Hydrogen-Rail (hydrail) Development

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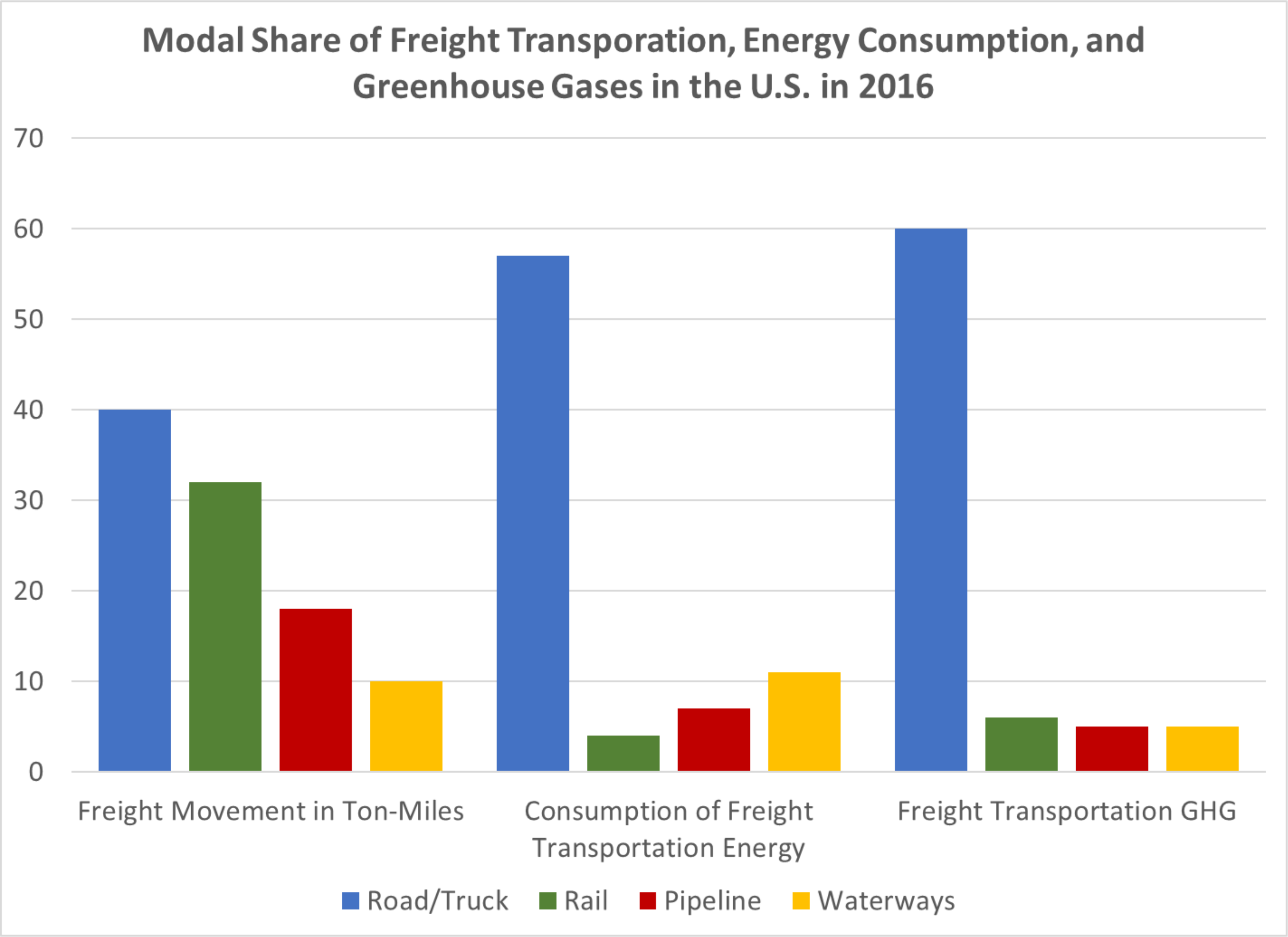
Current Rail Energy Efficiency and GHG



DOT (2018), ORNL (2018)

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Regulated Exhaust Emissions

- The US Environmental Protection Agency (EPA) has regulated the exhaust emissions from locomotives
- Four different tiers, depending on construction year of locomotive
- Increasingly stringent emission reduction requirements
- Tier 5 is now in discussion (see next slide)
- Achieving Tier 4 was already very challenging for manufacturers

	Duty-Cycle [b]	Tier	Year [c]	HC [i] (g/hp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)	CO (g/bhp-hr)	Smoke (percentage) [m]	Minimum Useful Life (hours / years / miles) [n]	Warranty Period (hours / years / miles) [n]
Federal [a]	Line-haul	Tier 0	1973-1992 [d, e]	1.00	9.5 [ABT]	0.22 [ABT]	5.0	30 / 40 / 50	(7.5 x hp) / 10 / 750,000 [o]	1/3 * Useful Life
		Tier 1	1993-2004 [d, e]	0.55	7.4 [ABT]	0.22 [ABT]	2.2	25 / 40 / 50	(7.5 x hp) / 10 / 750,000 [o] (7.5 x hp) / 10 / -	
		Tier 2	2005-2011 [d]	0.30	5.5 [ABT]	0.10 [k] [ABT]	1.5	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 3	2012-2014 [f]	0.30	5.5 [ABT]	0.10 [ABT]	1.5	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 4	2015+ [g]	0.14	1.3 [ABT]	0.03 [ABT]	1.5	-	(7.5 x hp) / 10 / -	
	Switch	Tier 0	1973-2001	2.10	11.8 [ABT]	0.26 [ABT]	8.0	30 / 40 / 50	(7.5 x hp) / 10 / 750,000 [o]	
		Tier 1	2002-2004 [h]	1.20	11.0 [ABT]	0.26 [ABT]	2.5	25 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 2	2005-2010 [h]	0.60	8.1 [ABT]	0.13 [l] [ABT]	2.4	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 3	2011-2014	0.60	5.0 [ABT]	0.10 [ABT]	2.4	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 4	2015+	0.14 [j]	1.3 [j] [ABT]	0.03 [ABT]	2.4	-	(7.5 x hp) / 10 / -	

(EPA, 2016)

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Proposed Tier 5 Emission Regulation

- California proposed rail emission regulation to be adopted at the federal level

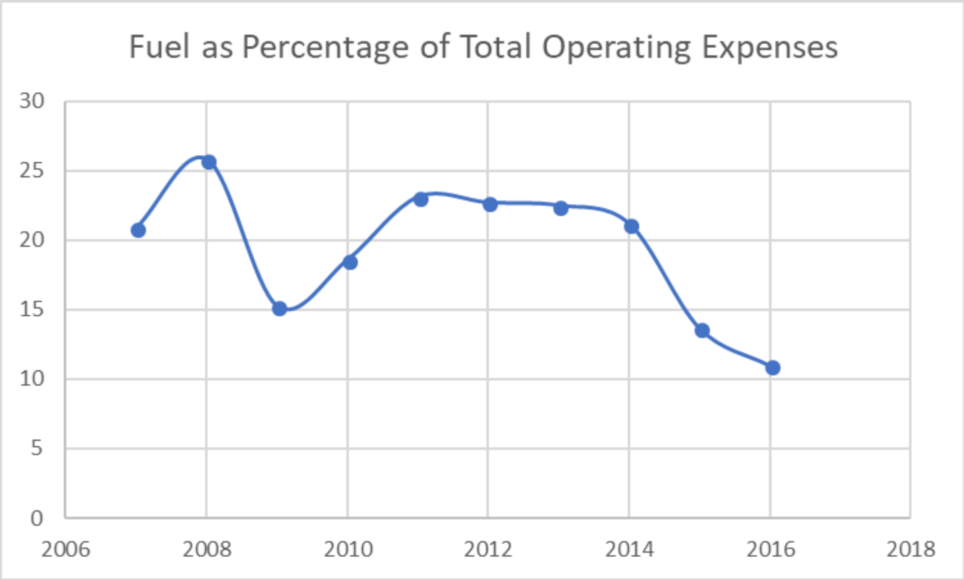
Potential Amended Emission Standards for Newly Manufactured Locomotives and Locomotive Engines

Tier Level	Proposed Year of Manufacture	NOx		PM		GHG		HC		Proposed Effective Date
		Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[1]	Standard (g/bhp-hr)	Percent Control[2]	
5	2025	0.2	99+	<0.01	99	NA	10-25%	0.02	98	2025
		With capability for zero-emission operation in designated areas.								

1. ARB, Technology Assessment: Freight Locomotives, 2016.[3]
2. Compared with uncontrolled baseline, reflects percent control over line haul baseline for illustrative purposes; ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.

(California Air Resources Board, 2017)

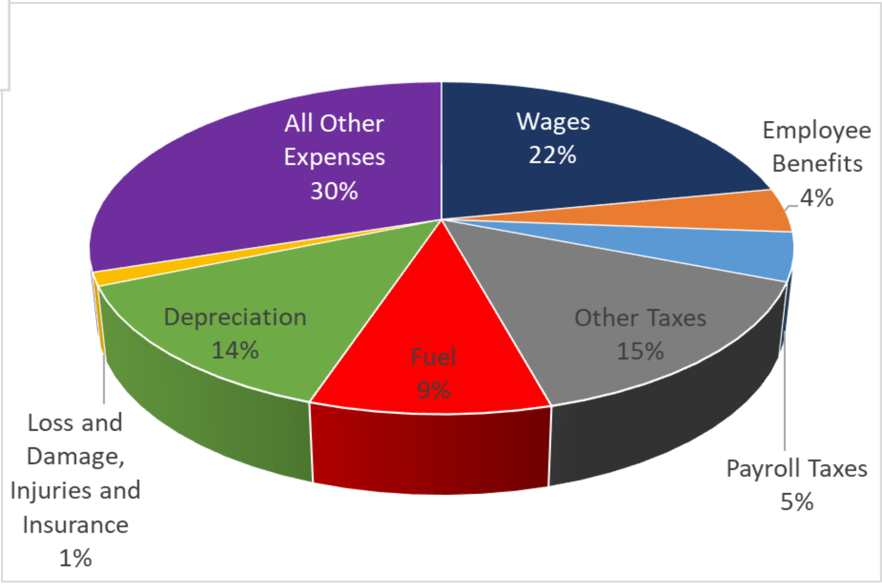
Class I Railroad Fuel Cost



(AAR, 2017)

- Interest from railways in alternatives high when diesel cost high, interest low when diesel cost low
- When diesel cost are high, often fuel surcharges introduced to shippers
- Average railroad diesel price for the last 10 years ~US$2.50 per gallon

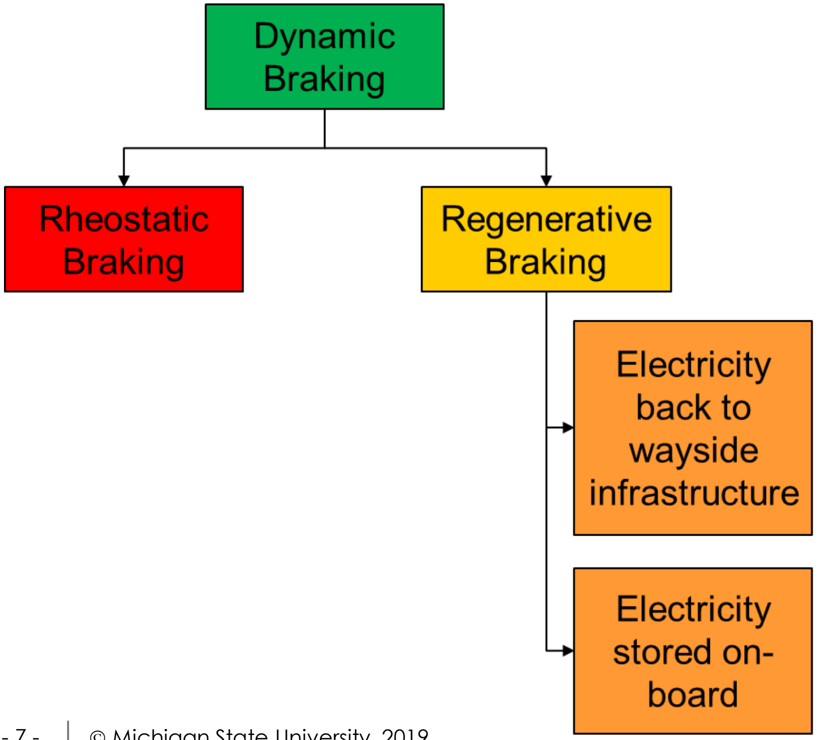
2016



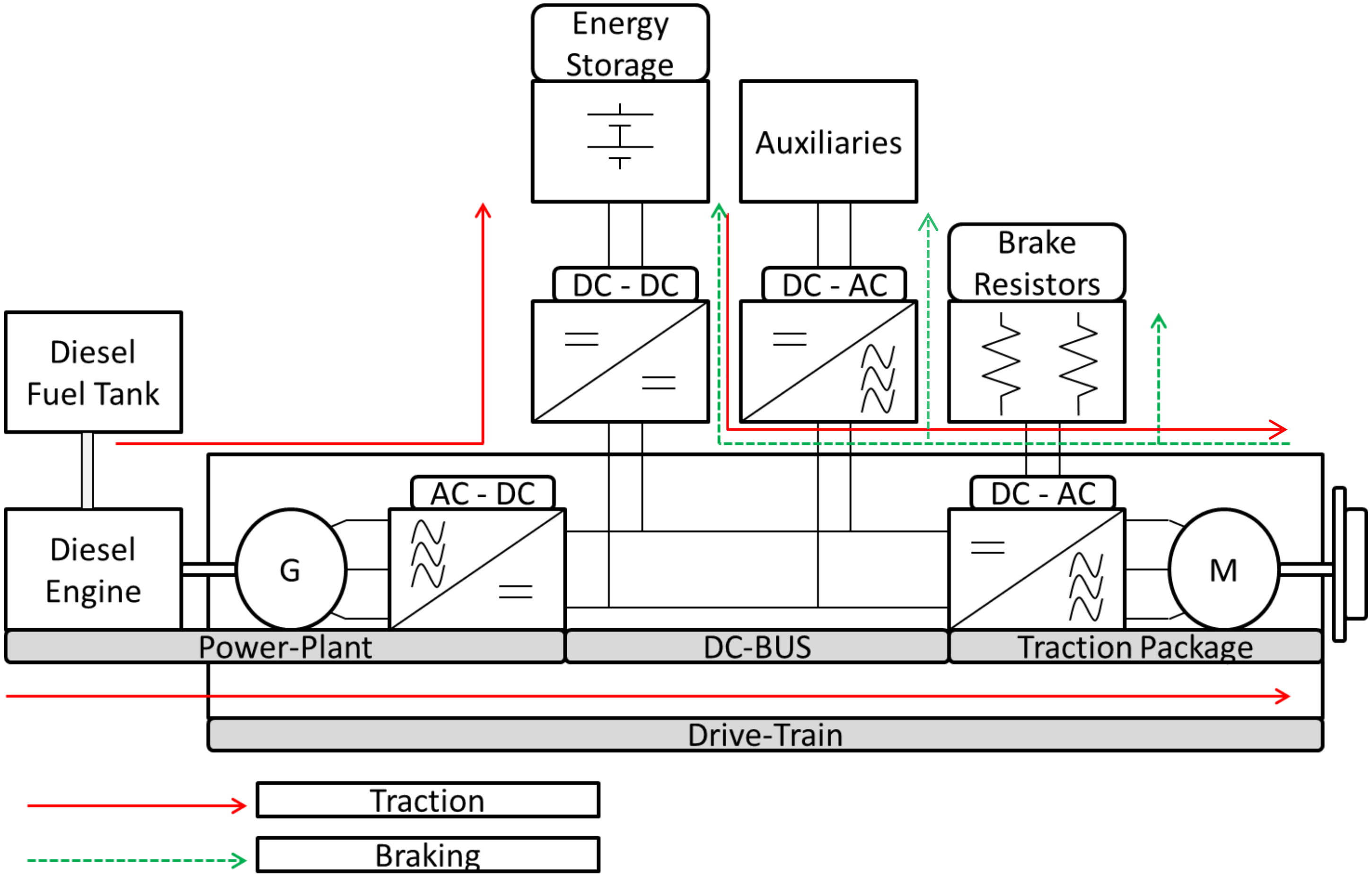
(AAR, 2017)

Dynamic Braking

- Traction motors are used as generators
- Generated electricity is:
  - Converted to heat in resistors, called rheostatic braking
  - Fed back into wayside infrastructure or stored on-board of train, called regenerative braking
- Reduces brake shoe/pad wear, e.g., replacement every 18 month rather than every18 days (UK commuter train example)
- Can reduces energy consumption. Typically ~30% in a regional train service



Energy Storage Hybrid Drive Train



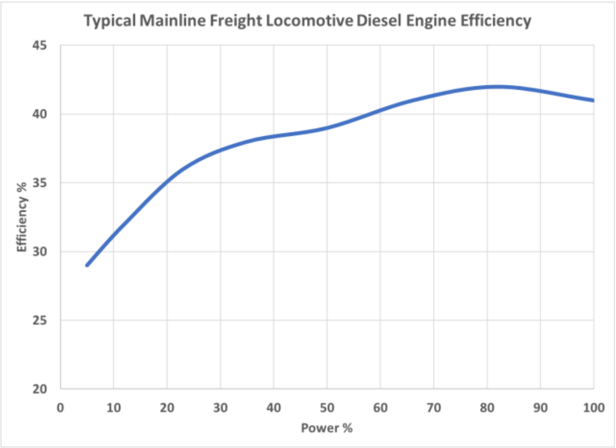
Prime Mover can be:

- Internal Combustion Engine
- Gas Turbine
- Electricity from Infrastructure
- Fuel Cell

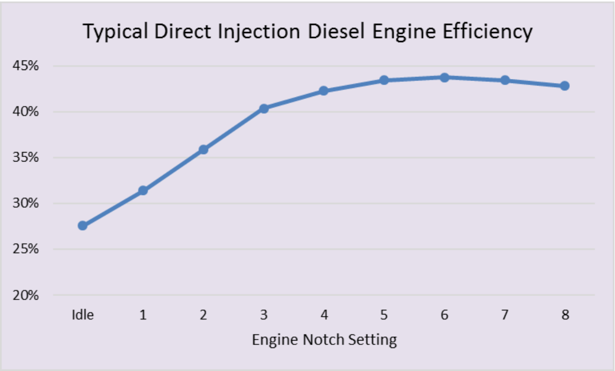
On-Board Energy Storage System (OESS) can be:

- Battery
- Fly Wheel
- Super capacitor

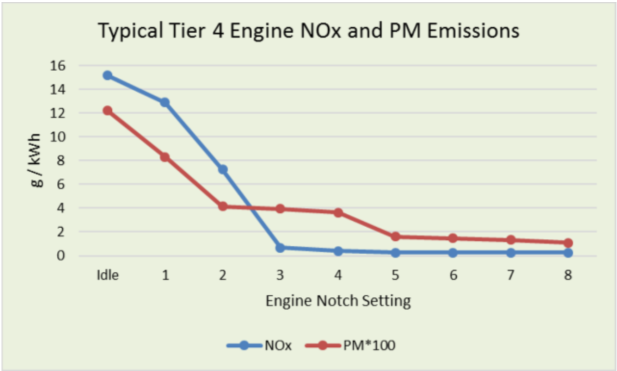
Typical Rail Diesel Engine Efficiency



Simpson (2018)



Bloedt (2019)

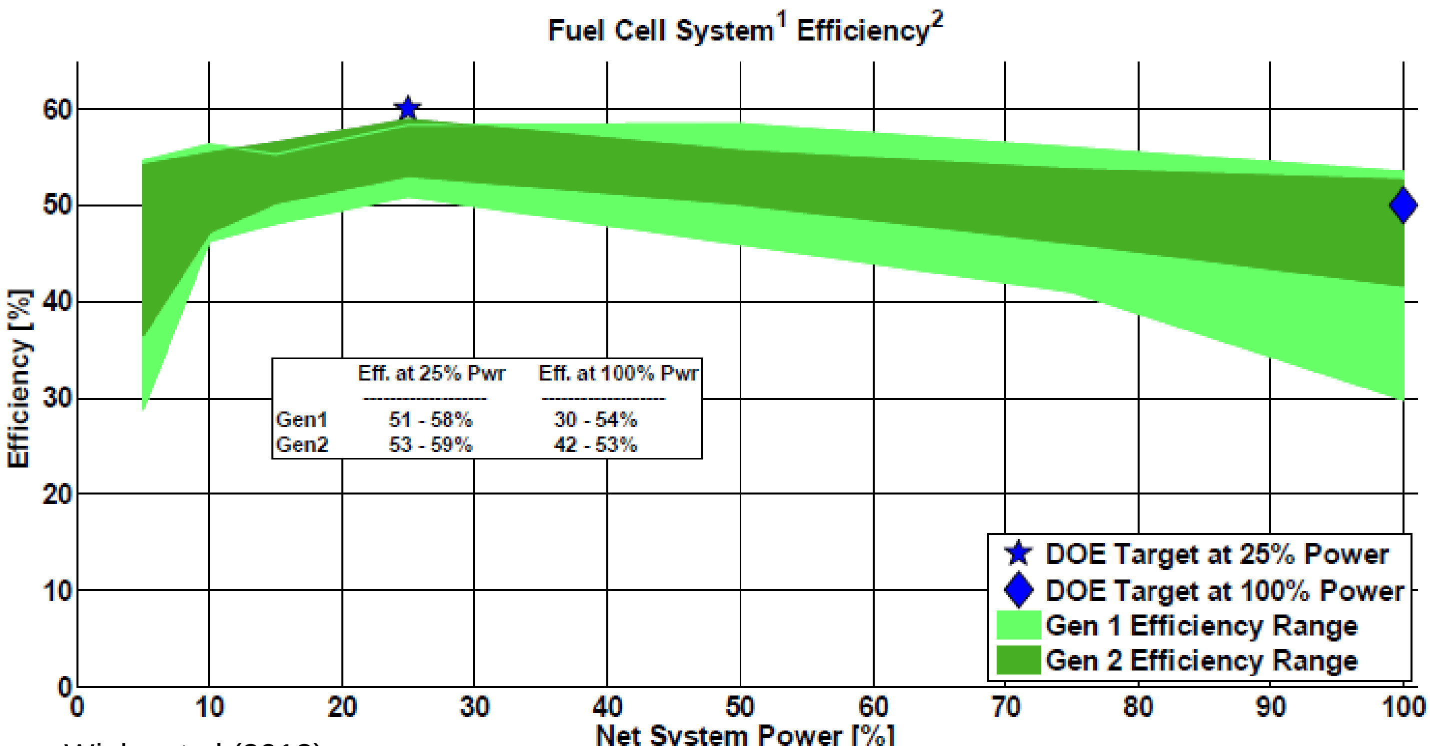


Bloedt (2019)

- Typical mainline locomotive duty-cycle diesel engine efficiency is 30%-34% (3.3MW diesel engine)
- Other drive system components have to be considered as well, including traction motors, gears, etc.
- Typical intercity passenger locomotive duty-cycle powertrain efficiency ~22%-25%
- Head-end power for passenger services is significant, particularly for regional trains, light rail, and streetcars
  - Can be 40%-60% of total energy demand
- Emissions for Tier 4 locomotive engines are lower at higher notch settings (i.e., power output)

Typical Fuel Cell System Efficiency

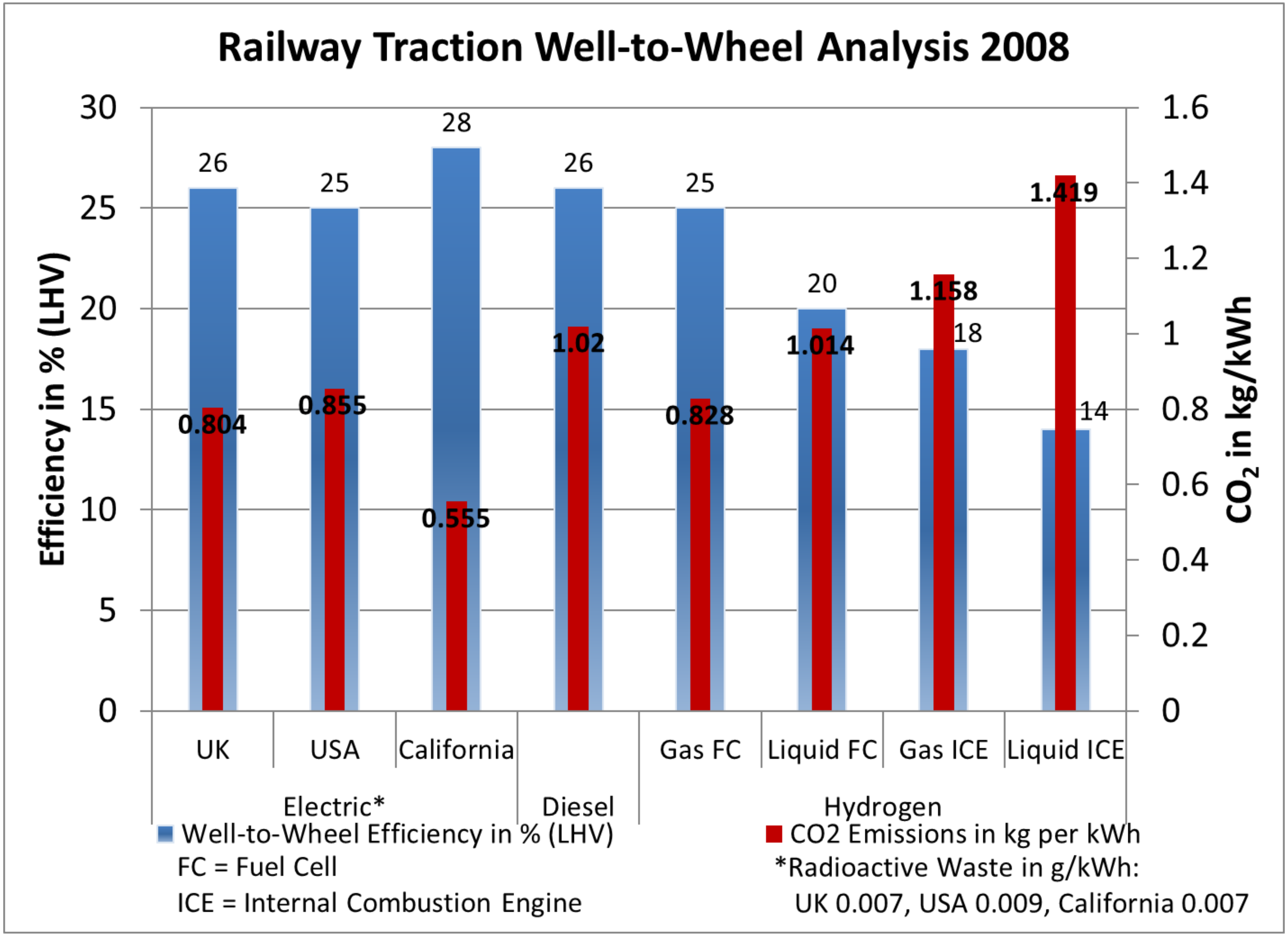
- Duty-Cycle primary powertrain (tank to wheel) system efficiency of ~45% and higher possible (~twice the efficiency of diesel-electric)
- Further efficiency increase / fuel reduction possible, if regenerative braking considered (hybrid)



Wipke et al (2012)

Fuel Cell Efficiency at ¼ Power	60%	57% (average)	--	53% – 59%	51% – 58%
Fuel Cell Efficiency at Full Power		43% (average)	--	42% – 53%	30% – 54%

Kurtz et al (2016)



All hydrogen produced from natural gas through steam-methane reforming

Hoffrichter (2012, 2013)

First Hydrail Locomotive

- First hydrail locomotive, demonstrated in 2002
  - Developed and designed in the U.S. (company later called Vehicle Projects Inc)
  - Mining locomotive
  - Proof-of-concept
  - Non-hybrid
  - PEM fuel cell
  - Metal-hydride storage
  - Replaced battery-powered version due to performance (higher power, longer range, faster refueling)
- Subsequently five mining locomotives for commercial operation in South Africa in 2012
- International hydrail conference series started in 2005
  - Dedicated to connect global experts
  - Raise awareness of technology
  - Created the term 'hydrail' to find developments regarding the technology easily

Source: Vehicle Projects Inc

Source: Vehicle Projects Inc

Passenger Hydrail Development Examples

- JR East railcar trialed in 2006/2007
  - 1 railcar
  - 130 kW Fuel Cell System
  - 350 bar H2 storage
  - 19 kWh battery
  - 100 km/h max. speed
- RTRI railcars, trialed in 2007/2008
  - 2 railcars
  - 120 kW Fuel Cell System
  - 350 bar H2 storage, 18kg H2
  - 36 kWh battery

Other Developments

- Vehicle Projects, BNSF, Army
  - Switch locomotive in 2009
  - 350 bar H2 storage, 68kg H2
  - 250 kW fuel cells
  - 1250 kW battery, lead-acid
- University of Birmingham
  - 1/5th scale locomotive in 2012
  - 1.1 kW fuel cell
  - 4.3 kWh batteries
  - 4.4 kW motors
  - Overall design suitable for full-scale vehicle

Current Developments

- Alstom Coradia iLINT (France/Germany)
- TIG/m streetcars (USA)
  - Plug Power fuel cell system

Photos: Brad Read, TIG/m. TRB Annual Meeting.

- CRRE streetcars/trams (China)
- Other manufactures are developing offerings
  - Siemens
  - Stadler
  - JR East / Toyota
- Projects
  - 3 in the UK, France, Poland, et al
- Canada
  - Some railroads have to pay charges due to higher emissions than allowable to achieve air quality standards in urban areas
  - Incentive of full tax write-off in the year that zero-emission vehicle placed in service

Past Research

- Regional train, several projects
- Mainline freight in Europe
- Well-to-wheel analysis
- Prototype development, design, and construction
- Prototype instrumentation

Current Research

- MSU CRRE involved in several projects with sponsors
  - Freight switcher
  - Regional passenger
  - Intercity type passenger
- Graduate and PhD research*
  - Heavy commuter
  - Regional passenger
  - Mainline freight

Several PhD projects. Many in collaboration with other institutions, including:

- University of California at Davis, Raphael Isaac
- University of British Columbia, Mohamed Hegazi
- University of Warwick, Michael Abbott, Athanasios Iraklis

California: Capitol Corridor

- Route
  - Roseville to San Jose, roundtrip
  - ~500km per roundtrip
  - 2 round trips a day
- Based on locomotive-hauled train with double deck coaches
  - 3 coaches
  - 1 café car
  - 1 cab car
  - Train mass ~ 467t
  - Speed limited by route at max. 79mph
- 3.3 MW locomotive, primarily based on Siemens Charger
  - Diesel-electric (Benchmark)
  - Diesel-hybrid
  - Hydrogen fuel cell (non-hybrid)
  - Hydrogen fuel cell hybrid

Source: Wiki Commons, Jerry Huddleston

Source: Wiki Commons, Pi.1415926535

Results

- Energy consumption reduction
  - Diesel-hybrid ~12%
  - H_2 fuel cell ~28%
  - H_2 hybrid ~38%
- High-level analysis
  - All equipment for hydrogen only and hydrogen-hybrid would fit (compressed H_2 gas storage)
  - Daily refueling possible
  - Similar journey times
  - Hydrogen-only locomotive has ~23% mass reduction, ballast might be needed
  - Hydrogen-hybrid locomotive has ~20% mass reduction, ballast might be needed
  - Locomotive would be taller than Charger but same as current coaches on the route

Conclusions

- Hydrail development since 2002
- Several successful proof-of-concept trials
- Commercial vehicles available for some services
- Technology suitable for many railway services
  - Demonstrator trains needed
  - Government funding needed
- MSU CRRE has expertise to assist with:
  - Techno-economic feasibility studies
  - Development

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