DOE Grant DE-EE-000-7800
Innovative Dual Fuel Aftermarket Emissions Solution
Final Scientific/Technical Report

Complete report can be found by searching for "DOE Grant DE-EE-000-7800 Innovative Dual Fuel Aftermarket Emissions Solution Final Scientific/Technical Report" on the DOE's official website

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I. Overview

Federal Agency and Organization Element to Which Report is Submitted: DOE EERE

Federal Grant Number Assigned by Agency: DE-EE-000-7800

Project Title: Innovative Dual Fuel Aftermarket Emissions Solution

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Vaztec Engine Venture, LLC (Vaztec Engine Laboratory)

Sub-Recipient Contract: DE-FOA-0001384/001, DE-FOA-0001384/002, DE-FOA-0001384/003

Project/Grant Period (Start Date, End Date): 5/8/17 – 6/30/19

Final Scientific/Technical Report Date: 9/30/19

This report has been modified and consolidated by Hydrogen on Demand Technologies for clarity and simplification. The complete report can be viewed on the US Department of Energy website.

The following report is the result of many months of testing funded and administered by the US Department of Energy. The goal was to prove what effect the infusion of small amounts of hydrogen gas have on the combustion characteristics and harmful exhaust emissions from diesel engines.

II. Results Summary

We far exceeded our primary project objectives by not only reducing PM (particulate matter) emissions by 64%, but by also reducing NO_x emissions by 77%, reducing CO_2 by 4.5%, and improving fuel efficiency by 9.94%. It should be noted that by not consuming 9.94% of fuel, ALL emissions were reduced by an additional 9.94%.

III. Executive Summary

Three companies, D-HAT™ (Formally known as BoostBox H2), (since re-branded D-HAT™ for Diesel Hydrogen Assist Technology, utilizing a patented Hydrogen fuel cell technology) NG1 Technologies (enhanced exhaust technology), and Vaztec (advanced air-intake technology), sub-recipients of DOE-EE-0007800, endeavored to combine their technologies to improve the three aspects of combustion: increased combustion efficiency (hydrogen enhanced combustion), efficient air intake (more air pressure), efficient exhaust (lower backpressure), to accomplish the grant objectives.

The objective of this project was to develop an advanced emission control system for Class 7 and 8 heavy-duty dual-fuel vehicles that eliminate or mitigates the negative effects of currently used diesel particulate filters (DPF) and selective catalytic reduction (SCR) emissions-treatment systems. The project was to combine multiple technologies that worked together to increase engine efficiency and reduce most emissions from the combustion process.

Our overall project goal was to improve fuel economy and reduce Particulate Matter (PM) emissions by 30% in Class 7 & 8 Heavy-Duty dual-fuel trucks, in doing so, eliminating or mitigating the need of the Diesel Particulate Filter (DPF) / Emissions After Treatment System (EATS).

Additionally, it was the team's goal to improve fuel efficiency and reduce maintenance costs to incentivize fleet operators and justify the expenditure to implement the new technologies that reduce emissions.

The majority of project testing was conducted on a 2013 Mack Pinnacle single-axle day cab (SADC) tractor equipped with an 11-liter 2012 Mack MP7 ATX engine provided by United Parcel Service (UPS). Additional testing was completed with a 2014 Mack Cummins LNG MTX, meeting project's dual-fuel objective.

It should also be noted that due to the test vehicle exhaust system configuration we were unable to test with the NG1 and D-HAT™ systems combined and completed the majority of the testing with only the D-HAT™ system deployed and functioning.

We far exceeded our primary project objectives by not only reducing PM (particulate matter) emissions by 64%, but by also reducing NO_x emissions by 77%, reducing CO_2 by 4.5%, and improving fuel efficiency by 9.94%. It should be noted that by not consuming 9.94% of fuel, ALL emissions were reduced by an additional 9.94%.

Our team was able to continue to refine our technologies (for example, installation and manufacturing techniques) and implement additional features (like on road Telematics to the D-HAT™ unit) due to this project, which help to make the overall solution to improved fuel efficiency and reduced greenhouse gas emissions devices more cost-effective and useful in the field. Additionally, the team was able to utilize testing resources that would otherwise be financially unavailable to our new companies.

Although not all aspects of the project were ultimately accomplished, and we will likely not replace EATS, this program definitively showed that the D-HAT™ device dramatically improved the performance of diesel combustion using Hydrogen Enhanced Combustion both on the track over 5000 miles of use and on a dynameter using the HHDDT profile. Such improvements will not only save fleets thousands of dollars in fuel and maintenance costs but will also provide much cleaner air and reduced greenhouse and smog creating gases.

The team was extremely encouraged by the results observed and are anticipating rapid commercialization of the technologies to help improve overall air quality and freight costs. Our system costs would reflect less than a 15-month Return on Investment (ROI) for most participating owners of diesel-powered systems.

IV. Accomplishments vs. Objectives

There were two budget periods for this project that had specific objectives (tasks) and requirements (milestones) associated with each period, with the overall project goal of achieving a 30% reduction in PM over existing baseline emissions equipment that would be standard on any commercial diesel truck produced after 2010.

Our testing was conducted using a 2013 Mack Pinnacle single axle day cab (SADC) tractor equipped with an 11-liter 2012 Mack MP7 ATX engine, with approximately 530k miles on the vehicle at the start of testing. All testing was conducted in accordance with EPA CFR49, Part 1065, SAE J2711, SAE J1264, and SAE J1321

Our team was able to complete most of the objectives of Budget Periods 1 and 2 and results are presented in the Summary of Technical Activities later in this report.

<u>Budget Period 1: Technology Testing, Data Collection, and Systems Development</u>

- Collect on-road data from proposed devices
- Testing of technologies
- Development of intake system for single cell
- Development and design of the catchment system
- Start of modeling & Flow analysis
- Test final-results of proposed technologies
- Completion of Phase I testing
- Milestone 1: Collection of emissions data on NG1 and BoostBox H2 separately and together

We were able to successfully collect emissions test data for the D-HAT™ system and have shown positive results for reduction in PM, NO_x, and CO_2 in accordance to the goal as measured by third party company infoWedge.

- Milestone 2: Combine D-HAT™ with NG1 on a single-cylinder testbed

Testing of a single-cylinder diesel engine was conducted as a baseline for the development of the Vaztec air intake solution. The baseline engine tests were conducted on a stock engine using a laboratory dynamometer. Particulate and gaseous emissions were measured by third party company infoWedge.

D-HAT™ successfully implemented electronic flow control for their hydrogen system to adjust the volume of hydrogen for this smaller engine application.

While baseline tests were accomplished in accordance to this goal, the team was not able to integrate the Vaztec advanced air intake system into a new engine design, therefore, we were not able to test all three technologies together.

- Milestone 3: Design Mapping software to optimize the fuel mixture

This required the development of a custom-engineered electronic control module and software that will recognize the combined technologies in optimizing vehicle performance. The team contacted Mack Trucks in seeking their assistance. Unfortunately, Mack was not able to support changes to the programming due to proprietary and legal restrictions of their intellectual property incorporated in the systems. The team then contacted OTR Performance; then PDQ Performance; then CZero, seeking a custom design fuel mapping software program needed for optimizing fuel mixture. No solutions were found that fit within the time and cost parameters of this grant, therefore the team was not able to complete this objective.

- Milestone 4: Demonstrate a reduction of particulate matter (PM) of at least 30% relative to baseline

Testing on the dynamometer at Penn State showed an 11% reduction in PM, while infoWedge performed continuous PM measurements during a 5000-mile track test at Mesilla Valley Transportation, utilizing the BF Goodrich proving track in Texas, showed a 64% reduction in PM - far in excess of project objectives.

<u>Budget Period 2: Finalize System Design, Prototype and Test</u>

- Test centrifuge effects
- Completion of modeling & flow analysis of centrifuge
- Completion of a prototype catchment system
- Compare spin catchment designs
- Chassis dyno and emissions testing
- Final Society of Automotive Engineering (SAE) testing
- Development of marketing strategy & commercialization
- Market launch

- Milestone 1: Determine if the NG1 system alone has enough space claim to create the required centrifugal effect to completely spin particulates to secondary catchment chamber or if a mechanical centrifuge is required

A spin catchment system was designed and fabricated through the team partner in Memphis, TN, however, resources and priority were given to refining and optimizing the existing NG1 and D-HAT™ technologies given the existing 64% improvement in PM measurements. This objective was not completed as the spin catchment system was not required to achieve the 30% minimum PM reduction.

- Milestone 2: Chassis dyno testing and emissions collecting

Chassis dynamometer testing was completed by Penn State University. After benchmark testing, we were able to successfully collect emissions test data with the NG1 TechFlo combined with the D-HAT™ and have shown positive results for reduction in PM, NO_x, and CO_2 in accordance to the project goal.

- Milestone 3: Complete spin catchment system

A spin catchment system was designed and fabricated through the team partner in Memphis, TN, however, resources and priority were given to refining and optimizing the existing NG1 and D-HAT™ technologies given the 64% improvement in PM measurements. This objective was not completed within the timeframe of the project.

- Milestone 4: Complete testing of all technologies on diesel truck engine in on-road application

InfoWedge performed continuous PM measurements during a 5000-mile track test at Mesilla Valley Transportation, utilizing the BF Goodrich proving track in Texas, which showed a 64% reduction in PM. Additionally, between official testing cycles, the tractor provided by UPS was driven and monitored from State College, PA to El Paso, TX to Laramie, WY, to State College, PA. This objective was successfully completed.

V. Publicly Available Scientific and Technical Information (STI)

There is no publicly available material that is duplicated in this report.

VI. Summary of Technical Project Activities

Through the project, the team conducted several rounds of testing with the D-HAT technology in four primary areas as summarized below.

1. Testing by Mesilla Valley Transportation Solutions was a long-duration track test of over 5,000 miles that comprised two major aspects of test: A/B fuel efficiency comparison of our test vehicle with a baseline vehicle under the same track conditions; and continuous emissions monitoring.
2. Testing by Penn State was a short duration track test combined with dynamometer testing where they were primarily monitoring fuel efficiency and emissions before and after hydrogen conditioning of the engine.

3. Single-Cell Testing was an experimental development project to attempt to integrate NG1 and D-HAT technologies with a new concept in air intake design from Vaztec that would eliminate valves and valve stems in the engine and to monitor fuel efficiency and emissions. (did not complete)

4. Over-the-road testing was conducted on various vehicles and the primary grant test vehicle to evaluate long term fuel efficiency utilizing the D-HAT technology.

Detailed third party reports provided in the links at the end of each section.

Testing with Mesilla Valley Transportation Solutions (MVST)

The test consisted of 5000 miles on the test vehicle to quantify the savings over time and break-in period of the technologies. Testing was conducted at a steady-state speed of 65 miles-per-hour on the BF Goodrich 9-mile test track near Pecos, Texas. Testing analyzed fuel consumption (reported by MVTS) and emissions measurement (reported by InfoWedge).

The test vehicle was a 2013 Mack Pinnacle single-axle day cab (SADC) on loan from United Parcel Service (UPS). The truck had 530,440 miles at the commencement of testing. Service and repairs were made to the truck prior to testing to ensure consistent, reliable performance throughout the test.

A second vehicle was used as a comparison for fuel economy tests, which was a 2015 Volvo SADC with 194,170 miles. Details of which can be found in the detailed report. Test procedures followed MVTS 2-truck procedures and utilized sophisticated data acquisition systems, fuel flow meters, and numerous sensors to accurately quantify changes in fuel consumption.

Two 53' dry-vans trailers were provided by the MVT fleet and were closely inspected prior to testing. Trailer tires were Wide Based Singles (WBS). Trailers were equipped with GreenWing trailer skirts and loads were secured to the floor and sides of the trailers. Total gross vehicular weight was 45,000 pounds.

Test results showed to be accurate and reliable, proven by the start/finish fuel economy value difference of -0.01% when the primary test truck was returned to nearly the same condition.

MVTS Test Results – 77% Reduction in NO_x. 64% Reduction in PM.

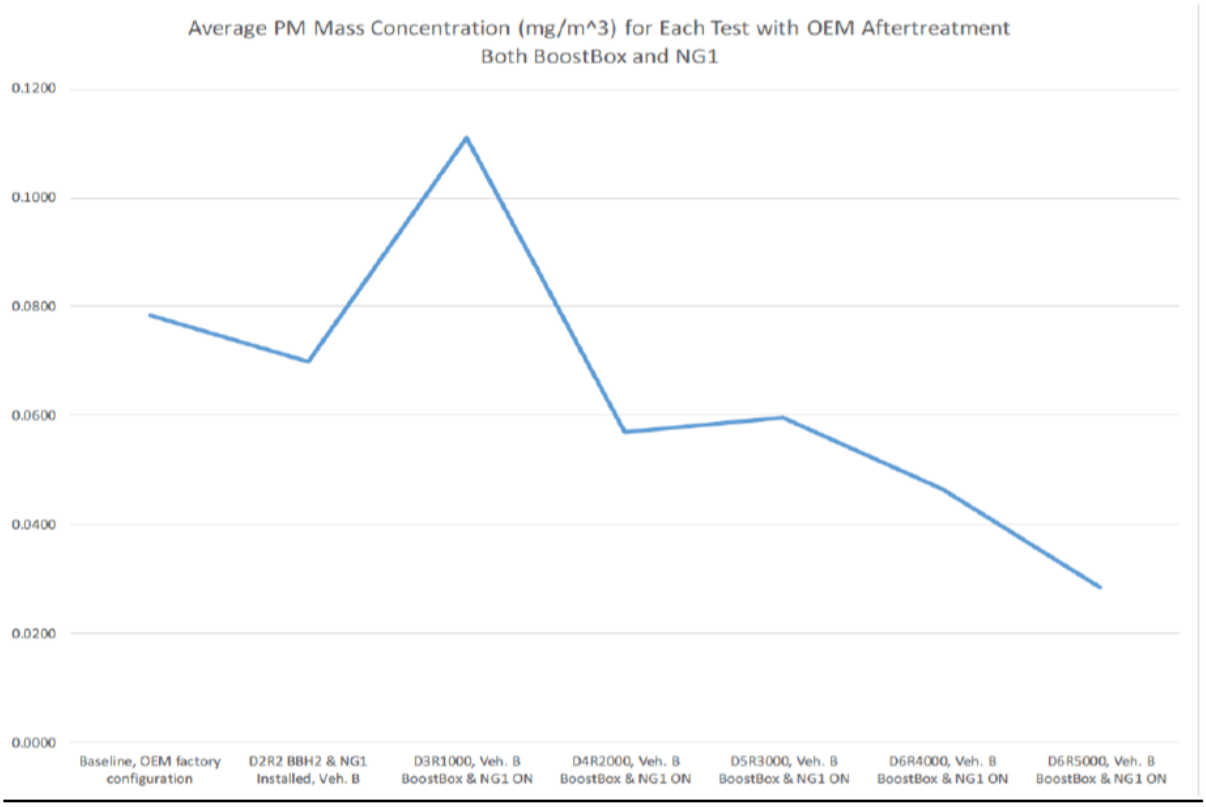
It was shown that at a steady-state 65 mpg track test, the fuel efficiency was not statistically different from the start to end of testing versus the comparable vehicle. Even though the test vehicle achieved a 10.14% improved fuel efficiency during the testing period, the second comparable vehicle also exhibited a similar improvement. Following testing, it was learned the engine of the primary test truck (Mack MP-7) used a multi-burst fuel injection system that may have prevented the D-HAT™ system from performing to its optimal extent. Given the previously stated issues related to modifying software related to fuel injection and combustion parameters, the team was not able to achieve significant relative fuel savings.

Emissions results showed a 64% reduction particulate matter (PM) emissions per mile over the course of testing. As can be seen in the table and graph below, the average mass concentration of PM in the exhaust steadily reduced from the baseline level to the point that, at the 5000-mile test it was 64% lower than the already low baseline. The 5000-mile average NO_x concentration was 77% lower than the baseline average.

“Test results indicate that adding the retrofit devices and using them for 5000 miles at highway conditions resulted in a PM concentration reduction of approximately 64% at the tailpipe for this vehicle. The already low baseline PM concentration of 0.0784 mg/m3 was reduced to 0.0283 mg/m3. Also, NO_x emissions were reduced by approximately 77%, from 72.2 ppm down to 16.6 ppm. Unfortunately, your fuel efficiency contractor measured a slight reduction in fuel efficiency of between 0.01% and 1.34%.” – Andrew Burnett, infoWedge

“All tests controlled or recorded parameters that could conceivably change emissions independently of the D-HAT™ (weather conditions, driver influence, etc.). No outside influences that could have affected emissions anywhere near the observed levels were identified. Therefore, we conclude that the emissions reductions were caused primarily by your retrofit device.” – Andrew Burnett, infoWedge

Baseline vs. BoostBox H2 & NG1	MPG	mi/kg fuel	mi/mol e fuel	Date	Approx Test Time	Averaging Data Start	Averaging Data End	Averaging Time (mins)	Avg. PM mg/m^3	Avg. NOx ppm	Avg. O2 %	Avg CO2 calc'd%	% Excess air	Exhaust Flow mol/mi	Avg PM mg/mol exh	Avg PM mg/mi
Baseline, OEM factory configuration	7.1	2.15	0.48	16-Jan	6:10	8:59:02	10:06:29	67.45	0.0784	72.2	7.82	8.39	61.10	400.0	0.00192	0.76736
D2R2 BBH2 & NG1 Installed, Veh. B	7.3	2.20	0.49	16-Jan	10:06	12:56:18	14:03:46	67.46	0.0699	53.4	7.60	8.54	58.37	383.5	0.00171	0.65636
D3R1000, Veh. B BoostBox & NG1 ON	7.3	2.20	0.49	17-Jan	20:31	23:27:10	0:34:39	67.48	0.1110	53.7	7.48	8.62	56.87	379.9	0.00272	1.03204
D4R2000, Veh. B BoostBox & NG1 ON	8.1	2.46	0.54	18-Jan	14:31	17:50:11	18:57:39	67.46	0.0569	35.9	7.17	8.82	53.29	333.4	0.00139	0.46382
D5R3000, Veh. B BoostBox & NG1 ON	7.9	2.37	0.53	19-Jan	8:00	10:58:10	12:05:37	67.45	0.0596	38.6	7.30	8.74	54.73	348.5	0.00146	0.50798
D6R4000, Veh. B BoostBox & NG1 ON	7.8	2.34	0.52	20-Jan	1:50	4:20:59	5:28:28	67.48	0.0464	25.2	7.47	8.62	56.78	358.1	0.00114	0.4066
D6R5000, Veh. B BoostBox & NG1 ON	8.5	2.57	0.57	20-Jan	16:51	18:48:35	19:56:04	67.48	0.0283	16.6	7.13	8.85	52.77	317.4	0.00069	0.21999
% Reduction from baseline to 5000 mi									**64%**	**77%**						**71%**
D7R5390, Veh. B Stock exhaust stack (NG1 OFF), DPF/SCR Bypass	8	2.42	0.54	21-Jan	13:11	3:07:08 AM	4:14:36 AM	67.48	0.2421	512.0	8.49	7.95	69.95	375.6	0.00592	2.22485
D7R5260, Veh. B Boostbox Off, NG1 ON, DPF/SCR Bypass	8	2.40	0.53	21-Jan	7:57	12:27:21 AM	1:34:49 AM	67.46	0.2096	494.9	8.05	8.25	63.94	364.6	0.00513	1.86929
D6R5130, Veh. B BoostBox & NG1 ON, DPF/SCR Bypass	8.1	2.45	0.54	20-Jan	10:27	9:55:04 PM	11:02:33 PM	67.47	0.2140	492.2	8.09	8.22	64.45	359.0	0.00523	1.87918
% Reduction from engine-out to tailpipe (both retrofits ON)									**12%**	**4%**						**16%**
% Reduction from engine-out to tailpipe (only NG1 ON)									**13%**	**3%**						**16%**



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MVTS BB H2 NG1 5000-mile test

infoWedge_Boost-BoxNG1-1pager

infoWedge_Boost-BoxNG1-initialPMResults

NTKSummary20180302-01

Test at Pennsylvania State University (Penn State)

The goal was to analyze and publish test results from the vehicle testing at Pennsylvania State University Larson Transportation Institute between October 31, 2017 – November 7, 2019. The D-HAT Project Team traveled to Penn State University to perform a chassis dynamometer test and a track test on the 2012 Mack MP7 UPS aftermarket equipped project truck donated by United Parcel Service. An institutional validated aftermarket data was generated using vehicle analytics, chassis dynamometer and fuel cycle testing on the vehicle test track. Both fuel and emissions will be captured during the aftermarket testing events.

Penn State Test Results – 9.94% Fuel Savings, 4.5% Reduction in CO_2,12% Reduction in NO_x, 11% Reduction in PM.

The first test iteration performed was the chassis dynamometer specific to emissions collection. The chassis dynamometer testing was performed generally in accordance with EPA CFR49, Part 1065 and SAE J2711 as practically determined by the Emissions Testing Protocol developed by Penn State University. The chassis dynamometer-based tests were conducted at an inertia load of 30,000 lb., as recommended by the sponsor. The emissions results show steady improvement from baseline in particulate matter (PM) emissions over the course of testing. As can be seen in the attached table and graphs, the average mass concentration of particulate matter PM in the exhaust steadily reduced from the baseline level to the point that, chassis dynamometer test was 11% lower than the already low baseline level. The NOx concentration was 12% lower than the baseline average. The concentration of CO_2 in the exhaust steadily reduced from the baseline level to the point that chassis dynamometer test was 4.5% lower than the already low baseline level. The fuel economy results on the chassis dynamometer show an improvement from baseline stock equipped truck to aftermarket D-HAT equipped truck of a 9.94% fuel improvement over the course of testing.