21st Century Locomotive Technology: Quarterly Technical Status Report 11 DOE/AL68284-TSR11

This is the quarterly status report for the 21st Century Locomotive Technology project, DOE Award DE-FC04-2002AL68284. This report covers activities performed July 2005 to September 2005.

Task 1: Advanced Fuel Injection

Objective

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

Progress since last report

Over the last quarter, we have continued exploration of the performance of a High-Pressure Common Rail (HPCR) fuel system on the single cylinder locomotive engine. A new version of common rail hardware was successfully integrated on the research engine and performance trends were quantified. In addition to evaluating the new generation hardware, we compared the engine performance resulting from two distinct fuel injection rate shapes.

Hardware upgrades completed:

The latest generation fuel injection hardware provides lower variation in fuel injection parameters. The new features on the fuel injection hardware includes 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 a Moehwald flow bench showed a decrease of cycle-to-cycle variability in rail pressure, rate of injection profile, and injected quantity. Lower variation in the fuel injection parameters allows for more precise control of the engine.

Experimental milestones accomplished over this quarter:

The experimental efforts have been focused on performance mapping of the HPCR system on a single cylinder locomotive engine at notch 4 (part-load) and notch 8 (high-load) operating conditions. The variables explored include:

- Rail pressure
- Overall injection timing
- Multiple injections
  - Number of injections/stroke
  - Relative size of injections
  - Relative spacing of the injections
- Injection rate shape
  - Fast needle open/close
  - Slow needle open/close

By changing control hardware internal to the common rail fuel injector we have tailored the fuel injection rate shape and explored its effect on engine performance. With the data collected over the last quarter, we determined which type of injection rate is preferred.

The effects of multiple injection strategies versus single injection strategies were quantified for both the fast and slow needle lift variations, as depicted in Fig. 1. The multiple injection strategies were determined via screening tests in which split, pilot, and post injection strategies were considered.

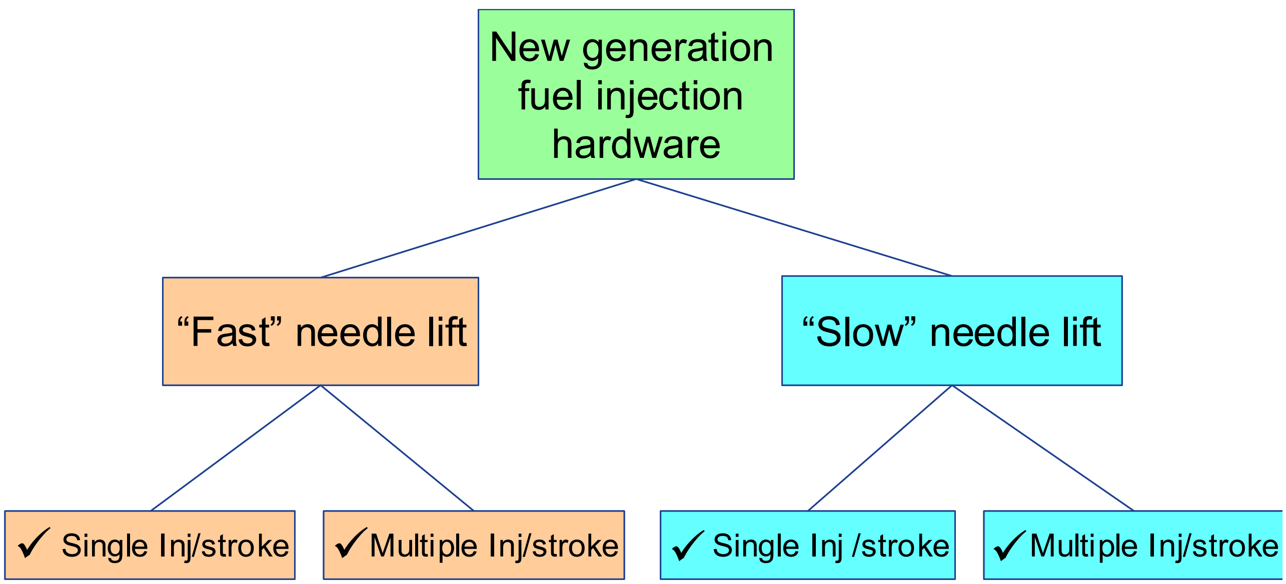

Figure 1 - Tree depicting the types of experiments that were performed in the last quarter on the GE Global Research single cylinder engine with a high-pressure common rail fuel system.

Planned activity for next quarter

Over the next quarter, the production Unit Pump System (UPS) will be installed on the single cylinder engine. The UPS dataset, which represents the production engine performance, will be collected to determine the fuel consumption benefit of the improved HPCR system at notch 4 and notch 8. UPS data will be gathered for more load conditions in preparation for duty cycle analysis on the HPCR versus UPS.

Task 3: Hybrid Energy Storage

Management events.

A technical status review of Tasks 3 and 4 was carried out at the GE Global Research facility in Niskayuna, NY on August 2, attended by both the DOE Project Officer and a HQ representative. Detailed technical results were presented and a hands-on demonstration of the driver's adviser locomotive simulator interface was made.

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

The long-term cell cycling data has shown higher rates of aging for large-amplitude cycles and lower operating temperatures. This data will assist GE Rail to set control parameters for the demonstration of the advanced hybrid energy storage system in Task 5.

The follow-up shock and vibration test of an instrumented hybrid-bus-design battery at room temperature was performed by GE Rail. High voltage insulation capability was compromised part-way into the test; however due to the room-temperature test plan it was possible for the test to proceed to completion. A teardown of the battery will be performed early October 2005, and the results will be communicated to the vendor to assist the design of a locomotive-worthy advanced battery system.

Task 4 Fuel Optimization Control Strategies

Overview of Accomplishments

The goal of Task 4 and Task 5 is to develop and demonstrate control strategies to save fuel in freight trains using both conventional and hybrid locomotives for propulsion. Primary focus in Task 4 has been to develop a methodology that can bring benefit to conventional locomotives, but which can be extended to locomotives equipped hybrid storage. Figure 1 shows a high level view of the systems developed to save fuel:

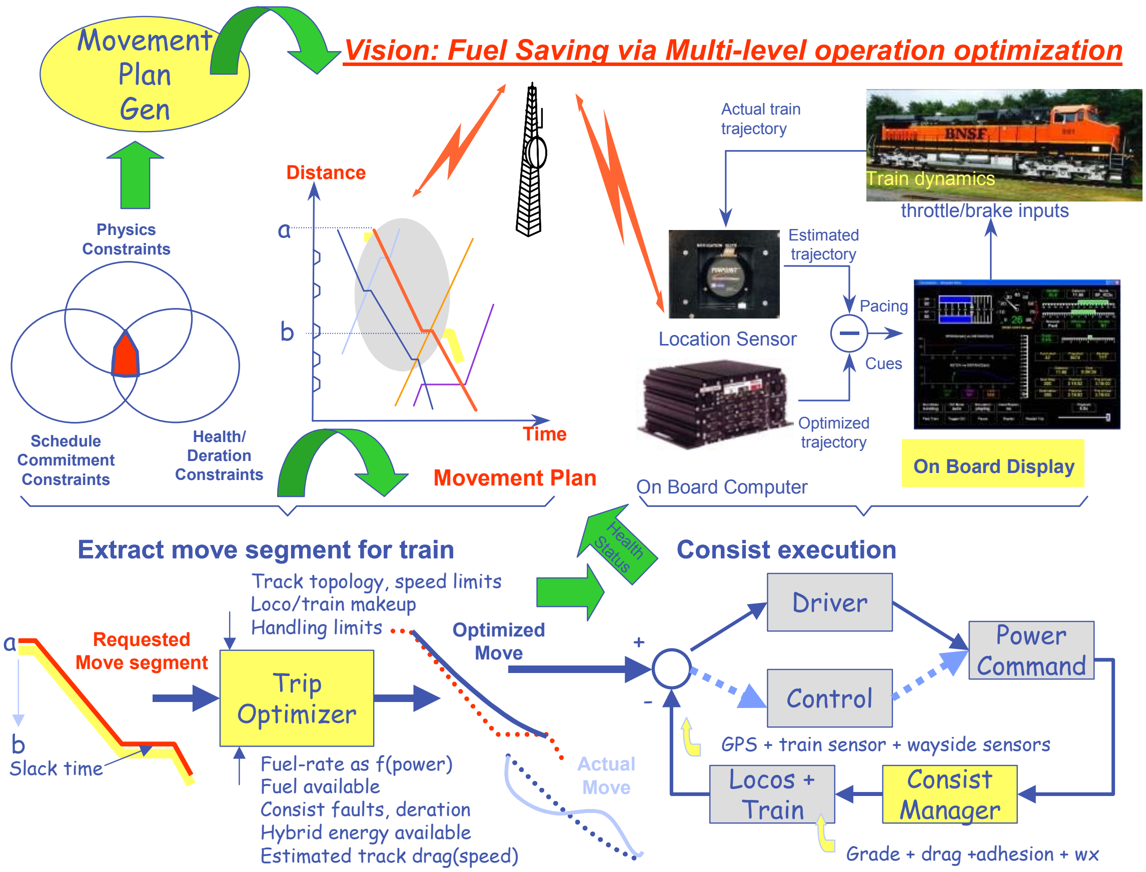

Figure 1 Overview of Freight Locomotive Optimization Strategies

The key systems developed in the effort are referred to as Consist Manager and Trip Optimizer.

Consist Manager - Consist Manager saves fuel by distributing power requested by the driver among the locomotives in the most fuel-efficient fashion. This system was shown to be simple to implement and is transparent to operations, and was shown to save from 1-3% fuel when used in typical duty cycles. It gains efficiency improvement during periods of part power requests of the locomotive consist by increasing power to some locos and decreasing power on others, exploiting the higher efficiency (indicated by lower specific fuel consumption (SFC) in lb/hp-hr) of locomotives with increased power. We completed a cross country (from Kansas City to LA on BNSF) field test of a Consist Manager prototype which showed the predicted 1-3% fuel savings with 1.5% average overall.

Trip Optimizer – Trip Optimizer provides an integrating framework for energy management in completing a freight haul from a mission perspective. That is, as shown in Figure 1, information provided by dispatch on the logistics of the load to be carried, starting point and destination, route to follow, power (locomotive) configuration, together with models and parameter values of associated models, are together used to synthesize the best way to drive the train to arrive at a specified time with the least fuel consumption. Trip Optimizer synthesizes the optimal speed to drive and the associated throttle setting, which minimizes fuel and satisfies speed restrictions (limits) along the route. The optimal "recipe" or *plan* for driving the train can be provided as coaching queues to the driver or executed closed-loop with feedback of certain locomotive variables plus GPS derived track location coordinates. With Trip Optimizer, the onboard crew has a tool to manage the journey in a completely novel way, by allowing explicit trades between journey completion time and the fuel used as opposed to operating at or near the speed limit all the time when give a track authority. For this increase in mission complexity, a crew with suitable incentives can save more than 4% fuel in a typical mission, for the same travel time, compared to manual operation, and where even a small amount of slack time is available, fuel savings exceeding 8% that are feasible. Focus of this project has been: to develop the required algorithms to compute fuel optimal trips in numerically robust ways—including new ways to simplify a complex optimization problem; to develop a means to follow the optimal plans in a coaching or closed loop fashion; to provide for a means to re-plan a partially completed trip in an efficient fashion; to develop a simulation means to prototype a real-time interactive system to demonstrate the concepts; and finally, in Task 5, to demonstrate the system on a revenue service locomotive.

Figure 2 shows the work plan developed to implement these systems, and Table 1 summarizes progress for each of the major Tasks. In total, all of the objectives have been met or exceeded as will be described in more detail below. Consist Manager has been successfully launched as a commercial product with two Class 1 Railroads with other opportunities pending. A complete real-time interactive simulation demonstration has been prototyped of the Trip Optimizer system, which is now undergoing user test prior to packaging for an on-train revenue service demonstration as part of Task 5. All of the Trip Optimizer functionality has been engineered to take conventional locomotives and replace them with hybrid locomotives, with energy storage strategy left as an optimization degree of freedom, another key Task 5 objective. That is, in computing the optimal driving trajectory speed and throttle, energy storage and retrieval is optimized concurrently to gain additional benefits in the freight haul mission.

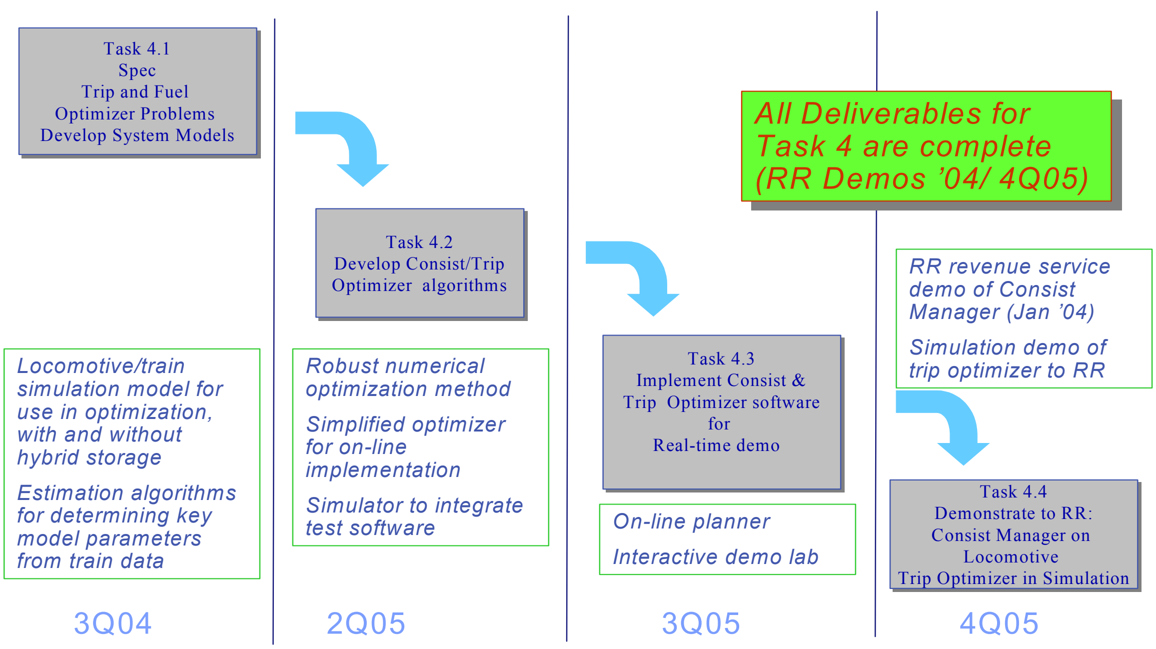

Figure 2 – Overview of Work Plan to Develop Consist and Trip Optimizer for Conventional Locomotives

	Accomplishment	Impact
√	New model based trajectory optimization algorithm for detailed trip plan calculation (Task 4.1/4.2)	Baseline driving plan to minimize fuel subject to constraints
√	Decomposition algorithm for sub-optimal calculations (Task 4.2)	100x reduction in time & complexity for real-time plan revisions
√	Design and implementation of interactive trip planning engine and simulator (Task 4.3)	On-line generation, revision and execution of trip plans
√	Interactive lab simulator for concept validation (Task 4.4)	Prototype drivable system with GUI for RR demo
√	RR field demonstration of "Consist Manager" fuel optimizer (1/2004) and simulation demo of Trip Optimizer (Task 4.4)	Consist Manager commercialized: 1st system installed NS July 2005

Table 1 – Summary of Key Accomplishments in Task 4 Sub-Elements

In what follows, we expand on the accomplishments in Task 4.3 and 4.4 completed in Q3 2005.

Trip Optimization Planning Implementation (Task 4.3)

OBJECTIVE

For the optimal trip plan algorithm in Task 4.2, develop a framework and computational methodology capable of real-time implementation, including efficient means to re-compute optimal plans when conditions change; develop a software system to execute optimal plans in either a coaching advisory fashion or closed-loop.

KEY ACCOMPLISHMENTS

We created an object-oriented environment that allows efficient handling of the large amounts of data that are required in developing, following and changing optimal trip plans. The framework allows the initial problem set-up, plan generation and control of execution, including re-planning in at or near real-time, e.g. while the train is in route to a destination. A key element of the architecture is the partition of any trip into segments. Boundaries of segments are arbitrary, but can be formed at natural spatial locations such as stations, sidings or speed restrictions. On each segment, solutions can be pre-computed then pieced together later to meet required travel time. A simple optimization formulation allocates travel-time among segments for minimum total fuel. Then the corresponding detailed plan can be looked up and pieced together to create the overall plan. It has been found that such plans, while strictly speak-ing sub-optimal, achieve >99.5% of the performance of a fully optimized plan. If trip parameters change, e.g. a speed limit on a segment, the full-blown optimization must be repeated, but only for that segment, greatly simplifying the calculations that must be carried out on-line. This has enormous value when a plan is changed in route. For example, if at the end of the 1st segment it was desired to change the travel time (up or down) for the remaining route, the 'new' travel time can be allocated to the remaining segments in a near optimal fashion, and the driver can switch to the new plan.

Optimal Trip Plan Demonstrations (Task 4.4)[1]

OBJECTIVE

Build an interactive real-time simulation environment to demonstrate the Trip Optimizer functionality, which includes an operator AAR-105 console and graphics user interface to allow a user community to experience Trip Optimizer to refine requirements for an on locomotive demonstration in Task 5.

KEY ACCOMPLISHMENTS

A planning and locomotive simulation environment was created using MATLAB/SIMULINK and associated tools called Real-time Workshop and the Dials and Gauges toolbox (Figure 3). These are all commercial off the shelf controls engineering software tools, which are ideal for prototyping complex systems such as Trip Optimizer. A key strength of this environment is the ability to rapidly prototype and change desired functions.

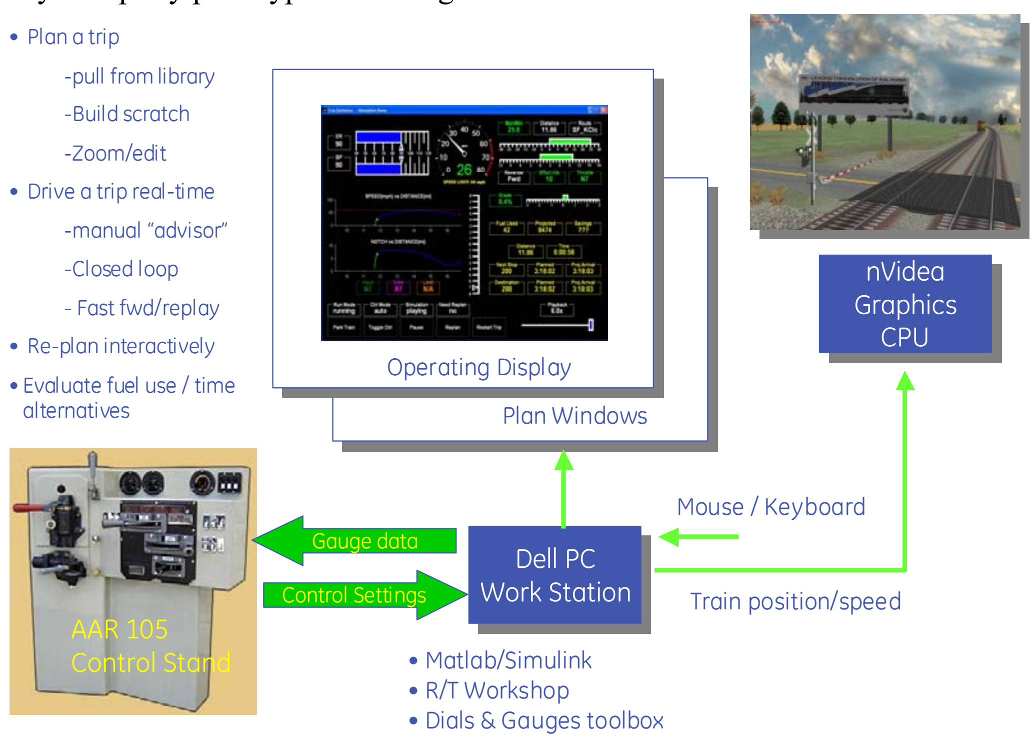

Figure 3 – Interactive Simulation Environment for Trip Optimizer System

The prototype system, implemented in a low cost PC-class workstation, has the capability to perform all the required Trip Optimizer functions plus a realistic driver cab emulation environment. Software is able to display conventional elements of a locomotive display including throttle and brake status, speedometer, accelerometer and tractive effort. Enhancements for Trip Optimizer include a look-ahead strip-chart showing the current speed,

[1] Consist Manager demonstration as part of this task was successfully completed in FY 2004 on a BNSF revenue service train and reported elsewhere

speed limit and optimal planned speed together with the current and optimal throttle (notch) setting. This 'loco cab' display also shows a palette of data regarding the trip status, distance to go, and performance statistics. The Real-time Workshop MATLAB code is interfaced to an AAR-105 full-scale control panel built by PI Engineering, which allows manual operator control with a standard control panel configuration. Control settings are read by the MATLAB code and locomotive states computed in MATLAB are displayed in special analog gauges that can be driven digitally. To add realism, a pseudo-3D display can be projected that is also driven by the MATLAB code to provide a sense of motion during a simulation run, but is not required. MATLAB tools are again exploited to provide a software environment with set-up windows to enable all the tasks associated with building and executing a plan. Numerous interactive features have been provided to: examine and manage the data needed for a plan; carry out optimization over segments using the optimal control software; launch and execute a plan; re-plan along the route. For training purposes, features were also included to zoom in on data, examine actual performance compared to plan (with driver manual control) and "fast forward" and "rewind" to interesting sections of the trip. While this interface is strictly for an engineering demonstration, it allows all the features of a potential commercial product to be demonstrated and evaluated, and will serve as the basis for on-locomotive demonstrations in Task 5.