Engines of Change & Future Fuels for US Freight Locomotives

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How to sustain rail freight & reduce rail emissions?

è Rail v truck advantage: work* v diesel fuel consumed (US)

↗ *Rail*	*42% of GTMs*	*using*	*~4.5B gallons of diesel fuel*
↗ Truck	30% of GTMs	using	~26.0B gallons of diesel fuel
↗ Ag use, waterway, pipeline, etc.			~19.5B gallons of diesel fuel
↗ US total diesel consumption			~50.0B gallons of diesel fuel**

è Successful technological changes meet various criteria

è Significant rail emissions improvements ***are*** occurring

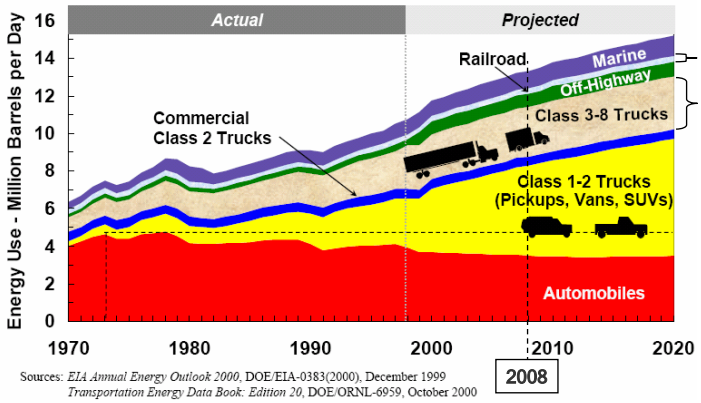
è Future locomotive propulsion (and fuels): which ones?

* Freight transportation work is commonly defined in terms of "gross ton-miles". One GTM is 1 ton of (freight+railroad car) moved 1 mile.

** http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp

What fuel(s) will support US ground transport?

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



Sources: *EIA Annual Energy Outlook 2000*, DOE/EIA-0383(2000), December 1999
Transportation Energy Data Book: Edition 20, DOE/ORNL-6959, October 2000

Rail = 42% of GTMs

Trucks = 30% of GTMs

= 72% of all US freight transport work

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5 key factors, changing ground freight transportation

- è **Technology**: Can it be *manufactured* and *applied*?
- è **Economics**: Is it *affordable*?
- è **Infrastructure**: Is it *supportable*?
- è **Sustainability**: Is it *long lasting* and *realistic*?
- è **Environment**: What *changes or impacts* will occur?

- è *Applicable to all modes of existing or proposed ground freight transportation*
  - ↗ *Rail, trucking, freight maglev, pipeline, etc.*

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Rail emissions progress

- **Fuel efficiency improvements**
  - UP, 12% reduction in (gallons/1000 GTMs) during past 11 years
  - Less fuel produces lower emissions per unit of work performed
- **EPA regulations, 3 loco. Tiers since 2000, 4th pending**
  - Major acquisitions of Tier 0-1-2 locomotives
  - Tier 4 by 2015-17: 80%/90% reductions in NOx and PM
- **Aftertreatment R&D**
  - BNSF-UP switcher DPF test, UP road oxicat test (both for CA)
- **UP-pioneered ultra-low emitting ("ULEL") Genset switchers**
  - 80% less NOx, 90% less PM, 16-37% less fuel/GHG compared to conventional yard switching locomotives … surpass EPA regs by 50-75%

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Switcher DPF retrofit: progress report

- **BNSF-UP program for CARB**
  - Program start '01, 2 units now equipped
  - >12 PM technologies screened, Swiss DPF technology selected
    - **95% PM removal goal**
  - UP unit in Oakland+Roseville since Dec'06
    - **Started at 83% PM removal, deteriorated to 75% PM removal after 1 year of service**
  - BNSF unit still in lab (SWRI) testing
    - **Similar 83% performance at start; oxicat upstream of DPF produced no major improvement**
  - No other DPF-equipped locos in world (including 100+ in Switzerland) have undergone this rigorous field testing and EPA federal test protocol evaluation

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Road unit oxicat retrofit: progress report

- EPA-UP experiment, now UP's
  - Started '06, 1 unit now equipped
  - Flow-thru catalyst in exhaust manifold
  - UP unit in field (LA basin) since Dec'06
    - 50% PM reduction, Tier 0 engine can meet EPA Tier 2 for PM, but …
    - 3 major failures of catalyst elements in first year of field service
- DPF+oxicat "lessons learned" to date
  - Technical progress is always difficult to forecast
  - Field testing is critical to making progress
  - Expect failures; this is "uncharted territory"
  - Technology cannot be "forced"

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Hybrid ULEL switchers: progress report

- Diesel-battery non-regenerative hybrids
  - UP first RR to acquire and use technology
    - 290 HP diesel recharges 25 tons* of batteries
    - 1 in Fresno, Apr06 (CA's first hybrid)
    - 10 in LA basin, '06-'07
    - All 11 units out-of-service for past 10 months for major modifications
    - 1-2 units now back in service at City of Industry

* Lead-acid batteries are not capable of deep cycling, and contain usable energy equivalent to ~50 gallons of diesel fuel.

- Future potential but technical issues still to resolve

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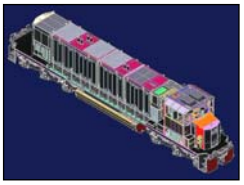
Genset ULEL switchers: progress report

- è UP-pioneered technology
  - Concept developed '03-'05
  - Prototype funded by UP, into LA Feb'06 →
- è 60 Gensets into LA basin during '07 →
  - è 80% less Nox, 90% less PM
  - è 16-37% less fuel (and greenhouse gases)
  - è NOx and PM 50-75% below current EPA regs
- è 4 more Gensets into Roseville '08 →
  - larger 6-motor units for classification hump
- è UP's technology now going worldwide
  - è Gensets ordered or investigated by other RRs in US, Canada, Mexico, South America, South Africa and Australia



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UP now has 61 ULEL Gensets working in LA basin

Genset locomotives at Santa Ana and Lemon Streets in Anaheim, CA, July 24, 2007

Photo courtesy of Jeffrey Bass

Union Pacific Railroad was the recipient of the Society of Automotive Engineers' 2006* "Environmental Excellence in Transportation" (E^2T) award in the mobility and engine emissions category, for pioneering Genset technology.

The 2005 winner was Honda Motor Car Company for introduction of the 2005 Honda Accord hybrid automobile.

SAE INTERNATIONAL

* award presented in Washington DC on May 16, 2007

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Why not electrification?

- è Freight RR electrification is technically feasible
- è Many studies by RRs and utilities
  - è Including Colton-Yuma, SP & SCE, 1969-1971
- è Will be very expensive
  - All economic studies non-justifiable ROI
  - 50kV overhead, transmission/substations, electric locomotives
- è Many unknowns re electric power supply in SW U.S.
  - RRs operate 24x7, cannot tolerate peak-hour utility restrictions
- è Could impair freight traffic if not implemented correctly
  - Train delays at "power change points"
  - Cannot electrify container yards

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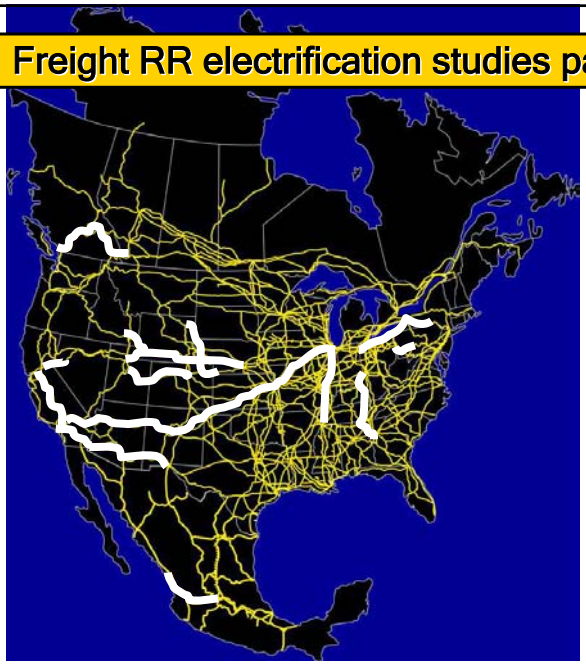
Freight RR electrification studies past 40 years



Extensive engineering and economic analyses were performed by 11 RRs:

- AT&SF (now part of BNSF)
- BN (now part of BNSF)
- Conrail (now part of CSXT)
- CP
- D&RGW (now part of UP)
- IC (now part of CN)
- NdeM (now part of KCSdeM)
- NYC (now part of CSXT)
- Southern (now part of NS)
- SP (now part of UP)
- UP

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Much of Europe is electrified; why not US?

- è **Fundamental differences in European and US railroads**
  - Purpose for railroads (passenger v freight) and sources of capital (government v free enterprise)
    - è **Typical EU freight train: 9,000 HP + 600 tons (psgr. train HP/ton)**
      in western US: 9,000 HP + 6,000 tons
  - How (and why) many European railroads were electrified

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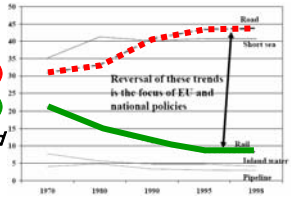
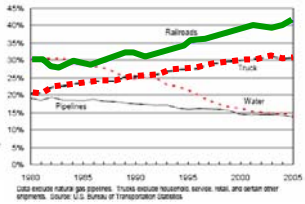
Europe is struggling to get freight off highways

- è **European rail network constraints**
  - N. American RRs are a network, European mostly intra-border
  - European economies have been overly-dependent on trucking for handling freight

EU truck (now 45%)
EU rail (now 9%)
of EU GTMs handled





US rail (now 42%)
US truck (now 30%)
of US GTMs handled

European Union **United States**

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

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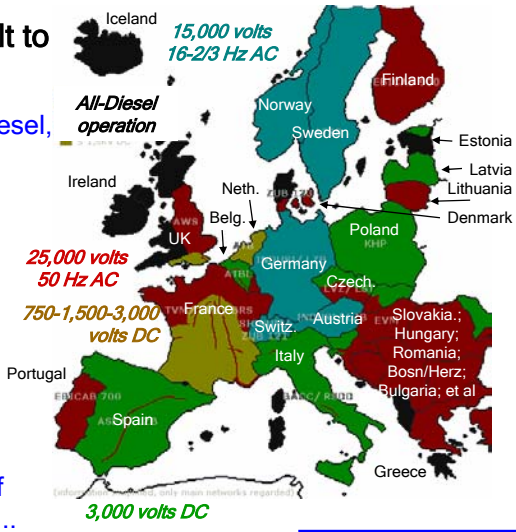
Electrified Europe: a highly-fragmented rail network

- è US-like operations difficult to achieve in EU
  - Europe: 49% train-miles diesel, 51% electrified
    - è 2 AC & 3 DC voltages
    - è 5 dimensional clearances (N. America has 1)
    - è 2 track gauges (N. America has 1)
    - è Cross-border operations limited by 11 different pantograph requirements on electric locomotives
  - One major consequence of marginal network planning ...



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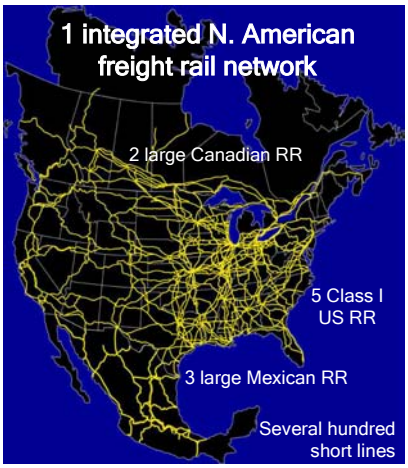
Difficulty for EU to achieve N. American rail benefits

24+ national or semi-privatized European systems

... versus ...



" In an increasingly integrated Europe, the coexistence of at least four different rail electrification systems ... represents a substantial hindrance to the requirements of interoperability in international traffic."

http://www.bueker.net/trainspotting/voltage.php

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Recent LA electrification proposal, "NJ" locomotives

- è NJ Transit operates largest fleet of electric locos in US
- è High-speed German design
- è This loco suggested for electrified LA basin freight trains

Photo courtesy of:
http://commons.wikimedia.org/wiki/Image:NECtrain3967.jpg,
image by Adam E. Moreia

NJ Transit operates on a portion of the former-Pennsylvania RR north east corridor, electrified in the 1930s using a Reconstruction Finance Corporation loan

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NJ electric psgr. locos: not suited for western frt.

Locomotive	Propulsion	HP	# motors	Tractive effort (pounds) at start	Tractive effort (pounds) at continuous speed
US freight	Diesel	4400 *=100%*	6 *=100%*	160,000# *=100%*	145,000# *=100% (11 MPH)*
"NJ" electric	Electric	7100 =161%	4 *= 67%*	71,000# *= 49%*	41,000# *= 28% (35 MPH)*

- è NJ's German-built passenger electrics are speed machines, not for heavy-grade freight service
  - è (4) of these German-built electric locomotives would be required to do work of a contemporary US diesel freight unit
  - è 9x effective cost penalty based on 3x greater investment and 1/3rd grade capability … compared to contemporary US diesel freight locos

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What technology could replace/supplant diesels?

- Batteries and flywheels (hybridization)
  - Low power density, inadequate except for hybrid applications
  - Short operating range but improving
  - Extensive R&D occurring (driven by hybrid auto market)
- Gas turbine
  - Low thermal and fuel efficiency in locomotive applications
- Fuel cells (with or without hybrid application)
  - Life cycle cost, durability in locomotive environment
  - Fuel source, lack of infrastructure & transportability issues
  - Short operating range

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Diesel: engine of choice for locomotives

- Continues as best-choice prime mover for locomotives
  - High power-to-weight ratio and durability
  - High overall thermal efficiency (40+%)
  - Technology is widely supported by market place
  - More diesel engine advances coming

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Future locomotive fuels or energy sources

- **Diesel**
- ***Regenerative diesel hybrids: storage batteries** (capacity; discharge rates; economics)
- ***Regenerative diesel hybrids: flywheels** (rotor & magnet materials, high-speed bearings)
- ***Syn. (F-T) diesel** (production volumes; CO_2 impact; overall economics)
- **Biodiesel** (engine warranty issues; consistency problems; pipeline restrictions)
- ***DME** (dimethyl ether; high-cetane … diesel cycle OK, low-PM; derived from coal)
- **LNG** (market competition; lack of infrastructure; requires dual-fuel for diesel engines)
- **CNG** (insufficient energy density; lack of infrastructure; not diesel cycle compatible)
- ***Hydrogen & fuel cells** (economics of H_2 sourcing; lack of infrastructure; fuel cell design)
- **Electrification** (questionable economics; power supply limitations; traffic impact)
- ***Alcohols** (insufficient energy density; corrosiveness; suitability for engines)
- **Gasoline** (energy density too low for locomotives; flammability)

* indicates fuel or energy source is still undergoing significant engineering R&D, may not be ready for heavy vehicle applications and/or commercial markets in large volumes

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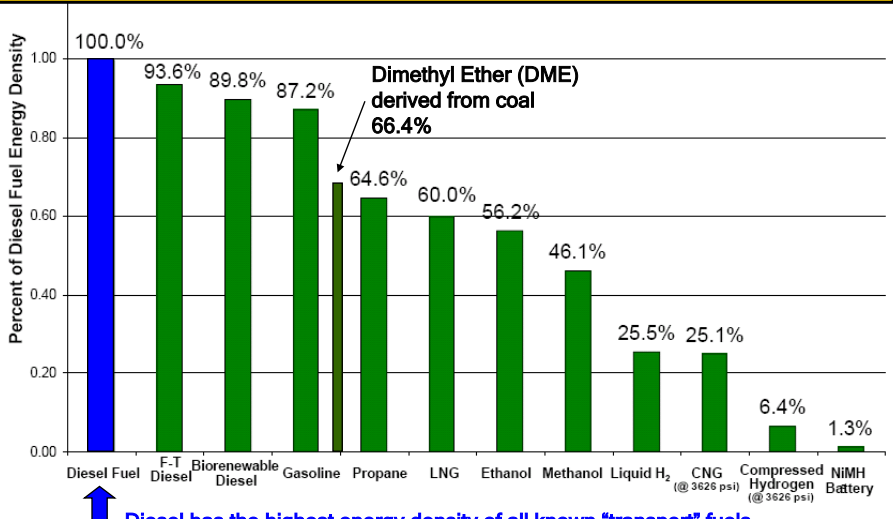
Fuels for ground transportation



Source: "Engines That Will Power the Future", Dr. James Eberhardt, DoE, 2001

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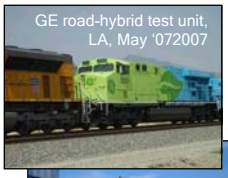
Hybridization most likely direction for locomotives

- è Flywheel energy storage
  - ↝ Continuing developments in bearing designs, materials; could apply to road and yard power
- è Battery energy storage
  - ↝ Immense R&D effort for "next generation" technology applicable to road and yard power
- è Road hybrid locomotives could enable capturing (regenerating) dynamic brake energy
- è When will technology break through's occur?
  - ↝ 2010? 2012? 2015?


GE road-hybrid test unit, LA, May '072007


UP Railpower yard hybrid, City of Industry CA, Feb '08

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Locomotive technology for the future

- è Continuing evolution of diesel engines
- è Aftertreatment
  - ↝ EPA Tier 3-4 reg. pending signature, technology being developed
    - è Development follows truck diesel market
- è Diesel hybrids (both road and yard service)
  - ↝ Flywheel and/or storage battery technologies
    - è Technology developments in parallel with automotive progress
- è Alternative fuels (maintaining basic diesel technology)
  - ↝ Biodiesel*; Fischer-Tropsch synthetic diesel; DME?
    - è Need to standardize characteristics, consistency & pipeline issues*
    - è Engine technical & reliability issues to overcome
    - è Production volumes and overall economics?

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