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Investigation of Diesel Engine Performance Using Water Diesel Emulsion

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Abstract
The investigation of water diesel emulsion (WDE) with 13% of water by mass on engine performance and exhaust emissions in a direct injection diesel engine was performed experimentally. The strategy followed in this work was to perform experimental work at different engine speeds and loads using automotive diesel (AD) fuel as reference for comparison reasons. Results showed an increase in brake specific fuel consumption when using WDE compared to AD.

1. Introduction

The presences of water in diesel fuel have been investigated by others. In a previous study conducted by Langer et. al. [1], they showed more than 19% increase in BSFC when 20% water emulsion was used. Abu-Zaid [2] found that as water content percentage increases in the emulsion (20%), BSFC increased significantly by more than 35% at high engine speeds. Other studies have shown contradictory results. Samec et. al. [3] found that using emulsion did not worsen BSFC. This conclusion has also been found by others [4, 5].

2. Experimental Conditions and Data Collection

Experimental work was conducted at two engine loads and six engine speeds as shown in table 1.

Table 1: Engine Speeds and loads considered in this work.

Engine speed (RPM)	Load (N.m)	
1200	150	200
1400	150	200
1600	150	200
1800	150	200
2000	150	200
2200	150	200

Each test point data represents an average of three sample points for the engine performance data per indicated. Since fuel consumption represents the most crucial reading in engine performance data, the maximum variation allowed in the repeated samples was +/- 5% from one sample point to another. The high-pressure injection pump (maximum of 600BAR) heated the return fuel thus heating the fuel in the 12L measurement tank. Therefore, between every test point the measurement fuel tank was replaced with a fully fuelled tank at the test cell ambient temperature. To start collecting engine data, the engine was operated with no load at a higher engine RPM than required to account for the engine speed drop once the load was applied by the dynamometer. The load was applied gradually then kept constant until the engine reached steady state. The steady state condition was satisfied once engine coolant reached a constant temperature. The engine performance acquisition system was set to automatically record data until a threshold value of 150 grams of fuel was consumed to minimize uncertainties in the measurements.

3. Effect of WDE on Engine Performance

Using the measurements of fuel and air consumption rates, engine speed and load, the engine performance data are shown in this section. Figures 1 and 2 show the brake specific fuel consumption (BSFC) for both fuels at all engine speeds and both loads. For WDE only diesel fuel mass flow is considered in BSFC calculation while water is ignored. At low speeds, the heat loss to the combustion chamber walls is high and combustion efficiency is low which result in higher BSFC. As engine speed increases, the friction power increases at a rapid rate resulting in a slow increase in the power than in fuel consumption and consequently increases BSFC. The BSFC for WDE is higher than that of AD by 8%. As engine speed increases, the variation in BSFC between the two fuels decreases to 5% for both loads.

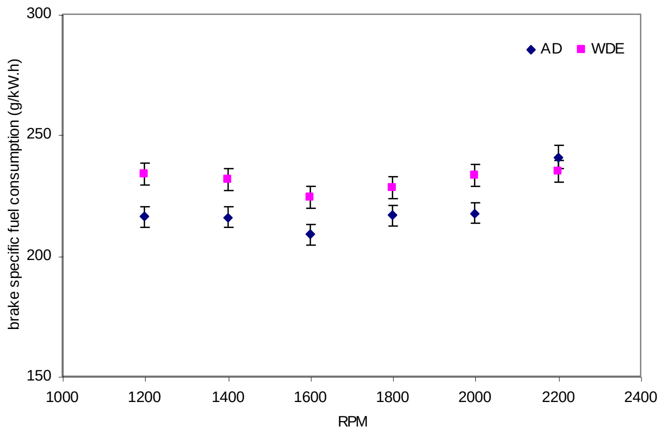

Figure 1: brake specific fuel consumption (BSFC) for the two fuels at all engine speeds and 150N.m.

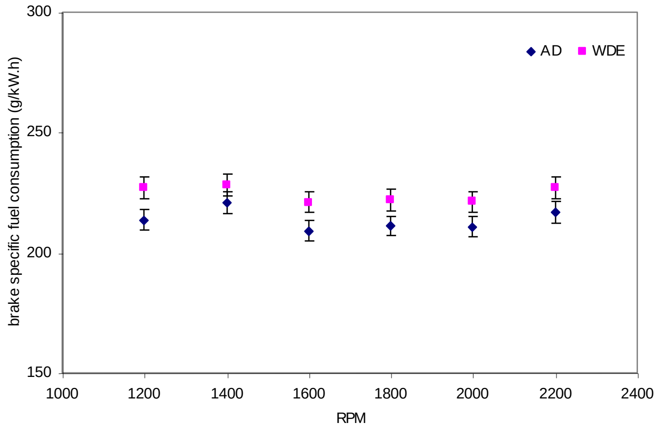

Figure 2: brake specific fuel consumption (BSFC) for the two fuels at all engine speeds and 200N.m.

From the engine performance results shown above, the maximum BSFC for WDE is much higher than that of AD. This indicates that if an existing engine, with pump-line-nozzle fuel injection system, is to be operated on WDE, more fuel needs to be injected for the same power output. If this engine were to be operated well below the rated power, there won't be any need for any modifications to the fuel injection system. However, if the WDE engine is to perform the same as the base engine, high-capacity injectors and possibly a larger fuel injection pump would be required. In addition, the injection timing may have to be optimized for better fuel consumption. In Figures 3 and 4, the term lambda represents the ratio of actual air fuel ratio to the stoichiometric air fuel ratio (inverse of equivalence ratio EQ_R). It is apparent that the air fuel ratio for WDE is lower than that of AD at both loads. This results from the higher fuel consumption of WDE due to its lower fuel input energy. At higher engine load the variation in lambda between the two fuels becomes bigger for all engine speeds. The higher engine load will reduce the values of lambda for both fuels because of the higher fuel consumption. Lambda is almost constant with engine speed for both fuels, however the increase in engine load has a significant effect on decreasing lambda at any engine speed compared to the same engine speed at lower load. In general, the maximum percentage of reduction in lambda with the increase in engine load (33% increase) for both fuels is almost the same which is 24%.

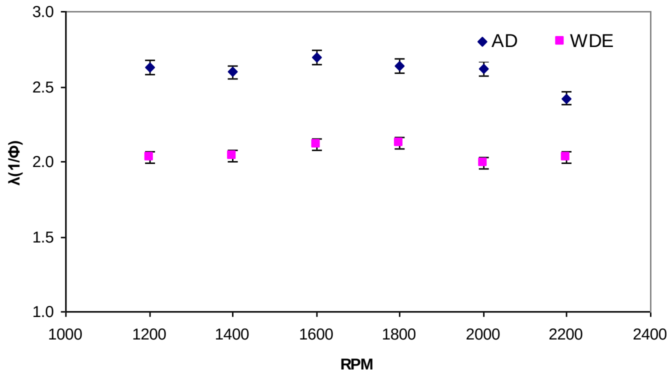

Figure 3: Relative A/F ratio for the two fuels at all engine speeds at 150N.m

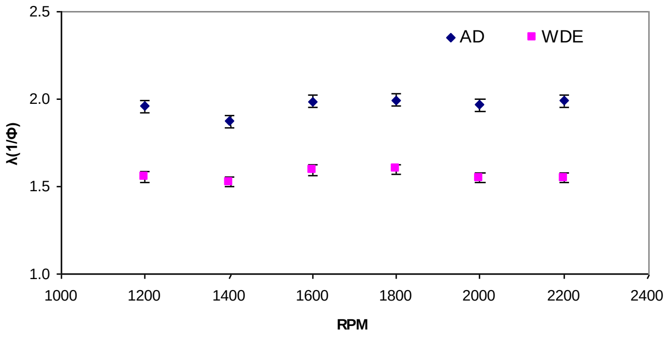

Figure 4: Relative A/F ratio for the two fuels at all engine speeds and 200N.m

Figures 5 and 6 show the exhaust temperatures for both fuels at all engine speeds and loads. The exhaust temperature increases with engine speed and load for both fuels. The exhaust temperature of AD is often higher than that of WDE especially at higher engine load (Figure 6). Although the start of combustion (SOC) for WDE occurs later than that of AD, exhaust temperature for both fuels is almost the same. This is due to the heat absorbed by water in WDE fuel. The latent heat of water in this case is cooling the charge due to the water evaporation. This is more evident at higher load (200N.m) due to the retarded SOC for WDE. The minimum reduction in the exhaust temperature when using WDE compared to AD was 3^0C while the maximum decrease was over 12^0C. Similar result was also represented in [2] where the exhaust temperature for the emulsion was always lower than that of standard diesel. Also another study [6] showed that the exhaust temperature reduction of 10^0C was noticed when running emulsified fuel on a city bus in London.

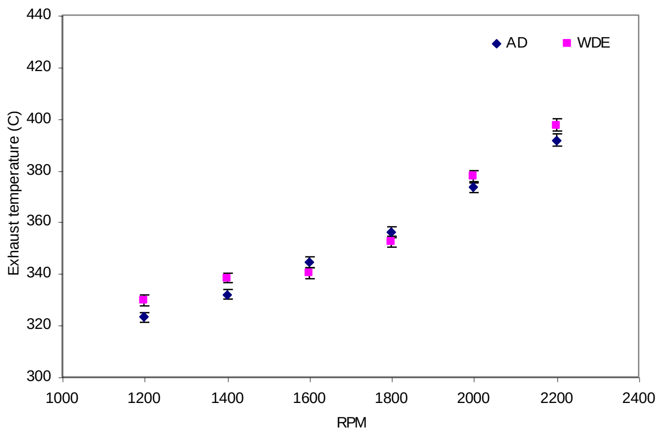

Figure 5: Exhaust temperatures for both fuels at all engine speeds and 150N.m.

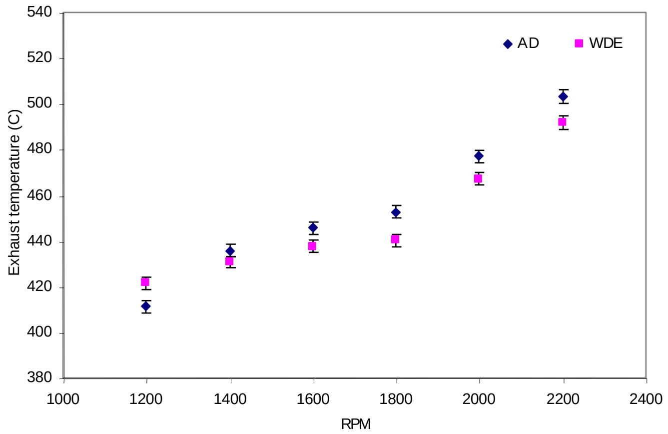

Figure 6: Exhaust temperatures for both fuels at all engine speeds and 200N.m.

The volumetric efficiency, which is the ratio of the real mass of air consumed per cycle to that of ideal mass ($m = \frac{PV}{RT}$), is higher in case of AD than that of WDE at all test points, Figures 7 and 8. The volumetric efficiency for both fuels increases with engine speed and decreases with load. The inlet air temperature in case of AD is lower than that of WDE, which results in lower values of ideal air mass. At 2000RPM and 150N.m the difference between the inlet air temperatures for the two fuels was the highest among other test points. This caused the volumetric efficiency between the two fuels at this test point to be the highest. Although the difference in their volumetric efficiencies is small (4%), however, this could be the reason of their different composition in residual gases.

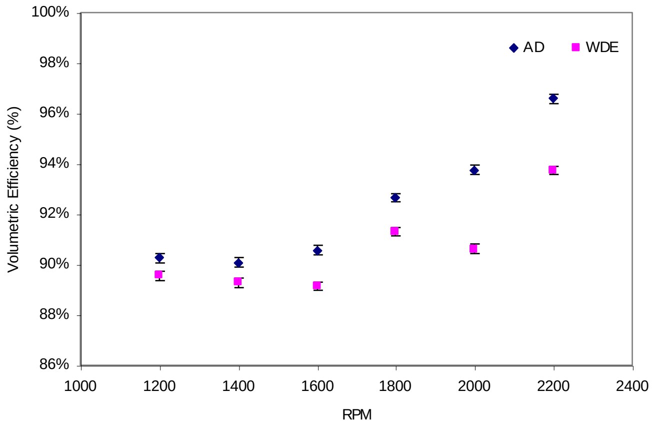

Figure 7: Volumetric efficiency for both fuels at various engine speeds and 150N.m.

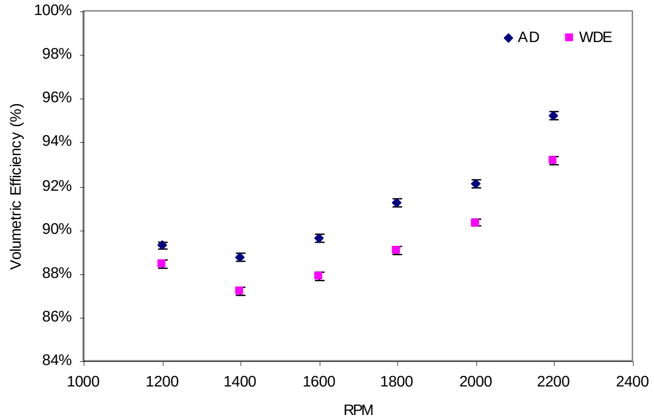

Figure 8: Volumetric efficiency for both fuels at various engine speeds

From the above engine performance results, using WDE as a replacement fuel for AD would mean higher running cost for the engine because of its higher BSFC but better engine work per cycle and hence better thermal efficiency. The absolute values for the thermal efficiency when using WDE ranges from 36% to 39% depending on the engine speed and load. It was noticed that the thermal efficiency for WDE was always higher than that of AD for the engine speed and load range studied. The average increase in thermal efficiency for WDE is approximately 1.5% higher than AD. However, the increase in thermal efficiency for WDE falls within the uncertainty range for this measurement. In general, trends in thermal efficiency for both fuels follow those of BSFC if diesel fuel is considered the only energy carrier.

4. Effect of WDE on Exhaust Emissions

Exhaust emissions represent an ensemble average of 60 readings at steady state condition of the engine. The steady state condition of the engine was confirmed with the steady readings of the exhaust temperature and NOx. In this work the NOx was all assumed to be nitric oxide (NO) since it is the predominant oxide of nitrogen produced inside the engine cylinder as explained in details elsewhere [7]. NOx and HC emissions are defined in terms of an emission index, which is the ratio of the mass flow rate of exhaust species to that of fuel. For WDE the mass flow rate of fuel is considered as diesel and water combined. WDE resulted in reduction of NOx emissions as shown in Figures 9 and 10. Increasing engine speed has a great effect in reducing NOx emissions for both fuels. However, increasing engine load increases NOx emissions for both fuels due to the higher combustion temperature.

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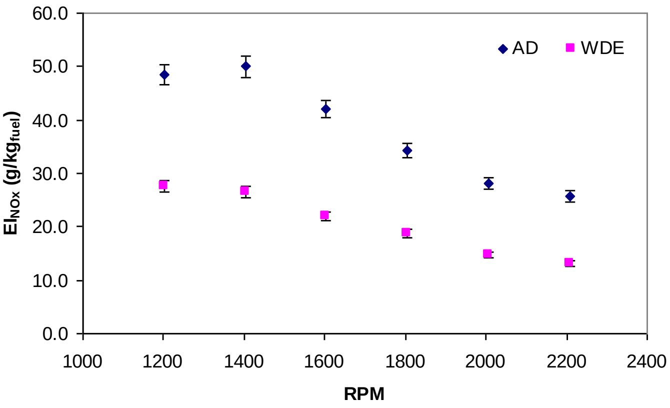

Figure 9: Emission Index of NOx for both fuels at all engine speeds and 150N.m.

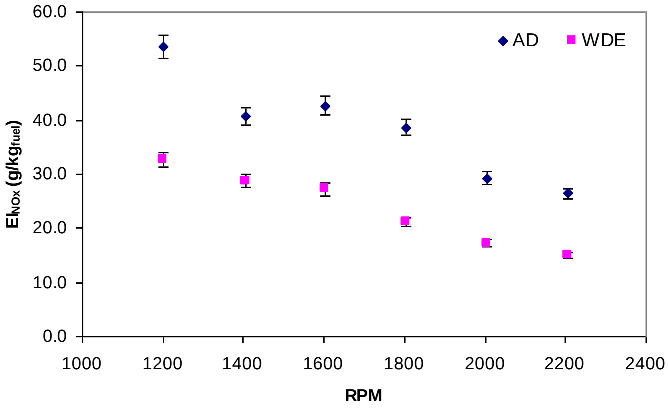

Figure 10: Emission Index of NOx for both fuels at all engine speeds and 200N.m.

The reduction in NOx emissions as engine speed increase indicates that the combustion temperature also decreases with the increase in engine speed. Since NOx formation is related to combustion temperature and combustion temperature is related to ignition delay, this could be investigated in future work. In general, NOx reduction increases by increasing engine speed or decreasing engine load, Figure 11.

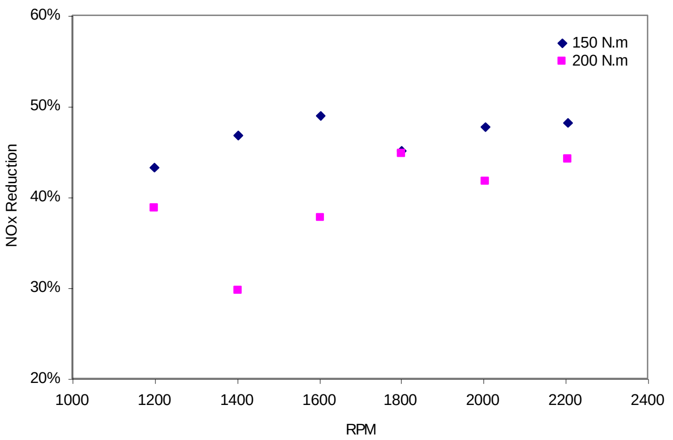

Figure 11: NOx reduction using WDE relative to AD at all engine speeds and both loads.

This high reduction in NOx from diesel engines while using WDE has attracted many researchers. Barnes et al. [6] have concluded that using 10% WDE on a city bus in London resulted in NOx and PM reductions of 14% and 38% respectively. Park et al. [5] showed a reduction of 29% in NOx was possible with 40% WDE. Langer et. al. [1] achieved a reduction in NOx up to 48% when using 15% emulsion and optimizing engine timing. Other studies [8] showed over 60% reduction in NOx emissions with 50% emulsion.

HC emissions for AD fuel behave similarly as NOx, they tend to decrease with an increase in engine speed and/or load, Figures 12 and 13. For WDE fuel, HC emissions decrease with engine speed and/or load till 1400RPM, it peaks at 1600RPM then it stays constant after that. Engine load has a greater effect in reducing HC emissions when WDE is used. If HC reading are to be excluded at 1600 for both loads, then the general trend for WDE is almost constant throughout the whole range of engine speeds indicating that engine speed does not affect HC emissions. At all engine speeds and loads WDE fuel produces less HC emissions than AD. The minimum reduction in HC is over 35% when the engine is operating at 1200RPM and 150N.m while the maximum reduction of HC is more than 92% at 1400RPM and 200N.m, Figure 14.

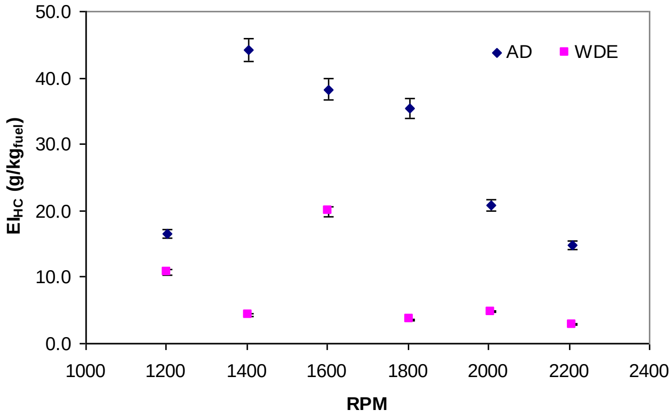

Figure 12: Emission Index of HC for both fuels at all engine speeds and 150N.m.

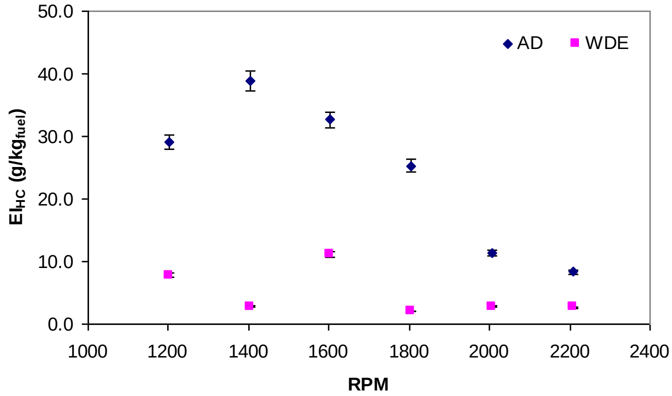

Figure 13: Emission Index of HC for both fuels at all engine speeds and 200N.m.

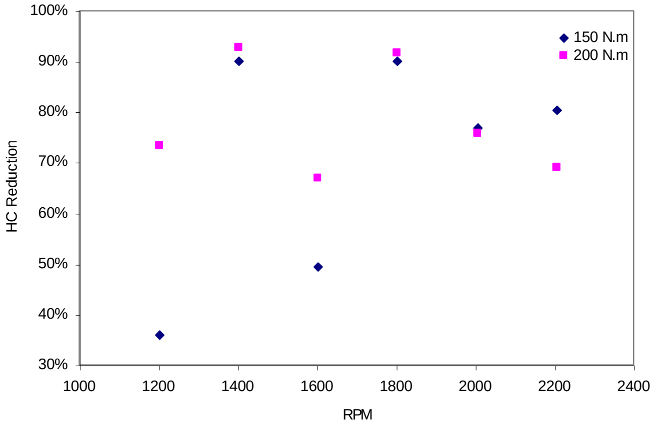

Figure 14: HC reduction using WDE relative to AD at all engine speeds and both loads.

In terms of HC emissions, Duncan et. al. [9] showed a small reduction of almost 12% when using 20% emulsion. The same reduction in HC was attained with Barnaud et. al. [4] when they used 13% emulsion. Samec et. al. [3] achieved a reduction in HC emissions by 52% when using 10% WDE.

If emissions are consistently and quantitatively related to one another, there is no need to measure each pollutant. Conversely, if the relationships are poor, each pollutant should be measured separately. Although PM was not measured during this study, some researchers have correlated HC and PM emissions. Mazzoleni et. al. [10] investigated correlations between automotive CO, HC, NO and PM emissions during a large scale on road vehicle exhaust emissions study in Las Vegas. The uncertainties of the regression parameters they used represent the 95% confidence level. They found a correlation coefficient (R^2) between HC and PM of 0.02. This poor correlation was also noted by Sagebiel et. al. [11] for 23 high emitting vehicles in an on-road study. However, when Mazzoleni et. al. used an average of multiple measurements; a positive correlation was evident between HC and PM with a correlation coefficient of 0.6. Yet, using the average measurements resulted in higher measurement uncertainties and variability for PM readings. Wagner et. al. [12] examined the application of high exhaust gas recirculation (EGR) to reduce nitrogen oxide emissions from diesel engines. Although their work objective was far from correlating exhaust emissions, however, it was clear from their HC and PM emission figures that both constituents were highly correlated. Given this, the reduction in HC found in this work for WDE relative to AD means it is likely that PM will also fall, although the reduction cannot be quantified without measurement.

5. Conclusion

The investigation of WDE and AD in direct injection diesel engine has been conducted. The increase in BSFC noted in this work when using WDE means more CO_2 into the atmosphere and as a result more greenhouse gases (GHG). In this work, CO_2 was directly measured while CH_4 and N_2O were measured as HC and NO_x. CH_4 typically represents a small fraction of the exhaust and may be ignored even for a global warming potential of 21. For vehicles expected to be powered by an engine with similar power output to the Hino engine tested here, a value of 0.2% (for industrial equipments) could be expected. N_2O has a global warming potential of 310. Therefore, a small amount of N_2O can make a significant contribution to GHGs. From the experimental results, at 1400RPM and 200N.m, which represents the minimum reduction in NO_x emissions for WDE relative to AD, the NO_x reading for AD and WDE were 41g/kg_{fuel} and 29g/kg_{fuel} respectively. This represents a 2.4% increase in the total GHG when using WDE compared to AD. The smallest increase in the total GHG (1.1%) was at 2200RPM and 150N.m while the biggest increase in the total GHG was 9% at 1200RPM and 150N.m. While there is uncertainty in the actual N_2O fraction for most typical values, the GHG increase is dominated by the increase in CO_2 through greater fuel use.

6. References

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