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This Technical Paper was prepared for presentation at the *NGV 2008 – 11th IANGV Conference & Exhibition*, held between 3 and 5 June, 2008, in Rio de Janeiro. This Technical Paper was selected for presentation by the Technical Committee of the event according to the information contained in the abstract submitted by the author(s). The contents of the Technical Paper, as presented, were not reviewed by IBP. The organizers are not supposed to translate or correct the submitted papers. The material as it is presented, does not necessarily represent Instituto Brasileiro de Petróleo, Gás e Biocombustíveis' opinion, or that of its Members or Representatives. Authors consent to the publication of this Technical Paper in the *NGV 2008 – 11th IANGV Conference & Exhibition Annals*.

Abstract

In the foreseeable future, for commercial road-transportation, there is no practical alternative to rival the diesel engine in efficiency and performance. There are many alternative fuel options; the most promising and practical of these is natural gas (NG). Dual-Fuel™ technology combines the most efficient powertrain to the most pragmatic alternative fuel; it enables a diesel engine to operate normally on diesel and a high proportion of NG. Needing no changes to the diesel engine, Dual-Fuel™ retains the performance and efficiency of the diesel cycle. By burning a high proportion of NG efficiently, Dual-Fuel™ delivers lower greenhouse gas, and achieves lower emissions of NOx and PM. Dual-Fuel™ also delivers significant economic benefits compared to diesel operation. From a national perspective, it delivers improved energy security by displacing the need for diesel fuel imports. Dual-Fuel™ is also perfectly compatible with biodiesel and bio-methane, delivering a near carbon-neutral solution. This paper describes the development and application of the Hawk™ ECU to both an integrated Dual-Fuel™ system and the generic Genesis Dual-Fuel™ system to enable US'04 and Euro 5 heavy duty vehicles to operate on natural gas to deliver the benefits of a Dual-Fuel™ combustion system.

1. Introduction

The transition from the oil-economy will take at least 50 years and along the way there will be many options. Peak-Oil and Global Warming necessitate change. Our industry is now on the brink of major changes and major decisions.

Many new and interesting concepts are emerging, including fuel-cells, hybrids and EV's. In reality, conventional powertrain will play a major part in this transition for at least the next 20 years. Currently and in the foreseeable future, there is no practical alternative to rival the diesel engine in efficiency and performance. There are many alternative fuel options, but currently, the most promising and practical of the "Alternative Fuels" is natural gas (NG). Dual-Fuel™ technology marries the most efficient powertrain to the most obvious alternative fuel; it enables a diesel engine to operate normally on diesel and a high proportion of NG.

By using an unchanged diesel engine, Dual-Fuel™ retains the performance and efficiency of the diesel engine. By burning a high proportion of NG efficiently, Dual-Fuel™ delivers lower carbon contribution, as NG is a low-carbon fuel and achieves lower emissions of NOx and PM. Globally, NG is a low-cost fuel. Therefore, Dual-Fuel™ delivers significant economic benefits compared to diesel operation. Where NG is plentiful and diesel is an expensive import, Dual-Fuel™ makes sense for an operator. From a national perspective, it delivers improved energy security by displacing the need for diesel fuel.

The engine operation is controlled by a patented Hawk™ Dual-Fuel™ engine management system (EMS) via a separate, integrated ECU. The Dual-Fuel™ ECU communicates with the OEM engine ECU to regulate accurate delivery of diesel pilot injection. The Hawk™ ECU is electronically integrated into the software of the OEM EMS. It takes the diesel demand signal and calculates new pilot diesel quantity and timing and gas injection quantity based on accurate and predictive air flow calculations.

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2. Dual-Fuel™ Technology

Dual-Fuel™ uses patented electronic control of diesel pilot injection to ignite a controlled pre-mixed charge of NG and air. The system incurs no change to the base diesel engine, which runs according to Diesel’s 4-stroke cycle, at high compression ratio with compression-ignition of a lean fuel-air mixture. The non-intrusive nature of the technology enables a Dual-Fuel™ engine to operate on 100% diesel in the absence of NG.

The high compression ratio of the diesel engine can be retained due to the high auto-ignition temperature of methane (352°C higher than diesel). Where spark-ignited NG engines have issues with the ignition of lean mixtures, the Dual-Fuel™ engine overcomes this with the diesel pilot injection. This pilot injection provides a multitude of ignition sites as the diesel spray droplets auto-ignite under compression. The result is that the Dual-Fuel™ engine can run with Lambda (excess air ratio) $\lambda \leq 2$.

Pilot injection is well understood and can be delivered by conventional diesel FIE. As with diesel combustion, the introduction of a pilot injection reduces the pre-mixed combustion phase. Similarly with Dual-Fuel™, the small diesel pilot results in minimized diesel pre-mixed combustion. This is the first mechanism for the reduction of both NOx emission and combustion noise.

Figure 1a and 1b show a comparison of fuel heat-release between diesel combustion and Dual-Fuel™ combustion. Clearly, the pilot injection in the case of Dual-Fuel™ is responsible for the elimination of the significant pre-mixed combustion phase. Also of note in Figure 1 is the similarity of the overall combustion event. Dual-Fuel™ is a hybrid combustion system, combining conventional diesel combustion with homogeneous gas combustion. Both systems respond according to conventional understanding. Figure 2 shows how NOx is reduced with increasing λ , as expected from lean-burn NG engines.

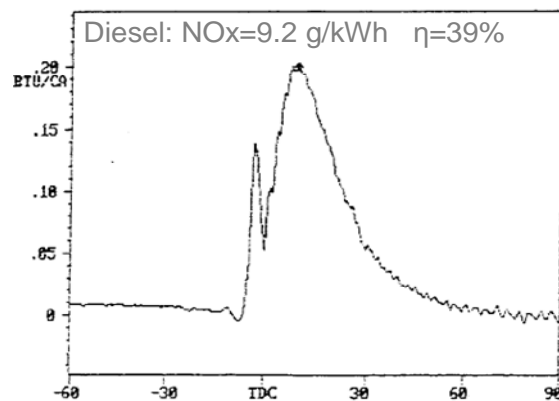


Figure 1a: Diesel Combustion Heat Release at 1800 rpm 70% load

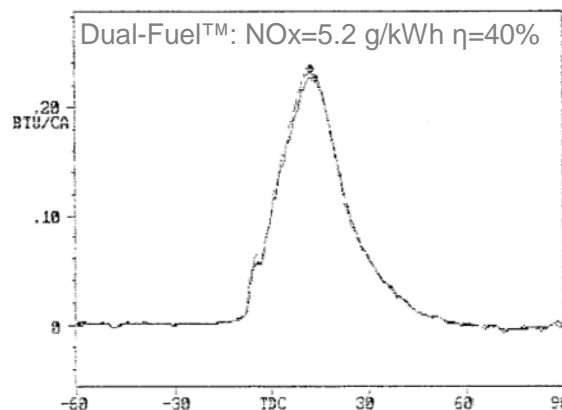


Figure 1b: Dual-Fuel Combustion Heat Release at 1800 rpm 70% Load

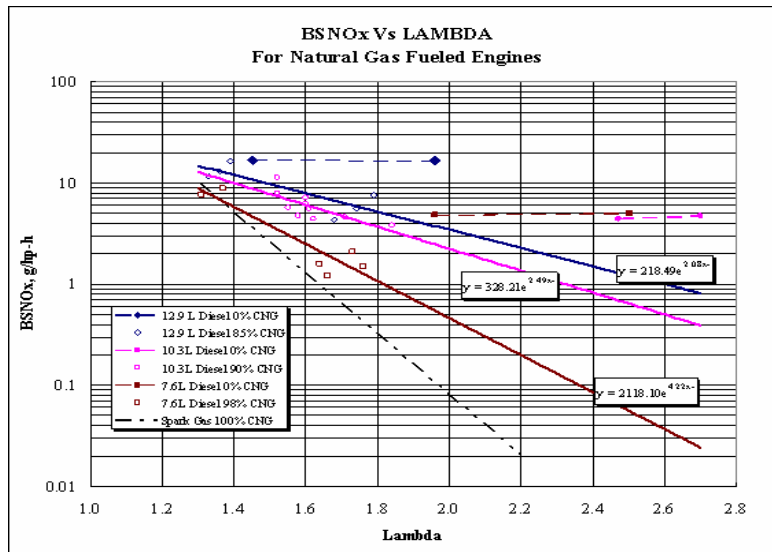


Figure 2: Reducing NOx with Lambda in NG Engines

Overall, the Dual-Fuel™ engine maintains the efficiency of the diesel engine, whilst delivering low NOx. Figure 3 illustrates how lower NOx is achieved from Dual-Fuel™ operation in a back-to-back engine test running at common conditions of similar efficiency.

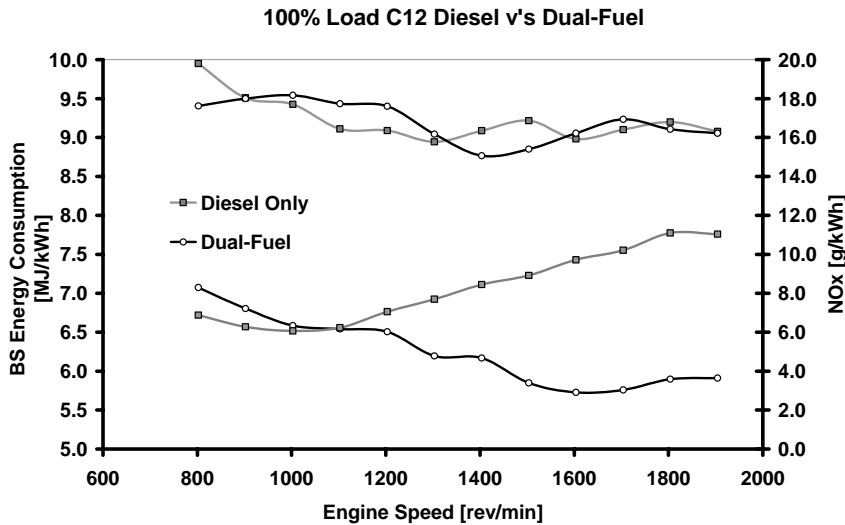


Figure 3: NOx and Efficiency at Full Load from Diesel and Dual-Fuel

By maintaining similar thermal efficiency and similar combustion rates, overall heat rejection to the coolant and the exhaust temperatures are similar to those of the base diesel engine operation. Figure 4 shows exhaust temperature comparisons between Dual-Fuel™ operation and conventional diesel operation of the same engine.

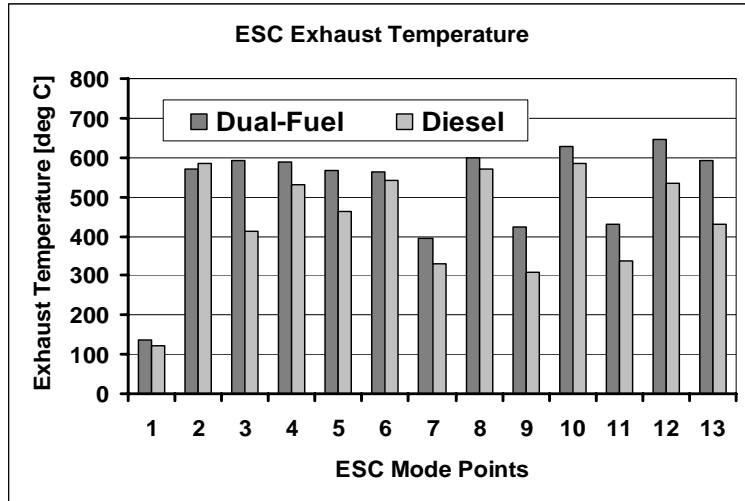


Figure 4: Diesel to Dual-Fuel Exhaust temperature Comparison over European Steady Cycle (ESC) Test [Caterpillar C-15]

Dual-Fuel™ imposes no additional thermal or structural load to the diesel engine. Durability testing conducted by Beck, P.J. et al in 1997, investigating oil quality and wear, concluded that Dual-Fuel™ operation will result in less wear and extended oil-change intervals. This conclusion was mainly attributed to the reduction of soot-in-oil from the inferred reduction in soot-based PM from the combustion of NG.

The emissions potential of Dual-Fuel™ has been demonstrated by independent, collaborative research. As the combustion system is based on diesel principals, the system responds to improvements in diesel technology. Previous work by Wong, H.C. et al 1996-98, has demonstrated how emissions are reduced with reducing pilot quantities and increasing injection intensities. Such approaches have been patented. Today, advanced diesel FIE is capable of delivering such “Micropilot” and delivering the associated emissions reduction capability. Dual-Fuel™ has also been combined with EGR and demonstrated significant NOx reduction potential. From US DOE funded research, reported by WONG, H.C. in 2003, NOx levels of 0.5 g/bph were achieved on US-heavy-duty cycle tests with a Dual-Fuel™ C-12 engine operating cooled EGR. Figure 5 illustrates the demonstrated emissions and the obvious potential of the Dual-Fuel™ system when combined with contemporary Euro 4 or US2007 engine hardware.

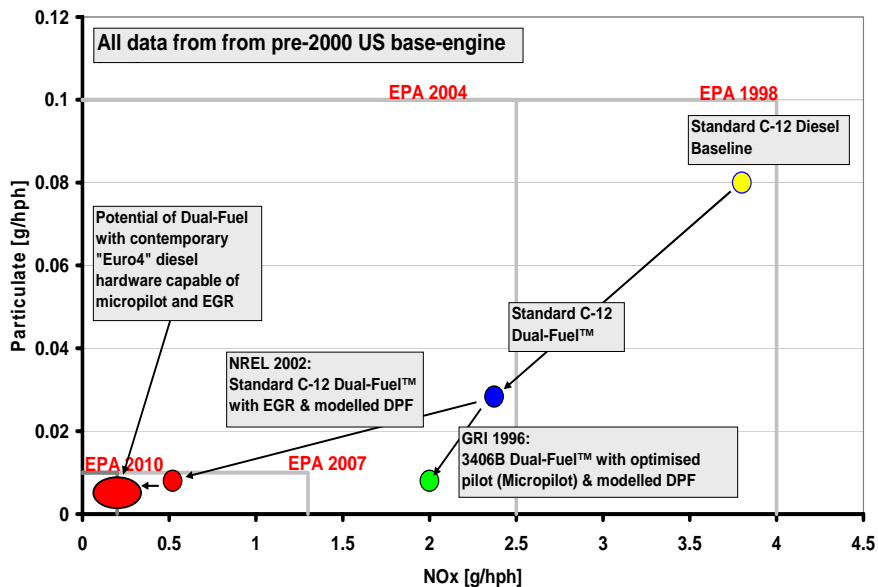


Figure 5: Potential of Dual-Fuel combined with contemporary “Euro 4” or “US07” diesel engine hardware

3. Dual-Fuel™ Control System

In an “Interfaced” system, the engine operation is controlled by a patented Dual-Fuel™ EMS via a separate, interfaced ECU. The Dual-Fuel™ ECU communicates with the OEM engine ECU, via controller area network (CAN) to regulate accurate delivery of diesel pilot injection. With cooperation from the OEM, the Hawk™ Dual-Fuel™ ECU can be electronically interfaced to the software of the OEM’s ECU. It takes the diesel demand signal and calculates new pilot diesel quantity and timing and gas injection quantity based on accurate and predictive air flow calculations. Figure 6 illustrates how the two ECU’s are integrated to deliver control of both diesel and gas. In this case, the demanded diesel quantity and timing is interrupted by the Hawk™ ECU, where a revised diesel quantity and timing is calculated for Dual-Fuel™ operation. This new information is then passed back to the OEM ECU via J1939 CAN-bus or direct line.

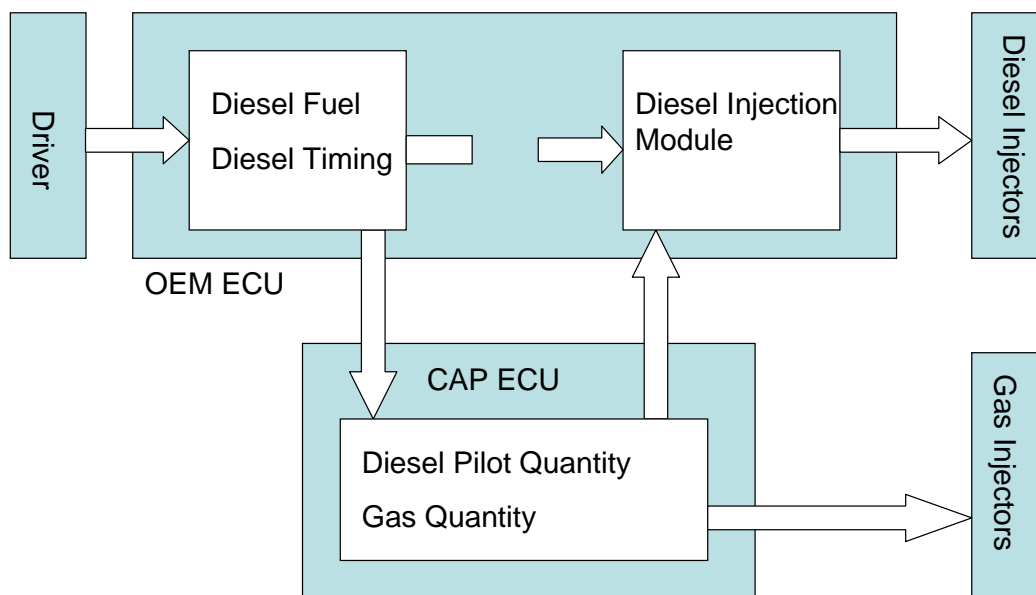


Figure 6: General ECU Integration Layout

For the Genesis retro-fit systems, where OEM cooperation is not a pre-requisite, diesel fuelling only is controlled by the Hawk™ via the J1939 CAN-bus. This system uses a separate CAN gateway to communicate total fuelling back to other vehicle systems to ensure normal and safe operation of other vehicle systems, such as automated transmissions, cruise control, electronic braking, traction control and power-take-offs.

Unlike normal diesel combustion, Dual-Fuel™ combustion is governed by close control of the air-fuel-ratio (AFR). Whilst Dual-Fuel™ combustion operates at similar AFR to diesel; boost air is accurately and rapidly controlled via a turbo by-pass valve. Close control over AFR is required to avoid combustion knock (detonation) or miss-fire. The Dual-Fuel™ ECU is fitted with on-board-diagnostic features and can detect faults with the operating system as well as detecting instances of combustion knock. If a significant fault is detected, or loss of NG fuel pressure, the control system will revert back to 100% diesel vehicle operation at the next engine cycle with near undetectable transition. The control of combustion knock is a critical feature of any NG fuelled engine. Knock is induced by poor gas properties, instantaneous extremes of temperature and pressure as well as low AFR (rich mixture operation). Knock detection and avoidance mechanisms must be instantaneous and deal with knock on a cycle-by-cycle basis. The Hawk™ has an integrated industry-standard ProSAK™ knock control microprocessor, coupled with two separate knock sensor input channels. If knock is detected, the control software will re-tune the operation of the system to avoid knock and maintain engine operation in gas-mode. In the limiting case where knock is too severe, the system will revert to 100% diesel operation. Under any normal condition, the engine will not knock. Thus any instance of knock represents a gas or system error state. This error state is recorded and reported via the Hawk™ on-board-diagnostic (OBD) system.

4. Hawk™ Dual-Fuel™ Control System Development

Clean Air Power chose Ricardo and MotoTron as their development partner in this project. Ricardo is the world's largest independent automotive engineering consultancy. Ricardo's Control and Electronics group has a strong track record in automotive systems and software engineering. Ricardo has over 250 man-years experience in developing production embedded software for OEMs and Tier 1 suppliers. They are a member of the Motor Industry Software Reliability Association (MISRA) Steering Group and is a regular contributor to MISRA working groups. Ricardo made a significant contribution to the MISRA-C:2004 Guidelines and is leading the MISRA activity on guidelines for the use of the Simulink modeling package with the Targetlink code generator for safety critical applications.

MotoTron is the builder of MotoHawk®, an embedded control software framework used by Ricardo to deploy applications built with The MathWorks' Simulink® or Stateflow® tools onto production electronic control hardware.

The Hawk™ development was undertaken in two main phases of hardware selection and software engineering. The software engineering phase was further sub-divided into three sections of work:

- Transfer and develop existing Clean Air Power control algorithms onto Hawk™
- Develop on-board diagnostic systems (OBD)
- Develop CAN-based service tool

4.1 Hardware Specification

The MotoTron MotoHawk® ECM565-128 ECU was selected as meeting all the technical requirements of the project. Additionally, the unit was proven in-field as durable and robust, being developed to heavy-duty and marine specifications. The ECM565-128 uses the Motorola MPC565 processor, common to many state-of-the-art automotive applications. The ECM565-128 is manufactured to a 6-Sigma quality system and is certified to international standards (SAE J1113 and Directive 89/336/EC for CE rating). The system specification includes the following attributes:

- 12 Gas injector drivers
- ProSAK™ knock control chip with 2 integrated knock sensor modules
- 2 Wide range oxygen sensor inputs
- Twin CAN channels
- 34 analogue inputs
- 15 digital high power outputs
- 16 digital low power outputs
- 128-pin waterproof connectors
- Heavy-duty and marine application capabilities



Figure 7: MotoTron MotoHawk® ECM565-128 ECU

<http://www.mototron.com/products/MotoHawkSuite/MotoHawk/ECUmodules/productECU565-128.php>

4.2 Software Engineering

4.2.1 Control System Software

The algorithms that have been developed by Clean Air Power were transferred to a graphical representation within MATLAB® and Simulink® coding environments using the MotoTron MotoHawk® development framework. Each algorithm (or function) within the model is defined as a library block with the main control model acting as a ‘place holder’ for each of the libraries. With this structure it is easy to create application specific software builds by simply swapping library blocks. The structure of each model is then held in an external database (or ‘recipe’) that defines the library blocks to be used for the required application. An example structure is shown in Figure 8 where each of the colored blocks refers to a specific ‘function’ in the application.

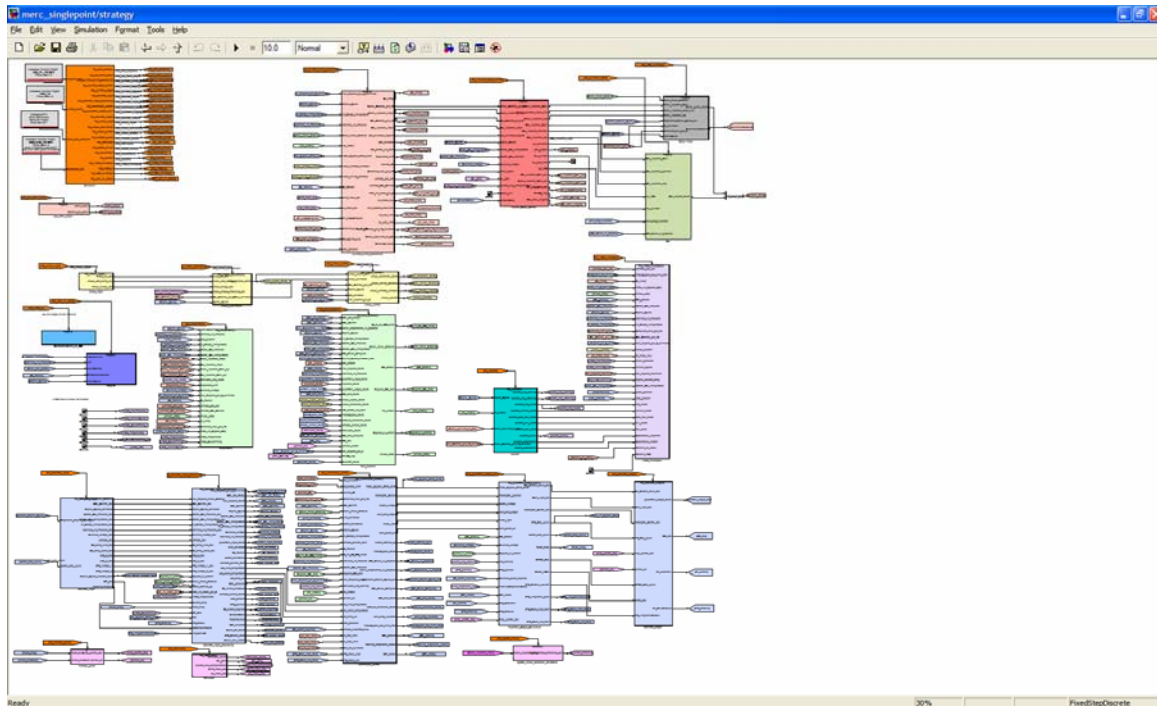


Figure 8: System Architecture

To put the application into perspective, well over 50% of the model is devoted to fault detection. Only the top ‘row’ of elements in the diagram is concerned with the control system.

4.2.2 On-Board Diagnostics (OBD) System

A large proportion of the system is concerned with OBD functionality. This performs the error checking within the system and can be split into 2 parts:

1. Hard errors – those concerned with checking the electrical connectivity of the system
2. Soft errors – those concerned with plausibility checks.

Hard errors on the inputs can be easily detected as very high or very low input voltages. These are flagged as open or short circuit errors dependant on the input circuitry of the ECU. If the input circuitry tends to pull-down the input voltage, then a very low voltage will indicate an open circuit error. Hard errors on the output circuits are more complicated to determine as they rely on additional circuitry inside the ECU. The outputs on the PCM-128 have an additional resistor in the circuit over which the voltage is read and then fed back as an additional input. This voltage can then be directly read as a current feedback. It is then possible to determine if the output being driven is ‘using’ current and a fault status inferred from this. OBD Stage 2 requires each input and output to be monitored in this way.

Soft errors consist of a number of different functions that are used in conjunction to prove system functionality. These are for example monitoring of the oxygen sensor. This can only be done by ‘knowing’ what

oxygen level is expected in the exhaust and whether the resulting reading is within an error band. If the oxygen level falls outside the error band, the fault which caused this may not be immediately apparent. Once any ‘hard’ faults are eliminated, the resulting ‘soft’ error can only really be called a ‘symptom’ and it requires a number of other checks to be performed on both the air and fuel systems to find and rectify the fault. Use of the service tool will be required to rectify a fault in this situation.

4.2.3 Service Tool

In addition to the basic control software, a J1939 compliant service tool was developed. The J1939 CAN message structure used in the service tool was implemented both in the Hawk™ and as an external database in ODX format. ODX is the Open Diagnostics data eXchange format that is used widely in the automotive industry and allows multiple tools to access the same ECU based functionality. The ODX provides building blocks of ECU functionality such as reading fault codes, driving outputs and reading inputs. A number of ECU commands may then be connected together with results being fed back in a known order and timeframe. It also allows any third party tool to interrogate the Hawk ECU to determine if a fault is stored or is currently active.

The service tool is designed using the MDT design tool from Sontheim GmbH (<http://www.s-i-e.de>). This is a flow chart based tool that interfaces directly to the ODX functions. It allows the service tool designer to build user interface screens and to connect buttons and screen elements directly to ODX commands. Complex functionality can be then either shown graphically or as a controlled sequence of events to allow easy fault finding and rectification. Fault screens may be opened and the faults read back (as text) for currently active faults, any previously stored faults and the freeze frame data for these faults. Freeze-frame data is valid for either the current active faults or for any previously stored faults. The freeze-frame data shows a number of ECU state variables and inputs at the moment the faults was detected. This allows the service engineer to understand the context in which the faults were logged.

5. Conclusions

The Dual-Fuel™ system developed by Clean Air Power has delivered reductions in regulated emissions and greenhouse gas emissions whilst demonstrating similar performance, efficiency and durability to the parent diesel engine. This technology has been proven commercially, enabling the practical operation of heavy-duty on-highway vehicles on natural gas and diesel.

The key to successful application of a dual-fuel technology lies within the control system. The Hawk™ Dual-Fuel™ engine management system provides a state-of-the-art, robust and powerful control system. Fast and accurate control is provided by patented CAN-based control. Robustness and OEM-compatibility is delivered by industry-standard software engineering and hardware. Regulatory compliance and operation is delivered by built-in OBD systems and interactive service tool.

The Hawk™ Dual-Fuel™ system delivers fast and flexible solutions to enable the practical use of natural gas and bio-methane in contemporary heavy-duty commercial vehicles.

6. Acknowledgements

The authors would like to thank their colleagues involved with this work and the Directors of Clean Air Power Ltd for granting permission to publish this paper. The authors would also like to thank Ricardo UK Ltd and MotoTron Inc. for assistance during the development of the Hawk™ EMS.

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