# DIESEL-CNG DUAL FUEL COMBUSTION CHARACTERIZATION USING VIBRO-ACOUSTIC ANALYSIS AND RESPONSE SURFACE METHODOLOGY

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# ABSTRACT

Engine conversion process from any diesel vehicle to a diesel-CNG dual fuel system requires additional fuel management. The need for an engine monitoring is vital to ensure the dual fuel operation run smoothly without excessive knocking, which may shorten the life of the engine. Knock and air-fuel ratio (AFR) sensors are commonly used for engine monitoring during fuel management setup. However, the engine output characteristics has been overlooked during the monitoring process. This study is aimed to explore a statistical approach by predicting the relationship between fuel management and engine output characteristics of diesel-CNG dual fuel engine using Response Surface Methodology (RSM). Two inputs which are CNG substitution rate and engine speed were used to predict the engine output characteristics in terms of engine performance, exhaust emissions, combustion pattern and combustion stability. Within the investigation, a statistical method was proposed to analyse the vibro-acoustic signal generated by a knock sensor installed at the outer cylinder wall of the engine. The frequency distribution analysis was applied to interpret the high variability of the vibro-acoustic signal. The results were used as the input for combustion stability in RSM analysis. It also provided useful information with regards to the engine stability. The response surface analysis showed that the CNG substitution rate and its properties significantly influenced the engine output characteristics. This study also describes the methodology to determine the accuracy and the significance of the developed prediction models. The prediction models were validated using confirmation test and showed good predictability within 95% confidence interval. Thus, it is concluded that RSM provide models that predict the engine characteristics with significant accuracy, which contributes to the effectiveness of diesel-CNG dual fuel engine conversion process.

**ABSTRAK**

Proses penukaran enjin dari mana-mana kenderaan diesel kepada sistem dwi bahan bakar diesel-CNG memerlukan pengurusan bahan bakar tambahan. Keperluan pemantauan enjin adalah penting untuk memastikan operasi dwi bahan api berjalan dengan lancar tanpa *knocking* yang berlebihan, yang boleh memendekkan jangka hayat enjin. Sensor bagi *knock* dan udara-bahan api (AFR) biasanya digunakan untuk pemantauan enjin semasa persediaan pengurusan bahan api. Walau bagaimanapun, ciri-ciri output enjin telah diabaikan semasa proses pemantauan. Kajian ini bertujuan untuk meneroka pendekatan statistik dengan meramalkan hubungan antara pengurusan bahan api dan ciri-ciri output enjin diesel-CNG dwi bahan api menggunakan Metodologi Permukaan Respon (RSM). Dua input iaitu kadar penggantian CNG dan kelajuan enjin digunakan untuk meramalkan ciri output enjin dari segi prestasi enjin, pelepasan ekzos, corak pembakaran dan kestabilan pembakaran. Semasa siasatan, kaedah statistik dicadangkan untuk menganalisis isyarat vibro-akustik yang dihasilkan oleh sensor *knock* yang dipasang di luar dinding silinder enjin. Analisis taburan frekuensi digunakan untuk menafsirkan kebolehubahan tinggi isyarat vibro-akustik. Hasilnya digunakan sebagai input untuk kestabilan pembakaran dalam analisis RSM. Ia juga menyediakan maklumat berguna berkaitan dengan kestabilan enjin. Analisis respon permukaan menunjukkan bahawa kadar penggantian CNG dan sifatnya telah mempengaruhi ciri output enjin. Kajian ini juga menerangkan metodologi untuk menentukan ketepatan dan kepentingan model ramalan yang telah dibangunkan. Model ramalan telah disahkan menggunakan ujian pengesahan dan menunjukkan ramalan yang baik dalam lingkungan 95% selang keyakinan. Oleh itu, disimpulkan bahawa RSM menyediakan model ramalan yang mengawasi ciri-ciri enjin dengan ketepatan yang signifikan, yang menyumbang kepada keberkesanan proses pengubahan enjin dwi bahan bakar diesel-CNG.

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AFR | Air Fuel Ratio |
| AI ATDC | Acoustic Index After Top Dead Centre |
| AI BTDC | Acoustic Index Before Top Dead Centre |
| ANOVA | Analysis of Variance |
| AP | Adequate Precision |
| BMEP | Brake Mean Effective Pressure |
| BRIC | Band-pass Rectify Integrate Compare |
| BSEC | Brake Specific Energy Consumption |
| BTE | Brake Thermal Efficiency |
| CAD | Crank Angle Degree |
| CCD | Central Composite Design |
| CD | Combustion Duration |
| cDAQ | compact data acquisition |
| CI | Confidence Interval |
| CNG | Compressed Natural Gas |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| COV | Coefficient of Variance |
| CPI | Consumer Pricing Index |
| CWT | Continuous Wavelet Transform |
| DAQ | Data acquisition |
| DDF | Diesel Dual Fuel |
| df | degree of freedom |
| DF-PCCI | Dual Fuel Premixed Charge Compression Ignition |
| DoE | Design of Experiment |
| ECU | Electronic Control Unit |
| EGR | Exhaust Gas Recirculation |
| EOC | End of Combustion |

| | |
|---|---|
| EPA | Environmental Protection Agency |
| ESC | European Stationary Cycle |
| EUI | Electronic Unit Injector |
| FDS | Fraction Design Space |
| FS | Full Scale |
| FTP | Federal Test Procedure |
| GHG | Greenhouse Gas |
| HC | hydrocarbon |
| HPDI | High Pressure Direct Injection |
| HOME | Honge Oil Methyl Ester |
| HRR | Heat Release Rate |
| Hz | Hertz |
| ICA | Independent Component Analysis |
| ID | Ignition Delay |
| IMEP | Indicated Mean Effective Pressure |
| IQR | interquartile range |
| JPJ | Department of Road Transport Malaysia |
| LNG | Liquefied Natural Gas |
| LOF | Lack of Fit |
| MAF | Mass Air Flow |
| MIDC | Modified Indian Driving Cycle |
| MS | Malaysia Standard |
| NGV | Natural Gas Vehicle |
| NI | National Instrument |
| $NO_x$ | nitrogen oxide |
| OBD | On-Board Diagnosis |
| OEM | Original Equipment Manufacturer |
| PME | Palm Methyl Ester |
| PP | peak in-cylinder pressure |
| PRESS | predicted residual square error sum |
| Q1 | first quartile |
| Q3 | third quartile |
| RM | Ringgit Malaysia |
| RNG | Renewable Natural Gas |

| | |
|---|---|
| ROI | Return On Investment |
| RON | Research Octane Number |
| rpm | revolution per minute |
| RSM | Response Surface Methodology |
| RSS | Root-Sum-Square |
| SDP | Symmetrised Dot Pattern |
| SLPM | standard litre per minute |
| SOC | Start of Combustion |
| SOI | Start of Injection |
| Std. Dev. | Standard Deviation |
| STFT | Short-Time Fourier Transform |
| SUV | Sport Utility Vehicle |
| TDC | Top Dead Centre |
| THC | total hydrocarbon |
| VGT | Variable Geometry Turbine |
| vol | volume |
| WVD | Wigner-Ville Distribution |
| 4WD | four wheel drive |
| $a$ | area of bore |
| $a_s$ | velocity of sound |
| $bp$ | brake power |
| $B$ | cylinder bore |
| $CV$ | Calorific Value |
| cc | cubic centimetre |
| $CO_2$/km | carbon dioxide per kilometre |
| $f_{u,s}$ | oscillation frequency of in-cylinder gas |
| ft-lb | foot pound force |
| g | gravity |
| g/s | gram per second |
| J/(kg-K) | Joule per kilogram-Kelvin |
| J/CAD | Joule per crank angle degree |
| $k$ | ratio of specific heat |
| K | Kelvin |

| | |
|---|---|
| kg | kilogram |
| kg/h | kilogram per hour |
| $kg/m^3$ | kilogram per metre cubic |
| kJ/kg/K | kiloJoule per kilogram per Kelvin |
| ks | kilo seconds |
| kW | kiloWatts |
| $l$ | Stroke |
| L | Litre |
| L/100 km | Litre per 100 kilometre |
| $m$ | mass |
| $\dot{m}$ | mass flow rate |
| $M$ | physical parameters |
| m/s | meter per seconds |
| $m^2$ | meter square |
| MJ/kg | mega Joule per kilogram |
| MJ/kWh | mega Joule per kiloWatts hours |
| mm | millimetres |
| $mm^2/s$ | millimetre square per second |
| MOhm | mega unit of resistance |
| MPa | mega Pascal |
| ms | milliseconds |
| mV/g | milliVolt per gravity |
| $n$ | number of working stroke per minute |
| $n_e$ | engine speed |
| Nm | Newton meter |
| $N_r$ | number of revolution per engine cycle |
| $^oC$ | degree Celsius |
| $P$ | pressure |
| Pa | Pascal |
| pC | pico Coulomb |
| ppm | part per million |
| psia | pound per square inch absolute |
| $R$ | gas constant of working gas |

| | |
|---|---|
| $R^2_{ajd}$ | adjusted $R^2$ |
| $R^2_{pred}$ | predicted $R^2$ |
| rel | relative |
| $R_i$ | measuring range |
| $R_u$ | random uncertainty |
| $s$ | number of nodes in the radial oscillation |
| $S_i$ | uncertainty in M |
| $S_u$ | Systematic uncertainty |
| tscf | trillion standard cubic feet |
| $T$ | temperature |
| $U_{overall}$ | overall uncertainty |
| $u$ | number of nodes in the circumferential oscillation |
| V | Volt |
| $V$ | volume |
| $X_i$ | variable |
| $\rho_{u,s}$ | vibration mode factor |
| $\gamma$ | specific heat ratio |
| $\eta_v$ | volumetric efficiency |
| $\theta$ | crank angle degree |
| $\lambda$ | minimum residual sum of squares |

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## CHAPTER 1

## INTRODUCTION

### 1.1 Background of research

Natural gas is an alternative fuel derived from non-renewable energy source. It has the lowest Greenhouse Gas (GHG) emissions compared to other fossil fuel. According to F. Königsson, natural gas offers 20% reduction in GHG emissions compared to gasoline and diesel because its chemical properties of methane that are larger in hydrogen to carbon ratio [1]. Furthermore, it is inexpensive compared to other fuel and its abundant resource which is sufficient for upcoming decades has appeared as a priority for fossil fuel replacements.

Natural gas can be utilized as Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG) or Renewable Natural Gas (RNG) using retrofitted kits. Retrofitted kits are additional components such as CNG tanks, Electronics Control Unit (ECU), pressure gas regulator, gas injectors and wire harness. These are commonly used for engine conversion into Natural Gas Vehicle (NGV).

Most CNG conversion kits systems for NGV are illustrated in Figure 1.1, which it depends on engine type. For spark ignition engine, it can be converted into either mono-fuel or bi-fuel systems. Meanwhile, for compression ignition engine, either mono-fuel or dual fuel system can be utilized. For mono-fuel systems, the NGV uses 100% CNG, while for bi-fuel systems; the NGV can alternately use 100% CNG or 100% gasoline. In the case of a dual fuel system, α% of CNG is mixed with β% of diesel fuel in the combustion chamber. The CNG is injected through intake manifold; either using the sequential port injection or by the fumigation method. Then it is mixed with air as a homogeneous charge. The homogeneous charge between air and CNG is ignited as it is initiated by diesel fuel combustion during the compression stroke.

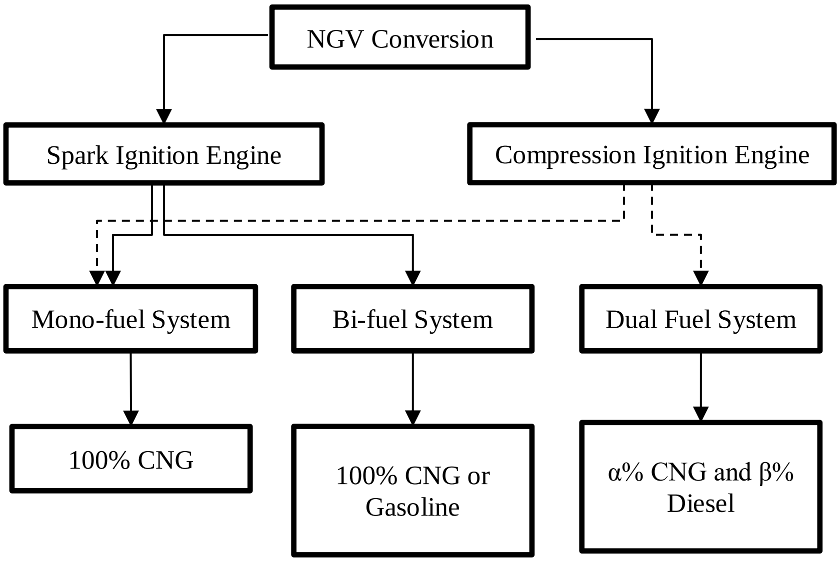


Figure 1.1: CNG fuel system for NGV conversion

According to NGV Global, there is existed about 23 million of NGVs in the world and may exceed 30 million by 2024 [2]. The NGV's market is dominated by passenger cars and its quantity is low compared to gasoline or diesel vehicle. In Europe, the NGV's market is low as 3% [3]. Meanwhile, in Malaysia, the registered NGVs are about 77 thousand compared to 14.68 million for other registered vehicles (cars, public service vehicles, and goods vehicles). This is less than 1% [4, 5]. Despite many efforts have been established in the development of CNG in road transport applications, there is still a barrier need to be addressed in order to enhance the NGV's market [6, 7].

The major obstacle for NGV development is the engine conversion, where it should be the main focus in this research because the availability of the conversion kits is feasible. However, the deployment into the existing vehicles is the key factor [8]. A survey has been conducted to get expert opinions on the NGV's research needed for energy policy development [9]. From the survey, it is noted that the short-term priority for NGV development is on the NGV and refuelling infrastructure. It means that the integration and test of the CNG conversion kits for different vehicle's engine would seek public intention towards the use of NGVs. Besides that, the other barriers for NGV's market penetration are vehicle availability, after-market conversion, refuelling stations, and government policies [10, 11].

In Malaysia, most of NGVs are converted into either mono-fuel or bi-fuel system; that are dominant by public transport service such as taxi. From Department of Road Transport Malaysia (JPJ), most NGVs for logistics vehicles use a mono-fuel system for their diesel engines. However, based on Malaysia's CNG infrastructure facilities, the dual fuel systems is the good option because its offer fuel flexibility where the engine can operates with 100% diesel if the CNG supply is not available [12]. In addition, typical diesel engine comes with common rail fuel injection system where possess great potential for diesel dual fuel (DDF) system due to its flexibility in controlling fuel injection for diesel fuel replacement.

## 1.2 Problem statement

The conversion kits or retrofitted kits for diesel dual fuel (DDF) systems are additional components installed to run dual fuels in diesel engine. It requires integration process to adopt the DDF components to the diesel engine. Even though no major modification is needed and is mostly add-on components, the configuration setup to operate the dual fuels requires accurate tuning process and it is challenging in order to ensure that the engine has comparable performance and stability. In addition, the exhaust emission aspect should take into account due to stringent emission regulation. For example, in United State, the conversion kits must comply with the Environmental Protection Agency (EPA) requirement to meet the standard emission regulation [13].

Normally, the tuning process for the DDF system involves fuel management setting to reduce the diesel fuel quantity and replace with the CNG fuel. The fuel management setting usually is based on the fuel quantity for both fuels. The CNG substitution rate is dependent on diesel engine installed with dual fuel systems. Therefore, the DDF systems installer uses additional instrumentations such as knock sensor and air-fuel ratio (AFR) sensor during the tuning process for measurement and monitoring purposes. Both inputs from these two sensors are used as the guidance for the DDF systems tuner to verify the dual fuel system operation limitation. This means that the dual fuel engine should have a similar air-fuel ratio compared to diesel mode without any knock event. The efficiency of this tuning method become questionable due to several aspects that might overlook during the tuning process such as actual engine performance, fuel consumption, exhaust emissions and its stability.

Furthermore, the conventional method for measuring engine stability is by observing several consecutive combustion pressures. Generally, the in-cylinder pressure sensor is implemented to measure the combustion pressure where it a suitable instrumentation to provide accurate information. Unfortunately, it is not a practical approach for commercial purpose since it is costly.

The Response Surface Methodology (RSM) has the capability to provide the relation between fuel substitution rate and engine output characteristics through its statistical approach. This approach may help DDF tuner to understand the characteristics of the engine installed with the dual fuel conversion kits. The design of experiment using RSM could provide an experimental technique for predicting the responses of engine performances, exhaust emissions, combustion patterns and combustion stability. In addition, these response characteristics can be presented graphically through its contour plot and response surface profile, which are useful for establishing responses values and operating condition as required. The modelling methodologies are capable to predict the untested conditions with significant accuracy as per reported by [14–16].

The functionality of the commercial knock sensor that provides knock detection indicator can be utilized to provide information regard to engine stability. However, the vibro-acoustic signal from the knock sensor has large variability due to different background noises comes from an engine. A statistical method can be introduced to eliminate the background noises and provides the vibration intensity index. Thus, it can display the distribution of the vibration intensity index that shows the stability of the engine.

## 1.3 Research questions

The research questions for this study as follows:

i. What statistical approach can be utilized to overcome the high variability of the acoustic index data for combustion stability data in Response Surface Methodology (RSM) analysis?
ii. What can be achieved by assessing the responses of designed experiments for predicting the engine's output characteristics, i.e. engine performance, exhaust

emissions, combustion patterns and combustion stability using RSM? In addition, how significant is the prediction models developed using RSM.

iii. What relationships can be established between fuel management and engine output characteristics for diesel-CNG dual fuel engine using RSM?

## 1.4 Objectives

The objectives of the research are as follows:

i. To propose a novel statistical approach for vibro-acoustic signal analysis method via the offline mode to overcome the high variability of the acoustic index data as the input for combustion stability analysis.
ii. To develop the significant prediction models of engine output characteristics using Response Surface Methodology (RSM) and validate through the confirmation test against the experimental values.
iii. To predict the relationship between fuel management and engine output characteristics of diesel-CNG dual fuel engine using RSM.



## 1.5 Scopes of study

The scopes of this research are as follows:

i. The investigation is based on diesel-CNG dual fuel system conversion kits (brand: GI GASITALY) is installed in Toyota Hilux 2.5L common rail direct injection diesel engine (engine model: 2KD-FTV) with no modification on the stock ECU.
ii. The study is focused on the fumigated CNG dual fuel system.
iii. The dual fuel set ratios are targeted at 10%, 20%, 30% and 40% of diesel replacement in term of mass ratio within the operating range of 1500 to 3500 rpm engine speeds.
iv. The steady-state dynamometer testing is considered for this study by using chassis dynamometer.

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