Hydrogen-Rail (hydrail) Development

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Current Rail Energy Efficiency and GHG


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.

<table>
<thead>
<tr>
<th>Duty-Cycle</th>
<th>Tier</th>
<th>Year</th>
<th>HC (g/hp-hr)</th>
<th>NOx (g/bhp-hr)</th>
<th>PM (g/bhp-hr)</th>
<th>CO (g/bhp-hr)</th>
<th>Smoke (percentage)</th>
<th>Minimum Useful Life (hours / years / miles)</th>
<th>Warranty Period (hours / years / miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line-haul</strong></td>
<td>Tier 0</td>
<td>1973-1992</td>
<td>1.00</td>
<td>9.5 [ABT]</td>
<td>0.22 [ABT]</td>
<td>5.0</td>
<td>30 / 40 / 50</td>
<td>(7.5 x hp) / 10 / 750,000</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>1993-2004</td>
<td>0.55</td>
<td>7.4 [ABT]</td>
<td>0.22 [ABT]</td>
<td>2.2</td>
<td>25 / 40 / 50</td>
<td>(7.5 x hp) / 10 / 750,000</td>
<td>(7.5 x hp) / 10 / -</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2005-2011</td>
<td>0.30</td>
<td>5.5 [ABT]</td>
<td>0.10 [ABT]</td>
<td>1.5</td>
<td>20 / 40 / 50</td>
<td>(7.5 x hp) / 10 / -</td>
<td>(7.5 x hp) / 10 / -</td>
</tr>
<tr>
<td></td>
<td>Tier 3</td>
<td>2012-2014</td>
<td>0.30</td>
<td>5.5 [ABT]</td>
<td>0.10 [ABT]</td>
<td>1.5</td>
<td>20 / 40 / 50</td>
<td>(7.5 x hp) / 10 / -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tier 4</td>
<td>2015+</td>
<td>0.14</td>
<td>1.3 [ABT]</td>
<td>0.03 [ABT]</td>
<td>1.5</td>
<td>-</td>
<td>(7.5 x hp) / 10 / -</td>
<td></td>
</tr>
<tr>
<td><strong>Federal</strong></td>
<td>Tier 0</td>
<td>1973-2001</td>
<td>2.10</td>
<td>11.8 [ABT]</td>
<td>0.26 [ABT]</td>
<td>8.0</td>
<td>30 / 40 / 50</td>
<td>(7.5 x hp) / 10 / 750,000</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>2002-2004</td>
<td>1.20</td>
<td>11.0 [ABT]</td>
<td>0.26 [ABT]</td>
<td>2.5</td>
<td>25 / 40 / 50</td>
<td>(7.5 x hp) / 10 / -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2005-2010</td>
<td>0.60</td>
<td>8.1 [ABT]</td>
<td>0.13 [ABT]</td>
<td>2.4</td>
<td>20 / 40 / 50</td>
<td>(7.5 x hp) / 10 / -</td>
<td></td>
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</table>

(EPA, 2016)
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

<table>
<thead>
<tr>
<th>Tier Level</th>
<th>Proposed Year of Manufacture</th>
<th>NOx</th>
<th>PM</th>
<th>GHG</th>
<th>HC</th>
<th>Proposed Effective Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2025</td>
<td>0.2</td>
<td>&lt;0.01</td>
<td>99</td>
<td>10-25%</td>
<td>0.02</td>
</tr>
</tbody>
</table>

With capability for zero-emission operation in designated areas.

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)
• 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
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 every 18 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

- 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)

Simpson (2018)

Bloedt (2019)
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)

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
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**
  - 1/5<sup>th</sup> 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
- 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

Photos: Brad Read, TIG/m. TRB Annual Meeting.
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%
  – H₂ fuel cell ~28%
  – H₂ hybrid ~38%

• High-level analysis
  – All equipment for hydrogen only and hydrogen-hybrid would fit (compressed H₂ 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
References