“ENGINES OF CHANGE”
Freight Locomotives & Fuels of the Future

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“ENGINES OF CHANGE”®

Trademark assigned to Union Pacific Railroad Company
by US Patent & Trademark Office, registration #3,400,209 (March 18, 2008),
applied to all ultra-low emitting locomotives in UP fleet
Union Pacific Railroad system

- 8,400 locomotives
- Largest US fleet
- Leader in acquiring Low- and Ultra-Low Emitting locomotive technologies
- $5B+ invested in EPA-certified locos since 2000
Union Pacific & the environment

✔ The “green” transportation solution
  ① Can move one ton 830 miles on one gallon of diesel fuel
  ② >70% of loco. fleet is EPA certified (new or overhauled)
  ③ Industry leader in emissions-reducing technologies

✔ 20% improvement in fuel efficiency since 1994
  ④ measured in gallons/1000 gross ton-miles
-US railroad infrastructure & operations
-Finding & managing technological change
-Background on US locomotives
-Emissions & environment
-Power plants & Fuels (energy sources)
-Electrification
-Summary
US railroad infrastructure & operations
Rail network viewed “corporately”

Rail network “as seen by” locomotives and cars (trains)
Economic & “network” realities

✓ Locomotives are long-term capital assets
  ① 17-20+ year financial life (v Class 8 trucks ~5 years)
  ② Limited production ~1,000/year (v Class 8 trucks 200,000/yr)

✓ N. American RR network is highly interdependent
  ① 5 US Class I, 2 large Canadian & 2 Mexican RRs + regs + S.L.s
  ② 1.4 million cars (67% non-RR owned) & 23,000 locomotives
  ③ Heavy volume of interchange, interoperability (unlike trucking)
  ④ International network (~7% carloads to/from Canada/Mexico)
  ⑤ Common gauge, appliances, refueling infrastructure, etc.

✓ A highly efficient & productive network
  ① US RR 42% GTMs (9% diesel fuel) v trucks 30% GTMs (52% fuel)
  ② EU RR 9% GTMS v trucks 52%
Future locos. & fuels: Which? When? Why?

Crossing the Kate Shelly High Bridge, Boone, IA, 1982
Finding & managing technological change
"The past is a good predictor of the future only when conditions in the future resemble conditions in the past. And what works for a firm in one context might not work for another firm in a different context."


Union Pacific Dash-9 locomotive at North Little Rock Shop, 1996 ... Cab from SP Dash-9 grafted onto carbody of CNW Dash-9
Innovation & disruptive technologies

“What use could this company make of an electrical toy?”

William Orton, president of Western Union in declining to purchase the Bell telephone patents in 1870s

“Disruptive products or services initially are inferior to existing offerings in the attribute that matters most in the mainstream.”

Christensen, Seeing What’s Next
Rates & routes of technological change

- **Revolutionary:** “moon shot”
  - High capex; high risk long-term errors; “better be right”

- **Blended:** “multiple entrants”
  - Managed capex; moderate risk; “add-on” solutions

- **Historic:** “evolutionary”
  - Low initial capex; low risk ST failure, high risk LT avoidance

Radical difference in capex strategies, rates of change and risks
Steele’s 9 misconceptions re technological change

**MISCONCEPTIONS**
- Always go for “best possible”.
- Technology is picked rationally.
- Change always occurs as planned.
- Success follows initial application.
- Technology has intrinsic value.
- Radical change will always succeed.
- Success is guaranteed by $s$.
- Enhancements guarantee progress.
- New technologies can be grafted onto existing businesses and operations.

**REALITIES**
- Use only what is “good enough”.
- Past practice limits future changes.
- Plan for things going wrong (Murphy).
- Future unknowns are risky.
- The customer (user) determines value.
- New is not necessarily better.
- Existing infrastructure often weakest link.
- Critical: Standards, constraints, routine.
- A new product and supporting business system must be jointly produced.

Background on US locomotives
Contemporary line-haul diesel locomotive

73+’ long
~415,000# (near max.)
5,000 gal. fuel

Fixed height
Fixed width
Limited length
**Energy density: Why diesel is #1 transport fuel**

![Bar chart comparing energy density of various fuels](chart.png)

- Diesel Fuel: 100.0%
- F-T Diesel: 93.6%
- Biorenewable Diesel: 89.8%
- Gasoline: 87.2%
- Propane: 64.6%
- LNG: 60.0%
- Ethanol: 56.2%
- Methanol: 46.1%
- Liquid H₂ (3,626 psi): 25.5%
- Compressed Hydrogen (3,520 psi): 25.1%
- NiMH Battery: 6.4%
- Other: 1.3%

Source: “Engines That Will Power the Future”, Dr. James Eberhardt, DoE, 2001
N. American locomotive technology, 1972-2008
How have US locomotives changed?

✦ Deregulation of the US RR industry, October 1980

① Restructuring, many yards closed, switcher production ceased

✦ Resurgence of the industry, growth (esp. int. & coal)

✦ Introduction of AC traction, 1992

✦ Regulation of locomotive emissions, 2000

✦ Introduction of ULELs (Hybrids and Gensets)
Multi-engine Genset switchers

✔ Major reduction in emissions using diesel fuel
  ① 80-90% reduction in NOx & PM emissions w/o aftertreatment
  ② 25% reduction in fuel & CO₂

✔ Innovative application of existing technology
  ① Off-road (truck derivative) diesel engines
  ② No change in operating environment or infrastructure
  ③ Does change maintenance, parts, training, etc.

Winner of the 2006 “Engineering Excellence in Transportation” (E²T) award for 2006 in the mobility-and-engine-emissions category from the Society of Automotive Engineers (SAE) in Washington DC

Winner of a 2008 “Blue Skies 2008” merit award from Calstart-Westart in Pasadena

Other 2008 merit award winners were Zipcar and Global Electric Motorcars
Hybrids & Gensets compared

뇌 Diesel-battery hybrids

- No regenerative braking
- “Road hybrid”=regen. brakes
- Typ. one 265 HP engine
- 25 tons of batteries (=50 gals.)
- Light duty, limited applicability
- VR lead-acid batteries, complexity

뇌 Gensets

- 2-3-4 engines (modular)
- Emissions/fuel = Hybrid
**Diesel-electric propulsion**

- Diesel engine generates power for traction motors
  - Electric locomotives
  - Diesel-electric locomotives (N. American standard since 1920s)
  - Most European diesel locos have had hydraulic transmissions
  - Europe now appears shifting to diesel-electric locomotives
  - Pre-hybrid automobiles also use hydraulic transmissions

- Benefits of electric (motor-driven) transmissions
  - Best transmission efficiency
  - Simplicity, ruggedness
  - Also key to tomorrow’s efficiency & enviro. improvements
  - Adaptability to hybridization
World’s first electric-motored locomotive

Le Fusee Electrique ("The Electric Rocket")

Built in France in 1893 by J. J. Heilman as a mobile “self-contained powerhouse on wheels”.

A steam engine turned a 485 HP Edison dynamo which powered 8 DC traction motors.

Built to demonstrate electric traction without the expense of electrification.
Electric motors facilitate hybridization

“Hybrid” = power plant + batteries for traction

Hybridization can improve locomotive efficiency
- Simple hybrid locomotives exist today (“Green Goats”)
- One regenerative road-hybrid under development
- Regenerative braking = re-use of some braking energy

Will hybridization be retrofitted to existing locos?
- Key issue #1 is size/weight of energy storage technology
- Key issue #2 is economics
- Difficult engineering challenge even for new locomotives

Q: When did Chicago first see a hybrid locomotive?
- Hint: It operated at Proviso Yard
UP demonstrated the original “Green Goat” diesel-battery hybrid switcher at Proviso Yard on March 12, 2003.

But, this was NOT the first hybrid locomotive in the Chicago area!

Chicagoland’s first hybrid locomotive experience was on November 18, 1926 when a gasoline-battery hybrid switcher was tested on the Proviso hump.

Battery performance was the limiting factor.
Emissions & environment
Rail emissions progress

Fuel efficiency improvements
- **UP**: 20% reduction in (gallons/1000 GTMs) since 1994
- Less fuel used > lower emissions per unit of work performed

EPA locomotive emissions regulations
- 3 Tiers since 2000, 4th and 5th pending
- Major acquisitions of Tier 0-1-2 locomotives (>5B worth)
- Tier 4 by 2015-17: 80%/90+% reductions in NOx and PM

New locomotive technologies
- UP funded 1st Genset (prototype unit) in 2005, now has 164
- Also has 21 diesel-battery Hybrid switchers
- Switcher “DPF” and SD60M “oxicat” test units
- Caterpillar-Progress Rail repowered SD40-2 test units
Engine emissions (basics)

Key emissions from internal combustion engines

- Gasoline or Diesel engines
- EPA has regulated*

*NOx

- Oxides of nitrogen (NO, N₂O, NO₂)
- Precursor to photochemical smog and ozone

*PM

- Particulate matter

CO₂

- Carbon dioxide (most common “greenhouse gas”)
- *Other GHGs include methane (=23x GHG impact of CO₂) from engines burning natural gas*
Power plants & fuels
Contemporary line-haul diesel locomotive

- 73+’ long
- ~415,000#
- 5,000 gal. fuel
- Fixed height
- Fixed width
- Limited length
- Near-max. weight
Relationship between engines & fuels

Engine types & fuels must be matched

- Diesel engines (compression cycle) require fuel oil (diesel fuel)
- Gasoline/ethanol engines (spark) require more-volatile fuels
- Diesel convertibility to NG but usually with HP penalty
- Large loco-size engines using NG require high-purity methane
- UP invested $15M in mid-'90s investigating high-HP NG tech.

Engine performance & emissions are interdependent

- Combustion chemistry, NOx v PM v fuel consumption (CO₂)
- Diesel aftertreatment next

Engine technology is market-driven

- Automobiles; trucks; off-road applications; locomotives; ships.
Long-term projection re engines & fuels

A Long Term Projection

- Fuel Cell Technology
- Hydrogen Production & Storage Technology
- Advanced Engine & Fuels Technologies
- Power Electronics & Energy Storage

- Gasoline/Diesel ICE Conventional
- Gasoline/Diesel ICE Hybrid
- Transitional Liquid Fuels Advanced ICE Hybrid
- H₂ Fuel Advanced ICE Hybrid
- H₂ Fuel Fuel Cell Hybrid

Today

From Ed Wall DEER 2004

2020 and beyond

Magdi Khair October 2006
US petroleum use

Since the 1973 Oil Embargo All of the Increase in U.S. Surface Transportation Fuel Consumption has been due to Heavy Vehicles

Rail produces 42% of US gross ton-miles using 9% of US diesel fuel.

Trucks produces 30% of gross ton-miles using 52% of US diesel fuel.

Transportation Energy Data Book: Edition 20, DOE/ORNL-6959, October 2000
Alternative fuels: What criteria?

✔ Technical realities

- How do various fuels impact emissions? Fuel efficiency?
- There is no “silver bullet” fuel!

✔ Infrastructure + standards + technological support

- Are engines and fuels compatible? Infrastructure in place?
There are no “silver bullet” fuels

✓ No single fuel satisfies all requirements or needs
  ① Emissions of NOx, PM and CO₂
  ② Example: Biodiesel fuel usually reduces CO₂ and PM, but NOx can increase

✓ Confusion and mis-information
  ① “... reduces emissions ...” without stating which emissions

✓ Need for measurement standards
  ① “Well to Wheels” measurements are all-inclusive (for fuel efficiency and for emissions)
  ② But, too often, conclusions are drawn based on incomplete “Tank to Wheels” measurements
  ③ Example: Commercial hydrogen is usually produced by reforming natural gas, a process which releases emissions
Possible alternative RR fuels

أشياء يمكن اعتبارها كبدائل محتملة

- **Biodiesel**
  - لا يعتبر البديل الجديد للمواد الصلبة
  - مشاكل الإmissions والضمان (زيادة NOx)
  - خيض أقل الطاقة 导致了更高的燃料消耗
  - مشاكل التخزين وال_infrastructure

- **Dimethyl Ether**
  - DME هو "نوع دبلوماسي" للوقود
  - سيحتاج إلى تقنية حقن الوقود
  - ليس مبردًا (LNG) ولكن له درجة التدفق المنخفض (20°F)
  - الإنتاج غير محدود

- **Other synfuels**
Hybrids & Gensets compared

✓ Diesel-battery hybrids

① No regenerative braking
② One 265 HP engine
③ 25 tons of batteries (=50 gals.)
④ Light duty, limited applicability
⑤ VR lead-acid batteries, complexity

✓ Gensets

① 2-3-4 engines (modular)
② Emissions/fuel = Hybrid
Harnessing energy from gravity & motion

Potential energy is the energy of “position” (usually height).

Kinetic energy is the energy of “motion”.

Regenerative braking

Capturing dynamic braking

- Dynamic braking has existed since 1940 *
- Convert kinetic (speed) and potential energy (elevation) to heat
- Downhill running and/or stops
- “Regeneration” avoids “waste to heat” for re-use
- Must have energy storage (batteries or flywheels)
- Key challenge: CARRYING THE EXTRA EQUIPMENT
In propulsion (motoring):
* Fuel (chemical energy)
* Engine power
* Electrical power
* Motor torque moves train

In dynamic braking:
* Motor torque from motion and/or gravity moves train
* Motors produce electrical power (reverse torque)
* Electrical power converted to heat

With regenerative braking:
* Power is stored for reuse by traction motors

Waste heat to atmosphere

Onboard energy storage
Railroad electrification
Key barriers to US rail electrification

- Rail electrification technology exists, subject to ...
- Massive capex investment
  - Example from Caltrain commuter proposal
  - 50 route miles, San Francisco-San Jose
  - $608 million (2008 revision)
- “End of wire” discontinuity for operations
  - Power change points, delays and service interruptions
- “Dual mode” locomotive: not an easy “fix”
- Where will the power come from?
- Impact on emissions
Electrification capex: #1 issue

Driven by infrastructure

- Substations, switch gear, distribution lines, overhead catenary, EMI mitigation for wayside communications, increasing overhead clearances, etc.

“... (need to) eliminate the tremendous cost of constructing overhead power supply lines, associated electric infrastructure and needed (railroad) roadway and bridge improvements.”

South Coast AQMD report on railroad electrification (1992)
At “wire’s end”: ?

Electric locos are “tethered” to catenary

1. Necessitates “power change” at end-of-wire
2. Electric to Diesel-electric and vice versa
3. Risk of “balkanizing” (breaking up) transcontinental rail network
4. Examine European performance re “rail borders”

- EU truck (now 45%)
- EU rail (now 9%)

European Union

% of gross ton-miles handled by different modes of transport

United States

US rail (now 42%)
US truck (now 30%)

Data exclude natural gas pipelines. Trucks exclude household, service, retail, and certain other shipments. Source: U.S. Bureau of Transportation Statistics.
“Dual mode” freight locomotives

- Start with a 4400 HP diesel-electric locomotive ...

- and add hardware for “straight” electric operation?
  - 50kV step-down transformer (6’x8’x10’, ~20,000#)
  - Switch gear, etc.
European rail electrification

- 49:51 diesel:electric train-miles
- 2 AC & 3 DC voltages
- 5 dimensional clearances (N. America 1)
- 2 track gauges (N. America 1)
- Cross-border operations limited by 11 different pantograph requirements on electric locomotives, or ...
- Complex multinational locos. with 2-3-4 pantographs and multi-voltage systems
“Electrifying” the nation

Grid & generating capacity is limited

One 4400 HP locomotive is the electrical equivalent of 2,200+ plug-in hybrid vehicles (“PHEV”) being recharged

“... the existing generation, transmission and distribution system in the US, if optimally utilized at all hours of the day, could provide enough power for plug-in vehicles to replace up to 73% of the nation’s cars, vans and SUVs (“light duty motor vehicle fleet”).

“Proper or optimal use of the power grid, however, may not be as simple as it sounds ... many of these (primary and secondary) circuits (do not have) any spare capacity ...”

Est. PHEV power load on typ. southern Cal. home

Charging load for one PHEV assuming plugged-in from 6PM to midnight
**Severity of US rail electric load**

“The railway traction load is ... one of the worst kinds of (electrical) load ...”

“Railway Electrification Systems and Configurations”, Bharat Bhargava, SoCal Edison, published in 1999 by the Institute of Electrical and Electronics Engineers (IEEE)

**RR electrification is a heavy “grid” load**

- 24 x 7 operations, single-phase feed
- US freight load would > all other rail electrification loads

<table>
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<tr>
<th>Rail operation</th>
<th>Power demand/train</th>
<th>Equiv. HP</th>
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<tbody>
<tr>
<td>Light rail</td>
<td>Up to-1 megawatts</td>
<td>&lt; 1400 HP</td>
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<tr>
<td>Heavy commuter</td>
<td>3-4 megawatts</td>
<td>4000- 5400 HP</td>
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<tr>
<td>High-speed intercity</td>
<td>4-6 megawatts</td>
<td>5400- 8000 HP</td>
</tr>
<tr>
<td>High-speed trains (TGV)</td>
<td>8-10 megawatts</td>
<td>10700-13400 HP</td>
</tr>
<tr>
<td>European freight</td>
<td>6-10 megawatts</td>
<td>8000-13400 HP</td>
</tr>
<tr>
<td>US freight trains</td>
<td>6-24 megawatts</td>
<td>8000-32000 HP</td>
</tr>
</tbody>
</table>
Passenger electrification inadequate for freight

25kV for passenger, likely 50kV for freight

- Power = volts x amps ... limits on current drawn thru catenary
- Higher voltage to handle greater power draw, minimize substations ... but also increases overhead clearance demands
- High-speed passenger locos unsuitable for most heavy-tonnage freight operations
US rail electrification studies
CO₂ emissions: electric RR v diesel

CO₂ intensity depends on energy source!

- RR electrifications can be powered from various energy sources
- Coal, oil or natural gas steam plants; nuclear; hydroelectric?
- Steam plant design (simple or combined cycle)?
- Grid distance plant-to-RR
- Wind & solar typ. are too variable for rail load

Example shown is for electric-powered train (coal thermal) versus diesel propelled 10+% greater CO₂-equiv. from electrification

Table 19 – CO₂-e Emission from Traction Types when hauling a 2600 tonne train at 45 km/h over 100 km, taken from report by Brian McCannor

U.S. Primary Energy Consumption by Source and Sector, 2007
(Quadrillion Btu)

- **Petroleum**: 39.8%
  - Percent of Source: 70%
  - Percent of Sector: 96%
- **Natural Gas**: 23.6%
  - Percent of Source: 24%
- **Coal**: 22.8%
  - Percent of Source: 8%
- **Renewable Energy**: 6.8%
  - Percent of Source: 57%
- **Nuclear Electric Power**: 8.4%
  - Percent of Source: 100%
  - Percent of Sector: 21%

- **Transportation**: 29.0%
- **Industrial**: 21.4%
- **Residential and Commercial**: 10.6%
- **Electric Power**: 40.6%

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1. Does not include 0.6 quadrillion Btu of fuel ethanol, which is included in “Renewable Energy.”
2. Excludes supplemental gaseous fuels.
3. Includes less than 0.1 quadrillion Btu of coal coke net imports.
4. Conventional hydroelectric power, geothermal, solar, PV, wind, and biomass.
5. Includes industrial combined-heat-and-power (CHP) and industrial electricity-only plants.
6. Includes commercial combined-heat-and-power (CHP) and commercial electricity-only plants.
7. Electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public.

Note: Sum of components may not equal 100 percent due to independent rounding.
Sources: Energy Information Administration, Annual Energy Review 2007, Tables 1.3, 2.1b-2.1f and 10.3.
An energy conversion exercise

Solar power

- Bright sunlight = 1 kW (1.34HP) per sq. yard
- Ave. solar cell efficiency = 15% (“best” 31+%)
- Assumes average daylight conditions
- Nominal solar cell power = 0.2 HP/sq. yard
- 4400 HP is nominally = 22,000 3’x3’ solar cells
- 22,000 x 9 ft.² = 198,000 sq. ft. (445’x445’ sq.)
- A 4400 HP locomotive (73’ long) shown below
- The superimposed box is a 445’ x 445’ area
Summary
## PROPULSION TECHNOLOGIES

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<th>Technology</th>
<th>Now</th>
<th>5 years</th>
<th>10 years</th>
<th>15 years</th>
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<td>Diesel cycle enhancements</td>
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<td>Gas turbines (base load)</td>
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<td>Fuel cells</td>
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<td>Electrification</td>
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## OPTIONS FOR FUELS & CONSTRAINTS

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<td>Diesel fuel</td>
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<td>Biodiesel</td>
<td>volume, engine suitability, NOx “bump” &amp; infrastructure</td>
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<tr>
<td>Dimethyl Ether (DME)</td>
<td>volume, infrastructure (vaporizes @ 20°F)</td>
</tr>
<tr>
<td>Ethanol (cellulosic)</td>
<td>engine technology, infrastructure; niche applications</td>
</tr>
<tr>
<td>Natural gas (LNG)</td>
<td>large-bore engine progress, infrastructure</td>
</tr>
<tr>
<td>H₂</td>
<td>infrastructure (need H₂ pipelines), WTW CO₂ solution(s)</td>
</tr>
<tr>
<td>Electricity from grid</td>
<td>electrification capex, gen. &amp; distr. (supply+demand) issues</td>
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</table>
Questions & comments