speed goes to very high.

The purpose of the road test was to verify the integrity and robustness of the installed system hardware under local and highway conditions. The road test was not for emission testing purposes. Figure 3 showsthe road test of the retrofitted test vehicle. During the road test, the vehicle was driven on the local road and highway, and then returned to garage. The vehicle was inspected for any loose parts. The functionality of the control system was verified again.

**Figure 3. Road test of retrofitted vehicle**

While the vehicle was in parked conditions, the emission control functionality was verified by fast free acceleration of the engine while monitoring the $NO_x$ sensor signals, both $NO_x$ and air to fuel ration (AF), with and without activating low pressure loop EGR system as shown in Figure 4.

At the beginning of the test, the low pressure loop EGR control function was activated and the engine was at idle (marked by marker A). AF ratio was at 23.6 and the $NO_x$ emission was at 20 parts per million (ppm) by $NO_x$ sensor in the exhaust. Then three free accelerations were conducted to verify the reactions from the low pressure loop EGR control. As shown from data at the high speed point (marker B at 1782 rpm), the $NO_x$ emission was kept very low at 54 ppm with the AF at 26.1. After the third acceleration, the low pressure loop EGR was deactivated as indicated by marker C point (at idle at 705 rpm) with AF at 40.4 and $NO_x$ at 85 ppm. At the marker point D (free acceleration to 1679 rpm), the AF was 29.2 with $NO_x$ emission at 353 ppm.

Four points were marked in Figure 4 explained the effectiveness of emissions reduction by low pressure loop EGR from the retrofitted vehicle. Table 1 shows the key parameters of marker points in Figure 4 indicated roughly more than 50% $NO_x$ emission reduction in ppm values.

The complete, raw emissions data from this testing has been submitted to TCEQ in support of this report.

**Table 1. Marker parameters in Figure 4**

| Marker in Figure 4 | Time Stamp (s) | Engine RPM | $NO_x$ ppm (sensor) | AF ratio (sensor) | Low Pressure EGR Valve Opening (%) |
|---|---|---|---|---|---|
| A | 11.23 | 711 | 20 | 23.6 | 45.0% |
| B | 37.83 | 1782 | 54 | 26.1 | 30.6% |
| C | 76.53 | 705 | 85 | 40.4 | 0.0% |
| D | 109.53 | 1679 | 353 | 29.2 | 0.0% |

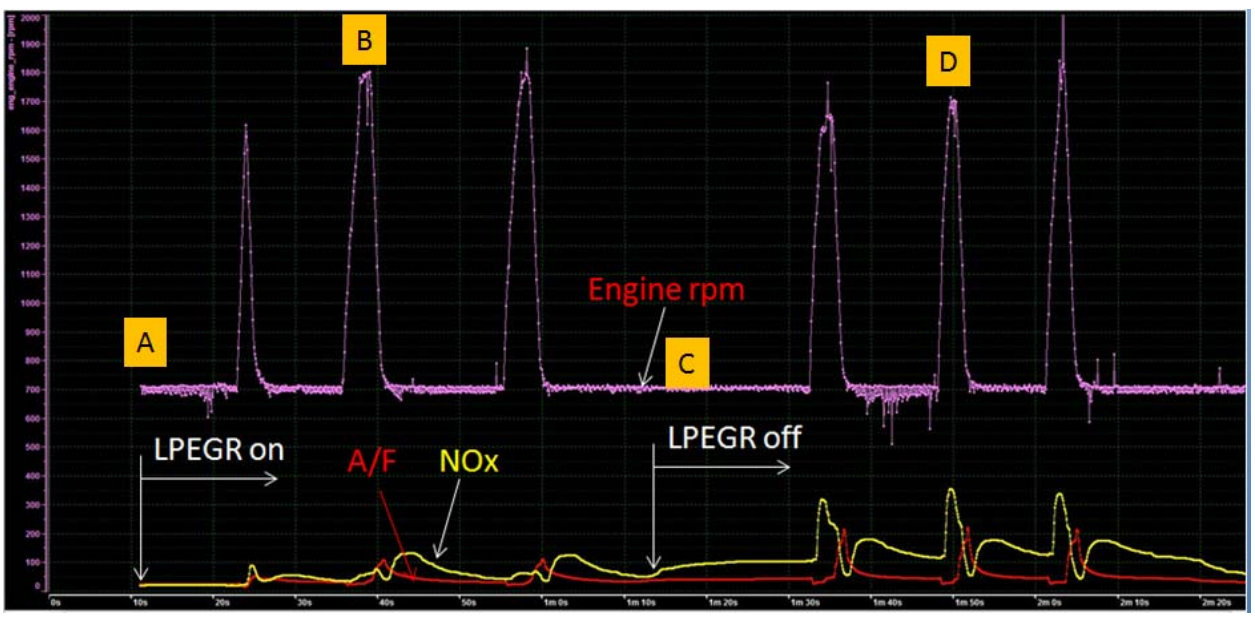


**Figure 4. Comparison of engine-out NOx reduction from retrofitted vehicle with low pressure loop EGR on and off**

### *Task 7*

From the Grant Activities (Scope of Work):

> *Task 7: Reporting*
>
> *2.7. Task statement: The PERFORMING PARTY will prepare and submit monthly detailed project reports and a comprehensive final report while ensuring compliance with all TCEQ program requirements*
>
> *2.7.1. The PERFORMING PARTY will coordinate all project resources to ensure compliance with NTRD program requirements while providing deliverables on-schedule and on-budget.*
>
> *2.7.2. The PERFORMING PARTY will generate monthly progress reports and a final report summarizing all aspects of the project based on data from the task completion reports.*
>
> *2.7.3. Schedule: The PERFORMING PARTY shall submit monthly reports to the TCEQ by no later than 10 days after the end of each month. The PERFORMING PARTY shall submit the final report to complete this task within 24 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.7.4. Deliverables: The PERFORMING PARTY shall submit monthly progress reports with associated billing statements and a final project summary report to the TCEQ upon completion of this task.*

The reporting tasks have been completed according to schedules.

## Discussion/Observations

### *Objectives vs. Results*

The goals of all tasks were met according to the project approved schedule and within the proposed budget. The target vehicle was retrofitted with the developed dual loop EGR system and road tested. No fuel economy penalty for the dual loop EGR system calibration developed and 50% emissions reduction level targeted. The project goal was achieved.

### *Critical issues*

No critical issues from both technical and financial areas existed during the project.

### *Technical and commercial viability of the proposed approach*

The technical approach of retrofitting the heavy-duty diesel engine with dual loop EGR system has been proven to be an effective way of reducing engine-out $NO_X$ emissions to up to 50% without fuel penalty in the project. The PM emissions were also reduced over 95% by retrofitting with a passive regenerated catalyzed DPF (cDPF). This approach is technically viable for retrofitting drayage trucks for reducing $NO_X$ and PM emissions. Because no urea SCR components were involved (no $NO_X$ aftertreatment system), the system complexity and cost of retrofit and cost of owning the technology are much lower than urea SCR retrofits and thus a commercially viable solution.

### *Scope for future work*

Currently the project demonstrated the technical feasibility and a test vehicle was retrofitted and tested on the road. More work is needed in the area of accumulating mileages and demonstrating durability in the areas of the components, control, and consistence of the effectiveness of emissions reduction. A follow-on project focusing on the durability demonstration of the retrofitted vehicle is necessary before applying for EPA/CARB approval for commercialization.

## Intellectual Properties/Publications/Presentations

No new intellectual properties were generated during the course of the project. Technical publications and presentations will be submitted at the proper events in the future.

## Summary/Conclusions

The goals of the all tasks have been accomplished and within budget. The test engine was tuned for low engine out emissions and then tuned to run under the transient FTP test cycle on the engine dynamometer to verify the emissions reduction and fuel economy impact. All systems installed were functioning as

expected. The 50% $NO_x$ reduction goal was achieved without fuel economy penalty. The test vehicle was retrofitted with the dual loop system and road tested. The dual loop EGR system on the retrofitted vehicle was verified to function accordingly.

## Acknowledgements

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