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

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WHO WILL MAKE BUSINESS HAPPEN?
**SPARTANS WILL.**

# 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

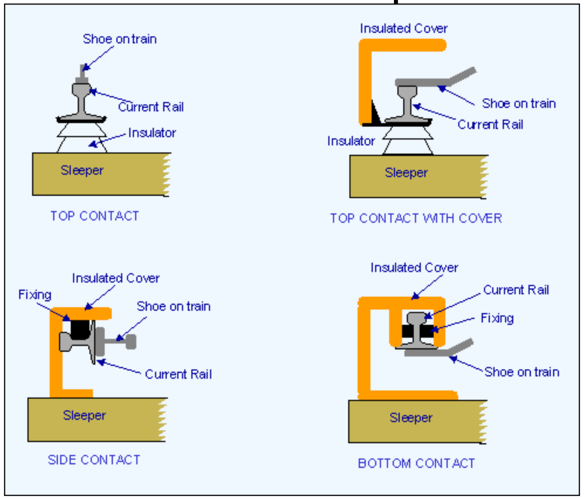
Replica of Siemens Electric Railway 1879, 3rd rail supply

Model of Edison (GE) Electric Railway 1880, running rail supply


First commercially successful diesel-electric locomotive 1924, built be GE, Ingersoll-Rand, & Alco

# 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







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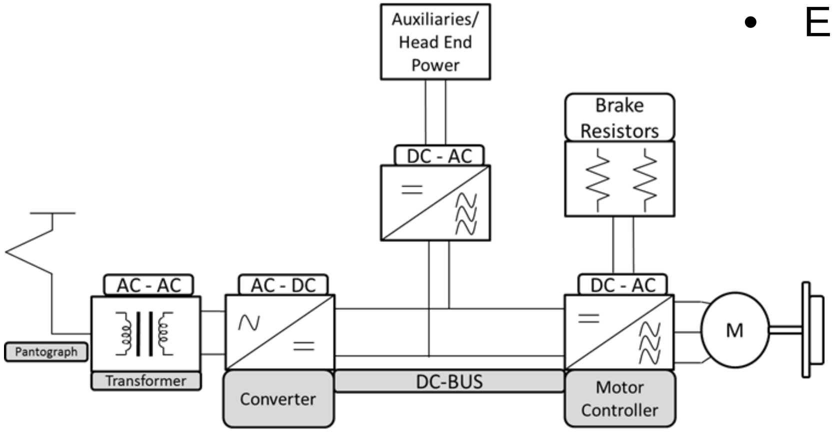
# Overhead Contact Systems (OCS)

- 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


Source: Ryan Stavely - ACS-64 Take 2Uploaded by Mackensen, https://commons.wikimedia.org/w/index.php?curid=31069155

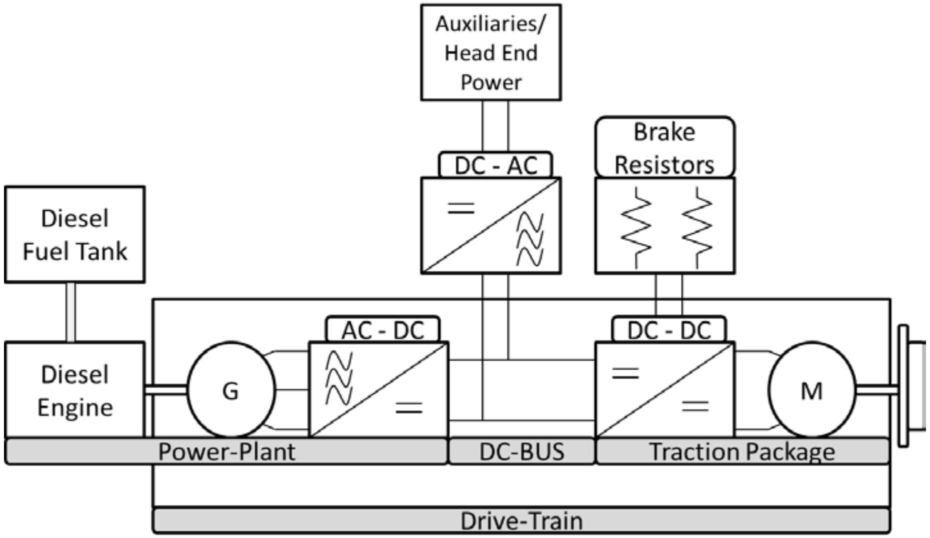



- Electrification is expensive:
  - ~$2 million per single track kilometer
  - Cost varies significantly with region
  - More in urban environments, less rural if power supply available
  - Cost varies with type of electrification
  - Most electrification schemes have been supported by the government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

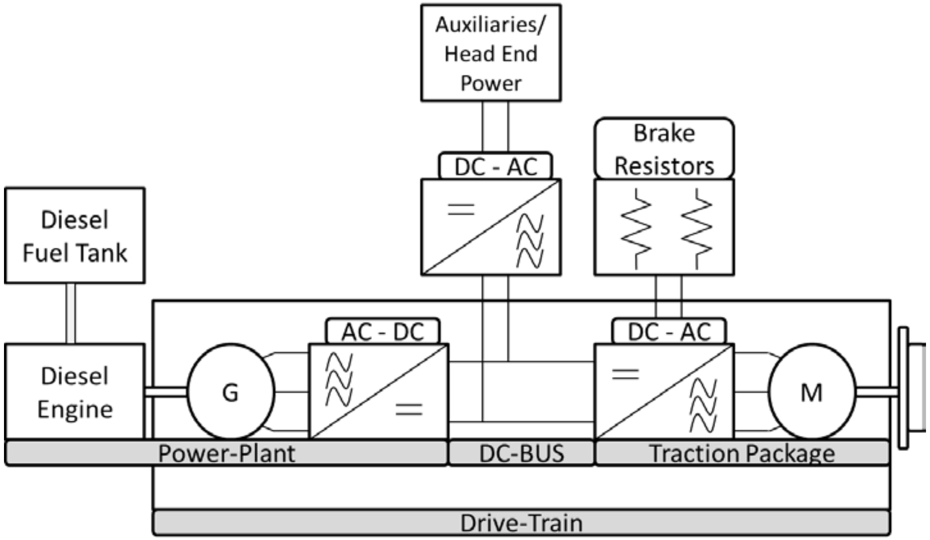
# Diesel-Electric Motive Power

- Most diesel railway vehicles are diesel-electric
- An electric locomotive with it's 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

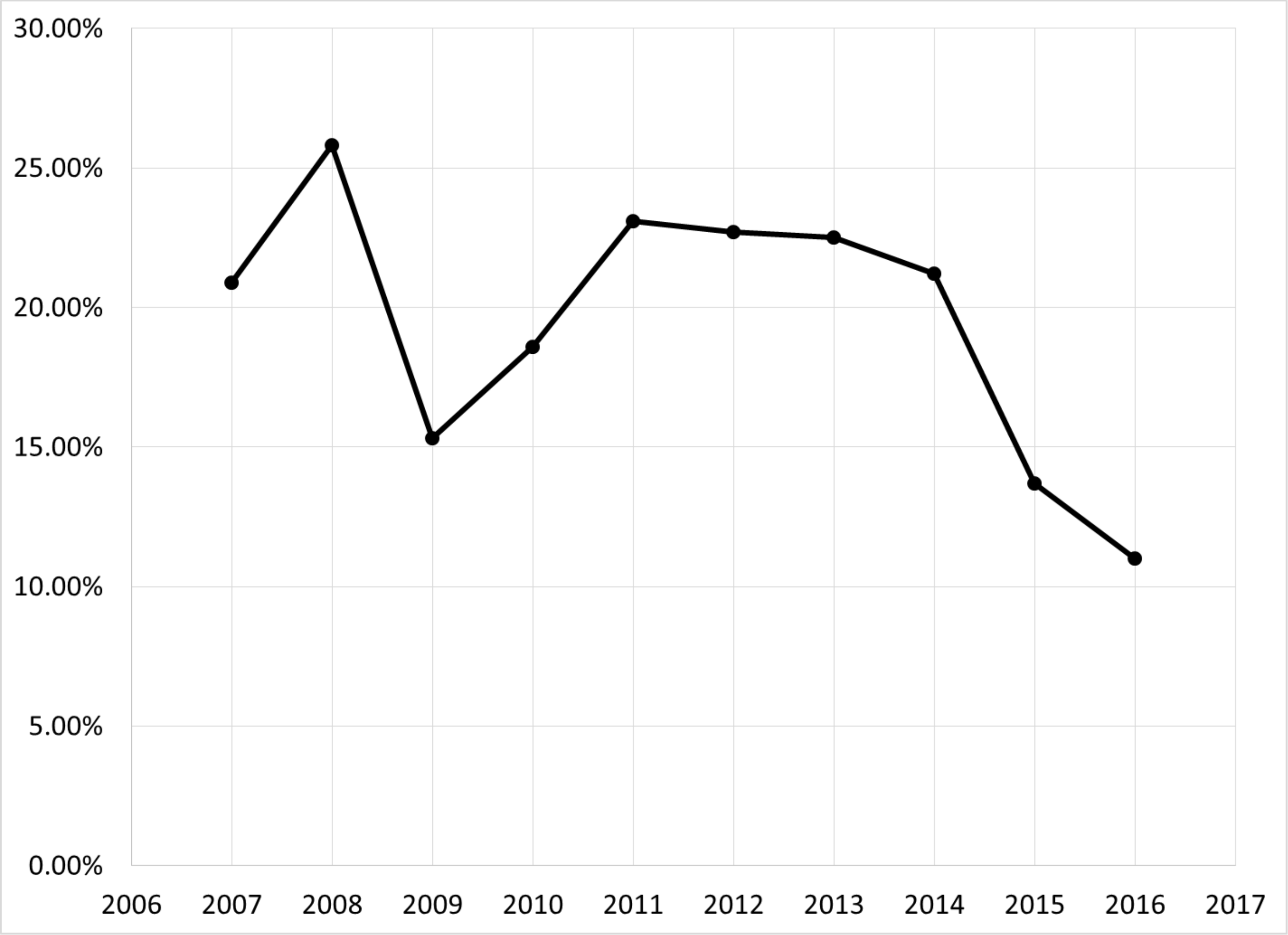
# Drivers for Alternative Motive Power

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

| | 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]<br>(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)

 

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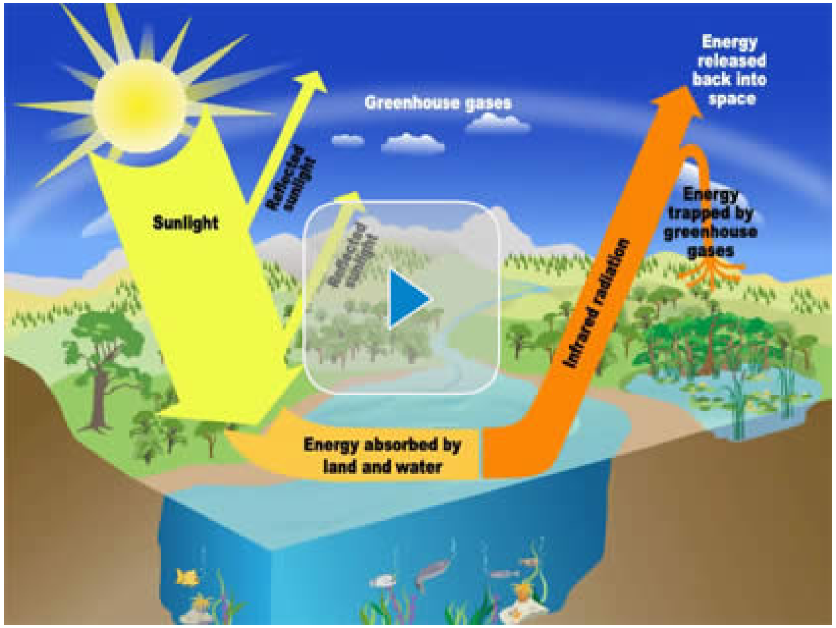
# Greenhouse Effect / Gases

- 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:**

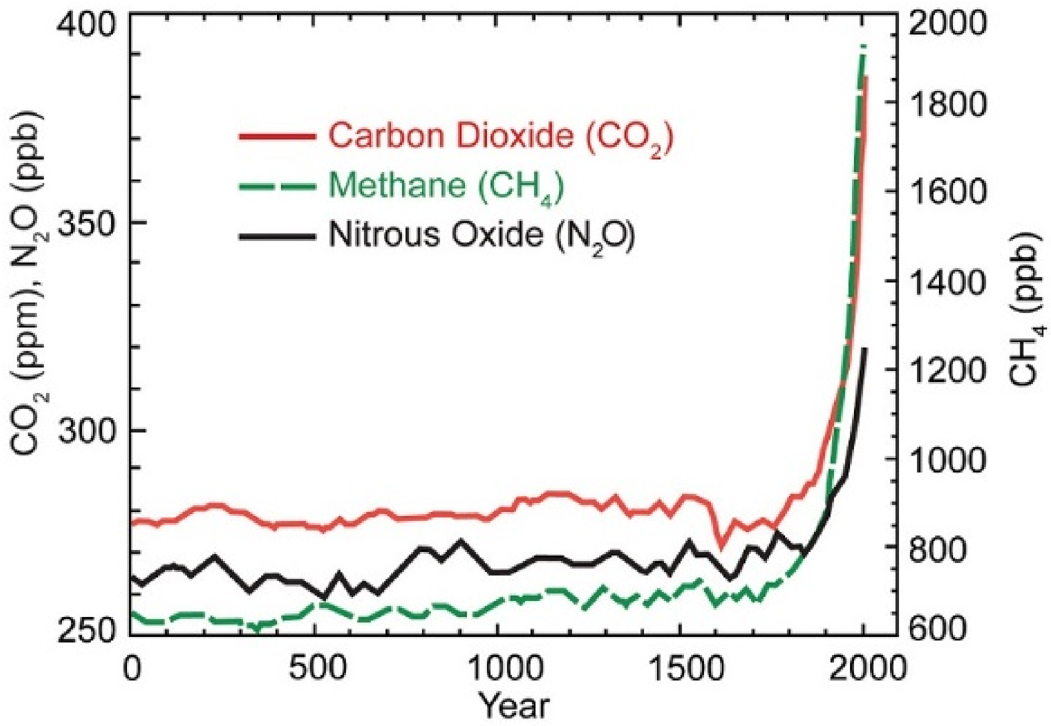
Water Vapour ($H_2O$)
Carbon Dioxide ($CO_2$)
Methane ($CH_4$)
Nitrous Oxide ($N_2O$)

# Global Warming

- Many GHGs occur naturally and they are part of the natural greenhouse effect
  - water vapour $H_2O$ (water cycle)
  - carbon dioxide $CO_2$ (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 ($CO_2$)
  - Methane ($CH_4$)
  - Nitrous Oxide ($N_2O$)
  - Sources include:
    - fossil fuel combustion
    - agricultural activity
    - Electric sparks and arcs ($N_2O$), 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 $CO_2$

# 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
  - $CO_2$ has GWP of 1
  - $CH_4$ has GWP of 28-36
  - $N_2O$ has GWP of 265-298
- Often impact of all GHG associated with an activity is expressed in $CO_2$ equivalent ($CO_2$-eq, $CO_2$e)




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

  - <u>Reactants</u>:
  - Hydrocarbon (fuel)
  - Oxygen (from air)

  - <u>Product</u>:
  - 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

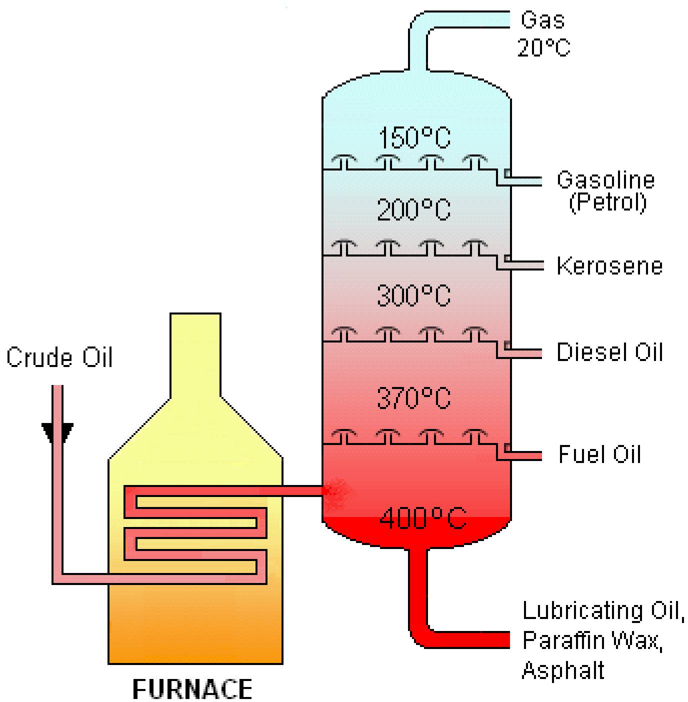
$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

$CH_4$ = 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 $C_aH_b$




Gasoline $\sim C_nH_{2.25\,n}$

Diesel $\sim C_nH_{2.12\,n}$

*Chemical Formula of Fuels*

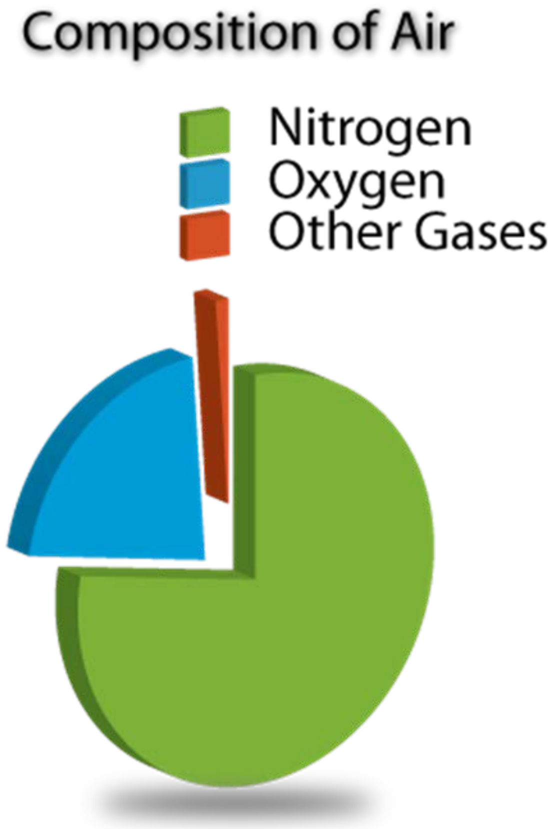
| Fuel | Chemical Formula |
|---|---|
| Hydrogen | H |
| Natural Gas / Methane | $CH_4$ |
| Propane | $C_3H_8$ |
| Gasoline (isooctane) | $C_8H_{18}$ |
| Diesel | $C_{16}H_{34}$ |

- $CO_2$ is linearly proportional to fuel consumption
  - Diesel: ~2.68 kg of $CO_2$ per litre of fuel

# Composition of Air

| Chemical | Composition by Volume |
|---|---|
| Nitrogen ($N_2$) | ~78% |
| Oxygen ($O_2$) | ~21% |
| Other gases, of which | ~1% |
| e.g., $CO_2$ | ~0.03% |
| e.g., $CH_4$ | ~0.0002% |



# Combustion with Air

## Oxides of Nitrogen

- At high temperatures air reacts with itself
  - Oxygen + Nitrogen -> NOx
  - Mostly $N_2O$, NO, and $NO_2$
- 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 $NO_x$
  - Selective Catalytic Reduction (SCR)
    - After-treatment solution
    - Chemical (Urea, Diesel Exhaust Fluid [DEF]), primarily ammonia ($NH_3$) and $CO_2$, added to the exhaust gas to convert $NO_x$ to nitrogen, water and small amounts of $CO_2$

# 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

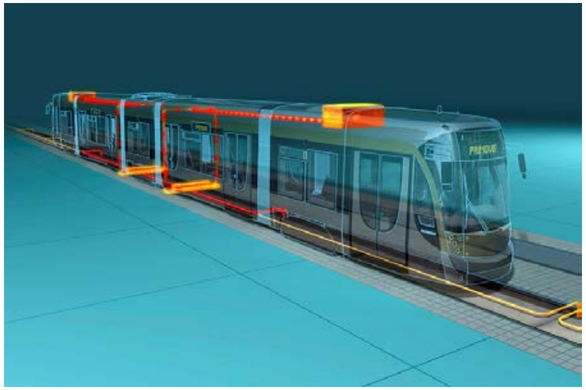
# Two Main Alternatives

- 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, bio-diesel, ethanol, hydrogen. Reduce cost or emissions or both

# Contents

# 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

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# 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]

# Contents



 

# 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


Source: By Roy Luck - Flickr: Union Pacific Genset switcher, Eureka Yard, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=16097400

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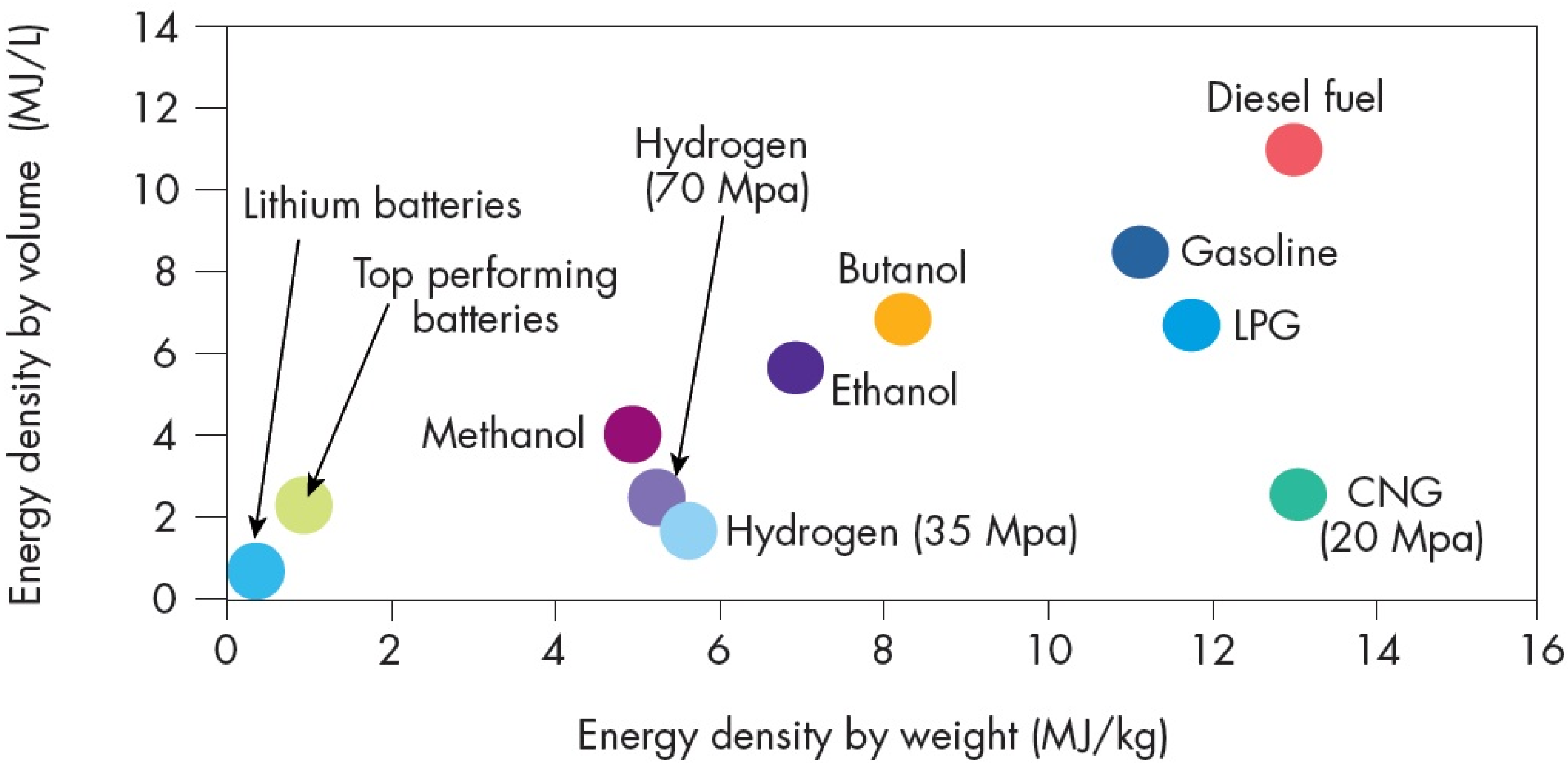
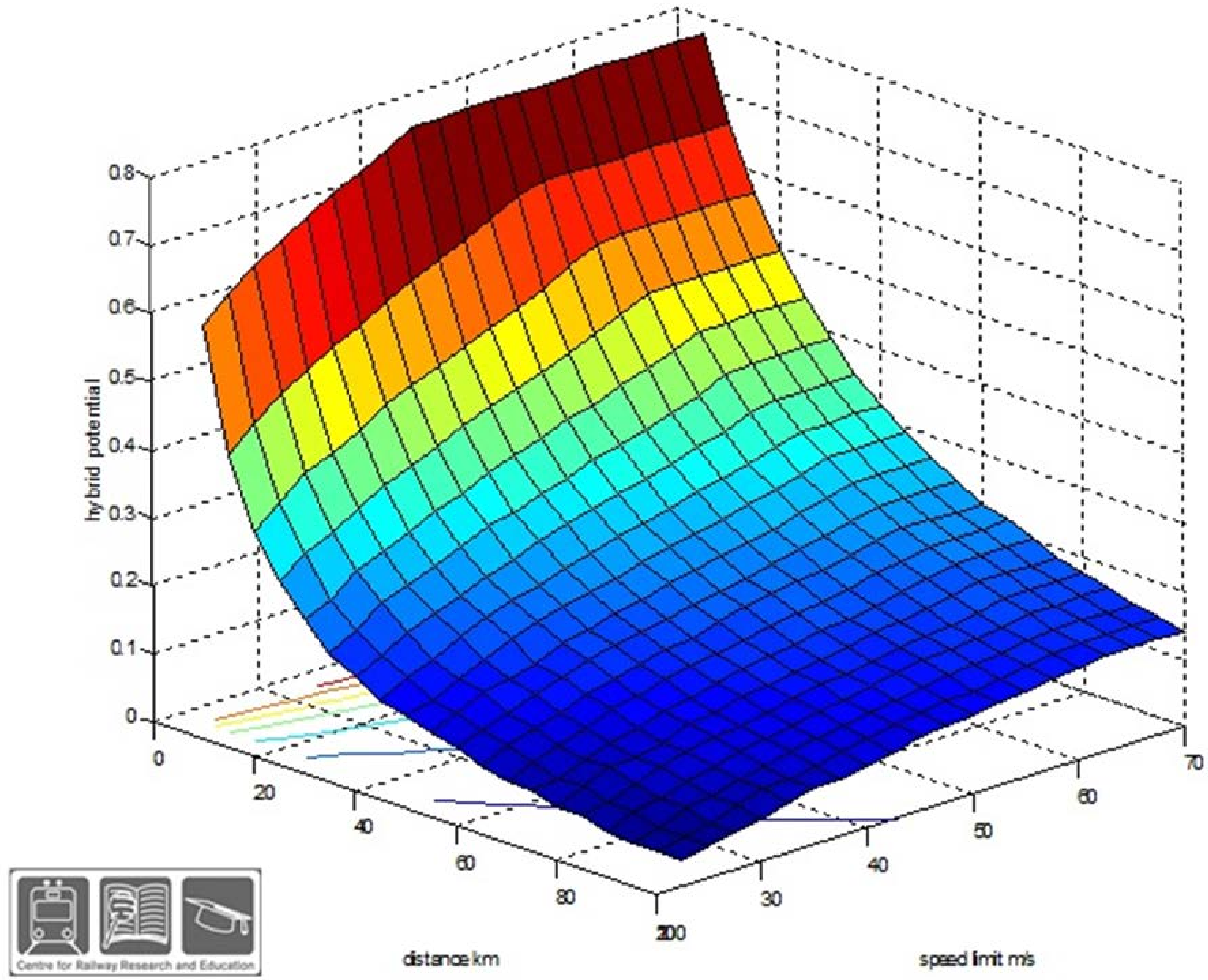
# Energy Density Comparison




(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







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# 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

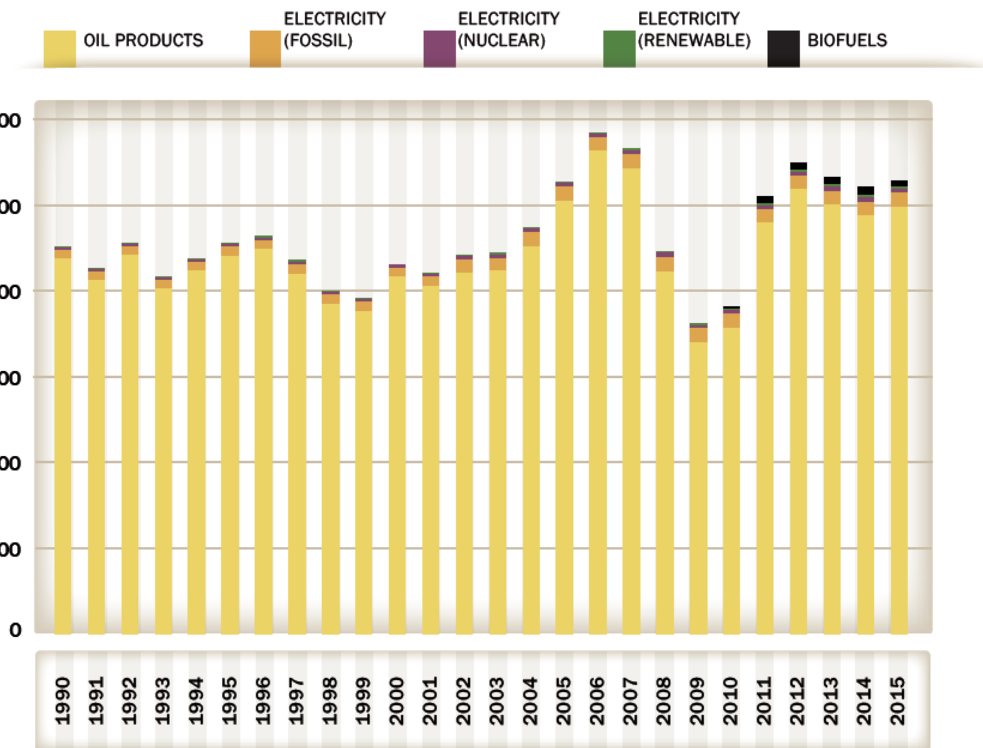
# On-Board: Energy Storage Only


- 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 re-charge time for full charge
- Partial electrification possible
- Opportunity charging possible for some duty cycles


[Video: Allen (2015) Wireless Trams in Seville]

# 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




Source: UIC & IEA (2017) Railway Handbook 2017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# 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 Cost Railway converted entire mainline fleet to LNG
  - In full operation now

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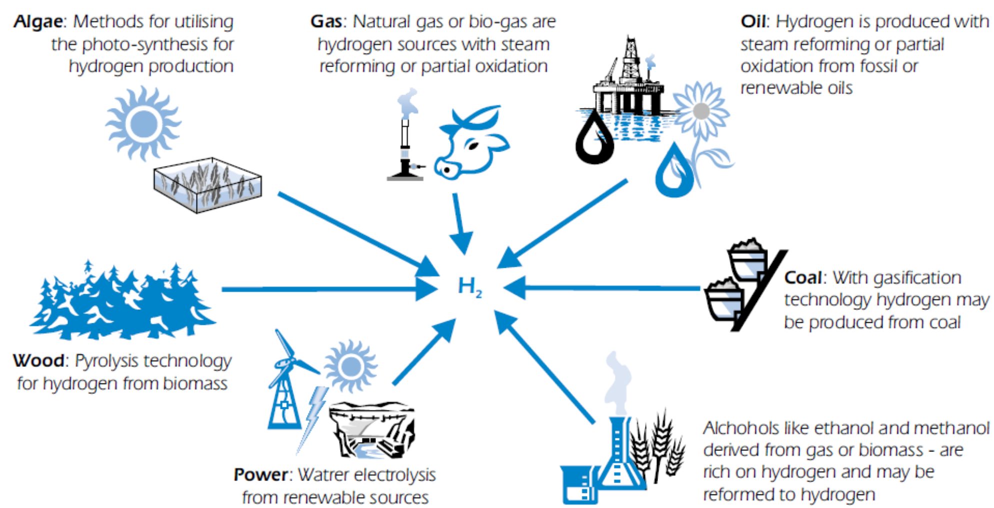
- Established Propulsion Systems
- Drivers for Alternative Propulsion Systems
- Wayside Options
- On-Board Options
- Hydrogen Fuel Cell (Hydrail) Option
  - Hydrogen as an Energy Carrier
  - Fuel Cell and Drive System Design
  - Example Projects

# Fuels/Energy Carries That Have No Carbon

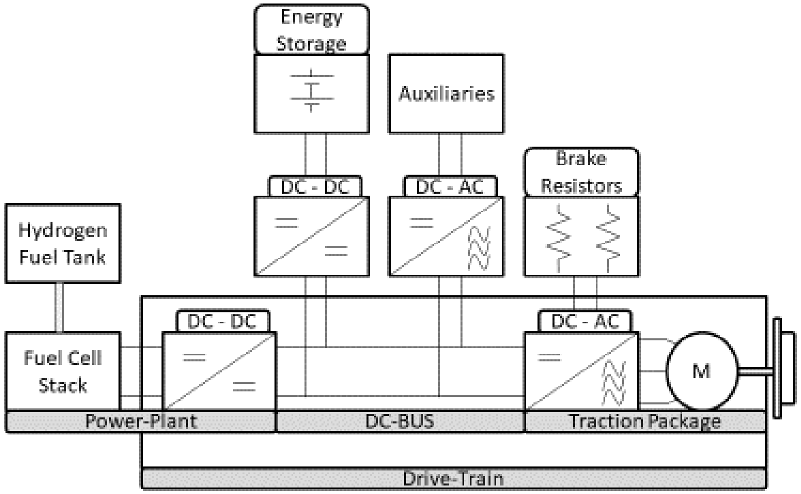
- Only two chemical fuels/energy carriers that do not contain carbon
  - Hydrogen
  - Ammonia ($NH_3$)
- Ammonia combustion possible but produces $NO_x$
- Hydrogen
  - Energy carrier, like electricity, has to be produced from something else, e.g., hydrocarbons, water
  - Most common element in the universe 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

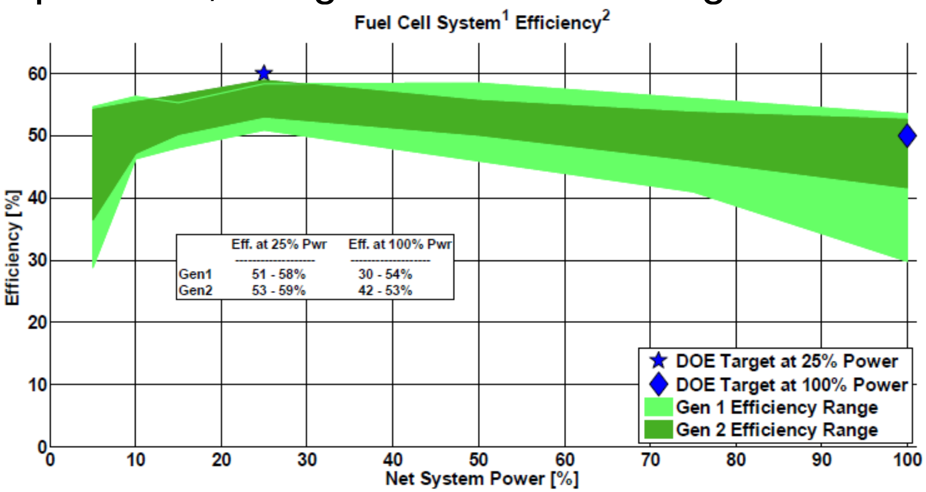




Source: International Energy Agency (2006)

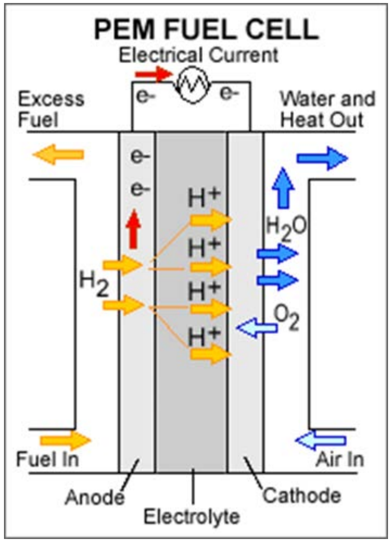
# Hydrogen Fuel Cell-Hybrid

- 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




Source: NREL (2012) National Fuel Cell Electric Vehicle Learning Demonstration Final Report




| | | | | | |
|---|---|---|---|---|---|
| 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% |

Source: NREL (2016) Fuel Cell Electric Vehicle Evaluation

# 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

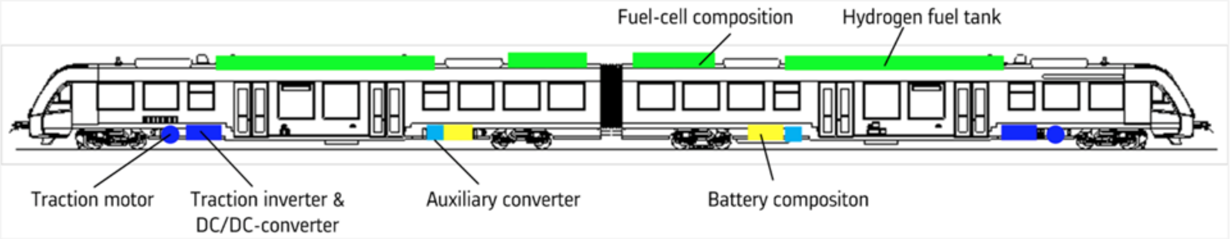
- Commercial vehicles now available
  - Alstom regional train
  - Streetcars from CRRC and TIG/m
- No harmful local emissions (water, water vapor)
- Can reduce GHG emissions (well-to-wheel)
- Can reduce fuel consumption


- Example UK study (hydrogen produced from natural gas):
  - 55% fuel reduction compared to diesel
  - 72% $CO_2$ 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% $CO_2$ reduction if hydrogen from natural gas
  - zero $CO_2$ 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?

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# Bibliography


AAR. (2017). Railroad Facts 2017 Edition.

Coombe, D., Fisher, P., Hoffrichter, A., et al. (2016). Development and design of a narrow-gauge hydrogen-hybrid locomotive. IMechE Part F: Journal of Rail and Rapid Transit. DOI: 10.1177/0954409714532921

Ernst & Young. (2016). Ergebnisbericht Studie Wasserstoff-Infrastruktur fuer die Schiene. https://www.now-gmbh.de/content/1-aktuelles/1-presse/20160701-bmvi-studie-untersucht-wirtschaftliche-rechtliche-und-technische-voraussetzungen-fuer-den-einsatz-von-brennstoffzellentriebwagen-im-zugverkehr/h2-schiene_ergebnisbericht_online.pdf

Hoffrichter, A. (2013). Hydrogen as an energy carrier for railway traction. http://etheses.bham.ac.uk/4345/

Hoffrichter, A., Hillmansen, S., & Roberts, C. (2015). Conceptual propulsion system design for a hydrogen-powered regional train. IET Electrical Systems in Transportation. Doi: 10.1049/iet-est.2014.0049

International Railway Journal (IRJ): Various Issues

Iraklis, A., Iraklis, C., & Hoffrichter, A. (December, 2016). Catenary Free Battery Electric Operation with Opportunity Charging for Light Rail Networks. IEEE Transportation Electrification Newsletter. https://tec.ieee.org/newsletter/december-2016

NREL. (2016). Fuel Cell Electric Vehicle Evaluation. https://www.nrel.gov/docs/fy16osti/66760.pdf

Railway Gazette International: Various Issues

Trains Magazine: Various Issues

UIC & IEA. (2017). Railway handbook 2017: Energy consumption and $CO_2$ emissions. https://uic.org/IMG/pdf/handbook_iea-uic_v3.pdf

# Videos

- Allen (2015) Wireless Tram in Seville: https://www.youtube.com/watch?v=Mdju2lpQfc4&app=desktop
- Alstom (2017) Alstom's hydrogen train Coradia iLINT first successful run at 80km/h:

  https://youtu.be/xoknkAu_RLc
- Bombardier (2012) Primove: Game-changing turnkey solution for tram systems: https://www.youtube.com/watch?v=g_afs6Y83c8&index=17&list=PLwMdN-ylsjO6eKyhVDW3XRjEyn50w8c5Q
- Tongtech (2009) How the Shanghai Maglev Transrapid works: https://www.youtube.com/watch?v=rmsvzOV7iXM
- University of Birmingham (2012) UoB Hydrogen Locomotive: https://www.youtube.com/watch?v=3i4zlBeKYgY