Blue hydrogen – Diesel dual-fuel engine technology development for a transition to a hydrogen economy

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3 Executive Summary

Using dual fuel H2/Diesel for heavy duty trucks is a way for Alberta to quickly reduce Greenhouse Gases from this segment. Techno-economic assessment performed in this project by the Transition Accelerator found that CO2 can be reduced in Alberta and using hydrogen Diesel dual fuel (HD2F) to help reduce the economic cost of transition from now to 2035 compared with using only fuel cell vehicles [1].

To develop, optimize and test HD2F technology a full size truck engine dynamometer test cell was commissioned at the University of Alberta to run on combinations hydrogen and Diesel. A large truck engine manufacturer provided test engines for the test facility. In addition, modern engine control hardware and emission measurement systems will be used in conjunction with state-of-the-art machine learning control to quickly develop and test control methods that maximize the hydrogen energy fraction in the hydrogen/Diesel fuel mix while maintaining acceptable emission level (NOx). The engine test cell has been commissioned and up to 70kg of H2 is available on site to allow for 15 liter truck engine testing. The developed machine learning control methods are applicable to a variety of energy systems including 100% hydrogen combustion.

This project had the objective to provide techno-economic assessment and to develop and build testing facilities for a dual fuel hydrogen Diesel engine. This test facility will help develop the technology which in turn will provide a path to transition to zero carbon transportation for heavy duty trucks.

4 Introduction

The project is to develop a technology-based solution for the co-combustion of hydrogen and Diesel in a freight transport Diesel truck, effectively reducing carbon emission. The new truck powertrain, called hydrogen-Diesel dual-fuel (HD2F), plans to use the blue hydrogen produced in Alberta. In Alberta, blue hydrogen is produced by steam reforming of natural gas and the CO2 byproduct is sequestered back into the ground. With planned zero-emission targets in all energy sectors, HD2F engines are a short to medium term cost-effective GHG reduction option. Truck conversions to HD2F technology is relatively low cost and will have an immediate impact on GHG reduction up to 50%. Upon large-scale deployment of the HD2F technology, a CO2 reduction of 500 kt/yr in 2030 and a peak of 2200 kt/yr in 2040 is predicted. This will clear the pathway for effective and smooth market penetration of zero-carbon technology of hydrogen fuel cell trucks. As a result of commercial deployment of the technology, an immediate GHG reduction will happen at a very low cost, jobs are created in the clean energy sector, and blue hydrogen infrastructure is rapidly developed [1]. The University of Alberta and a Truck Engine original equipment manufacturers (OEM)

(Cummins) will develop HD2F technology. Current Diesel engine technology is advanced and highly equipped with electronics and sensors, so it is essential for HD2F technology to be developed in collaboration with (Cummins) the Truck Engine OEM.

HD2F technology enables all sizes and classes of Diesel trucks (from pickup to class 8 heavy haulers) to consume blue hydrogen. The technology will first be implemented on a medium-size truck engine to match our experimental facility. Then class 8 freight trucks will be developed as they will consume large amounts of blue hydrogen. Class 8 medium- and long-haul trucks operating between Edmonton and Calgary will be the initial focus.

The objectives of the project are to meet the long-term goals of GHG reduction, increase demand for blue hydrogen, job creation in clean energy, application of artificial intelligence in energy systems, R&D of clean powertrain systems, hydrogen supply chain, and hydrogen system component production. The HD2F program is designed in three phases. Phase 1 is the subject of the current proposed project. Phase 2 of the project will consist of system integration on three candidate trucks for road testing. Upon completion of Phase 2, a more extensive scale deployment of the system on 100 trucks is planned, targeting two tonnes of blue hydrogen use per day.

Knowledge or Technology Gaps: this project is developing the technology to maximize H2 usage in dual fuel H2/Diesel truck engines while maintaining existing stringent emission regulations. There is a gap in the integration of the H2 injection with the production engine control and developing flexible machine learning control methods.

5 Project Description

The University of Alberta in collaboration with a Truck Engine OEM (Cummins) has developed a technology to replace a large fraction of Diesel fuel used in a freight transportation truck with blue hydrogen produced in Alberta. The technology, called HD2F, is the co-combustion of blue hydrogen and Diesel in a dual-fuel internal combustion Diesel engine. Over the short and medium term, this technology reduces greenhouse gas emissions (GHGs) of Diesel freight transport at a lower cost than competitive technologies such as fuel cells. It also provides a base demand for blue hydrogen resulting in infrastructure development in Alberta that will create jobs in the clean and sustainable carbon-free energy sector.

Knowledge or Technology Description: the project objective is to maximize H2 energy content in HD2F class 8 truck engines to minimize GHGs and other harmful emissions such as NOx. This will be done through a combination of simulation and model-based control. The model-based control then needs to be made suitable for incorporation in a class 8 truck.

Updates to Project Objectives: there are no changes to the original project objectives. Significant progress has been made on the simulation models and on engine testing at University of Alberta with a smaller engine. Transport Canada import requirements were met and the OEM engine (Cummins) has been imported. The extensive measurements on the existing smaller 4.5l engine in University of Alberta on-campus lab have confirmed that with proper control, high H2 replacement is possible. This confirms the original project objective to test this technology on larger engines.

Performance Metrics: the success of this project is generally measured in these three ways: (1) completion of the engine test facility; (2) a techno-economic assessment of the technology; (3) a pathway forward for commercialization of this technology that also creates economic activity and jobs in Alberta.

6 Methodology

The objectives of the project are:

1. To develop the HD2F technology for use in heavy truck applications at TRL stages of 4-7 for immediate GHG reduction.

2. To train highly qualified personnel (HQPs) for the future of the Alberta hydrogen economy and create immediate R&D jobs.

3. To plan for, and prepare, an industrial-scale demo truck project at the TRL stage of 8 and above.

The project will deliver:

1. An OEM prototype of the HD2F engine ECU.

2. Design and components of the hydrogen system delivery for truck applications.

3. A mathematical model of HD2F powertrain for exploring other possible applications such as public transit, school bus, garbage truck, and delivery trucks.

4. Proof-of-concept data, a large set of experimental data for techno-economy model development.

5. A techno-economic analysis of GHG reduction and benefits of the project.

The methodology followed is

1. Perform a more detailed techno-economic assessment of HD2F to provide an economic framework for future commercialization.

2. Build a state-of-the-art test facility to develop and optimize HD2F on a full scale engine system based on initial research and development on the smaller engine.

3. Work with local Alberta companies so that a commercialization pathway is found.

7 Project Results

The project has been successful on the three main tasks:

1. A techno-economic assessment of the technology provides economic scenarios where HD2F provides a transition pathway that both reduces economic cost and reduces GHG more quickly to 2035 – see [1].

2. The engine test facility is complete and will allow full size truck engine testing with 70kg of hydrogen onsite. The testcell is shown in Figures 1 and 2.

3. A pathway forward for commercialization of HD2F with Diesel Tech Industries (DTI) in Edmonton has been established [2] which should create economic activity and jobs in Alberta.

   The techno-economic assessment was performed by the Transition Accelerator, a partner in this project, and they published a technical report detailing possible scenarios for the use of HD2F in Alberta [1]. There report show the utility of H2/Diesel trucks to both reduce greenhouse gas and as a transition to provide a short to medium demand for H2 to allow H2 infrastructure to be built. This report provides both the economic framework and the possible greenhouse gas reduction potential of HD2F trucks and is being used by our industrial partners to formulate their business plans.

   The engine testcell facility is a dyne-systems eddy current dynamometer capable of absorbing 522kW at 1200rpm with a maximum speed of 3600rpm. The test facility has 1200l of Diesel fuel and over 70kg of H2 to allow for test of a 15 liter class 8 truck engine over the full engine speed load range. Diesel and H2 flow measurement are also integrated into the fuel system. A flexible engine control system (dSpace Microautobox III and RapidPro Power electronics) allow for rapid prototyping of engine controls including conventional and machine learning methods. Existing University of Alberta emission measurement system (MKS MultiGas 2030) is also available for measuring the exhaust emissions.

   An important part of this project is supporting possible commercialization of HD2F internal combustion truck engines. This has been accomplished in these three ways: (1) DTI, based in Edmonton, will be supported by this facility; (2) we have partially transferred the machine learning engine control to DTI in Edmonton and engine modeling to Hydra in Vancouver since two graduate students have graduated and have been hired at these companies (one at each company); (3) We have built a flexible test facility that can also be adapted to test 100% H2 engine in the future.

8 Key Learnings

The techno-economic analysis of HD2F as a technological option show that it provides an important transition to zero GHG emission heavy duty transportation. It will allow the hydrogen infrastructure to be built be providing a demand for hydrogen.

As part of this project, preliminary HD2F test results were obtained on our existing 4.5 liter Diesel engine. Details of the testing and engine setup are available in [3, 4]. Some key results from this work are summarized below and are from [5].

In this work, Diesel fuel is replaced by H2 fuel calculated based on the injected energy of the fuel – the lower heating values of the two fuels are used. Several engine loads at 1500 RPM were tested and the fuel injection timing optimized. The Diesel injection timing is varied and the H2 compared to Diesel energy fraction is maximized as a function of engine load at an engine speed of 1500 RPM. The engine load is plotted as a function of Indicated Mean Effective Pressure (IMEP) which is a measure of torque normalized by the engine displacement. For reference, this industrial production engine running on Diesel fuel has approximately 18 bar IMEP at full load.

The goal is to maximize the H2 fraction to reduce CO2 emissions. This was done subject to constraints on the speed of combustion in the cylinder and the exhaust emissions were also

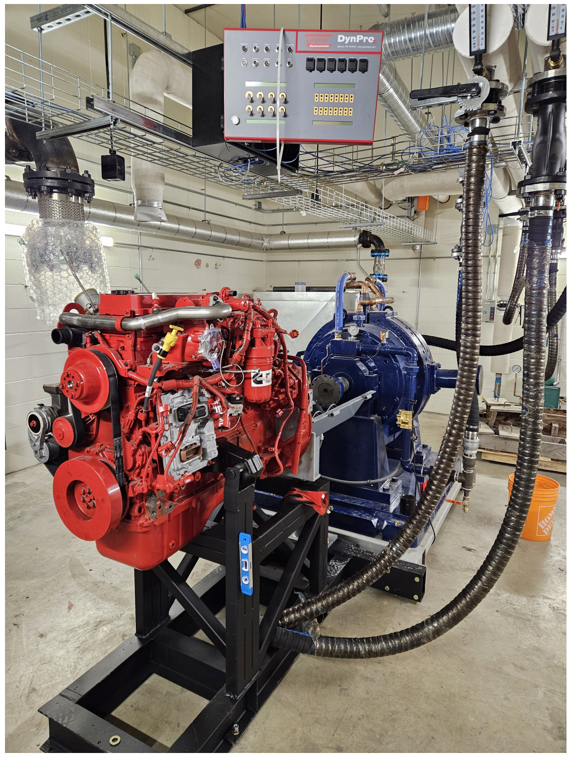

Figure 1: Engine Testcell - Engine and Dynamometer

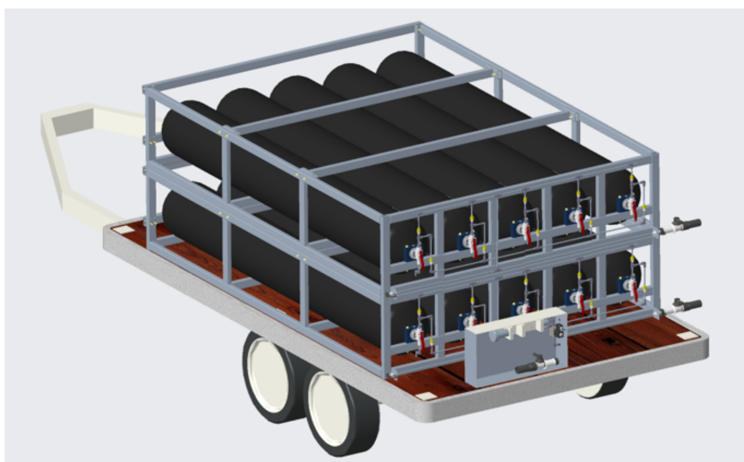

Figure 2: Hydrogen Storage Trailer

measured.
The “best case” H2 fuel energy fraction over the part load range from 4 to 12.5 bar IMEP is shown in Figure 3.
Up to 85% of the Diesel energy was replaced at 8 bar IMEP (mid-load of the engine) with the H2 energy fraction reducing to approximately 50% at 12.5 bar IMEP (two thirds full load of the engine) as shown in Figure 3. However, since it is also important to consider the durability of the engine and the exhaust gas emissions, the H2 fraction was limited as the load increased to maintain engine durability and avoid excessively fast and potentially

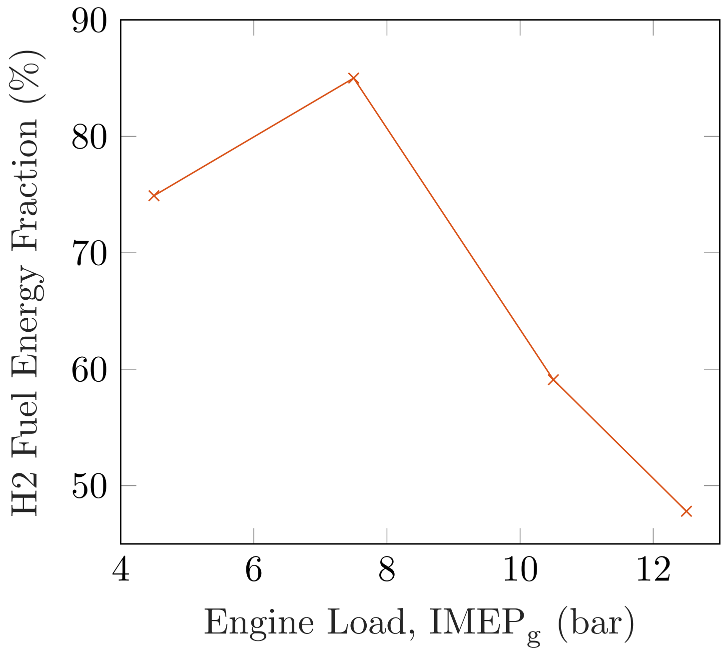

Figure 3: “Best case” Hydrogen energy fraction as a function of engine load

damaging combustion.
The CO2 emissions for these cases and the 100% Diesel is shown in Figure 4 showing a CO2 reduction corresponding to the energy fraction of H2. A large reduction in CO2 emissions using HD2F compared to straight Diesel is realized.

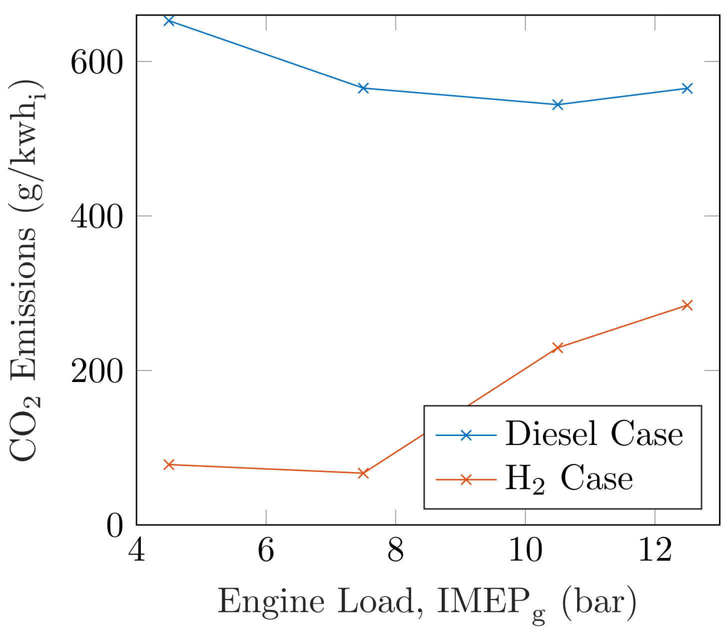

Figure 4: CO2 Emissions (H2/Diesel from Fig 3) with corresponding Diesel-only cases

In addition, the measured engine out NOx in [g/kWh] as a function of engine load is shown in Figure 5. As expected, the introduction of H2 roughly doubles the engine out NOx. One way to mitigate this would be through exhaust aftertreatment.

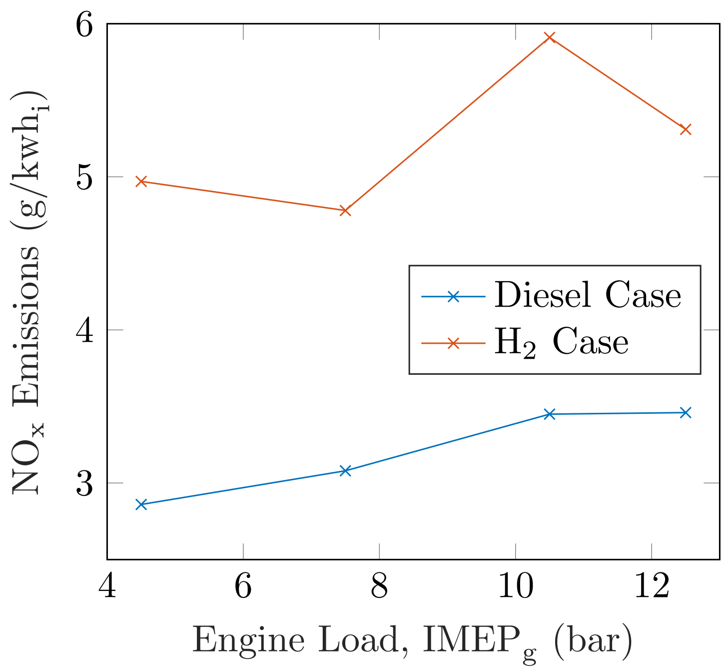

Figure 5: NOx Emissions (H2/Diesel from Fig 3) with corresponding Diesel-only cases

The corresponding measured particulate (soot) in [mg/kWh] as a function of engine load is shown in Figure 6, and as expected, the soot decrease is higher for higher levels of H2 energy fraction. At the lower loads the with high H2 energy fraction the soot reduction in the exhaust is as high as a factor of 6.5

Finally, the corresponding gross engine thermal efficiency η_{th} as a function of engine load is shown in Figure 7. This figure shows that for these "best case" tests the engine efficiency is comparable between HD2F and straight Diesel, although at a load of 10.5 bar the HD2F has almost 10% higher efficiency.

The availability of this engine testcell to optimize HD2F truck engines will allow us to work with our industrial partners to optimize their commercial product to maximize hydrogen used (minimize Diesel), reduce harmful emissions such as soot,and help accelerate the engine control development, and test the reliability of their product. This will be essential for this complex technology to succeed in a very competitive sector.

The broader impact of this project is to develop an immediate demand for hydrogen which will help accelerate knowledge in the hydrogen economy. This development includes the transportation and supply of hydrogen, and safety standards including regulations. In addition, unique machine learning control expertise in Alberta, that is applicable to a wide variety of energy conversion systems, will be further developed.

9 Outcomes and Impacts

Project Outcomes and Impacts: Our research into HD2F has helped understand the trade offs between hydrogen energy replacement (of Diesel) and engine parameters such as

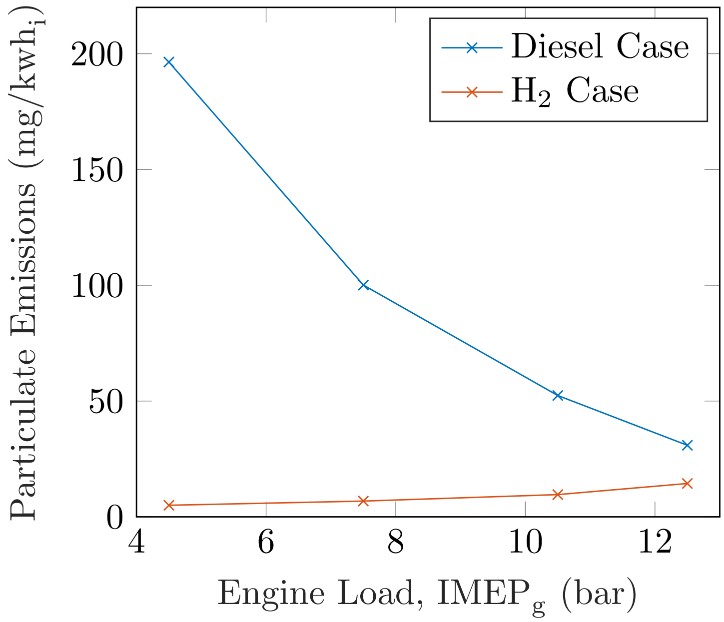

Figure 6: Soot Emissions (H2/Diesel from Fig 3) with corresponding Diesel-only cases

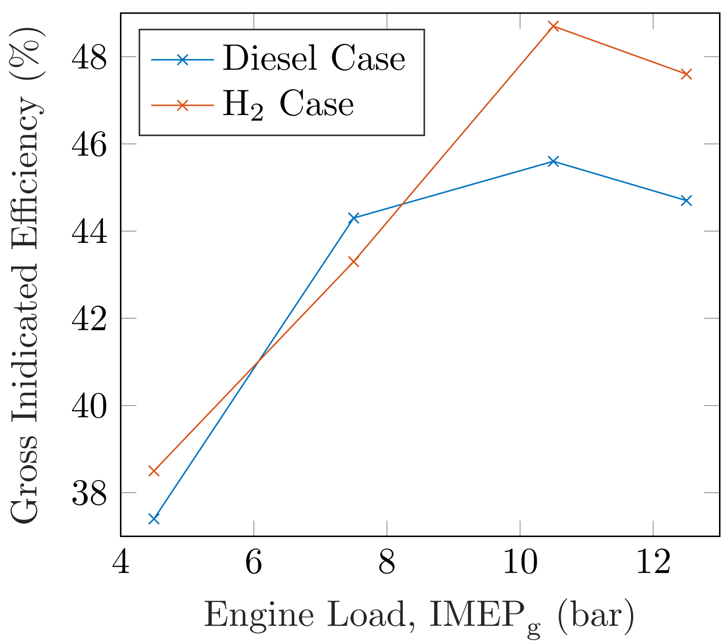

Figure 7: Engine thermal efficiency (H2/Diesel from Fig 3) with corresponding Diesel-only cases

engine efficiency and emissions. This understanding will be essential for commercialization. Further, our progress in machine learning control will be applied to HD2F to provide computationally efficient and expedite control algorithm calibration. These methods require both engine models and experimental data. We now have the ability to collect this critical experimental data in the controlled environment of the newly developed test-stand. This should both speed up current product development and improve the performance of the commercial products being developed and also allow further research and development into new products.

Clean Resources Metrics: For these clean resource metrics we have met or exceeded the project targets (Target/Actual) as per the table below

Metric	Target	Actual
$ in Data-Enabled innovated	$100,000	$100,000
TRL advancement	4 to 7	partner DTI TRL7+
Number of publications	2Jour, 4Conf	7Jour and 6Conf
$ in Clean Technology	$1,659,560	$1,659,560
Number of of field pilots/demonstrations	2 lab demos	2lab demos
Number of of HQSP trained	12	12:4PhD,3MSc,3BSc,2PDF
Number of Existing Sector HQSP jobs retained	8	8
Number of of new jobs from project	6	4
Number of projected jobs created	1250	1250
Number of Students	3PhD, 4 Msc	4 Phd, 3MSc
From future deployment partnership agreements MOUs	3	3
Number of New policies created	1	1
Number of New Products services	1	1
Number of New Spin-Off Companies created	1	1 DTI
Number of projected GHG emissions reductions from future deployment to 2030	500kt	500kt

We have also supported North American Construction Group in a feasibility project on converting large mining trucks to H2/Diesel by helping them establish baseline values of engine efficiency and emissions for pure Diesel operation using an engine dynamometer.
In this project, 12 HQP are being trained (7 graduate students, 2 PDFs and 3 undergraduate students).

Program Specific Metrics: Research contract with engine OEM (Cummins) now signed and 6.7 liter engine imported with Environment Canada approval. Simulation Model (GT Power) extended to H2/Diesel by adding a laminar flame speed model for H2. The GT model has been calibrated for Diesel/H2 and used as a "digital twin" to develop AI/ML engine control.

Project Success Metrics: These Project Success Metrics have been met or exceeded (more details below):

- HD2F technology lab demonstration - TRL 4 – done
- HD2F technology lab demonstration - TRL 7 – done
- Expand the blue hydrogen testing and R&D infrastructure – done
- HD2F Retrofit kit – through partner DTI

- Business scenarios and commercialization pathways – through Transition Accelerator, Global Edmonton, and DTI

Hydrogen Diesel dual Fuel (HD2F) has been demonstrated on the lab engine TRL 4 using prototyping control hardware – as shown in Figures 3 – 7 . Up to 85% Diesel replacement with H2 has been obtained at mid-load to 50% at high mid-load. Depending on the driving cycle of the particular truck application, 50% H2 replacement seems possible which should reduce CO2 by 50%. Further, initial engine fuel injection strategies have been identified to maximize H2 replacement (for CO2 reduction) and engine thermal efficiency while minimizing exhaust emissions and subject to engine durability considerations. the model predictive engine control has been combined with machine learning to speed up realtime computation. This allows implementation of machine learning control on low cost control hardware suitable for a vehicle.

Project Outputs: A list of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project is given in the reference section below. We have published the following papers relevant to this project [6, 7, 8, 4, 3, 9, 10, 11, 12, 13, 14].

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10 Benefits

Economic: this project is helping local companies develop products for converting existing trucks to hydrogen-Diesel. These products can be sold worldwide. This will create long lasting jobs and increased economic activity in Alberta. It is expected that HD2F will create immediate demand for hydrogen and thus help drive the hydrogen economy in Alberta.
Environmental: this project has the potential to both reduce Greenhouse Gases (GHG) and other harmful emissions such as soot from the heavy duty transportation sector. This could help improve urban air quality.
Social: this project is a high technology project which will help strengthen stakeholder involvement engine OEM (Cummins) and also provide entrepreneurship opportunities in the areas of machine learning, controls, in the hydrogen economy, in techno-economic assessment, and in measurement and testing.
Building Innovation Capacity: this project provided:

- Training in the areas of machine learning, controls, in the hydrogen economy, in techno-economic assessment, and in measurement and testing.

- Retained one HQP in a local company, attracted 3 students from Germany, recruited engine/testcell expert
- A full functioning full size truck engine testcell was developed with the following characteristics: (1) 500kW capacity; (2) dual fuel capability (liquid fuel is currently Diesel) and 70kg of 350 bar H2 onsite; (3) laboratory emissions measurement system - MKS FTIR system, and ; (4) high speed development controllers for rapid prototyping

11 Recommendations and Next Steps

The long term plan for commercialization of the technology is proceeding with a local company in Edmonton with support from (Cummins) (engine OEM). This is ongoing work where the machine learning control will be ported to cost effective production vehicle control hardware.
Based on the project learning and due to the increasing demand to further reduce GHG's the next steps to advance the innovation are: (1) use a combination of physics based models and measured data to reduce the amount of experimental data and to speed up development and calibration of the machine learning control - first using simulation, then in the testcell; (2) initiate 100% hydrogen combustion investigation for heavy duty transport - first using simulation, then in the testcell.

12 Knowledge Dissemination

Current Status:

- Hydra – collected extensive data on their truck that is part of the AMTA road show to provide baseline Diesel and H2/Diesel fuel and emissions data - completed
- DTI – on going communications about supporting their efforts in H2/Diesel. They have hired one of the graduate students from this project and we are working with them to develop version 2 of their engine control. DTI supported us in H2 infrastructure build including tank frames
- Diversified – initial communications on H2/Diesel and working with DTI to retrofit buses
- AMTA – working with them on H2 refueling and Portable Emission Measurement System (PEMS)
- Engine OEM (Cummins) we meet bi-weekly on control and diagnostics that is applicable to all power sources on mobile systems (engines/fuel cells/batteries)
- City of Edmonton Bus Fleet Operations – initial meetings on H2/Diesel Bus conversion and use of this facility

Future

- Continue to work with the above partners
- With DTI we have submitted an Expression Of Intent to Natural Resources Canada – On-road transportation de-carbonization for class 8 trucks

- Submitted an NSERC Alliance grant with engine OEM (Cummins) in a related area (Machine Learning Control)

- Engine OEM (Cummins) must approve all media reports if their name is mentioned so here is removed

With our project partner the Transition Accelerator and at the University of Alberta we have been engaging stakeholders in Government (Provincial, City and Federal) as well as commercial/non-profit (AMTA, Hydra, DTI, Innovative Fuel Systems, and the City of Edmonton). We have a strong partnership with engine OEM (Cummins) with two other ongoing projects in the area of machine learning controls and diagnosis that meet bi-weekly.
We have published the following papers relevant to this project [6, 7, 8, 4, 3, 9, 10, 11, 12, 13, 14]
A three month visit with RWTH Aachen has also been helpful in developing realtime capable model based control using machine learning.

13 Conclusions

Techno-economic assessment indicates that the introduction of retrofitted Diesel vehicles to accept hydrogen as a second fuel (i.e. HD2F technology), could provide a way to address the vehicle availability challenge. It would also create demand for fuel hydrogen and expand the network of hydrogen fueling stations thereby reducing them as a barrier for the deployment of the more efficient HFCE vehicles when they are eventually commercialized. This approach would help to introduce the LH, HD freight sector to hydrogen vehicles and fueling stations in a way that avoids range anxiety. For example, if hydrogen fuel is not available for a given trip, the HD2F vehicle would simply revert to a Diesel-only vehicle, and the trip is not at risk. Until an extensive hydrogen fuel network has been deployed, this flexibility of HD2F vehicles is seen by carriers as a very positive attribute of the HD2F vehicles compared to the HFCE alternative.
A full sized truck engine test cell has been commissioned and has the capability to run with Diesel and with hydrogen. Unique features of this testcell include 70kg hydrogen onsite, rapid prototype controllers, machine learning control expertise and implementation, laboratory grade emission measurements. This provides a unique capability in western Canada.
Preliminary results using the smaller engine in the lab results show that large H2 energy replacement of Diesel is possible. Tests with 0 – 90% Diesel replacement (by Diesel energy content) for low to high-mid load have been tested. At some mid-load operating points thermal efficiency gain of 10% over the equivalent Diesel only point was observed coupled with a reduction in CO2 corresponding to the H2 replacement - a very promising result.
The Techno-economic analysis done so far by the Transition Accelerator indicates that with an H2-Diesel ICE (40:60 by energy) would reduce GHG's by 32% for class 8 trucks. Further the conversion cost is estimated at $50,000 per truck while the current incremental cost of a fuel cell truck is $250,000 making this technology an excellent option for the transition to 100% H2.