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# Comparing Diesel Fuels at Various $T_{90}$ Distillation Temperatures: Engine Performance, Vibration and Emissions

Gerald Jo. C. Denoga*and Edwin N. Quiros

*Department of Mechanical Engineering*
*University of the Philippines Diliman*
*Quezon City 1101 PHILIPPINES*

## ABSTRACT

The performance of a Diesel engine was evaluated using fuels with varying $T_{90}$ distillation temperatures. The $T_{90}$ distillation temperature is an indicator of the yield of Diesel fuel extracted from crude oil. A higher $T_{90}$ can translate to better utilization of raw petroleum resources. This experiment verified if high distillation temperatures have any effects on torque, power, specific fuel consumption and emissions. Engine vibrations were also measured and analyzed using accelerometers. Tests were done on a light truck engine connected to a chassis dynamometer.

## 1. INTRODUCTION

One of the most pressing and pervasive issues in the world today is the responsible use of energy from fossil fuels. In the Philippines, diesel fuel is widely used as a cheaper, energy efficient, and environmentally friendly source of energy for transportation.

This article presents a comparative study of engine performance, vibrations and emissions using diesel fuels with different distillation temperatures. Considering that most of the public transportation sector is powered by diesel technology, research in this area could have great impact. Investigations in engine performance with respect to power and fuel efficiency are critical. Given the economic status of the Philippines, as well as the rising cost of petroleum products in the global market, the primary consideration of the local consumer would be to reduce operating costs.

One method of reducing operating costs is to reduce the unit cost of fuel. From an oil refinery standpoint, the yield of diesel fuel per barrel of crude oil can possibly be increased by harvesting fuel with higher distillation temperatures. Economically, a higher recovery rate translates to cheaper fuel for the consumer.

Unfortunately, higher distillation temperatures tend to decrease the volatility of the fuel. It is reported that less volatile types of fuels have better volumetric fuel economy, at the expense of high unwanted emissions. Black smoke and particulate matter are key issues for

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*Correspondence to: Department of Mechanical Engineering, Melchor Hall, Quezon City 1101, Philippines

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| Sample | A1˜A7 | B1˜B7 | C1˜C7 | D1˜D2 |
|---|---|---|---|---|
| Distillation Temperature at 90% Volume Evaporated, $T_{90}$ | 363°C | 368°C | 373°C | 335°C |
| Cetane Index | 56.6 | 58.4 | 55.9 | 55.7 |
| Fuel Density at 15°C (kg/L) | 0.8434 | 0.8373 | 0.8465 | 0.8332 |
| Kinematic Viscosity at 40°C ($mm^2/s$) | 3.766 | 3.775 | 4.022 | 2.796 |
| Microcarbon Residue, % mass | 0.013% | 0.019% | 0.013% | 0.019% |

Table I. Fuel Sample Characteristics.

diesel engines. While a lot of of research is being made in engine technology to address these issues, this study focuses instead on the role of fuels.

This investigation seeks to verify if fuel distillation temperature has a significant effect on the emissions and performance of a direct injection diesel engine. Fuel samples were categorized by the fuel distillation temperature at 90% recovery ($T_{90}$). The engine was run at various speeds while measuring torque, power, specific fuel consumption and smoke emissions.

Engine vibration was also measured for each fuel blend. Engine noise, vibration and harshness (NVH) is the undesirable offshoot of the high pressures in the diesel combustion process. Due to developments in engine technology, the NVH levels are now significantly lower and comparable to gasoline engines. This study also investigated if engine vibrations are significantly sensitive to variations in fuel distillation temperatures. Statistical analysis was applied to gauge which fuel blend runs smoothest and, thus, most suitable for passenger car applications. Further, time- and frequency- domain analysis may account for the differences in engine performance.

## 2. EXPERIMENTAL SETUP

This paper describes the engine tests conducted on twenty-three (23) diesel fuel samples provided by a major petroleum company. The tests were intended to determine the effect on engine performance, vibration characteristics, and smoke emissions of the different diesel fuel blends. The fuel blends were classified into four categories coded as A, B, C, & D based on the $T_{90}$. Category A had 7 samples (A1 to A7), B with 7 samples (B1 to B7), C had 7 samples (C1 to C7), and D had samples D1 & D2. Selected average properties of the four fuel categories tested are shown in the Table I below. The $T_{90}$ of the fuels increases with Fuels A to C. Fuel D comes from a different petroleum company.

### *2.1. Engine Test Setup*

A light truck engine was selected for the tests that were carried out at the facilities of Pilipinas Engine Remanufacturing and Reconditioning Corporation (PERRC). The engine test bed was fitted with an Isuzu 4BC2 diesel engine (3.2 ltr. displacement), an eddy-current dynamometer instrumented to read torque, engine speed, oil pressure, and fuel volumetric flow rate. An infrared thermometer was used to measure temperatures of the cooling water outlet (at exit of the engine water pump) and exhaust pipe near the exhaust manifold. A Zexel smoke meter was used to quantify smoke emissions from the engine. The use of a light truck diesel engine was intended to obtain test data from a typical direct-injection engine currently used in light commercial trucks and jeepneys. The test engine has the following specifications:

| | | |
|---|---|---|
| *Engine Name* | : | *Isuzu 4BC2* |
| *No. of Cylinders* | : | *4 in-line* |
| *Bore x Stroke (mm)* | : | *102 x 100* |
| *Displacement (cm3)* | : | *3,268* |
| *Compression Ratio* | : | *17.0* |
| *Output (kW @ rpm)* | : | *65 @ 3,500* |
| *Torque (N-m @ rpm)* | : | *200 @ 2,200* |

The manufacturer's performance curves of this engine indicating the variation of torque, power output, and specific fuel consumption at full load over the engine speed range are shown in Figure 1.

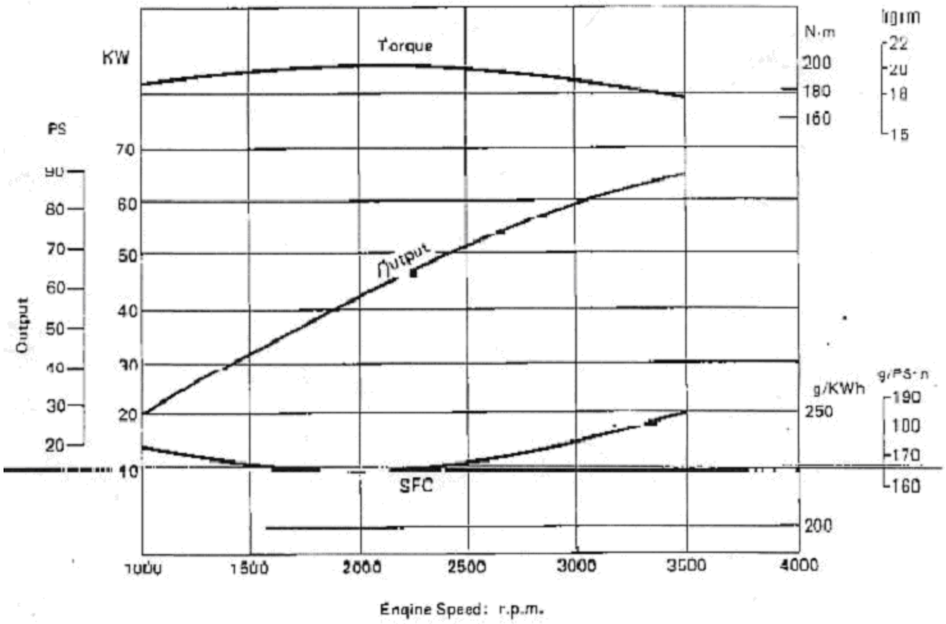

Figure 1. Engine Performance Curves from Manufacturer.

### 2.2. *Vibration Measurement Test Setup*

Vibration measurement was done with a PrufTechnik AG Vibrospect FFT vibration analyzer. The Vibrospect console obtained readings from two piezoelectric accelerometers magnetically mounted on the engine block. Both accelerometers were of type VIB 8.510 and used as passive sensors using the line-drive amplifier of the Vibrospect console. The rated accelerometer transmission factor was $5.35\mu A/ms^2$ sensitive to frequencies of 2Hz to 3.5kHz. The Vibrospect console was programmed to a transducer sensitivity of $53.5\mu A/ms^2$ and measured acceleration combined with a DC offset, to prevent number overflow. The sensors were connected to the Vibrospect console using shielded BNC cables.

Measurement synchronization was facilitated by a laser optical trigger reflected off the exposed belt sheave. This belt sheave was directly coupled to the crankshaft. The Vibrospect console was timed to get 4096-sample-long readings at a sampling rate of 8 kHz at the same crank position within each engine revolution.

The procedure implemented for the tests is the full-load variable speed test. This test determines the variation of torque, power output, vibration levels and specific fuel consumption over the engine speed range when the engine is running at full load. Engine full load was achieved by adjusting the fuel rack of the injection pump to a maximum position using an attached cable that can be locked in position. The dynamometer field strength is then adjusted for maximum load at the set engine speed.

At the start, the engine is brought to normal operating temperatures by running it under light load for approximately 10 minutes at about 1000 rpm. Stability is realized when steady readings of speed, torque, pressures, and temperatures are obtained. The rest of the test procedure basically consists of the following steps:

a) After the initial stabilization period, the engine is run at the set engine speed.
b) The load is adjusted to maximum power while maintaining the set engine speed.
c) The engine is run at this condition for some time until speed, torque, lube oil and cooling water temperatures, pressures have stabilized
d) The fuel consumption measurement is performed after which, other data are gathered (speed, load, temperatures, pressures, smoke number)
e) Accelerometer readings were taken together and synchronously with the optical trigger timing signal, with the Vibrospect console
f) Decide next engine speed and repeat step a).

The test ends after taking data at the predetermined maximum engine speed (3500 rpm).

The full-load tests were run at engine speeds of 1200, 1500, 2000, 2500, 3000, & 3500 rpm. At 1200 rpm, the full-load condition was determined by the highest fuel rack position for which stable engine operation was achieved. It was found that going beyond this fuel rack position, which is still less than maximum, caused the engine to run erratically together with excessive smoke emissions. The fuel rack position was fixed at maximum for the rest of the test speeds. Because of its different fuel rack position, data at 1200 rpm are not considered in the performance comparison of the fuels tested. In addition, it was observed that vibration readings at 3500 rpm still produced number overflows, and are not considered.

The fuel samples were tested in the following order: A1~A7 ($T_{90}$ = 363°C), C1~C7 ($T_{90}$ = 373°C), D1~D2 ($T_{90}$ = 335°C), and B1~B7 ($T_{90}$ = 368°C). The fuel lines and filter were flushed before running with a new fuel sample.

Engine friction power was not measured during the tests.

### *2.3. Vibration Analysis Procedures*

After all the measurements were taken, all of the vibration readings were pre-processed using mathematical software. First of all, the DC offset from the signal was removed by zeroing the

DC component within the frequency domain, and then transformed back into a time signal.

Due to the fluctuations in the shaft speed, all of the recorded signals then had to be synchronously averaged. The time-domain signals were sliced into individual engine cycles. Depending on the shaft speed, each raw signal could be sliced from 5 to 14 segments. Then, each segment was resized to sample lengths of 4096. All of the stretched segments from one signal were then averaged in the time domain. This procedure would produce a very coherent signal leaving only the components directly correlated to the periodic engine cycles.

The resulting enhanced time signals would then be subject to statistical analysis. The mean vibration levels were evaluated by getting the root mean square (RMS) of the acceleration values. The exposure levels (L10, L50, L90) were also obtained by statistical analysis of the preprocessed data. Strictly speaking, these exposure levels are used to characterize noise signals. However, a suitable parameter was needed to represent the higher and harsher vibrations that an engine briefly undergoes during the detonation. RMS values would be insufficient to represent such impulsive signals. The L10 value indicates the vibration levels that are exceeded only 10% of the cycle. The L50 value indicates the median vibration levels. The L90 value represents the minimum vibration that is exceeded 90% of the cycle time.

## 3. RESULTS AND DISCUSSION

The following presents discussion of engine performance results in terms of torque, power, brake specific fuel consumption, and smoke emissions.

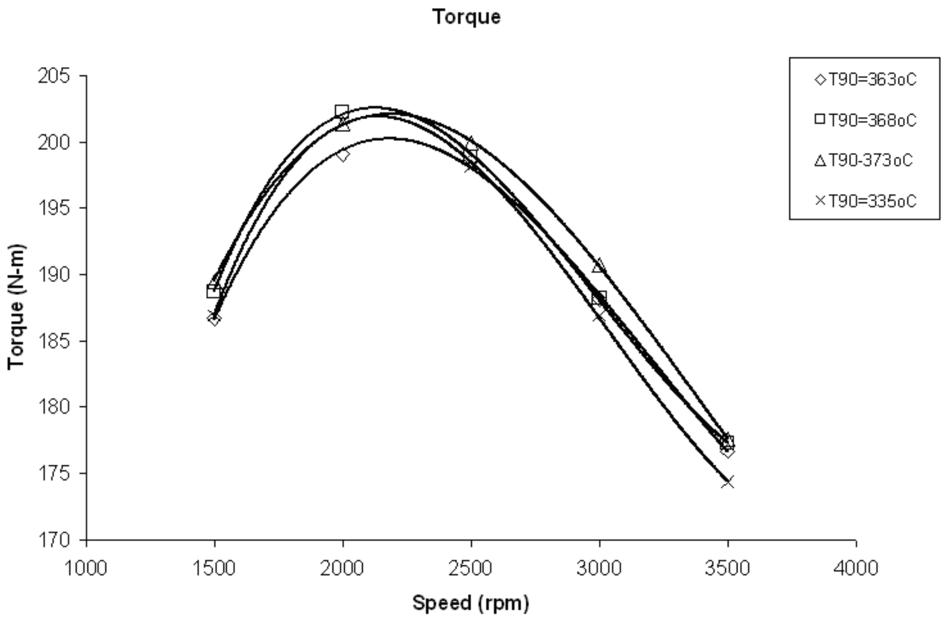

Figure 2. Graph of Brake Torque vs. Engine Speed.

### *3.1. Brake Torque*

Engine torque increases with engine speed and peaks at about mid-speed then decreases with rising engine speed. The decrease in torque at higher engine speeds is due mainly to increasing power loss to friction as engine speed goes up. A decrease in engine air intake with increasing engine speed also contributes modestly to this drop in torque. In addition, the decrease in torque as engine speed is lowered from the maximum torque region is due chiefly to increased heat losses in this range.

It is observed from the torque curves of the fuels tested (Figure 2) that in general:

- the torque variation is roughly 18% over the engine speed range. This is a relatively flat curve.
- the difference between the highest and lowest torque exhibited by the fuels at each operating speed differed by 2% to 5%.
- overall, this torque variation among the fuels is not deemed significant
- the peak torque of the various fuels occurred very close to 2200 rpm, the speed cited for maximum torque in the manufacturer's engine performance curve

### *3.2. Brake Power*

Figure 3 shows the graph of engine brake power versus engine speed for the fuel samples tested. In the evaluated speed range, brake power increases with engine speed because of increased

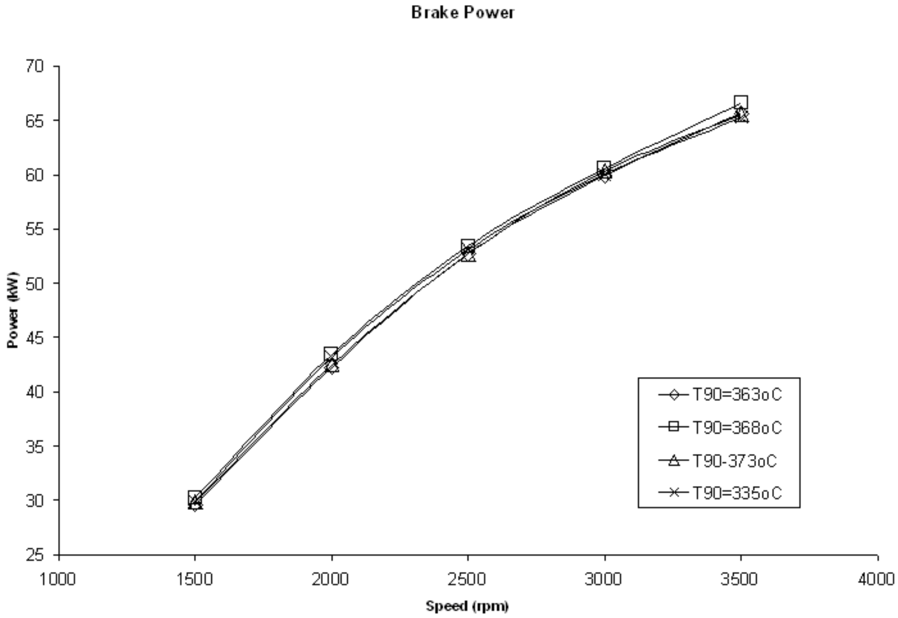

Figure 3. Graph of Brake Power vs. Engine Speed.

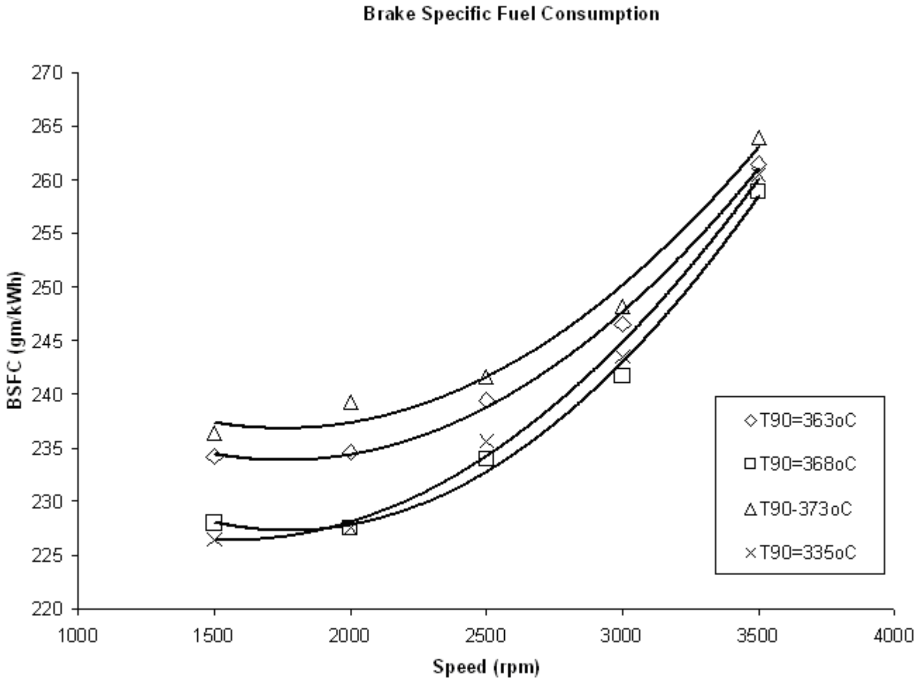

Figure 4. Graph of Brake Specific Fuel Consumption vs. Engine Speed.

number of power cycles per unit time. However, the increased friction and reduced volumetric efficiency at higher engine speeds (2500 rpm and above) reduce the slope of the power curve.

As seen from Figure 3, the brake power output of the various fuels is practically similar over the engine speed range tested.

### *3.3. Brake Specific Fuel Consumption (BSFC)*

Figure 4 shows the graph of brake specific fuel consumption versus engine speed for the fuel samples tested. Since the BSFC curve typically fits well a second-degree polynomial, the BSFC plots shown are curve fits of the BSFC data for each fuel. The fitted curves could give estimates of the minimum BSFC and at what engine speeds they will occur.

For engine speeds lower than at minimum BSFC, heat losses are significant (more time for heat transfer per cycle) so that BSFC is higher. At higher engine speeds, friction losses dominate thus increasing BSFC. In addition, reduced volumetric efficiency tends to increase BSFC.

In looking at the preceding graph, it should be noted that Fuels A, B, & C come from the same petroleum company while Fuel D is made by a different company. As seen from the graphs, the differences in BSFC at low speeds are more pronounced. The expectation that a higher $T_{90}$ results in higher BSFC tends to be confirmed by Fuels A, C, & D. It is thought that higher volatility promotes better combustion and fuel economy. Fuel B however, seems to

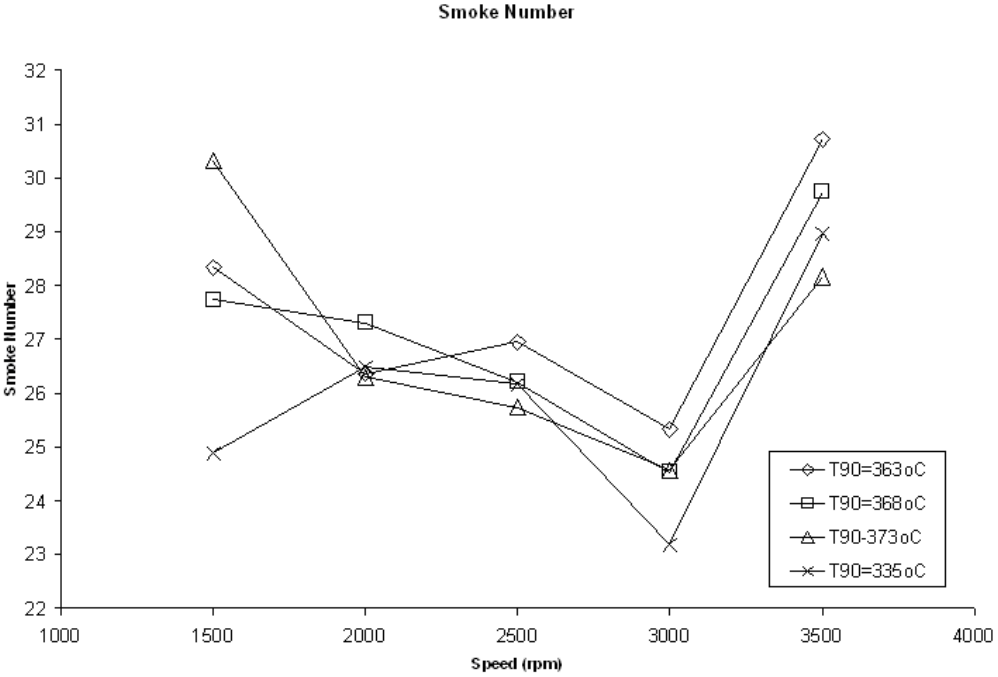

Figure 5. Graph of Smoke Number vs. Engine Speed.

contradict this trend among the fuels. This observation on Fuel B may be related to the fact that Fuel B was tested after Fuel D. If fuel D "cleaned up" the fuel delivery system, then Fuel B benefited from this effect. Unfortunately, this was not verified further in the tests.

At higher speeds (3000-3500 rpm), the maximum BSFC difference among the fuels is about 2%. This is regarded insignificant considering also that the engine rarely goes to this speed range in operation.

### *3.4. Smoke*

Figure 5 shows the measurements taken of the Smoke Number of the exhaust gas versus engine speed.

It is observed from the smoke emissions of the fuels tested that in general:

- the smoke number decreases with increasing engine speed up to 3000 rpm
- The relatively steep increase in Smoke Number from 3000 to 3500 rpm exhibited by the fuel samples may be due to the increased difficulty of properly mixing the air and fuel spray at higher engine speeds. Combustion efficiency thus suffers resulting into increased smoke and fuel consumption.
- the fuels have essentially similar smoke emissions in the 2000 - 3500 rpm range. In general, emissions are best between 2500 - 3000 rpm.

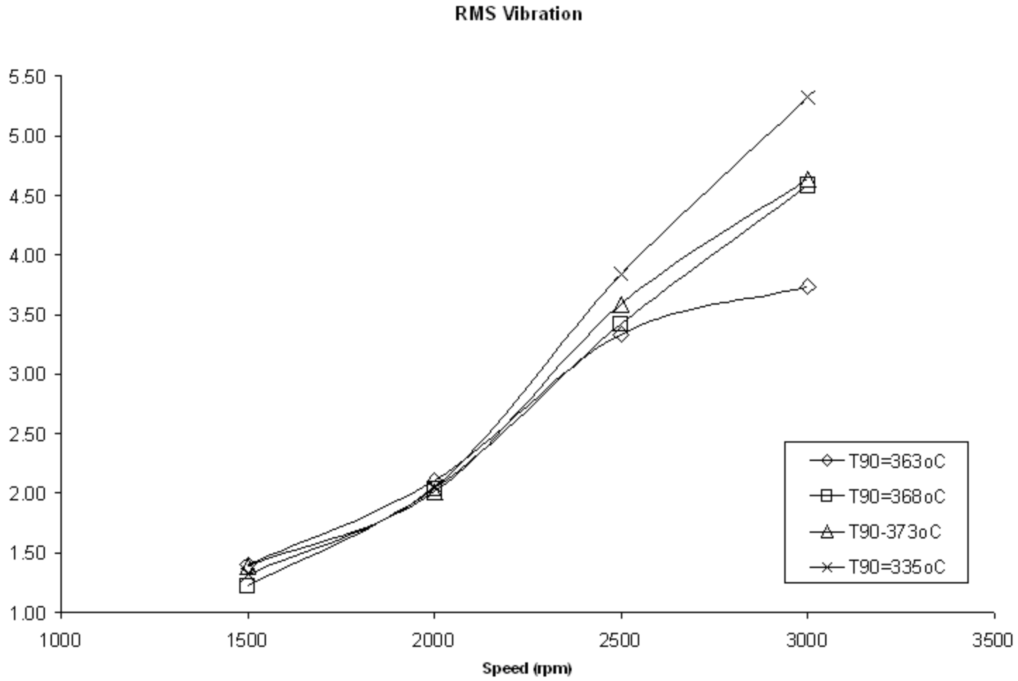

Figure 6. Graph of RMS Vibration vs. Engine Speed.

The preceding graph does not exhibit any consistent trend of the Smoke Number with the fuel distillation temperature $T_{90}$. The smoke number varies inversely with $T_{90}$ temperature only for high speeds, and for half of the data. In addition, the differences rarely exceed 9%, making any trends statistically insignificant.

This lack of discernible patterns is noteworthy. Less volatile fuels are predicted to have higher smoke numbers. It is theorized that other factors, in addition to distillation temperature, play a significant role in engine emissions.

### *3.5. Vibration Levels*

Figure 6 shows the graph of the RMS acceleration value versus engine speed. Similar to power, engine vibrations increase with speed because there are more power cycles per unit time. The detonation of fuel and the reciprocating engine dynamics translate to vibrations measurable by the accelerometer. Deviations from a straight line graph result from combustion events that are nonlinear with respect to engine speed.

The preceding graph of RMS vibration does not show any discernible relationship with distillation temperature. Similar to the graph of power, the curves are quite similar. Differences in vibrations do increase at higher speeds, but data at 3500 rpm were ignored due to number clipping and overflow.

The L10 vibration levels were sought as indicators of the peak vibration levels, indicative

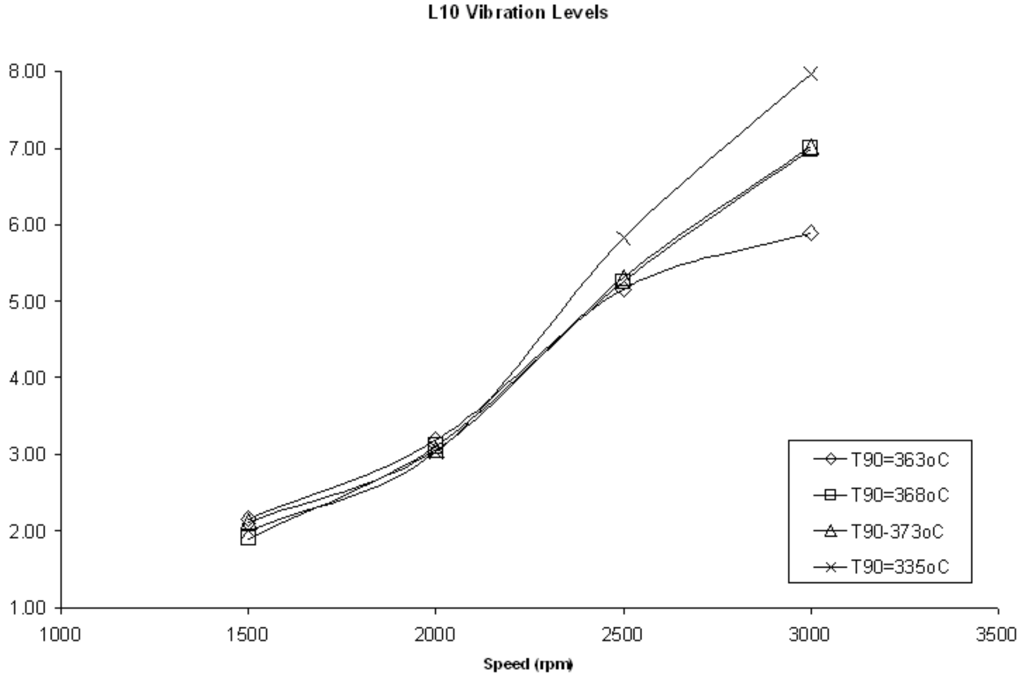

Figure 7. Graph of L10 Vibration Levels vs. Engine Speed.

of the vibrations during fuel detonation. Similar to the RMS acceleration, the curves are very similar. No discernible trend could be found with respect to $T_{90}$ distillation temperature.

## 4. CONCLUSION

Full-load variable-speed tests on a light truck direct-injection engine were conducted to determine if the distillation temperature $T_{90}$ of diesel fuel had any significant impact on engine performance, emissions and vibrations. Data obtained from the tests show that there are no significant differences in torque, power, smoke number, and vibration levels among fuels with moderately varying $T_{90}$ temperatures. Results indicate that fuel economy slightly improved with lower $T_{90}$ temperatures, the improvement being more pronounced at lower engine speeds. The Smoke Number of the fuels tested decreased with increasing engine speed before sharply going up at the highest engine rated speed. Vibration levels increased with engine speed as expected.

The observed weak correlation between the $T_{90}$ distillation temperature of the fuels tested and most of the engine performance parameters measured is deemed important. Thus, diesel fuels with higher $T_{90}$ distillation temperatures may be used in engines without markedly compromising engine performance, emissions, and vibrations. This implies that a greater portion of crude oil can be made available for engine use, therefore increasing profitability from a petroleum refining standpoint. It also maximizes the usefulness of an increasingly limited energy resource.

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