Design of Experiments to Determine Factors Contributing to Fuel Economy

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April 1, 2008

Abstract
Presented in this paper are the results of an experiment investigating factors potentially contributing to automotive fuel economy. A custom hardware/software interface was designed to communicate with the vehicle electronic control unit (ECU) via the on-board diagnostics (OBD-II) port in order to extract information used in calculating fuel flow. Fuel flow was the response variable analyzed using a Box-Behnken Design (BBD) response surface methodology (RSM) from varying the air filter, vehicle speed, engine speed and loading. A model was developed and optimized to provide insight into improving (or maintaining improved) fuel economy.

Keywords: Fuel economy, design of experiments, Box-Behnken, response surface methodology, OBD-II

Introduction
It is a common concern for car owners that they may not be doing everything within their abilities to get the best fuel economy out of their daily-driven vehicle(s). Moreover, many people would not even know which factors contribute significantly to the efficiency of their car. This experiment aimed to put a few of these factors to the test in order to better educate the driving audience.

In order to get accurate readings for an experiment such as this, data should be read real-time via the vehicle OBD-II (On-Board Diagnostics) port, required on all vehicles manufactured as of the 1996 model-year (OBD-II.com, 2008). However, a specialized interface is required to communicate via the OBD-II port.
OBD-II Hardware Interface

A custom interface was developed to communicate with an ISO 14320-4 protocol-equipped vehicle (the test vehicle was a 2004 Chevrolet Optra). A schematic of the circuit developed (using National Instruments Multisim™) is given in Figure 1.

![Figure 1 - ISO Protocol OBD-II Interface Schematic](image)

The only uncommon component of the circuit is the ELM323 – a microcontroller that converts ISO 9141-2 and ISO 14230-4 protocol communication into RS-232 (serial) data. In order to maintain the integrity of the circuit, a PCB was laid out and constructed for use during the experiment. The layout (designed in National Instruments Ultiboard™) is shown in Figure 2.
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Figure 2 - ISO Protocol OBD-II Interface PCB Layout

A 3D model representation of the PCB is shown in Figure 3.

Figure 3 - ISO Protocol OBD-II Interface PCB 3D Model
The header, J2, is a Phoenix Contact™ connector that allowed wiring to be run from the PCB to the J1962F OBD-II connector (as shown in Figure 4) (N/A). Once the data had been converted to RS-232 format, it was transferred via serial-USB converter (connected to the DB9F connector, J1) to the custom software interface on the connected laptop.

Data Logging Software

A custom GUI (Graphical User Interface) was developed for logging the received data using the GUIDE (Graphical User Interface Development Environment) tool in Matlab™. A screenshot of the GUI is shown in Figure 5.

The GUI requested data from the vehicle ECU (Engine Control Unit), read the response, cleaned & parsed the message(s), performed calculations on valid ECU messages and wrote the data & results to a CSV (Comma-Separated Value) file.

Response Variable

The goal of this experiment was to determine which factors contribute to fuel economy – a good indication, easily calculated from the available parameters, is instantaneous fuel flow. Using dimensional analysis, one can determine that fuel economy would be derived from fuel flow as shown in Equation 1.
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\[ \text{Fuel Economy } (l/100km) = K \times \frac{\text{Fuel Flow } (g/s)}{\text{Density of Gasoline } (g/l) \times \text{Vehicle Speed } (km/h)} \quad (1) \]

‘K’ is a constant of unit conversion(s). Therefore, there is a direct relationship between fuel flow and fuel economy (or an inverse relationship if considering the imperial measure of fuel economy, mpg), as one would expect. Furthermore, fuel flow is calculated as shown in Equation 2.

\[ \text{Fuel Flow } (g/s) = \frac{\text{Mass Air Flow } (g/s)}{\text{Stoichiometric Ratio } (g/g)} \quad (2) \]

However, MAF (Mass Air Flow) was not an available PID (Parameter ID) on the test vehicle, therefore further calculation was required. Using available PIDs, MAF could be approximated using the Ideal Gas Law as shown in Equation 3 (Wikipedia, 2008).

\[ \text{Mass Air Flow } (g/s) \propto \frac{\text{Engine Speed } (\text{RPM}) \times \text{Manifold Air Pressure } (\text{kPa})}{\text{Intake Air Temperature } (\text{°C})} \quad (3) \]

Using the above relationships, the response variable (fuel flow) was calculated for analysis, as described in later sections.

**Factors**

The factors selected to be investigated for their contribution to fuel economy are outlined in the following sections.

**Air Filter**

The air filter installed in the test vehicle (2004 Chevrolet Optra) was selected as a factor due to the fact that it determines the amount and quality of air permitted into the intake. The filters (levels) selected are the existing (assumed dirty) OEM (Original Equipment Manufacturer) filter, a new (clean) OEM filter and a K&N Engineering™ air filter. Of particular interest was whether there would be a significant difference between OEM and K&N, as the K&N has long been marketed as a superior product (worth its extra cost).
Vehicle Speed

The speed of the vehicle (km/h) was selected as a numeric factor that may contribute to fuel economy. The range of interest was 45-65 km/h – normal city driving. Therefore, the levels chosen were 45 km/h as the low level and 65 km/h as the high level – also, this would generate a center point at 55 km/h.

Engine Speed

Engine speed (rpm) was another numeric factor selected as a probable contributor to fuel economy. The range of interest was 1000-3000 rpm – 1000 rpm is the engine speed of normal cruising & idling and 3000 rpm is an engine speed of normal-moderate acceleration. Therefore, the levels chosen were 1000 rpm as the low level and 3000 rpm as the high level – this would also generate a center point at 2000 rpm which is a good indicator of normal driving.

Load

The final factor selected for investigation was loading – a categoric factor. The levels chosen were ‘normal’ and ‘high’, where ‘normal’ is the absence of, and ‘high’ is the presence of, the following loading conditions:

- Air conditioning
- Rear defroster
- Headlights, high beams and fog lights
- Dash and dome lights
- CD player
- Inverter powering laptop via aux port

Response Surface Methodology Design

The RSM (Response Surface Methodology) design of experiments schemes considered are outlined in Table 1.

<table>
<thead>
<tr>
<th>RSM Design</th>
<th>Alpha</th>
<th>Filter Factor Type</th>
<th>Number of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD</td>
<td>(\sqrt{2}) (Rotatable)</td>
<td>Categoric</td>
<td>54</td>
</tr>
<tr>
<td>CCD</td>
<td>1 (Face Centered)</td>
<td>Numeric</td>
<td>30</td>
</tr>
<tr>
<td>BBD</td>
<td>N/A</td>
<td>Numeric</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 1 - RSM Designs for Consideration
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Note that all the above mentioned designs have one center point. Intuitively, the filter type would be a categoric factor, which would leave only two numeric factors (vehicle speed and engine speed). This would force the design to be CCD (Central Composite Design), as a BBD (Box-Behnken Design) requires at least three numeric factors. Moreover, the design would require 54 runs because composite design would be duplicated for each categoric factor.

However, if the filter type was considered to be a numeric factor with the levels assigned as -1 for Dirty OEM filter, +1 for the K&N filter and the center point (0) for the clean OEM filter, a face-centered CCD could be utilized to reduce the number of runs to 30.

Furthermore, if this numeric filter scheme was used, it is only varied over 3 levels (as are the other two numeric factors); therefore, a BBD design could be used to further reduce the number of runs to 26 as well as introduce rotatability. This design was chosen for this experiment.

**Analysis of Variance**

The data was collected using the interface described in the previous sections and a backward selection was performed on a quadratic process order model in Design-Expert™ to generate the ANOVA (Analysis of Variance) shown in Table 2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1.108E+006</td>
<td>5</td>
<td>2.217E+005</td>
<td>20.33</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>A-Filter</td>
<td>16760.35</td>
<td>1</td>
<td>16760.35</td>
<td>1.54</td>
<td>0.2302</td>
<td></td>
</tr>
<tr>
<td>B-Vehicle Speed</td>
<td>78991.58</td>
<td>1</td>
<td>78991.58</td>
<td>7.24</td>
<td>0.0145</td>
<td></td>
</tr>
<tr>
<td>C-Engine Speed</td>
<td>8.737E+005</td>
<td>1</td>
<td>8.737E+005</td>
<td>80.11</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>A²</td>
<td>58832.81</td>
<td>1</td>
<td>58832.81</td>
<td>5.39</td>
<td>0.0315</td>
<td></td>
</tr>
<tr>
<td>C²</td>
<td>42423.10</td>
<td>1</td>
<td>42423.10</td>
<td>3.89</td>
<td>0.0633</td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>2.072E+005</td>
<td>19</td>
<td>10906.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>1.316E+006</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Analysis of Variance (ANOVA) Table
Based on the ANOVA, the terms B, C and A² were significant with C² added to the model by the backward selection and A added for hierarchy. The model produced an $R^2$ value of 0.8425 and an adjusted $R^2$ value of 0.8010 which is in reasonable agreement with the predicted $R^2$ value of 0.7221. The model diagnostics are shown below in Figure 6 to Figure 9.

Based on the diagnostic, one can notice an outlier in the normal distribution and variance. Furthermore, the Box-Cox Plot indicated that a logarithmic transform of the data was recommended. Therefore, a (natural) logarithmic transform was performed (with $k=\lambda=0$) and the ANOVA shown in Table 3 was generated using backward selection on a quadratic process order.
Based on the ANOVA, the terms B, C and \( C^2 \) were significant with CD and \( A^2 \) added to the model by the backward selection and A & D added for hierarchy. The model produced an \( R^2 \) value of 0.9565 and an adjusted \( R^2 \) value of 0.9386 which was in reasonable agreement with the predicted \( R^2 \) value of 0.9021. The model diagnostics are shown below in Figure 10 to Figure 13.
Based on the above diagnostics, the distribution of the residuals appears normal and the variance appears to be constant. Therefore, it can be assumed the model appropriately fits the data collected.

There was an interaction effect between the engine speed (C) and the load (D) – this interaction is illustrated in Figure 14.

The equation associated with the model determined using the described ANOVA, is given using coded terms in Equation 4.

\[
Fuel\ Flow = e^{(6.2 + 0.056A + 0.16B + 0.75C - 0.017D - 0.088CD - 0.15A^2 - 0.47C^2)}
\] (4)
Optimization

Using numerical optimization to minimize fuel flow, the following operating conditions are determined.

1. Dirty OEM filter.
2. 46.70 km/h vehicle speed.
3. 1010.94 rpm engine speed.
4. Normal loading

These operating conditions give a fuel flow value of 98.922. Interestingly, the dirty OEM filter provided the best fuel economy. For comparison, Table 4 below outlines the minimized fuel flow for each filter.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Fuel Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dirty OEM</td>
<td>98.922</td>
</tr>
<tr>
<td>Clean OEM</td>
<td>115.923</td>
</tr>
<tr>
<td>K&amp;N</td>
<td>105.593</td>
</tr>
</tbody>
</table>

Table 4 - Fuel Flow by Filter

The minimum fuel flow when using the clean OEM filter is 17.2% higher than with the dirty OEM filter, while the fuel flow when using the K&N filter is 6.7% higher.

Results and Conclusions

The results of the analysis described in the previous sections lend insight into the factors contributing to fuel economy and could potentially give a driver a mechanism for reducing fuel consumption. The largest contributor was found to be engine speed (rpm) which is a direct measure of driving behaviour. If a driver does not regularly execute manoeuvres requiring above normal acceleration or drives in an appropriate gear for the given speed limit, the engine speed will remain within a range that will maximize fuel economy.

Also, disposable air filters, such as OEM, are supposed to be changed every 6-12 months (Memmer). The dirty OEM filter used in the experiment was 13 months old and performed even slightly better than the clean replacement. This could result in monetary savings ($14.66 per filter) if the vehicle owner properly inspects the air filter every 6-12 months for blockage and condition, without any loss of fuel economy.
Furthermore, the K&N air filter did not immediately perform as well as the original OEM filter. However, because it is a high-flow air filter, the ECU (electronic control unit) will add more fuel due to the increased air flow, which results in K&N’s advertised power increase (K&N Engineering, Inc., 2008); but the ECU will compensate for this condition with use. Moreover, the K&N filter is reusable which, should the fuel economy rival the OEM, may ultimately save the vehicle owner money at a price of $56.90.

It is recommended that further replication be run with the K&N filter once the ECU has adapted to the added air flow, to gain a better response for fuel flow during the life of the filter. Also, other reusable air filters should be considered, such as FRAM™ SynWash long life air filters.

Other factors that should be considered for future experiments are tire pressure, cargo weight, cargo distribution, gasoline octane, surface grade (downhill, flat and uphill) and oxygen sensor feedback (removed O₂ sensor(s) simulating typical O₂ sensor failure). If further experimentation is conducted with any of the above factors, a ½-fraction, face-centered CCD should be used in place of a BBD to significantly reduce the number of required runs at the expense of rotatability.

References


N/A. J1962 Vehicle Connector, Type A. Which OBD-II protocol is supported by my vehicle? ScanTool.net, Phoenix, Arizona, USA.
