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Preliminary investigation of the Wabtec NextFuel engine for hydrogen/diesel dual fuel operation

Fuels - Alternative & New Fuels

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ABSTRACT

The Wabtec NextFuel locomotive engine is a 4,500hp US EPA Tier 3-compliant engine capable of 100% diesel operation or dual-fuel operation using up to 75% natural gas with diesel ignition. A NextFuel engine was modified to evaluate hydrogen/diesel dual-fuel operation with the goal of reducing greenhouse gas emissions. At low power operation, up to 90% substitution was possible. At higher loads, substitution rates were limited to as little as 23%. Fast rates of combustion, pre-ignition and knocking were observed at high and low load operating conditions and limited further increases in hydrogen substitution. At the final operating conditions, particulate matter and CO2 emissions were significantly decreased while meeting Tier 3 emissions. Engine efficiency was similar to diesel operation at the same NOx emissions. These results suggest that dual-fuel hydrogen operation can provide a path for efficient operation with lower GHG emissions; however, more studies are required to understand the nature of the abnormal combustion events and their impact on reliability.

1 INTRODUCTION

Global efforts for decarbonization are transforming the transportation sector. While battery-powered vehicles are becoming increasingly prevalent in light-duty applications, full electrification remains challenging for heavy-duty long-haul transport, such as rail and marine. The U.S. Department of Energy recognizes hydrogen as a particularly well-suited solution for these applications, including locomotives [1]. Consequently, alternative decarbonization strategies are being explored, focusing on low-carbon, carbon-free, and renewable fuels compatible with internal combustion engines (ICEs) [2].

Hydrogen emerges as a promising fuel for large engines in the transportation sector. Its carbon-free nature, potential for production via electrolysis from renewable energy sources, and compatibility with future fuel cell technologies make it an attractive option. Hydrogen ICEs could facilitate the development of hydrogen infrastructure while fuel cell technology continues to mature. One significant advantage of hydrogen as a fuel is its ability to operate under very lean conditions, resulting in lower flame temperatures and consequently reduced NOx emissions [3,4,5]. This characteristic makes hydrogen particularly attractive for meeting stringent emission standards.

However, hydrogen's use as a fuel for ICEs presents several challenges that require thorough characterization including its low energy storage density compared to diesel, special material requirements to prevent leakage and embrittlement, and potential for abnormal combustion in ICEs, such as pre-ignition and knocking [3]. Understanding the benefits and challenges of hydrogen is crucial for the successful implementation of hydrogen as a low-carbon fuel.

To address the challenges and advance the use of hydrogen in heavy-duty applications, innovative approaches are needed. Wabtec, a global leader in freight locomotive production, is committed to developing clean and efficient technology solutions for future locomotives. Building on their experience with natural gas/diesel dual fuel locomotives, Wabtec has identified the NextFuel™ platform as ideal for initial performance testing of a hydrogen/diesel dual fuel engine [6,7]. This dual fuel locomotive has the potential to bridge the gap to a new fueling infrastructure because it can operate in a low-CO2 mode using a combination of diesel and carbon-free hydrogen when hydrogen is available but switch to 100% diesel in places where the hydrogen fuel is not available. Additionally, it is potentially a retrofit solution, making it easier and more cost-effective to convert a fleet of locomotives and this can accelerate the transition to the new fuel.

The use of hydrogen in ICEs has been the subject of numerous studies, with researchers exploring various aspects of engine performance, emissions, and operational challenges. Pre-ignition and knocking are significant concerns in hydrogen-fueled engines due to hydrogen's low ignition energy and high flame speed [3]. Previous studies have investigated these phenomena, noting their dependence on factors such as engine load, hydrogen equivalence ratio, and combustion phasing [4,8,9]. Research has shown that optimizing parameters such as injection timing, mixture formation, and scavenging processes can help mitigate abnormal combustion issues [5,10,11,12].

In this paper, we present a comprehensive study of a hydrogen-diesel dual-fuel engine adapted from a natural gas-diesel platform for locomotive applications. Our work builds upon previous research by examining pre-ignition and knocking phenomena across a wide range of conditions, with a particular focus on the effects of diesel injection timing and rail pressure. We also provide novel insights into hydrogen accumulation in the crankcase under various operating conditions. Furthermore, we assess the overall engine emissions and quantify the CO2 reduction potential of this technology in a real-world locomotive application. It is important to note that while there is a substantial body of research on hydrogen use in spark-ignited (SI) engines, there is significantly less literature specifically addressing diesel/hydrogen dual fuel engines. This scarcity of directly applicable research makes our study particularly unique and important, as it bridges a significant gap in the current understanding of hydrogen use in heavy-duty applications.

By addressing these critical aspects of hydrogen dual-fuel engine operation, our study aims to extend the state of knowledge of hydrogen combustion for dual fuel ICEs while targeting practical implementation in heavy-duty long-haul transportation. Given the limited research on diesel/hydrogen dual fuel engines, our findings contribute significantly to filling this knowledge gap and provide valuable insights for the future development of hydrogen-powered locomotives.

The remainder of this paper is organized as follows: Section 2 details our experimental setup, Sections 3-6 present our findings related to key aspects of hydrogen dual fuel engines and Section 7 concludes with a summary and recommendations for future research and development of hydrogen-powered locomotives.

2 EXPERIMENTAL SETUP

For this study, we employed an EVO NextFuel™ medium speed dual fuel engine and controller, representing a state-of-the-art platform for heavy-duty locomotive applications. This EPA tier 3 capable V12 engine, with a rated power output of 4500 GHP (3355 kW), exemplifies cutting-edge technology in the field of dual-fuel systems. Table 1 summarizes the key specifications of this engine. The engine utilizes a high-pressure common rail system for precise diesel fuel delivery, complemented by a multi-port fuel injection system for the alternative fuel, in this case, hydrogen. To maintain consistency with previous research and ensure comparability of results, we retained the baseline NextFuel™ compression ratio of 15:1 and associated engine hardware for this testing phase. However, the air-handling system for the engine is simplified from the production engine leading to performance results that are similar to the production hardware, but not exactly the same. This is particularly notable in the higher than usual CO and HC emissions during natural gas dual fuel testing.

Table 1: Specifications of the EVO NextFuel™ Medium Speed Dual Fuel Engine.

Parameter	Units	Value
Number of Cylinders		12
Max Cont. Rating	kW	3355
Max Speed	RPM	1050
Min Speed	RPM	300
Number of Valves/Cyl		4
Compression Ratio		15:1
Cylinder Bore	mm	250
Cylinder Stroke	mm	320

Locomotives are characterized at specific power settings called notches. The notches range from Idle to Notch 8 with idle generating no power and Notch 8 generating 100% of rated power. Table 2 shows the relative power ratings for each of the notches for the engine used in this study.

The hydrogen substitution ratio (SR) was calculated based on the energy content of the fuels as shown in Equation 1 where m_g and m_d represent the mass quantity of gaseous and diesel fuel injected into the cylinder and LHV_g and LHV_d represent the lower heating value of the two fuels. This calculation of SR represents the fraction of the total fuel energy provided by hydrogen, calculated as the energy content of the hydrogen divided by the sum of the energy content of both hydrogen and diesel fuel. This method allows for a consistent comparison of performance across different operating conditions.

Table 2: Percent of rated power at each notch.

Notch	Percent of Rated Power
Idle	0
Notch 1	7
Notch 2	13
Notch 3	28
Notch 4	39
Notch 5	52
Notch 6	69
Notch 7	84
Notch 8	100

Prior to commencing hydrogen testing, we conducted a comprehensive review of the engine design to identify and mitigate potential risks associated with hydrogen as an alternative fuel. This assessment led to several critical modifications to ensure safe and reliable operation. Firstly, we modified the port fuel injection system to address the unique challenges posed by hydrogen, particularly focusing on enhanced sealing to prevent leakage and mitigating the risk of hydrogen embrittlement in system components.

$$SR[\%] = \frac{m_g LHV_g}{m_d LHV_d + m_g LHV_g} \quad (1)$$

Furthermore, recognizing the potential for rapid pressure rise in case of abnormal combustion events with hydrogen, we implemented robust safety measures. As illustrated in Figure 1, the engine crankcase, intake manifold, and exhaust manifold were all fitted with carefully designed explosion relief provisions. These modifications serve as safeguards, allowing for controlled release of pressure in the unlikely event of an explosion, thereby protecting the engine's structural integrity and ensuring operator safety.

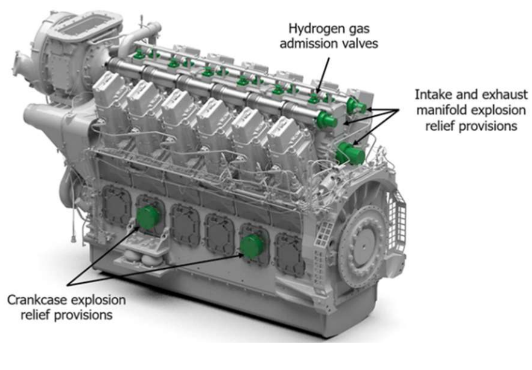

Figure 1: Modified EVO NextFuel™ Engine with Hydrogen-Specific Safety Features.

The hydrogen gas admission valves are positioned along the top of the engine, ensuring precise and efficient delivery of the gaseous fuel. These valves, highlighted in green in the image, were modified in response to the potential challenges of sealing and embrittlement that is associated with hydrogen gas. The valves were also modified for higher flow rates to enable shorter injection durations.

The experimental test cell included the previously described NextFuel™ engine coupled to a water brake dynamometer. The test facility utilized heat exchangers to achieve intake manifold temperatures and pressures representative of a North American heavy haul locomotive application. The hydrogen fuel was conditioned and delivered to the engine in gaseous form at prescribed temperatures and pressures. A Gast R4P vacuum pump was connected to the crankcase ventilation outlet in order to provide precise control over crankcase vacuum conditions. A crankcase mounted vacuum sensor was used for closed loop control of the vacuum pump variable speed motor and flow conditions were captured using a J-TEC VF563 flow meter.

For accurate in-cylinder pressure measurement, each cylinder was equipped with an AVL QC34D flush mounted, water-cooled pressure transducer. The test apparatus also included hydrogen concentration measurement sensors that provided 1Hz feedback. Data acquisition was used to capture standard engine parameters as well as crank angle resolved cylinder pressures. Cylinder pressure data were used to calculate heat release crank angles and durations as well as maximum rate of pressure rise and other pertinent combustion characteristics. Real time monitoring of the crank angle at 10% of heat release proved to be useful in identifying changes in combustion stability.

Neoxid NEO974HT sensors were used to sample hydrogen concentration in the crankcase as well as the intake manifold, while a Neoxid NEO983HT was used for exhaust manifold gas sampling. Gaseous exhaust emissions were measured with a state-of-the-art emissions bench. Particulate emissions were measured using an AVL415-S smokemeter that was previously correlated with gravimetric particulate data.

With the experimental setup fully configured and calibrated, we proceeded to conduct a comprehensive series of tests to evaluate the engine's performance under various operating conditions. The following section presents the results of these tests, focusing on key performance metrics such as power output, efficiency, and emissions. By analyzing these parameters across different hydrogen substitution ratios and engine loads, we aim to provide insights into the potential and challenges of hydrogen-diesel dual-fuel operation in locomotive applications.

3 COMBUSTION ANALYSIS AND IN-CYLINDER PRESSURE CHARACTERISTICS

The performance of the hydrogen-diesel dual-fuel engine was evaluated across a range of operating conditions to assess its viability as a low-carbon alternative for locomotive applications. Testing showed nominal hydrogen dual fuel combustion to be comparable to the natural gas dual fuel combustion observed in prior NextFuel™ dual fuel engine testing. At high loads, fast rates of combustion and knocking phenomenon similar to those in natural gas operation were also observed with varying severity and frequency. The existing control algorithms and knock strategies discussed by Yerace et. al demonstrated adequate control of the engine to enable reuse of these strategies for this testing [7]. Unlike natural gas operation, hydrogen dual fuel operation was not limited by lean air-fuel ratio concerns, so dual fuel modes were achievable at Notch 1 and 2 operating points without modification of control strategies. Knock was observed across a wider range of operating points, occurring with hydrogen at power levels below those which are knock limited on natural gas.

Pre-ignition was found to intermittently occur during hydrogen dual fuel operation. This phenomenon had not been previously observed in natural gas dual fuel operation of the NextFuel™ engine. Early ignition of hydrogen, often prior to the start of diesel injector current, happened more frequently than knock and had varying severity dependent upon the crank position at the start of combustion and the quantity of hydrogen, with earlier ignitions and higher substitution ratios tending towards higher peak pressures. While variations in operating parameters could reduce the frequency of preignition events, no method was found to completely avoid them during operation with meaningful quantities of hydrogen substitution. This necessitated limiting operation to conditions where pre-ignition could not generate enough pressure to cause immediate damage if the hydrogen were to fully combust prior to top dead center (TDC). This restriction becomes the most limiting factor to substitution ratio (SR) at rated power, where the largest quantities of hydrogen are required to achieve a given SR and nominal combustion is closest to the hardware design limits.

It was observed that abnormal combustion cycles were not evenly distributed and tended to be clustered in successive combustion cycles. Select in-cylinder pressure traces from one such cluster of abnormal combustion modes is shown in Figure 2 These traces were taken at a constant engine speed, load, start of injection, and substitution ratio over a short period of time from a single cylinder. This sequence of events included cycles in which knock and pre-ignition occurred independently of each other, as well as a single cycle with both phenomenon present.

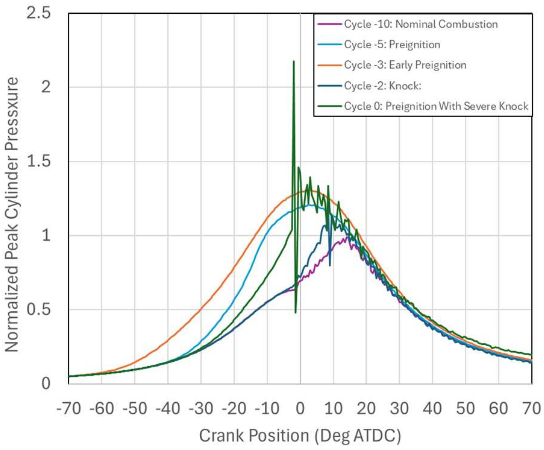

Figure 2: Example in-cylinder pressure traces for different combustion modes.

Select combustion characteristics from the full sequence of combustion events including the traces in Figure 2 are shown in Figure 3. The sequence begins with relatively stable combustion, heat release consistently beginning near top dead center and a consistent peak pressure magnitude and location. Six cycles prior to the severe knock event, the location of peak pressure moves earlier while peak pressure rises, indicative of a faster rate of combustion. This was followed by pre-ignition events with early starts of heat release, a knocking event without preignition, and ultimately a severe knock event with preignition. After this severe event, abnormal combustion continued for a further 13 cycles until the cylinder returned to a stable condition.

The relationship between these combustion phenomena, if any, and the mechanism driving the clustering behavior of abnormal combustion is not yet understood and is an area for further study. What is known is that as the quantity of hydrogen fueling was increased, the frequency of all abnormal combustion modes tended to increase, as did the resulting peak cylinder pressures. Avoiding this undesirable combustion activity was one of the primary limitations on increased hydrogen substitution, especially at higher operating notches.

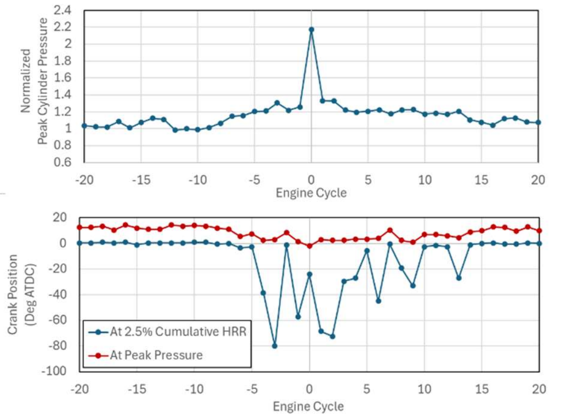

Figure 3: Per-cycle combustion indicators for successive engine cycles.

4 ANALYSIS OF HYDROGEN-DIESEL DUAL-FUEL ENGINE PRE-IGNITION BEHAVIOR

Pre-ignition in hydrogen-diesel dual-fuel engines presents a significant challenge due to hydrogen's low ignition energy and high flame speed. This analysis focuses on characterizing maximum hydrogen substitution ratio (SR) at different operating conditions, examining pre-ignition and its sensitivity to engine parameters like diesel injection timing and pressure. Pre-ignition was characterized using an arbitrarily selected pre-ignition metric (PIM) calculated from the heat release rate. The PIM is equal to the standard deviation of CA10, calculated from the high-speed cylinder pressure data. In this preliminary testing, the PIM was found to correlate strongly with the fraction of pre-ignitions and was straightforward to calculate in real time during testing without the need for additional post-processing. The metric is unitless and indicates whether the frequency of pre-ignitions is increasing but does not actually indicate pre-ignition frequency. In future work, pre-ignition counting algorithms will be tested to provide more quantitative metrics of preignition frequency.

At Notch 7 (nIMEP ~19.7bar), Figure 4 shows the frequency of abnormal combustion versus injection timing for different hydrogen substitution ratios. As SR increases, PIM rises. Interestingly, advancing injection timing decreases abnormal combustion frequency. This trend may be explained by earlier initiation of normal combustion, consuming hydrogen before conditions conducive to pre-ignition develop. Advanced timing alters temperature and pressure profiles throughout the cycle, potentially creating less favorable conditions for pre-ignition. It's important to note that pre-ignition, by definition, occurs before diesel injection. Therefore, the direct interaction between diesel spray and H2-air mixtures doesn't impact pre-ignition. However, this interaction could indirectly affect subsequent cycles by influencing hot spot formation or exhaust residual conditions. To increase SR while limiting abnormal combustion, early injection timing should be used. However, very early injection may lead to excessive peak cylinder pressures and NOx emissions, highlighting the complex trade-offs in dual-fuel engine optimization.

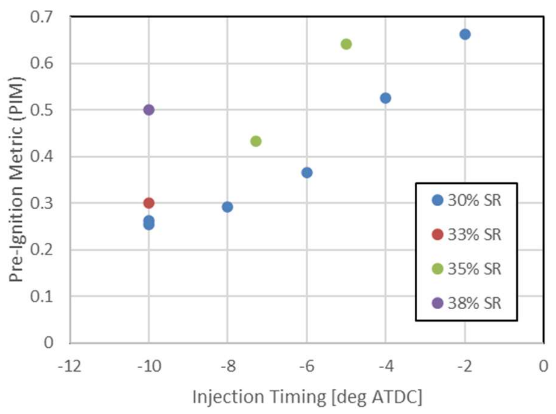

Figure 4: PIM versus diesel injection timing at Notch 7 (nIMEP ~19.7 bar) for various hydrogen substitution ratios (SR).

Moving to a lower power setting, Notch 4 data (nIMEP ~ 10.7bar) shows more flexibility in maximizing SR. Figure 5 illustrates abnormal combustion frequency versus SR, rail pressure, and injection timing. Consistent with Notch 7, earlier injection timings reduce abnormal combustion likelihood. However, unlike Notch 7, increasing rail pressure at Notch 4 leads to higher abnormal combustion frequency, contrary to expectations. This rail pressure effect provides new insights into combustion dynamics. Higher pressures likely accelerate combustion due to faster injection and deeper fuel penetration. The observation that this increases pre-ignition frequency suggests a complex relationship between injection parameters and pre-ignition, beyond simple mixing time influences.

Notch 5 (nIMEP ~ 12.7bar) presents a more complex scenario. Figure 6 reveals a divergence in pre-ignition behavior between 4-degree and 8-degree injection timings at higher SR values. Notably, and in contrast to the trends observed at Notches 7 and 4, the more advanced timing (8 degrees) appears to result in more pre-ignition at higher SR values. This unexpected behavior underscores the complexity of optimizing dual-fuel engine parameters across different operating conditions.

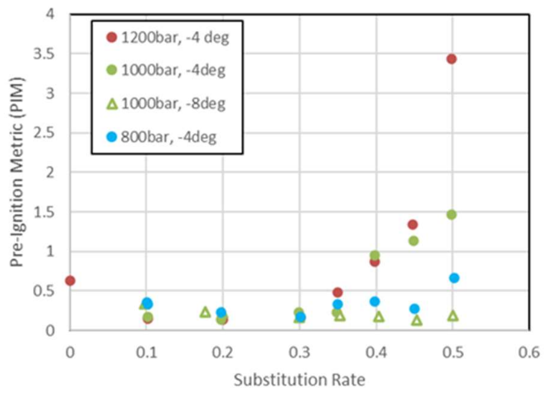

Figure 5: PIM as a function of hydrogen substitution ratio (SR), rail pressure, and injection timing at Notch 4 (nIMEP ~10.7 bar).

The effect of injection timing on pre-ignition varies significantly across notches. At Notches 7 and 4, advancing injection timing generally reduces pre-ignition frequency. However, Notch 5 exhibits a contrasting trend, where more advanced timing (8 degrees) leads to increased pre-ignition at higher substitution ratios. This variability underscores the complex relationship between injection timing and pre-ignition behavior across different power settings. While combustion temperatures aren't strongly affected by power level due to constant compression ratio, surface temperatures may increase at high loads, potentially influencing pre-ignition behavior. The air-fuel ratio (AFR) and combustion timing have a more significant impact on combustion temperatures. The observed increase in pre-ignition events with higher hydrogen substitution rates is consistent with results reported in the literature for SI engines.

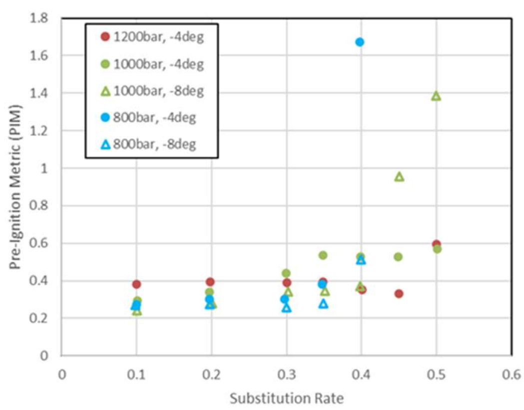

Figure 6: PIM at Notch 5 (nIMEP ~12.7 bar) comparing 4-degree and 8-degree injection timings across various hydrogen substitution ratios (SR).

In conclusion, this analysis highlights the intricate relationships between hydrogen substitution ratio, injection parameters, and engine operating conditions in a hydrogen-diesel dual-fuel engine. The varying and sometimes counterintuitive effects of injection timing and rail pressure across different notches emphasize the need for more detailed and fundamental studies as well as careful optimization at each operating condition. These findings have significant implications for engine design and control strategies, suggesting that a one-size-fits-all approach is unlikely to yield optimal performance across the entire operating range of a hydrogen-diesel dual-fuel engine. These findings provide crucial insights for optimizing engine parameters to mitigate pre-ignition risks in hydrogen-diesel dual-fuel operations.

While managing pre-ignition is critical for combustion control, another important aspect of hydrogen-diesel dual-fuel engine operation is the behavior of gases that escape past the piston rings into the crankcase, known as blowby. The unique properties of hydrogen, particularly its low density and high diffusivity, can lead to increased concentrations in the crankcase, potentially affecting engine lubrication and safety. To comprehensively assess the viability of hydrogen as a fuel in locomotive applications, it is essential to understand these crankcase dynamics. The following section presents our analysis of crankcase flow and blowby, providing insights into this often-overlooked aspect of hydrogen-diesel dual-fuel engine operation.

5 CRANKCASE FLOW AND BLOWBY ANALYSIS

The analysis of crankcase ventilation is crucial for ensuring the safety and reliability of hydrogen in a dual-fuel engine. Total crankcase flow is comprised of cylinder blow-by, turbocharger compressor seal bleed flow, and fresh air intake past the crankcase seal. Measurements were performed at various Crankcase Pressure (CCP) ranges across different notches, simulating conditions typically observed over an engine's lifetime.

A labyrinth drive end seal is employed in the current system, which serves as a source of fresh air into the crankcase as CCP decreases. As expected, total crankcase flow was observed to increase with lower CCP, primarily due to increased fresh air intake past the crankcase seal. This was validated by measurements of crankcase flow at different CCP levels after engine shutdown. Additionally, blow-by flow rate increased with increasing engine power due to the higher cylinder pressures at high engine power.

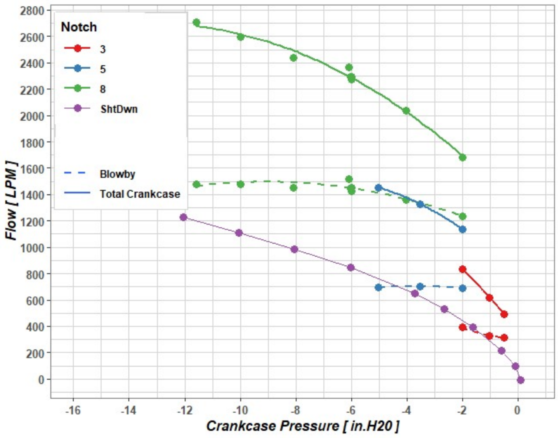

Figure 7: Total crankcase flow and derived blowby flow for different power levels and crankcase vacuum settings.

The relationship between total crankcase flow, estimated blow-by flow, power levels, and CCP settings is illustrated in Figure 7. Blow-by flow rate was found to be sensitive to CCP when the CCP was near zero, but was insensitive to CCP when CCP was sufficiently low. Interestingly, similar sensitivity to CCP was noted in Notch-3 blow-by flow in the range of -2 to 0 in H2O as was seen in Notch-8 in the range of -5 to -2 in H2O. In contrast, little sensitivity of blow-by flow rate to CCP was observed in Notch-5 in a similar CCP range. These observations suggest that blow-by may be affected by in-cylinder boundary conditions and ring dynamics.

In the current system, hydrogen concentration in the crankcase is maintained lower than 4% by volume using dilution with fresh air, which often required lower CCP than the engine would experience in the field. For conditions with higher CCP, particularly at lower powers where the CCP is already relatively close to zero, diesel-only operation was used to obtain flow measurements.

To limit hydrogen concentration in the crankcase outside the flammability range, dilution with external air is a viable option. This can be achieved by designing for specific labyrinth seal flow characteristics and possibly additional active ventilation of the crankcase to reduce CCP below the levels of todays production engines.

Hydrogen concentration in the crankcase can be estimated if the crankcase flow rate, the blowby flow rate, and the hydrogen/air ratio in the intake manifold are known. The blowby hydrogen concentration was estimated by assuming perfect air-hydrogen mixing and neglecting blowby of the combustion products. The hydrogen concentration in the crankcase can then be estimated based on the ratio of blow-by flow to total flow through the crankcase. Since blowby flow of post-combustion gases is neglected, it is expected that this calculation will over-estimate the crankcase hydrogen concentration.

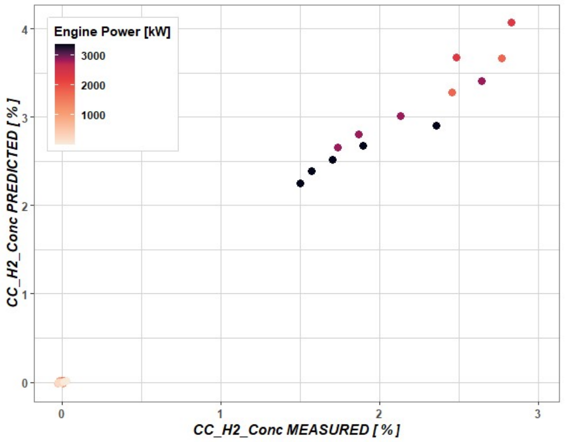

Figure 8: Predicted hydrogen concentration in the crankcase versus measured hydrogen concentration in the crankcase.

A comparison of the predicted hydrogen concentration in the crankcase to the measured hydrogen concentration is provided in Figure 8. This comparison offers insight into the margin to operating limits and suggests that strategies to control the hydrogen concentration in the crankcase involve decreasing the blowby flow rate or increasing the crankcase dilution rate.

The predicted concentrations are consistently observed to be higher than measured, indicating two key points:

- A portion of blow-by is split across pre-combustion and post-combustion phases.
- The prediction is conservative and can be used to limit or estimate crankcase hydrogen concentration for different operating conditions.

These findings are considered to have significant implications for the design and operation of hydrogen-diesel dual-fuel engines, particularly in managing crankcase conditions and optimizing engine performance across various operating parameters. Future research should focus on refining these predictions and developing more sophisticated models for crankcase hydrogen concentration under different operating conditions. Additionally, the effects of aged or damaged pistons, rings, and cylinder liners should be considered to better evaluate the crankcase conditions over a locomotive's lifetime.

6 EMISSIONS ANALYSIS

The motivation for investigating a hydrogen/diesel dual fuel engine is to improve the global warming footprint of locomotive engines. Hence the greenhouse gas emissions are important for this engine, but other criteria pollutant emissions must also be controlled for this to be a viable technology. This section describes the emissions characteristics of the hydrogen dual fuel engine across a range of operating conditions. The analysis focuses on how varying hydrogen substitution ratios (SR) affect different emissions and performance metrics at various engine power levels, or notches.

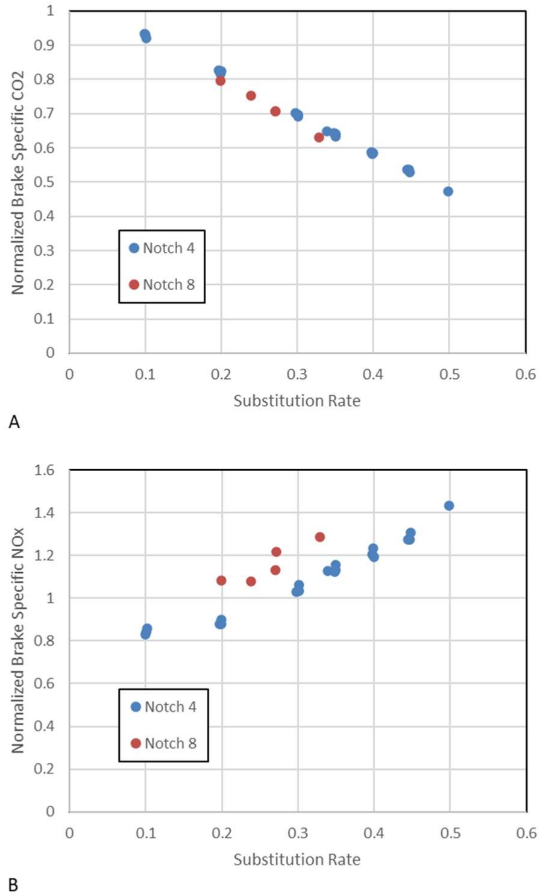

Figure 9: Effect of hydrogen substitution rate on (A) normalized brake specific CO2 emissions and (B) normalized brake specific NOx emissions for Notch 4 and Notch 8 operating conditions.

Figure 9 illustrates a key finding of this study: the trade-off between CO2 reduction and NOx emissions as hydrogen SR increases for constant diesel injection timing. Figure 9A shows that a 20% increase in SR led to a 30% decrease in CO2 emissions. However, as seen in Figure 9B, this environmental benefit comes with a 30% increase in NOx emissions. This inverse relationship was consistent across different power levels, including 100% rated load (Notch 8) and 40% rated load (Notch 4), suggesting that the CO2 reduction benefit of increased hydrogen substitution is accompanied by increased NOx emissions, likely due to faster or advanced combustion. Additional engine tuning can mitigate the NOx increase to provide a net CO2 benefit at NOx parity.

It's important to note that, with this hardware configuration, excessive abnormal combustion was observed at substitution ratios above 50% for Notch 4 and 35% for Notch 8, preventing further SR increase. This limitation indicates an optimal range for hydrogen substitution, balancing emissions reductions with engine stability and performance.

Figure 10 provides insight into NOx emissions behavior at very low power levels. For Notches 1 and 2, representing power levels below 10% rated power, NOx emissions showed an interesting trend reversal. Initially increasing with hydrogen SR up to about 50%, NOx then decreased, even falling below baseline diesel-only levels at very high substitution ratios (above 90%). This suggests potential benefits of hydrogen dual fuel technology for low-load operations. As the SR is increased above 50% at these low power conditions, the diesel quantity becomes very small and the combustion event becomes dominated by the flame propagation of the very lean hydrogen-air mixture. As described in much of the H2-ICE literature, a lean pre-mixed hydrogen-air flame can provide a stable combustion event while generating only small amounts of NOx. These results suggest one strategy for providing high SR and low NOx emissions simultaneously by controlling the diesel quantity to very small amounts.

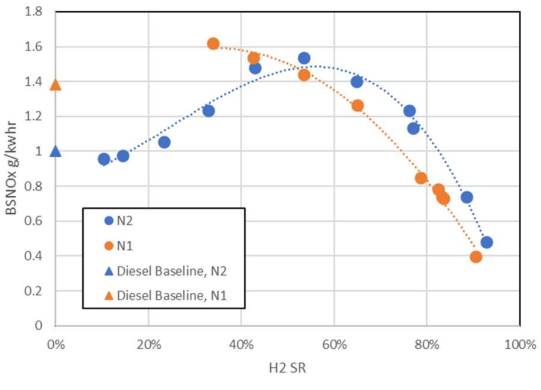

Figure 10: BSNOx emissions vs. hydrogen substitution ratio (H2 SR) for Notch 1 (N1) and Notch 2 (N2) conditions. Diesel baseline values are shown for reference.

To address increased NOx at higher substitution ratios at higher power levels, several engine control strategies were employed. For power levels between 40-50% rated power, a combination of retarded diesel injection timing and lowered diesel rail pressure was used. These adjustments were facilitated by the reduced particulate matter emissions associated with increasing hydrogen substitution.

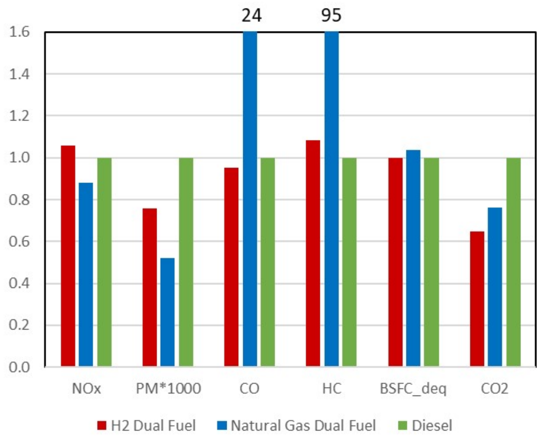

Figure 11: Comparison of normalized emissions and performance metrics for H2 Dual Fuel, Natural Gas Dual Fuel, and Diesel engines. Note that CO and total HC values for Natural Gas Dual Fuel exceed the chart scale.

Figure 11 represents the culmination of this emissions analysis, providing a comprehensive comparison of this engine operating as a hydrogen dual fuel engine, a traditional diesel and a natural gas dual fuel engine. This figure shows the duty-cycle rollup, a weighted average over all notches, offering a holistic view of emissions and performance metrics.

At a ~30% duty-cycle-averaged hydrogen substitution ratio, the hydrogen dual fuel engine achieved a 35% CO2 reduction from the diesel baseline, outperforming the natural gas dual fuel configuration, which only managed a 25% CO2 reduction at a ~75% duty cycle CH4 substitution ratio. Total hydrocarbon emissions were marginally increased compared to the 100% diesel case but drastically reduced (over 90%) compared to natural gas dual fuel. This is because hydrogen does not contain carbon and so unburned fuel does not generate unburned hydrocarbon or CO emissions and furthermore hydrogen has a broader flammability limit so it combusts more completely and can assist in the completion of combustion of the diesel fuel.

The hydrogen dual fuel engine maintained diesel equivalent specific fuel consumption comparable to 100% diesel operation, while showing significant improvement over natural gas dual fuel. Carbon monoxide emissions were marginally lower than those of the 100% diesel configuration but reduced by over 90% compared to natural gas dual fuel. Particulate matter was reduced by 40% compared to 100% diesel and was equivalent to natural gas dual fuel performance.

These results highlight hydrogen's potential as a cleaner alternative fuel, particularly in reducing greenhouse gas emissions and improving air quality. However, NOx emissions remain a key challenge, requiring careful balancing against fuel consumption and substitution ratio.

In conclusion, while the hydrogen dual fuel engine demonstrates promising results in CO2 reduction and overall emissions performance, challenges in NOx control and high substitution ratio stability persist. Future research should focus on advanced combustion control strategies to mitigate NOx formation while maintaining CO2 reduction benefits, as well as long-term durability studies to assess the impact of hydrogen combustion on engine components. The potential benefits of this technology make it an important area for continued development in the pursuit of cleaner transportation solutions.

7 SUMMARY

This comprehensive study examined the performance, emissions, and operational characteristics of a hydrogen-diesel dual fuel engine adapted from a natural gas-diesel platform for locomotive applications. The research aimed to evaluate the potential of hydrogen as a low-carbon fuel alternative while addressing key challenges associated with its use in internal combustion engines.

The experimental setup utilized a EVO NextFuel™ medium speed dual fuel engine, modified with hydrogen-specific safety features and instrumented for detailed combustion and emissions analysis. Testing was conducted across a range of operating conditions, focusing on combustion behavior, pre-ignition phenomena, crankcase dynamics, and emissions performance.

Key findings from the combustion analysis revealed that hydrogen dual fuel operation was more prone to knock than the natural gas dual fuel configuration and knocking was experienced at lower power levels for hydrogen dual fuel than for natural gas dual fuel. Additionally, pre-ignition events, not previously observed with natural gas, occurred intermittently during hydrogen operation. These events were more frequent at higher substitution ratios and became a limiting factor for hydrogen utilization, particularly at rated power.

The pre-ignition analysis demonstrated complex relationships between hydrogen substitution ratio, injection parameters, and engine operating conditions. Advancing injection timing generally reduced pre-ignition frequency, but this trend was reversed at some intermediate power levels. These findings highlight the need for careful optimization of engine parameters across different operating conditions to mitigate pre-ignition risks.

Crankcase flow and blowby analysis revealed the importance of managing hydrogen concentration in the crankcase. The study found that dilution with fresh air could effectively maintain hydrogen levels below the flammability limit. A predictive model for crankcase hydrogen concentration was developed, providing a conservative estimate for operational guidance.

Emissions analysis demonstrated significant potential for CO2 reduction with hydrogen dual fuel operation. When substitution ratio was increased without changing the other engine control parameters, CO2 could be reduced by as much as 35% at rated power and over 50% at part load. However this results in a ~30-40% increase in NOx emissions, presenting a key challenge for future development. By adjusting the engine control parameters, NOx could be reduced and at a 30% duty-cycle-averaged hydrogen substitution ratio, the engine achieved a 35% CO2 reduction compared to the diesel baseline, outperforming natural gas dual fuel.

The study identified several areas requiring further investigation:

- The mechanism driving the clustering behavior of abnormal combustion events, particularly the relationship between knock and pre-ignition.
- Refinement of predictive models for crankcase hydrogen concentration under various operating conditions.
- Advanced combustion control strategies to mitigate NOx formation while maintaining CO2 reduction benefits.
- Long-term durability studies to assess the impact of hydrogen combustion on engine components.
- Optimization of injection parameters and combustion phasing across the full operating

range to maximize hydrogen substitution while minimizing abnormal combustion events.

- Investigation of strategies to increase hydrogen substitution ratios at high power levels without compromising engine stability or safety.
- Further exploration of the potential benefits of hydrogen dual fuel technology for low-load operations, where NOx emissions showed promising reductions at very high substitution ratios.
- Development of more sophisticated models to understand and predict pre-ignition behavior across different operating conditions.

In conclusion, this study demonstrates the significant potential of hydrogen-diesel dual fuel technology for reducing greenhouse gas emissions in locomotive applications. While challenges remain, particularly in controlling NOx emissions and managing abnormal combustion at high substitution ratios, the overall performance improvements and emissions reductions warrant continued research and development. Future work should focus on addressing the identified challenges and optimizing engine performance across all operating conditions to fully realize the benefits of this promising technology in the pursuit of cleaner transportation solutions.

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR: Air-Fuel Ratio

CCP: Crankcase Pressure

nIMEP: net Indicated Mean Effective Pressure

PIM: Pre-ignition metric

PM: Particulate Matter

SI: Spark-Ignited

SR: Substitution Ratio

TDC: Top Dead Center

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