Rail Traction:
The **economics** of transiting towards Hybrid & Hydrail

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  PhD Student, University of Pisa
• Why hybridise?
• University of Pisa & Hybrid Technologies
• Economics of Hybridisation
• Towards Hydrail
Conventional Rail Traction Technologies

• Electric Traction (1881):
  • Expensive infrastructure, Lower operating cost, renewable energy (?), regenerative braking (?)
  – DC Electric Traction
    » 1.5kV / 3kV DC supply to railway locos.
  – AC Electric Traction
    » Predominantly 25 kV AC supply; Regenerative braking possible; Presently most efficient mode.
    » Upper-bound of the regenerated voltage is restricted by the catenary voltage – at higher speeds, leads to inability of the regenerated power to be fed to the grid.
Conventional Rail Traction Technologies

• Diesel Traction (1893):
  – Oil-dependent, emissions, Flexibility of operations,
  – **Diesel-electric traction**
    » Diesel engine + alternator/generator produces onboard electricity.
    » Dynamic braking possible; more effective than regenerative braking (of electric traction) - avoids wear & tear of wheels & brake- blocks
    » Can be most easily hybridised
  – **Diesel-mechanical & diesel hydraulic traction**
    » Use mechanical or hydraulic transmission to power the wheels
Hybrid Rail Traction

• Hybrid: *with more than one source of on-board power* …
  » ICE + batteries, ICE + batteries + supercaps,
    fuel cells + batteries, fuel cells + batteries + supercaps
  » *First used by Greeks/Romans/Vikings* on oar & sail powered boats

• Series / parallel architectures
Key drivers for hybridisation

- Energy costs escalating rapidly
  - Train energy consumption dependent on gradients, maximum speeds & stopping patterns
  - Typically constitute around 15-20% of total expenses; and growing
  - Varies 19 - 33 kWh/1000 (German ICE, MEET project)
  - $\Sigma$ lifecycle energy costs $>>$ original investment costs

- Reduce carbon footprint
- Economic sense
Hybrid Rail Traction

• Advantages over conventional technologies
  » Regenerative braking (savings: from 10 to 25%)
  » Prime mover operates at efficient zone of fuel maps
  » Energy booster for achieving higher acceleration
  » Can be run as ZEV

• Is most advantageous when the load varies considerably e.g. passenger services

• Hybridisation degree dependent upon duty cycle
  » Benefits from downsizing prime mover negate weight of additional components
  » Fuel savings >> 15 - 20%, emission reduction > 50%
• Why hybridise?
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• Economics of Hybridisation
• Towards Hydral
Parallel-Hybrid scooter Prototype
HYS - Università di Pisa & Piaggio

Vehicle Prototype

Hybrid drive-train
FC-based hydrogen Vehicle
(in the framework of EU funded FRESCO Project)
1- Layout study
FC-based hydrogen Vehicle
(in the framework of EU funded FRESCO Project)
2-vehicle under test at DSEA Labs
FC-based hydrogen Vehicle
(in the framework of EU funded FRESCO Project)
3 - vehicle being prepared for on-track tests
ENFICA-FC Project

1) Technical specifications/acquisition:
   - Chopper
   - Inverter
   - Motor
   - Battery

2) Design and realisation of AMU

3) Power-train integration

4) Lab tests:
   - Of the electricity generation system loaded with resistors
   - Of the whole power train loaded with artificial mechanical load
ENFICA-FC Project

• On 26th May 2010, a new world record of 135 km/h for 45 minutes established, overcoming Boeing’s 2009 record of 120 km/h for 20 minutes.
• Flew on fuel cells powered by H$_2$ gas @ 350 bar!
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Economics of hybridisation: Case studies

• Scenarios
  » Existing railway planning to switch to hybrid locos
  » New railway, planning traction mode between electric, diesel & hybrid

• Case A
  – To determine the break-even traffic of an existing railway, planning to switch to hybrid traction
    » electric vs. diesel vs. hybrid

• Case B
  – To determine the break-even traffic for a new railway
    » electric vs. diesel vs. hybrid
Economics of hybridisation: Case A

Economics of Hybrid Traction

<table>
<thead>
<tr>
<th>Passenger - km (million)</th>
<th>Cost ($ million)</th>
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<tbody>
<tr>
<td></td>
<td>Electric Traction</td>
</tr>
<tr>
<td>1</td>
<td>645</td>
</tr>
<tr>
<td>2</td>
<td>660</td>
</tr>
<tr>
<td>3</td>
<td>675</td>
</tr>
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<td>4</td>
<td>690</td>
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</table>

Electric Traction

Diesel Traction

Hybrid Traction

1-2 July 2010 | Istanbul, Turkey

sixth international hydrail conference
Economics of hybridisation: Case B

Graph showing the cost of traction ($ million) versus passenger-km (million) for different types of traction: Electrical, Diesel, and Hybrid. The cost increases with the increase in passenger-km for all types of traction.
Examples of hybrid locomotives/trains

- America
  » Rail Power (2004)
  » GE (2008)
  » BNSF (2009)

- Asia
  » JR East (2007): Orders for 10 more this year
  » RTRI (2007)
  » JR Freight (Toshiba, 2010)

- Europe:
  » France (Bombardier, 2007) Ten French regions ordered 144 hybrid trains
  » UK
  » Holland (Alstom, 2009)
Transiting to hybrids

- Increasing number of railways are switching to hybrid powered trains
- Manufacturers
  - Bombardier
  - Hitachi
  - Toshiba
  - Mitsubishi
  - Alstom
  - Siemens
  - ABB
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How to kickstart Hydrail?

• Costly FC-based generation system (approx 5000 €/kW vs. 50 $/kW for ICEs)
• FC stack life is still well behind that of ICEs
• Some technical issues still to be solved (low temp storage, system reliability etc.)
• Inadequate hydrogen production & infrastructure
• Too many standards and regulations

So what can we do today?

• Build prototypes and demonstrators
• Make people realise that it’s a safe technology
• Adopt technologies that can be adapted to hydrail later, with the minimal inputs
• This could be possible by adopting hybrid propulsion
Series-hybrid trains

- **Fuel to Wheels**: Mechanical power $P_{s}(t)$ is converted to mechanical power $P_{u}(t)$.
- **Electric Drive**: Energy Management System (EMS) manages the flow of power between fuel and electric components.
- **Driver inputs** and **Other signals** are integrated into the system for optimal performance.

Diagram elements include:
- **EG**: Fuel-to-Electric Generator
- **PC**: Power Converter
- **ES**: Energy Storage (Battery)
- **EM**: Electric Motor
- **DC Bus**: Distribution of power between components
A FC-based drive train is just another series-hybrid drive train, in which:

- The fuel is hydrogen
- The EG is based on fuel-cells
Pure FC-based propulsion or hybrid solution?

**Pure FC-loco**
- Avoids additional cost & weight of energy storage

**Hybrid FC-loco solution**
- Reduced size of FC (reduction increases with variation in duty cycle)
- Lower costs, higher life

Hybridisation works better when the duty cycles and load fluctuates more: best solution for suburban or intercity trains or shunters.
Hydrogen Fuel-cell based propulsion general scheme

HSS: Hydrogen Subsystem
FCGS: Fuel-cell based generation system (fuel converter)
ES: Energy Storage
ED: Electric Drive
Electro-mechanical hybrid trains may be already competitive (1)

Track FAENTINA (Firenze-Faenza) 100km – 17 intermediate stops

Comparison of Hybrid and conventional vehicles in terms of consumption and emissions

Electro-mechanical hybrid trains may be already competitive (1)
“Vettore Idrogeno” Project:
FC-based Vehicle – Preliminary layout

- FC-Based Electricity Generator
- Braking Rehostat
- Filters
- Auxiliary Load Electronic Converter
- Hydrogen Tanks
- Electrochemical Battery
- Electric converter for propulsion motors
3) FC-based hydrogen Locomotive (study)

Performance analysis in comparison with electromechanical hybrid

<table>
<thead>
<tr>
<th>ICE-based</th>
<th>[kg/km]</th>
<th>Simulation Results</th>
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<tbody>
<tr>
<td>Fuel Consumption</td>
<td>0.48</td>
<td>(auxiliaries enclosed)</td>
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<tr>
<td>CO2</td>
<td>1.5</td>
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<td>CO</td>
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<tr>
<td>PM</td>
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<table>
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<th>FC-based</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption</td>
<td>0.18</td>
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Hydrogen Fuel-cell based propulsion
An evolutionary approach

Introduction of Hybrid propulsion in railway may:
- give immediate advantages in terms of fuel consumption
- give some zero-emission range
- pave the way towards FC-based hybrid propulsion
Questions?

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