

Development of a Phenomenological Dual-Fuel Natural Gas Diesel Engine Simulation and Its Use for Analysis of Transient Operations

Shuonan Xu, David Anderson, Amrit Singh, Mark Hoffman,
Robert Prucka, and Zoran Filipi
Clemson Univ.

ABSTRACT

Abundant supply of Natural Gas (NG) in U.S. and cost-advantage compared to diesel provides impetus for engineers to use alternative gaseous fuels in existing engines. Dual-fuel natural gas engines preserve diesel thermal efficiencies and reduce fuel cost without imposing consumer range anxiety. Increased complexity poses several challenges, including the transient response of an engine with direct injection of diesel fuel and injection of Compressed Natural Gas (CNG) upstream of the intake manifold. A 1-D simulation of a Cummins ISX heavy duty, dual-fuel, natural gas-diesel engine is developed in the GT-Power environment to study and improve transient response. The simulated Variable Geometry Turbine (VGT) behavior, intake and exhaust geometry, valve timings and injector models are validated through experimental results. A triple Wiebe combustion model is applied to characterize experimental combustion results for both diesel and dual-fuel operation. The ignition delay and injection timing are determined through an iterative calculation based on Start of Combustion (SOC) and a predictive ignition delay correlation. The simulation was subsequently utilized to characterize power delivery delays experienced by the driver during transient tip-in/tip-out conditions. Simulation was able to trace the experimentally observed trajectory, and the transport delay of the natural gas charge induction was identified as the root cause. The insight enabled dynamic adjustment of the diesel injection quantity to compensate for the natural gas induction delay. The diesel compensation algorithm was finally validated throughout the operating range.

CITATION: Xu, S., Anderson, D., Singh, A., Hoffman, M. et al., "Development of a Phenomenological Dual-Fuel Natural Gas Diesel Engine Simulation and Its Use for Analysis of Transient Operations," *SAE Int. J. Engines* 7(4):2014, doi:10.4271/2014-01-2546.

INTRODUCTION

Increasingly stringent fuel economy and CO₂ emission regulations are providing impetus for engineers to develop high efficiency engine technologies. Diesel engines dominate the heavy duty market, due to their intrinsically higher thermal efficiency. However, traditional diesel engines suffer from the tradeoff between the NO_x and soot emissions for which various exhaust aftertreatment systems have been developed. While the diesel engine manufacturers continue to refine their products in response to the recently introduced CO₂ reduction regulation [1], an emerging market trend stimulates increased focus on Natural Gas (NG) utilization in the HD sector. Recent advancements of the NG drilling technology have greatly increased the estimated US and global reserves [2]. As a consequence, all forecasts indicate that the price will remain roughly \$2 lower on the diesel fuel gallon equivalent basis for many years to come. Main constituent of NG is Methane, considered to be a relatively clean fuel, less prone to soot formation during combustion than diesel, and with lower CO₂ emission potential. All of this makes NG a very attractive option

for HD sector. Given the Vehicle Miles Traveled, conversion of HD diesel to NG or dual-fuel operation is the most rapid and effective way of increasing NG utilization for transportation [3].

Engines currently offered by OEMs are invariably conversions to SI combustion. The compression ratio is lowered compared to diesel; the engine operates with stoichiometric mixture in order to enable application of a Three-Way Catalyst for cleaning up the exhaust. Dual-fuel natural gas-diesel engines offer an alternative. In that case, the conversion from a conventional diesel engine requires little modification of engine hardware. High compression ratio is retained, and the engine can operate lean; hence, there is a prospect of achieving roughly the same thermal efficiency as in the case of a diesel baseline. Most dual-fuel engines are designed to work interchangeably in diesel-only or dual-fuel mode. This eliminates driver range anxiety, since the truck can continue running on diesel fuel if a natural gas filling station is not available.

The common configuration of a dual-fuel engine has a natural gas injector located in the intake upstream of the manifold. The natural gas mixes with fresh air and EGR during the intake stroke, where it is then inducted into the cylinder during the intake stroke, where

mixing continues due to charge motion. The NG and air mixture is then ignited via the energy released by the combustion of a diesel spray, rather than a conventional spark. The multiple ignition points are spread spatially throughout the cylinder even in very lean conditions. Previous research has demonstrated that even a very small quantity of diesel spray generates much more ignition energy than that of a spark plug [4].

Dual-fuel engines have been studied before. Early research effort was pursued by Karim et.al [5, 6, 7, 8]. Several problems such as knock and combustion instability were identified and studied [5, 9, 10]. A combination of the flame propagation through the natural gas-air mixture and a high compression brings a risk of knock, especially at high loads where natural gas substitution rates are elevated. At light load conditions, dual-fuel engines are subjected to combustion instability due to slow flame propagation in a very lean mixture. Possible cylinder-to-cylinder variations can exacerbate the instabilities. Incomplete combustion and flame quenching contribute to methane slip, a phenomenon of a great environmental concern as methane has 25 times the greenhouse effect of CO₂ [11].

More recent dual-fuel engine research efforts were focused on maximizing natural gas substitution rate. Specifically, range of dual-fuel operation is extended by avoiding knock at high loads and ensuring combustion stability at low loads. An advanced pilot injection dual-fuel engine concept was proposed [12, 13, 14, 15, 16, 17, 18]. This concept applies an advanced (~60 BTDC), small amount of diesel fuel injection as the ignition source, with the port fuel injected natural gas as the main heat release source. In this concept, the onset of combustion is predominately controlled by chemical reactions. The advanced diesel injection results in a long ignition delay and better charge mixing, thereby reducing the rich pockets of diesel fuel and minimizing soot emissions. The better mixing of diesel and surrounding air and natural gas mixture also helps the ignition of natural gas, resulting lower local temperatures and reducing NO_x emissions. However, combustion stability at low load remains a problem and combustion characteristics are not yet fully understood.

The main objective of this work is to develop a simulation tool for analysis of dual-fuel operating strategies, in conjunction with experiments. Simulation enables investigation of a broader operating space, and much more efficient optimization of the engine fuel-injection calibration. Even when in-depth experimental data are available, the simulation can complement the results by providing values of parameters that cannot be easily measured, such as the residual concentration in any given cylinder. In particular, a predictive simulation of a complete turbocharged engine system is invaluable for detailed characterization of transients, and development of strategies for improving the dynamic response.

Generally, a 3-D simulation provides detailed spatial resolution of the combustion process and has high prediction accuracy. Previous multi-dimensional simulation work by Reitz et.al, Krishnan et.al and Hountalas et.al [17, 18, 19, 20, 21, 22] has been conducted on dual-fuel concepts and it produced valuable insights about in-cylinder processes. However, the 3-D simulation comes with high computing cost, and it is not suitable for system level analysis or studies of transient operations. Instead, 1-D modeling of the dual-fuel engine provides a very good compromise between predictive capabilities and computational efficiency [23, 24, 25].

Transient analysis of a dual-fuel engines carried out here is motivated by experimentally observed drivability issues. In real world operation, during tip-in or tip-out conditions, drivers have experienced a lag in the dual-fuel engine response. Thus, a 1-D simulation tool is developed and applied to generate the required insight, and subsequently devise control strategies for smooth torque delivery under very dynamic conditions.

The baseline 1-D simulation represents the Cummins ISX heavy duty engine. Data pertaining to intake and exhaust geometry, cam profiles and turbo machinery maps are used to configure the engine system. VGT behavior is validated through experimental results. The triple Wiebe combustion model was calibrated based on experimental combustion results for both diesel and dual-fuel combustion. The ignition delay and injection timing are determined through an iterative calculation based on Start of Combustion (SOC) and a predictive ignition delay correlation.

After a thorough validation of the simulation, the tool is utilized to investigate experimentally observed power delivery delays experienced during transient tip-in/tip-out conditions. A simulation of the transient event quantified the transport delay. This enabled development of the algorithm that manipulates the diesel injection quantity to compensate for the natural gas induction/transport delay. Finally, the algorithm is validated throughout the operating range, and the findings are summarized in the closing section.

EXPERIMENTAL APPARATUS

The experiment has been conducted on the Cummins ISX 550 dual-fuel engine on a chassis dynamometer with the engine mounted on the class 8 HD truck. The engine is a turbocharged inline six, intercooled, with direct injection. Fuel pressure is generated from the injector plunger pushed by the injector rocker actuated by the fuel cam. The injection timing and quantity are controlled by varying the volume of fluid within the two injector chambers. [Figure 1](#) shows experimental instrumentation on the tested engine. The specifications are given in [Table 1](#).

Table 1. Engine Specifications

Engine type	Diesel/Dual-fuel 4-stroke
Configuration	In-line 6-cylinder
Air intake	Turbocharged, intercooled
Fuel type	Diesel D2, Natural gas
Diesel Injector type	Unit injector
Firing order	1-5-3-6-2-4
Displacement	15 liter
Bore	137mm
Stroke	169mm
Connecting rod length	0.22m
Compression ratio	17:1
Rated power/rpm	405kW 2000rpm

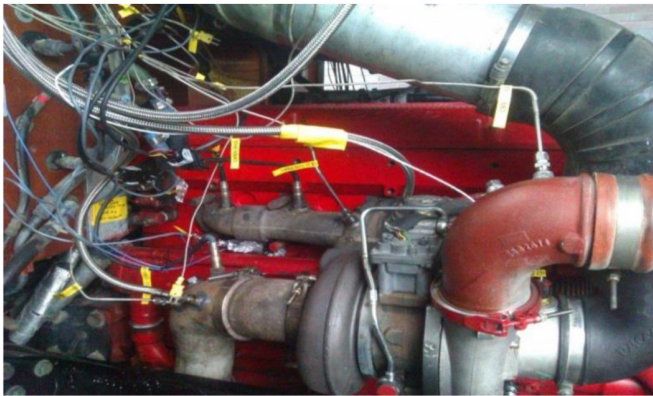


Figure 1. Experimental instrumentation on the Cummins ISX dual fuel engine

The engine head was modified to install the knock resistant GH15DK piezoelectric pressure transducers in cylinders 5 and 6. Cylinder pressure signals were amplified by MICROIFEM piezoelectric amplifiers within an AVL IndiSmart data acquisition while a National Instruments CompactDAQ with 9205 and 9213 series modules was utilized to sample additional signals. Diesel fuel flow was measured by an AVL KMA Mobile; NG and air flows were measured using FOX FT2 inline flowmeters. Turbo shaft speed was measured by a PicoTurn rotational speed sensor. Air temperature, oxygen sensors, manifold pressure and other additional sensors were mounted on the engine for a comprehensive data acquisition. The complete list of measured signals is:

Time based:

- Intake manifold air pressure
- Exhaust manifold air pressure
- Intake gas temperature
- Exhaust gas temperature
- Intake equivalence ratio
- Exhaust equivalence ratio
- Turbo shaft speed
- Compressor inlet and outlet air pressure and temperature
- Turbine inlet and outlet air temperature and pressure
- Diesel, natural gas and air flow rates

Crank angle based:

- Cylinder pressures
- Engine knock

The truck was tested on a chassis dynamometer, and engine speed-load sweeps were carried out for both diesel-only and dual-fuel operation. Figure 2 illustrates cyclic and cylinder to cylinder variations of measured cylinder pressure data from a dual fuel operation case. Coefficient of variation (COV) of indicated mean effective pressure (IMEP) in cylinder 5 and cylinder 6 are 1.4% and 1.2%, respectively. Ensemble averaged cylinder pressure information from 500 consecutive cycles was used for heat release analysis and the comprehensive data set listed above enabled validation of both in-cylinder process and turbocharged engine system behavior.

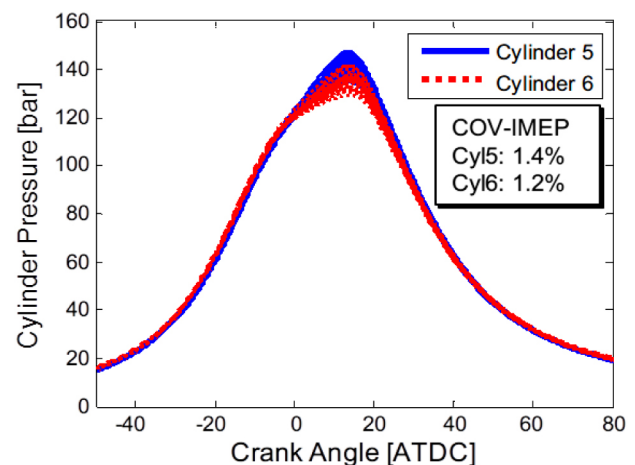


Figure 2. Cyclic and cylinder to cylinder variations of measured cylinder pressure data

ENGINE MODELING

A comprehensive 1-D simulation of the Cummins ISX 550 dual-fuel natural gas diesel engine is developed in GT-Power. A schematic of the model is shown in Figure 3.

The intake and exhaust geometry have been carefully measured and used to configure the model. An accurate profile of the exhaust manifold is crucial for yielding satisfactory results because gas dynamics produce effects on both VGT and EGR. Figure 4 shows a layout of the exhaust manifold geometry on the Cummins ISX engine utilized in the simulation model.

The intake and exhaust valve lift profiles were measured on the camshaft. Since the head was removed from the engine during profile measurement, instead of referencing the TDC to the crankshaft, an OEM wedge was applied to a slot on the camshaft and set as a reference point. The reference point was not necessarily the actual TDC position because a small free play exists between the wedge and the camshaft. Hence the TDC position was further calibrated in the GT-Power model for enhanced accuracy.