

Birmingham Centre for Railway Research and Education

Dr Stuart Hillmansen
Senior Lecturer in BCRRE

A big thanks to the team at BCRRE
Twitter @BCRRE

Decarbonisation and the role of Hydrogen

“I would like to see us take all diesel-only trains off the track by 2040 ...

I am calling on the railway to provide a vision for how it will decarbonise”

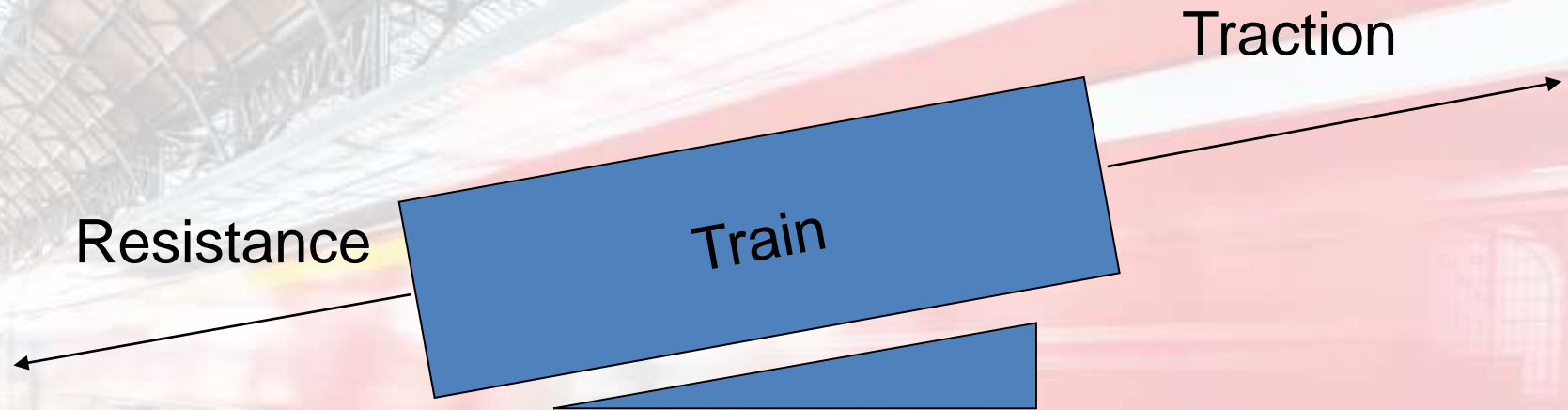
Jo Johnson, 12 February 2018



Why we like trains

- $F=Ma$
- How much acceleration?
- How much Mass?
- What Force?
- How fast?
- How much Power?
- How much Energy?
- How much does the Energy cost?

Physics of traction



Mass* Acceleration =(Traction – Resistance – slope)

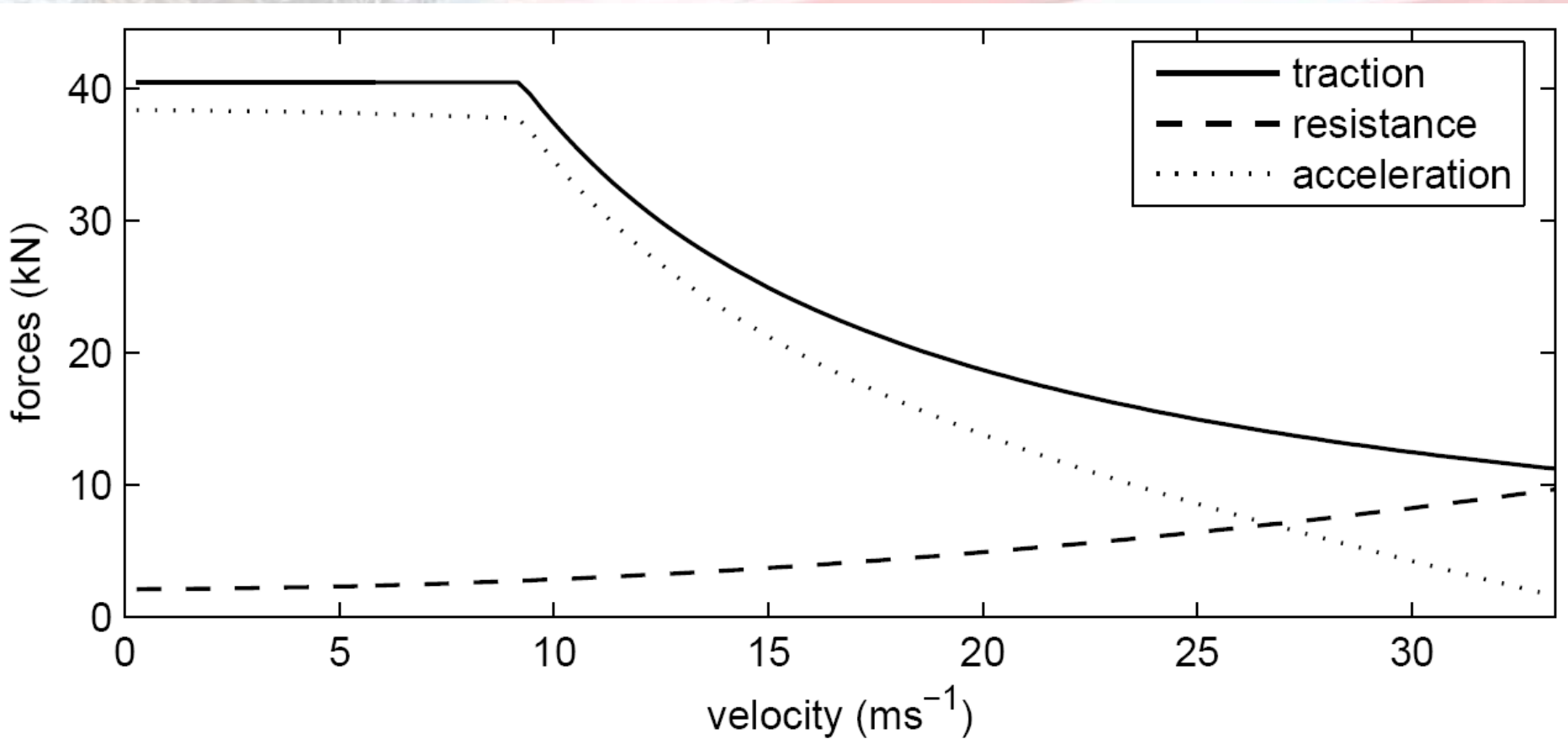
$$M (1 + \lambda) \frac{d^2 s}{dt^2} = T - \left(c \left(\frac{ds}{dt} \right)^2 + b \left(\frac{ds}{dt} \right) + a + \frac{d}{r} \right) - (Mg\theta)$$

A spectrum of challenges

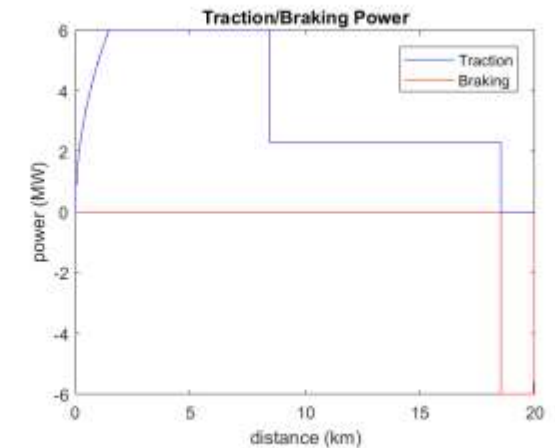
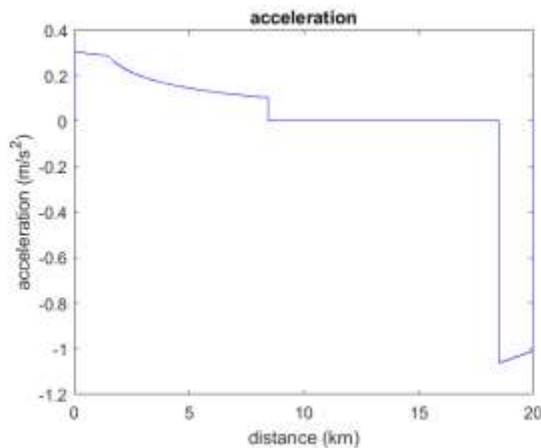
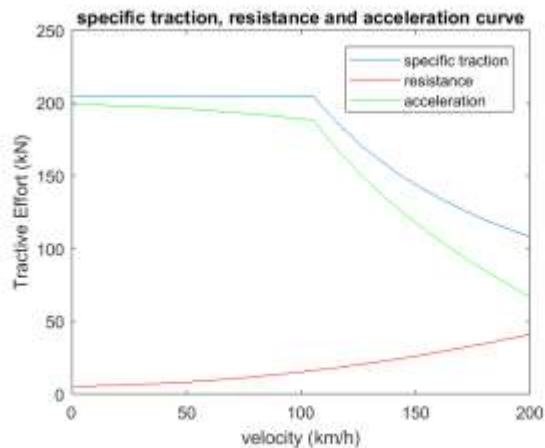
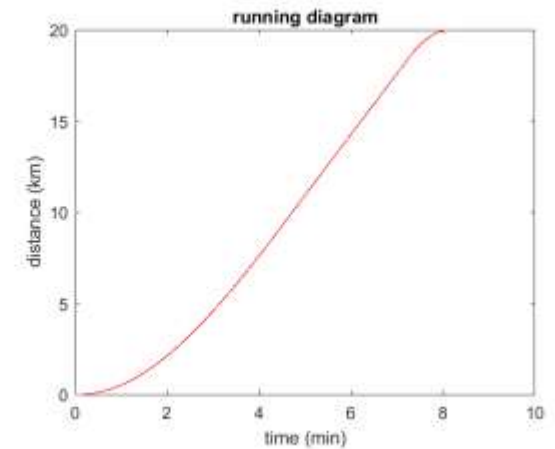
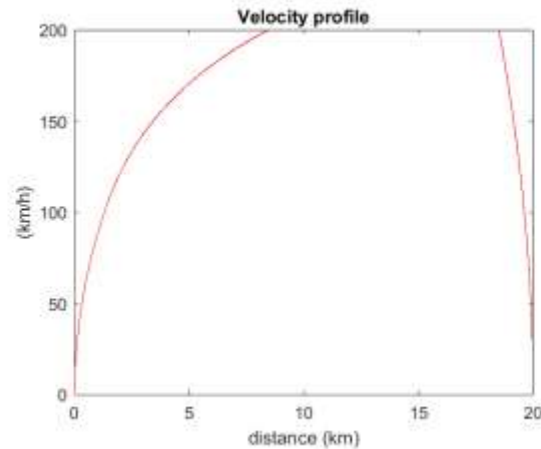
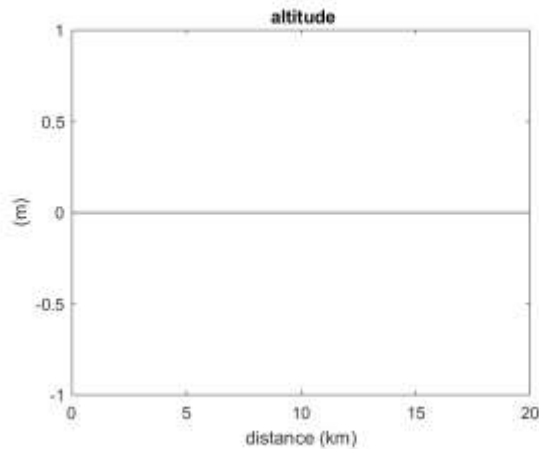
- Low Power, modest speed
- High Power, high speed



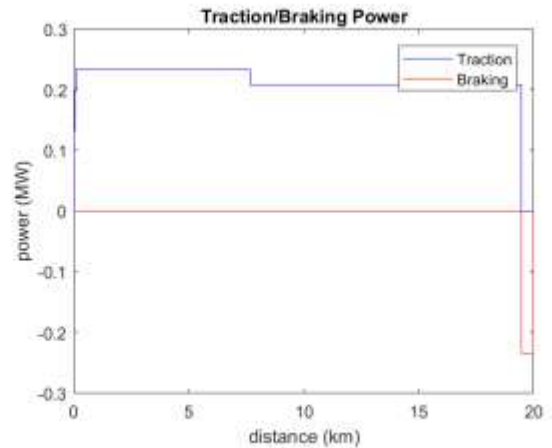
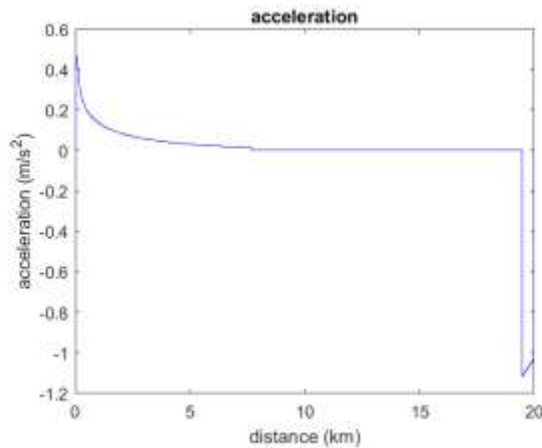
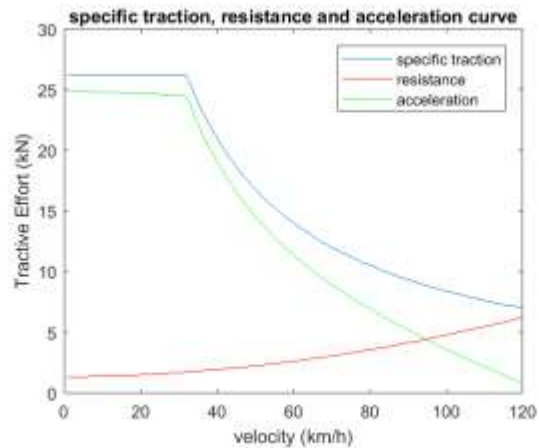
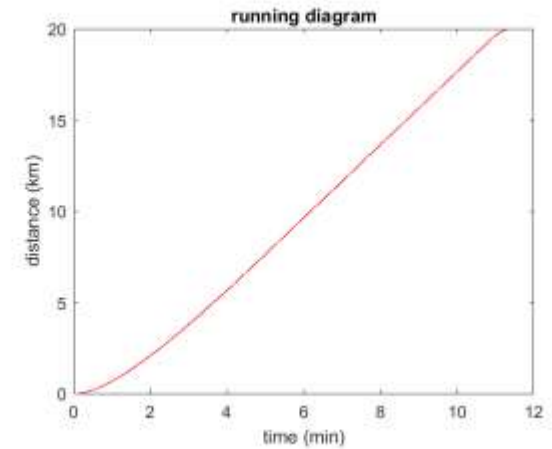
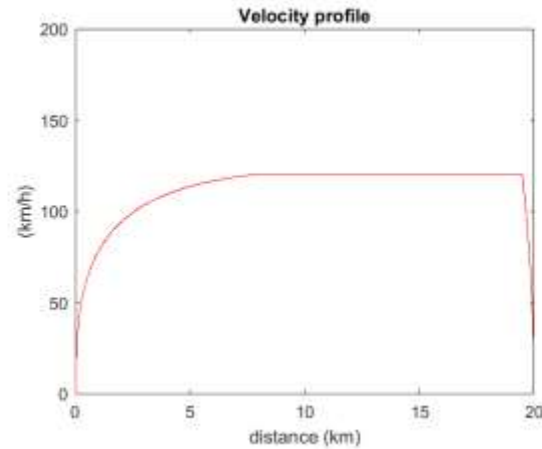
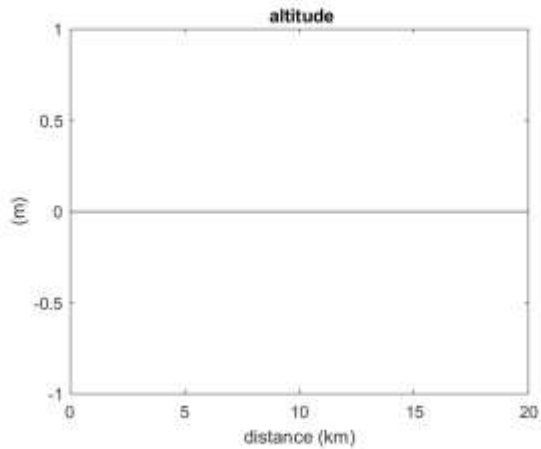
Tractive and resistive forces



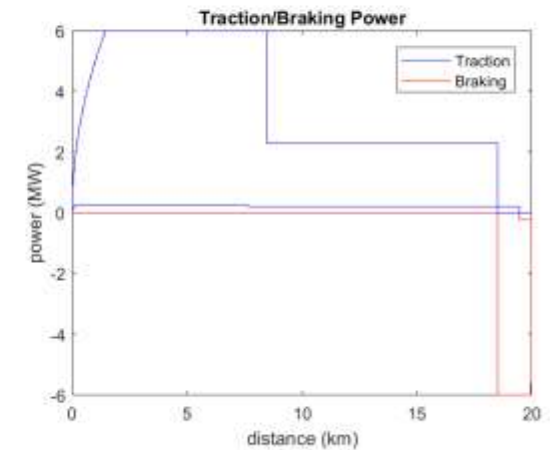
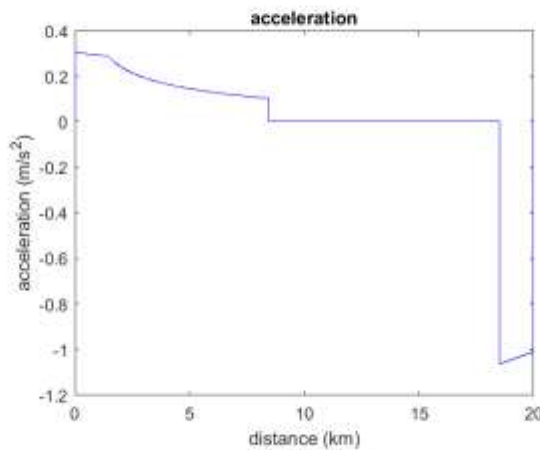
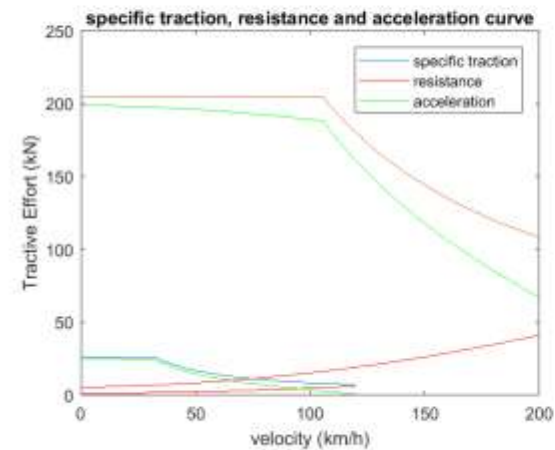
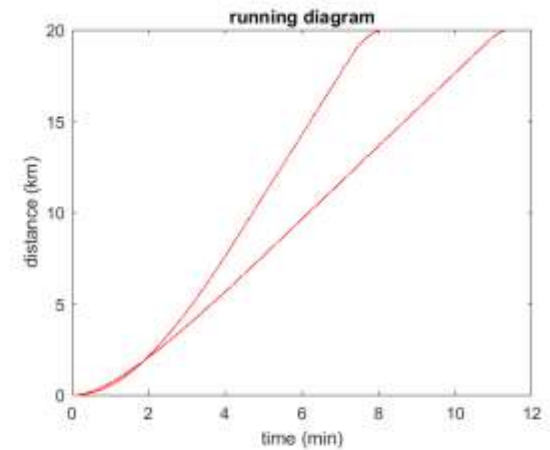
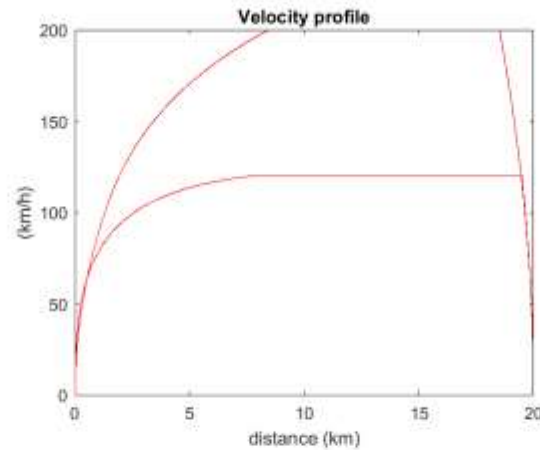
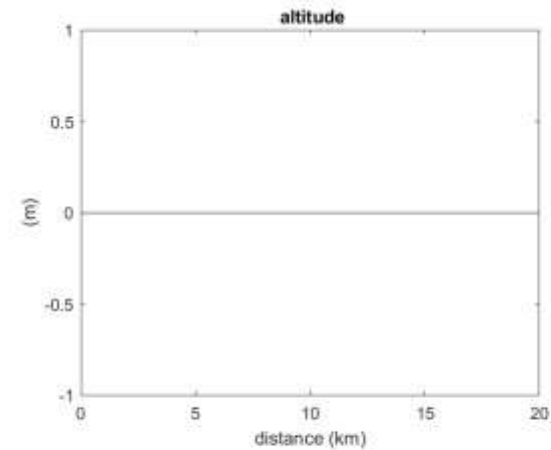
Class 390 performance analysis



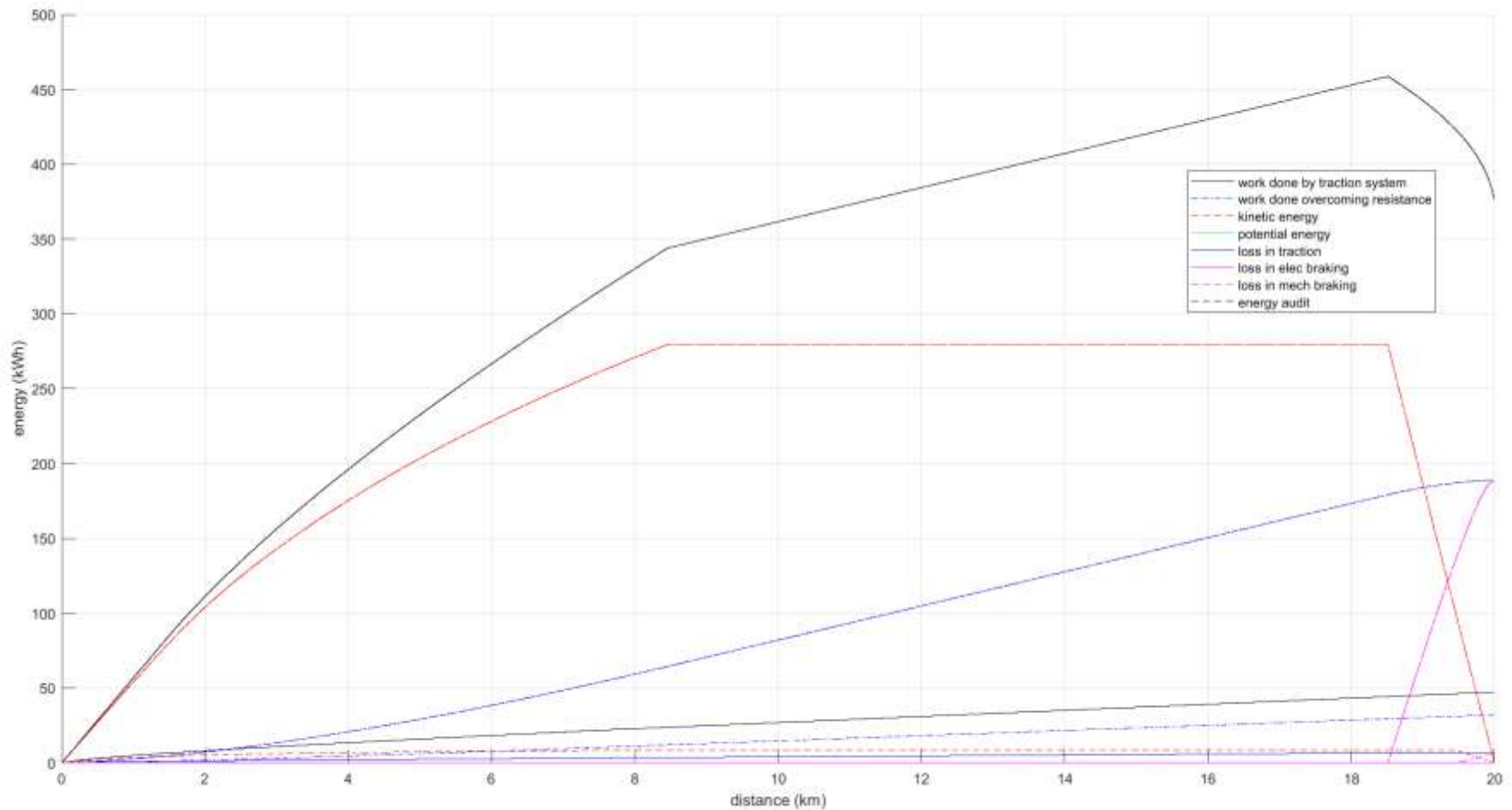
Class 14x performance analysis



Comparison of trains at the extremes of performance



Energy analysis comparison



Regen metrics

Power to be absorbed is approximately the rated traction power.

Energy is related to Kinetic Energy

Class 390 would need at least 300 kWh battery pack. It would need to absorb about 6 MW.

- There is no battery with these specs – so you would end up with a battery probably with ~2 MWh – this would be 20-40 tonnes

Class 14x would need about 8 kWh. It would need to absorb about 300 kW.

- There is no battery with these specs – so you would end up with a battery probably with ~100 kWh – this would be 2-4 tonnes

Metric for hybridisation and discontinuous electrification

Distance where the work done overcoming the resistance to motion at line speed is equal to the Kinetic Energy.

At distances of this and probably 1 or 2 times greater it is beneficial to have regen.

For a class 14x this is approx 5 km

For a class 390 this is approx 25 km

Discontinuous electrification

Need to consider:

Small gaps (neutral sections) – coasting

Medium gaps (~hundreds of metres) – coasting with some energy storage

Slightly bigger medium gaps (~few kms) – energy storage

Very big gaps (10-100 kms) – bi-Mode hydrogen or diesel

Energy Storage Capability (in MJ/kg) for bi-mode (3.6 MJ = 1 kWh)



Hydrogen	142 MJ/kg (HHV)
Compressed natural gas (CNG):	50 MJ/kg
Petrol:	44 MJ/kg
Diesel fuel:	39-42 MJ/kg
Ethanol:	30 MJ/kg
Coal:	29 MJ/kg
Ammonia	18.6 MJ/kg
Biomass:	15 MJ/kg
Domestic waste:	9 MJ/kg
Liquid petroleum gas (LPG):	45-50 MJ/kg
Steel flywheel:	0.014 MJ/kg
Battery:	0.01-0.56 MJ/kg

Summary

Very high speed and long distant trains are best powered using electrification

Modest speed and routes where there is a mix of electrification could be bi-mode hydrogen

Hydrogen is not the solution for all types of railway – but can form an important part in a decarbonised railway

Fuel cell trains

- Overview of Hydrail at UoB
- Introduction to the principles of Fuel Cell power units
- Why hydrogen?
 - Zero emissions at point of use
 - Better range than batteries
 - Easy of refuelling
 - Sources of hydrogen
 - Effectively an electric train
 - FC products now reaching maturity and lower costs

Our contribution to research in Hyrdail: 15 leading research publications (since 2003)

The application of fuel cell technology to rail transport operations

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Abstract: Fuel cell technology has in recent years undergone a period of rapid development. This evolution has been driven by the requirements of developed countries to reduce the emission of greenhouse gases, with particular emphasis placed on reducing CO₂ emissions. This article discusses the possibility of using fuel cell technology for rail vehicle propulsion, with the United Kingdom chosen as a case study. A brief review of fuel cell technology and its application within the UK is presented. It is concluded that, although the technology for fuel cell power will be suitable within the next few years, its adoption by mainline UK rail operators will be delayed considerably until existing diesel vehicles have reached the end of their useful life. By this time the technology of fuel cells will be well proven within other transport markets and its transfer to rail markets will be facilitated. This will be augmented at this time by increasing diesel fuel prices. However, the adoption of fuel cell technology for light rail/tram systems does offer advantages in terms of infrastructure development and aesthetics which could make it a serious option for new and upgraded light rail/tram schemes.

Keywords: fuel cell, hydrogen economy, motive power

1 INTRODUCTION

In response to the global effort to reduce the environmental burden of CO₂ emissions, the rail industry has already anticipated changes in the relevant emissions standards. There has been a sustained improvement in diesel-powered vehicles and for electric vehicles there are continuing efforts to reduce emissions in power generation. Rail travel is considered to be an environmentally friendly form of transport, but there is considerable scope for improvement. Currently in the United Kingdom, the number of electric rail vehicles outnumber diesel-powered vehicles by approximately 2:1. The electric vehicles are favoured in the congested South-East for commuter services, where the power is supplied via the third rail system. The high-speed East and West Coast mainlines are also electrified along most of the route, offering high-speed services to the North of England and Scotland from London. Diesel locomotives and diesel multiple units (DMUs) are used on routes with a lower density of passenger and freight traffic, where the investment required to electrify the route has proved prohibitive. The approximate energy required

for rail travel is 0.8–0.9 MJ per passenger-km for a load factor of 0.5. This already compares well with the 1.4–2.8 MJ per passenger-km for road vehicles with passenger occupancy of 1.3 persons per vehicle [1]. Electrified rail propulsion offers the further advantage of reduced CO₂ emissions associated with large-scale power production. For example, France uses nuclear power with virtually zero CO₂ emissions to supply approximately 37 per cent of its total energy requirements [2]. Therefore current rail travel has a significantly lower environmental burden than other forms of transport, and future reductions in CO₂ emission can be achieved by encouraging more people to use rail as a method of transportation. In the UK the Strategic Rail Authority (SRA) aims to increase passenger usage by 50 per cent and freight tonnage by 80 per cent over the next 10 years, as set out in their ten-year plan [3].

Fuel cell development for current vehicular applications has concentrated on the private automotive industry. For example, the California fuel cell partnership [4, 5] is a unique collaboration of vehicle manufacturers, energy companies, fuel cell technology companies and government agencies. Their mission is to develop new technologies to improve the environmental sustainability of road vehicles. An initial goal is to have up to 60 vehicles in operation before the end of 2003. Similar goals have been specified for a fleet of

The MS was received on 27 October 2002 and was accepted after revision for publication on 10 March 2003.

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SPECIAL ISSUE PAPER 291

IET Electrical Systems in Transportation

Research Article

Conceptual propulsion system design for a hydrogen-powered regional train

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Abstract: Many railway vehicles use diesel as their energy source but exhaust emissions and concerns about economical fuel supply demand alternatives. Railway electrification is not cost effective for some routes, particularly low-traffic density regional lines. The journey of a regional diesel-electric train is simulated over the British route Birmingham Moor Street to Stratford-upon-Avon and return to establish a benchmark for the conceptual design of a hydrogen-powered and hydrogen-hybrid vehicle. A fuel cell power plant, compressed hydrogen at 350 and 700 bar, and metal-hydride storage are evaluated. All equipment required for the propulsion can be accommodated within the space of the original diesel-electric train, while not compromising passenger-carrying capacity if 700 bar hydrogen tanks are employed. The hydrogen trains are designed to meet the benchmark journey time of 94 min and the operating range of a day without refuelling. An energy consumption reduction of 34% with the hydrogen-powered vehicle and a decrease of 55% with the hydrogen-hybrid train are achieved compared with the original diesel-electric. The well-to-wheel carbon dioxide emissions are lower for the conceptual trains: 56% decrease for the hydrogen-powered and 72% reduction for the hydrogen-hybrid assuming that the hydrogen is produced from natural gas.

1 Introduction

Currently, most railway vehicles use electricity for propulsion, which is either supplied through wayside electrification infrastructure or on-board diesel-generator sets. In the European Union (EU), the share of electrified railway lines is about 33% and the majority of traffic is carried on those lines but, in other areas, such as North America, non-electrified lines are the norm [1]. Diesel combustion releases emissions at the point-of-use, such as particulate matter and nitrogen oxides, and reduction of these is mandated in the United States [2] and the EU [3]. Furthermore, hydrocarbon combustion leads to emission of Greenhouse Gases, and many countries, including the United Kingdom, have ambitious targets to reduce these [4]. In addition to the emission concerns, the economical supply of diesel is uncertain. In Europe, it is set cost-effective to electrify a significant additional proportion of the railway network, including regional lines. And the cost of large-scale wayside electrification is prohibitive for many railway administrations around the world. For all aforementioned reasons, an alternative energy source to diesel is required for railway motive power. Hydrogen can be produced from many feedstocks, similar to electricity, and when utilised in a fuel cell, generates electricity and heat while having as exhaust pure water [5, 6]. In addition, it has been shown that hydrogen-powered railway vehicles can reduce overall Greenhouse Gas emissions [7]; therefore hydrogen is an attractive alternative to diesel for railways. Ideally, a few hydrogen-powered railway vehicles exist but most of these are prototypes and no full-scale heavy rail passenger train is currently in service [8–12]. Previous research [13] has considered the general feasibility of hydrogen-hybrid railway vehicles where the focus was on the control strategy between the different components, and not the detailed system design. In the current paper, a conceptual design is presented, which considers the mass and volume implications of the drive system change together with an assessment of the practicality of a hydrogen-powered solution. A benchmark diesel-electric regional railway vehicle is selected and the performance parameters and journey time over a corresponding route in Britain are determined with computer simulation. Then, a conceptual design for a

hydrogen-powered and hydrogen-hybrid regional train is developed and these are simulated over the same route. Next, the performance of all three trains are compared, including range, journey time, vehicle efficiency and carbon emissions.

2 Benchmark simulation

The single train simulator software, developed by the Birmingham Centre for Railway Research and Education, was employed for the investigation presented in this paper. The simulator has been used extensively for previous research [14–17] and three new vehicles have been created for this paper, while a route that already existed in the programme was selected.

The single train simulator solves the equations of motion of a railway vehicle through numeric integration, see (1)–(5) [5, 15, 18]

$$F = ma \quad (1)$$

$$F = m(l + \lambda)a \quad (2)$$

$$F = TE - [mg \sin(\alpha) + Cv^2 + Bv + A] \quad (3)$$

Overall

$$m(l + \lambda)a = TE - [mg \sin(\alpha) + Cv^2 + Bv + A] \quad (4)$$

Or

$$m(l + \lambda) \frac{d^2x}{dt^2} = TE - \left[mg \sin(\alpha) + C \left(\frac{dx}{dt} \right)^2 + B \left(\frac{dx}{dt} \right) + A \right] \quad (5)$$

where a is the acceleration (metre per second squared (m/s^2)), A , B and C are the constant terms of resistance in the Davis equation [19]; d is delta, change of the following variable; F is force (kiloneutron (kN)); g is the acceleration due to gravity ($9.81 m/s^2$); m is mass (kilograms); x is the vehicle displacement (metres); t is



INTERNATIONAL HYDRAIL CONFERENCE

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International Hydrail Conference 2016

Mon, 07/04/2016 - Tue, 07/05/2016 | Birmingham, UK

The Eleventh International Hydrail Conference was hosted by the University of Birmingham Centre for Railway Research and Education in Birmingham, UK on 4-5 July 2016, and conferees were also encouraged to attend the Institution of Mechanical Engineers' Railway Challenge competition on Sunday 3 July 2016. Date/Time: Monday, 4 July 2016 (09:00) - Tuesday, 5 July 2016 (17:30) HYDROGEN RAIL NEWS UPDATE: BMVI STUDY EXAMINES THE ECONOMIC, LEGAL AND TECHNICAL PREREQUISITES FOR THE DEPLOYMENT OF FUEL...

Seventh International Hydrail Conference

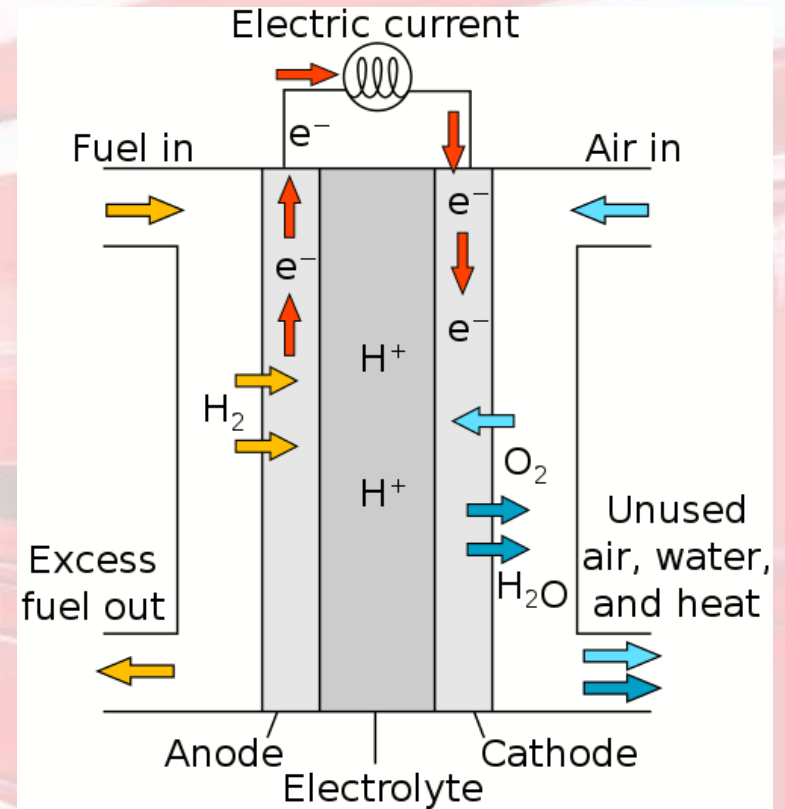
Tue, 07/03/2012 - Wed, 07/04/2012 | University of Birmingham, UK

Download Speaker Presentations The 7th International Hydrail Conference was hosted by the Birmingham Centre for Railway Research and Education in the Gisbert Kapp Building on the Edgbaston Campus of the University of Birmingham. The conference featured presentations by experts in a wide range of fields related to the development, deployment, and use of hydrogen and fuel cells in railway transportation. Highlights of the conference included a keynote presentation from the Chief Scientific...

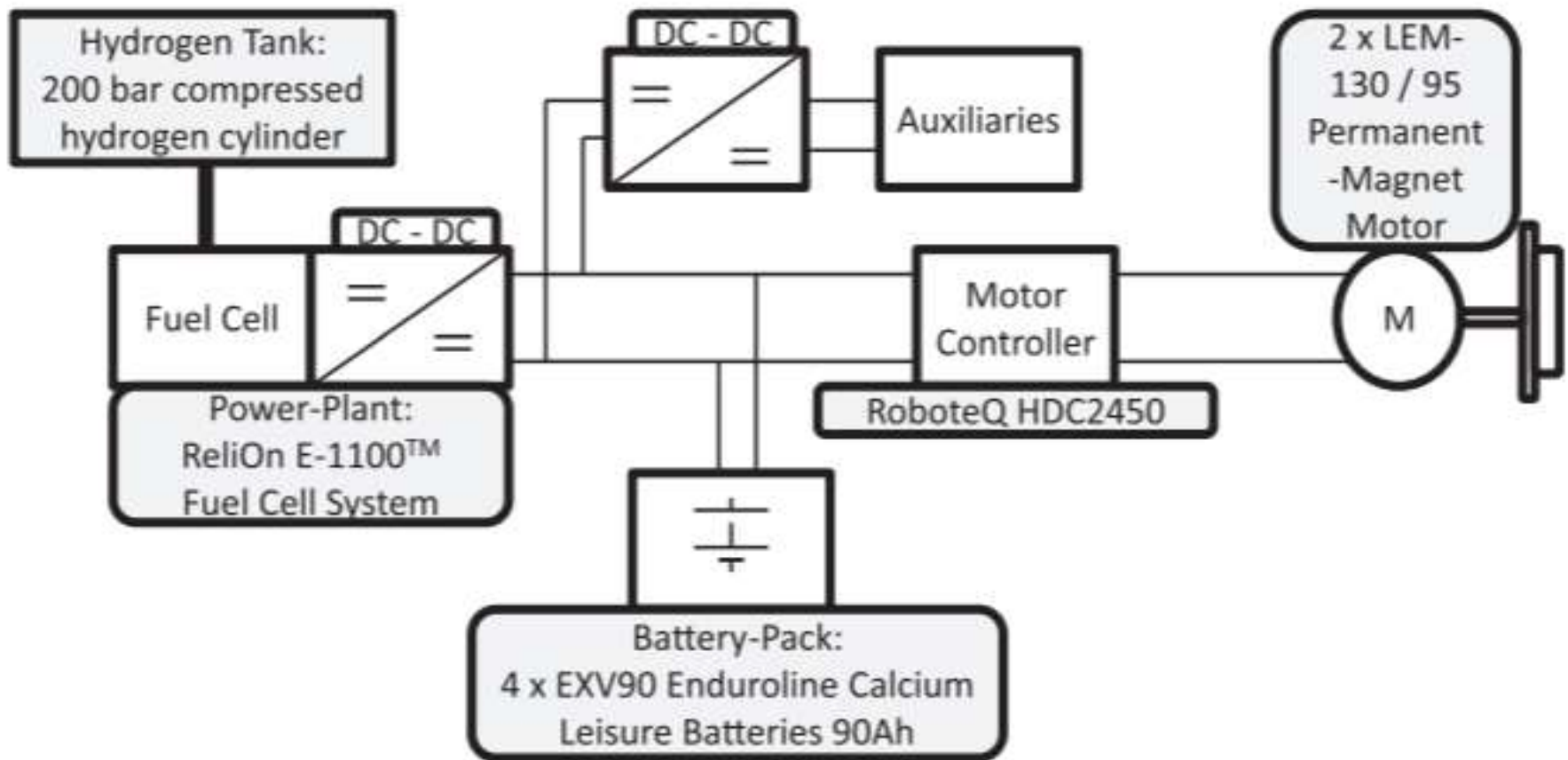
Practical Work – Institution of Mechanical Engineers: Railway Challenge



PEM Fuel Cell







Industry funded activity

- UK industry - RSSB – [Powertrain challenge](#) (finished 2016)

Future Railway Powertrain Challenge

Fuel Cell Electric Multiple Unit (FCEMU) Project

FCEMU Project - Phase 1 Report - Issue 1

University of Birmingham, Hitachi Rail,
Fuel Cell Systems Limited



Primary Author: Stephen Kent

Contributors: Dimantha Gunawardana, Tom Chicken
& Rob Ellis

Issue Date: June 2016

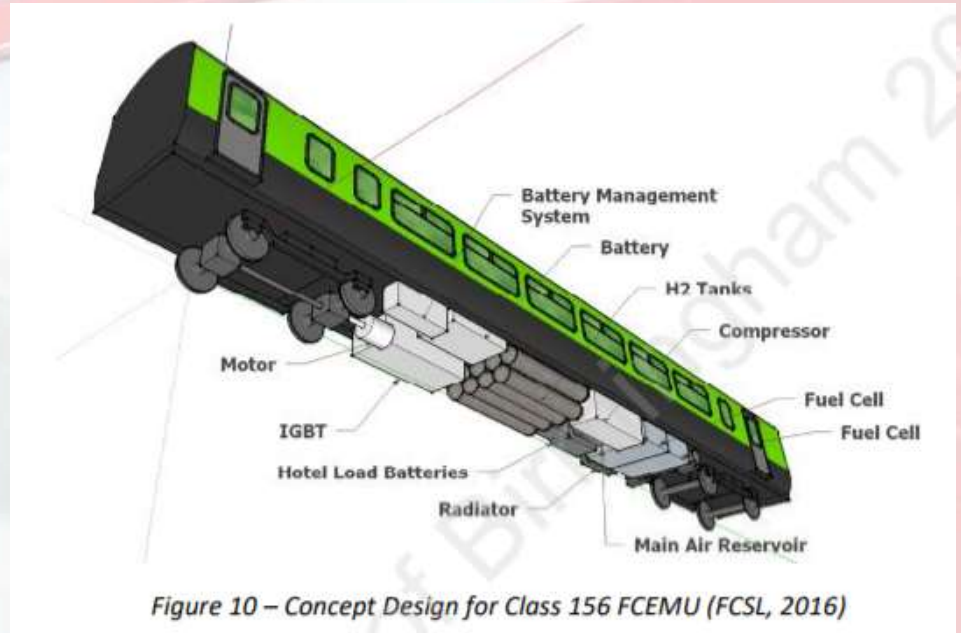
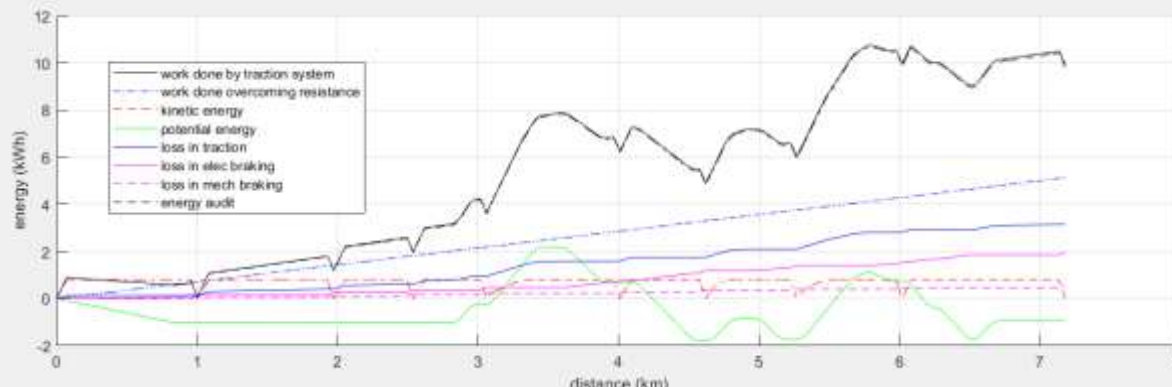


Figure 10 – Concept Design for Class 156 FCEMU (FCSL, 2016)



Hydrogen Storage Technologies

- Types:-
 - Liquid Storage
 - Cryo Storage
 - Metal Hydrides
 - Compressed Gas
 - 700 Bar
 - 350 Bar

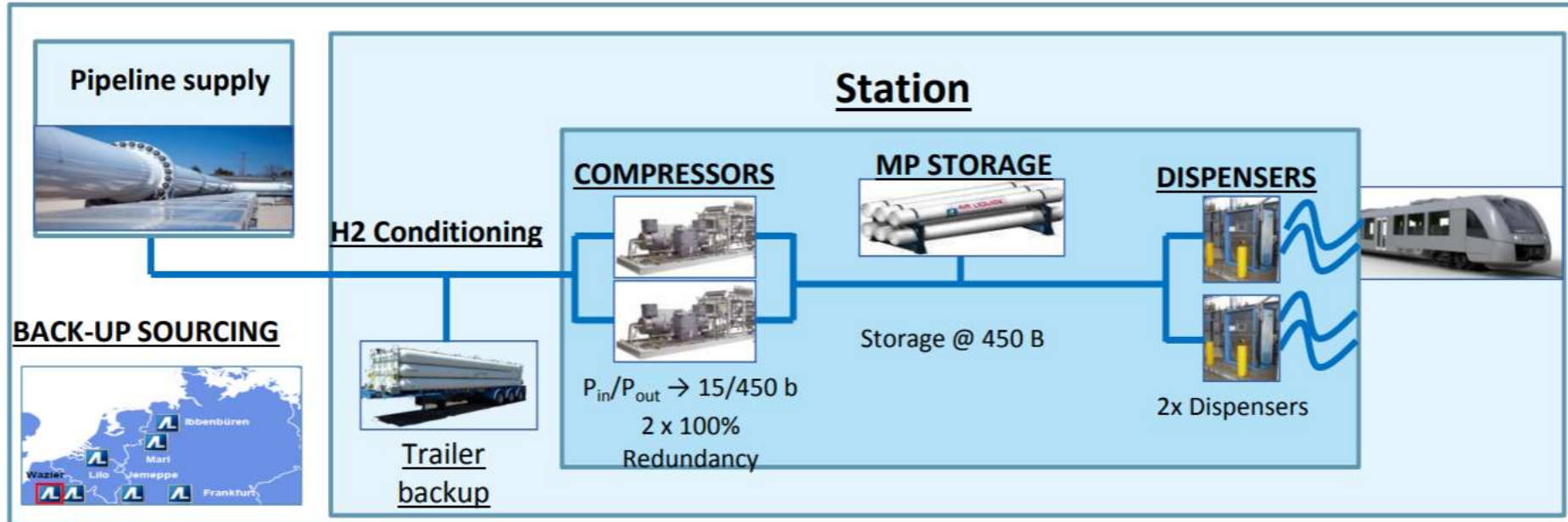


Hydrogen Supplies

- Natural Gas
 - Steam Reforming
 - Fracking
- Electrolysis
 - From The Grid
 - From Renewable Sources
- Algae + Biomass



Pipeline connection offers highest H2 supply reliability



AIR LIQUIDE, THE WORLD LEADER IN GASES, TECHNOLOGIES AND SERVICES FOR INDUSTRY AND HEALTH

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27/06/2017

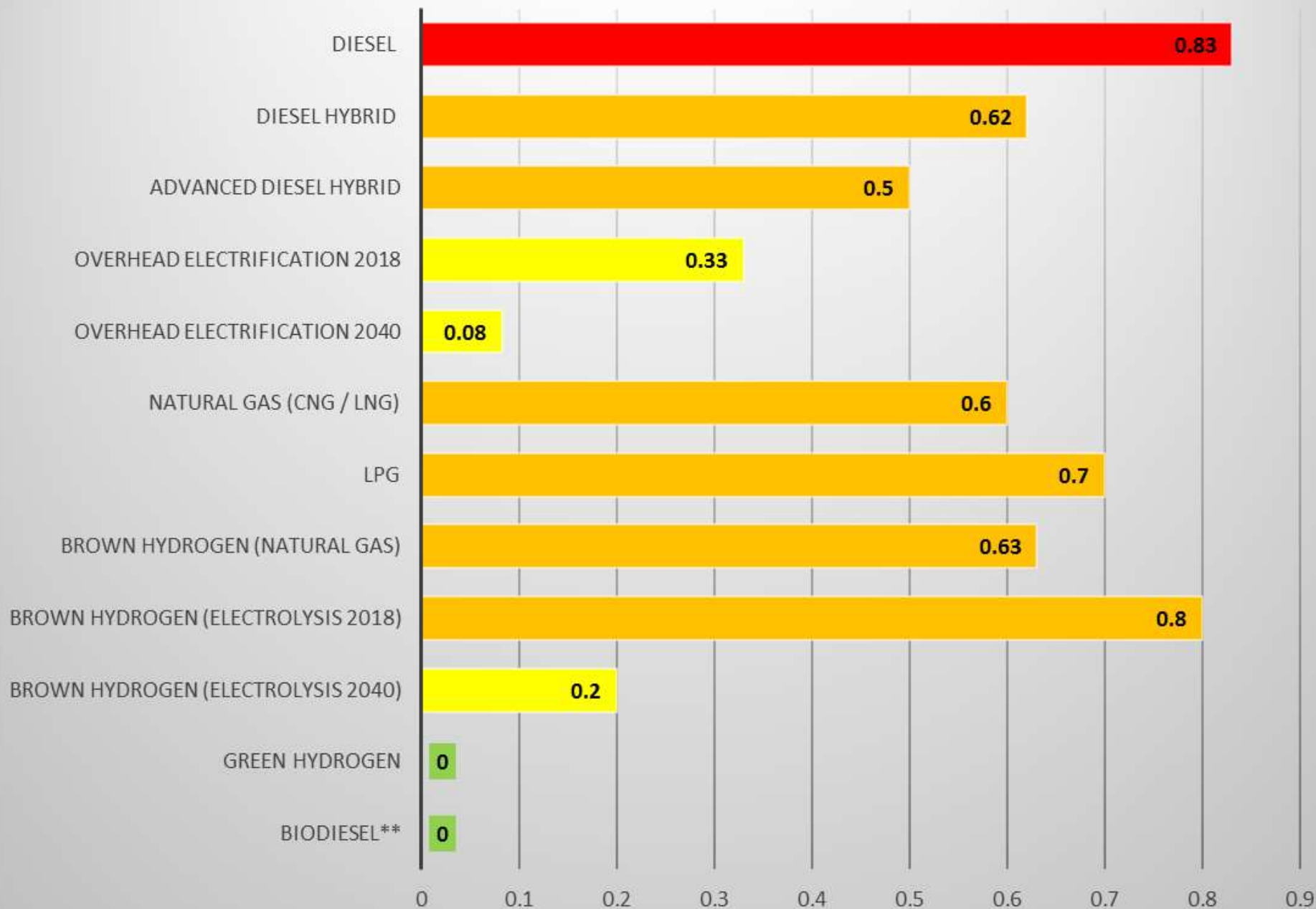
P. de Raphelis – H2 Energy Business Development

Hydrail Conference 2017

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- https://hydrail.appstate.edu/sites/hydrail.appstate.edu/files/12_raphelis.pdf

CO2 Emissions (kgCO2e/kWh)*

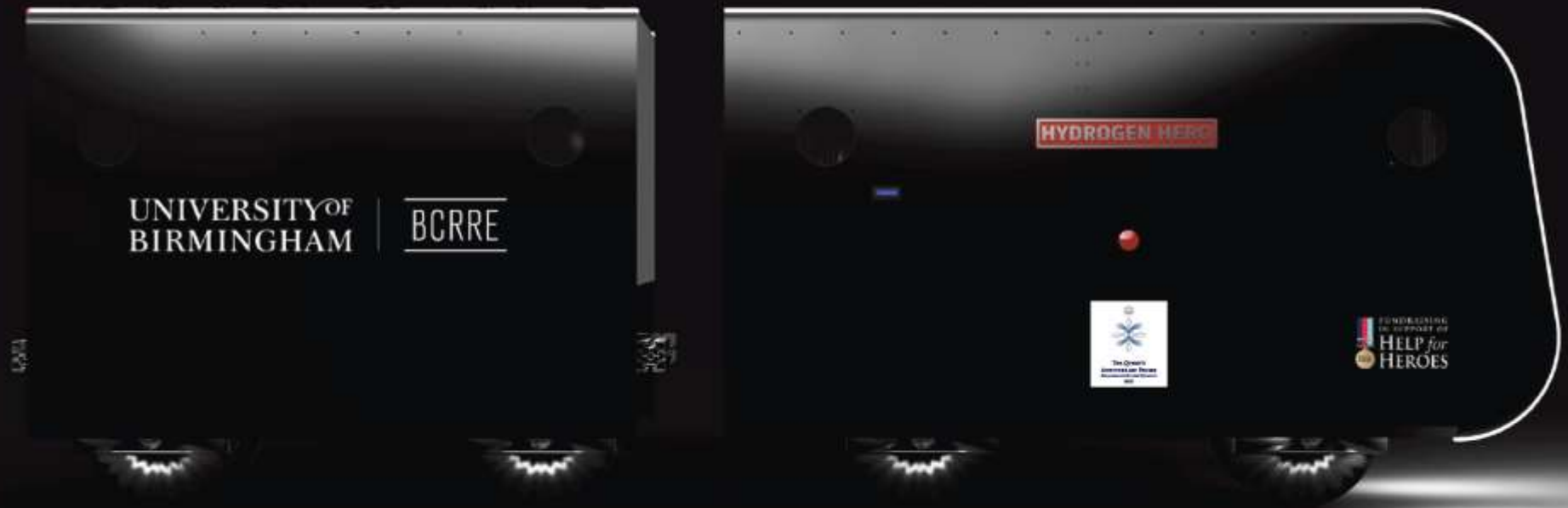


Conclusion

- Route to decarbonisation is complex.
- Electrified railways are dependent on the ongoing effort to decarbonise grid electricity.
- Hydrogen Bi-mode and energy storage are a good option of achieving the benefits of electrification away from the wires.
- Hydrogen is being seriously considered – watch this space!

But!!!

- Where does the hydrogen come from – better to use electricity directly?
- Aren't batteries getting better – well yes but unlikely to compete in the long term.
- High pressure.
- Explosive.
- Flammable.



HYDROGEN HERO

- Our students are brought up on hydrogen – they would have big safety concerns about using a liquid fossil fuel.

Network

NEWS FROM INNOTRANS

BCRRE and Porterbrook plan UK's first hydrogen train



Andrew Roden
Contributing Writer
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PORTERBROOK and the Birmingham Centre for Railway Research and Education (BCRRE) signed a memorandum of understanding at InnoTrans in Berlin on September 19 to develop the UK's first standard gauge hydrogen-powered train.

Porterbrook will supply a Class 319 electric multiple unit to BCRRE for conversion. The deal will allow both organisations to demonstrate how hydrogen-powered trains could be deployed across the UK rail network.

Development has recently started, and the train - to be known as HydroFlex - will begin testing and embarking on demonstration runs in summer 2019. The train will be able to operate on 25kV AC overhead and 750V DC third-rail routes, while the addition of a hydrogen fuel cell will enable it to operate in self-powered mode without the need for diesel engines.

A team from BCRRE recently demonstrated *Hydrogen Hero*, a narrow-gauge fuel cell-powered train, at the Rail Live event in June this year (RAIL 856).

Present at the signing was Secretary of State for Transport Chris Grayling, who joined discussions afterwards on the potential to 'decarbonise' the railway in terms of emissions at source.

"This exciting partnership between Porterbrook and the University of Birmingham is a great example of how forward-thinking businesses and our world-class universities can work together to deliver innovation that matters. I look forward to seeing the HydroFlex train coming to the UK railway in the very near future," he said.

Porterbrook Chief Executive

Mary Grant said: "I am delighted that BCRRE has chosen to work with Porterbrook on this exciting fuel-cell project. The HydroFlex will not only showcase rail innovation, it will also demonstrate how the private sector railway can effectively partner with educational bodies to jointly deliver real benefits to passengers, train operators and the communities our railways serve."

BCRRE Senior Lecturer in Railway Systems Dr Stuart Hillmansen added: "Hydrogen-powered trains offer a cleaner alternative to current diesel trains, and this project demonstrates the opportunities and value of innovation in the rail industry."

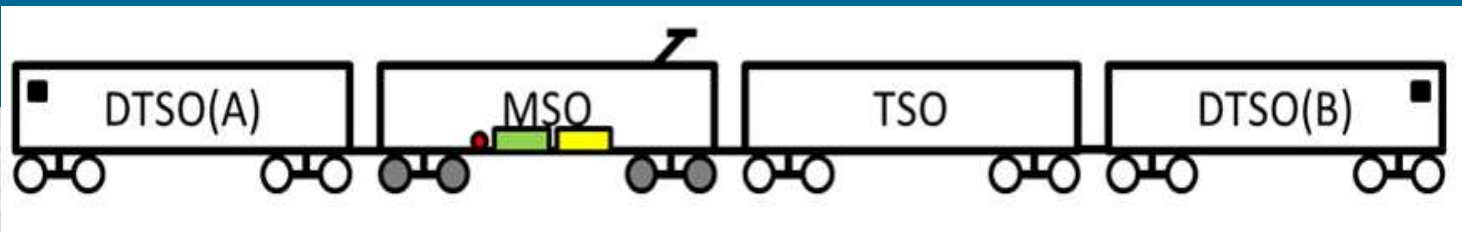
[@AndyRoden1](#)

An artist's impression of the HydroFlex train. PORTERBROOK.



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FLEX** | porterbrook 
in partnership with
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Zero emissions for a greener railway