Power Futures Group

Report of RRUK funded project:

Feasibility and benefits of Future Power Technologies – a preliminary analysis

R. Chen, P. Rama, R. Thring

Department of Aeronautical and Automotive Engineering, Loughborough University

S Hillmansen, R A Smith

Department of Mechanical Engineering, Imperial College London

Z Rahal, A Bauen, D Hart

Imperial Centre for Energy Policy and Technology, Imperial College London

May 2005

Loughborough University

icept

Imperial College London

1. Contents

1. CONTENTS 1

2. EXECUTIVE SUMMARY 3

3. INTRODUCTION TO THE RRUK POWER FUTURES GROUP AND THE FEASIBILITY OF FUTURE POWER TECHNOLOGIES PROJECT 5

3.1. Overview of analysis methodology 6

4. DUTY CYCLE ANALYSIS AND PROPULSION TECHNOLOGY ANALYSIS ... 7

4.1. Duty Cycle Analysis 9

4.1.1. Vehicle Platforms 9

4.1.2. Duty Cycles 10

4.2. Propulsion Technology Analysis 11

4.2.1. Base Case 12

5. AVAILABLE TECHNOLOGIES 15

5.1. Diesel Propulsion Technology 15

5.2. Electrification Technology 15

5.3. Fuel Cell Technology - PEMFC 16

5.4. Solid Oxide Fuel Cell Technology 19

5.5. Potential Future Hybrid Technology 21

5.6. Energy Analysis 25

5.7. Summary of propulsion technologies 33

6. ECONOMIC AND ENVIRONMENTAL ASSESSMENT 35

6.1. Introduction 35

6.2. Fuel and Powertrain Options 35

6.3. Methodology and System Boundaries 36

6.4. Energy Requirements of Transport 36

6.5. Carbon Dioxide Emissions from Transport 39

6.6. Costs of Transition 41
6.6.1. Fuel Consumption Costs 41
6.6.2. Capital Expenditure 42
6.7. Analysis 45
6.7.1. Economics 45
6.7.2. Emissions 50
7. CONCLUSIONS 53
8. REFERENCES 55
9. APPENDIX 1 58
9.1. Detailed expertise of each core member of the Power Futures Group 58
9.1.1. ICEPT 58
9.1.2. ICL Railway Research Group 59
9.1.3. ICL Sustainable energy and Hybrid Power Research Groups 59
9.1.4. Loughborough Combustion and Energy Conversion Group 60
9.1.5. Fuel Cell and Hybrid Vehicle: 60
9.1.6. Internal combustion engines 60

2. Executive Summary

Rail offers advantages in terms of environmental performance in comparison with many other modes of transport. However, as alternatives such as air and road transport improve and new technologies are introduced, the advantages are reduced. To maintain or increase them, new technologies and systems will also have to be introduced in the railways. Railway Research UK, an EPSRC-funded research centre, has provided funding to a team comprising groups within Loughborough University and Imperial College London, to conduct preliminary analysis on some of the possible future power and fuel combinations with regard to their economic and environmental characteristics.

A wide range of technologies and alternative fuels could potentially be introduced into rail. A subset of these was analysed for the present study, including the use of both proton exchange membrane and solid oxide fuel cells as prime movers, hybridisation with energy storage, and fuels such as natural gas, biofuels and hydrogen. Base case diesel and overhead electrified data were also considered. Modelling was conducted using rail-specific duty cycles for intercity passenger transport, urban commuting, and freight.

The modelling suggests that hybridisation of diesel engines provides an improvement in energy efficiency of up to 10-20% for passenger trains, and hence a reduction in CO_2 emissions. Freight efficiency was unaffected due to its already flat load curve. The use of PEM hybrid systems also offers advantages, with the primary benefit being realised for high speed and freight trains, at around 25% reduction. Urban cycles with fuel cells sized to meet peak load were found to be more efficient than those sized to meet mean load, but this translates into larger and more expensive fuel cells. SOFC in the configuration modelled offered limited advantages in terms of on-board efficiency.

The degree of hybridisation and the maximum recoverable braking energy are key parameters in the analysis. High braking energy recovery and reuse would be ideal, but is typically both costly and heavy, and so for the majority of the analysis 30% is considered reasonable.

In order to put the figures for improvements possible through a change or modification in prime mover into context, the cost and CO_2 emissions from drive cycles were also considered.

Costs of introduction of the different chains were estimated from known data, given that many new technologies have not reached cost maturity. Emissions from drive cycles were calculated using the specific energy figures modelled in the initial analysis, and efficiency figures from fuel chains found in literature. By introducing the full fuel cycle as part of the analysis, the efficiency of fuel provision can be balanced against the efficiency of use.

The model shows that significant reductions in specific CO_2 emissions can be achieved using different fuel chains in conjunction with the new technologies. In comparison with a diesel ICE base case, emissions can be reduced by as much as ~80% under different scenarios. Hybridisation, electrification and the use of fuel cells all offer promising benefits. However, many of these options offer significant increases in cost for the near term, of up to 30%. Only as mass-production takes place do these costs come below current technology. Many of the options do offer major reductions in CO_2 emissions, with biodiesel, electrification and fuel cells showing potential reductions of at least 60% and approaching 80%. Using the results calculated, rail compares very favourably with other modes of passenger and freight transport.

This study has been conducted over a short time frame and with very limited resources. It shows that the introduction of new technologies into rail could significantly improve its environmental performance, sometimes with only small cost penalties. As CO_2 emissions from every source become more tightly controlled, and energy prices rise, the introduction of these new technologies will make increasing commercial sense. Further, more sophisticated analysis into these fuel chains and technologies would provide the robust data needed to allow the rail industry to make informed decisions about implementing these new technologies and maintaining the current advantage over competing transport modes.