Hybrids Traction Systems-
What’s in store for the future of train propulsion?

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Lecture outline:

• Energy issues for rail
• Preliminary comments on hybrids
• Mechanical flywheel energy storage (Matthew Read)
• Energy management strategy (Qi Wen)
• Concluding remarks
Professor,
you know that in this country trains are pulled by locomotives, not by differential equations

Trans Newcomen Soc, Vol 72, No 1, p2, 2000-2001
Railway Gazette, pp3-4, Nov 1952.
Letters, The Times, April 4, 1912.

The writer said he was between 1845 and 1850 a junior partner in a Newcastle Glass Manufacturing firm, in which R Stephenson and G Hudson were also partners. **G Stephenson came to see the firm in 1847**, and said,

“I have credit of being the inventor of the locomotive, and it is true I have done something to improve the action of steam for that purpose.

**But I tell you, young man, I shall not live to see it, but you may, when electricity will be the great motive power of the world.”**
Typical energy kWh used per 100 passenger km if full:

<table>
<thead>
<tr>
<th></th>
<th>kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>68</td>
</tr>
<tr>
<td>Bus</td>
<td>32</td>
</tr>
<tr>
<td>Commuter train</td>
<td>1.6</td>
</tr>
<tr>
<td>Tube train</td>
<td>4.4</td>
</tr>
<tr>
<td>Inter city electric</td>
<td>3.0</td>
</tr>
<tr>
<td>Inter city diesel</td>
<td>9.0</td>
</tr>
</tbody>
</table>
Trains: mode share problem

• Rail in UK produces 2% CO$_2$ emissions for 7% pass km- good news!
• But only has 7% mode share-bad news!

• Suppose the transport market increases by 2.5%/y, then will double in 16 years
• Further suppose that rails mode share doubles and we completely decarbonise the railway (both highly optimistic!)

• Then, (by proportion sums) emissions of CO$_2$ will increase by 34%
<table>
<thead>
<tr>
<th>Mode</th>
<th>Long distance load factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban bus</td>
<td>20%</td>
</tr>
<tr>
<td>Intercity coach</td>
<td>60%</td>
</tr>
<tr>
<td>Intercity rail</td>
<td>40%</td>
</tr>
<tr>
<td>Other rail</td>
<td>30%</td>
</tr>
<tr>
<td>Domestic air</td>
<td>70%</td>
</tr>
<tr>
<td>Cars</td>
<td>30%</td>
</tr>
</tbody>
</table>

Source: DfT Update to Figure 11.1 in Delivering a Sustainable Railway
Land transport energy use

- Acceleration, braking
- Air resistance
- Rolling resistance
- Thermodynamic inefficient energy chain
Acceleration, braking

- Go at constant speed!
- Change speed gently
- Reduce mass
- Recover braking energy (role of hybrids)
At constant speed $V_1$, undershoot of target time $T$ is $\Delta T$  
At speed $V_2$, time is exact  
Dwell as fraction of target $= \Delta T/T = \text{fractional decrease in speed, } (V_1-V_2)/V_1$  
Ratio energy used $= (V_2/V_1)^2 = (1-\Delta T/T)^2$

Example:

$T=55$ minutes, $\Delta T=5$ m, $V_1 = 120$ kph, distance, $s = 100$ km  
Then  
$V_2 = 109.1$ kph and ratio energy used $= 83\%$
Air resistance

• Depends on frontal area/length: train is good, convoy system
• Improve details: skirt, carriage connection, close windows
Rolling resistance

• The train has the advantage of the stiff steel wheel on steel rail: low rr and low coefficient of friction

• Adhesion low (disadvantage when there are leaves about)
Energy loss

- Reduce energy chain thermodynamic inefficiency
- For electric at power station
- For diesel in IC engine (efficiency depends also on speed)
- Fuel cell?
The Hybrid Principle

Source: Toyota Motor Corporation
Hitachi JR East fuel cell hybrid

The developed fuel cell hybrid railcar is equipped with fuel cells (130kW: 65kW×2), and a hydrogen tank beneath the floor and a lithium ion type accumulator battery on the roof.

Maximum speed : 100km/h
Starting acceleration : 2.3km/h/s (Same as an electric train)
The question of scale:

• UK road fuel in 2006 was some 1.8 trillion MJ-more than electricity currently generated *
• Now H or electric cars have about twice the well to wheel efficiency of IC engines
• Then to eliminate oil for transport would require more than a 50% increase in electricity generation and infrastructure
• The idea that electricity made from wind, tide and solar power can replace oil for road transport is naïve
• A huge increase in nuclear power generation is essential

Traction Components

Diesel Engine → AC Generator → Converter → Inverter → AC Motor

Constant Efficiencies
Battery Model

Manufacturer’s Model:

Diesel Engine → AC Generator → Converter → Inverter → AC Motor → Storage Battery
Traction Controller

Driver Demand (notch selection)

Diesel Engine

Speed

Load

Traction Controller

Inverter/Motors
Traction Controller – Hybrid

- Diesel Engine
- Driver Demand (notch selection)
- Inverter/Motors
- Battery

Diagram:

- Traction Controller
- Speed Load
- Driver Demand (notch selection)
Inter-City Hybrid Train Study

- 2 power cars
- 8 trailer/motor cars
- 450-500 tonne approx weight
London-Bristol Simulation (as Timetabled)

- 300kWhr: 13%
- 200kWhr: 11%
- 100kWhr: 9%
- Non-Hybrid: 100%

Battery Size vs. Fuel Consumed
Potential for hybrid rail vehicles

Energy consumption in UK passenger rail vehicles

<table>
<thead>
<tr>
<th></th>
<th>Energy consumption (million MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diesel</strong></td>
<td></td>
</tr>
<tr>
<td>Intercity DEMU</td>
<td>2.2</td>
</tr>
<tr>
<td>Regional DHMU</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Total diesel</strong></td>
<td>4.7</td>
</tr>
<tr>
<td><strong>Electric</strong></td>
<td></td>
</tr>
<tr>
<td>Total electric</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Use of engine power in diesel multiple units

Source: 'Improving the efficiency of traction energy use', RSSB report
Application of hybrid system

• Hybrid types and configuration

• Storage device key feature for all types
Energy storage devices

• Ragone plot allows comparison of devices:

  - Initial assessment of suitability using time characteristics
  - Identify devices for regenerative braking

\begin{figure}
  \centering
  \includegraphics[width=\textwidth]{energystorage.png}
  \caption{Ragone plot showing specific energy and power for different storage devices.}
\end{figure}
Further factors affecting hybrid system choice

- Ease of integration with conventional power-train
- Aims of power-train control strategy
- System requirements of device
- Cost, reliability and lifespan

Hitachi
(Lithium-ion)

ULEV-TAP2
(Flywheel)

Bombardier
(Ultracap)
Electrical hybrid systems

• Electrical transmission
  – Losses in energy conversions
  – Oversize to capture braking energy
  – Bulky and expensive power electronics

E.g. ULEV flywheel is 38% mass, and 15% volume of Energy Storage Unit

Source: ULEV-TAP2 Public Report
Kinetic energy storage

- **Mechanical transmissions for flywheels**
  - Potentially efficient recovery and use
  - Applicable to diesel hydrodynamic (most suitable)
  - Difficulty in transmitting power across speed range

- **Research performed at Imperial**
  - Composite flywheel designed for 1.2 MJ useful capacity
  - Tested at 22,000 rpm, 2500 Pa
  - Automotive ‘mechanical hybrid’ using power-split transmissions
Secondary energy storage system (SESS)

- Secondary energy storage device discharges flywheel
- Provides initial acceleration
- Flywheel stores 85% of total energy
- Majority of energy through PGS

Schematic of energy storage system
SESS devices

- Potential configurations for diesel vehicles
  - Diesel-electric with supercap/FMG storage
  - Hydrostatics with accumulator storage
    - High pump power density
    - Accumulators - efficient storage, reasonable specific energy, and energy density
Future work

• Experimental work to test hydrostatic system performance
  – Validate detailed model
  – Investigate system configurations

• Characterise system parameters (size, volume, cost...)
• Simulate Class 170 type vehicle and duty cycle
• Investigate trade-off between installed power and storage
Based on realistic data

- Real-world running cycles;
- Vehicle model parameters determined based on real train (Inter-city 125);
- Real battery module designed for hybrid rail vehicle (0-120 kWhr);
- One EMS is obtained from hybrid train manufacturer;
Based on Empirical and Optimized Energy Management Strategies

Rule-based EMS
- Obtained from industry
- Parameters are trained by real-world running cycles

Optimal Control based EMS
- Based on Optimal Control Theory
- Discretized and solved numerically
Battery Module

- Li-ion Battery
- Designed for Hybrid Rail Vehicle Application
- Operating Capacity <Rated Capacity

Source: Hitachi Rail
Some initial results…

- Optimality, Battery Capacity and Fuel saving
• Specific fuel consumption rate:

Specific fuel consumption rate \( \frac{\Delta F(C_B)}{\Delta C_B} \)

![Graph showing fuel consumption rate vs. battery operating capacity](image-url)
- Optimality and Battery Capacity
UK Energy Flow Chart 2007

http://news.bbc.co.uk/today/hi/today/newsid_7724000/7724044.stm
Concluding remarks:

- Railways cannot rest on their environmental credentials
- Best contribution globally is to increase mode share
- Long term electricity is the answer
- Hybrids can play a part in the short to medium term
- Flywheels and mechanical transmissions can be useful
- The energy management strategy is critical in determining hybrid performance
- Expanding and decarbonising our electricity supply is top priority
- The fuel cell for cars, maybe trains, absolutely depends on a low carbon hydrogen source