21st Century Locomotive Technology: Quarterly Technical Status Report 20 DOE/AL68284-TSR20

This is the quarterly status report for the 21st Century Locomotive Technology project, DOE Award DE-FC04-2002AL68284. This report covers activities performed October 2007 to December 2007. As the activities of Task 1 were completed this quarter, the complete task is summarized in this report.

PROJECT MANAGEMENT 1

TASK 1: ADVANCED FUEL INJECTION 1

BULLETED SUMMARY 1

OBJECTIVE 1
APPROACH 1
  MODELING EFFORTS 1
  BUILD HPCR ON SCE 1
  COMPARE UPS AND CRS 2
  DIAGNOSTICS 2
  TRANSFER FUNCTION DEVELOPMENT 2
RESULTS AND ACCOMPLISHMENTS 2
  COMBUSTION MODELING 2
  MULTIPLE INJECTIONS (PILOT AND POST INJECTIONS) 2
  BOWL GEOMETRY 3
  INJECTOR AND NOZZLE GEOMETRY 3
  DUTY CYCLE ASSESSMENTS 3
CONCLUSIONS 3

INTRODUCTION 4

OBJECTIVE 4

APPROACH 4

MODELING EFFORTS 4
BUILD HPCR ON SCE 4

COMPARISON UPS – CRS 5
DETERMINE BASELINE ENGINE PERFORMANCE USING CURRENT PRODUCTION UNIT PUMP SYSTEM. 5
TWO-POINT NOX PARITY SCREENING 5
DIAGNOSTICS 6
NEEDLE LIFT SENSOR, FUEL PRESSURE TRANSDUCERS, AND IN-CYLINDER PRESSURE TRANSDUCERS. 6
EEPS 6
TC IN ENGINE HEAD 6
IN-CYLINDER IMAGING 7
OPACITY METER 7
MOEHWALD INJECTION RATE MEASUREMENTS (EMI 2) 7
TRANSFER FUNCTION DEVELOPMENT 7

RESULTS AND ACCOMPLISHMENTS 7

MODELING 7
BOWL GEOMETRY 8
MULTIPLE INJECTIONS 8
PILOT INJECTIONS 9
POST INJECTIONS 9
INJECTOR AND NOZZLE GEOMETRY 9
DAMPING VOLUME 10
NUMBER OF HOLES 10
NOZZLE FLOW 10
CONE ANGLE 11
NEEDLE LIFT PROFILE 11
FUEL SULFUR LEVEL 11
DUTY CYCLE ASSESSMENT 11

CONCLUSIONS 11

ACRONYMS 12

Project Management

A paper titled "Application of energy storage batteries to hybrid locomotives and mine trucks" incorporating some work on hybrid locomotive carried out under Task 3 of this project was presented at EVS-23 (Electric Vehicle Symposium), Anaheim CA, December 2-5, 2007. The paper was marked by the standard DOE acknowledgement and disclaimer. The activities of task 1 were completed in this quarter and this status report summarizes the complete task.

Task 1: Advanced Fuel Injection

Authors: Roy Primus (Primary Contact), Florian Pintgen, Jennifer Topinka, and Anthony Dean
GE Global Research
One Research Circle
Niskayuna, NY 12309
Ph: 518/387-5945, Fax: 518/387-7258, email: *primus@research.ge.com*

GE Project Manager: Lembit Salasoo
Ph: (518) 387-5024, email: salasoo@research.ge.com

DOE Technology Development Manager: John Fairbanks
Ph: (202) 586-8066, email: john.fairbanks@ee.doe.gov

NETL Project Manager: Christopher Johnson
Ph: (304) 285-4718; e-mail: christopher.johnson@netl.doe.gov

Bulleted Summary

Objective

- Develop and demonstrate an advanced fuel injection system to minimize fuel consumption, while meeting Tier 2 emissions levels.

Approach

MODELING EFFORTS

- Developed combustion model for locomotive engine and calibrated the model via test data.
- Used combustion model to optimize fuel injection strategy.

BUILD HPCR ON SCE

- Implemented advanced fuel injection system on single cylinder locomotive engine
- Investigated the hardware space (injector, nozzle and bowl geometry) and fuel injection command sequence to determine most advantageous fuel injection strategy.
- Engine performance was evaluated by specific fuel consumption (SFC), nitrogen oxides (NOx) emissions, and particulate matter (PM) emissions.

COMPARE UPS AND CRS

- Determined baseline engine performance using current production unit pump system.
- Established a method to compare the brake performance of the SCE operation with the HPCR and UPS fuel system.
- Adopted two-point interpolation method to compare engine performance (UPS vs HPCR) at constant NOx emissions.

DIAGNOSTICS

Leveraged diagnostics to gain understanding of combustion event and performance. Diagnostic tools included:

Diagnostic	Measurement
Needle lift sensor	Diesel fuel injector needle valve lift and fall rate
Fuel pressure transducers	Fuel pressure in the common rail accumulator and fuel injector
In-cylinder pressure transducers	Combustion chamber pressure over engine cycle
Engine Exhaust Particle Sizer	Exhaust soot particle number and size distribution
TC in engine head	Metal temperature at various locations in the engine head
In-cylinder Imaging	Real-time, high-speed videos of the combustion event
Opacity meter	Real-time light extinction of engine exhaust for PM estimation
Moehwald (EMI 2)	Injection Rate measurements

TRANSFER FUNCTION DEVELOPMENT

- Determined optimized fuel injection parameters via designed experiments.
- Developed transfer functions and models, which guide and allow down-selecting the combinations of hardware and injection commands for various engine loads.

Results and Accomplishments

COMBUSTION MODELING

- Calibrated and commissioned the CFD combustion model at the University of Wisconsin-Madison to predict the performance of the locomotive engine.
- Validated the CFD combustion model for SCE with HPCR experimental data.
- Developed a CFD mesh to minimize computation run time.
- Exercised a genetic algorithm optimization process to identify the optimum (HPCR) high-pressure common rail design variables for N8. Design variables included fuel pressure, injection schedule, and fuel spray cone angle.

MULTIPLE INJECTIONS (PILOT AND POST INJECTIONS)

- Explored pilot injection experimental space (dwell and duration) at both medium and high load conditions for selected rail pressures and documented effect on engine performance.
- Quantified PM benefits for post injections and their effect on SFC-NOx tradeoff.

BOWL GEOMETRY

- Experimentally evaluated two piston crown geometries, with corresponding optimized fuel injector nozzles.

INJECTOR AND NOZZLE GEOMETRY

- Investigated engine performance effects of the various fuel injector hardware parameters including: injector damping volume, number of nozzle holes, nozzle flow, spray cone angle, and needle lift profile.

DUTY CYCLE ASSESSMENTS

- Quantified fuel savings entitlement and emissions of the common rail system at Notch 2 to Notch 8 (N2- N8).

Conclusions

- The HPCR fuel system gives substantial leverage on the SFC-NOx tradeoff curve and PM emissions due to its flexibility in fuel injection.
- Changes in nozzle geometry have been proven to allow for further engine performance benefits. Number of holes seemed to have the strongest effect on PM, followed by rail pressure and nozzle flow.

Introduction

General Electric's (GE) 21st Century Locomotive Program has the objective to develop freight locomotive engine technology and locomotive system technologies, which maximize the fuel efficiency while meeting Tier 2 freight locomotive emissions. The Tier 2 regulations have been in effect since 2005 in the US. GE's response to the T2 emission regulations was to develop a completely new locomotive. In order to meet future regulation like Tier 3 and Tier 4, GE is looking ahead, and developing new technologies and engine concepts. Existing technologies allow to a certain degree a reduction of emissions at the cost of increased fuel consumption.. Compliance with tighter NOx and PM regulations while achieving a fuel consumption benefit requires new technologies; this is the objective of GE's program.

The following report summarizes GE's efforts over the past 4 years, Oct 2003 to Dec 2007. GE has focused on the development of an advanced fuel injection system and demonstrated and quantified the benefits of this system over the existing technology currently in use. This program enabled GE's fundamental research on advanced fuel injection systems on medium speed diesel engine. GE has shown the benefits of the advanced fuel injection system. Currently the new technology is in the product plan on various engine applications for a product launch in 2-5 years.

Objective

Develop and demonstrate an advanced fuel injection system to minimize fuel consumption, while meeting Tier 2 emissions levels.

Approach

GE focused on a high-pressure common rail (HPCR) system as an enabling technology to reach the program objective. A Bosch high-pressure common rail (HPCR) system was implemented on the Global Research Center (GRC) locomotive single cylinder research engine (SCE). Parameters dictating the engine performance are: Rail pressure, injection schedule, and nozzle and bowl geometry. In order to better understand the combustion phenomena, CFD (KIVA) studies were performed in collaboration with the University of Wisconsin – Madison. The KIVA modeling work provided input and guidance for the experimental study on the single cylinder engine. In order to quantify the performance improvement achieved by using the HPCR system, we developed a methodology that allows comparison to the Unit Pump System (UPS). The UPS represents the baseline, as it is the production fuel system. Advanced diagnostics and transfer functions are used to guide the fuel system optimization process.

Modeling efforts

The CFD (KIVA software package) analysis was performed in collaboration with the University of Wisconsin – Madison and modeling work provided input and guidance for the experimental study on the single cylinder engine. Results from the N8 optimization study were used to guide the experimental roadmap. Furthermore, model optimizations at N4 and N1 were carried out.

Build HPCR on SCE

Fuel injection has a significant effect on a diesel engines' performance as the combustion process is controlled by the rate of mixing and the fuel atomization. To explore the opportunity for performance and emissions improvements by advanced fuel injection, a flexible common rail system has been installed on the locomotive single cylinder research engine. The system, which is provided by Bosch and shown in Figure 1, is capable of up to four injection events per cycle and can produce injection pressures above 1800 bar. The HPCR system allows real time adjustment of fuel pressure and injection schedule.

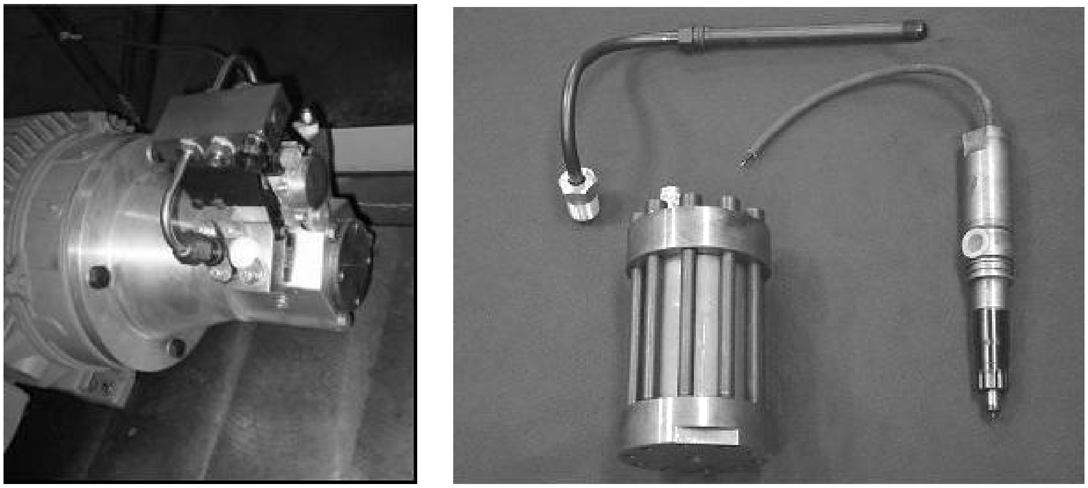

Figure 1: Common rail fuel system components. *(Left)* High-pressure fuel pump. *(Right)* Accumulator, high-pressure fuel line, and injector.

Comparison UPS – CRS

To quantify the observed performance improvements with the advanced fuel injection system, a baseline was determined using the UPS fuel injection system. Also, a method allowing for faster engine performance improvements at NOx parity levels was developed.

DETERMINE BASELINE ENGINE PERFORMANCE USING CURRENT PRODUCTION UNIT PUMP SYSTEM.

A friction adjustment was performed to compare the brake specific performance of the HPCR to the UPS. The engine camshaft drives the fuel pump for the UPS, while the fuel pump for the prototype HPCR system is driven electrically. For the HPCR, the power required to drive the HPCR pump was calculated and deducted from the brake horsepower generated by the engine. Given this adjustment, the brake specific values for the UPS and the HPCR are calculated with consistent auxiliary loads.

TWO-POINT NOX PARITY SCREENING

A majority of the experimental testing has been focused on screening the engine performance at various fuel injection strategies. For a fixed injector and bowl geometry, the independent parameters are fuel injection pressure, number of injection events and their relative timing in the engine cycle. The experimental evaluation consisted of comparing fuel consumption (notch-by-notch) of the UPS and HPCR at the notch-specific NOx target. The notch-specific target NOx value was the NOx level produced on the single cylinder engine with the production unit pump system at the appropriate fuel injection timing (nominal production engine fuel injection timing.) Instead of tuning the HPCR fuel injection timing (combustion phasing) to get precisely the target NOx, we used (for fast screening studies) a method to screen fuel injection strategies that did not require this time-consuming tuning process. The screening methodology involved collecting two data points at each injection strategy as shown in Figure 2. One data point is slightly advanced, yielding higher than target NOx, and the second is slightly retarded, yielding lower than target NOx. By interpolating, we estimate the fuel consumption at the target

NOx emission level. In this manner, we were able to quickly quantify the fuel consumption impact from each particular injection strategy and rail pressure.

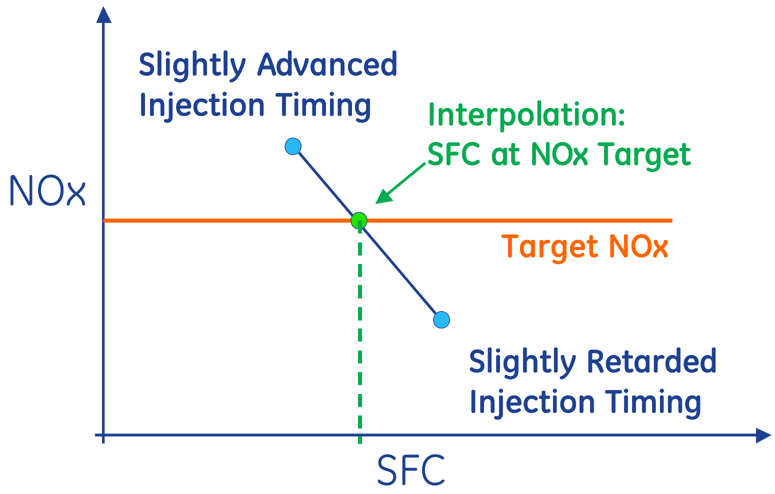

Figure 2: Approach for screening experiments involved collecting two data points at each fuel injection strategy and estimating SFC performance at target NOx emissions.

Diagnostics

In order to gain a better understanding of the combustion event and performance, a variety of diagnostics were installed on the single cylinder engine test-bed. An optically accessible engine head was installed at the end of 2006. This allowed for the combustion event visualization via a high-speed camera. The engine head also allows also for illumination of the cylinder and studies on fuel spray, fuel mixing. In addition, the modified engine head is equipped with thermocouples to record the metal temperatures at eight locations. Furthermore an engine exhaust particle sizer (EEPS) was installed. Each of the diagnostic tools are described in more detail below:

NEEDLE LIFT SENSOR, FUEL PRESSURE TRANSDUCERS, AND IN-CYLINDER PRESSURE TRANSDUCERS.

The fuel system components were instrumented to record key fuel injection parameters including needle lift, command current to fuel pump, and fuel line pressure. This information was helpful in comparing the fuel injection performance of the UPS versus the high pressure common rail (HPCR).

EEPS

The EEPS was purchased with GE funding, but it was used to accelerate the common rail investigations by providing a real-time indication of PM. The system is capable of measuring concentrations across the PM size range of 5 nm to 560 nm. The EEPS provided direct insight into PM trends with changing fuel injection strategy.

TC IN ENGINE HEAD

Our engine head had embedded thermocouples to record the metal temperatures at eight locations, including the hottest regions of the combustion chamber. Four of the temperature measurement locations are located in the valve seats and four are positioned a few millimeters under the metal surface of the firing deck. The metal temperatures give insight to shifts in the bulk gas temperature due to various fuel injection strategies and changes in other experimental parameters such as fuel type and quality.

IN-CYLINDER IMAGING

An optically accessible engine head was installed on the single cylinder engine test bed at the end of 2006. A production engine head was modified to accommodate the optical access and allowing also for illumination of the cylinder. GE performed the design and fabrication of the system independently of the DOE-funded program, but this system was available to the program to study the fuel spray, fuel mixing, and combustion characteristics of various fuel injection strategies and hardware.

OPACITY METER

The opacity meter was installed across the engine exhaust stack to monitor the soot levels in engine exhaust stream. In parallel, the particulate matter is quantified with filter samples, which are processed and weighed after the engine run. The advantage of the opacity meter is the real time measurement of soot levels. A transfer function in between filter measurements and opacity meter output can allow for a real time estimation of PM.

MOEHWALD INJECTION RATE MEASUREMENTS (EMI 2)

The injection rate measurements system allows to precisely determining the fuel quantity in the cylinder as a function of time. The knowledge of the fuel quantity is crucial for the development and validation of CFD models and the dependence of injection quantity on injector geometry and rail pressure. Furthermore is allows to gain understanding of the of pilot and post injection fuel quantities as a function of commanded injection duration.

Transfer function development

The performance optimization process included the use of designed experiments, which quantified the engine performance as a function of input parameters like injector geometry, timing schedule and rail pressure. This allowed for the development of a response surface of the targeted performance parameters, which are specific fuel consumption (SFC), NOx emissions and particulate matter (PM). The knowledge of the response surface allowed for identifying the beneficial combustion effects of specific input parameters and faster performance optimization of parameter combinations.

Results and Accomplishments

Major accomplishments pertaining to the advanced fuel injection system are the combustion model utilization, optimization of the injection schedule, and hardware, and the performance benefit estimation across the duty cycle. Hardware variations included orifice plate, nozzle configuration, and other details regarding the injector design and bowl geometry. To understand the effect of these variables, GE has executed designed experiments to understand the role of each parameter on the engine performance and emissions.

Modeling

The developed CFD combustion model, which has multiple injections capability, predicts the combustion event very well as shown in Figure 3. The KIVA-predicted performance trends and heat release curves were shown to match well with experimental data for the UPS as well as the HPCR configuration. The model is therefore well calibrated and can be used for optimization studies. This allowed us to build confidence in modeling capability for use on locomotive-scale engines providing a foundation for further analysis.

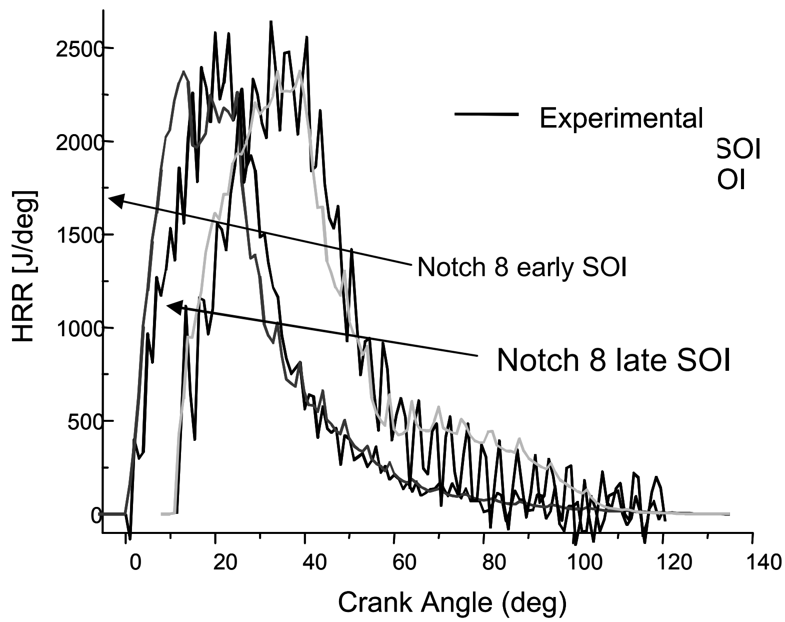

Figure 3: Predicted heat release rates show good agreement with the experimental data. Examples are presented for two different injection timings, start of injection (SOI).

Bowl Geometry

Two piston crowns were tested. Piston crown geometries, here arbitrarily referred to as A and B, vary mainly by their extent of re-entrant like shape. Piston A provided a larger SFC benefit over Piston B, but had the tendency for higher PM. The optimized injector configuration was found to be strongly dependent on the bowl geometry.

Multiple injections

Atomization, penetration, fuel injection rate and ultimately mixing are the determining factors of the fuel injection event and have significant impact on a diesel engines' performance. Multiple post and pilot injection commands allow for a flexible injection rate over the combustion cycle and various load conditions. This flexibility is one key advantage of the HPCR over the constrained UPS injection schedule.

Multiple injection strategies have been explored for both piston crown geometries. We completed a screening study to efficiently explore the multiple-injection design space using piston A. The injection strategy, which gave the best results for a specific nozzle/orifice plate configuration, was repeated with a varied injector configuration. The trends observed by changing between single injection and multiple injections were found fairly similar. This indicates that the performance shift between multiple injections and single injections is consistent, even with small fuel injector nozzle/orifice plate changes. Note that the performance shifts between single and multiple injections were not found to be transferable across piston bowl geometries. While certain multiple injection commands offered benefits using piston A, the performance shift was not necessarily observed with piston B. We have evaluated the heat release rates to show how the combustion event is tailored by using multiple injections per stroke.

Using piston geometry B, we explored in detail single-pilot and single-post injection schemes. In order to find the optimum pilot injection strategy, we explored a wide range of pilot injection durations and dwell times. For post injections the injection duration and location was varied in a similar fashion as for the pilot injection. The studies were carried out for several rail pressure levels and a range of main injection advance angles. In order to understand to what extend the benefits observed for pilot and post injections are additive, combinations have been tested for certain injection schedules.

PILOT INJECTIONS

For selected cases, we showed that the addition of pilot injections provides a SFC benefit (at constant NO_x level) over the single injection. The addition of pilot injections was found to have little impact on PM emissions. For single injections, the rail pressure was found to have a strong effect on SFC. For rail pressures levels leading to a higher SFC with a single injection, the SFC benefits observed for adding on a pilot injection were larger. At full load, pilot injection strategies have shown an improvement for limited NO_x levels over the UPS. At part load, pilot injections improved the NO_x-SFC trade-off compared to the UPS over a wider range of NO_x levels.

POST INJECTIONS

The addition of post injections allowed for significant reduction in PM. In selected cases at part load a simultaneous benefit in SFC was observed. The relative PM reduction using post injection was approximately twice at part load than at full load. The post injection duration was found to have a strong impact on the engine performance at all loads tested. While larger fuel quantities in the post injection decreased the PM emissions further in our study, the NO_x-SFC tradeoff turned unfavorable for prolonged post injection durations. For specific load conditions, the engine performance was found to be fairly insensitive to the location of the post injection. In order to achieve NO_x parity with an additional post injection, the main injection timing had to be slightly advanced.

Injector and Nozzle Geometry

Geometrical fuel injector parameters such as number of holes, nozzle flow cone angle, have been studied over a wide range. This study resulted in a down selected set of nozzle geometries to be tested with multiple injection strategies. While the focus in those studies was on part load (Notch 4) and full load (Notch 8), a wide range of injection pressures was covered. In a second step, designed experiments have been executed in order to explore and optimize the multiple injection strategy.

The following key parameters defining the nozzle geometry have been studied: Total nozzle flow, number of holes, spray cone angle, and needle lift profile. The needle lift profile was shaped by changes in the needle seat diameter and sac volume and various orifice plates.

We demonstrated that specific nozzle geometries (hole number and angle) could offer fuel benefits at NO_x-parity over our baseline nozzle with a very minor increase in PM emissions. The nozzle geometry selection was based on single injection performance. The optimum nozzle selection process was based on the observed SFC benefits at Tier 2 NO_x-emissions levels while meeting PM regulations. Among the geometries tested, the most favorable nozzle geometry at part load was found to be different to the most favorable one at full load. Also, performance results where strongly dependent on rail pressure. Therefore the overall optimum nozzle geometry has to be determined on a duty cycle basis.

DAMPING VOLUME

The initial injection system was found to exhibit unacceptably high variations in injection rate and also low cycle-to-cycle repeatability. An improved design, including an integrated high pressure damping volume, lowered the variation in fuel injection parameters significantly. The new features on the fuel injection hardware included a high-pressure accumulator integrated into the fuel injector, an orifice between the injector accumulator and the larger "common rail" accumulator, and a check valve between the aforementioned accumulators. Testing on an EMI 2 measurement device (Moehwald flow bench) showed a decrease of cycle-to-cycle variability in rail pressure, rate of injection profile, and injected quantity, Figure 4. Lower variation in the fuel injection parameters allowed for more precise control of the engine.

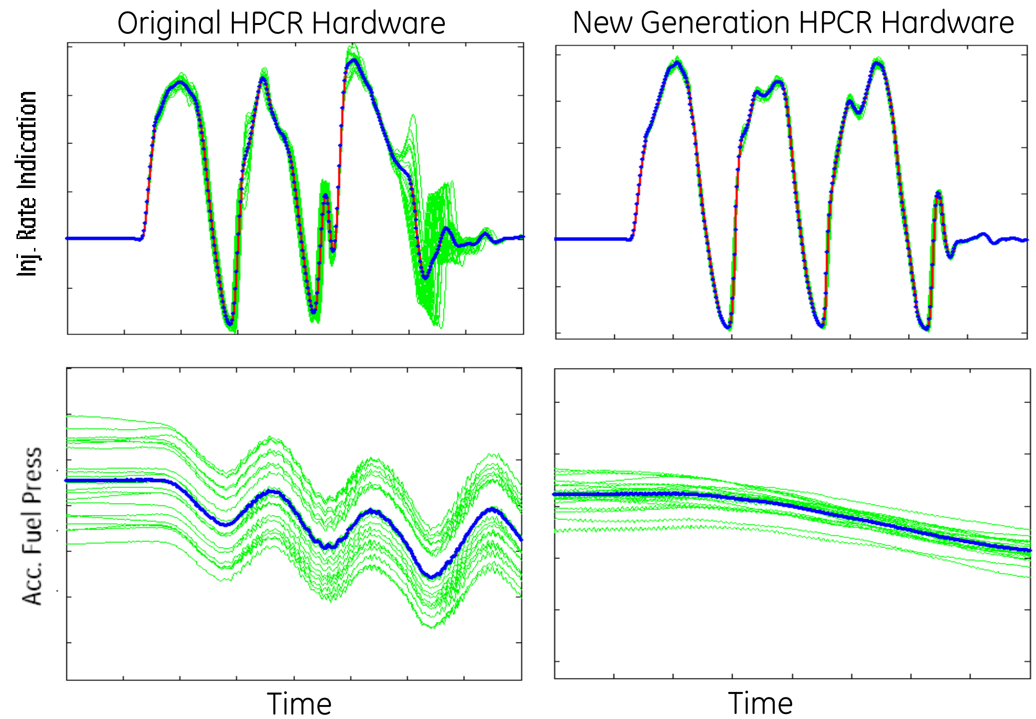

Figure 4: Injection rate shape and fuel rail pressure for 20 consecutive cycles [green] and their average [blue].

NUMBER OF HOLES

Nozzle flow, number of holes and hole diameter are dependent variables, from which only two can be chosen independently. In our nozzle geometry study we changed flow and number of holes independently. The number of nozzle holes was varied by up to four. The PM emissions level was strongly dependent on the number of holes. The effect of number of holes was notably stronger than the effect of injection pressure in the range tested. The specific fuel consumption seemed to be less affected by the number of holes and more a function of the fuel injection pressure. The dependence of PM emissions on fuel injection pressure was found to be fundamentally different for various hole numbers.

NOZZLE FLOW

The nozzle flow area was changed over a range of approximately 20% of the base line flow rate. The rates of needle velocity in the opening and closing where unchanged. Other parameters, including number of holes and spray angle, were held constant in the first set of designed experiments, in order to isolate the effect of total flow. To understand possible interaction between nozzle parameters, in later experiments, multiple parameters have been changed simultaneously. The study was carried out for a range of injection pressures. While the results indicated a fairly monotonic trend of particulate matter as a function of nozzle flow area, the effect on fuel consumption was found to be more complex.

CONE ANGLE

In order to explore the effect of spray cone angle on engine performance study the cone angle changed over a range of approximately 4% of the baseline nozzle. In the range studied, the trends for PM and specific fuel consumption were found to be opposite. Changing the cone angle monotonically led to a benefit in fuel consumption while the PM emissions increased and vice versa.

NEEDLE LIFT PROFILE

Needle seat diameter and orifice plate flow were found to have a strong effect on the needle lift profile. The needle seat diameter was increased by up to 12.5% compared to the baseline nozzle while the orifice plate flow was changed by up to a factor of two. A study was performed to investigate four different combinations of seat diameter and orifice plate flow. The choices were made to achieve four distinct needle lift and fall rates for the test matrix. The choice of seat diameter seemed to affect the PM emissions only for low injection pressures. The fuel consumption is affected for all injection pressures, even though the effect is minor compared to the other nozzle parameters studied. For certain needle lift profiles fuel consumption benefits have been observed. The effects were stronger at part load than at full load.

FUEL SULFUR LEVEL

Three different fuels with sulfur levels, changing by more than a factor of 200, were tested. As expected, a linear dependence of PM emissions on fuel sulfur level was found. The quantitative results at hand now allow for a better comparison of the data taken on the single cylinder engine to data taken on other engines run with different sulfur levels.

Duty Cycle Assessment

Multiple injection and hardware performance studies were carried out mainly for two notches, full load and part load. Nevertheless, for the most favorable hardware, we collected data over a larger range of notches. This provided a notch-by-notch performance comparison between HPCR and the production fuel system. Characterizing the engine performance over a range of loads is important since the locomotive duty cycle performance is a weighted average of all notches. While the notch-by-notch performance comparison provided a more refined performance characterization, the consideration of two load-points only (full and part load) appeared to be sufficient for a first order assessment.

Conclusions

The HPCR fuel injection system delivered SFC performance benefits and met or exceeded the goals of this program. At full and part load these benefits were measured at Tier 2 NOx emission levels. Changes in nozzle geometry have been proven to allow for further engine performance benefits. Clear trends have been identified and quantified. For the range studied, the number of holes seemed to have the strongest effect on PM, followed by rail pressure and nozzle flow. Changing the spray cone angle was found to have monotonic but opposing trends for SFC and PM. In this case, a trade-off function between SFC and PM was identified. Multiple injection strategies have been shown to allow for additional fuel and emission benefits over the optimized nozzle geometry single injection results. Pilot injections have been successfully proven to reduce the NO_x emissions, especially at part load. Post injections have been shown to give significant reduction in PM, without imposing a measurable SFC penalty. Additional diagnostics, like in cylinder visualization of the combustion event and particle size measurements in the engine exhaust, allowed for further understanding and guidance of engine development.

The PM emissions transfer function from Single Cylinder Engine to Multi-Cylinder Engine was identified as complex. For example, the PM levels on the SCE are typically lower than measured on the MCE. As a consequence, there remains uncertainty for PM targets for SCE in order to ensure Tier 2 PM compliance on a locomotive.

Next step for the HPCR development program is to transition the HPCR fuel injection recipe (hardware configuration, fuel pressure and fuel injection profile) to the Multi-Cylinder Engine and then to a full locomotive. In addition, HPCR fuel injection is an enabler for high fuel efficiency at even lower emissions levels when combined with Exhaust Gas Recirculation (EGR). EGR can lead to a significant NOx reduction but PM emission levels increase. At high injection pressures, the HPCR system can achieve significant PM emissions reductions. Future work on efficiency improvements should include the combination of HPCR and EGR concepts.

Acronyms

CFD	Computational Fluid Dynamics
EEPS	Engine Exhaust Particle Sizer spectrometer
GE	General Electric
HPCR	High pressure common rail
KIVA	A computer software for analyzing engine combustion
MCE	Multi cylinder engine
NOx	Nitrogen oxides
N2 ... N8	Notch 2 … Notch 8
PM	Particulate matter
SCE	Single cylinder engine
SFC	Specific fuel consumption
TC	Thermocouple
UPS	Unit pump system