

Accurate and Continuous Fuel Flow Rate Measurement Prediction for Real Time Application

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ABSTRACT

One of the most critical challenges currently facing the diesel engine industry is how to improve fuel economy under emission regulations. Improvement in fuel economy can be achieved by precisely controlling Air/Fuel ratio and by monitoring fuel consumption in real time. Accurate and repeatable measurements of fuel rate play a critical role in successfully controlling air/fuel ratio and in monitoring fuel consumption.

Volumetric and gravimetric measurements are well-known methods for measuring fuel consumption of internal combustion engines. However, these methods are not suitable for obtaining fuel flow rate data used in real-time control/measurement.

In this paper, neural networks are used to solve the problem concerning discontinuous data of fuel flow rate measured by using an AVL 733 s fuel meter. The continuous parts of discontinuous fuel flow rate are used to train and validate a neural network, which can then be used to predict the discontinuous parts of the fuel flow rate. A comprehensive and detailed neural network (NN) modeling technique for engine application is presented. The experiments in this study are designed to collect informative data for steady states, where the speed and load are fixed. Different neural network structures are compared, including feed-forward NN, feed-forward NN with delays and non-linear autoregressive model with exogenous inputs (NLARX). The NLARX is determined to be the best structure for fuel flow rate prediction. The training process and input choices for catching fast and slow dynamics are illustrated in the paper. Additionally, for real-time control and measurement purposes, a fuel flow rate model is maintained to be as simple as possible by minimizing the structure based on NN identifiable properties.

This study shows that NLARX could accurately predict fuel flow rate with a R-square above 0.99.

INTRODUCTION

One of the most critical challenges facing the diesel engine industry is how to improve fuel economy and reduce emissions. Current technologies for fuel efficiency improvement and emissions reduction are highly dependent on combustion modification technologies including injection technologies and real-time advanced control systems. Combustion modification technologies modify combustion systems that will either aid or complement the actions of engines. In these technologies, fuel flow rate measurements are essential for control purpose and thus play an important role in the development of techniques for emissions reduction and fuel economy improvement. A fuel flow rate model with good prediction performance is even more apparently needed.

Volumetric and gravimetric methods are well-known methods for measuring internal combustion engine fuel consumptions. In the volumetric approach, the volume of fuel consumed by the engine is recorded. The fuel consumed is equal to the consumed volume multiplied by the temperature-dependent fuel density. The drainage time of a defined volume is measured and used to convert consumed fuel volume to fuel consumption. A fundamental characteristic of this approach is that the measurement is discontinuous. This discontinuous variable is not suitable for the purpose of control.

Fuel gravimetric systems, such as, AVL 733S Dynamic Fuel Meter, consist of a measuring vessel filled with fuel and suspended on a balance system. The fuel consumption rate is determined by calculating the vessel's time related weight loss. Fuel flow rate measurements are continuous during the

consumption of the fuel in the vessel and discontinuous during the refilling of the fuel meter.

Alternative fuel measurement system designs which are popular in engine fuel measurement applications are based on the Coriolis Effect or use a servo controlled displacement measurement technique [1]. These designs are generally more expensive but they have the advantages of both continuous fuel measurement and fast response. For example, the AVL 733S is rated at <440ms while the AVL coriolis based system (AVL 735S) is specified as <125 ms, a key advantage when investigating engine transient response. When a fast response is not required, some economic fuel metering systems are always the sought-after solutions for lots of applications [2].

Virtual sensors have been utilized in various areas, such as, engine and emission monitoring and vehicle dynamics. A key advantage of NNs is that they can be used as an arbitrary function approximation mechanism without knowing the complicated underlying process, a highly advantageous and economic way to measure fuel flow rate. NN modeling belongs to one of nonlinear regression techniques. It is easy for NN to run in engine control unit as NNs could be composed of digital information.

Neural networks have been successfully used in many engine based applications including emissions, boost pressure and EGR prediction [3, 4, 5]. Bose and Kumar [6] use fuzzy logic to predict the engine emissions, but one of the inputs is cylinder peak pressure, which is difficult to obtain in standard production engines. How to choose effective inputs based on easily obtained parameters is of great importance for building successful models. Exhaustive input searching is the most difficult tasks for building models in engine application. Schilling et al chose inputs based on a sensitivity analysis [7].

In developing a fuel flow rate model, the following general and unique issues need to be considered:

1. The input choices are quite difficult. The basic fuel flow equations could not be used directly as many variables are either unmeasurable or unreliable
2. The transient information is difficult to capture for fuel flow rate
3. Capturing both steady state and transient fuel flow rate reliably in a single model is extremely difficult
4. Models are too complicated for real time control and measurement purposes

Consequently, this paper focuses on the development of fuel flow rate models in the steady state.

Problem (1) will be overcome by choosing the particular inputs which excited the system in the application, to include: where start of injection (SOI), common rail pressure (RP) or

fuel ratio between main and total fuel injected (FR) - in different load and speed points. Problem (2) is overcome by doing extensive perturbation experiments for different torque and speed points with steady state speed-load demand but excited fuel system parameters (e.g. SOI, RP and FR). Problem (3) will be overcome by using neural networks employing the methodology of a non-linear autoregressive model with exogenous inputs (NLARX) to predict the fuel flow rate. Problem (4) is overcome by using neural network identifiable properties to find a fuel flow rate model with good performance, then reducing the structure size through minimizing the number of delay parameters.

A fuel flow rate model should be simple to implement, easily trained or re-trained, and should have good performance in the prediction of unseen data. Moreover, to be used for diesel operation, these models should also catch as much as possible dynamics of the system. In this paper, identification experiments are designed to catch all kinds of characteristics of fuel flow rate. The models are developed to estimate the fuel flow rate based on possible parameter changes in engine operation. This model could be used for monitoring fuel flow rate, optimizing engine operation, and achieving control purpose.

This paper reports on work which has successfully identified a NLARX model that captures the dynamics of fuel flow rate with an accuracy of R-square of 0.99 for both training and validation and high regression coefficient. The training and validation data are collected using extensive point by point system identification experiments. The model could be used for control development in practical. This paper demonstrates a comprehensive and detailed modeling technique that could be used in engine applications. The method is highly flexible and could help solve similar problems in other engine applications.

In summary, the modeling process comprises the following five steps:

1. The first step is to study the mechanisms of the fuel flow rate meter. The purpose of this step is to understand the properties and dynamics of fuel flow rate and choose appropriate modeling techniques
2. The second step is to design a data collection experiment to catch all of the dynamics of the fuel flow rate
3. The third step is to construct the 'best' fuel flow rate estimation model structure by going through a process of selecting different neural network structures and then evaluating the performance of each
4. The fourth step identifies the unknown parameters in the best model structure and validates the model.

5. The final step is to reduce the model size by minimizing the number of delay parameters.

The above steps will be described in detail later in this paper.

The continuous parts of the discontinuous fuel flow rate measurement, as measured by the AVL 733S fuel mass balance, are used to train and validate a neural network model. The discontinuous parts of the fuel flow rate are then predicted by using neural networks. It will be shown that the developed neural network model predicts the fuel flow rate with very good accuracy for discontinuous parts of the fuel flow rate measurement.

In **Section 1 - introduction**, a brief background of the research is introduced. **Section 2** describes the measurement principles of the fuel flow meter used in this work and details the fuel supply and metering system. **Section 3** describes the experimental facility for the data collection and the real-time measurement system integration. **Section 4** outlines the detailed procedure for data collection and preparation. **Section 5** reviews the different neural networks architectures that can be considered as candidates for the fuel flow rate model. **Section 6** describes the training process and structure minimization procedure. **Section 7** shows the results of fuel flow rate models in steady state scenario. **Section 9** provides conclusions on this work.

FUNDAMENTALS OF THE FUEL FLOW RATE METER AND EXPERIMENTAL SYSTEM

AVL 733S FUEL BALANCE

Basic Principle

The AVL 733s design utilizes the gravimetric measuring principle in which fuel is supplied to the engine from a measuring vessel, the weight of which is continuously measured [8].

A schematic in [figure 1](#) outlines the main components of the AVL fuel balance. The measuring vessel is suspended on a bending spring. A mechanism which is designed to be both frictionless and hysteresis-less, translates mass into displacement. The displacement is then measured using a contactless capacitive displacement pick-up which sends the resulting voltage signal to a microprocessor. The system is fully automated in respect to both measurement and calibration procedures.

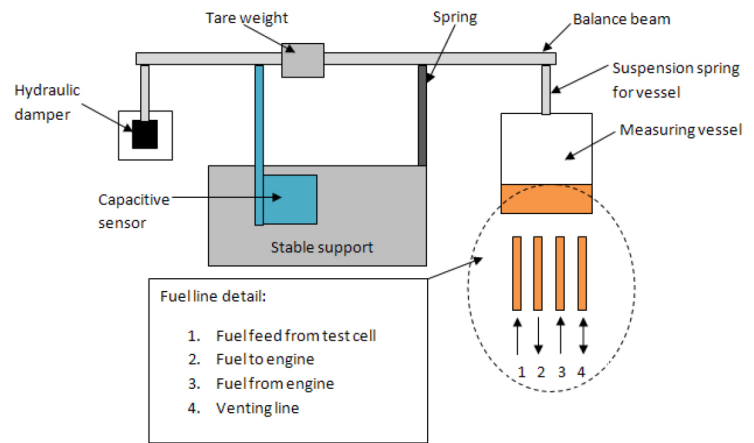


Figure 1. AVL 733S Measurement Principle [8].

The measurement vessel has both an engine fuel return line and a venting line thus emulating a vehicle fuel tank. This ensures that there is a continuous separation of air and vapor in the measurement system - the engine feed and return lines.

Advantages of the Gravimetric Fuel Measurement

The gravimetric principle used by the meter has the advantage of direct measurement of fuel consumption mass rate and is thus not subject to the additional measurement needs (fuel temperature) of a similar volumetric system and thus reduces the likelihood of experimental error. i.e. the fuel meter is insensitive to fuel temperature changes which can be significant when the measuring circuit includes a return line from the engine.

A further key advantage is the inherent capability to provide a continuous fuel consumption measurement up to the total mass of the measurement vessel when full. For the larger 1800g vessel in the 733S range, this translates into an ability to continually measure fuel consumption for most passenger car sized engines on many of the internationally known test procedures. Total consumption can thus be determined directly without integration and is thus very reliable.

Limitation of Gravimetric Fuel Measurement

The key limitation with a gravimetric fuel measurement system is the time required to refill the measuring vessel and a pre-determined dampening time. Measures can be taken to reduce the refilling time to a minimum but it remains. The frequency of refills is a function of the physical size of the measurement vessel, the configuration of the fuel supply to the meter, the engine fuel consumption rate and the configuration of the fuel meter - whether it has been set to fill to a volume less than the measurement vessel volume (for increased measurement resolution). The other limitation compared to alternative techniques that employ a coriolis or displacement meter, is the much slower response time. Thus,

this type meter is far better suited to steady state test applications.

The Test Cell Measurement Circuit

The 733S fuel meter in isolation provides accurate fuel mass rate measurements even when the fuel temperature inside the measuring vessel changes, this is a consequence of the fuel meter measuring fuel mass directly. However, the design of the whole fuel measurement system remains critical for reducing fuel temperature variation and hence fuel temperature derived experimental error i.e. the fuel mass in the measurement circuit itself must remain constant. As an example of the effect of temperature gradient in the measurement circuit, if the temperature of a system of volume 1000 cm^3 were to change by 1°C during the measurement time for a fuel of density 0.85 g/cm^3 and expansion coefficient $0.001 \text{ per}^\circ\text{C}$, the mass of the fuel in the measurement circuit will be reduced by $1000 \times 0.85 \times 0.001 \times 1 = 0.85 \text{ g}$. If during this measurement interval the engine consumes 50 g , the fuel meter measures the engine fuel consumption less the mass change in the measurement circuit, thus the resulting error would be $(50 - (50 - 0.85)) / 50$ which is 1.7% . The measurement circuit also needs to remain deaerated and the geometric volume must also be constant (avoiding pressure related expansions).

As such, the measurement circuit implemented for the Caterpillar C6.6 diesel engine employed during this work is carefully designed and configured to avoid sources of error. A schematic of the major components and fuel transfer lines of the system are illustrated in [figure 2](#).

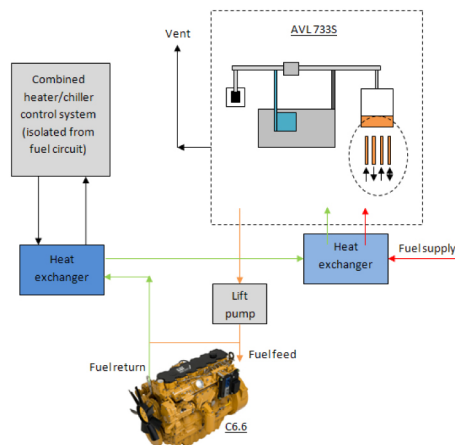


Figure 2. Fuel metering circuit.

Measurement Modes and Configuration Parameters Relevant to this Work

The 733S fuel meter has three main measurement modes; 1). individual and multiple measurements with preselected measurement time, 2). individual and multiple measurement

with preselected weight and 3). interval (start/stop) measurement. For the experimental work reported in this paper, mode 2 was used with a filling level of 250 g (amplification mode 4 setting - for maximum accuracy).

Output Signals, Measurement and Conversion

For the work reported in this paper, the fuel measurement system was configured to use the analogue (0-10V) output of the 733S fuel meter which was sampled at greater than 10 Hz (the measurement rate of the fuel meter) by a National Instruments PXI-6255 card mounted in a NI PXI-1042Q chassis. The acquired voltage was then converted into instantaneous fuel rate using a calibration equation, this being a function of the configured measurement parameters of the fuel meter.

EXPERIMENT FACILITY

The engine that is used in this study is a Caterpillar C6.6 ACERT heavy-duty off-highway engine. This is a 6 cylinder engine with a Caterpillar common rail fuel system. The engine calibration used in this work produces up to 159 kW at rated speed (2200 rpm) with peak torque of 920 Nm at 1400 rpm . The engine has been modified with a high pressure loop EGR system and a variable geometry turbine for experimental purposes.

The engine is fully instrumented to measure air, fuel and cooling system pressures, temperatures and flow rates. The fuel flow rate is measured by AVL 733S Fuel Mass Balance. Emissions data is gathered principally using AVL 415 smoke and 439 opacity meters (offering steady state and transient measurement respectively) and a Horiba 9100 exhaust gas analyzer measuring nitrous oxide, carbon dioxide, carbon monoxide, unburnt hydrocarbons and oxygen. The temperature and pressure at the exhaust port, are measured for each of the six cylinders. This is supported by exhaust manifold, post turbocharger, pre/post EGR cooler/control valve temperature and pressure measurements. [Figure 3](#) shows the engine facility.

DATA COLLECTION

INTRODUCTION FOR DATA COLLECTION

An example of real fuel flow rate signal, with a pattern of measurement then discontinuity is presented in [figure 4](#). The purpose of the work reported herein is to estimate the engine fuel flow rate during the periods when the fuel meter is refilling and stabilizing.

AVL 733S Fuel Mass Balance



Figure 3. Instrumented Caterpillar C6.6 Diesel engine.

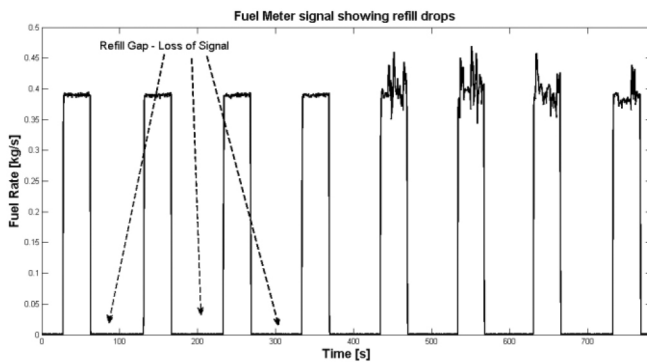


Figure 4. An example of fuel meter signals with refill gaps after 35 seconds at 2050 RPM at 457Nm.

In order to accurately estimate the instantaneous engine fuel consumption rate during these discontinuous periods, experimental data covering different dynamic characteristics of the Caterpillar C6.6 medium duty diesel engine have been acquired. They are split into training and validation subsets. This data collection approach is designed to cover a wide range of engine operating points and hence fuel meter operational cases and encompass as many of the features of the fuel consumption behavior as is possible from a practical experimental approach. The data set is recorded from the C6.6 engine with a sampling frequency of 33.3 Hz.

SPEED AND LOAD POINTS FOR SYSTEM IDENTIFICATION

The data are generated for a total of 35 different operation points with load that could be up to 70% of peak torque over three speed points 1050, 1550 and 2050rpm.

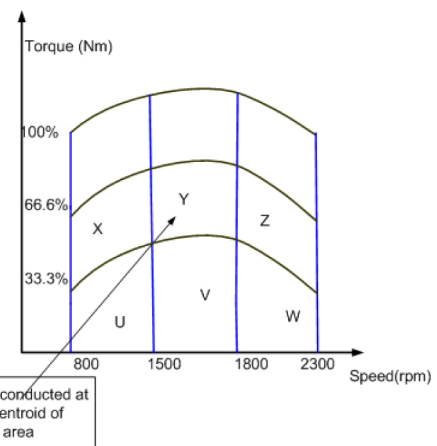


Figure 5. Segmentation of torque and speed for the whole engine operating range.

In order to collect the required data for steady state engine operation, the complete engine operating range is segmented into nine zones as indicated in [Figure 5](#). The system identification experiments were conducted at the centers of these nine zones, with the engine rpm being maintained constant using the speed governor algorithm implemented in the NI LabVIEW real-time control system which controls the engine fuel injection [9]. The load is applied using a Froude AG400 HS dynamometer controlled by a Cadet V14 system, and is again held constant. The applied engine load was limited to 70% of rated torque for the purposes of this work. Thus, the whole system identification experiment is reduced to the six zones (X, Y, Z, U, V, and W) as outlined in [figure 5](#).