21st Century Locomotive Technology: Quarterly Technical Status Report 26 DOE/AL68284-TSR26

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

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

To successfully interface the hybrid battery system to the hybrid locomotive, a key interface is the thermal management of the battery. Work in previous quarters has focused on determining the thermal properties of the hybrid battery, together with accurate heating and cooling system transient power consumption, and applying these to the system model. Analysis has shown that the battery cycling during hybrid locomotive missions produces an average level of resistive losses that greatly exceeds the conductive heat leak of the well-insulated battery system. Further, the high-power operation of the hybrid battery is sufficiently well distributed throughout typical locomotive missions, that the thermal management system is rarely called on to heat the battery; the majority of the thermal control duty cycle requires active cooling of the battery. The combined energy requirements for battery thermal management (cooling air circulation and battery heating) are an order of magnitude less than the locomotive propulsion energy and equivalent fuel saved by the hybrid battery system. Therefore the parasitic losses due to hybrid sodium battery thermal management do not significantly reduce the fuel saving benefits of the hybrid locomotive.

In this quarter, we have finalized, based on extensive simulations of the battery system, the control algorithms for advanced thermal management of the hybrid locomotive battery. In particular, we:

1. Thoroughly analyzed of the performance and robustness of the optimal thermal management algorithms proposed in the previous quarter, and obtained limits on the thermal performance of the battery system
2. Completed design of an enhanced thermal management control system to obtain almost-optimal performance
3. Analyzed the robustness of the resulting control system by varying several key battery parameters which are not exactly known. The results are very encouraging.
4. Evaluated the impact of enhanced controls on battery life. The results suggest that optimizing the control system design could considerably reduce resistance rise (over a standard mission) in comparison with the baseline controller.

Performance limits on thermal controls

In the previous quarter, we had identified several metrics to quantify battery thermal performance and had developed a solution, based on mathematical programming, to the problem of identifying the best possible performance (or the entitlement) of the thermal management system. In this quarter, we verified the improved performance of the optimal thermal control by analyzing a second and third representative locomotive cycle, and repeating the analyses for a cooling system with lower heat transfer coefficient (HTC). We found that the performance benefits of optimal thermal control apply for the new cases as well.

Enhanced thermal management design and robustness analysis

The optimal thermal management strategy of the previous section delivers the best possible performance of the system, but is not easy to implement directly due to heavy computational requirements of the mathematical programming algorithms. We have therefore developed a series of realizable control system designs without the heavy computational load, culminating in a control system design which closely matches the theoretical best performance, but which can easily be implemented in real-time. Figure 1 compares the performance of 4 different thermal control algorithms applied to 2 different hybrid locomotive missions. The 4 algorithms are:

1) baseline control strategy

followed by 3 *improved* control strategies

2) optimized thermal control strategy
3) realizable control strategy A
4) realizable control strategy B

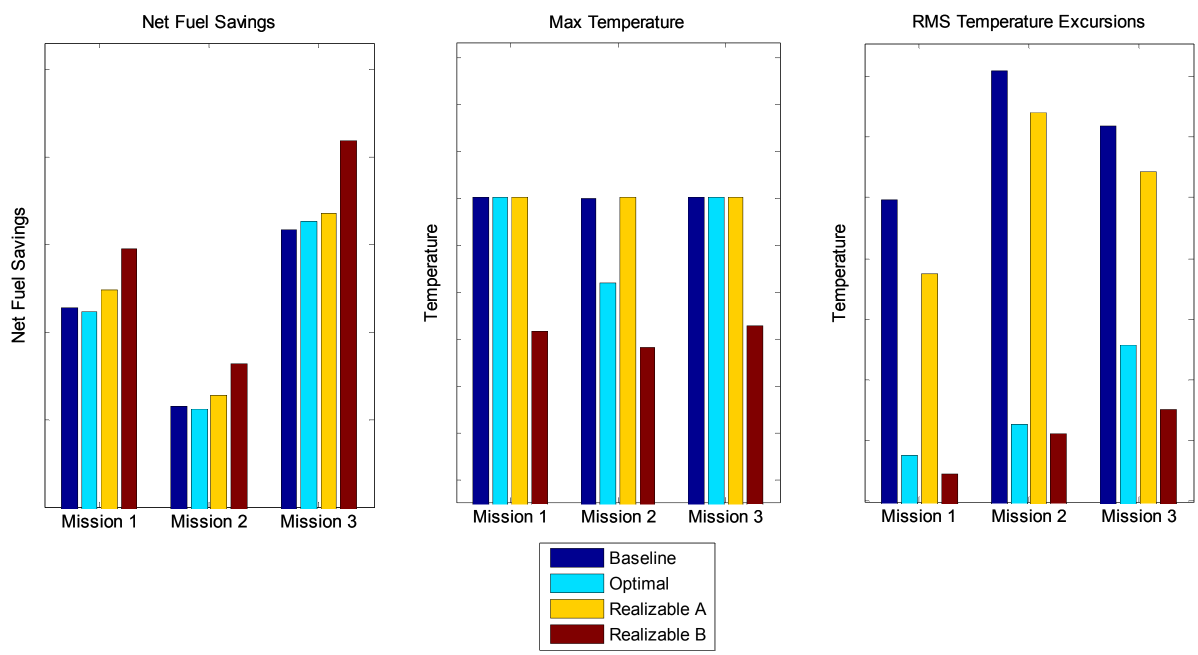

Figure 1: Comparison of battery thermal control performance.

It is found that the optimal strategy and "Realizable A" strategies are only partly successful in reducing peak temperature of the missions. However, the "Realizable B" strategy successfully lowers peak temperature for all the missions. The RMS temperature deviation for the improved control strategies is always lower than the baseline control, with best results from "Realizable

B". The optimal thermal control fuel savings is close to the baseline case. Since the optimization addresses a combination of low temperature error and high fuel savings, the optimized solution generally shows slightly worse fuel savings than Realizable Control Strategy A and B. The realizable control strategy B gives best performance in all 3 metrics, and will therefore be the control algorithm of choice in future work.

Control robustness

An important step completed in this quarter was to verify the sensitivity of this optimal solution to variations in the parameters of the physics-based battery model. For example, in order to model the battery temperature dynamics, we need the heat transfer coefficient (HTC) from the battery to the cooling air, obtained by either computational analysis or experimental measurement. However, it is likely that the real operational values of HTC or other parameters do not exactly match those from model analysis and may also change during the 20-year locomotive design life; it is thus important to verify that the optimal performance does not deteriorate when the model parameters are varied.

We evaluated the robustness of this enhanced control design with respect to variation in model parameters (HTC, air flow, cell resistance, ambient temperature, etc). The new controls outperform the unoptimized baseline in all cases, showing that the performance improvement is not sensitive (i.e., is robust) to such parameter variations. This gives us confidence that the simulated performance benefits can be validated by tests on real hardware, where such parameter variations are unavoidable. In particular, the fuel savings are higher, peak temperatures are lower and electrical aging stressors are less with the new controls.

Battery life study

Since battery life plays an important role in determining the commercial viability of the hybrid locomotive application, we incorporated cell degradation growth into our battery system model. As a result, we could predict the resistance rise with the baseline unoptimized controls and compare it with the enhanced controls. The results are very encouraging, showing that the optimal solution ages the battery more slowly than the baseline control, while the "Realizable B" strategy ages the battery even more slowly.