William W. Hay Railroad Engineering Seminar

Freight Railroad Energy: Alternatives & Challenges

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University of Illinois at Urbana-Champaign
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Freight Railroad Energy: Alternatives & Challenges
Agenda

- Energy & work (U.S. total & freight RRs as % of U.S. total)
- Managing technological change (importance v difficulties)
- North American freight RRs (defining characteristics)
- Energy density of diesel fuel & alternatives (Btu's per gallon)
  - Biodiesel, Fischer-Tropsch syn fuel & DME
  - Liquefied natural gas, LNG
  - Battery & flywheel energy storage
  - Electrification of U.S. freight RRs
- Electrification of European RRs (lessons learned)
  - Dual-mode locomotives ("electro-diesels")
  - Unconventional alternatives to steel wheel-on-steel rail
- Efficiency improvements (example: aerodynamics)
Energy and work

• Energy = capacity for doing work
• Work = application of force to a body over a distance
  – Energy enables work
• Where does "railroad" energy come from?
  – Fuels (chemical or electrical)
  – Management of potential energy (elevation) & kinetic energy (motion)
• What changes will we likely see? Why (or why not)?
Energy 101: where it comes from, what it does

Frt. RRs consume ~3.5B US gal. diesel fuel/year (0.5% of US energy, 1.3% of US petroleum)

Trucks 4.8 Quads/year = 4.8% total US energy & produces ~29% of total ton-miles *

Frt. RR 0.5 Quads/year = 0.5% total US energy & produces ~40% of total ton-miles *

57.5% of all US energy consumed is unusable due to inefficiencies

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1 Quad equals 7.2008 Billion US gallons = 27.258 Billion liters of diesel fuel equivalent

* Ton-mile statistics from US DOT Bureau of Transportation Statistics

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Michael Iden, P.E., Union Pacific Railroad

William W. Hay Railroad Engineering Seminar, University of Illinois Urbana-Champaign, February 15, 2013
Transport sector energy efficiency

• Lowest overall eff. of the 5 primary energy uses (25%)
• Largest source of energy inefficiencies: automobiles
  – Typ. automobile (gasoline) puts 14-26% of fuel energy to wheels
    "... the potential to improve (automotive) fuel efficiency with advanced technologies is enormous."
    http://www.fueleconomy.gov/feg/atv.shtml

• Best performer: locomotives
  – Typ. locomotive (diesel-electric) puts ~33% of fuel energy to wheels
  Union Pacific's fuel efficiency (gallons per 1000 gross ton-miles) has improved 19% since 2000.
  http://www.uprr.com/she/emg/operations.shtml

• Loco. diesel engines ~40% thermal eff. (thermo law limited)
Technological change (in general)

"It takes several lifetimes to put a new energy system into place, and wishful thinking can't speed things along."

Vaclac Smil, IEEE Spectrum magazine, July 2012 re alternative energy

- Invention (an idea)
- Innovation (engineering a working thing)
- Diffusion & commercialization (putting it to work)

- Learning curves, human behavior, variabilities
- Technological intervention
  - Disruptive technologies; the "better mouse trap"; inventiveness
- Technological change can be ... very difficult
Steele’s 9 misconceptions about tech. change

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<thead>
<tr>
<th>MISCONCEPTIONS</th>
<th>REALITIES</th>
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<tbody>
<tr>
<td>◦ Always go for “best possible”</td>
<td>◦ Use only what is “good enough”</td>
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<td>◦ Technology is picked rationally</td>
<td>◦ Past practice limits future changes</td>
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<td>◦ Change always occurs as planned</td>
<td>◦ Plan for things to go wrong ( … Murphy)</td>
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<td>◦ Success follows initial application</td>
<td>◦ Future unknowns are risky</td>
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<td>◦ Technology has intrinsic value</td>
<td>◦ Customer (user) determines value</td>
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<td>◦ Radical change will always succeed</td>
<td>◦ New is not necessarily better</td>
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<td>◦ Success is guaranteed by investment</td>
<td>◦ Infrastructure is often the weakest link</td>
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<td>◦ Enhancements guarantee progress</td>
<td>◦ Standards, constraints, routine are critical</td>
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<td>◦ New tech. on exist'g business &amp; ops.</td>
<td>◦ New tech. requires new support system</td>
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N. American frt. RR: technological change

- Master Car Builders Association (MCB) formed in 1867
  - Initial standardization of US railroad rolling stock & hardware
- Automatic air brakes (1872 ... mandated by regulation 1893)
- Automatic couplers (1873 ... mandated by regulation 1893)
- Electrification (Balt. 1895, PRR pre-WWII, not sustained)
- Steam-to-diesel propulsion (1920s ... WWII~1954)
- Assoc. of American Railroads (AAR, 1934) eqpmt. & op'g. standards
- Gas turbine locos. (1940s~1969, not sustained)
- Roller bearing journals (1930s ... mandated for interchange '91-'94)
- E-controlled pneu. brakes, ECP (1990s ... partial adoption)
- PTC (1980s/90s ... 2016 mandate)
Factors affecting tech. change on frt. RR

- **Interchange/interoperability requirements**
  - To support the continental freight system
  - 25,000 locomotives on North America
- **Infrastructure constraints**
  - Axle load & clearance limits, shops, servicing facilities, etc
- **Ownership structure (especially of frt. cars)**
  - 66% of 1.4M N. American frt. cars are owned by non-RR entities
- **Industry standardization (AAR & AREMA)**
- **Regulatory reqmts & limitations (FRA, EPA, OSHA, etc)**
- **Capex requirements**
- **Economic conditions**
- **Etc**

"America's system of rail freight is the world's best."

The Economist magazine, July 22, 2010

Staggers Act deregulating the US railroad industry became law on October 14, 1980
N. American freight rail: **Class I rail systems**

- CN
- UP
- KCS (incl. KCS de Mexico, ex-TFM)
- BNSF
- CSX
- CP
- Ferromex (not shown)
- NS
Transcontinental "run-thru" trains

Stockton CA - Albany NY

Auto. train CN-UP
Oshawa-Denver
Oshawa~Toronto

Los Angeles

Memphis

Intermodal train
UP-NS
LA-Atlanta

Perishables train
UP-CSXT

Denver
From "Fusee Electrique" to Evo's & ACe's

"Electric Rocket" by J. J. Heilmann (France, 1893)
Steam boiler + generator + (8) DC motors (2 trucks)
100 tons weight, nominal 590 HP

Contemporary diesel-electric AC-DC-AC locomotive
Diesel engine + alternator + inverters + (6) AC motors
208~217 tons weight, 4300-4400 HP
Energy density of diesel & alternative fuels

Diesel v biodiesel fuels

• ~10% less energy density than petro. diesel
• BioD does not reduce all emissions (NOx usually increases)
• Fuel storage/use issues (cloud point, hydroscopic, etc)
• New fuel injection techs. (common rail injection) v particle size
• A "perfect storm" situation re regulatory divergence:
  – Engine/emissions regs. forcing new engine technologies
  – Fuels regs. forcing major shifts in fuels
• EPA Tier 4 emis. reg. (new locos. 2015+) requires aftertreatment
  – Greatest technological change in locos. since dieselization
• Loco. engine technology vastly different than truck
  – Loco. market ~1,200 engines/year max.
  – Class 8 truck market >100,000 engines/year
Other liquid fuels: *F-T diesel & DME*

- **Ideal goal:** min. reduction in energy density (operating range)
  - See Eberhardt's chart from 2001
- **Synthetic diesel ("F-T")**
  - Coal to liquid (CTL) or gas to liquid (GTL) Fischer-Tropsch fuel
  - No infrastructure changes
  - F-T has ~7% less energy density than petro. diesel
  - Lower vehicle emissions but likely higher at source
- **Dimethyl ether (methoxymethane)**
  - Evaporates at -11F (cannot use conventional vented fuel tanks)
  - (Coal, gas or biomass) to methanol to DME
- **What about Liquefied natural gas (LNG)? ...**
Liquefied natural gas (LNG)

- Not a direct substitute for diesel fuel
  - Cryogenic fuel (-260F), 1.75 gal. LNG = 1 gal. diesel fuel (Btu basis)
  - Onboard storage impractical; fuel tenders to maintain operating range
- Engines must be dual-fuel (diesel pilot + gas predominant)
- Will be a complex technological change (*"5 challenges")
  - Increasing availability of natural gas in the U.S.
  - Liquefaction plants
  - Locos. & engines that can use dual-fuel (gas+diesel pilot)
  - LNG tenders & refueling infrastructure
  - Changes to train ops., loco. maintenance to facilitate
- Are the economics of LNG favorable???
  - If "yes", LNG may substitute for some % of RR diesel fuel

* See ASME paper RTD2012-9409 "Liquefied Natural Gas as a Freight Railroad Fuel: Perspective from a Western U.S. Railroad", Omaha, NE, October 16, 2012
Dual-fuel (LNG+diesel) loco. research

• Not a new effort (8th analysis or attempt since 1930s)
  – See: "Evaluation of NG-Fueled Locomotives" (2007)

• Numerous dual-fuel programs underway
  – Dual fuel locos. & engine technologies
    • Various injection pressures (high v low pressure)
    – AAR Natural Gas Fuel Tender Technical Advisory Group (TAG)
      is developing performance standards for LNG fuel tenders
      • Car design, connections, safety, maintainability, etc
  • Interoperability will require performance standards
    – Non-interoperability poses a risk to interchange operations
CN dual-fuel test consist

CN Railway at Edmonton, Alberta, Canada, November 27, 2012
Battery (energy storage) locomotives

- **Not new technology!**
  - Leo Daft's 3rd rail "Ampere" converted to batteries in 1885
  - (2) battery locos. on North Shore Line (IL) 1927-1963
  - (21) battery hybrid locos. on UP 2006+ (7 still operating)

- **Greatest issues: technology & economics**
  - Safety
  - Capacity, discharge cycles & life
  - Affordability versus capability

- **Great concept (especially for braking energy capture)**
  - Store dynamic braking energy instead of dissipating as heat
  - However, economics challenged by multiple energy conversion inefficiencies (motors in DB > storage > back to motors)
Daft's "Ampere", 1885
GE battery switcher, 1922
Twin Branch RR (IN) battery loco, 1930
North Shore Line #455 (IL), 1957

http://www.monon.monon.org/rr/twinbranch.html
http://donsdepot.donrossgroup.net/dr0200/cns456b.jpg

GE-Exide Battery locomotive in Cleveland enroute C&NW Proviso Yard, 1928
Photo: C&NW Historical Society

Green Goat switcher, 2010
Flywheel (energy storage) locomotives

• "Mechanical battery"
  – Capture and re-use dynamic braking energy
  – Energy in ("spin up") & energy out ("spin down")

• Researched in the 1990s
  – FRA 5000 HP Acela power car w/ gas turbine (+flywheel proposed)
  – UP project to build flywheel energy storage "slugs"

• Technology and economics
  – Containment of high-speed rotors
  – Rotor bearings & high-vacuum housings
  – Cost

• Ultimate "race" may be Batteries v Flywheels
Electrification

- **Electric locomotives under overhead catenary**
  - Typ. 15kV, 25kV or 50kV AC for contemporary operations
  - Centralized emissions v mobile-source emissions

- **More efficient than diesel-electric? (unclear)**
  - Depends on electricity source (hydro, nuclear, thermal, etc)
  - Inefficiencies & losses in generation, transmission & switching
  - Typ. ~33% overall efficiency Diesel-Electric versus Electrified!

- **Greatest hurdles: infrastructure, capex & power**
  - Massive investment in & construction of overhead system
  - Phased construction, lagging conversion diesel > electric
  - Adequacy of power & grid ability to support the load

- **Risk of train delays at power change points (ex: electric>diesel)**
Overhead wires: *life line for electric locos.*
EU RR electrification: *the frequent baseline*

- >50% of train ops. in Europe are electric powered
- Most EU rail systems were (many are) govt. built & funded
- Most EU systems focus *(exceptionally well)* on passengers
  - Freight takes a weak 2nd place
  - Example: 60 MPH German iron ore trains dodging psgr. trains
  - Average EU freight train is 6000 HP & 1,000 tons (coupler limitations)
  - Average UP freight train is 9000 HP & 8,000 tons (max. 21,000 tons)
- **US freight and European railroads differ greatly**
  - Typ. 2-track mainline in Germany: 200-300 TPD (mostly psgr.)
  - UP 3-track mainline in Nebraska: 120-150 TPD (all freight)
- **EU locomotives: country-specific designs & approvals**
  - *Most locos. cannot cross borders due to incompatibilities*
Why do EU RRs lag US in freight share?

• Harvard JFK School paper in 2005
• Top-4 policies needed to increase EU RR frt. share
  – #1: improved interoperability (!)
  – #2: balancing freight & passenger services
  – #3: enhancing RR infrastructure
  – #4: promoting competition for RR frt.
Frustration on the Orient Express

- Orient Express: Calais-Prague, 2000 miles, across 6 countries

"Bye bye" (as the Austrian locomotive is removed from the train)

"That's gone, and an Italian locomotive will come all the way ..."

"... and join THAT because THAT is the Orient Express without a locomotive!"

Mr. Suchet watches (and waits) at Brenner Pass for his 6th (and final) locomotive:

(3) images at right from: http://www.youtube.com/watch?v=Y6B_BnlbQU4

http://www.pbs.org/wgbh/masterpiece/suchet/index.html
Transcontinental "run-thru" trains

- Perishables train
  - UP-CSXT
  - Stockton CA - Albany NY

- Intermodal train
  - UP-NS
  - LA - Atlanta

- Auto. train
  - CN-UP
  - Oshawa-Denver

Stockton-Sacramento

Los Angeles

Denver

Memphis

Chicago

Albany NY

Oshawa~Toronto

Atlanta
US v EU rail systems: interoperable v not

N. American rail system
- <<1% electrified
- 1 track gauge
- 3 clearance plates
- standardized equipment
- extensive interchange
- handles 40% of frt. GTMs (US)
- investor owned

European rail system
- 50+% electrified
- 3 track gauges (UK+cont., SP+Port., FSU)
- 5 clearance plates (NO double-stacks)
- country-specific locomotives (some multi-)
- very little interchange
- handles 8% of frt. GTMs (EU-15)
- govt. or semi-privatized

http://www.bueker.net/trainspotting/voltage_map_europe.php
Electrified heavy haul in northern Europe

Electrified LKAB iron ore trains in Sweden & Norway have been mentioned as a model for electrifying US freight RRs.

The railroad is only 247 miles long, connecting 1 mine with 2 ports.

LKAB trains are 68 cars long (UP bulk trains up-to-140 cars).
Electrification variant: dual-mode locomotives

• Diesel-electric locomotive
  – N. American frt. locos. already "packed"
  – New in 2015+ must also have extensive aftertreatment equipment

• Electric locomotive
  – Totally dependent on electrified infrastructure (no wire, no power)

• Dual-mode or "Electro-diesel" (diesel-electric + electric)
  – Greatest issue: onboard space & weight capacity
  – Needs pantograph, transformer (high-to-low V), switchgear, etc

• "Adding" pantograph, xformer, etc to US freight locomotives?
  – Not feasible
Dual-mode psgr. v freight diesel locomotive

**Passenger**
- Pantograph
- Step-down transformer & HV switchgear
- (2) Cooling systems
- 2,400 gallons fuel
- 4 traction motors
- 288,000 pounds weight

**Freight**
- Power electronics
- (1) 4300-4400 medium-speed (905-1050 RPM) diesel engine w/ generator
- (2) high-speed (1800 RPM) diesel engines w/ generators
- 5,000 gallons fuel (+108%)
- 6 traction motors (+50%)
- 420,000 pounds weight (+45%)

**Specifications**
- 3,600 diesel HP
- 5,300 electric HP
- 71,000 pounds maximum starting pulling effort
- Max. 110 MPH (+57%)

- 185,000 pounds maximum starting pulling effort (+160%)
- Max. 70 MPH
- Operating range 2x (+100%)
Unconventional alternatives to steel wheel/rail

- **Maglev (magnetic levitation)**
  - New infrastructure and "floating" stock

- **LIM (linear induction motors)**
  - Proposed as modification to existing track & rolling stock
  - Induction coils embedded in track, Al reaction plates under equipment
  - Accelerative capabilities but downhill performance (braking) unknown

The "cheapest" energy: efficiency

• Efficiency improvements to eliminate wasted energy
  – Onboard & system controls
    • Improvements v added technological complexity
  – Rolling stock redesigns (weight, capacity, etc)
    • Overall long cycle of improvement (years-to-decades)
  – Aerodynamics (reduced drag resistance)
    • Limited by car ownership structure (66% owned by non-RRs)
    • Must start somewhere
    • Simplest improvements best, often quickest, lowest risk

• Arrowedge™
**ARROWEDGE™**

- Double-stack train bluff body pressure reduction
  - US patent granted, additional US & Canadian patents filed
  - Initial operation Joliet/Global 4 - Long Beach/ICTF corridor
  - Other aspects of double-stack train drag under investigation
"The road of discovery, in whatever field, can always be recognized by the 'bleached bones' of those who failed to make the grade, for it takes not only courage, but extraordinary endurance to sustain the voyager."


Lima-Hamilton exited the locomotive business on September 11, 1950.