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The Effect of Three-way Catalyst Selection on Component Pressure Drop and System Performance

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ABSTRACT

The objective of this paper is to provide an estimate of the potential effect of substrate and exhaust system backpressure on engine performance. Parameters include fuel consumption, CO_2 emissions, and horsepower. Results were obtained on an engine test stand, and statistical analysis was used to understand the relationships between variables. Tradeoffs between catalyst substrate selection and engine performance for the particular engine used in this study are described. Finally, the potential impact of exhaust system backpressure on real world driving conditions is discussed.

INTRODUCTION

Catalyst backpressure management on modern gasoline engines has been extensively studied throughout the industry from the effect of washcoat parameters [1] to specifics substrate effects on acceleration performance [2] and the impact of designing lower backpressure products to optimize OEM systems [3]. Beyond catalyst design, exhaust system design has also been investigated from manifolds [4] to mufflers [5] and exhaust piping considerations [6]. In addition, the fundamental relationships of air consumption and backpressure management have also been investigated [7]. In this study the effect of substrate design (i.e. cell/in^2 and wall thickness) will be investigated on a stock converter system through simulations of a range of backpressures that represents a range of substrate product combinations.

This study was conducted to characterize the effect of changing backpressure on a bench engine over a range of speed and load conditions. Measurements of an actual vehicle exhaust back pressure were used to provide baseline conditions for the engine bench work.

The concept of this testing program is to characterize engine performance over a range of backpressures created by adjusting a dampening valve on the tailpipe of the bench engine. Stock chassis exhaust system backpressures were collected at the engine's rated power condition on a chassis dynamometer and transferred to a bench engine. For the bench testing all exhaust components were removed from the system to allow the damping valve to simulate their backpressure. The measured chassis system backpressure was tuned on the bench engine and utilized for the baseline or reference point for backpressure adjustment during testing. Figure 1 illustrates the layout described.

A stock engine with OEM calibration was mounted on the test stand used for the study. No attempts were made to tune the calibration during the program. All relevant engine parameters were monitored as well as emissions output. The backpressure of the exhaust system in the engine bench was varied by 20% of the stock vehicle system backpressure, by changing the dampening valve position from 10% below to 10% above the operating mid-point of the stock vehicle system pressure.

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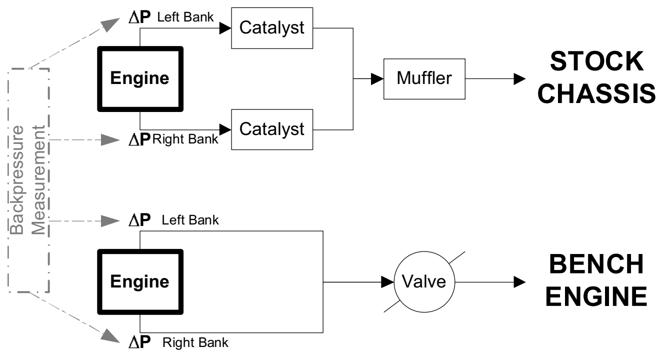

Figure 1 System layout for baseline data collection

EXPERIMENTAL DESIGN

ENGINE SELECTION

A Ford F250 truck, model year 2007 5.4 liter 3 valve 8 cylinder engine, was used for this study. The engine was calibrated for Tier 2 Bin 5 emissions performance. Baseline stock exhaust system characterization was conducted on the chassis before testing on the engine bench.

TESTING MATRIX

A testing matrix was designed to look at engine performance over a range of speed and load conditions.

RPM	1000 1500	2000 2500	3000 3500 3750	4000 4250 4500	5000 5200

Table 1 Engine Speed Conditions (RPM)

Throttle Position	25%	50%	75%	100%

Table 2 Engine Load Conditions (Throttle %)

EXPERIMENTAL PROCEDURE

STOCK EXHAUST SYSTEM CHARACTERIZATION

The baseline F250 chassis was characterized over the range of speed and load conditions listed in Table 3.

RPM	Throttle %	Ignition BTDC	Backpressure Response kPa (PSI)
3500	100	14	55.2 (8.0)
3900	100	16.5	69.6 (10.1)
4000	100	17.5	71.0 (10.3)
4100	**100**	**15.5**	**73.0 (10.6)**

Table 3 Engine Speed Conditions (RPM)

The targeted baseline backpressure condition for the study is at the rated power condition of 4100 rpm. The backpressure value of 73 kPa was applied to the bench engine for the same engine operating conditions.

BENCH ENGINE TESTING PROCEDURE

The 4100 rpm wide open throttle (WOT) condition from the stock exhaust system was set-up on the bench engine and the variable restriction plate was tuned to achieve 73 kPa at the same location after the engine manifold. Characterization of the engine rpm, backpressure, exhaust temperature, fuel consumption, exhaust mass flow rate, and air-fuel ratio was completed at the same time.

After the baseline condition was completed on the bench engine a set procedure was used to step up from 1000 to 5200rpm in the increments defined in Table 1, and then rpm was stepped down, starting at WOT and then 75%, 50%, 25% throttle respectively. Sufficient line-out time was used at each experimental set point so that operating conditions such as temperature were at steady values. The same set of data collection was completed as with the baseline characterization plus we obtained full modal emissions data.

ESTIMATION OF SIMULATED SUBSTRATE PRESSURE DROP

The results from the baseline characterization work on the bench engine at 4100rpm and WOT conditions generated exhaust gas characteristics that were applied to predict the pressure drop of the stock catalyst substrates. This allows for the estimation of the effective change in substrate backpressure that is simulated by the change in system backpressure (from the dampening valve adjustment). Figure 2 provides details of the catalyst architecture.

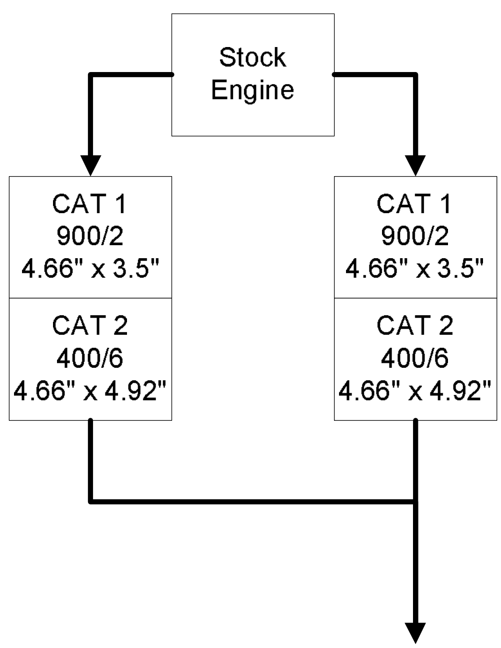

Figure 2 Stock Catalyst System Architecture

The pressure drop model published by Florchinger et al. [8] was used for the calculation of each converter in the system (to determine the substrate contribution to system pressure drop). Data collection from the baseline condition is summarized in Table 4. Calculations also included an assumed 1 mil thickness of coating on the substrate.

Measure	Value	Unit
RPM	4100	rpm
Throttle	100	%
Inlet Gas Temperature	835	C
Inlet Gas Mass Flowrate (each bank)	95	g/s
Exhaust Backpressure	73	kPa

Table 4 Data Collection for Catalyst Backpressure Estimation

The calculated backpressure of each catalyst is summarized in Table 5 based on the data collection listed in Table 4.

	Value	Unit
Total System Backpressure	73	kPa
CAT 1 900/2	8.7	kPa
CAT 2 400/6	6.5	kPa
Total Substrate Backpressure (measured before 1 bank of catalyst)	15.2	kPa
Balance (assumed to be the non catalyst contribution)	57.8	kPa

Table 5 Estimated Catalyst Backpressure And System Backpressure Summary

The range of + / - 10% on the system backpressure (73 kPa) was chosen for this study, this equates to a targeted high and low backpressure on the system from 80.3 – 65.7 kPa. Using + / - 10% also is equivalent to a simulated substrate change of ±6.9 kPa (which covered the targeted range for various substrate product simulations). As confirmation that this range is acceptable for a potential substrate contribution to the system the low pressure drop combination of 600/2 (cells/in^2 and wall thickness (mils)) and 400/3 substrates were calculated. Relative to the 900/2 and 400/6 combination (higher backpressure) which is used in the stock configuration the combination of 600/2 and 400/3 substrates provide the lowest pressure drop while maintaining the close coupled functionality of the first substrate and the UBC functionality of the second substrate. Results show that this change in substrate configuration would simulate a decrease in substrate backpressure of ~ 5.2 kPa. This was determined to be well within the range covered by the study to represent potential substrate impacts.

TESTING RESULTS - HORSEPOWER

The summary of the corrected horsepower results across engine speed by load and backpressure are illustrated in Chart 1 below.

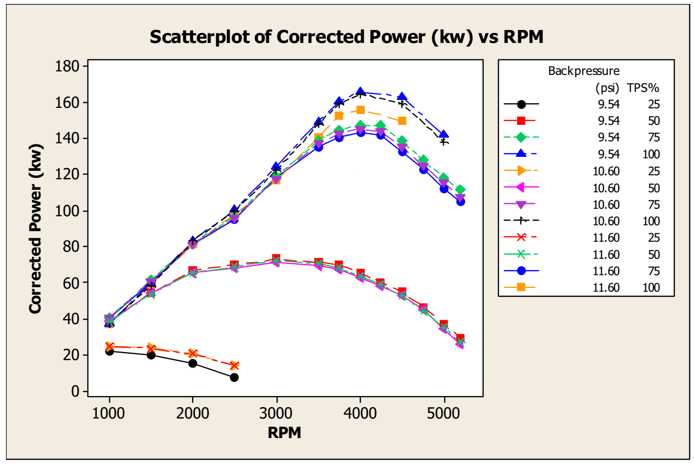

Chart 1 Corrected Horsepower Results

These results demonstrate that the combination of high engine speeds and high load conditions are required to observe the effects of changes in catalyst backpressure. It is notable that the 25% throttle condition does not follow the theoretical expectations (as observed in the other conditions). A high degree of engine performance variability was observed at these conditions, it was determined that the engine was not tuned to be able to accept such changes in backpressure (additional work with spark timing would likely be required to assess how to further address these conditions). This could not be further investigated during the study. Therefore this portion of the data was disregarded for further analysis.

Characterization of the changes in engine power observed at the low, nominal and high backpressure conditions at 75% throttle illustrates a consistent symmetrical effect at low and high backpressure as a function of engine speed, Chart 2. The largest changes (positive or negative) in engine power are observed at the highest engine speeds under these conditions.

In this study Delta Horsepower or Delta Backpressure is defined as the change in horsepower or backpressure relative to the nominal set-point conditions.

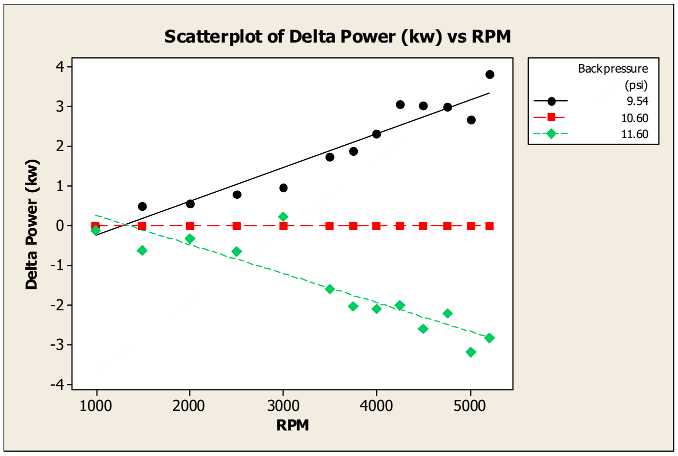

Chart 2 Horsepower at 75% Throttle Condition

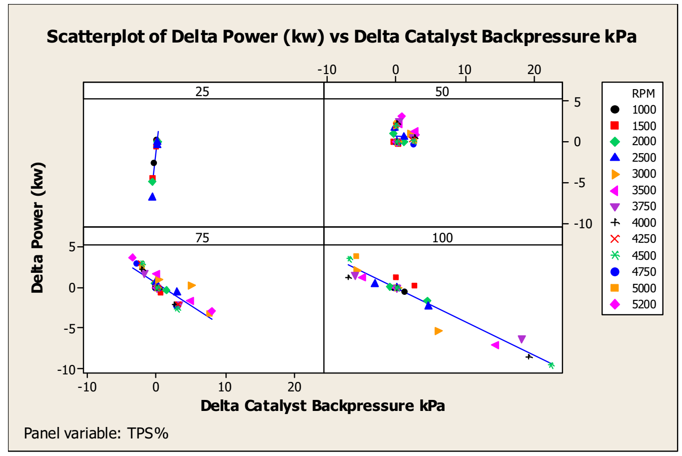

Chart 4 Effects Of Actual Measured Backpressure On Horsepower (All Throttle Conditions)

Specifically focusing on the 4000 rpm condition at 75% throttle illustrates the linear relationship between the changes in engine backpressure (set point) and the changes in engine power. Here the effect of changing backpressure on engine horsepower is observed to be approximately 0.30 kw for every 1 kPa (or 3 hp for every 1 PSI) change in backpressure set point under these operating conditions, detailed in Chart 3.

Due to the similarities in the trends between the 75% and 100% throttle conditions a combined statistical analysis of these conditions was completed. In doing so it was confirmed that they have the same sample slope and were therefore combined over the range of speeds. Taken together they provide an estimate of approximately 0.44 kw/kPa (~4hp / PSI).

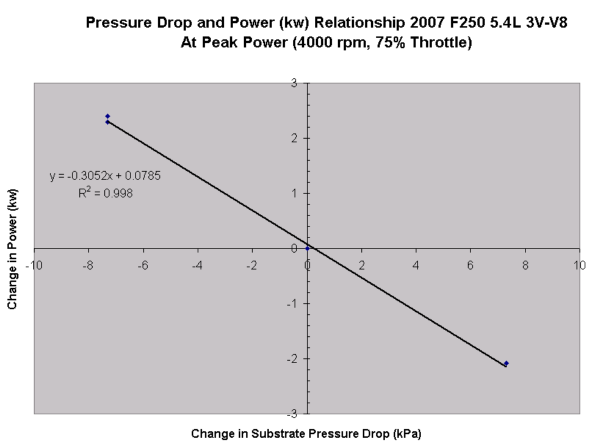

Chart 3 Effects of Backpressure Set Point on Horsepower

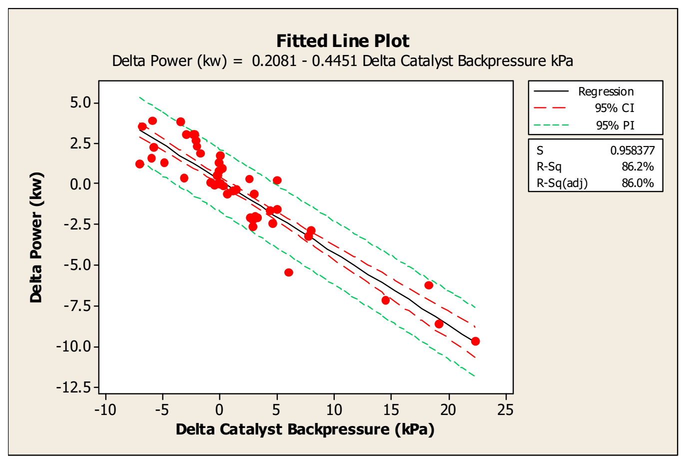

Chart 5 Effects Of Actual Measured Backpressure On Horsepower (Combined 75% And 100% Throttle)

Plotting the actual measured backpressure, instead of the set point, at the catalyst position versus the measured engine power demonstrates further refinement of the effects of backpressure. The minimal effect is observed from 25%-50% throttle at what we consider to be low load conditions. A more consistent effect is observed from 75% and 100% throttle over the range of engine speeds.

To ensure that all relevant parameters were considered during the study, a statistical principal components analysis was made to determine what parameters contributed the most to the measured horsepower response and to understand correlations between them.

Statistically significant model parameters in rank order include:

- Engine speed
- Throttle position and manifold vacuum
- Changes in catalyst backpressure
- Air fuel ratio
- Exhaust gas flow rate
- Inlet Air and Water Temperature
- Oil Pressure

After engine speed and engine load, system backpressure is the next most important variable affecting horsepower. The coefficient for backpressure changes from this model is 0.40 kw/kPa (or 3.7 hp/PSI). This value was used for future analysis of the results for comparison of substrate design impacts on performance.

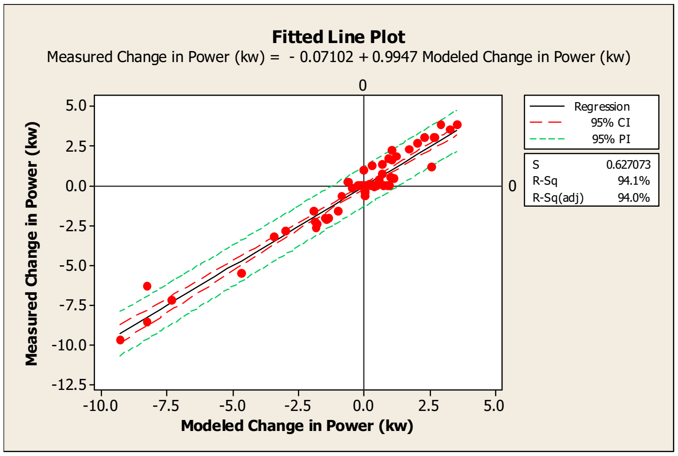

Chart 6 Regression Analysis Of Actual Changes In Horsepower Vs. Predicted Changes In Horsepower

We used these results and relationships among the variables to evaluate the impact of changes in substrate design on engine performance. To develop our estimates, we first calculated the total substrate backpressure of the stock 900/2+400/6 configuration and converted it into an equivalent single 900/2 substrate having the same contour diameter of 118.4mm (4.66”). At equivalent back-pressure the single 900/2 substrate has a length of 157.1mm (6.185”). Using this new 118.4mm (4.66”) diameter by 157.1mm (6.185”) length part dimension and the input parameters from Table 4 the back pressure of various substrate cell and web configurations were calculated (Table 6). The 0.40 kw/kPa (3.7 hp/PSI) relationship was used in this case to demonstrate the effects of substrate design choices on engine power, Chart 7.

Product	Calculated Backpressure (kPa)	Change in Backpressure (kPa)	Change in Power (kw)
900/2	15.2	0	0.0
600/2	9.10	-6.10	2.44
400/3	6.14	9.06	3.62

Table 6 Substrate Comparisons

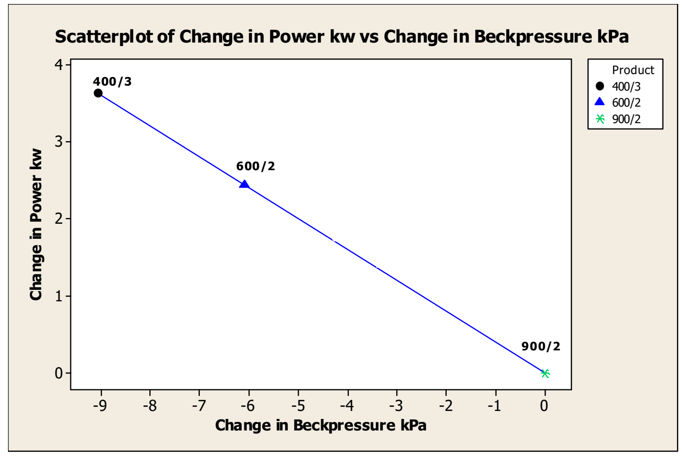

Chart 7 Comparisons of Various Substrate Technologies

The extreme case of moving from 900/2 to 400/3 could offer as much as approximately 3-4 kw at these operating conditions. Contrasted with 600/2 where approximately 2.5 kw is observed. Note that the trade-offs of emissions performance are not discussed here but do need to be considered.

Further statistical analysis was conducted to investigate the potential influence of variation in the substrate and coating parameters, assuming normal distribution functions for substrate cell density, web thickness and coating thickness, and assumed manufacturing variation or ranges. The following ranges are applied to a 20,000 iteration Monte Carlo analysis.

Product Attribute	Average	STDEV
Substrate Cell Density (cpsi)	600 or 900	5
Substrate Web Thickness (mil)	2.75	0.08
Catalyst Coating Thickness (mil)	1.0	0.2

Table 7 Product Attributes Summary

Substrate backpressures were calculated for both bare and coated substrate distributions. Conditions for the pressure drop calculations were the same as the conditions listed in Table 4. Results are compared from bare substrates to coated substrates for pressure drop and then translated into the potential power influence.

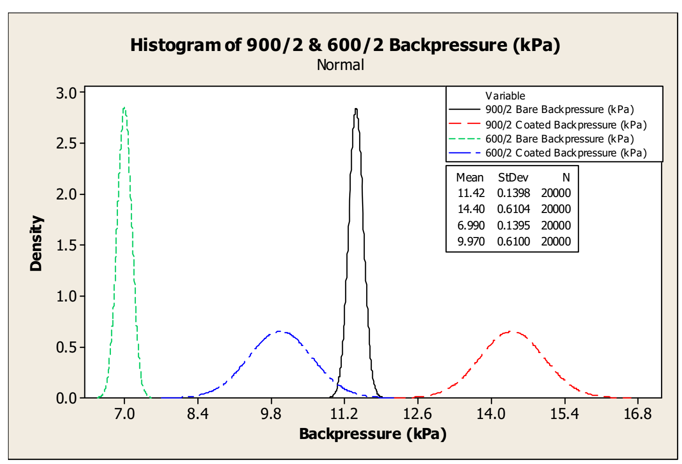

Chart 8 Pressure Drop Distributions

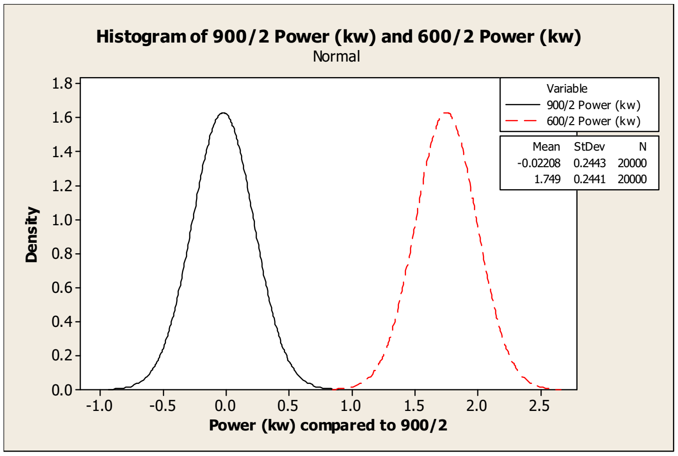

Chart 9 Horsepower Change Distributions

Results show a clear differentiation between 900/2 and 600/2 for pressure drop, despite variability in substrate and coating attributes.

In summary, these results indicate measurable changes in engine power with substrate selection with the range of current product offerings. It is notable these are observed at the high speed and load condition where the effect of changes in backpressure of the system is most pronounced. Based on the findings from this study typical driving modes at lower speeds and loads would likely see a reduced impact on power.

TESTING RESULTS - CO_2 and FUEL ECONOMY

Analysis of theses results for specific fuel consumption and CO_2 emissions were also completed. Similar to the engine power results, testing and data collection concentrated on the most sensitive portion of the test conditions under high speeds and loads. Analysis of conditions below 75% throttle did not yield any measurable differences in performance and is likely indicative of the driving modes included in emission certification testing. Additional studies specifically focused in on these modes using a chassis system would be needed. However, these results are useful for high speed and high load condition for engine design and engineering safety margin perspectives.

Specific fuel consumption (SFC) is defined by [9]

$$SFC = \frac{\dot{m}}{P}$$

Where, $\dot{m}$ is the gravimetric consumption rate (lbs/hr) and P is the engine power (hp), SFC units are in (lbs/hp*hr)

Comparing the results from the 75% throttle condition over the range of engine speeds shows a trend in SFC that is consistent with the expectation of lower fuel consumption with lower exhaust backpressure. The changes are in the ½ -1% range of the nominal condition in SFC over the range of backpressure tested. A box plot of these results are provided in Chart 8

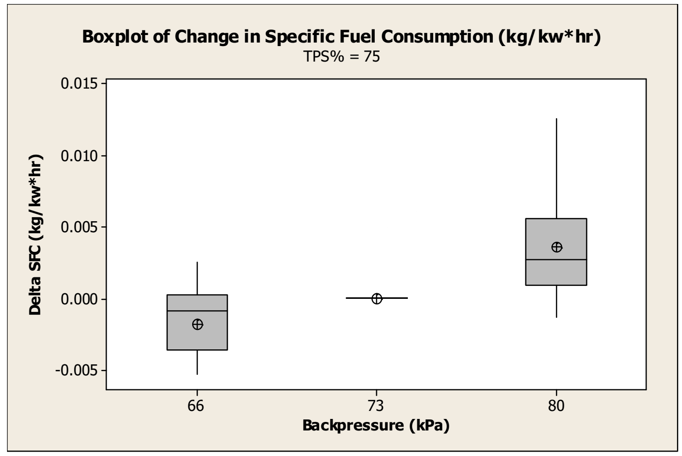

Chart 10 Box Plot Of Specific Fuel Consumption

Similarly the results of the CO_2 emissions are consistent with the specific fuel consumption results. Higher backpressure leads to higher CO_2 emissions.

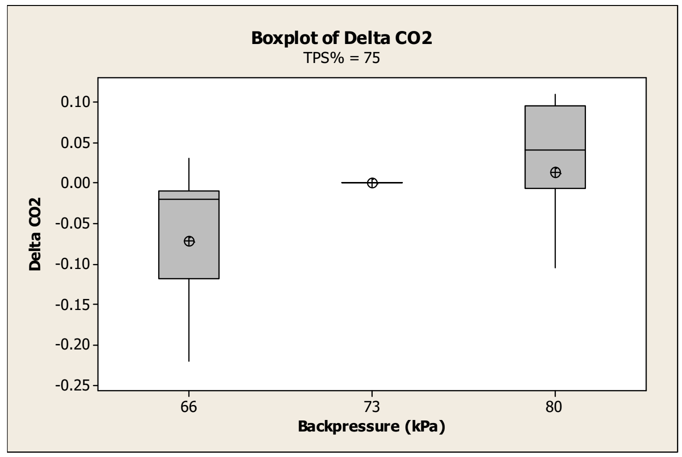

Chart 11 Box Plot Of CO_2

CONCLUSION

Characterization of the potential effects of substrate design on engine performance was completed. Changes in engine power, fuel consumption and CO_2 were demonstrated at high engine load and speed conditions.

Specifically for engine power and backpressure on a 5.4L V8, the results show ~0.4kw improvement for every 1 kPa (3.7hp/PSI) in backpressure at peak power conditions within the range tested.

For specific fuel consumption and CO_2, the increase in SFC and CO_2 was demonstrated with increasing backpressure. Also the contribution from the substrate is estimated to be within the range of ≤ 1% (without additional engine tuning)

It is also important to note that the performance changes presented here are less sensitive at low load and speed conditions. Depending on the application and driving modes for performance certification the effects presented may offer varying level of impact. These requirements should be considered when investigating the optimization of substrate design.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

RPM: Revolutions per Minute
WOT: Wide Open Throttle
CAT: Catalyst
SFC: Specific Fuel Consumption
CCC: Close Coupled Catalyst
UBC: Underbody Catalyst