DOE Heavy Vehicle Systems Optimization peer review

21st Century Locomotive Technology (locomotive system tasks)

presented by

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21st Century Locomotive (system) Technology

Solicitation Technical Goal: Locomotive efficiency improvements

Project Objectives

•Locomotive system developments for 15-20% fuel usage reduction through energy management and fuel optimization:

- •capturing and storing regenerative braking energy
- •fuel optimization control (route, terrain, and train characteristics)

FY 2003-2005 Focus

•develop and test advanced energy storage system modules

•demonstrate advanced hybrid locomotive energy management system

•develop and demonstrate locomotive consist manager

•develop and demonstrate trip optimizer

Planned Duration
January 2003 to December 2007

DOE Funding/Industry Cost Share
FY03: $799k/799k FY04: $355k/355k FY05: $575k/575k FY06: $335k/335k

Railroad modality: 2.5% national fuel usage
Project's 20% fuel reduction gives **0.5% impact on national fuel usage**

Project deliverable *Advanced hybrid energy management demonstration on GE's "on-board" proof-of-principle hybrid locomotive demonstrator*

Project deliverable
Consist manager demonstration on Class 1 RR 2x1740mi mission

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Accomplishments

1: Accomplishment – Selected high-energy-density, temperature-insensitive Na-NiCl$_2$ energy storage technology

2: Project Deliverable – Demonstration of hybrid locomotive on test track with advanced EMS controls, February 2005

3: Project Deliverable – Track demonstration of locomotive consist fuel optimizer using one degree of freedom controls, February 2004

4: Accomplishment – developed interactive fuel optimizer demo simulator and demonstrated trip optimizer to railroads

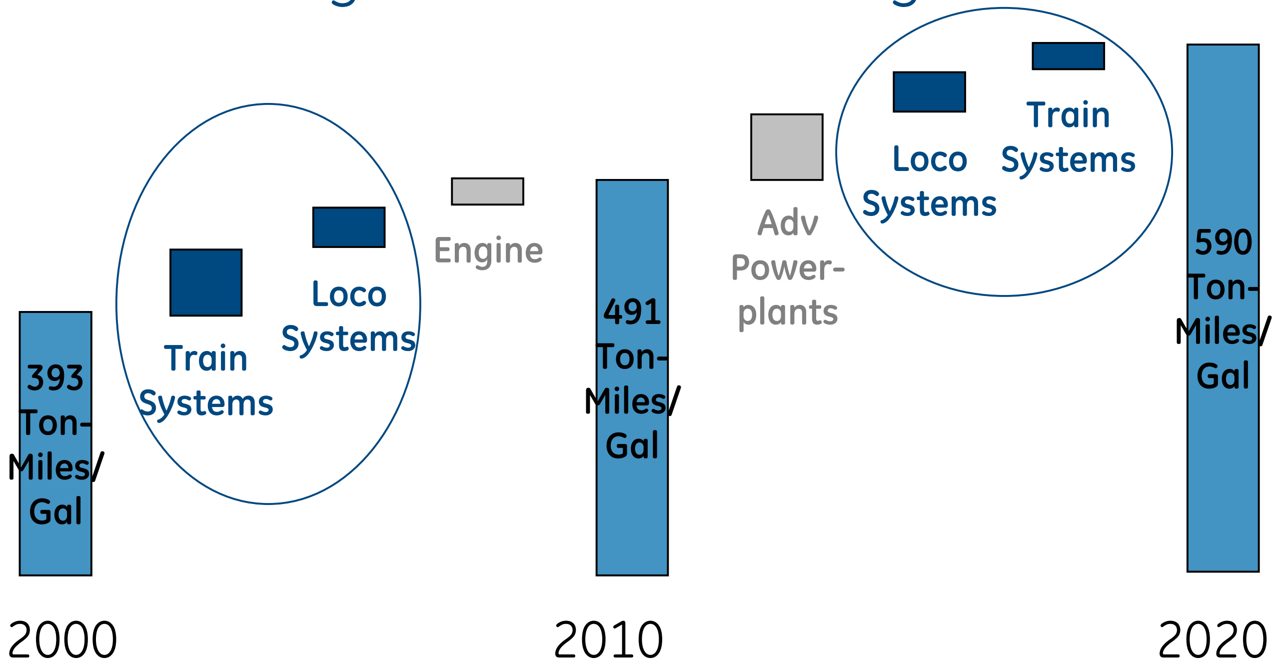
Significant Future Milestones

Project Deliverable – Hybrid locomotive test track demonstration incorporating the integrated fuel optimization controls – December 2007

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
15455	HVSO	Enabling Technologies	Exploratory Research	4-06

21st Century railroad efficiency vision

speed up locomotive and train efficiency rate-of-change, to move from 400 ton-miles/gal to 600 ton-miles/gal



- **Hybrid energy storage**
- **Consist & trip fuel optimization**

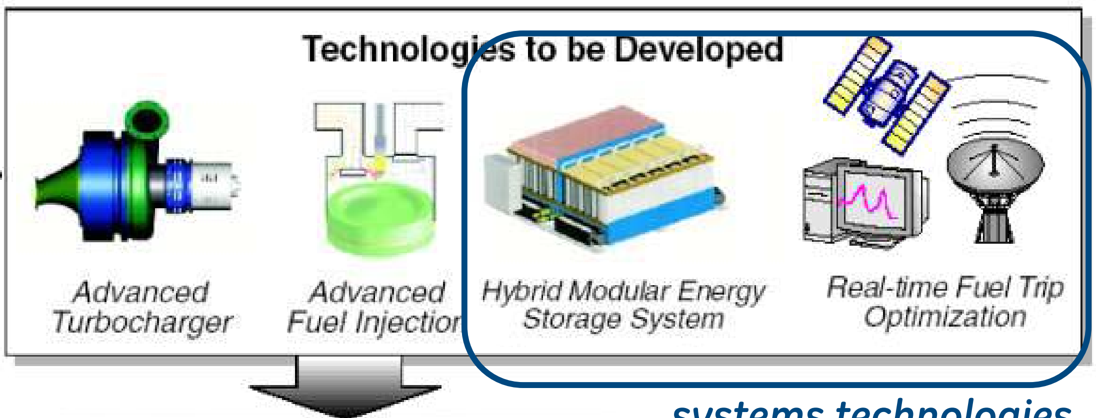
21st Century Locomotive Technology project

Freight locomotives 25% lower fuel usage by 2010 (incl. engine tech)

20% fuel reduction from systems technologies:

0.5% national total

Four-Year, $10 Million Project to Develop and Demonstrate 21st Century Locomotive Concepts



systems technologies

21st Century Locomotive Features

- Tier II compliant
- Up to 25% reduction in fuel consumption

Benefits

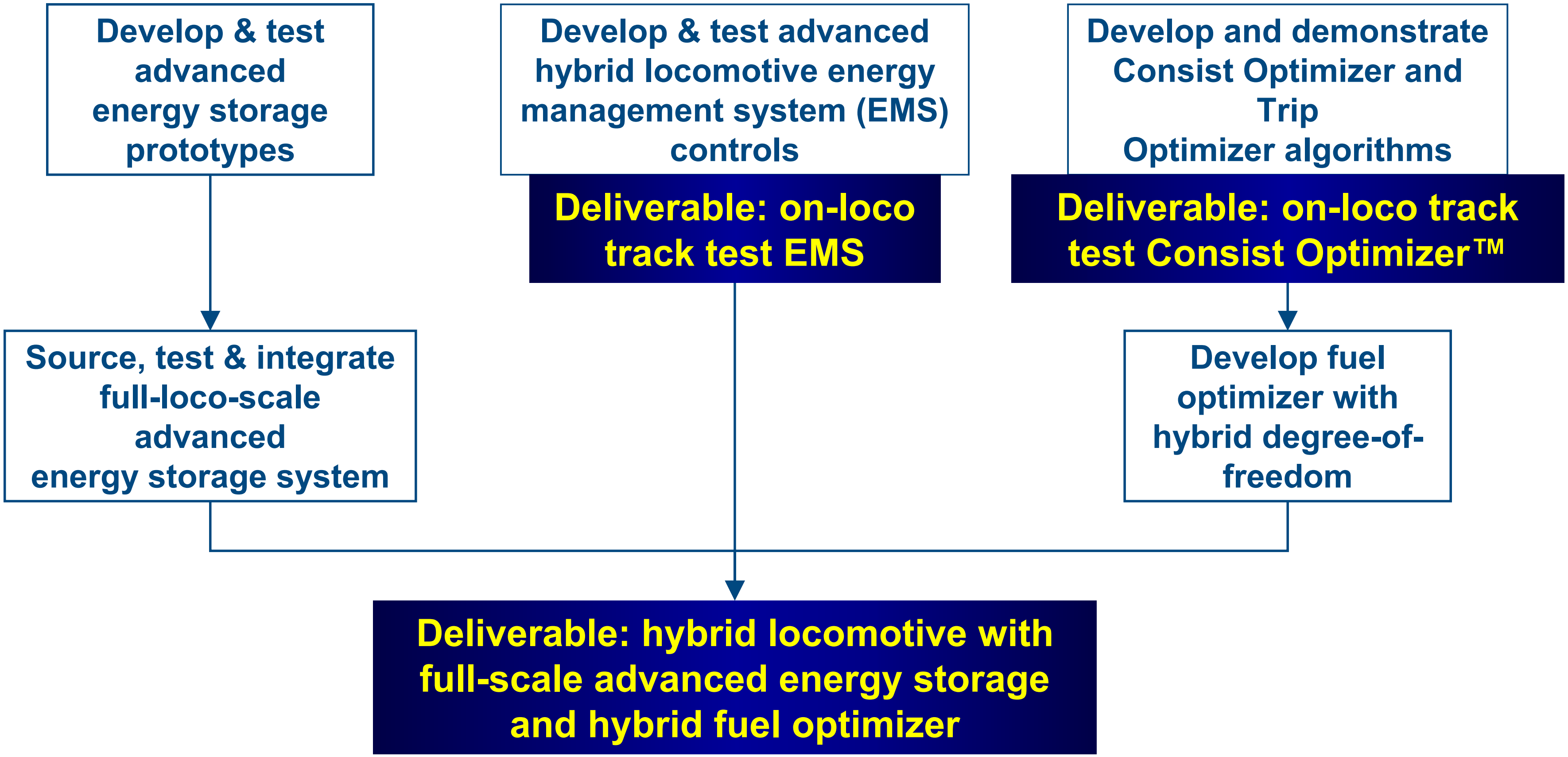
- ***Energy reduction***:
  Fuel savings of 750-950 million gal/yr
- ***Environmental impact***:
  Reduction of HC+NOx by 232 million lb/yr
- ***Competitiveness***
  20-25% annual savings in fuel consumption after meeting the regulatory requirements of Tier II, which result in a more competitive rail industry
- ***Economic:***
  Lowers U.S. dependence on foreign oil

Project Deliverables

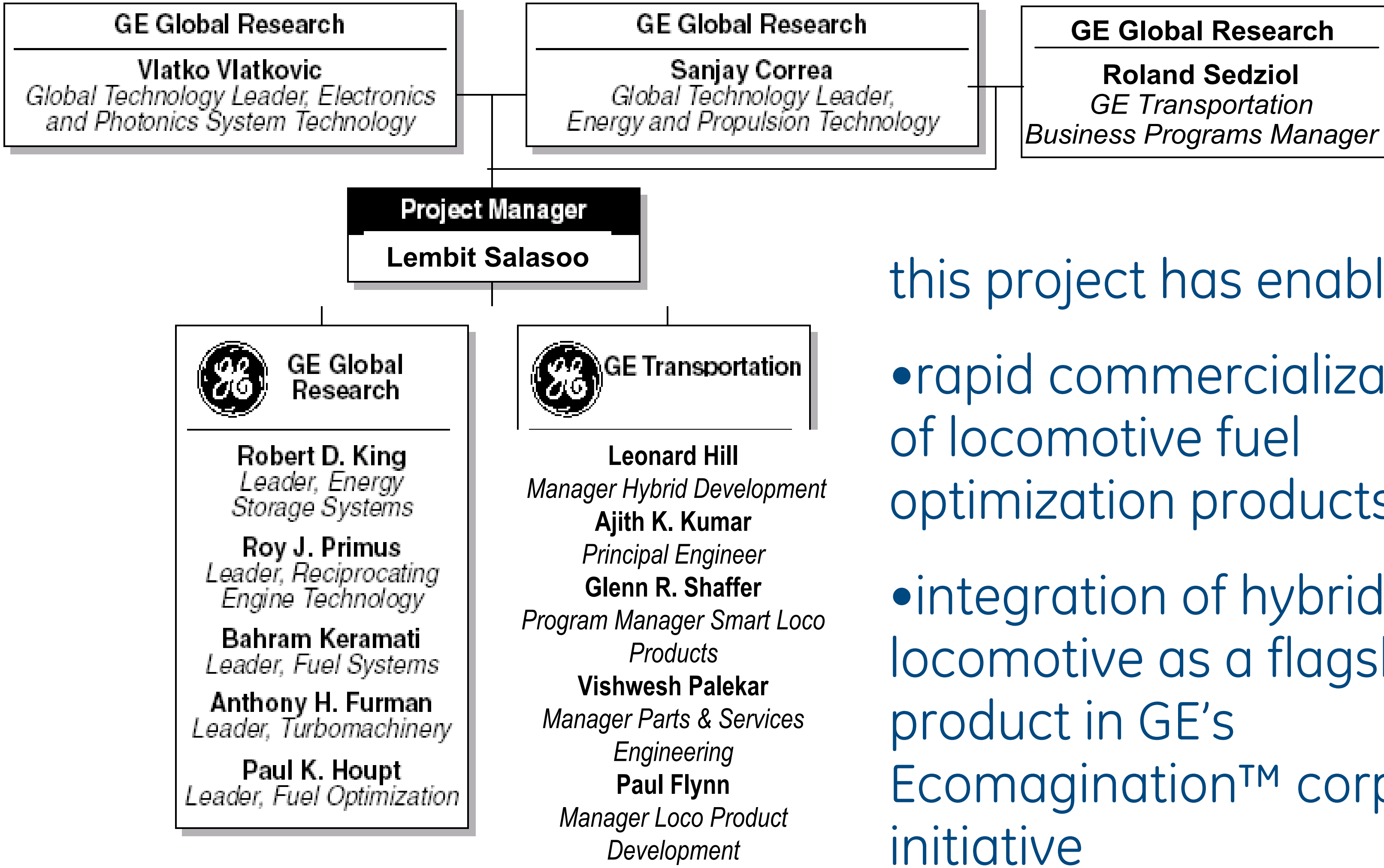
- Development and demonstration of hybrid energy storage, fuel optimizer, advanced fuel injection and turbocharger system
- Final report

Project approach:

- parallel technology tasks enabling integrated field validations
- early optimization deliverable: quick commercialization for fuel impact



Tight coupling to GE Transportation business



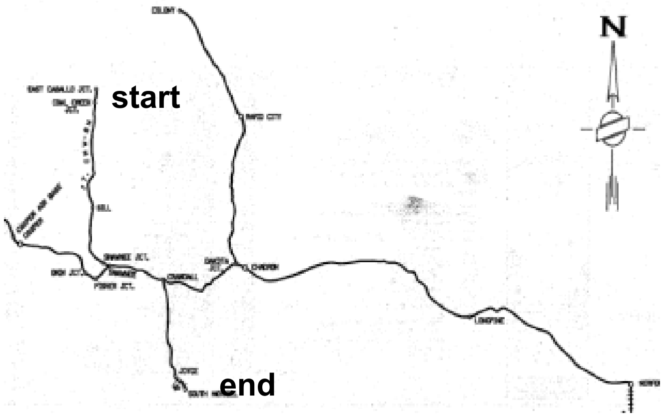
this project has enabled:

- rapid commercialization of locomotive fuel optimization products
- integration of hybrid locomotive as a flagship product in GE's Ecomagination™ corporate initiative

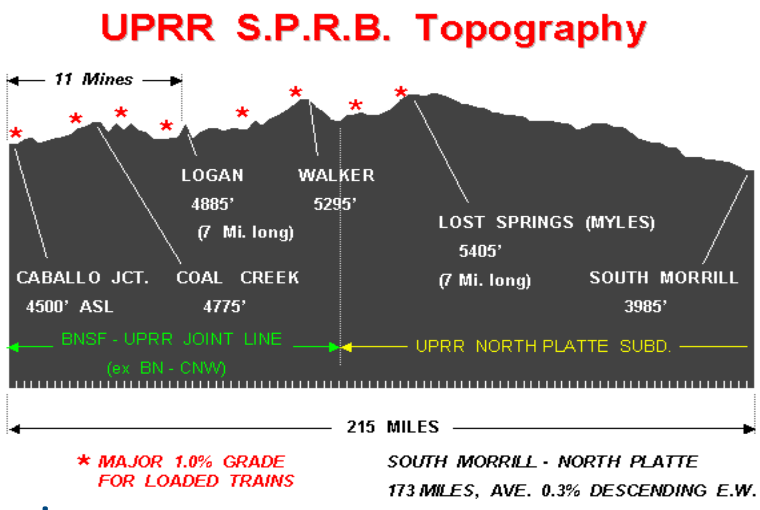
Accomplishment summary: 20% railroad fuel savings = 0.5% national fuel savings

- 1) Accomplishment – selected high-energy-density, temperature-insensitive $Na\text{-}NiCl_2$ energy storage technology
  - Vendor is developing locomotive-worthy system
- 2) Project Deliverable – Demonstration of hybrid locomotive on test track with advanced EMS controls, February 2005
  - Controls ready for integration with advanced energy storage and hybrid degree-of-freedom fuel optimizer on hybrid locomotive prototype
  - **GE announces Hybrid Locomotive in 2004 Annual Report 15% fuel savings**
- 3) Project Deliverable – Track demonstration of locomotive consist fuel optimizer using one degree of freedom controls, February 2004
  - Consist Manager™ **Commercialization**: several installations. **1-2% fuel savings**
- 4) Accomplishment – developed interactive fuel optimizer demo simulator and demonstrated Trip Optimizer™ to railroads
  - New algorithms for Trip Optimizer™ optimal planning designed & implemented in simulation environment: **fuel savings > 4%**

Accomplishment : select hybrid energy storage technology: develop requirements



Analyze multiple missions



Performance Requirement

- 1,500 kW continuous charge/discharge power
- 1,000 kWh useable energy

Mechanical and Environmental

- Ambient temperature specification - 40C to +55C
- Locomotive shock/vibration specification

Life

- 7 year useful life (any combination of storage or service)

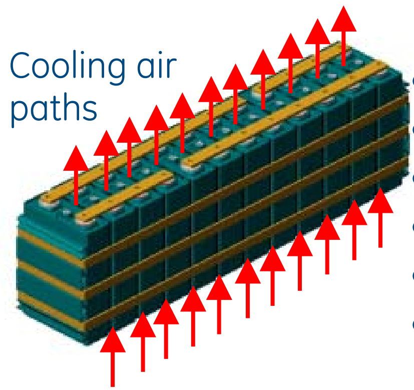
Accomplishment: select hybrid energy storage technology: concept studies by battery vendors

Ni-MH concept (A1)

Sub-pack or module

- Module > pack > rack
- Liquid-cooled modules
- Heater/chiller required
- Module-level monitoring

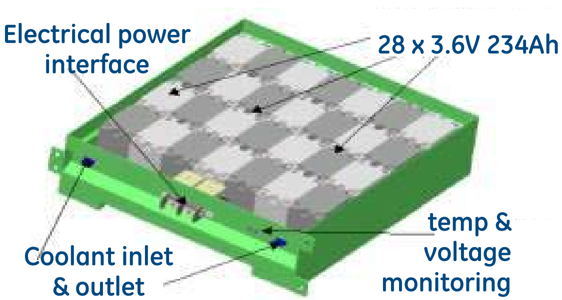
Ni-MH concept (B)



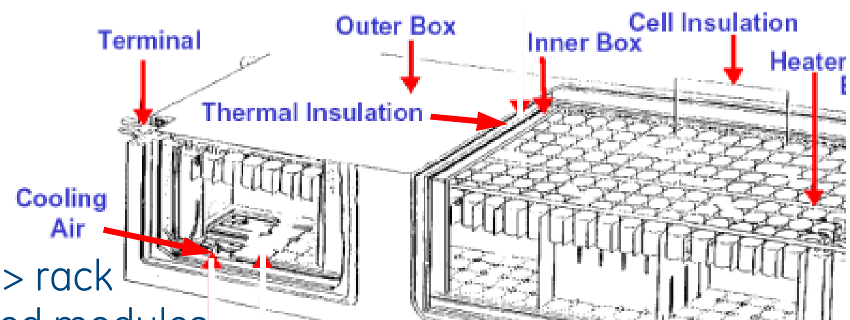
- Module > pack > rack
- Air-cooled modules
- Heater/chiller required
- cell-cell cooling plates
- Complex inlet air manifold
- Module-level monitoring

Li-ion concept (A2)

- Module > pack > rack
- Liquid-cooled modules
- Heater/chiller
- Cell-level monitoring



Na-$NiCl_2$ module & concept (C1)



- Module > rack
- Air-cooled modules
- Forced ambient air fans
- 300C operating temperature
- Environmentally sealed, thermally insulated module
- Module-level monitoring

Accomplishment: select hybrid energy storage technology: Battery tradeoff: $NaNiCl_2$ selected

Hybrid locomotive battery tradeoff

Pass	Marg	Fail
1	0.5	0

No.	Concepts	Score	System					Reliability
			relative weight	relative volume	cooling medium	battery management	cooling impact on size & weight	# Batt. Sets per 20 yr.
		Importance	2	1	3	4	2	2
		USL	3	3	3	5	3	3
		LSL	1	1	1	1	1	2
		Tolerance						
		Units	1,3,9	1,3,9	1,3,9	1/3/9	1/3/9	Batt Sets
1	NiMH; Co. A1	1.00	3	5	5	3	5	2.2
2	Li ion; Co. A2,	0.75	3	5	5	9	3	2.2
3	NiMH; Co. B	0.88	9	9	3	3	9	3.3
4	Na-NiCl2, energy design; Co. C1	1.75	3	3	1	1	1	2.9
5	Na-NiCl2, power design; Co. C2	1.75	3	3	1	1	1	2.9

Accomplishment. Select hybrid energy storage technology: Lab evaluation of advanced energy storage prototype and system

Develop data for GE Transportation hybrid locomotive design

- ✓aging effects (cell level) => control design
- ✓ripple current effects (cell level) => power circuit design
- ✓shock and vibration (module level) => iterate module design

Risk reduction

- ➢Validate functional performance of improved modules (module level)
  - Electrical, thermal & vibration (vendor together with GE Transportation)

accelerated vibe test of COTS $Na\text{-}NiCl_2$ module, prior to finalize loco-specific module detailed design

Conclusion: cells OK, vendor will redesign battery system assembly

Project deliverable Design & test hybrid loco energy management system (EMS) controls, integrate to loco & track test

• Developed & lab tested secondary SOC estimation algorithm (correct long-term drift & data corruption). Challenging, 2 algorithm iterations

•**Track tests** performed on "on-board" hybrid proof-of-principle locomotive, November 2004 – January 2005

•**Successful validation**

- • robust acquisition of battery temperature & electrical data in noisy loco environment
- • estimation of nickel-metal hydride SOC

•**Benefits for Hybrid Locomotive**

- • avoid battery degradation due to out-of-range operation
- • maximize utilization of battery capacity: improved fuel benefits and reduced battery footprint

•**Next steps**

- •Apply capability and algorithms to combined field validation of advanced energy storage and fuel optimization in Task 5

Technology commercialization: Hybrid Locomotive

Energy Storage Technology task identified and developed advanced battery system technology for GE's breakthrough Hybrid Locomotive

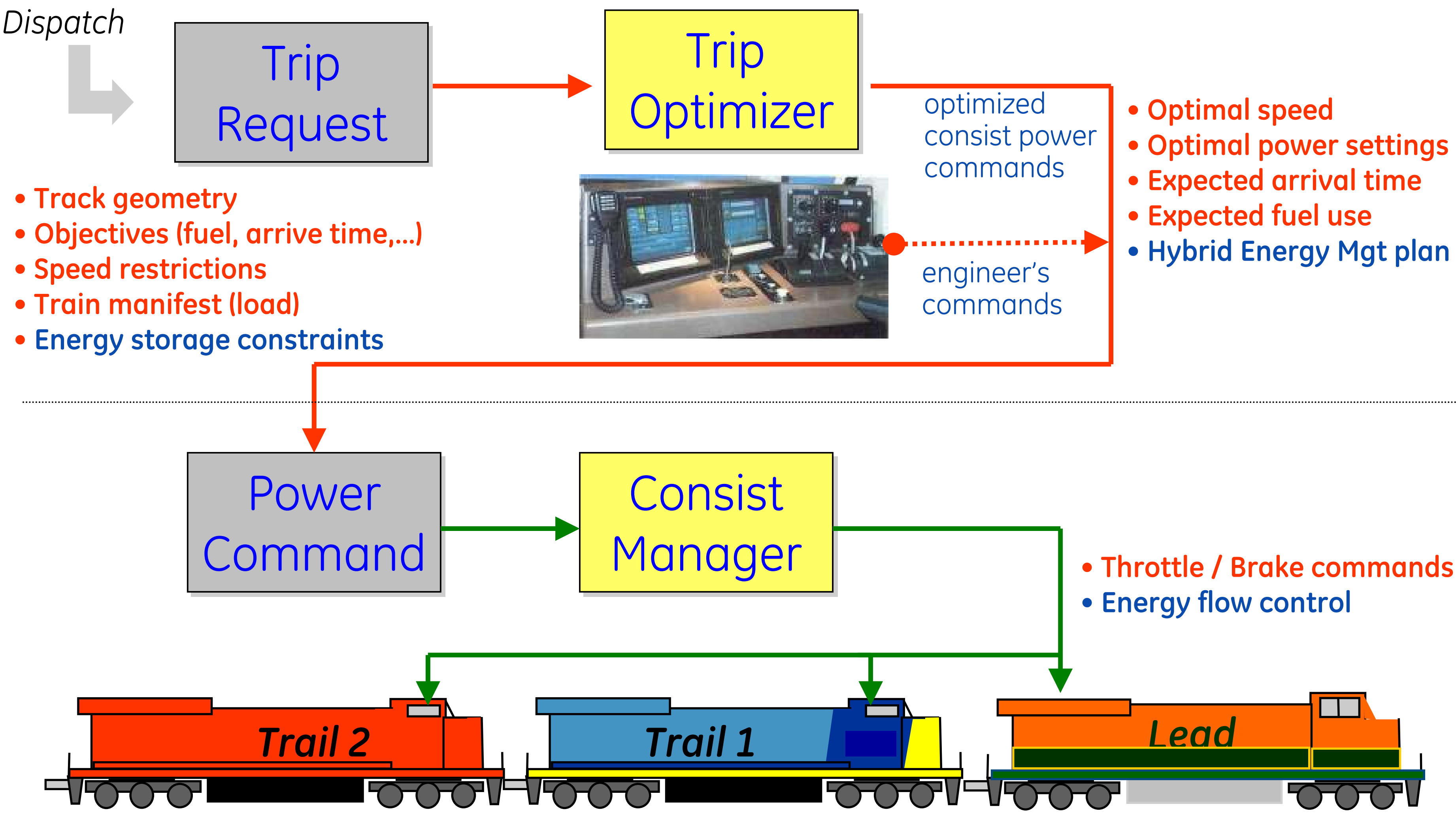
15% fleet-wide fuel savings = 580Mgal p.a.

sodium nickel-chloride system applicable to other vehicles

"... a locomotive that could capture [dynamic braking] energy and store it in batteries for later use could generate a 2,000-horsepower boost and use up to 15% less fuel...and reduce emissions another 10%... GE is working to unleash this potential to drive future performance and growth" - GE 2004 Annual Report, p34

Fuel use optimization concepts

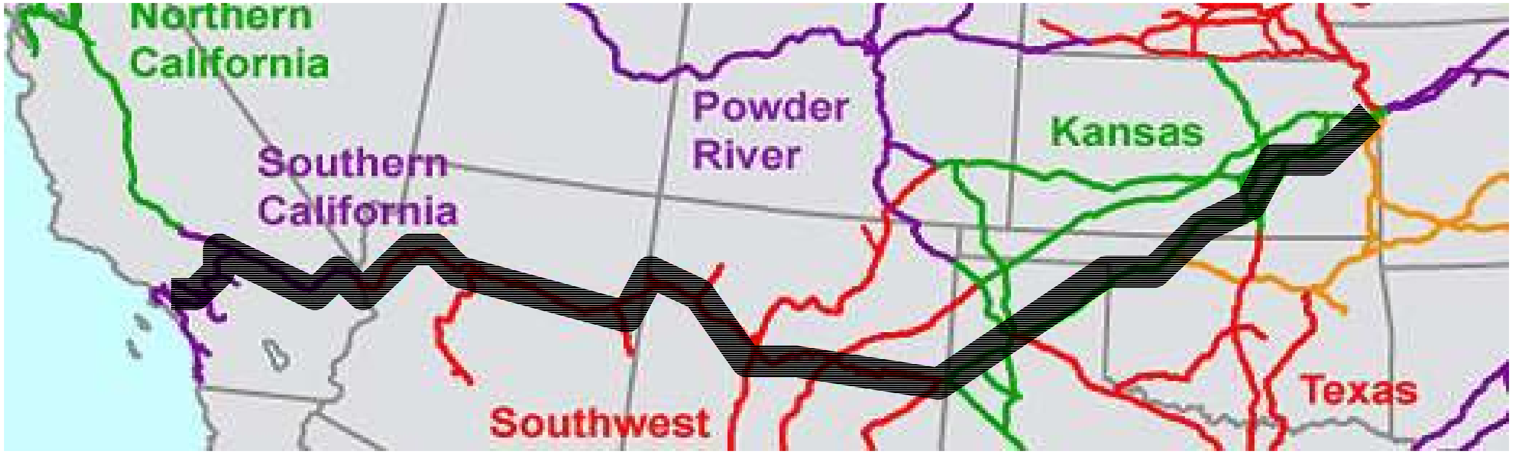
Find speed and throttle to minimize fuel use in a trip



Divide power among consist for best efficiency

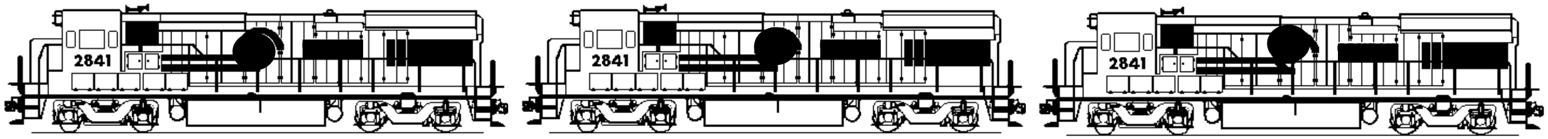
Project deliverable Consist manager™ Class 1 Railroad demonstration

- 3400 Mile cross country revenue service trip, Kansas-City to Los Angeles and back
- Fuel savings > 2% possible
- Average of 1-1.5%



Technology commercialization: Consist manager™

Fuel Optimization Technology task enables GE's Consist Manager™ product introduction



N1 → **Train line control** → **N8** → **Train line control** → **N8**

Optimally assign power between locomotives

…2% fleet-wide savings = 76Mgal p.a.

Further savings through combination with hybrid

Excerpt from GE Transportation brochure:

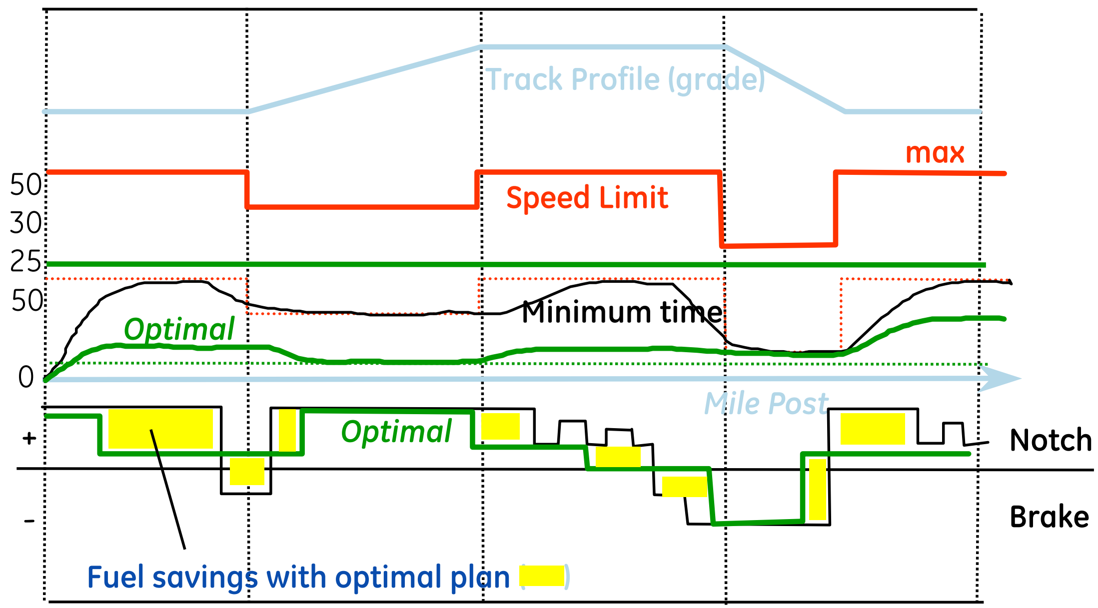
GE offers a comprehensive portfolio of fuel savings solutions

Consist Optimization	Consist Manager[2] – optimizes fuel and horsepower per locomotive within consist	1 to 3% for each locomotive in consist	• Crew comfort and ease of use • Emissions reduction

Accomplishment Trip Optimizer™ demonstration: concept outline

Computes, displays and executes **driving plan** to minimize fuel, subject to constraints

trade fuel vs trip time, exploiting slack time



Requirements

- Minimize fuel consumption, with and without hybrid storage
- Achieve travel time objectives or constraints
- Minimize journey-to-journey fuel usage variability
- Get savings benefit on every locomotive, new & installed base

" … We want to ensure every engineer performs like the best engineer every day, and we are providing incentives to do so…"
Craig Hill, BNSF at GE GRC 3/27/02

Accomplishment : Trip Optimizer™ demonstration: Real-time demo lab shows trip optimizer to railroads

- Plan a trip
  - -pull from library
  - -Build scratch
  - -Zoom/edit
- Drive a trip real-time
  - - opt 1: Manual “advisor”
  - - opt 2: Closed loop
  - - opt 3: Fast fwd/replay
- Re-plan interactively
- Evaluate fuel use / time alternatives

Operating Display

Plan Windows

Graphics CPU

Mouse / Keyboard

PC workstation

PC workstation

Train position/speed

Gauge data

Control Settings

21st Century Locomotive Technology – future work

Next 12 months

- Vendor supplies locomotive-worthy advanced battery modules supplied by vendor
- Validation testing of advanced battery modules
- Supply full-locomotive set of advanced battery modules and install to prototype hybrid locomotive
- Design and bench test fuel optimizer controls with hybrid degree-of-freedom

2007

- Project culmination – field validation of hybrid locomotive with full scale advanced energy storage system and hybrid degree-of-freedom fuel optimizer controls imagination at work