21st Century Locomotive Technology: Quarterly Technical Status Report 28 DOE/AL68284-TSR28

This is the quarterly status report for the 21st Century Locomotive Technology project, DOE Award DE-FC04-2002AL68284. This report covers activities performed October 2009 to December 2009.

Project Management Events

In 2009, GE Transportation was awarded a contract by Canadian Pacific Railway Limited (CP) to equip 200 locomotives with its Trip Optimizer fuel savings product. Work completed under the Fuel Optimization task of this 21st Century Locomotive Technology project developed fundamental algorithms which have enabled this product. The Trip Optimizer was first tested on 18 CP-owned GE Evolution Series locomotives. The pilot testing was conducted in three subdivisions that have significantly different geographical characteristics including mountainous regions in British Columbia, the Saskatchewan prairies and undulating, winding track in Northern Ontario. More than 500 train starts and 50,000 revenue miles were accumulated during the test.

"Results measured by CP on intermodal freight of various train lengths and weight have shown a fuel savings ranging from 6% to more than 10% depending on territory," said Pierre Comte, President GE Transportation Intelligent Control Systems. Through January 2010, 200 Evolution Locomotives are in service with Trip Optimizer and have accumulated more than 270,000 miles in revenue service at CP. Currently, other pilots are being conducted including bulk commodity service testing that is showing even greater fuel savings. Pilot trials at BNSF and CSX railroads, combined with CP, have resulted in 670,000+ miles being logged with Trip Optimizer in control. If every train in North America used Trip Optimizer it would save approximately 630 million gallons of fuel per year, the equivalent of eliminating more than one million cars from the road.

Additionally, GE initiated work to locate its state-of-the-art battery manufacturing plant on the GE Energy campus in Schenectady, NY. The $100 million battery factory will bring 350 jobs to the site and expands the company's clean energy initiatives. The facility is scheduled to be fully operational by mid-2011. GE has invested more than $150 million to develop advanced battery technologies, including a high energy density, sodium-based battery that will provide energy storage for future product applications. Plans are for the new product line to serve the rail, marine, mining, telecommunications and utility sectors, including the hybrid locomotive application. Overall, GE believes that advanced battery manufacturing could grow into a $1 billion business over the next decade. The selection of sodium battery technology as the appropriate hybrid locomotive energy storage solution, and the development of technologies for battery integration to the locomotive in this 21st Century Locomotive Technology project were key drivers for GE's decision to enter advanced battery manufacturing.

These two significant decisions demonstrate the impact of the GE-DOE 21st Century Locomotive Technology project, which has developed important locomotive fuel efficiency technologies, that have subsequently been further developed by GE for commercialization.

Task 5: Demonstrate hybrid locomotive concept with full-scale storage modules, and fuel optimizer

The full-scale sodium energy storage modules need to be integrated to the hybrid locomotive platform, in particular to the thermal management interfaces and controls provided by the locomotive system. Analysis of the thermal response of batteries enables design of the thermal management controls for the battery. Current work is focusing on validation of the physics-based thermal model using an instrumented quarter-scale battery module.

A major objective of this task is to combine the fuel optimizer (also known as "trip optimizer") and energy storage battery technologies developed in previous tasks, in particular by addition of an extra degree of freedom representing control of the hybrid system to the fuel optimizer, followed by demonstrationof the resulting Hybrid Trip Optimizer on a locomotive platform.

Validation of battery thermal models

A quarter-scale sodium battery module with internal forced-air cooling with extensive internal temperature monitoring was supplied to the project. Since the top of the battery is removable to adjust sensors, it has a higher heat leak than a fully sealed battery, but nevertheless the apparatus is well-suited to study thermal behavior. The objectives of the test plan for this battery include determination of the thermal parameters such as heat capacity and heat transfer coefficients, validation of the battery thermal model and validation of the thermal response to the thermal controls developed under this project.

The battery surface heat transfer was measured over a range of internal temperatures by noting the equilibrium mean temperature at a range of values of heater power, as shown in Figure 1.
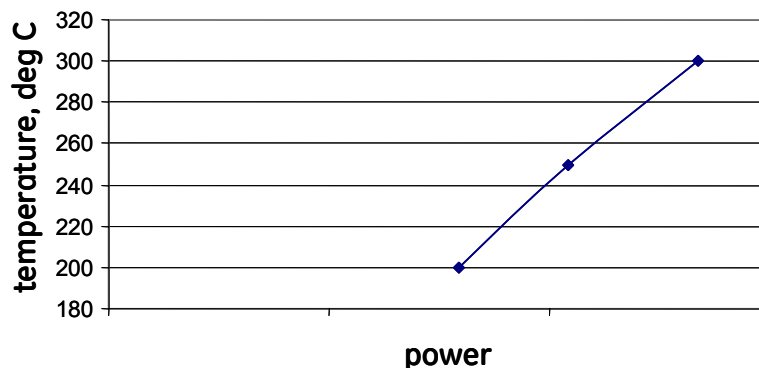

Fig. 1: Equilibrium test battery temperature vs. heater power.

The effective heat capacity was obtained by measurement of the battery natural cooling.once the temperature maintenance heaters were de-energized, as shown in Figure 2.
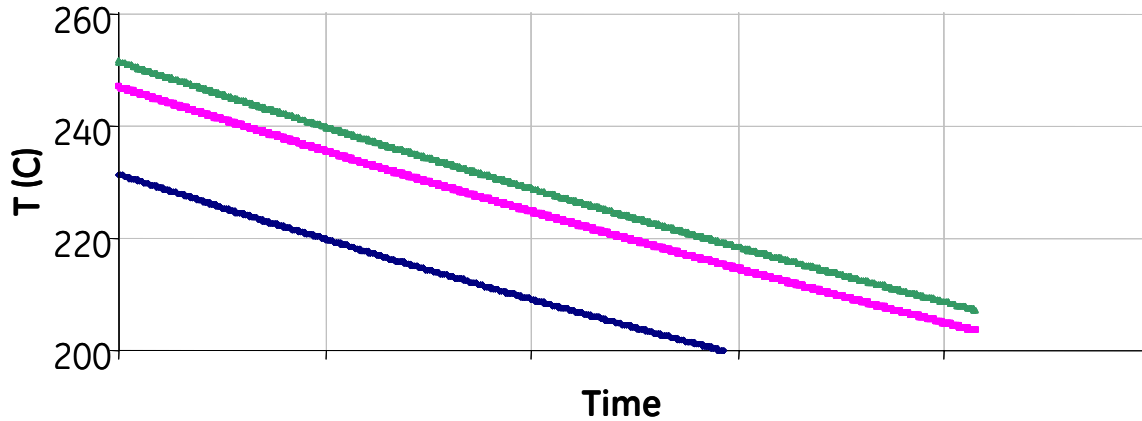
Fig. 2: Test battery cooldown.

The battery cooling was also measured at different cooling flow rates, as shown in Fig. 3, in order to obtain the battery heat transfer coefficients to cooling air.
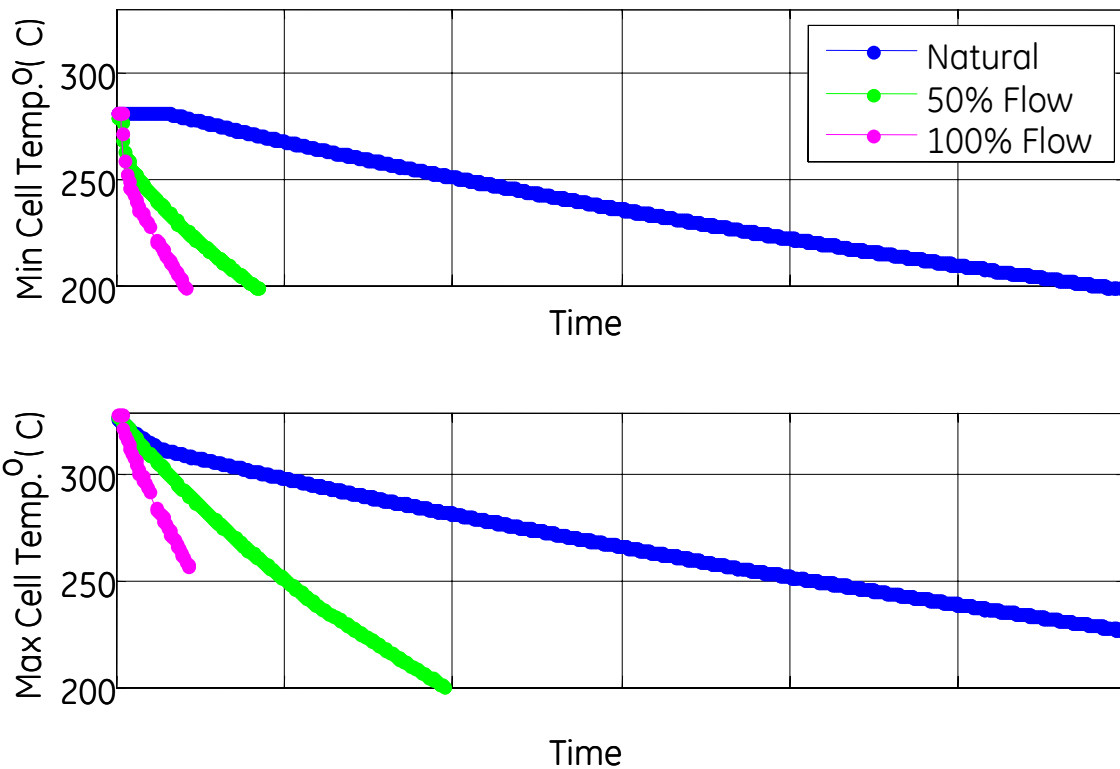

Fig. 3: Test battery cooling vs flow rate.

A simple electrical charge-discharge cycle was then used to exercise the battery, first without active cooling, and then coupled with a simple on-off cooling cycle, as shown in Figs. 4 and 5. Analysis of these results is in progress, to validate the thermal model performance. These tests will be followed by testing under a representative locomotive cycle in order to compare performance of baseline thermal control strategy and the optimized strategies developed under this project.
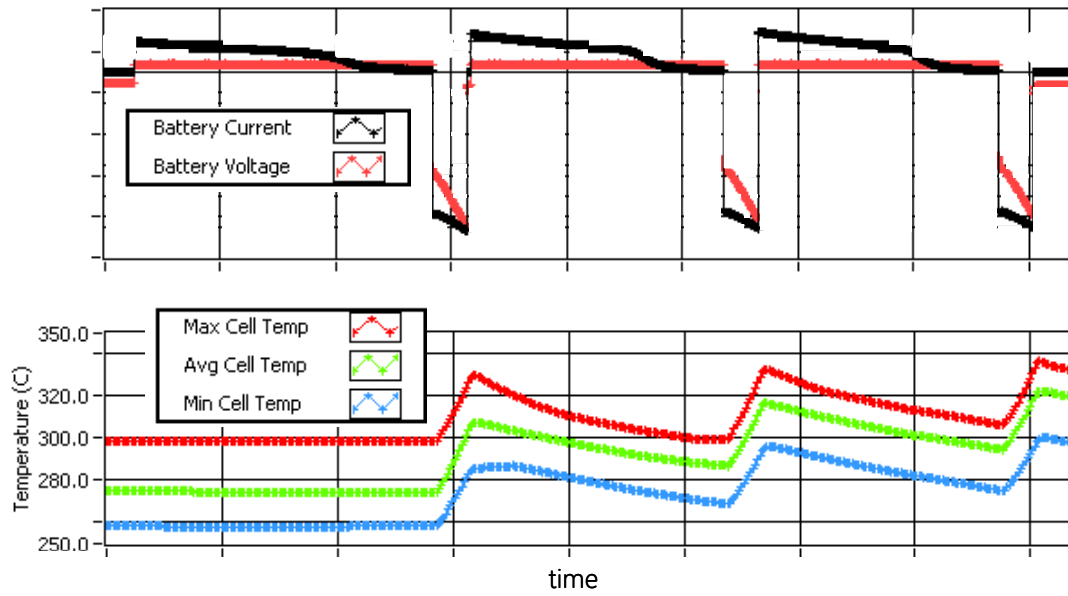
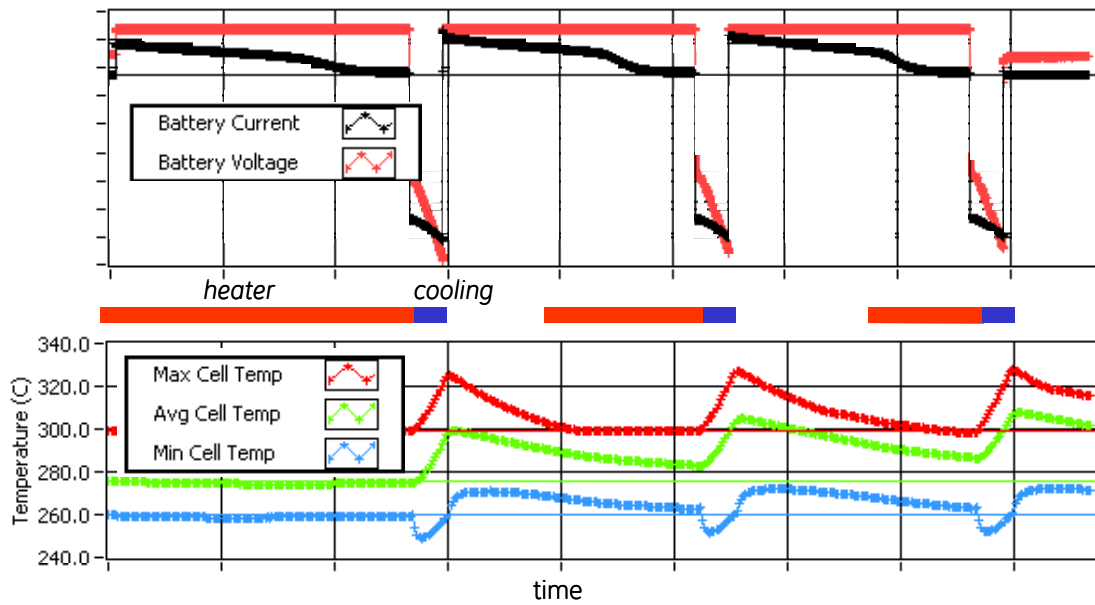**Fig. 4: Test battery simple cycle performance, no ventilation.**

Fig. 5: Test battery simple cycle performance, with ventilation.

Formulation of the Hybrid Trip Optimizer (HTO) Problem

The hybrid trip-optimizer (HTO) problem is a natural generalization of the thermal optimization work we did in the first and second quarter. In the last quarter of 2009, we took the decisive steps towards mathematically formulating the problem of optimizing overall system performance of the hybrid locomotive system.

The idea is to use advanced optimization techniques to calculate the optimal strategy (or plan) to drive a train powered by hybrid locomotives. By "optimal strategy", we mean a sequence of speed, throttle and dynamic brake (and if necessary, air brake) commands to the train, plus power commands to charge or discharge the battery. The calculated plan is used as a set-point to an automatic control system which actuates the throttle and brake to follow the planned speed while charging and discharging the battery (within thermal limits) according to the plan.

The problem of optimizing the train throttle and brake inputs *without* the hybrid battery has already been solved in the Fuel Optimizer task of this project. This solution is at the core of a control system called "Trip Optimizer" (TO). TO is now a mature product with proven fuel savings and has undergone commercial pilot programs on two Class I railroads in daily revenue service, operating over a wide range of track, tonnage, and power configurations. The 4-13% fuel savings demonstrated by TO is achieved by managing train momentum in order to eliminate unnecessary braking while respecting all speed limits and arriving at the destination in a timely manner. A schematic of the overall control system for the existing TO product is shown in Figure 6. In principle, the HTO system, which is the eventual goal of this work, will have a similar overall structure (although it will be more complicated). At present, we are focusing on the optimization problem and entitlement calculations. This will allow us to
1. Quantify the best expected fuel savings from the hybrid locomotive system equipped with sodium batteries, and
2. Develop implementable train control systems which will realize the fuel saving potential of the hybrid locomotive.
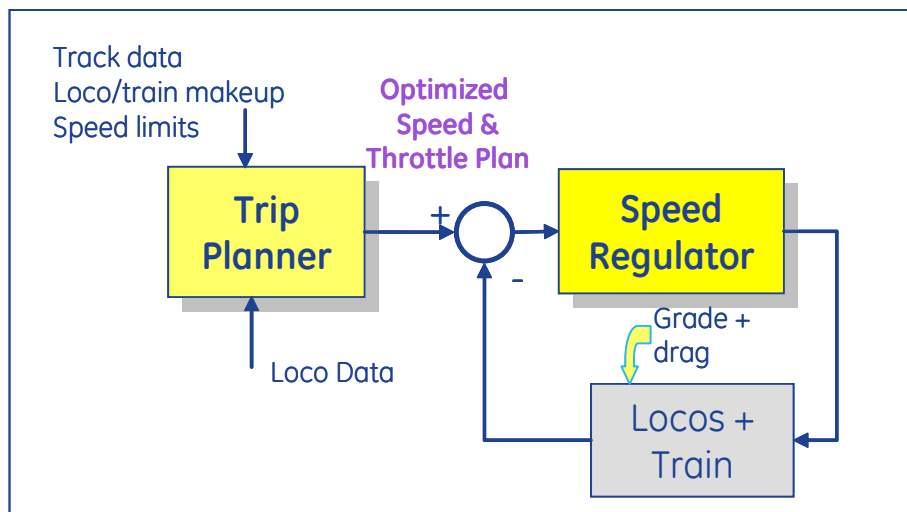

Figure 6: Current Trip Optimizer Implementation

It is our expectation that the benefits of the HTO will exceed the sum of the benefits due to hybrid energy storage alone, and the benefits of TO alone.

The HTO problem is an optimal control problem whose optimization variables are the following time functions:
1. u(t) = Train speed at time t
2. x(t) = Train position at time t
3. P(t) = Total power available at the train wheels (positive implies motoring, negative braking)
4. P_b(t) = Cell power at time t (= battery power averaged over number of cells)
5. V(t) = Mean cell voltage
6. Q(t) = Battery State of Charge
7. I(t) = Battery Current

Note that the battery temperature is not included in the optimal control formulation; we assume that the temperature control system can keep the temperature within bounds. We have already developed good temperature controls over the past year.

The objective of the optimization problem is to find u, x, P, P_b, V, Q, I as functions of time such that the overall trip time is within a small percentage of the theoretical minimum-time *without a hybrid battery* for the same trip and such that fuel usage is minimized. The theoretical minimum-time is computed using current TO technology. The objective function includes energy and power slew rate terms.

The constraints on the optimization problem are as follows:
1. Train Dynamics

$$m\frac{du}{dt} = \frac{P}{u} - g(x) - a - bv - cv^2$$
$$\frac{dx}{dt} = u$$

2. Battery SOC

$$\frac{dQ}{dt} = I$$

3. Ohm's law and energy balance for battery (V_o is the open-circuit voltage)

$$V - V_0 = IR(Q)$$
$$P_b = VI$$

4. Locomotive power and train speed limits
5. Arrival time constraint (t_f is final time, x_f is final distance)

$$x(t_f) = x_f$$

The resulting problem becomes a large-scale nonlinear programming problem which can be solved using proven technology used for TO.