Overview of Alternative Motive Power and Hydrogen Fuel Cell Propulsion for Rail Vehicles

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AGENDA

- Established Propulsion Systems
- Drivers for Alternative Propulsion Systems
- Wayside Options
- On-Board Options
- Hydrogen Fuel Cell (Hydrail) Option
Contents

• Established Propulsion Systems
  - Wayside Electrification
  - Diesel-Electric
• Drivers for Alternative Propulsion Systems
• Wayside Options
• On-Board Options
• Hydrogen Fuel Cell (Hydrail) Option
Established Propulsion Systems

• Two primary systems:
  - Continuous wayside power supply through electrification infrastructure (Direct Current [DC] or Alternating Current [AC])
  - On-board power supply through diesel engine generator-set

• Wayside Electrification
  - Electrification in specific locations, e.g., Amtrak North East Corridor (NEC) and urban railways, e.g., New York Subway
  - Introduced in 1879 by Siemens
  - Useful for very high speed ( >125mph) railways and high density operation (e.g., 2min headway)

• On-Board Diesel
  - Diesel-Electric system most common in North America (other power transmission systems possible, e.g., diesel-hydraulic for multiple units common in Europe)
  - Electric drive system plus on-board power plant
  - Introduced in 1920s in the USA; prototype operation present previously
3rd Rail Electrification

- Additional rail next to running rails
- Running rails carry return current
- Always DC, typical voltage 600V, 750V
- Comparatively high electrical losses ($I^2R$ losses)
  - Requires many substations where AC is converted to DC (as AC industrial, public grid)
  - No requirement for transformer on-board train
  - Voltage needs to be relatively low as rail is close to the ground to avoid short circuit (arcs)
- Available power is limited (in transit, voltage increases underway on many systems)
- Low clearance requirements
  - Popular with subways - smaller tunnels possible
- Low visual impact
Overhead Contact Systems (OCS)

- Electricity is supplied through an overhead system of wires
- Allows higher voltages than ground-level as can be further away from the ground and other structures
- AC or DC. Modern mainline systems are 25kV, industrial frequency at 50/60Hz AC
- Usually single phase AC (not 3 phase AC)
  - 3 phases require two overhead conductor lines and 3rd phase via running rails
- Lower electrical losses
- Requires transformer on the motive power vehicles
- Visual impact

- Electrification is expensive:
  - ~$2 million per single track kilometer
  - Cost varies significantly with region
  - More in urban environments, less rural if power supply available
  - Cost varies with type of electrification
  - Most electrification schemes have been supported by the government (e.g., for energy security)
Diesel-Electric Motive Power

- Most diesel railway vehicles are diesel-electric
- An electric locomotive with its own power-plant (diesel engine generator-set)
- Many components the same as in wayside electric motive power vehicle

DC Traction Motors

AC Traction Motors
Internal Combustion Engines

• Two main types:
  - Spark Ignition (Otto Cycle), rarely used in rail
  - Compression Ignition (Diesel Cycle)

• Diesel Engine
  - Popular in railway applications
  - Compressed air and associated heat ignites fuel
  - High efficiency
    • max. ~45% in rail applications
    • duty cycle lower, typically between 18%-25%
    • Efficiency limited by the Carnot Cycle
  - Produces high amount of torque, which is useful in rail
  - Diesel fuel combustion with air leads to emissions that impact local air quality as well as results in Greenhouse Gas (GHG) emissions
Contents

• Established Propulsion Systems
• Drivers for Alternative Propulsion Systems
  – Cost
  – Local Emissions / Air Quality
  – Greenhouse Gas Emissions
  – Combustion of Hydrocarbons
• Wayside Options
• On-Board Options
• Hydrogen Fuel Cell (Hydrail) Option
Drivers for Alternative Motive Power

Two main drivers:

1. Cost
   - Fuel cost
   - Increase propulsion system efficiency to reduce consumption
   - Infrastructure cost, particularly for electrification
   - Energy security

2. Emissions
   - To comply with regulation and improve local air quality
   - Operational constraints (e.g., long tunnels)
   - Visual impact, particularly for overhead electrification

- Sometimes Performance
  - Acceleration
  - Tractive effort
  - Power
  - Electrification almost never commercially viable on sole performance increase but might be only option, e.g., very high speed trains
Class I Railroad:
Fuel as Percentage of Operating Expenses

Source: AAR (2017) Railroad Facts
Exhaust Emissions

• Nitrous Oxide ($N_2O$) causes SMOG
• Particulate Matter (PM) causes cancer
• Legislation limits amount of allowable emissions
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>
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<tbody>
<tr>
<td><strong>Federal</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>1/3 * Useful Life</td>
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<td></td>
<td>Tier 1</td>
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<td>0.55</td>
<td>7.4 [ABT]</td>
<td>0.22 [ABT]</td>
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<td>25 / 40 / 50</td>
<td>(7.5 x hp) / 10 / 750,000</td>
<td>1/3 * Useful Life</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>1/3 * Useful Life</td>
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<td>Tier 3</td>
<td>2012-2014</td>
<td>0.30</td>
<td>5.5 [ABT]</td>
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<td>(7.5 x hp) / 10 / -</td>
<td>1/3 * Useful Life</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>1/3 * Useful Life</td>
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<tr>
<td><strong>Switch</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>
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<td>(7.5 x hp) / 10 / 750,000</td>
<td>1/3 * Useful Life</td>
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<tr>
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<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>1/3 * Useful Life</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>1/3 * Useful Life</td>
</tr>
<tr>
<td></td>
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<td>1/3 * Useful Life</td>
</tr>
</tbody>
</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 Standard (g/bhp-hr)¹</th>
<th>Percent Control¹</th>
<th>PM Standard (g/bhp-hr)¹</th>
<th>Percent Control¹</th>
<th>GHG Standard (g/bhp-hr)¹</th>
<th>Percent Control¹</th>
<th>HC Standard (g/bhp-hr)</th>
<th>Percent Control¹</th>
<th>Proposed Effective Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2025</td>
<td>0.2</td>
<td>99+</td>
<td>&lt;0.01</td>
<td>99</td>
<td>NA</td>
<td>10-25%</td>
<td>0.02</td>
<td>98</td>
<td>2025</td>
</tr>
</tbody>
</table>

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)
Greenhouse Effect / Gases

• Solar radiation either
  – reflected back into space or
  – absorbed by Earth

• Planet releases some energy back into the atmosphere as infrared radiation (heat)

• Infrared radiation is released
  – Some into space
  – some absorbed by Greenhouse Gases (GHGs)
    • slow or prevent heat release to space

• Absorbed energy by GHGs is re-emitted, warming Earth’s surface and the lower atmosphere

• This cycle is called the Greenhouse Effect

(EPA, 2014)

Major GHGs:
Water Vapour (H₂O)
Carbon Dioxide (CO₂)
Methane (CH₄)
Nitrous Oxide (N₂O)
Global Warming

• Many GHGs occur naturally and they are part of the natural greenhouse effect
  - water vapour H₂O (water cycle)
  - carbon dioxide CO₂ (carbon cycle)

• GHGs have different impact on the greenhouse effect
  - Water vapour is the most abundant GHG and the most important in the natural greenhouse effect
  - Global concentration of water vapour is not substantially affected by human activity

• Human activities add GHGs, such as
  - Carbon dioxide (CO₂)
  - Methane (CH₄)
  - Nitrous Oxide (N₂O)
  - Sources include:
    - fossil fuel combustion
    - agricultural activity
    - Electric sparks and arcs (N₂O), e.g., in substations

• Observations and models show that average global temperature has been rising

• Most scientist (~97%) agree that the temperature rise is due to higher concentrations of GHGs in the atmosphere, in particular CO₂
Global Warming Potential (GWP)

- Each GHG
  - absorbs a different amount of heat
  - remains in the atmosphere for a different amount of time

- GWP allows comparison of global warming impact of different GHGs
  - CO₂ has GWP of 1
  - CH₄ has GWP of 28-36
  - N₂O has GWP of 265-298

- Often impact of all GHG associated with an activity is expressed in CO₂ equivalent (CO₂-eq, CO₂e)

Change of GHG concentration in the atmosphere over the last 2000 years (EPA, 2009)
Hydrocarbon Fuel Combustion

- Hydrocarbons are fuels that consist of carbon and hydrogen, e.g.,
  - Natural Gas
  - Petroleum
    - Gasoline
    - Diesel
  - Coal

- Combustion of fuel is a chemical process, with

  - **Reactants:**
    - Hydrocarbon (fuel)
    - Oxygen (from air)

  - **Product:**
    - Water
    - Carbon Dioxide

- A perfect fuel and oxygen mixture is called stoichiometric combustion

  - Pure, exact amount of chemicals is present to achieve the stoichiometric reaction
**Stoichiometric Combustion**

**Example:**
Combustion of one mole methane with oxygen

\[ CH_4 + 2O_2 = CO_2 + 2H_2O \]

- \( CH_4 \) = methane
- \( O_2 \) = oxygen
- \( CO_2 \) = carbon dioxide
- \( H_2O \) = water

- In most practical applications, including the railway, this is not possible
  - Pure chemicals are not present e.g., air instead of pure oxygen
  - Results in emissions
Petroleum-Based Fuels

- Mixed hydrocarbon fractions $C_a H_b$

- $CO_2$ is linearly proportional to fuel consumption
  - Diesel: $\sim 2.68$ kg of $CO_2$ per litre of fuel
# Composition of Air

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Composition by Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen ($N_2$)</td>
<td>~78%</td>
</tr>
<tr>
<td>Oxygen ($O_2$)</td>
<td>~21%</td>
</tr>
<tr>
<td>Other gases, of which</td>
<td>~1%</td>
</tr>
<tr>
<td>e.g., $CO_2$</td>
<td>~0.03%</td>
</tr>
<tr>
<td>e.g., $CH_4$</td>
<td>~0.0002%</td>
</tr>
</tbody>
</table>
Combustion with Air

**Oxides of Nitrogen**

- At high temperatures air reacts with itself
  - Oxygen + Nitrogen → NOx
  - Mostly N₂O, NO, and NO₂

- Reduction strategies
  - Lower combustion temperature
  - Reduce excess oxygen
  - After-treatment solutions

- In a Diesel engine
  - Exhaust gas displaces excess air through Exhaust Gas Recirculation (EGR)
    - Less spare oxygen
    - Less nitrogen
    - Therefore less NOₓ
  - Selective Catalytic Reduction (SCR)
    - After-treatment solution
    - Chemical (Urea, Diesel Exhaust Fluid [DEF]), primarily ammonia (NH₃) and CO₂, added to the exhaust gas to convert NOₓ to nitrogen, water and small amounts of CO₂
Incomplete Combustion

Carbon-Based Emission

- Results in other emission than water and CO$_2$
  - Hydrocarbon (HC), i.e., unburned fuel
  - Pure carbon
    - Soot
    - Particulate Matter (PM)
  - Carbon Monoxide (CO)

- After-treatment essentially tries to complete the combustion process

- Reduction options for PM emissions:
  - Increase oxygen content by reducing EGR
    - But then NO$_x$ levels increase
  - Oxidise with controlled combustion in after-treatment
    - Diesel Particulate Filter with regeneration strategy (burn carbon off at frequent intervals)

- High EGR levels increase soot build-up
  - Can cause premature component failure
Two Main Alternatives

• Wayside power supply
  – Inductive loops to avoid visual impact and increase robustness (particularly relevant for light rail)
  – Advanced ground level electrification to reduce visual impact (particularly relevant for light rail)
  – Linear motors, improves performance and does not rely on wheel-rail interface for motive power
  – Magnetic levitation, improves performance and does not rely on wheel-rail interface

• On-board power supply
  – Energy storage devices, e.g., flywheel, batteries, supercapacitors. Reduce energy consumption and allow a certain independent operating range away from primary power sources
  – Alternative fuels or energy carriers, e.g., natural gas, biodiesel, ethanol, hydrogen. Reduce cost or emissions or both
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• Drivers for Alternative Propulsion Systems
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  – Advanced Ground-Level Electrification
  – Linear Motors
  – Magnetic Levitation (Maglev)
• On-Board Options
• Hydrogen Fuel Cell (Hydrail) Option
Wayside: Inductive Loops

- Electricity supply to vehicles is through inductive loops in the ground
- No overhead or 3rd rail necessary
- Reduces visual impact significantly
- Increases resilience through covered infrastructure
- Currently, more expensive than conventional electrification
- Also used for buses and cars
- Example: Augsburg tram, Nanjing tram

Video: Bombardier (2012) Primove: Game-changing turnkey solution for tram systems
Wayside: Advanced Ground Level Electrification

- Uses a 3rd rail that is buried in the ground
- Only energized when the vehicle is on top of it
- Reduces visual impact
- Currently, significantly more expensive than conventional overhead electrification
- Example: Bordeaux Tram
Wayside: Linear Motors

- Traction motor is split into two parts
  - One is installed on the vehicle
  - One is installed on the track
- Reduces visual impact
- Improves performance as no longer dependent on wheel-rail adhesion
- Also used in magnetic levitation vehicles
- Currently, significantly more expensive than conventional electrification
- Example: Vancouver Skytrain
Wayside: Magnetic Levitation (MagLev)

• Uses electromagnets instead of wheels to guide the vehicle, provide motive power, and transfer loads
• Magnets on the train and in the track
• Improves performance as no longer relies on wheel-rail interface
• Technology is not new, has been developed and been in operation since the 1980s in low-speed operation
• Allows for very high speeds
• Currently, extremely expensive
• Example: Shanghai airport link

Video: Tongtech (2009) How the Shanghai Maglev Transrapid works
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• Wayside Options
• On-Board Options
  - Energy Density of Energy Storage
  - Potential for Regenerative Braking
  - Genset Locomotives
  - Energy Storage Hybrids
  - Bio-Fuel
  - Natural Gas
• Hydrogen Fuel Cell (Hydral) Option
On-Board: Gensets

- Locomotives that have more than one diesel engine generator-set (genset), usually three
  - Individual gensets are turned on or off depending on power demand
- Can reduce emissions
- Can reduce fuel consumption
- Traction and drive system control for quick response and sustained tractive effort essential
- May result in lower reliability as three rather than one genset
- May result in higher reliability if designed accordingly as failure of one genset still allows operation of the locomotive at lower power rating and ‘limp home’ mode

Energy Density Comparison

(IEA, 2009)
Regenerative Braking

- Kinetic energy converted into electrical in traction motors during braking
- Electricity either returned to wayside infrastructure or stored on-board
- Potential for energy recovery largely dependent on duty cycle
- Frequent braking events, e.g., for station stops, have high potential
- Speed less important
On-Board: Energy Storage Hybrids

• A hybrid vehicle has a primary power plant and an on-board energy storage device

• Primary power-plant
  - Transformer (Wayside electrification)
  - Combustion engine
  - Turbine
  - Fuel cell

• Storage device
  - Batteries
  - Flywheels
  - Supercapacitors

• For most duty cycles, allows downsizing of primary power-plant, e.g., diesel engine

• Allows regenerative braking

• Enables full electric operation for a specific period

• Reduces fuel consumption and emissions, local and GHG

• Used in several applications:
  - Switching (significant downsizing of diesel engine possible)
  - Regional trains (significant reduction in energy consumption)
  - Light rail, to overcome gaps in wayside infrastructure
On-Board: Energy Storage Only

- Currently, most energy storage devices (batteries, flywheels, supercapacitors) do not allow a long operating time/range
- Primary application in hybrids
- Some battery-only application
  - Freight, limited, e.g., Norfolk Southern 999
- Significantly higher cost compared to diesel
- No emissions
- Similar or better performance than diesel or wayside electric
- Long recharge time for full charge
- Partial electrification possible
- Opportunity charging possible for some duty cycles

Alternative Fuel: Bio-Fuel

- Attractive option due to relatively high energy density per volume compared to alternatives
- Possible reduction in cost
- Possible reduction in emission
- Overall effect on the environment largely dependent on source for bio-fuel (e.g., biodiesel & ethanol)
- Several trials, globally, where conventional diesel was blended with bio-fuel
  - Typical contribution of bio-fuel 20-30%
- Blended approach common for current diesel fuel
  - U.S. has a large, if not the largest, biofuel contribution to diesel fuel for rail applications
- Example: Amtrak trial on Heartland Flyer with 20% biofuel

Alternative Fuel: Natural Gas

- Reduces GHG emissions, not necessarily all local emissions, depending on after-treatment (still combustion with air)
- Can take advantage of relatively low fuel cost
- Prime mover can be
  - Compression ignition engine
  - Spark ignition engine
  - Turbine

- Compressed natural gas (CNG)
  - Limited operating range
  - Suitable for switching, road-switching, maybe shortline use
  - Technology less complex than LNG

- Liquefied natural gas (LNG)
  - Similar operating range with a tender
  - Requires a specific ratio of diesel to operated, e.g., 20% diesel
  - Suitable for long-haul

- Typically efficiency slightly lower than diesel (~2-3, percentage points)
Alternative Fuel: CNG

- Several projects world-wide
- CNG usually used in spark ignition engines
- CNG is usually stored on the motive power vehicle but might have a tender to extend range

- Examples:
  - Napa Valley Wine train
  - Russian Railways
  - Norfolk Southern
  - Indiana Harbor Belt
Alternative Fuel: LNG

- Significant interest in LNG
- Can reduce local and GHG emission for line-haul locomotives
- Can reduce operating cost
- Several projects globally
  - Russia, use of gas turbine
  - North America, use of compression ignition/diesel engine
    - Most Class Is have trial projects
    - Regional railroads
- EMD and GE offer conversion kits
- Requires a tender car for acceptable range
- Typically a 20% diesel, 80% natural gas mix; diesel at low notch setting and to start the engine
- Florida East Coast Railway converted entire mainline fleet to LNG
  - In full operation now
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• Established Propulsion Systems
• Drivers for Alternative Propulsion Systems
• Wayside Options
• On-Board Options

• Hydrogen Fuel Cell (Hydrail) Option
  - Hydrogen as an Energy Carrier
  - Fuel Cell and Drive System Design
  - Example Projects
Fuels/Energy Carries That Have No Carbon

- Only two chemical fuels/energy carriers that do not contain carbon
  - Hydrogen
  - Ammonia (NH₃)
- Ammonia combustion possible but produces NOₓ
- Hydrogen
  - Energy carrier, like electricity, has to be produced from something else, e.g., hydrocarbons, water
  - Most common element in the universe and very common on Earth
  - Highest energy density by mass but low by volume
  - Can be used in combustion engine but more commonly in fuel cells as more efficient
  - No harmful emissions at the point-of-use, only water vapor
  - Reduction of GHG if produced from Natural Gas but potential to avoid GHG if produced from renewables

Hydrogen Fuel Cell-Hybrid

- Hybrid drive system
  - Fuel cell power plant
  - On-board energy storage, e.g., batteries
- Power plant meets average power
- Energy storage allows regenerative braking and meets peak power
- Hydrogen storage for long range
- Duty-Cycle Primary Drive System efficiency of 45% possible (~twice the efficiency of diesel-electric)
- Further efficiency increase / fuel reduction possible, if regenerative braking considered


Alternative: Hydrail

• Increasing interest globally
  – Primarily light rail and regional trains
  – Metrolinx in Toronto is considering high-power commuter rail vehicles, e.g., locomotives
• Several studies show viability
• Several proof-of-concept demonstration projects in the past, e.g.,
  – Vehicle Projects / BNSF switch locomotive
  – Railcars in Japan
• Commercial vehicles now available
  – Alstom regional train
  – Streetcars from CRRC and TIG/m
• No harmful local emissions (water, water vapor)
• Can reduce GHG emissions (well-to-wheel)
• Can reduce fuel consumption
• Example UK study (hydrogen produced from natural gas):
  – 55% fuel reduction compared to diesel
  – 72% CO₂ reduction compared to diesel
• Typical energy saving from several studies show range from 20% to 50%, depending on the duty cycle

Video: University of Birmingham (2012) UoB Hydrogen Locomotive
Hydrail: Alstom iLint

- Range 600 km – 800 km
- Refueling ~15 min, once a day
- 350 bar tanks
- ~180 kg hydrogen storage
- ~40% CO₂ reduction if hydrogen from natural gas
  - zero CO₂ if renewable, ‘green’ hydrogen
- Power per two car train
  - 2 x 200 kW fuel cell
  - 2 x 225 kW battery power
- Maximum speed 140 km/h (~87 mph)

Source: Ernst & Young (2016) Ergebnisbericht Studie Wasserstoff-Infrastruktur fuer die Schiene

Video: Alstom (2017) Alstom’s hydrogen train Coradia iLint first successful run at 80km/h
Summary

• Most established drive systems are electric, either power is supplied through wayside electrification or on-board diesel engine generator set
• Electrification has best performance of conventional systems
• Electrification is expensive but at a certain, high number of trains cheaper than the other options
• Main drivers for alternative propulsion are cost and emissions
• Alternatives to established systems can be wayside or on-board systems
  – Wayside alternatives are usually more expensive than conventional electrification
  – On-board alternatives address cost and emissions in varying degrees
• Hybrids can reduce emissions and operating cost while retaining diesel engine or utilize an alternative power plant
• Alternative fuels/energy carriers have potential to reduce fuel consumption, cost, and emissions
• Hydrogen fuel cell propulsion system for railway applications (Hydrail) is being introduced in Light Rail and Regional Passenger Service
• Hydrail is technically feasible for switch, road-switch, and commuter rail services
• Hydrail is possibly feasible for mainline intercity freight and long-distance passenger service (depends on duty cycles, refueling arrangements, and business case)
Thank You

Questions?

E-Mail: andreash@msu.edu
Bibliography


International Railway Journal (IRJ): Various Issues


Railway Gazette International: Various Issues

Trains Magazine: Various Issues

Videos


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