21st Century Locomotive Technology:
Quarterly Technical Status Report 6 DOE/AL68284-TSR06

This is the quarterly status report for the 21st Century Locomotive Technology project, DOE Award DE-FC04-2002AL68284. This report covers activities performed April to June 2004.

PROJECT MANAGEMENT EVENTS

TASK 1: ADVANCED FUEL INJECTION

OBJECTIVE

PROGRESS SINCE LAST REPORT

PLANNED ACTIVITY FOR NEXT QUARTER

TASK 2A: ADVANCED TURBOMACHINERY – ELECTRICALLY ASSISTED TURBOCHARGER

OBJECTIVE

PROGRESS SINCE LAST REPORT

PLANNED ACTIVITY FOR NEXT QUARTER

TASK 3: HYBRID ENERGY STORAGE

SUBTASK 3.1: SPECIFY AND DESIGN ADVANCED MODULAR ENERGY STORAGE UNITS

SUBTASK 3.3: LAB TEST ADVANCED ENERGY STORAGE PROTOTYPE MODULES AND SYSTEM

SUBTASK 3.4: DESIGN HYBRID LOCOMOTIVE ENERGY MANAGEMENT SYSTEM (EMS) CONTROLS

SUBTASK 3.6: INTEGRATE SYSTEM AND TRACK TEST HYBRID LOCOMOTIVE WITH ADVANCED EMS CONTROLS

TASK 4: FUEL USE OPTIMIZATION

OVERALL OBJECTIVE

SYNOPSIS

SUBTASK 4.1: DEVELOP OPTIMIZER ALGORITHMS

SUBTASK 4.2: SIMPLIFIED OPTIMIZATION ALGORITHMS

PLANNED ACTIVITY FOR NEXT QUARTER: FUEL OPTIMIZER
Project Management Events

A successful half-yearly review of the 21st Century Locomotive Technology project with DOE was done on May 12 and 13, 2004. The May 12 portion of the review at the GE Global Research Niskayuna NY site covered progress on Task 1 (common rail injection) and Task 2 (turbocharging) deliverables; it included inspection of the common rail injector system installed on our single cylinder research engine and the massive compressed air facility and armored cells used for our advanced turbo experiments. On May 13, Tasks 3 (hybrid technology) and 4 (optimization) were reviewed at the GE Rail Erie PA site, where operation of the GE onboard hybrid demonstrator locomotive was shown.

Task 1: Advanced Fuel Injection

Objective

Develop and demonstrate an advanced fuel injection system to minimize specific fuel consumption (SFC), while meeting Tier 2 emission levels.

Progress since last report

Over the last quarter, progress has been made on both the experimental and the modeling front of the advanced fuel injection task. Experimental work to map the performance of the High Pressure Common Rail (HPCR) system on a locomotive is in progress. Thus far, the experimental trends agree with the trends predicted by KIVA modeling.

The experimental milestones accomplished over this quarter include:
- Obtaining baseline data with the production Unit Pump System (UPS)
- Establishing a method to compare the brake performance of the single cylinder engine operating with the UPS versus the HPCR
- Launching the common rail optimization study

The HPCR is currently being evaluated on the engine. The testing is structured around six sigma experimental design to ensure that maximum information can be extracted from the data. The experimental regimes chosen are guided by the modeling results. The performance of the engine with HPCR will be discussed at the next meeting with DOE representatives.

The KIVA code is being used at the University of Wisconsin to predict the performance and emissions of various scenarios with the HPCR system, as it will be implemented on the single cylinder engine. Investigations into optimum injection schedules have been completed for notch 8. The notch 4 optimization that was started last quarter continued and a notch 1 optimization began with the goal of reducing NOx, soot and fuel consumption simultaneously.

Having completed the required code modifications, injector parameters were then varied over a range of interest in a micro genetic algorithm optimization. Each simulation is evaluated based on a merit function that included fuel consumption and soot and NOx emissions. At present the best
performing simulation has a merit value of 246. The target merit value is 333, so we will keep the optimization running with the goal of further increasing the merit value.

Planned activity for next quarter

Over the next quarter, the HPCR optimization studies, experimentally and via KIVA modeling, will continue. Performance maps will be created to show the fuel economy benefit as well as the emissions entitlement of the advanced fuel system. The genetic algorithm optimization at the University of Wisconsin will continue to run.
Task 2A: Advanced Turbomachinery – Electrically Assisted Turbocharger

Objective

Validate prototype electrically assisted turbocharger unit to full speed and power and develop conceptual design for multi-cylinder engine.

Progress since last report

A detailed review of the electrically assisted turbocharger (eTc) activity, including design, development and testing was presented to DOE representatives on 5/4/2004. In summary, the locomotive scale eTc met the program goals.

Additional modeling and simulations were performed to evaluate the potential improvement of the modified turbocharger on passenger locomotive station-to-station transit times under different scenarios of train size, turbocharger assist levels, engine idle rpm level, and station duty cycle.

Design activity to scale the electrically assisted turbocharger system to the Tier II EVO V12 locomotive is on hold due to funding cutbacks for the 2004 DOE fiscal year.

Planned activity for next quarter

No activity is planned on this task during the next quarter.
Task 3: Hybrid Energy Storage

Subtask 3.1: Specify and design advanced modular energy storage units

Detailed discussions were initiated with our selected vendor for development and delivery of evaluation-scale enhanced-capability modules. Agreement on the detailed technical work will be concluded in the next project quarter.

Subtask 3.3: Lab test advanced energy storage prototype modules and system

Life-cycle testing has been initiated. The testing protocol has been designed to establish the baseline cycling life entitlement of the advanced energy storage technology. It is expected to continue for at least 12 months.

Subtask 3.4: Design hybrid locomotive energy management system (EMS) controls

Continued laboratory testing of energy storage battery behavior has been performed to develop a battery state estimation procedure. Completion of nickel-metal hydride battery test protocols has led to an algorithm for evaluating the battery internal state.

It was decided to apply the upgraded EMS controls to both battery technologies in the GE onboard hybrid demonstrator locomotive. Encouraged by the successful development of temperature compensation for NiMH, we initiated a similar testing protocol for the nickel-cadmium battery bank, with the objective of obtaining temperature-compensated operating limits for the upgraded EMS controls.

Subtask 3.6: Integrate system and track test hybrid locomotive with advanced EMS controls

The DOE team was able to inspect the GE Rail onboard hybrid locomotive and also ride the locomotive on the GE test track during the May 13 project review in Erie, PA.

Preparations for the track test included an extensive evaluation of the installed hybrid batteries. After consultation with the battery manufacturers including an onsite visit, the batteries were cleaned, overhauled and tested to establish their existing capability. Due to GE Rail’s business requirements there were competing demands on access to the locomotive and test facility, and consequently installation of the upgraded EMS features to the hybrid locomotive has slipped to August.
Task 4: Fuel Use Optimization

Overall Objective

Develop and demonstrate advanced algorithms for fuel savings in freight locomotive consists with and without hybrid energy storage elements.

Synopsis

Control strategies to save fuel for the overall freight locomotive consist are being developed along two major directions: (1) Consist Manager--control logic which takes the commanded power by the driver (throttle notch) and distributes it among operating locomotives in the most fuel efficient manner, and (2) Trip Optimizer--control logic which works in collaboration with the driver and dispatcher to plan and drive a trip, taking into account the power consist, terrain and freight load and operating constraints along the way. In January, we demonstrated in a “breadboard” implementation and 3400 mile test run on the BNSF railroad that Consist Manager offers the potential to save 1-3% fuel with full autonomy to the driver and would be compatible with existing operations. Trip Optimizer requires a change to operations but with the potential to save 4-8% on fuel. Both systems can be applied to conventional or hybrid locomotive consists for additional savings.

Subtask 4.1: Develop Optimizer Algorithms

We have achieved some major progress in development of reliable methods for computing optimal driving plans in Trip Optimizer, and have developed a simplified way to re-optimize a partially completed plan in an efficient way.

Computing a driving strategy for a freight consist to minimize fuel subject to operating constraints is difficult because of the many constraints and conflicting objectives. For example, over a 100 mile journey, speed limits may change 50 times and have thousands of decision variables (e.g. 50 m.p.h. average speed with 1 second control updates). To form a numerically reliable baseline in solving these optimal control problems, we require numerically robust solution techniques, accomplished with proprietary software. In this problem formulation, the objective function can include fuel consumed, total emissions generated, target arrival time, rate of change of throttle position (e.g. as a penalty against induced slack-action) and other performance related variables. Constraints incorporated can include speed restrictions along the route, and power limits.

Information about the track grade and curvature is part of locomotive train dynamic model.

We have completed simulation studies of optimised trajectories on a variety of terrains, grades, and speed restriction profiles. Our analysis shows the typical trade-off of fuel savings versus journey time that results. While the exact shape of the trade-off curve varies with terrain, the load and the specific speed constraints, they all exhibit the large reduction in fuel consumption per marginal hour of additional travel time. This means even small increases in journey time taken when slack time is available or slow orders are ahead have large potential fuel savings.
Subtask 4.2: Simplified Optimization Algorithms

We have developed a new search algorithm that we think can radically reduce the complexity to both apply Trip Optimizer to longer trips, and more importantly to allow on the fly recalculation of plans following an interrupt. We use a proprietary approach to partition then match up and link the segments back together on each segment to meet the overall time objectives with the least average fuel. Since no large optimizations are carried out, it can be done in or near real-time. Moreover, if, part way through a journey conditions change, the “plan” can be re-optimized over the remaining segments, taking into account the changed conditions.

Planned activity for next quarter: Fuel Optimizer

While we did not succeed in applying the Trip Optimizer strategy to the hybrid operating scenario this quarter, our confidence in robust and efficient ways to calculate optimal trajectories has greatly increased, and we will begin application to models with hybrid storage as we continue to conduct case studies with varying terrains, consists and loads representative of realistic Class 1 railroad freight operations. We will also extract data from our January 2004 Consist Manager tests on BNSF to form fuel use reference baselines. With actual engineer data on predicted fuel use, we can then compare the range of benefits: from Consist Manager ‘assistance’, to optimal and sub-optimal Trip Optimizer solutions to the same Trip Optimized consists working with hybrid storage.

To allow design and evaluation of potential operator interfaces for Trip Optimizer, we will also be assembling a real-time interactive work station. This real-time facility will use our Simulink simulation models with actual cab hardware control inputs. Outputs from the simulator will be displayed in a 3D graphics display with an “out the window” world view. This will allow design and testing of trip planning scenarios with simplified but realistic cab environment that a driver might experience, to gain insight into the best way to interactively carry out a plan and also handle the train safely.