

Design and Control Options for an Intermediate
Temperature Solid Oxide Fuel Cell / ZEBRA Battery
Hybrid System for Vehicle Applications
(Project ABSOLUTE)

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The ABSOLUTE Project Partners

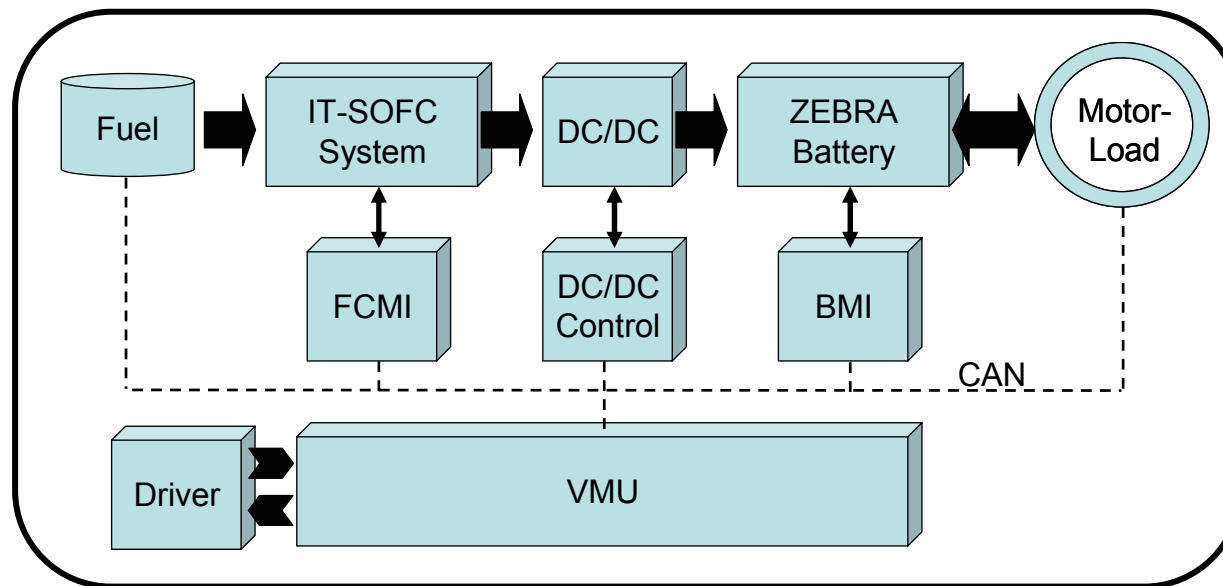
Project ABSOLUTE – Advanced Battery Solid Oxide fuel cell
Linked Unit To maximise Efficiency.

Sponsored by the UK DTI as part of the
Foresight Vehicle program.

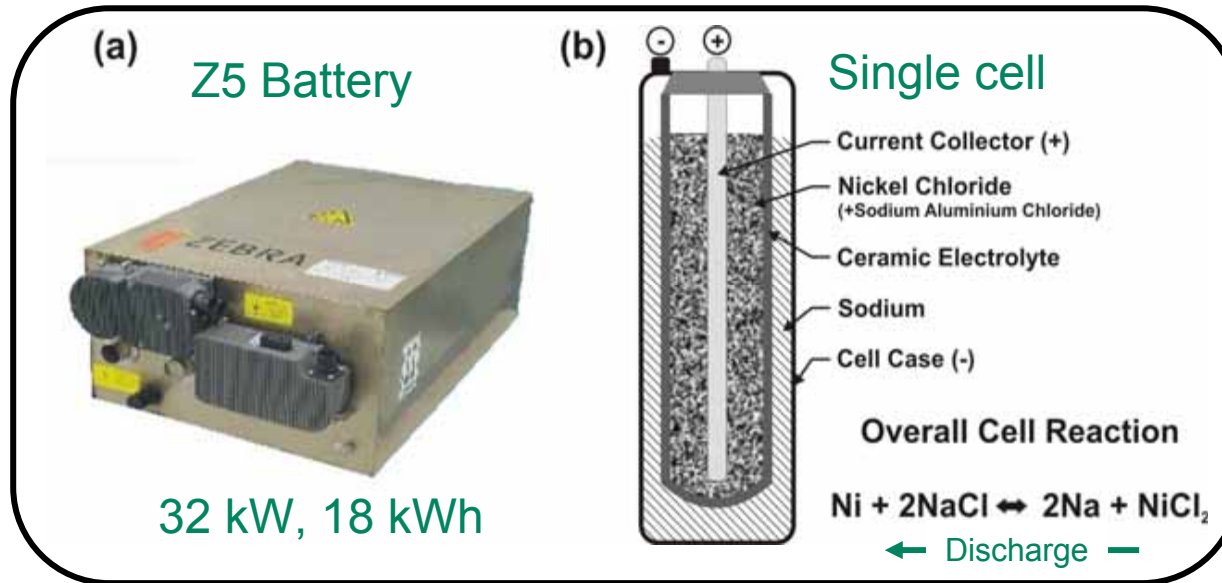
- Imperial College London (UK)
 - strong track record in solid oxide fuel cell technology
- Beta Research and Development (UK)
 - over 20 years experience of developing the ZEBRA battery, taking the technology from a laboratory curiosity to a commercial product
- MIRA Ltd. (UK)
 - world leaders in vehicle engineering and testing

Aim of the ABSOLUTE Project

- Combine a (high temperature) ZEBRA battery and an intermediate temperature solid oxide fuel cell (IT-SOFC)
 - Surpass the efficiency of a purely fuel cell driven vehicle
 - Extend the range of a purely battery driven vehicle
 - Option to operate on hydrocarbon fuel



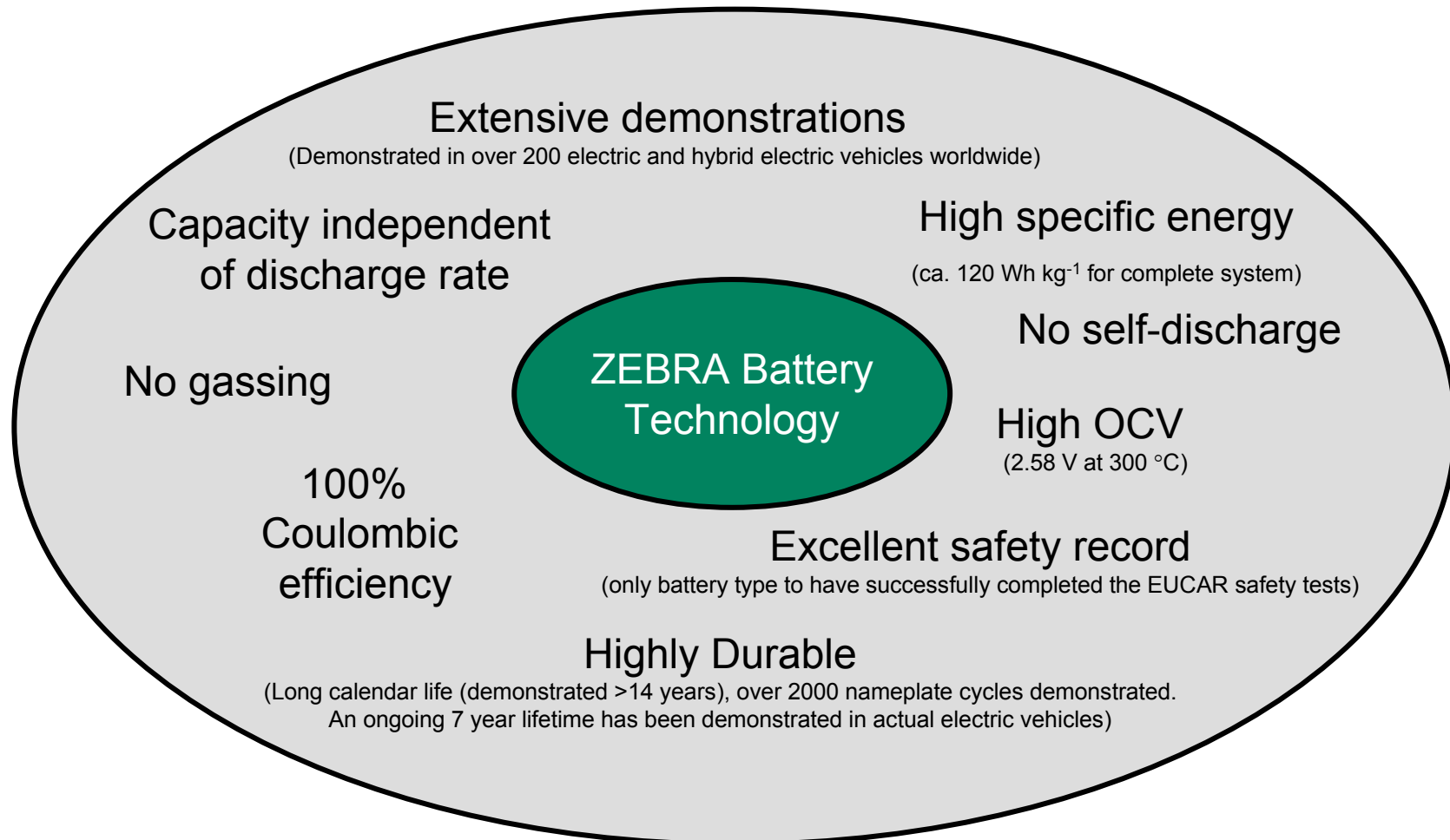
The ZEBRA Battery



- The **negative** electrode - molten **sodium** (when charged) and the
- The **positive** electrode - **nickel / nickel chloride** (when charged).
- The charged state lies to the right hand side of the cell reaction (as it is shown in Figure), and discharge results in the formation of nickel and sodium chloride.
- Ionic conduction occurs via Na^+ through a $\beta''\text{-Al}_2\text{O}_3$ (β -alumina) electrolyte.
- Typical operating temperature **270-350°C**, high temperature required to ensure adequate ionic conductivity of the electrolyte.

The ZEBRA Battery

Advantages



The ZEBRA Battery

Disadvantages

- Battery must be kept hot when not in use to be ready for operation
 - >100 W lost as heat
 - Battery energy used to sustain temperature
- Long start-up time from cold (5 hours+)
- When used alone in an electric vehicle **range is limited** – requires **grid connection**.

Solid Oxide Fuel Cells (SOFC)

For Automotive Applications

- Few examples of SOFCs in vehicles
 - APU / range extenders (Delphi, Webasto)
- Benefits of SOFCs for vehicular applications over PEMFC
 - Greater fuel flexibility
 - Heat produced can service the reformer
 - High durability (stationary power requires longer lifetime than vehicle)
 - Potentially lower cost materials
- Challenges
 - Lower power density (stacks) than PEMFC
 - Poor thermal and redox cycling properties (they don't like start/stop cycling)
 - Long start-up times from cold
- These challenges can be avoided or minimised by:
 - Avoiding excessive start-up/shut-down cycles (always on)
 - Hybridisation with another power source (i.e. by using a battery to accommodate the maximum and dynamic load)
 - Lowering the operating temperature of the SOFC.

Intermediate Temperature SOFC

- Operation in the 'intermediate' temperature range 500-800°C range affords certain advantages over high temperature SOFCs for vehicular applications
 - Faster start-up
 - Better thermal and redox transient performance
 - Lower cost materials requirement
 - Simplified systems requirements

The Hybrid System

Perceived advantages of ABSOLUTE system

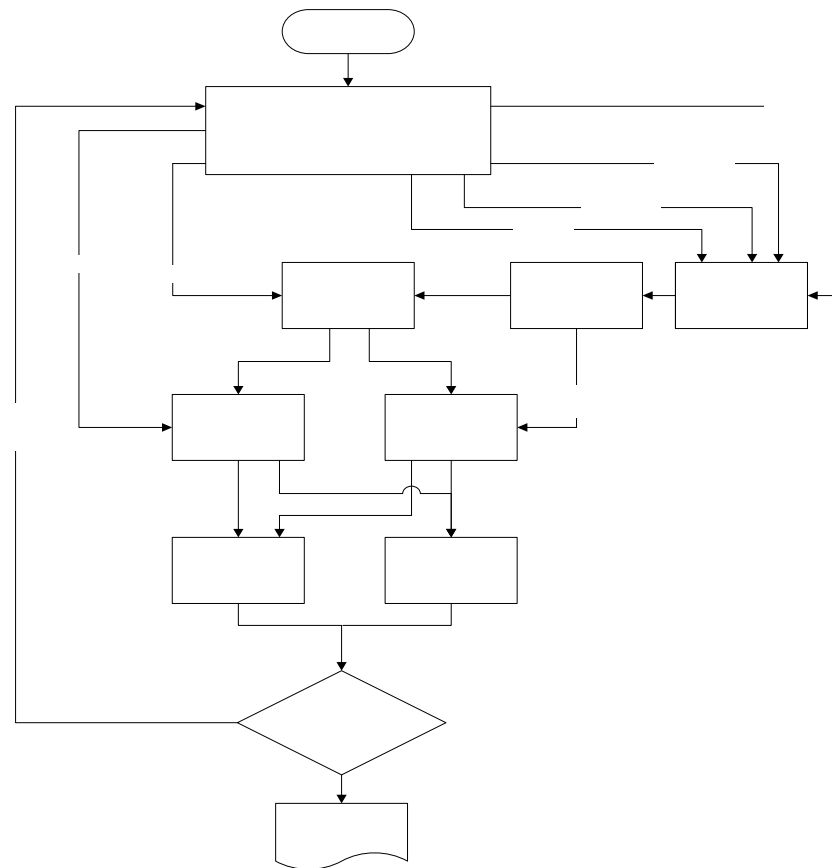
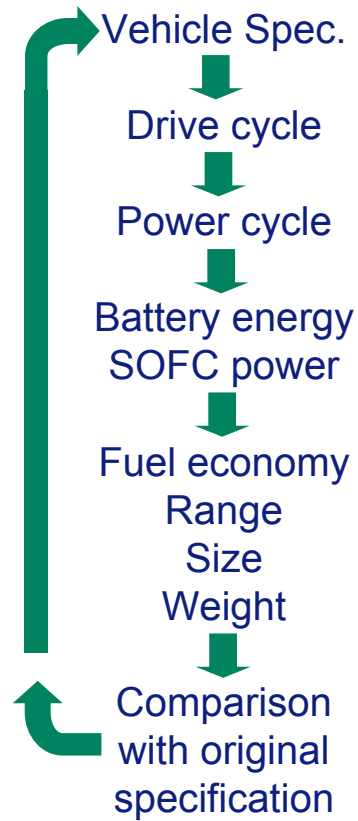
ABSOLUTE Hybrid Advantages		
All-Electric Hybrid	ZEBRA Battery	IT-SOFC
• Quiet operation • Efficient drive train and power sources • Fast acceleration at low speeds • Regenerative braking • Electronic control of all aspects of the vehicle • Conducive to the trend for increasing electrification of vehicles • Lower overall CO₂ emissions than ICE	• Rapid dynamic response • Regenerative braking • Proven technology in vehicles • No emissions • High charge/discharge efficiency • Uncomplicated cooling requirement • Four times the range of equivalent weight lead acid batteries	• High efficiency • Low emissions • Tolerance to a wide range of fuels with simplified fuel processing requirement compared to PEFC • Potential for thermal synergy between fuel cell and battery

Design Assumptions / Features

- Battery provides maximum power and satisfies load transients.
- The fuel cell operates in a predominantly '**always-on**' mode, during drive and non-drive time (so avoiding excessive redox and thermal cycling during stop/start operations).
- Fuel cell supplies **constant power** to the battery during drive and non-drive time – so reducing exposure of the fuel processor to load transients.
- Battery is not reliant on mains charge.
 - However, the system can, of course, accept mains charge if required.
- The hybrid system should be **charge neutral over a 24 hour** period. Range is fuel limiting not charge limiting.
- Intention of design is to minimise the size of the IT-SOFC and DC/DC converter – hybrid can be considered '**battery dominant**'.

Vehicle Modelling

Predict fuel cell and battery size, range and fuel economy



Start

Define Vehicle Type and Concept
(Vehicle type; nature of hybrid; role of fuel cell and battery, fuel type)

Fuel type

Drive-time

Define optimised
fuel cell power and
battery energy
capacity

Vehicle Modelling

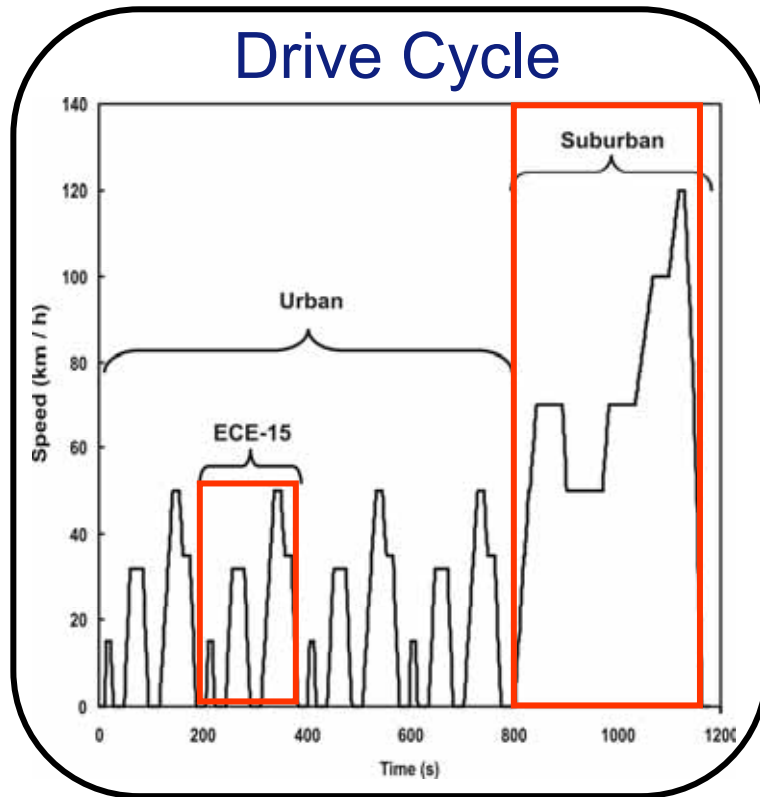
Predict fuel cell and battery size, range and fuel economy

Vehicle and drive train parameters	City car	Light delivery van	Taxi
Vehicle weight (kg)	800	950	1834
Driver weight (kg)	80	80	80
Max. Vehicle weight (kg)	1180	1550	2520
Vehicle weight for model simulation (kg) - M	960	1230	2100
Drag coefficient - C_d	0.32	0.4	0.35
Rolling resistance coefficient - f_r	0.015	0.015	0.031
Equivalent frontal area (m ²) - A	1.8	2	2.25
Acceleration due to gravity (m ⁻²) - g	9.8	9.8	9.8
Air density (kg ⁻³) - ρ	1.25	1.25	1.25
Vehicle auxiliary load ^a (kWe)	0.8	0.8	0.8
Proportion of regenerative braking captured - α_{regen}	0.4	0.4	0.4
Motor efficiency ^b - η_m	0.93	0.93	0.93
Transmission efficiency - η_t	0.95	0.95	0.95
Power converter efficiency - η_c	0.98	0.98	0.98

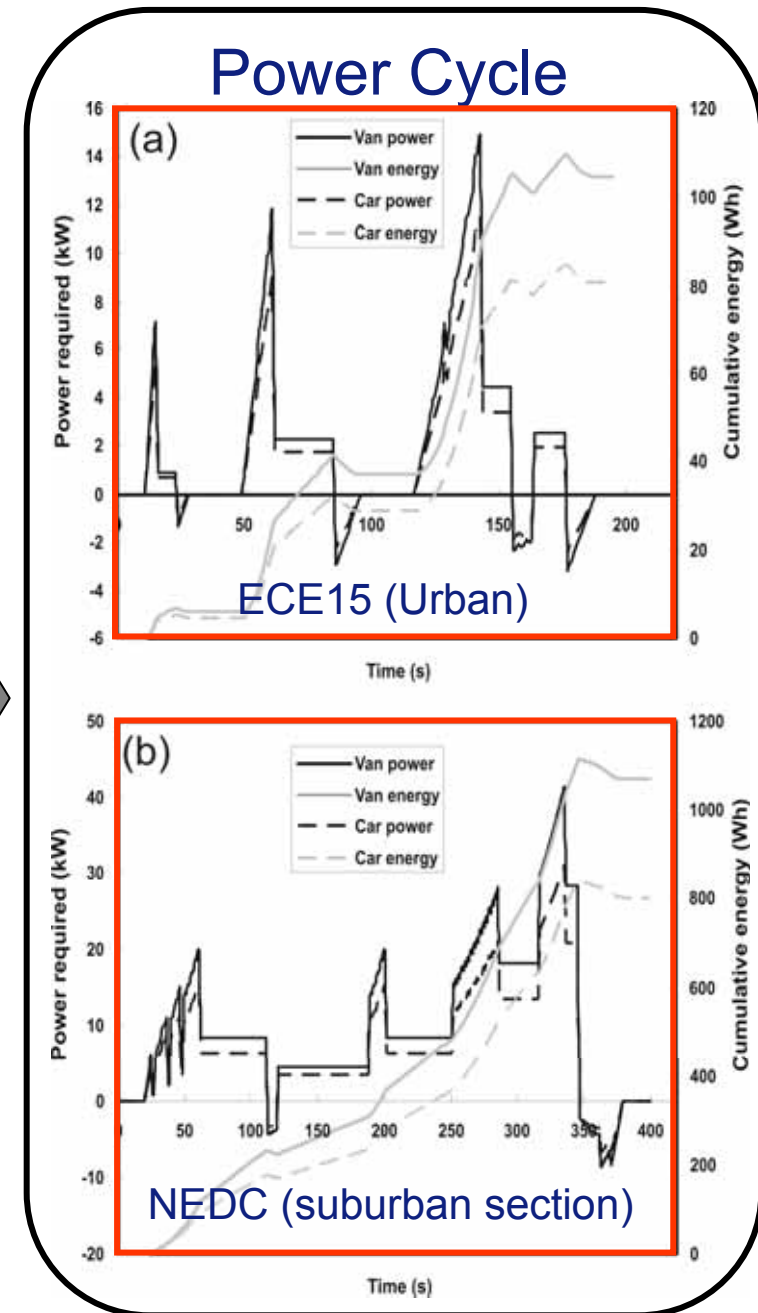
- Drive cycles - ECE-15 (urban), NEDC (urban/suburban)
- Fuels – compressed hydrogen gas (250bar), compressed natural gas (250bar), LPG

Vehicle modelling

Drive cycle to power cycle



Vehicle
Parameters

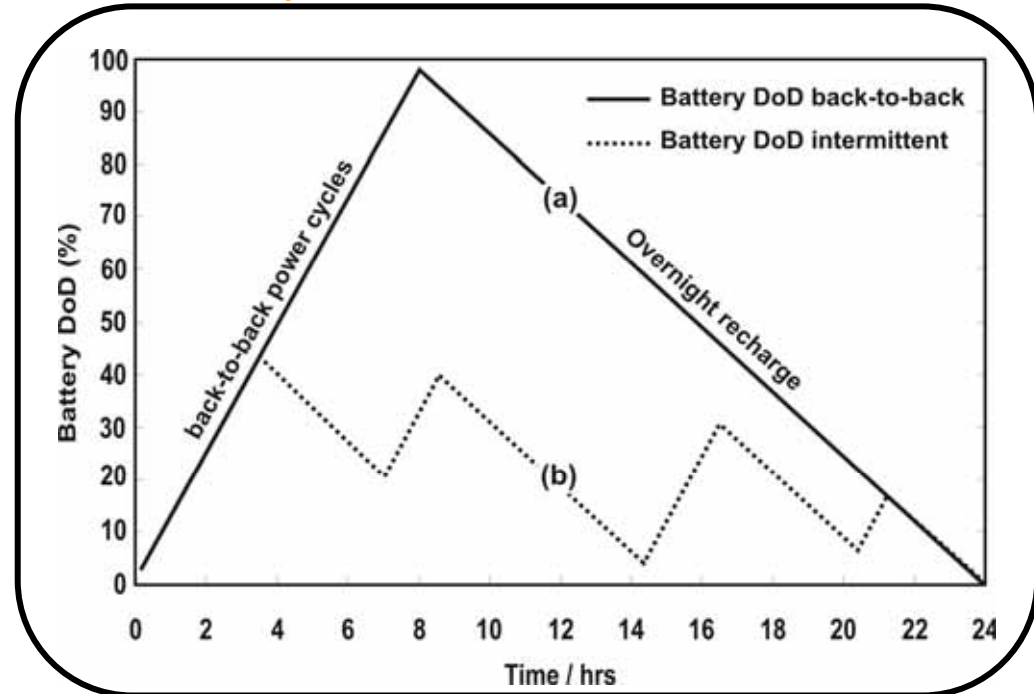


The Energy Balance

The 'whole day' drive cycle

- Whole day (holistic) drive cycle must be considered (drive time and non-drive time).
- Charge neutrality required over 24 hour period.
- Back-to-back drive cycles are worse case scenario for battery energy requirement

Example for 8 hours total drive time



Energy balance over 24 hour period:

Aux. load energy + Traction energy – FC energy = Battery Energy

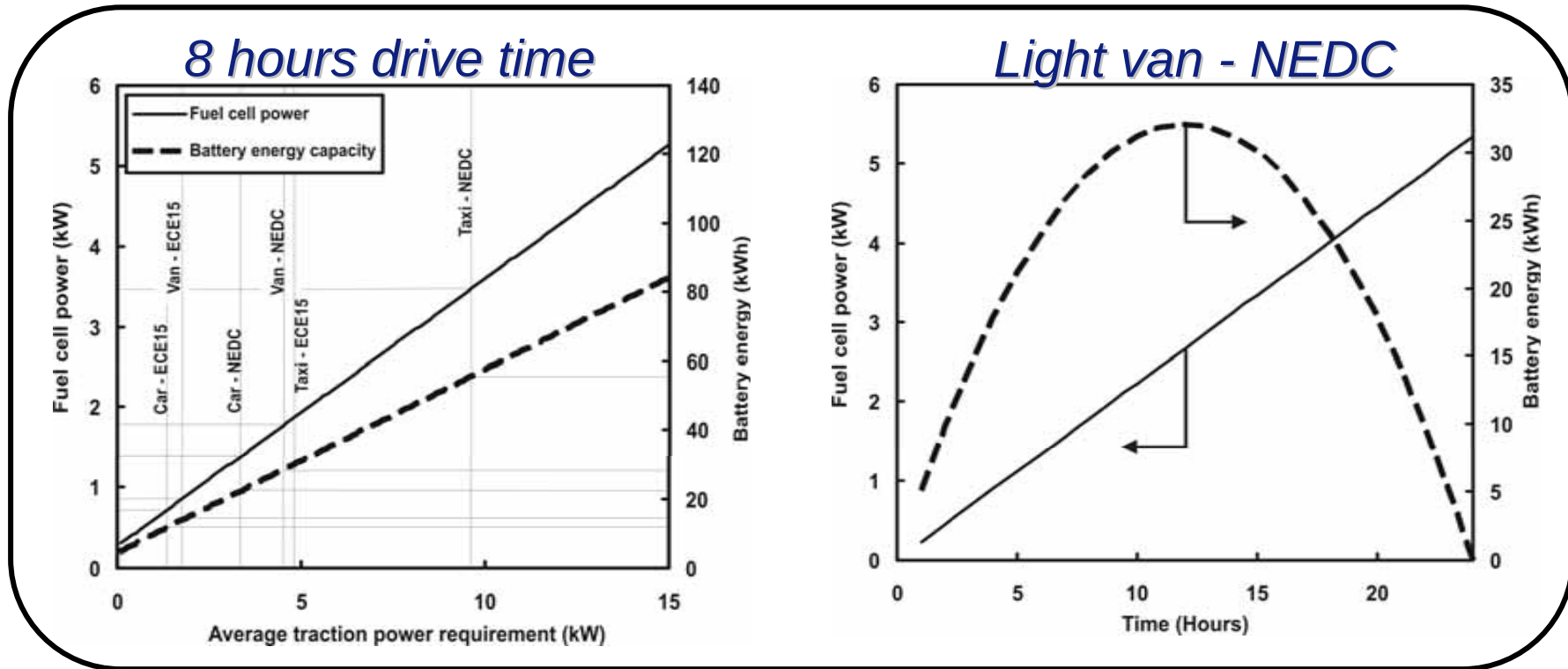
$$P_{aux} t_{drive} + P_{traction} t_{drive} - P_{fc} t_{drive} = \text{Battery Energy}$$

$$\text{Battery Energy} = P_{fc} t_{non-drive}$$

Vehicle Modelling Results

Fuel Cell and Battery Size

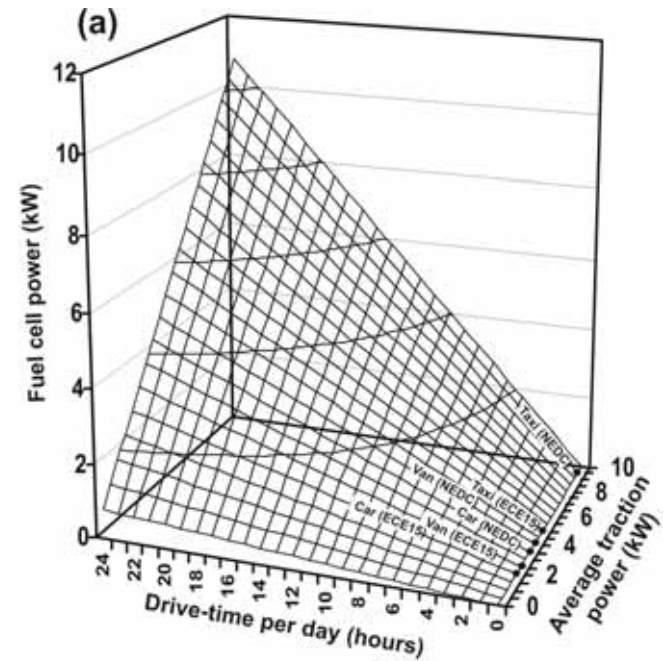
- Increasing average traction power (larger vehicle) increases fuel cell power and battery energy
- For a given vehicle, battery size has maximum at 12 hours drive time – system becomes fuel cell dominant at long drive times (it becomes a fuel cell car).



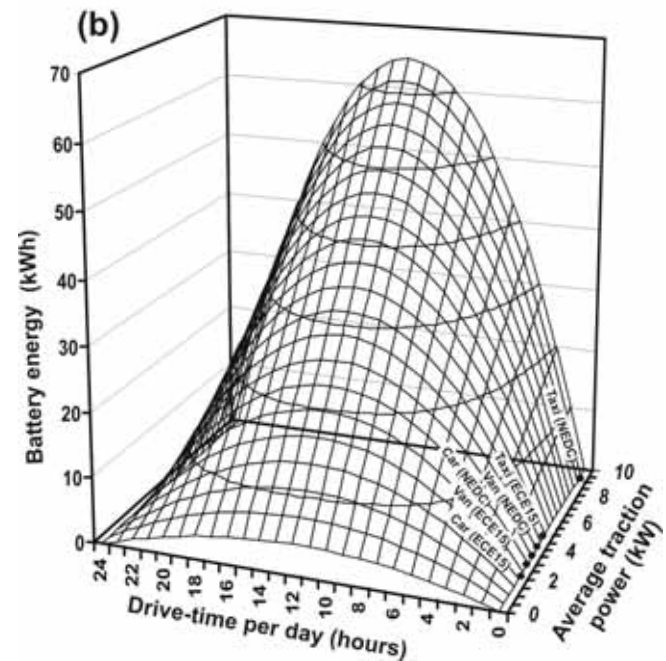
Vehicle Modelling Results

Fuel Cell and Battery Size

FC Power



Battery Energy

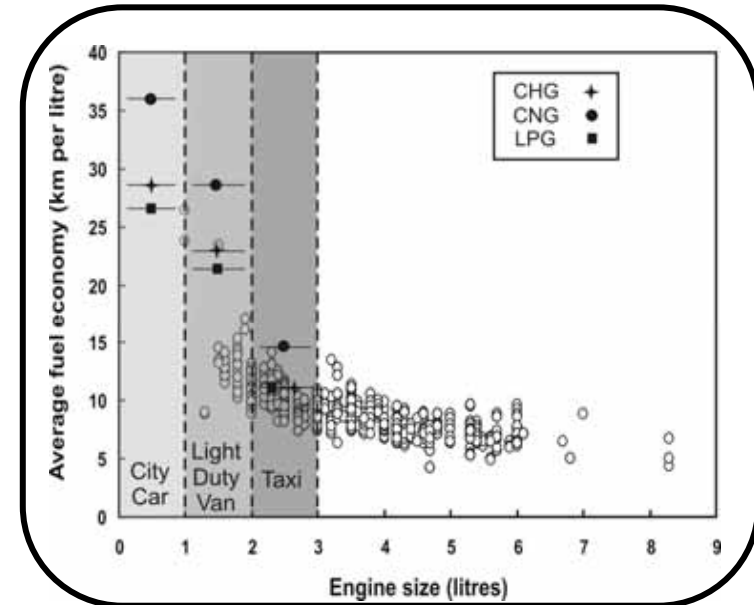


Vehicle Modelling Results

Fuel Economy and Range

- Range and fuel efficiency decreases with increasing vehicle size.
- Urban driving less efficiency than suburban driving.
- Fuel economy advantage greatest for smaller vehicles.

Model Year 2006 Fuel Economy Guide [www.fueleconomy.gov]
US Department of Energy



Including electric vehicles and hybrids.

	City Car		Light Delivery Van		London Taxi	
Fuel Economy (km l ⁻¹ equivalent)	ECE-15	NEDC	ECE-15	NEDC	ECE-15	NEDC
CHG	25.7	30.8	22.0	24.0	11.2	11.8
CNG	33.3	39.8	28.4	30.9	14.5	15.2
LPG	25.3	30.3	21.6	23.5	11.0	11.5
Range (km)						
For 50 litre tank						
CHG	81.7	97.8	67.7	76.0	35.5	37.3
CNG	329.7	391.2	278.8	304.1	142.2	149.2
LPG	748.7	896.6	639.0	697.0	326.0	241.9

Different Modes of Operation

- In practice, varying modes of operation are encountered during **driving, recharge and standby.**
- Example:
 - Max. fuel cell power if battery low.
 - Min. fuel cell power (standby) if battery fully charged.
- Models of the fuel cell system and battery are necessary to simulate the full range of operating conditions.

Modes of operation

Driving

- | | |
|---------------------------------------|--|
| • Fuel cell nominal power | Fuel cell operating at design point. Battery can receive regenerative braking energy. |
| • Fuel cell maximum power | Fuel cell operates at maximum power when battery charge is low – decision required at what state-of-charge this occurs. Battery can receive regenerative braking energy. |
| • Fuel cell off – battery only | Used when mains recharge is available and trip length within capacity of battery alone. Battery can receive regenerative braking energy. |
| • Fuel cell on but no power delivered | Situation in which battery is at, or close to, full charge and fuel cell disengaged to avoid over charging. Battery cannot receive regenerative braking energy. |

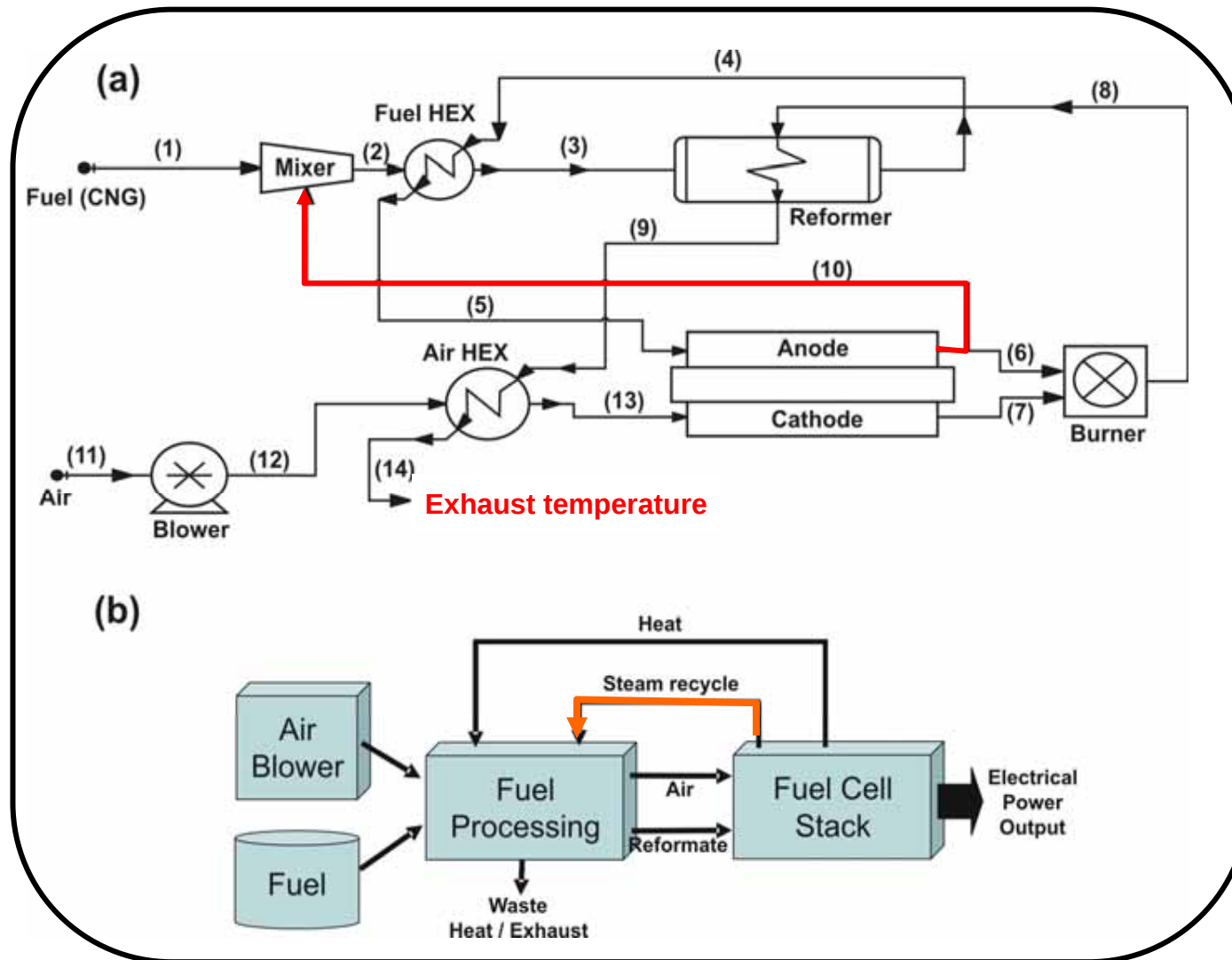
Recharge

- | | |
|----------------------------|---|
| • Fuel cell nominal power | Fuel cell delivers power at its design point for recharge over non-drive-time. |
| • Fuel cell adaptive power | Fuel cell delivers power at off-design point rate, greater or less than nominal power for rapid or extended recharge time. Recharge power needs to be programmed by user based on the time of next expected use of vehicle. |

Standby

- | | |
|---|---|
| • Fuel cell and battery at operating temperature | Fuel consumed to maintain temperature of fuel cell and battery (electrical heating of battery) |
| • Fuel cell cold, battery temperature self-sustaining | Battery powers electrical heaters to maintain its own temperature. Typical power required to maintain temperature is 100 W. |
| • Fuel cell cold, battery cold (charged) | |
| • Fuel cell cold, battery cold (discharged) | |

IT-SOFC System Modelling



IT-SOFC System Modelling

- 5 kWe (limit of what would be used in ABSOLUTE vehicle, APU)
- Methane fuel – high fuel efficiency
- 700-800°C, IT-SOFC range (anode supported planar)
- Partial internal reforming
- *gPROMS ModelBuilder* 2.3.5 (Process Systems Enterprise)
- Steam reforming:
 - Steam reformer technology is **well developed**.
 - Steam reformers can be used with a **wide range of fuels**.
 - No introduction of oxygen is required (as for partial oxidation).
 - **High hydrogen yield** – the highest efficiency of all of the reforming technologies.
- Steam reforming can have the problem of **long start-up time** and **poor transient response**. However, since a *nominally* ‘always-on’ / constant load strategy is adopted for the IT-SOFC, this is less of an issue.
- Stack model based on: P. Aguiar, C.S. Adjiman, N.P. Brandon, J. Power Sources 138 (2004) 120-136.

IT-SOFC System Modelling

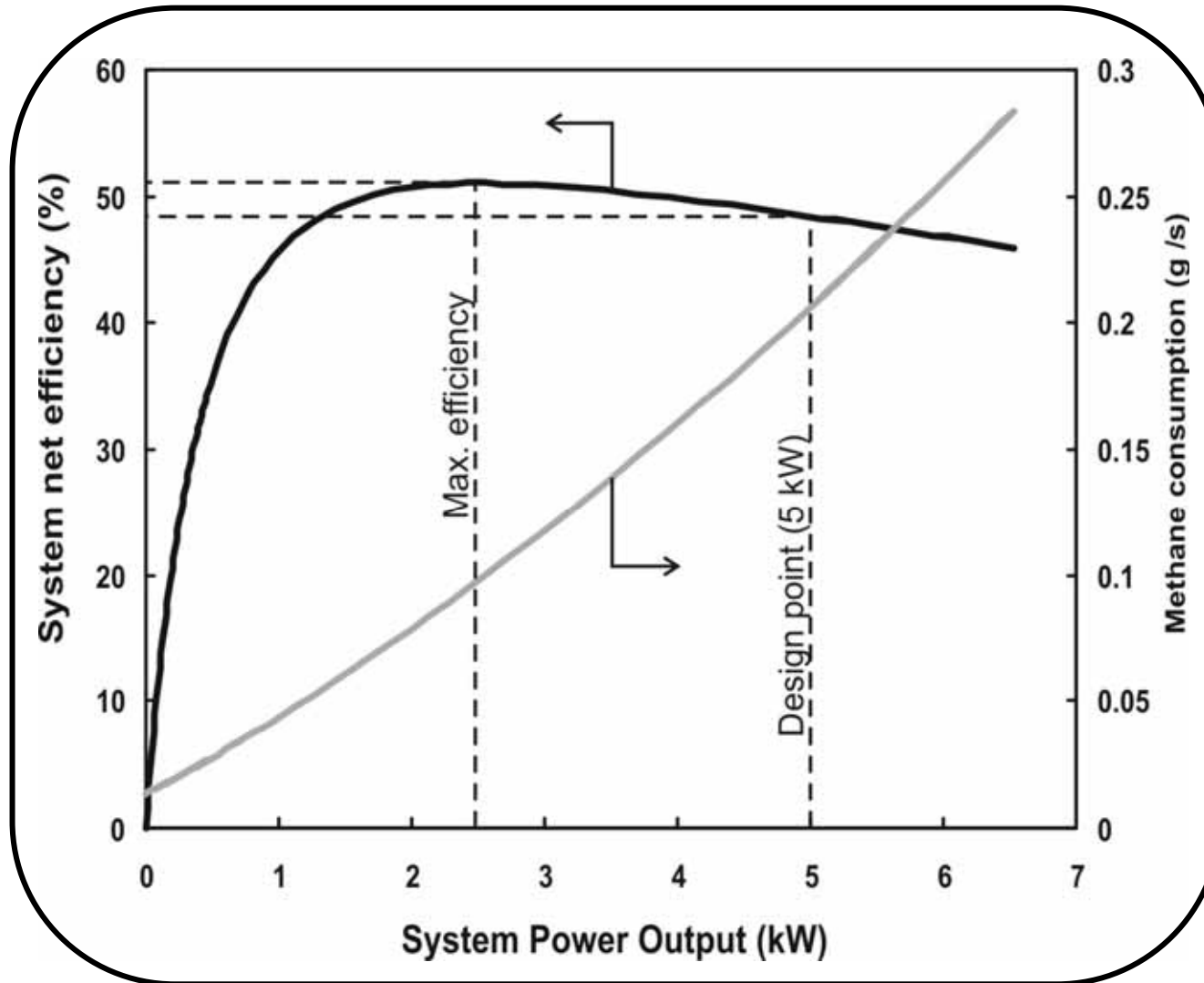
Model results - System Efficiency, Exhaust Temperature

- Approx. 48% system net electrical efficiency predicted.
- Exhaust temperatures compatible with battery.
- 8:1 turn-down ratio.

Stream	Temperature (°C)
Methane feed (1)	25
Fuel HEX inlet (2)	711
Fuel inlet of reformer (3)	733
Fuel reformer outlet (4)	762
Fuel inlet to stack (5)	740
Fuel at stack outlet (6)	875
Air at stack outlet (7)	862
Burner exhaust (8)	1002
Air HEX inlet (9)	962
Fuel recycle (10)	875
Air feed (11)	25
Air blower outlet (12)	38
Air inlet to stack (13)	793
Exhaust gas (14)	267

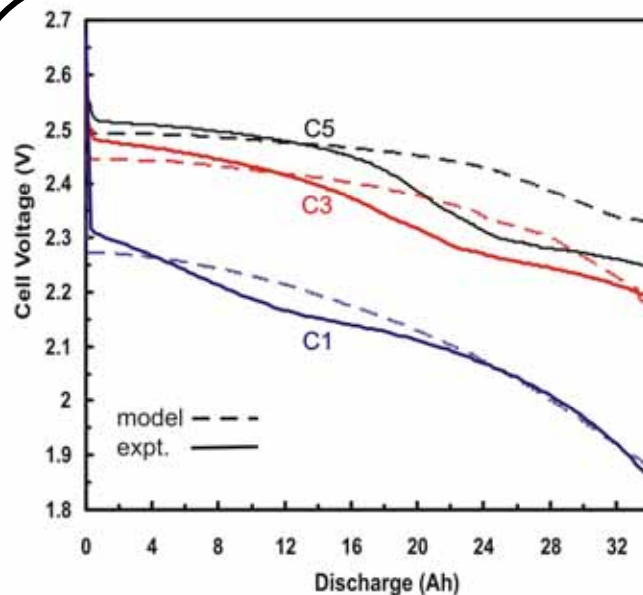
IT-SOFC System Modelling

Model results - System Efficiency, Exhaust Temperature

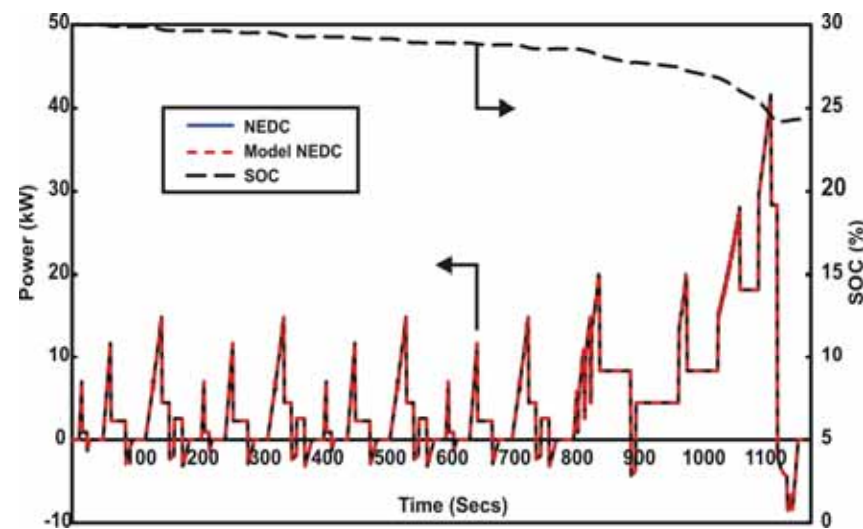


ZEBRA Battery Modelling

- **Aim:** To predict battery response during transient operation and assess modes of operation when operating with fuel cell.
- MATLAB / SIMULINK; electrical and thermal considerations



Discharge profile for cell

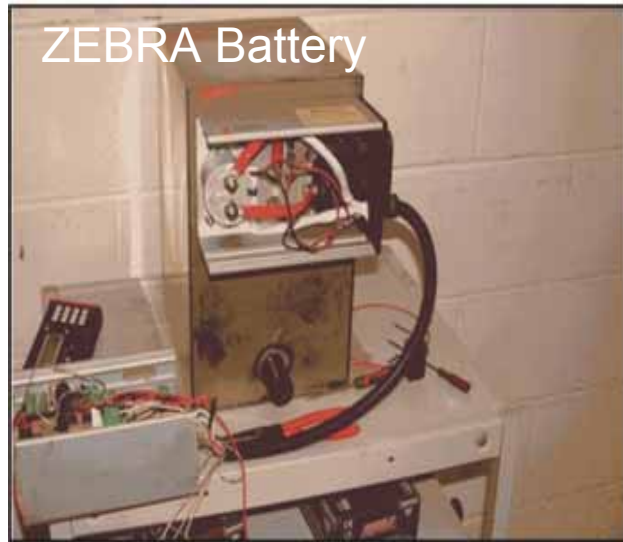


Power cycle model for battery

Demonstration System

'Bench Top' Prototype

- Electrical integration and control strategies exercised.
- System scaled to approx. 1/10th actual size
- 300 W_e IT-SOFC (700-800°C) anode supported technology
- ZEBRA battery (10 ML2P cells; 45 Ah; 2 kW_{max})
- Control code for FCMI, BMI and VMU. All interfaced with CAN



ZEBRA Battery



Fuel Cell Test Station

Test System Specification

- Reformate simulation (6 gas lines).
- Direct injection humidification.
- 1 kW electronic load.
- Large elevator furnace.
- Back-pressure control.
- Differential pressure measurement.
- Water condensation stage.
- 32 voltage sense I/P.
- 32 thermocouple I/P.
- Off-gas analysis (mass spectrometry and gas chromatography).
- Current interrupt.
- Electrochemical impedance.
- UPS backup.

Summary

- A combination of high temperature battery (ZEBRA) and high temperature fuel cell (IT-SOFC) is being investigated for automotive applications.
- Impressive range and fuel economy predicted for LPG and CNG although compressed hydrogen not suitable due to range limitation.
- Vehicle modelling implies that the ABSOLUTE hybrid will suit small to medium size vehicles run up to 10 hours per day.
- Fuel cell and battery models demonstrated.
 - The opportunity for thermal integration has been identified.
 - Models will be used to simulate hybrid performance and system efficiency over more complicated 'whole day' drive cycles.
- 'Bench-top' demonstration system commissioning underway.

The authors thank the organising committee and ASME for the opportunity to present this work

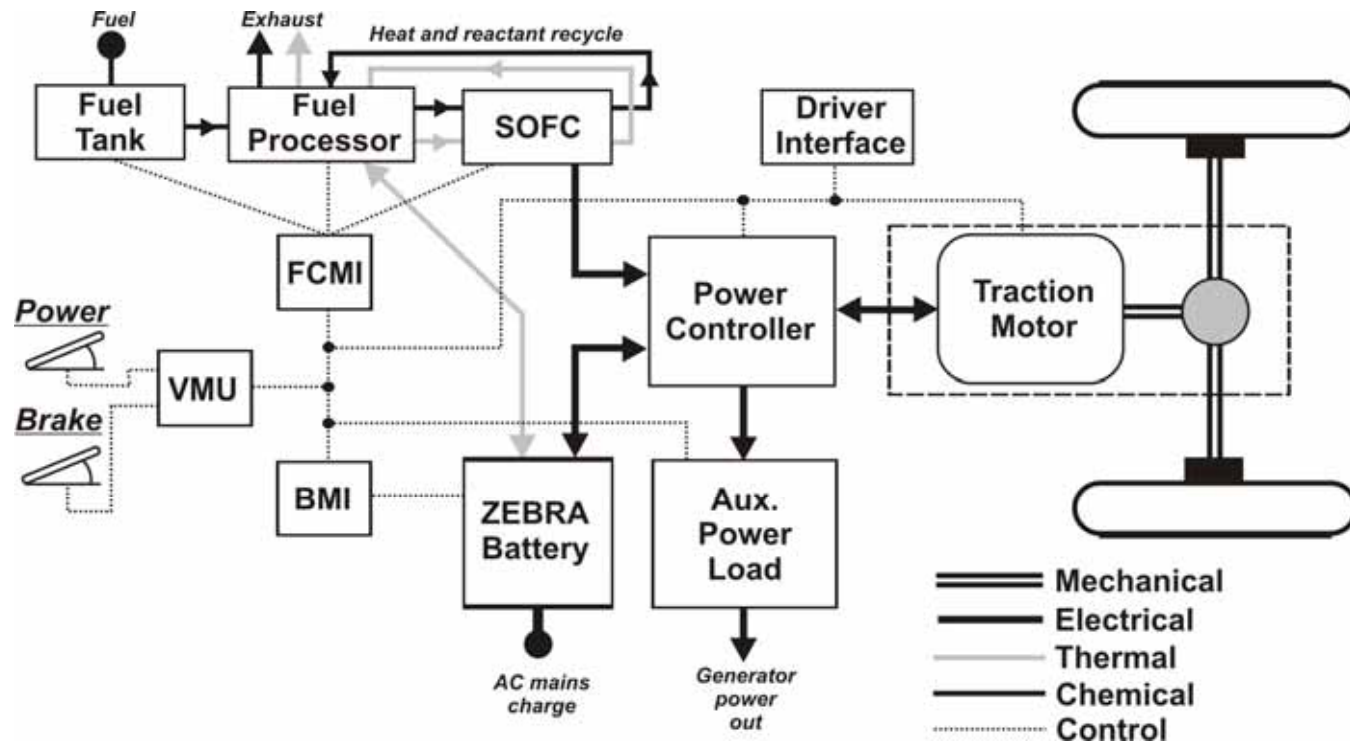
Thank you for your attention

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Additional Slide

ABSOLUTE Vehicle system

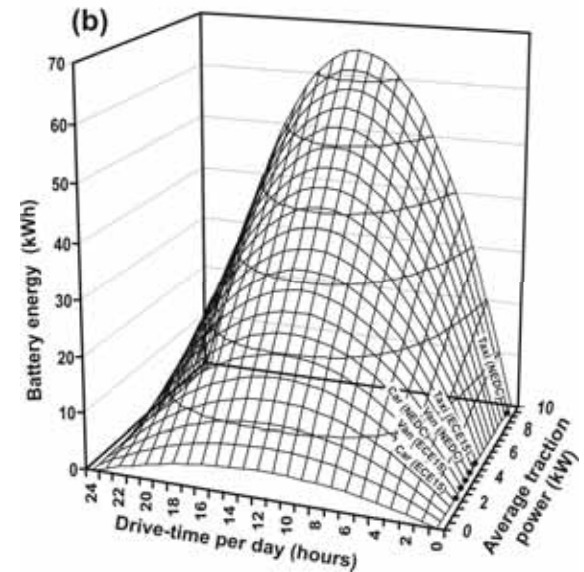


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Model Parameters

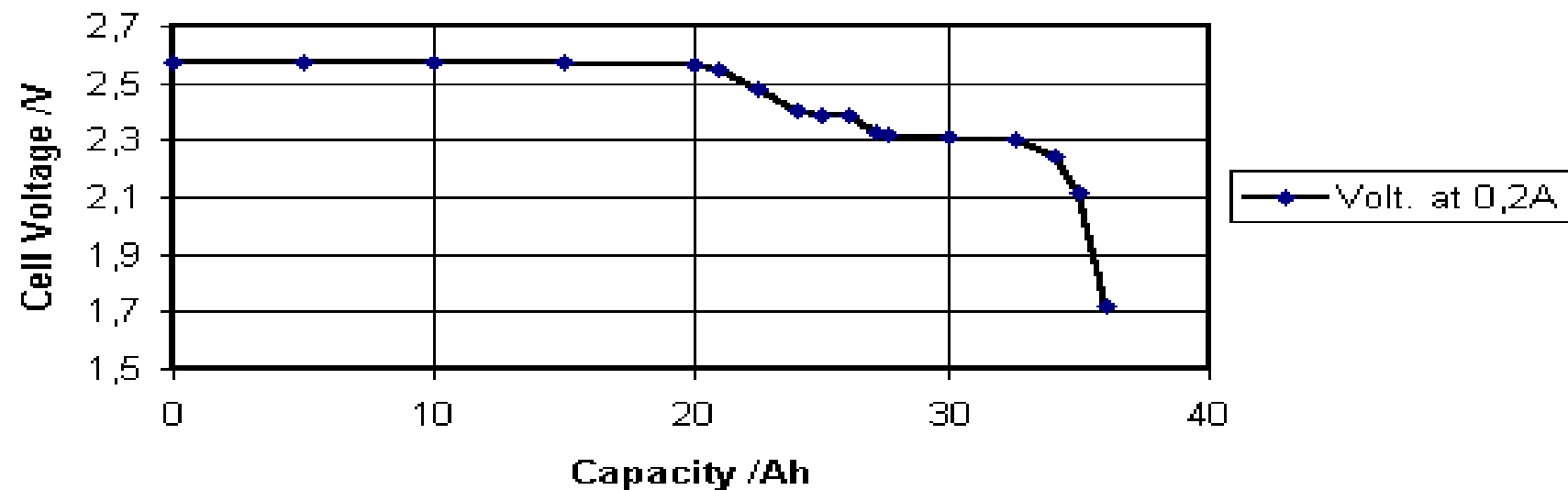
Parameter	Value
Net electrical DC power (W)	5077
Air blower power (W)	300
Electrical DC efficiency (%)	48.1
Anode exhaust recycled (%)	64
Fuel utilisation factor	0.75
Air ratio	7
Current (A)	200
Average current density (A m^{-2})	5000
Voltage (V)	27.9
Average cell voltage (V)	0.73
Power output (W)	5578
Electrical DC efficiency (%)	53.1

Battery Energy and Fuel Cell Power



Additional Slide

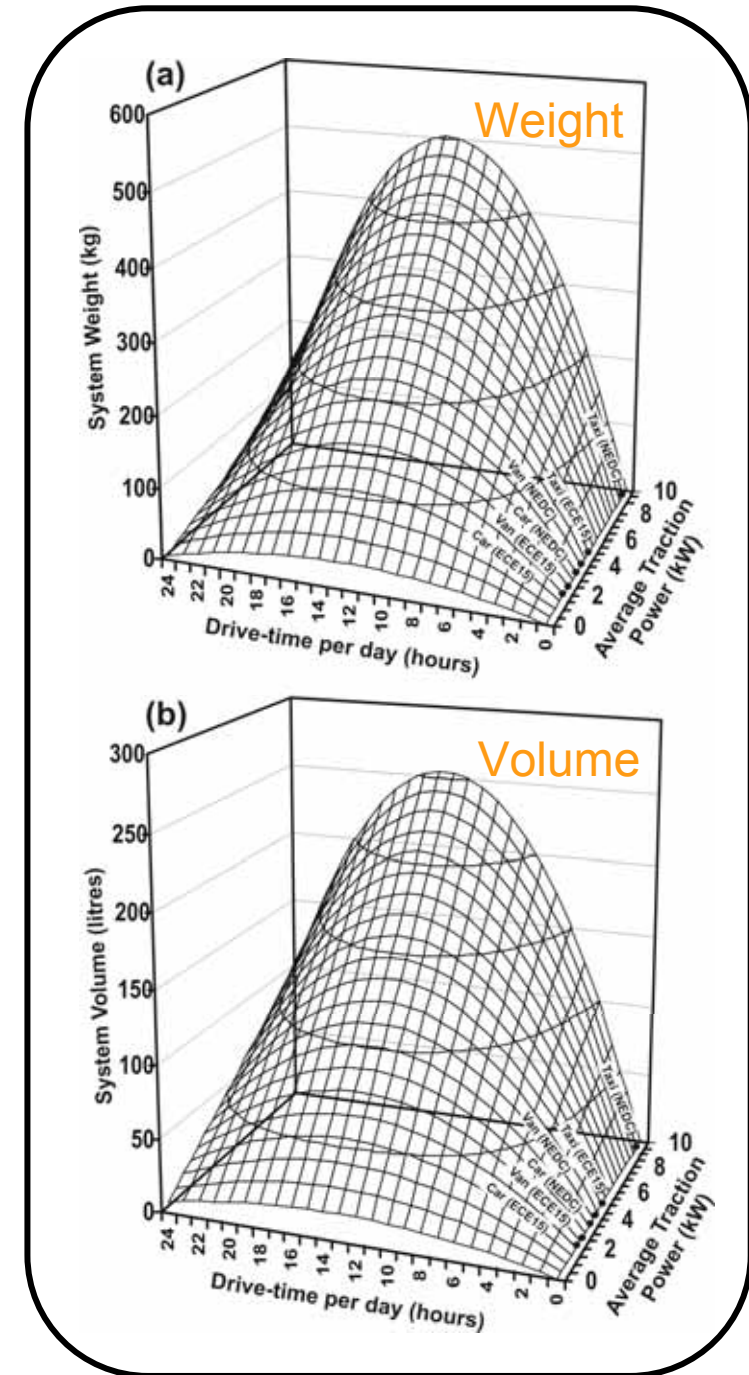
Battery Discharge Profile



Vehicle Modelling Results

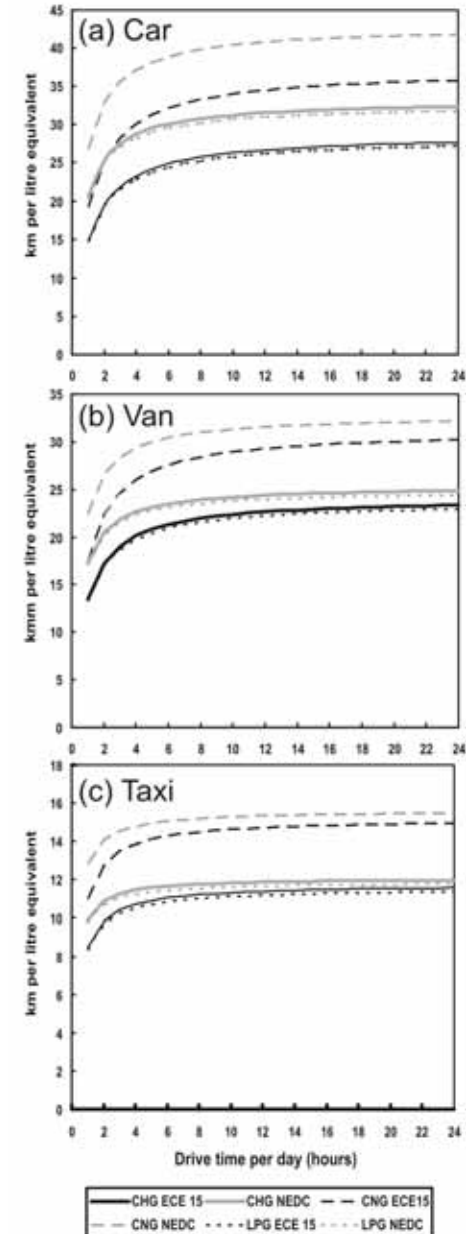
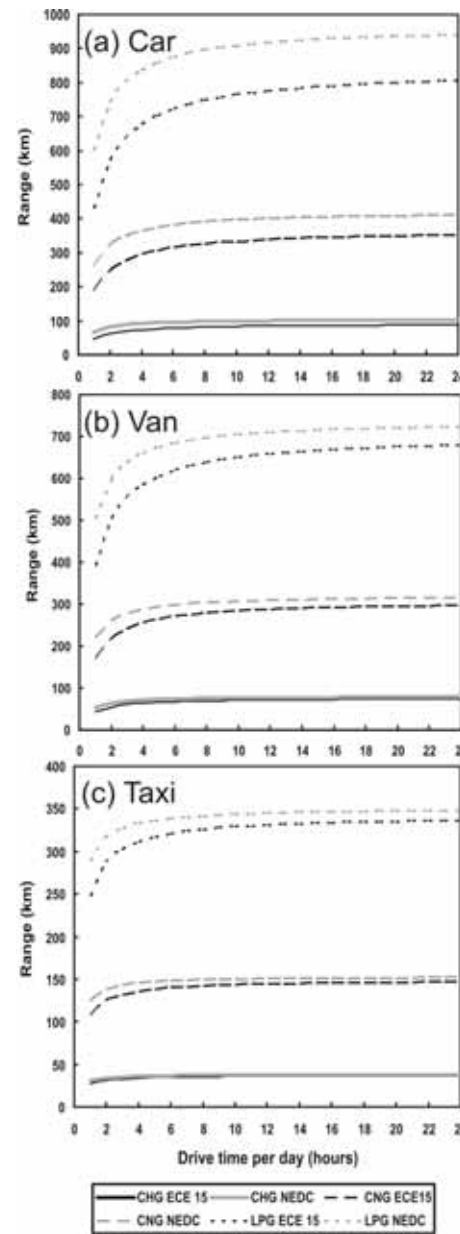
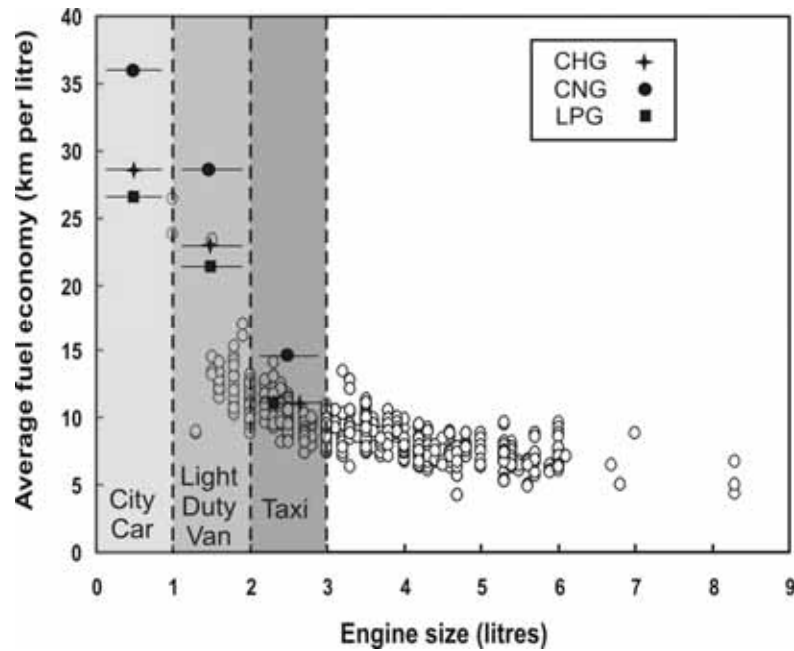
System Weight and Volume

- Stack
 - 100 W/kg
 - 100 W/litre
- Battery
 - 145 Wh/kg
 - 330 Wh/litre



Additional Slide

Fuel Economy



Additional Slide

Fuel Cell Power to Battery Energy Ratio

