ARB Freight Locomotive Advanced Technology Assessment

Union Pacific Railroad (UP)

BNSF Railway (BNSF)

September 3, 2014

Sacramento, California

California Environmental Protection Agency

Air Resources Board

Technology Assessment Objective

- Help inform planning for near, mid, and long-term planning horizons.
  - Sustainable Freight Plan
  - State Implementation Plan
  - Scoping Plan, etc
- Identify current state of advanced technologies that provide opportunities for emission reductions.

Summary of Findings Handout

	Technology	Performance (rel to Tier 2)	Cost	Operational Considerations	Status	Next Steps	Key Challenges
Tier 2/3		5.5 g/bp-hr NOx, 0.1-0.2 g/bp-hr PM	~$2.3M/unit	Compatible with national fleet	Full-Scale Commercial Production		Nat'l standards, engine tech advances were necessary to bring Tier 2 to commercial introduc
Tier 4	Combustion improvements, enhanced cooling, and Exhaust Gas Recirculation (EGR)	75-85% NOX and PM reductions	~$3 million per unit to account for enhanced combustion, cooling and systems integration	Compatible with national fleet			
LNG	dual fuel (60-80% NG) retrofits for Tier 2/3 or HPDI for Tier 4	Same as Tier 2/3 for retrofits, 75-85% NOx/PM reductions for Tier 4, No DPM when using NG	Locomotive +$1M for each tender car, but fuel costs 50% less	Need for tender car, NG fueling infrastructure			
Tier 4+	SCR for NOX, DOC and DPF for PM	90% reduction , 70% NOx/PM reductions beyond Tier 4	~$4 million per unit. Possible maintenance cost increases for after-treatment.	Compatible with national fleet, will require maintenance/supply for urea			
On-Board Battery Hybrid	On-board batteries to power locomotives	Up to 10% NOx and PM additional reductions, due to reduced fuel consumption	~$4 million per unit	Compatible with national fleet			

	Technology	Performance (rel to Tier 2)	Cost	Operational Considerations	Status	Next Steps	Key Challenges
Battery Tender Car	Battery tender connected to locomotive. Could potentially be connected to T2-T4+ locomotives.	Zero emission miles	Locomotive +$5M for each tender car. Costs should go down as production levels increase and electricity cheaper than diesel.	Compatible with national fleet if there's a national charging infrastructure, otherwise potential operational impacts	Concept	Policies and funding for R&D	Overcoming potential operational impacts (ARB funded UofI Study)
Catenary	Electric power provided from catenary lines	Zero tailpipe, upstream emissions for power generation	Range of ~$30 to ~$300 million per mile but would be amortized over many years.	Compatible with national fleet if there's a national catenary system	Technology used in U.S., Europe, Russia, China and other parts of the world.	Policies and funding needed for capital costs and research and development.	Capital costs of infrastructure. Studies needed on system design, electric power plants, and existing infrastructure modifications.
Fuel Cell	Proton Exchange Membrane (PEMs), Solid Oxide Fuel Cell (SOFC)/Gas Turbine	Zero tailpipe, upstream emissions for hydrogen generation	Not available	Compatible with national fleet if there's a national fueling system	PEMS: Conceptual phase, with BNSF small prototype switcher locomotive. (BNSF 1205: Green Goat converted to fuel cell) SOFC/GT: Concept Paper	Policies and funding needed for research and development.	

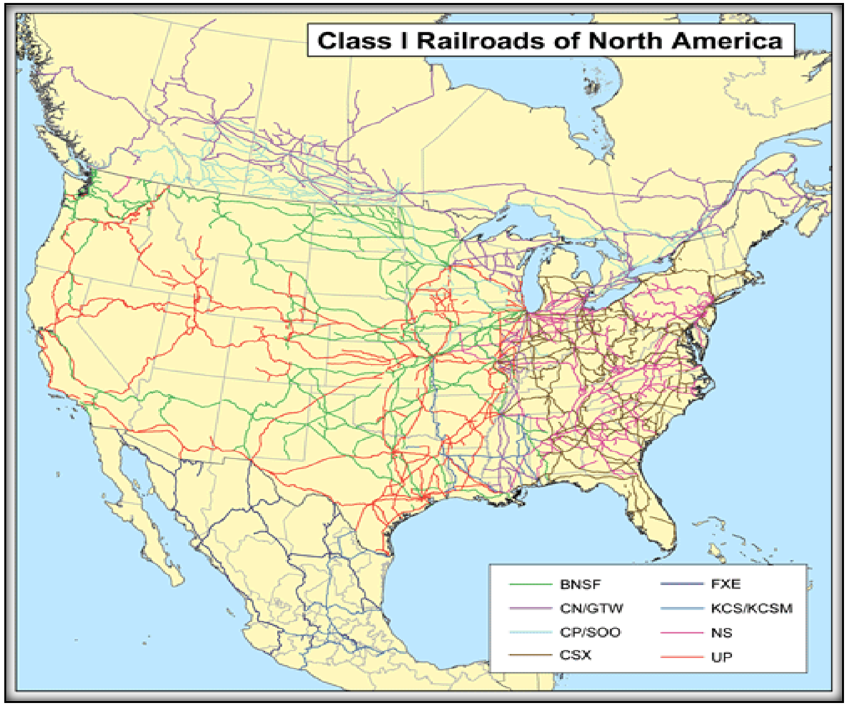
Agenda

- Background on North American Freight Rail Operations
- Historical Evolution of Technology and Operations
- Framework for Technology Assessment
- Assessment of Technologies to Reduce Locomotive Emissions

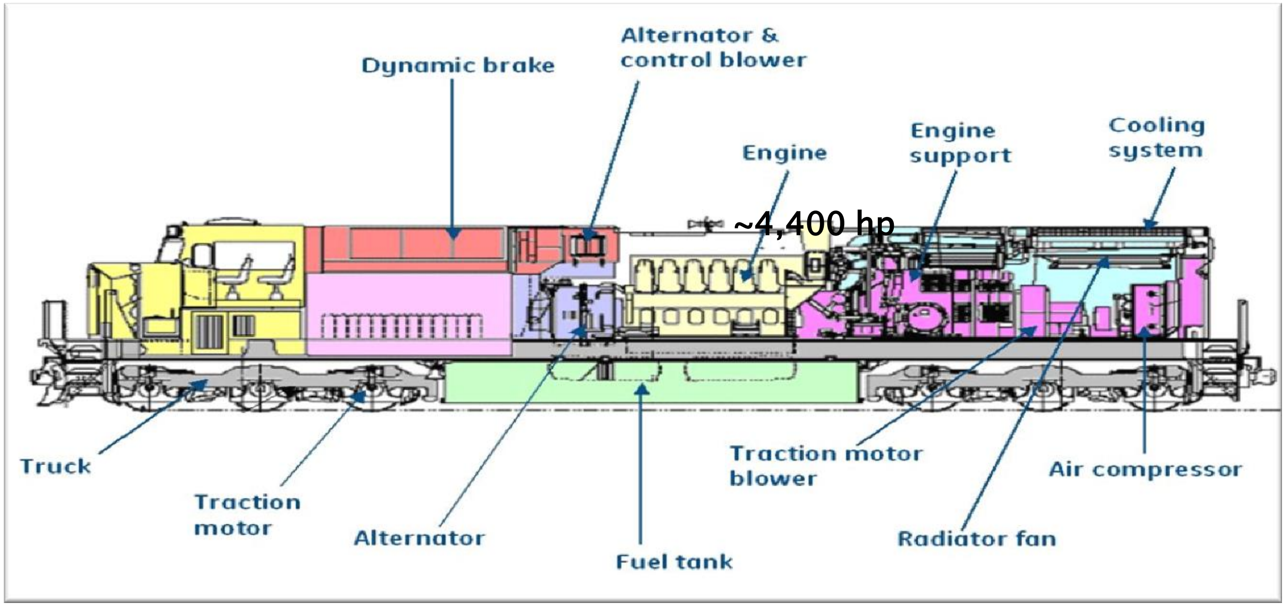
Background on Freight Rail and Locomotive Operations

Basics on U.S. Freight Diesel-Electric Locomotive Operations

- Seven Class I (Major) Freight Railroads in US
- Operating on 160k miles of track with Chicago as a major hub.
- UP and BNSF National Fleet of ~15,000 locomotives.
  - 10,000 interstate line-haul and 5,000 regional and switch locomotives



Freight Diesel-Electric Locomotive



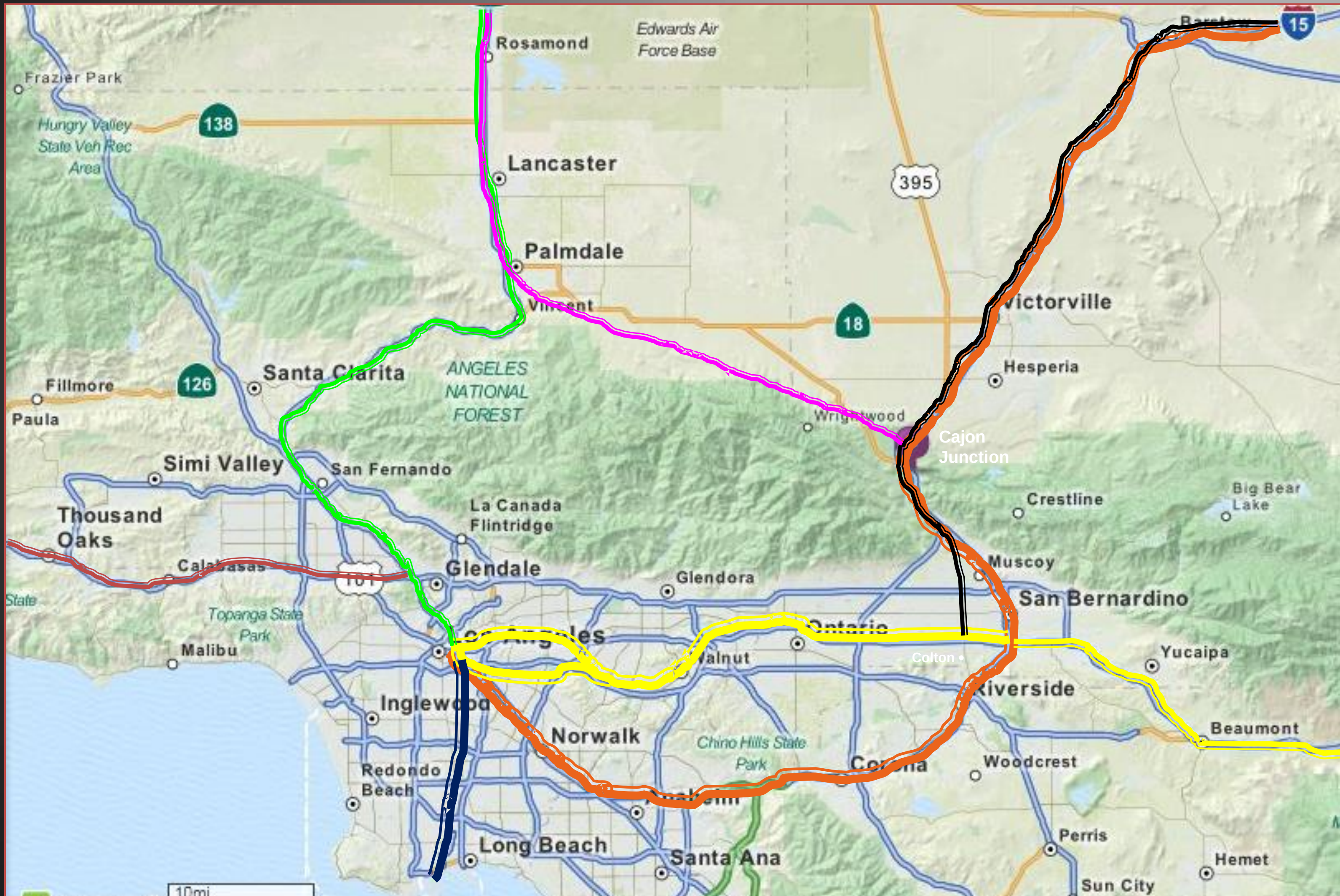
Courtesy of GE

- Diesel engine powers electric alternator which provides electricity to the locomotive traction motors/wheels.
- Two Domestic Manufacturers: General Electric (GE) and Electro-Motive Diesel (EMD)

Types of UP and BNSF Locomotives in California

- Interstate Line Haul (4,400 hp)
  - Pull long trains across the country (e.g., Chicago to Los Angeles)
  - Consume ~330,000 gallons of diesel annually.
  - Operate 5-10% of time within California
- Medium Horsepower (MHP) (2,301-4,000 hp)
  - Regional, helper, and short haul service.
  - Consume ~50,000-100,000 gallons of diesel annually.
  - Most operations in California or western region.
- Switch (Yard) (1,006-2,300 hp)
  - Local and rail yard service.
  - Consume ~25,000-50,000 gallons of diesel annually.
  - Most operations in and around railyards.

UP and BNSF Major Freight Train Routes to South Coast Air Basin



UP Cajon / Palmdale (8 trains per day)

UP Coastal (1 train per day)

Alameda Corridor (UP and BNSF: 45 trains per day)

BNSF Transcon (66 trains per day)

UP Sunset (40 trains per day)

UP Cajon / Cima (9 trains per day)

Northern UP, Metrolink Valley Sub (9 trains per day)

Historical Evolution of Locomotive Technology and Operations

Historical Rail Fuel Improvements

- 50% improvement in efficiency since 1980 (~1.8%/year)
  - Due to operational and technology improvements
  - FRA and rail roads project continued fuel efficiencies of about 1% per year.
- Operations:
  - Unit trains for bulk commodities (e.g., coal, ethanol, grain, etc.) and double-stack containers for intermodal.
- Technology:
  - Locomotive combustion (e.g., electronic and common rail fuel injection) and locomotive pulling power (i.e., tractive effort)
  - Distributed Power Units (DPUs), Idle Reduction Devices (IRDs) and Trip Optimizers.

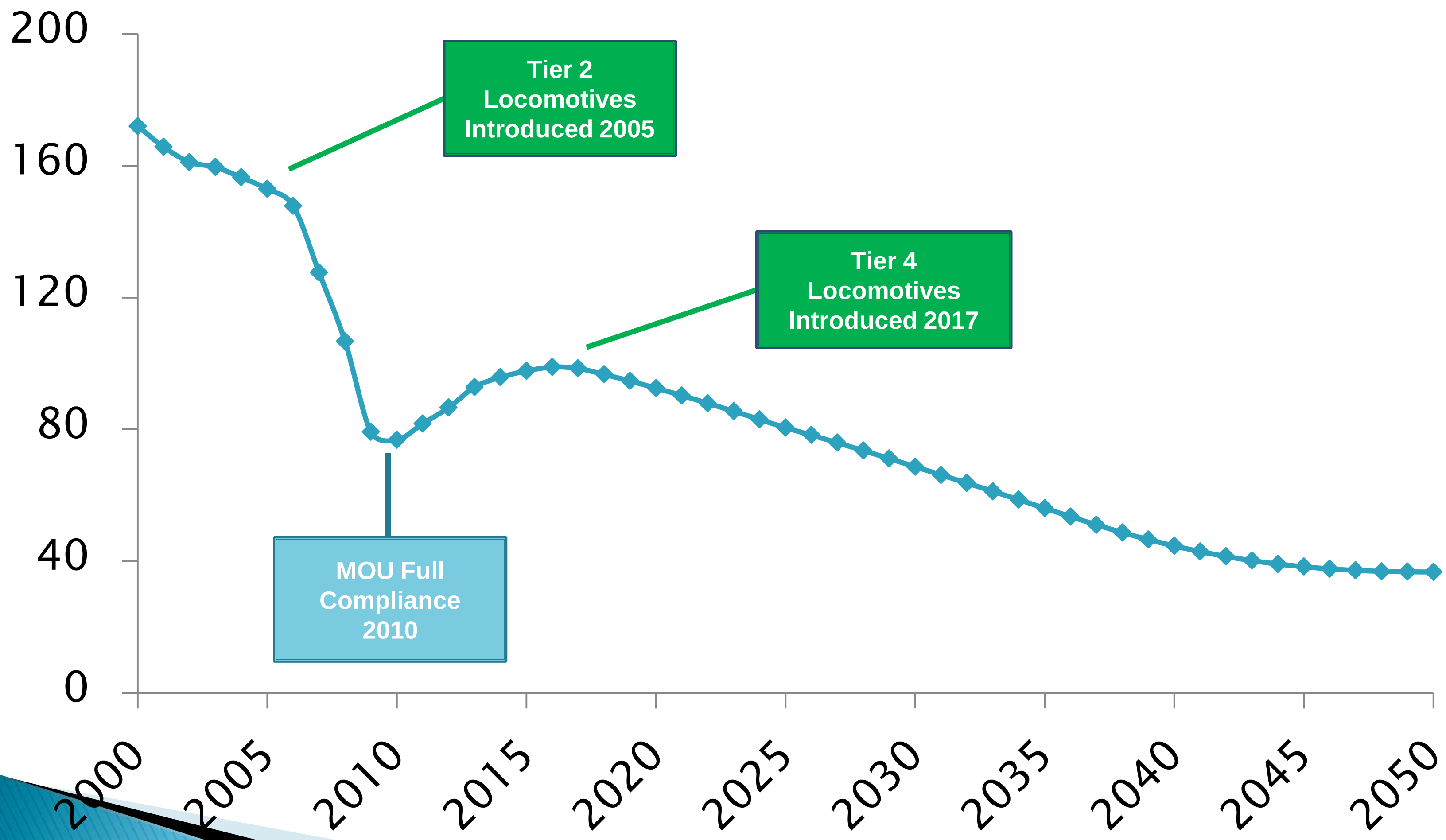
U.S. EPA Line-Haul Locomotive Emission Standards (g/bhp-hr)

Standard	NOx (g/bhp hr)	Percent Reduction from Pre Tier 0	PM (g/bhp hr)	Percent Reduction from Pre Tier 0
In-use/pre-Tier 0	13.5		0.6	
Tier 1	7.4		0.45	
Tier 2	5.5	~60%	0.2	~67%
Tier 3	5.5		0.1	
Tier 4	1.3	~90%	0.03	~95%

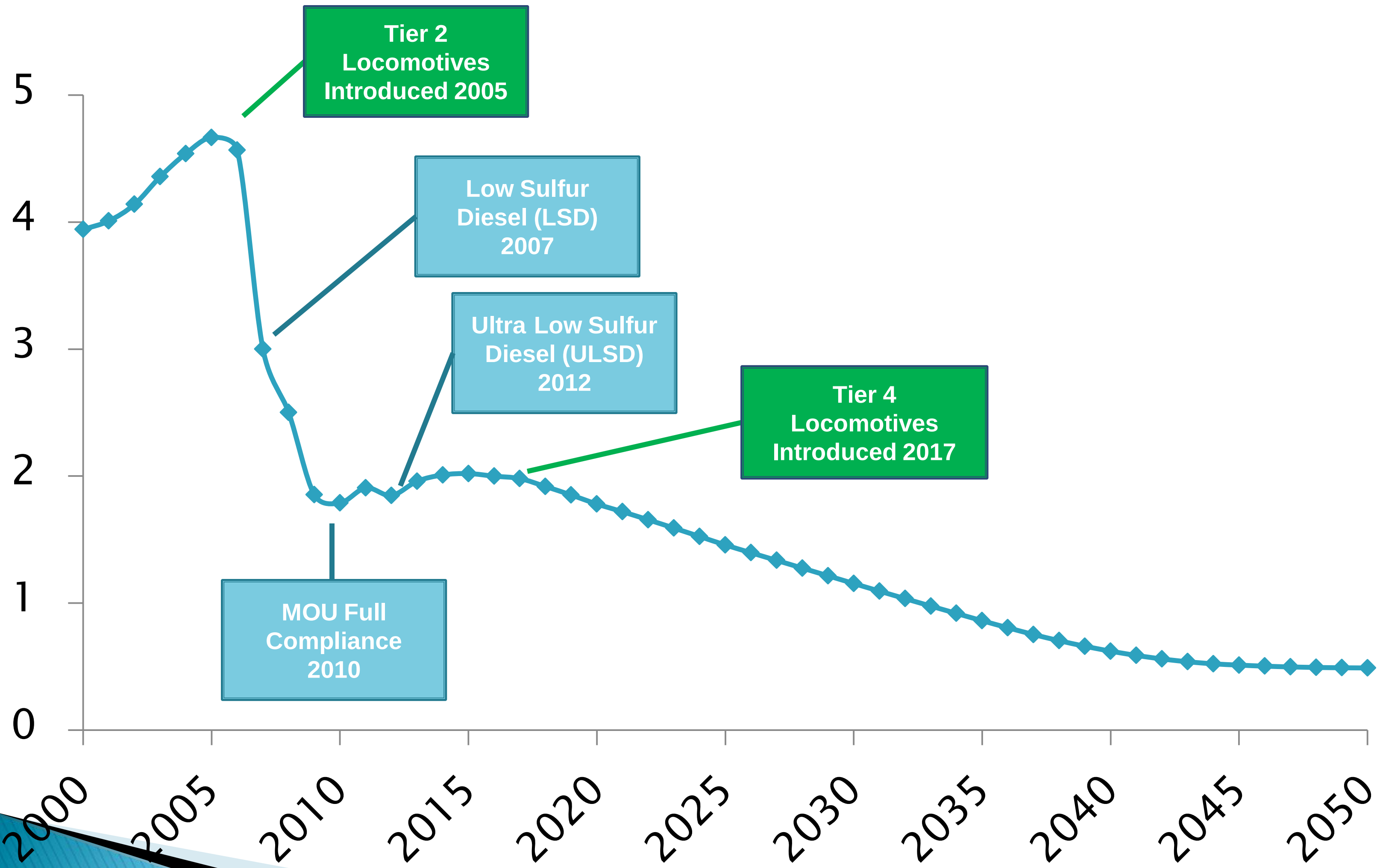
ARB & Local Programs to Reduce Emissions

- 1998 Locomotive NOx Fleet Average Agreement in South Coast Air Basin:
  - 67% and 50% NOx and PM reductions, respectively.
  - Full compliance by 2010 to achieve nearly a Tier 2 NOx average.
- 2005 ARB/Railroad Agreement
  - 20% PM, some NOx reductions
  - Full compliance by June 30, 2008.
- CARB Diesel Fuel Regulation – Intrastate Locomotives:
  - 14% and 6% PM and NOx reductions.
  - Full compliance by 2007.

Statewide NOX Emissions from Line-Haul Locomotives



Statewide PM2.5 Emissions from Line-Haul Locomotives



Framework for Technology Assessments

Key Performance, Fueling, Operational, and Economic Considerations

- Locomotive Performance
  - Tractive Effort (Pulling Power)
  - Emission Reductions
  - Fuel Efficiency
- Fueling and Operating Conditions
- Operations and Economics
  - Durability (up 30 years or more)
  - Reliability
  - Safety
  - Compatibility with Existing Fleet
  - Timing of Development, Testing and Production
  - Costs (Capital, Fuel, Maintenance)

Today's Tier 3 Locomotive Performance

Engine and Fuel Efficiency	Value

*Medium Speed Engine.
** Revenue Ton Miles.

Emissions Level	grams/bhp-hr
NOX	5.5
PM	0.1
HC	0.3

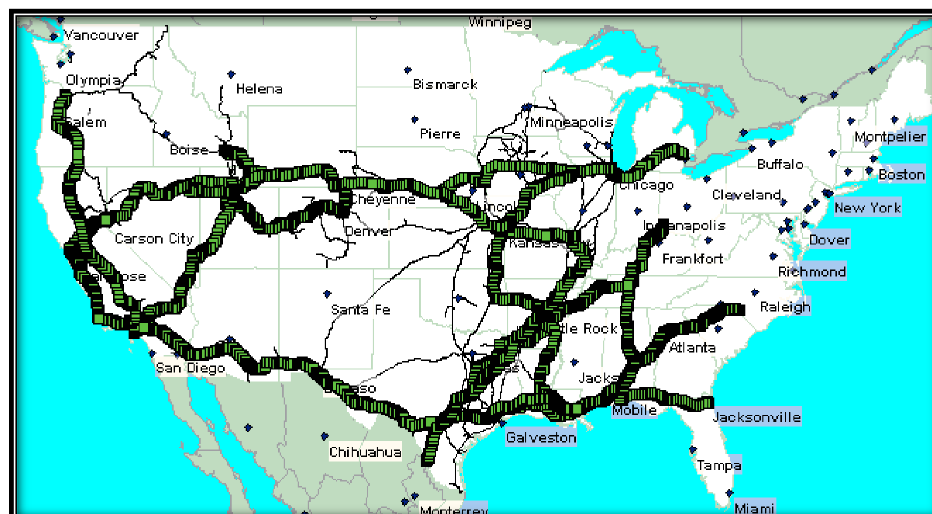
Existing Locomotive Refueling and Operating Conditions

- Refueling intervals are approximately 1,000 miles based on current refueling infrastructure.
  - For example – Chicago to Los Angeles routes:
  - Existing major refueling locations in BNSF and UP Kansas City, KS , BNSF Belen, NM, UP El Paso, TX, Rawlins, WY.
- U.S. freight locomotives operate in extreme temperature ranges, travel over extreme mountain grades, and below sea level to 9,000’ elevations.

UP and BNSF's Locomotive Operations

- Dynamic National Fleet:
  - 8,400 of 10,000 interstate line haul locomotives operated in the South Coast Air Basin (SCAB) in 2013.
- Foreign Power:
  - Foreign power" are locomotives leased/exchange from other Class I railroads.
  - UP/BN operated ~4.5% foreign power* in SCAB in 2013.
  - Nationally up to 10% of locomotives are borrowed from other Class I railroads annually.

60-day movement of one interstate freight line haul locomotive



Courtesy of Union Pacific Railroad

Locomotive Acquisition Rates and Useful Life

- Acquisition* of Locomotives
  - GE and EMD build about 500-1,200 locomotives annually for world-wide use.
  - UP and BNSF combined acquired ~500 new locomotives annually for U.S. operations between 1996-2014. (* New locomotives can be purchased, leased, and exchanged.)
- Interstate Line Haul Locomotives:
  - US EPA estimates 30 years for fleet turnover
  - ~20 years for interstate service.
  - ~10 years for regional service.
  - ~10-20 years for switch service or sell to shortline railroads.

Historical Development of Today's Tier 2/4 Technologies

Stage	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Compliance Date
Concept/Design	■	■						
Lab Engine Testing		■	■	■				
Prototype and Demo Locos (1-5 units)				■	■			
Pre-Production Loco Field Tests (20-75 units)						■	■	
Commercial Production								■

Actions Needed to Develop Tier 2/4 Locomotives

- U.S. EPA locomotive national emissions standards:
  - 1998 and 2008 locomotive rulemakings
- Engine technology advances:
  - Advanced combustion (e.g., turbochargers, EGR).
  - Electronic and common rail injection systems.
  - Advanced systems integration.

Advanced Locomotive Technology Assessments

Approach to Assessing Advanced Locomotive Technologies

- Emission Reductions
- Technology Description
- Operational Considerations (including infrastructure)
- Demonstration Status and Production Capacity
- Costs (Capital and Operating)
- Next Steps to Demonstrate and Deploy
- Key Challenges

Locomotive Technologies Evaluated

- Tier 4:
  - Diesel-Electric
  - Natural Gas (LNG/CNG)
- Tier 4+:
  - Tier 4 with Aftertreatment (SCR, DOC, and DPF)
- Battery Hybrid:
  - On-Board (Locomotive) Battery
  - Battery Tender (connected to locomotive)
- Electric:
  - Catenary (Single or Dual Mode Locomotives)
- Fuel Cell Technologies:
  - Proton Exchange Membrane (PEMs)
  - Solid Oxide Fuel Cell/Gas Turbine (SOFC/GT)
- Other Advanced Propulsion Systems

ARB Funded Study of Economic and Operational Impacts on California Rail

- University of Illinois (U of I) will assess:
  - Potential operational impacts, costs, and savings of advanced locomotive technologies.
  - Focus on technologies that might limit operations to South Coast Air Basin or California.
    - For example, battery tenders, all-electric.
  - Potential time delays to switch different types of locomotives on trains at exchange point railyards.
  - Assess potential for mode shifts, if there are time delays (e.g., from rail to trucks or ships).
- U of I study – draft by late 2014.

Tier 4 Diesel-Electric Freight Interstate Line Haul Locomotives

GECX 2015 – GE Tier 4 Prototype

GECX 2023 and 2024– GE Tier 4 Demonstrators

Tier 4 Diesel-Electric Freight Interstate Line Haul Locomotive

Criteria	Assessment
Emission Reductions	75-85% NOx-PM: Reductions from Tier 2/3.
Technology	Combustion improvements, enhanced cooling, and Exhaust Gas Recirculation (EGR).
Technology Performance: Fuel Efficiency	Similar to Tier 3, but there may be a fuel penalty for advanced emission controls.
Technology Performance: Fuel Tank and Range	Unchanged from Tier 3
Operational Consideration: Compatible w/National Fleet	Yes, compatible with national fleet

Tier 4 Diesel-Electric Freight Interstate Line Haul Locomotive

Criteria	Assessment
Operational Consideration: Infrastructure	No major changes needed.
Costs (preliminary estimates)	~$3 million per unit to account for enhanced combustion, cooling and systems integration costs. Increase on-par with technology cost increases between Tier 2 and Tier 3.
Current Status	GE: Support field service testing of 20 pre-commercial production units for full scale commercial production from 2015-2017. EMD: Full scale commercial production by 2017.

Dual Fuel (LNG-Diesel) Line Haul and CNG Switch Locomotives

GE Dual Fuel Test Locomotive

Canadian National – EMD/CAT/PR Dual Fuel Test Locomotives

BNSF – EMD Tier 2 Dual Fuel Test Locomotives

Source: http://www.j[illegible].com/gas_updates_165.shtml

Railroad Industry:
Long History of Gas Rail Test Programs

- Propane locomotive in 1930's.
- LPG Gas Turbine locomotive in 1950's.
- BN CNG Efforts in 1980's.
- Gas Rail Initiative and LNG switchers in 1990's.
- S. California LNG Line Haul Locomotive early 2000's .
- A number of recent rail LNG test programs:
  - Canadian National, BNSF, etc.

Tier 3/4 Dual Fuel Freight Interstate Line Haul Locomotive

Criteria	Assessment
Emission Reductions	Tier 4: 75-85% NOx-PM reductions from Tier 2 levels, no DPM when using NG
Technology	• 60-80% (LNG) to retrofit existing Tier 2/3 locomotives. • High Pressure Direct Injection (up to 95% LNG): new Tier 4
Technology Performance: Fuel Efficiency	Not Available.
Technology Performance: Fuel Tank and Range	Not Available. Note: 30,000 gallon LNG tender could potentially fuel two locomotives up to 2,200 miles.
Status	BNSF/GE: 2 line haul prototypes and tender BNSF/EMD: 2 line haul prototypes and tender CN/EMD: 2 MHP prototypes and tender

Tier 3/4 Dual Fuel Freight Interstate Line Haul Locomotive

Criteria	Assessment
Operational Consideration: Infrastructure	Need major investment in LNG fuel infrastructure, retrofit existing locomotives, and build FRA compliant tenders.
Operational Consideration: Compatible w/National Fleet	Potential issues with tenders if national fueling network is not available.
Costs (preliminary estimates)	\$1 million for ~30,000 gallon tender. Costs should go down as production levels increase. Fuel price: up to 50% less than diesel
Next Steps	Cost-benefit analysis, operational impact analysis, infrastructure analysis, on-going testing, federal regulatory approvals

Dual Fuel Locomotives Key Challenges:

- Energy Density vs. Diesel (130,000 BTUs):
  - LNG 60%, CNG 25%.
  - Need more volume to be diesel equivalent.
- Will Cost-Benefit Bear Out?
  - Natural gas fuel infrastructure (e.g., liquefaction plants and refueling centers) and capital costs versus lower fuel costs.
- Railroads are assessing the operational impacts with the use of dual fuel locomotives and tenders.
- Currently, no emission reductions beyond Tier 4.

Tier 4+ or Near-Zero Emission Locomotives:

Tier 4+ Diesel-Electric or Dual Fuel Freight Interstate Line Haul Locomotive

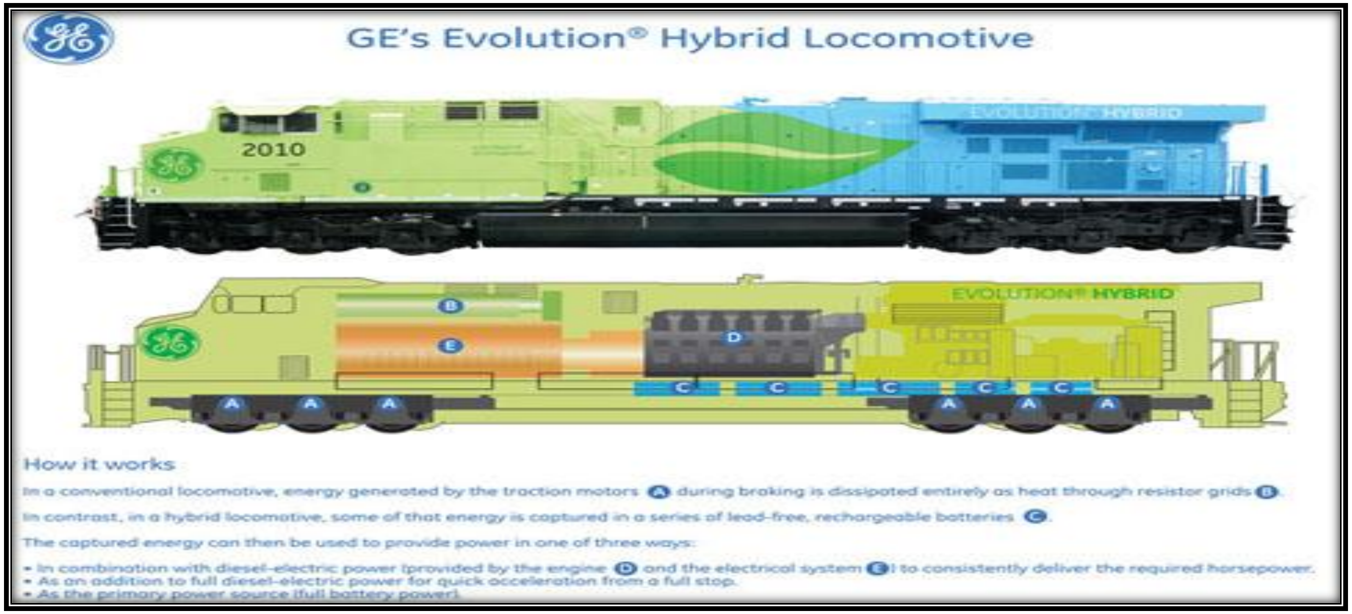
Criteria	Assessment
Emission Reductions	90% reductions from Tier 2, 70% NOx/PM reductions beyond Tier 4
Technology	Selective Catalytic Reduction (SCR) – NOx. Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF) – PM control
Technology Performance: Fuel Efficiency	Diesel: should be similar to Tier 4 LNG: should be similar to Tier 4 LNG
Technology Performance: Fuel Tank and Range	Diesel: should be similar to Tier 4 LNG: should be similar to Tier 4 LNG
Status	Concept Phase

Tier 4+ Diesel-Electric or Dual Fuel Freight Interstate Line Haul Locomotive

Criteria	Assessment
Operational Consideration: Infrastructure	No major infrastructure changes, but urea supply depots needed.
Operational Consideration: Compatible w/National Fleet	Yes, compatible with national fleet.
Costs (preliminary estimates)	~$4 million per unit* to account for aftertreatment. Increase on-par with technology cost increases between Tier 2 and Tier 3. Possible maintenance cost increases for after-treatment devices.
Next Steps	Policies and funding needed for research and development.
Key Challenges	Engine compartment space, and policies/investments to get technology to commercial introduction.

*ARB estimate.

GE On-Board Locomotive Batteries and Transpower Concept for Battery Tenders



GE On-Board Locomotive Batteries

Criteria	Assessment
Emission Reductions	Up to 10% NOx and PM additional reductions, due to reduced fuel consumption with zero emissions miles.
Technology	Locomotive on-board batteries.
Technology Performance: Fuel Efficiency	Not Available.
Technology Performance: Fuel Tank and Range	Not Available.
Status	Conceptual phase, with prototype.
Key Challenges	At this time, on-board batteries may be limited by the lack of space available on a locomotive.

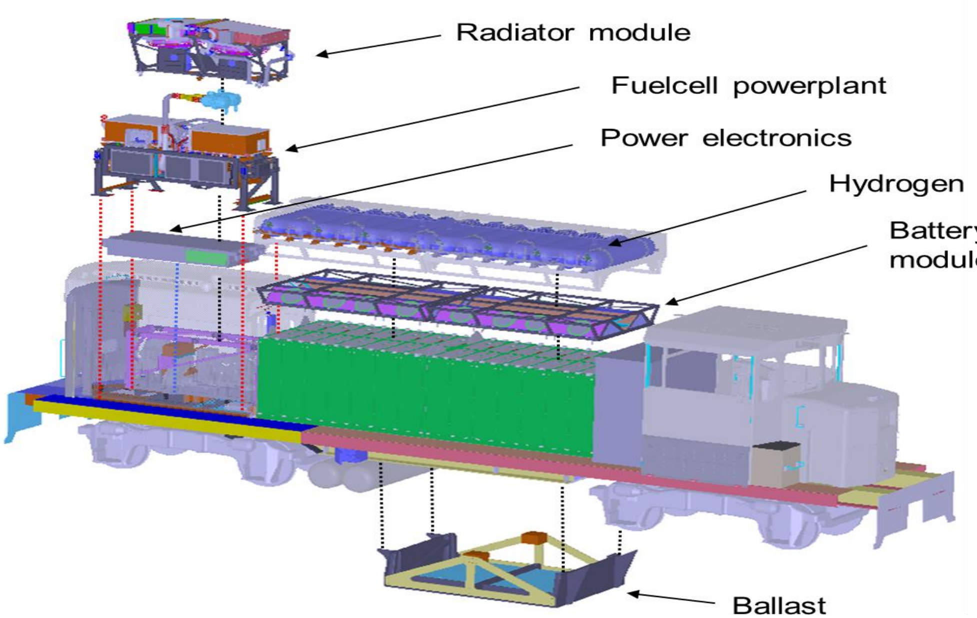
Transpower Concept for Battery Tender

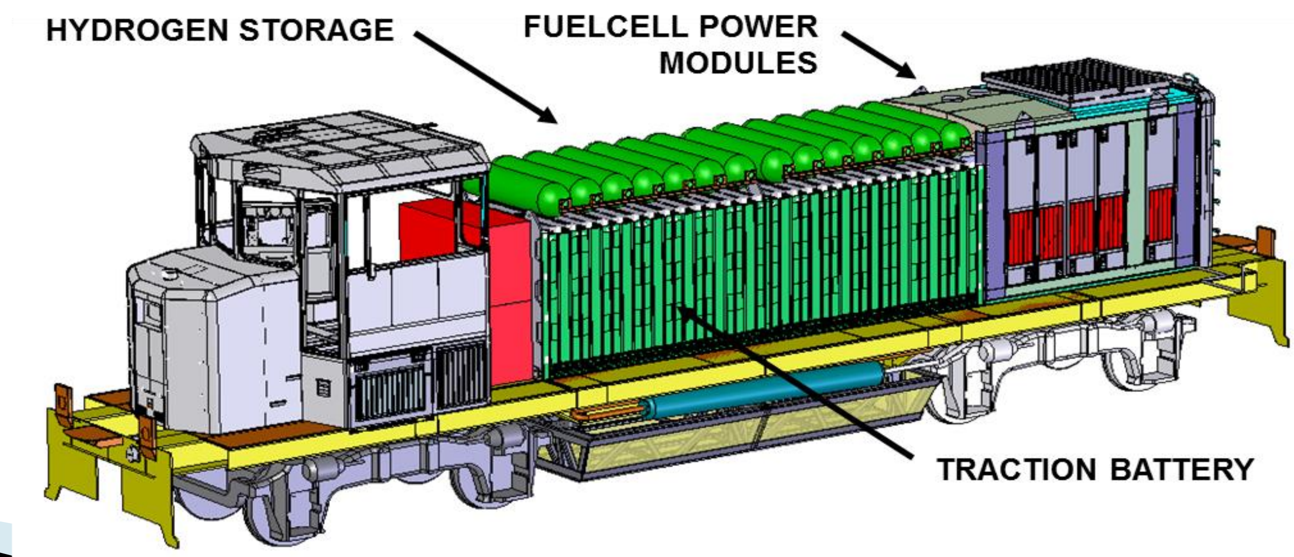
Criteria	Assessment
Emission Reductions	Zero-emission miles for duration of battery capacity
Technology	Battery tender connected to locomotive. Could potentially be connected to T2-T4+ locomotives.
Technology Performance: Fuel Efficiency	Not Available.
Technology Performance: Fuel Tank and Range	Not Available.
Status	Conceptual phase.

GE On-Board Locomotive Batteries and Transpower Concept for Battery Tender

Criteria	Assessment
Operational Consideration: Infrastructure	• None for on-board battery locomotive. • Tender will require national charging infrastructure or limited to operation within certain areas
Operational Consideration: Compatible w/National Fleet	Yes, if national charging infrastructure
Costs (preliminary estimate)	• $~5M for Tier 4 locomotive with on-board batteries. $5M for battery tenders. Costs should go down as production levels increase and electricity cheaper than diesel.
Next Steps	Policies and funding needed for research and development.
Key Challenges	Compatibility with national fleet and operational impacts for tender.

PEM Fuel Cell Locomotive





PEMS Fuel Cell
Interstate Line Haul Locomotive

Criteria	Assessment
Emission Reductions	Zero emissions on hydrogen.
Technology	Proton Exchange Membrane (PEMs).
PEMS - Potential	Thermal efficiency could be higher than current locomotives (up to ~50%).
Technology Performance: Energy Efficiency	Not available.
Technology Performance: Fuel Tank and Range	Not available.
Status	Conceptual phase, with BNSF small prototype switcher locomotive. (BNSF 1205: Green Goat converted to fuel cell)

SOFC/GT – Fuel Cell
Interstate Line Haul Locomotive

Criteria	Assessment
Emission Reductions	Near-zero emissions, possibly beyond Tier 4+.
Technology	Solid Oxide Fuel Cell/Gas Turbine (SOFC/GT).
SOFC/GT - Potential	Enough theoretical power to operate an interstate line haul locomotive. Thermal efficiency up to 70%. For reference the thermal efficiency of diesel locomotives is 40%.
Technology Performance: Energy Efficiency	Not available.
Technology Performance: Fuel Tank and Range	Not available.
Status	Conceptual phase. UC Irvine: ARB/SCAQMD funded concept paper.

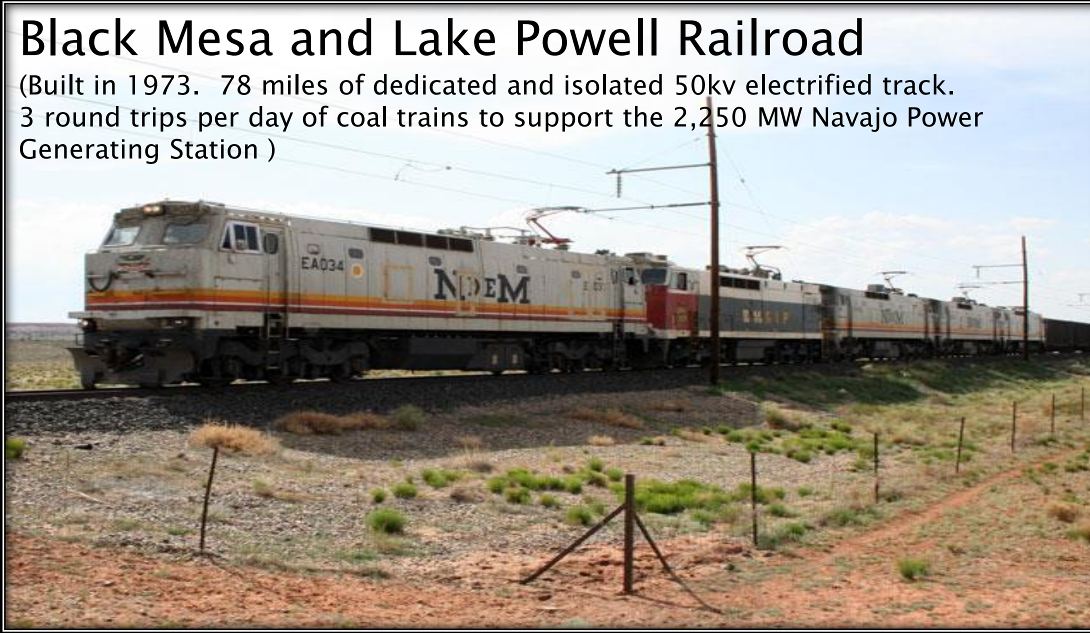
PEM or SOFC/GT – Fuel Cell Interstate Line Haul Locomotives

Criteria	Assessment
Operational Consideration: Physical Infrastructure	No major changes.
Operational Consideration: Compatible w/National Fleet	Need national fueling infrastructure (e.g., hydrogen).
Costs (preliminary estimates)	Not available.
Next Steps	Policies and funding needed for research and development.

Freight Railroad Electrification

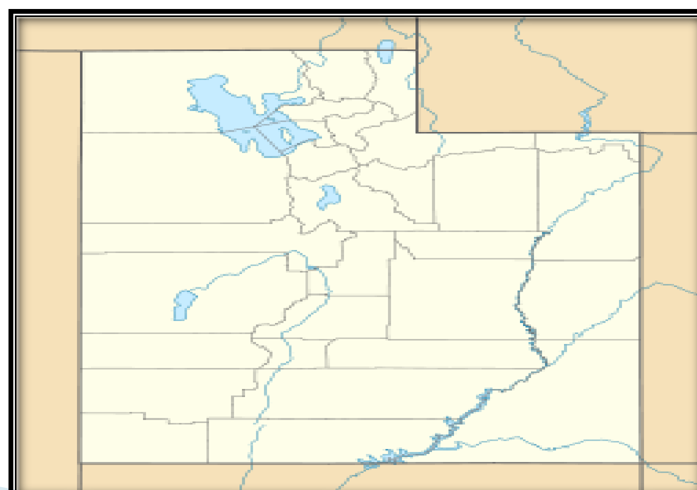
Black Mesa and Lake Powell Railroad

(Built in 1973. 78 miles of dedicated and isolated 50kv electrified track.
3 round trips per day of coal trains to support the 2,250 MW Navajo Power Generating Station)



Deseret Power Railroad

(Built in 1984. 35 miles of dedicated 50kv electrified track.
7 – GE electric locomotives. Operate up to four locomotives pulling ~75 coal hoppers on 3 trains per day to support the 460 MW Bonanza Power Plant).



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Freight Railroad Electrification

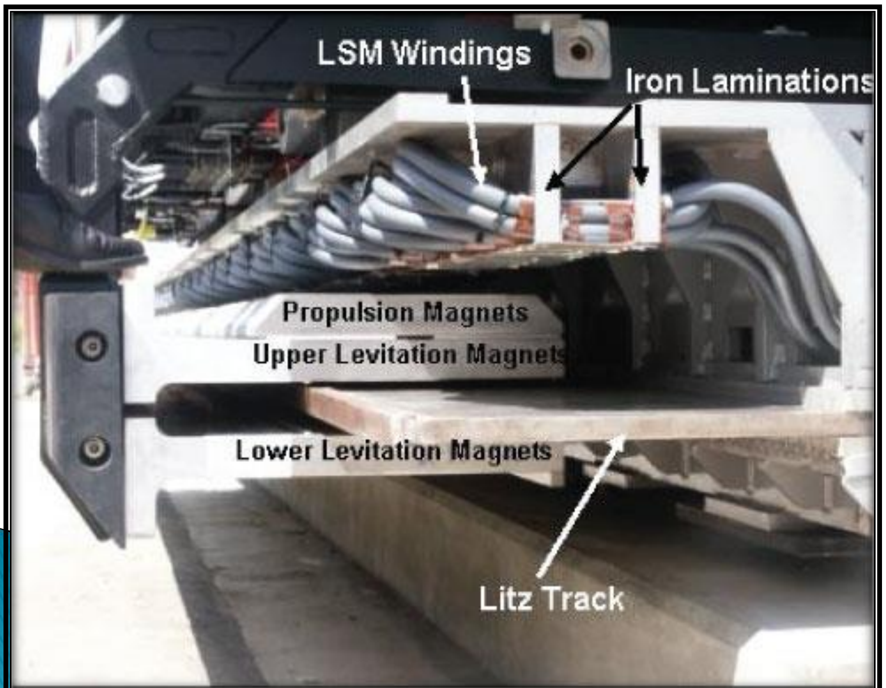
Criteria	Assessment
Emission Reductions	Zero stack emissions. Emissions from electric power plants.
Technology	Electrification with catenary.
Technology Performance: Energy Efficiency	Not available.
Technology Performance: Fuel Tank and Range	Range is as far as catenary lines extend.
Status	Technology used in U.S., Europe, Russia, China and other parts of the world.

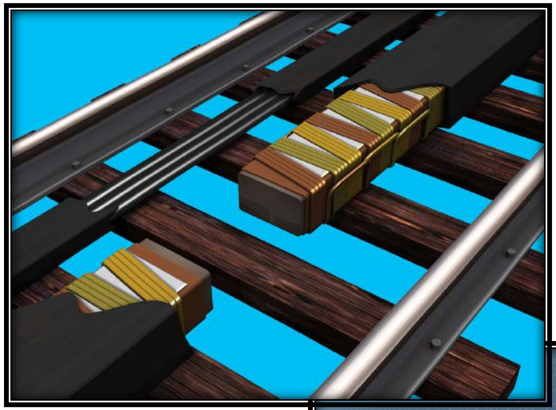
Freight Railroad Electrification

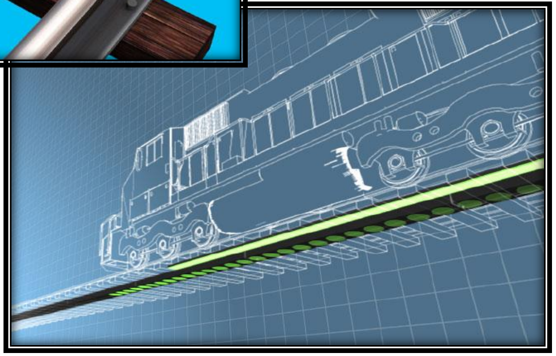
Criteria	Assessment
Operational Consideration: Infrastructure	Catenary, electric power plants and substations.
Operational Consideration: Compatible w/National Fleet	Will require exchange railyards, unless national system is electrified.
Costs (preliminary estimates)	Wide range, dependent on design of electrified system (e.g. 50kv vs. 25kv). Range of ~$30 to ~$300 million per mile but would be amortized over many years.
Next Steps	Policies and funding needed for capital costs and research and development.
Key Challenges	Capital costs of infrastructure. Studies needed on system design, electric power plants, and existing infrastructure modifications.

Other Technologies for Consideration: Advanced Rail Propulsion Systems

- Linear Induction Motors (LIM)
- Linear Synchronous Motors (LSM)
- Maglev
- Concepts that should be explored further for applications to freight rail.







Key Findings

- Future technologies will need be advanced through a variety of mechanisms:
  - On-going R&D for technology and infrastructure
  - Public and private investments in development and demonstration of technology, fuels and infrastructure.
  - Policies to promote and develop these technologies and to accelerate their deployment.

Key Findings

- All of the technologies assessed are viable, but timing and costs vary.
- Tier 4 standards are likely to be met only with EGR technology.
- Tier 4 standard could have been met with SCR and DPF.
  - SCR can control NOx from an engine that's tuned for fuel efficiency.
- LNG may be economically viable but GHG benefits dependent on methane leakage rates.

Key Findings

- Tender and fuel cells show promise for long-term technologies, but research and demonstration projects are needed.
- Some technologies may not be compatible with national system.
    - University of Illinois study will help identify the operational and economic impacts of advanced technologies including fuel tenders.

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