Power/Energy Storage Technologies and Energy Management

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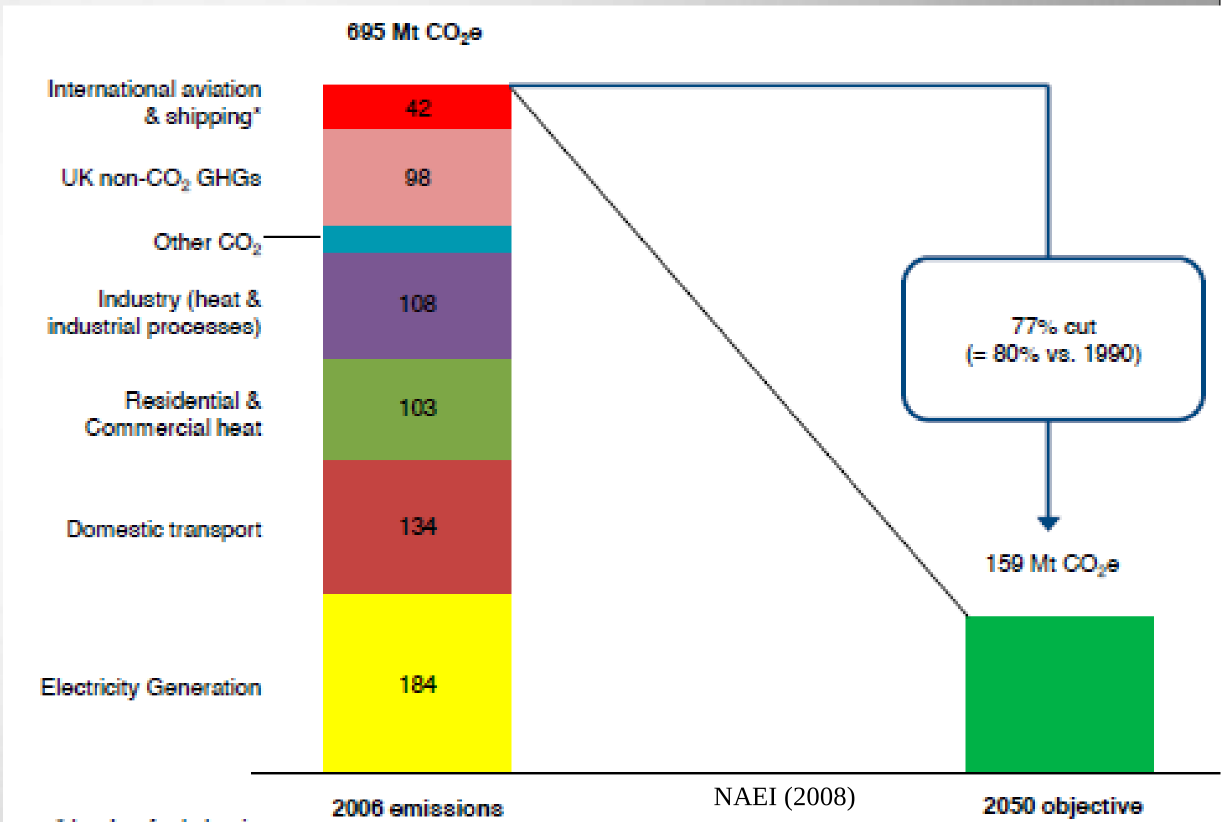
Drivers for Change
Increased focus on Energy Storage

- Reduce reliance on fossil fuels
- Commitment for reducing GHG emissions (80%, 2050)
- Accommodating increasing supply demand



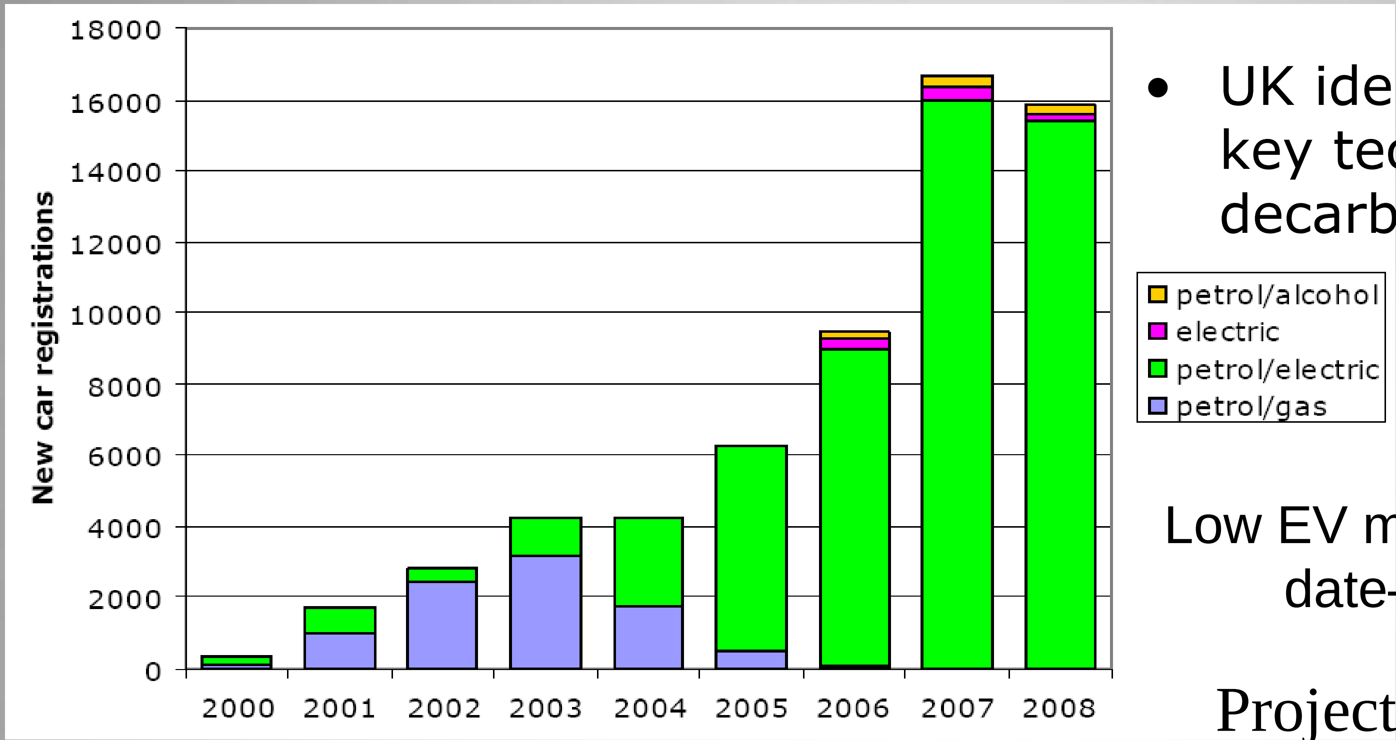
Mean Emissions Trend (10yr)

↓ Cars

↑ Industry, Domestic Demand

↑ Aviation

Domestic Transport Moving in Right Direction



UK new alternatively fuelled vehicle registrations (CENEX, 2009)

- UK identifies electric drive as key technology for decarbonising roads

Low EV market penetration to date—179 vehicles in 2008

Projected to increase considerably
by 2013—customer driven.
Commuter/second vehicles

- Road Transport accounts for 22% of UK CO_2 emissions

Power and Energy Storage Technologies: Are any the perfect choice for you ?

Intermittent/variable generation
(unpredictable in real time)

- Off-shore wind
- On-shore wind farms
- Solar
- Tidal/Wave

(15% by 2020)

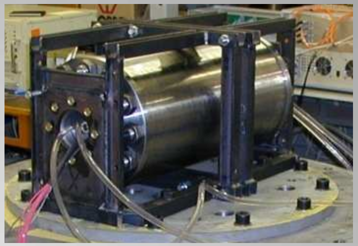
- Power stations
  - Petrol/Diesel
  - Gas, nuclear, coal
  - CHP, hydro…

electrical, thermal, mechanical

Intermittent/variable duty
(unpredictable in real time)

- Domestic buildings
- Industrial/Commercial Buildings
- Automotive Vehicles
  - domestic, public, commercial
- Aerospace
  - Commercial, military
- …..

Flywheels



30kW, 60krpm, 300Wh Rotor 15kg, system >60kg

- •Energy stored in rotating mass
- •Energy input and recovery by elect. or mech. coupling
- •Energy storage proportional to mass of rotor and the square of rotational speed and rotor radius
- •Considered as peak power buffers
- •Stationary systems often use high mass rotors
- •Peak power supply and recovery limited only by gearbox or motor/generator
- •Safety necessitates strong containment
  - – high proportion of mass
- •Diagnostics and prognostics to be able to run flywheels closer to their theoretical mechanical limits
- •Energy loss ~35% per hour due to friction losses
- •Lifetime of 15-20 years anticipated
  - – main degradation in bearings
- •Potential material supply constraints if exotic core materials and/or rare earth magnets used (e.g NdFeB,SmCo)
- •Requires little infrastructure

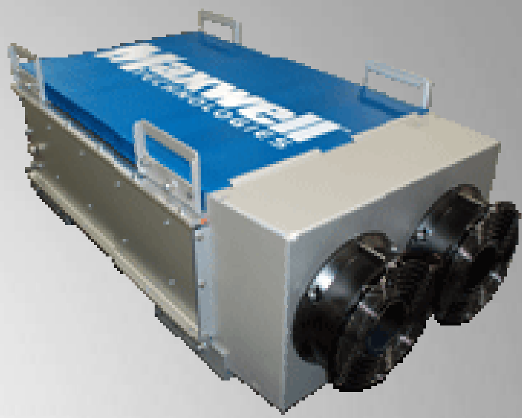
60kW, 60krpm, 112Wh Rotor 5kg, system 25kg

(Flybrid Systems LLP, 2009)

Part of 20MW flywheel plant at Beacon Power Corp., Mass.

(THE ASSOCIATED PRESS, 2009)

Super/Ultra Capacitors

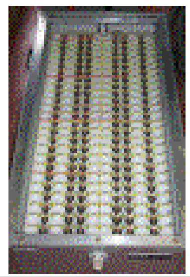


- Proximity of electrostatic charges allows energy storage
- High power density—ideal for rapid charge/discharge—limited only by internal impedance and associated electronics.
- Can be fully discharged without damage
- As with electrochemical batteries, no limit to number of series/parallel units.
- Energy density relatively low compared with batteries
- High stored energy requires plates with high surface area and high permittivity dielectrics.
- Need temperature control for efficiency and lifetime.
- Requires cell balancing
- Relatively safe (needs protection from over-voltage)

Future ?

-Combined battery/supercap solutions

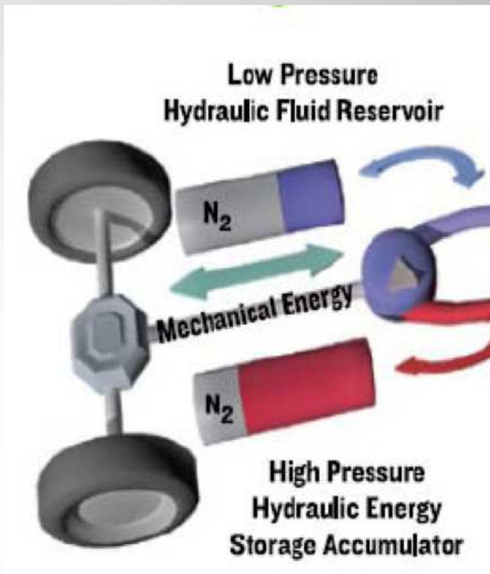
-Use ‘nano-pitting’ of cell plates to increase surface area



300 × saft supercaps
350F/cell (~50F total)

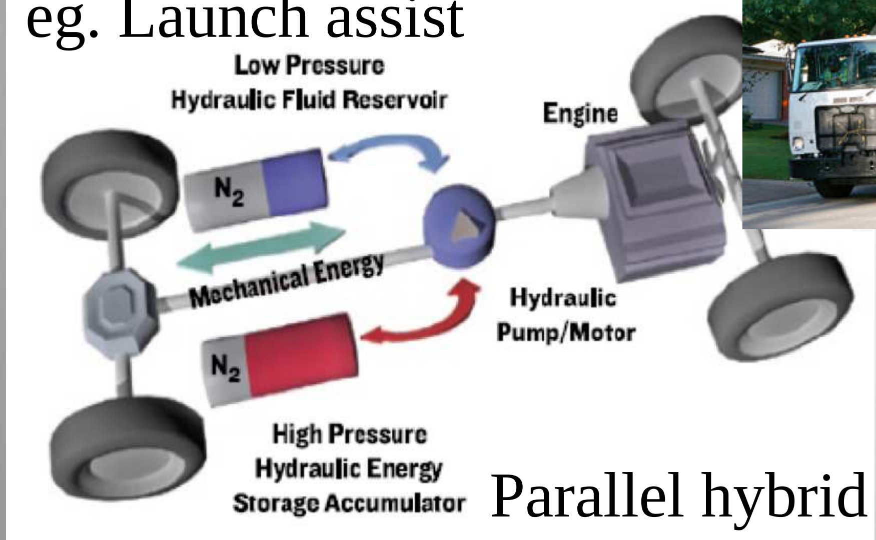
Hydraulic Storage (eg. Lotus Cars UK, Valentin Technologies, Parker)

-No primary infrastructure dependencies
-Secondary infrastructure for servicing already available
-High power density/Low energy density (requires larger accumulators).
-Readily combined with other technologies



Series Hybrid

eg. Launch assist



Parallel hybrid

(Parker)

Valentin Technologies

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High Temperature Sodium Nickel Chloride Battery—ZEBRA

Individual cells installed in vacuum insulated casing to reduce heat loss

Operational characteristics

- High temperature battery module 270℃-350 °C
- Heat loss about 3℃ per/h (90W)
- Internal resistance reduces with increased temperature
- During charging battery can absorb heat
- Requires high utilisation for maximum benefit

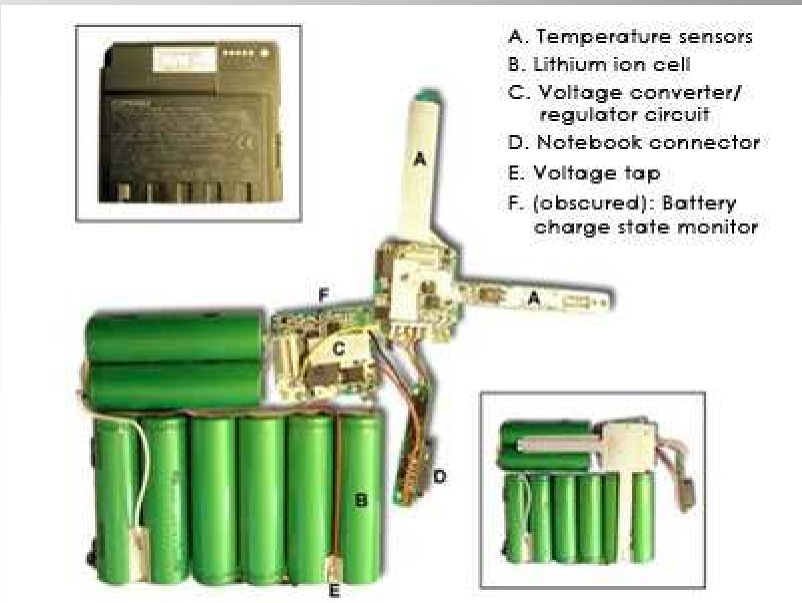
Advantages

- High nominal cell voltage 2.58V
- Capacity independent of rate, Ah(in)=Ah(out)
- 100% coulombically efficient, accurate DoD estimation is possible
- High energy density of 150Wh/kg (4x higher than lead-acid, and 3x nickel-metal hydride)

Li-ion/polymer

•Becoming preferred solution
•High energy density ~170Wh/kg
•Impediments
- -cost
- -support infrastructure
- -supply of Li (S. America)
- -damage, exposure of Li
- -thermal runaway
- -precise cell charge/discharge control required
- -thermal environment needs consideration

•Companies like ‘A123 Systems’, Mitsubishi, among others, looking to use as load levelling for automotive, solar, wind etc infrastructure (‘MW level’ systems)

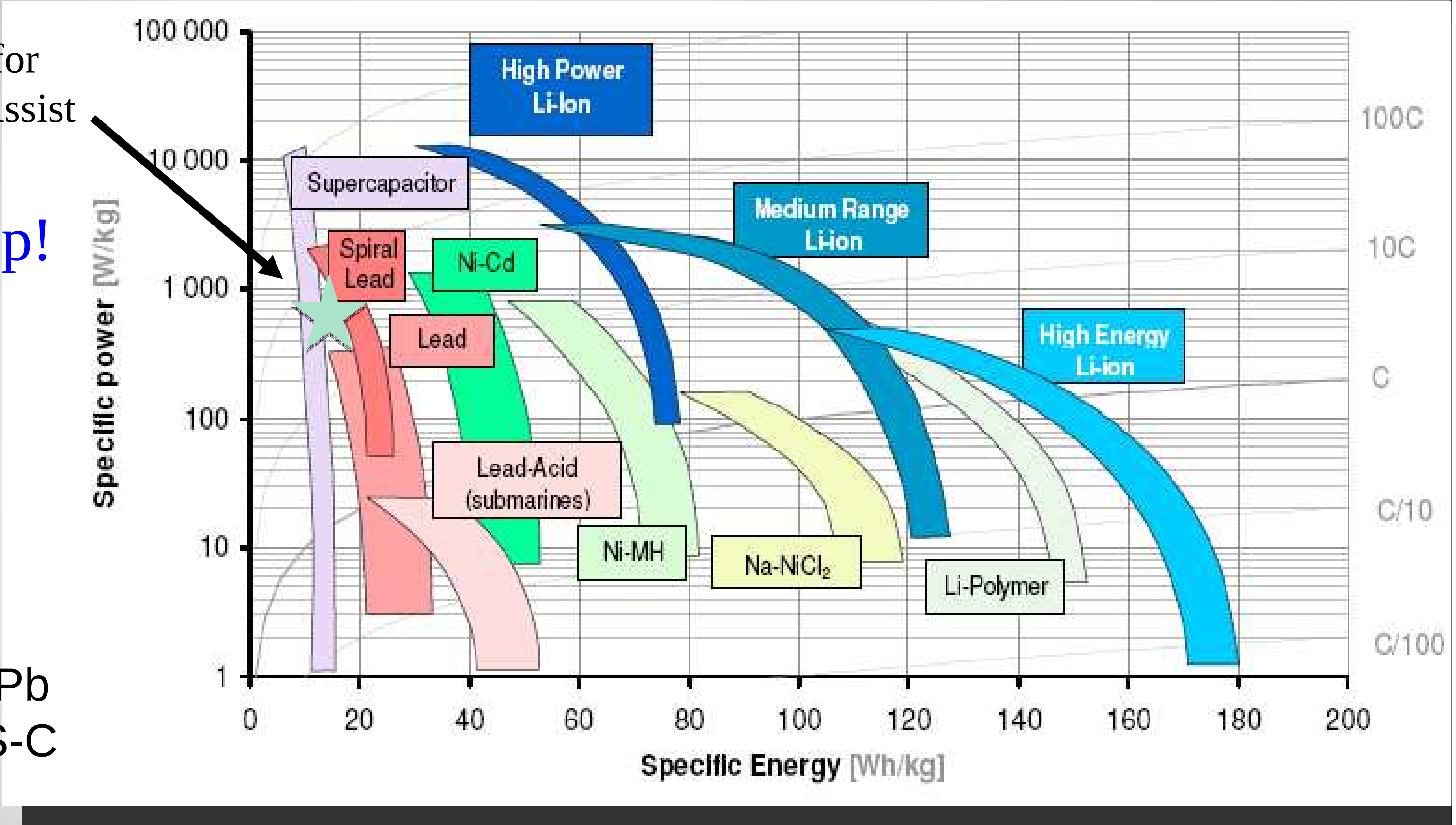


(ZD Net UK)

- Future: dope graphite anode with silicon nanowires ? (stanford uni)

Future for Lead-Acid ?

Freedom Car Goal for
Maximum Power-Assist



(ALABC)

Combined Pb/supercap!

- Carbon-based negative electrode, PbC
- High cycle life
- 90% DoD
- Low cost
- Energy D. approaching Pb
- Power D. approaching S-C
- Readily disposable
- Infrastructure exists
- Cheaper per cycle than Pb

A Fuel-cell or Hydrogen Economy ?

•H_2-most abundant element in Universe
•Essentially endless supply
•Typically used in fuel-cells
-by product, water/steam
-'pollution or emission free' (?)
-can be expanded to support grid energy/power—from renewable sources
-well-proven technology
-safe ?

Considered by many to be THE ideal solution

•Not a producer of energy !
•Energy storage medium (electrochemical)
•Requires reforming (eg gas) or electrolysis (eg from methanol) for extraction
•Or, separation of water using 'harvested electricity' !!! Very inefficient use of electricity (~25% conversion efficiency)
•Solid Oxide ? High temp ?
•Alkane (Meth…) based ?

FUEL-CELLS (candidate for localised stand-by systems):
Efficiency ~40-50%
3000 × more volume required than petrol wrt. Energy
Leakage a safety issue, so ideally liquefied (→0 K), then still ¼ volume/energy ratio of petrol

Is Efficiency Important ? Or $C0_2$?

- If we are consuming a resource
- Limited output power/transient availability

•Harvesting not ‘consuming’ a resource

•‘Harvest’ more and store energy !

Heating/stress of components—need to be larger—more components/equipment—cooling

Cost to manufacturer and operator
Increased efficiency—better profit margin
Incentive to invest—Better for consumer

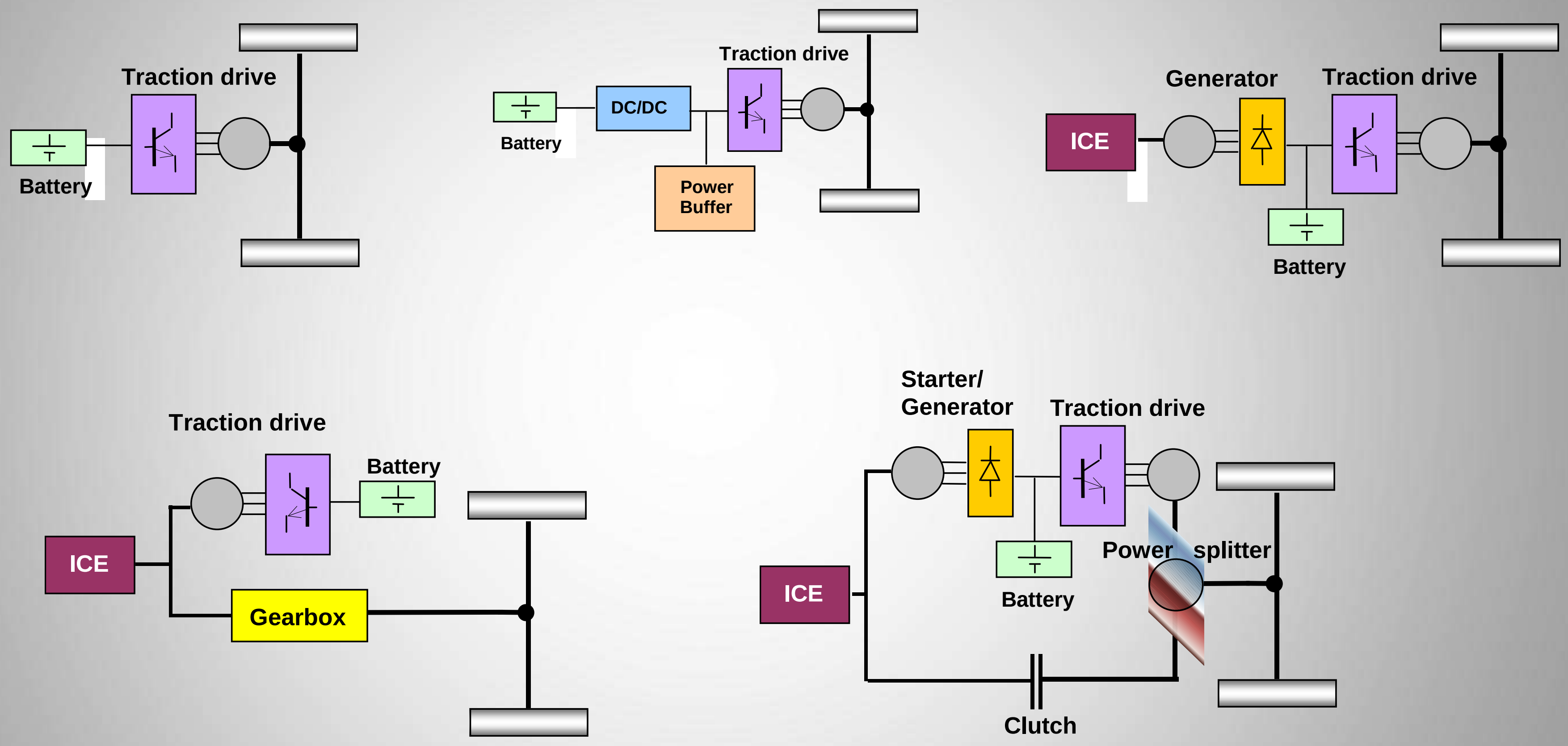
!!! IPR !!!

Cost, Reliability and Robustness over-arching factors!

Managing Power through Energy Storage

Recover energy from heat ‘loss’ output

Energy Management



Energy Management:Predictive Control

Predict drivetrain characteristics for a short time in the future based on previous behaviour, and provide ‘optimal’ apportioning of energy from/to the multiple sources: driving cycle assumed to be unknown to controller

- Can’t provide generic solution for all drive trains/components
- Requires custom solutions in general
- However, may be some merit in considering alternatives to classical underlying principles

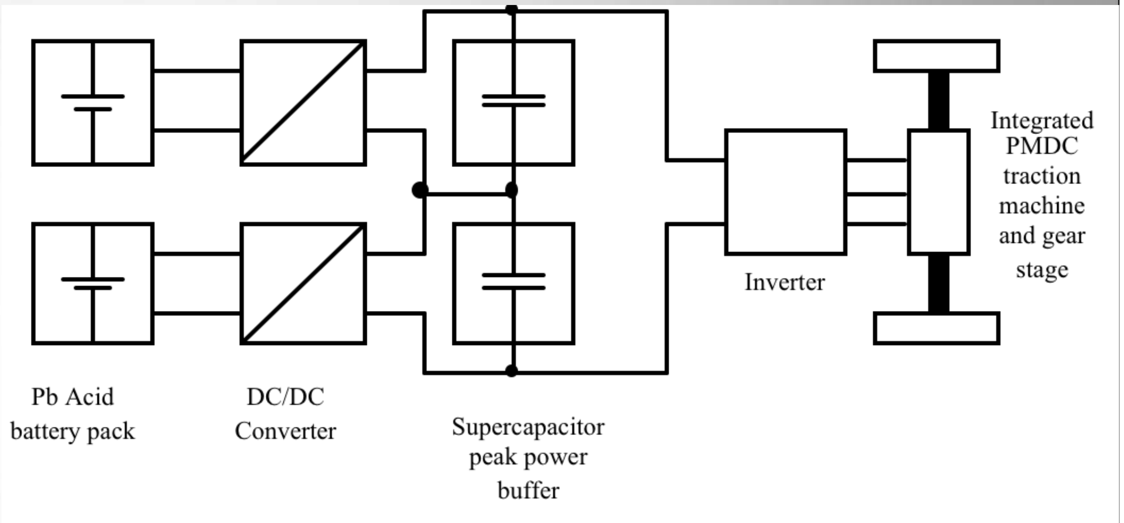
eg. Specifying controlled dc-link ! Some benefits can be obtained by allowing

dc-voltages to vary.

Predictive control of EV with Peak Power Buffer

- PPB aims to reduce transient

  requirements of battery.
- Battery supplies mean power.



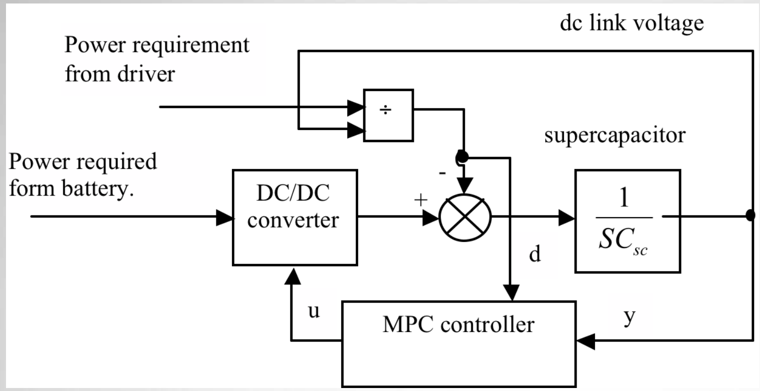
-Classically: try to maintain dc-link to to traction drive

-Now allow dc-link to vary.

Consider impact on <u>regen</u>' braking.

ECE15 driving cycle with a mean 1.5% downhill gradient

Allow dc-link to vary whilst penalising deviations from mean battery voltage



$$J(u,k)=\sum_{j=Nc}^{N}(\hat{y}(k+j\mid k)-r(k+j)+\delta(k+j))^{T}(\hat{y}(k+j\mid k)-r(k+j)$$

$$+\delta(k+j))+\left\{\lambda^{2}\sum_{j=1}^{N}u^{T}(k+j-1)u(k+j-1)\right\}$$

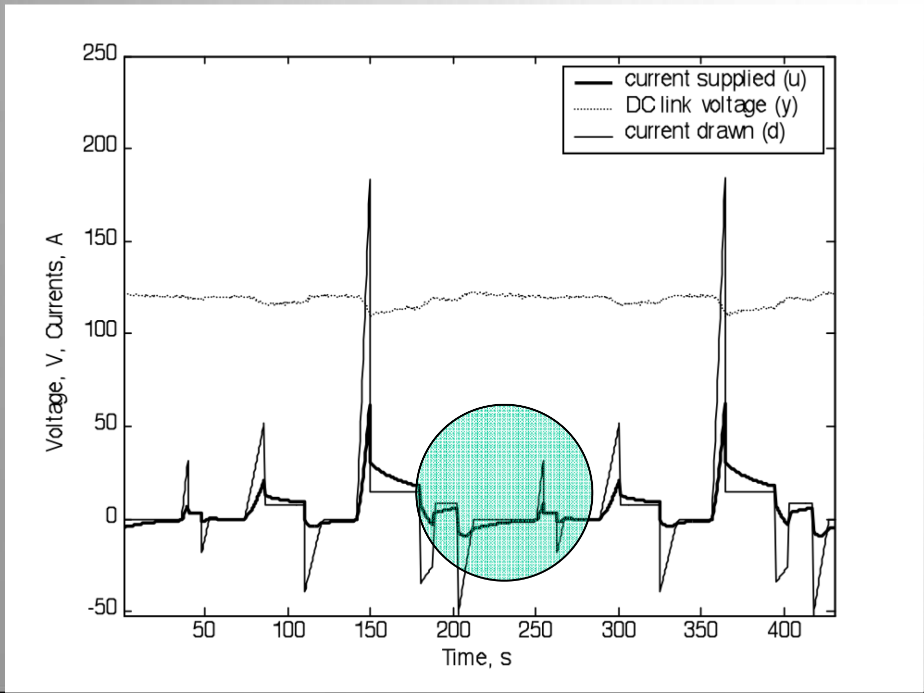
subject to the linear inequality constraints

$\tilde{\psi}(k)\leq\tilde{\Psi}(k)$ &

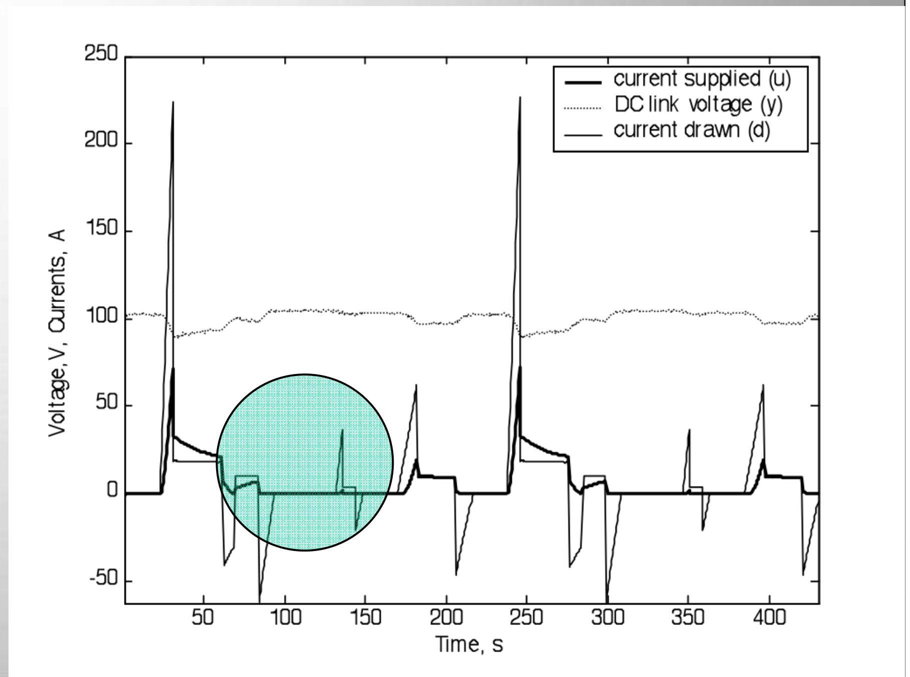
$|\delta(k)|\leq\delta_{\max}$

Allow 25% change in dc-link voltage

Classical



'Zone' Control: PH 8 secs



Potential Benefits

ENERGY FLOW

Controller	Energy drawn from battery /kJ	Energy returned to battery /kJ	Net energy expenditure /kJ
MPC zone control	262	0	262
dc-link voltage control	318 (121%)	56 (21%)	262

Zone control minimised circulating energy

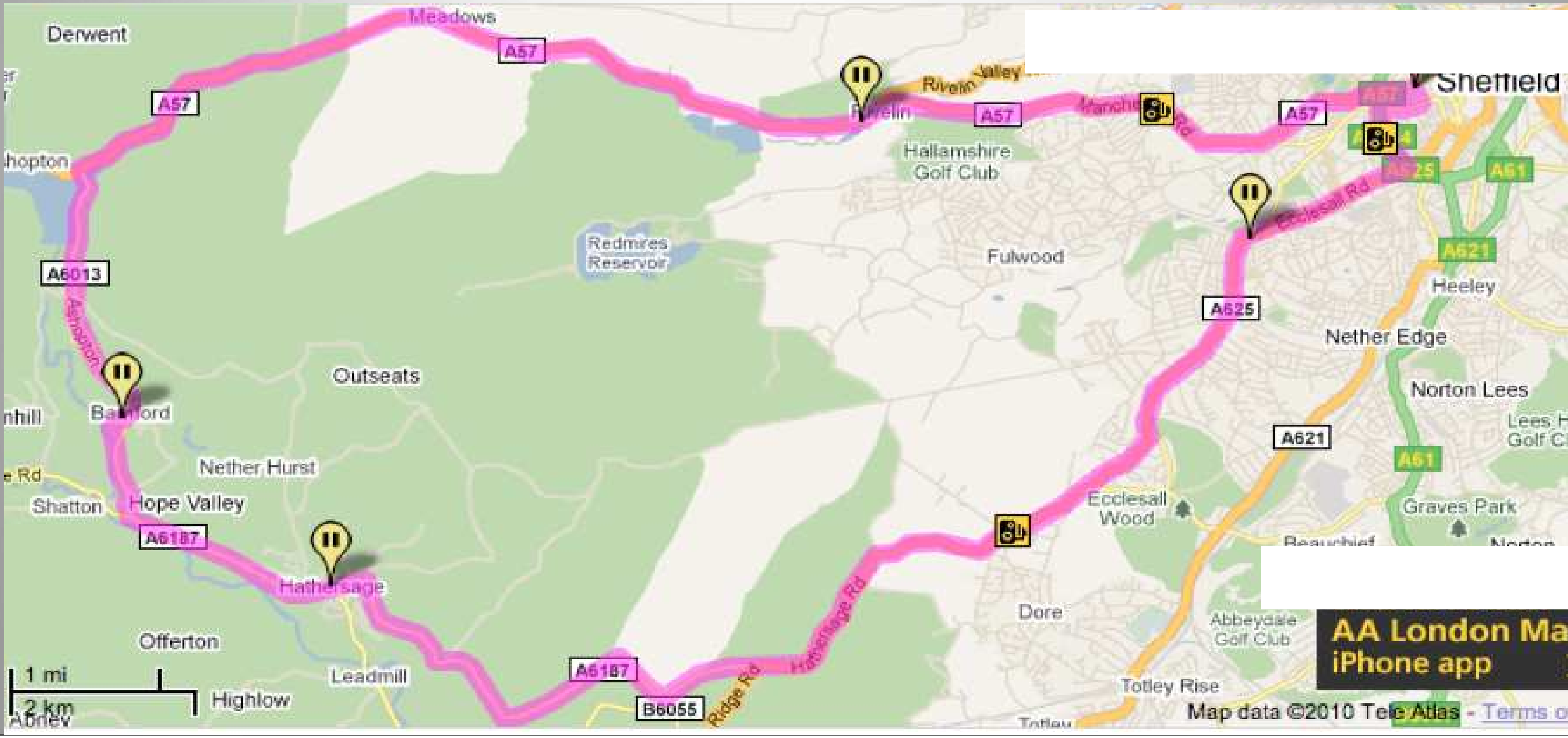
Since normal operation is for net energy expenditure, the dc-link of the PPB will normally be lower than that allowed classically, thereby facilitating increased regeneration

Should result in higher overall drivetrain utilisation efficiency

Management of Driver Behaviour Could also Provide Significant Benefits !

Driver Behaviour
(multiple drivers, single driving cycle)

- Driving cycle includes Sheffield (UK) city centre and 'Peaks' (D'shire)
- Distance travelled for each trial is ~40km
- 'Circular' route so mean gradient=0
- Trials at same time of day: chosen to minimise traffic variations



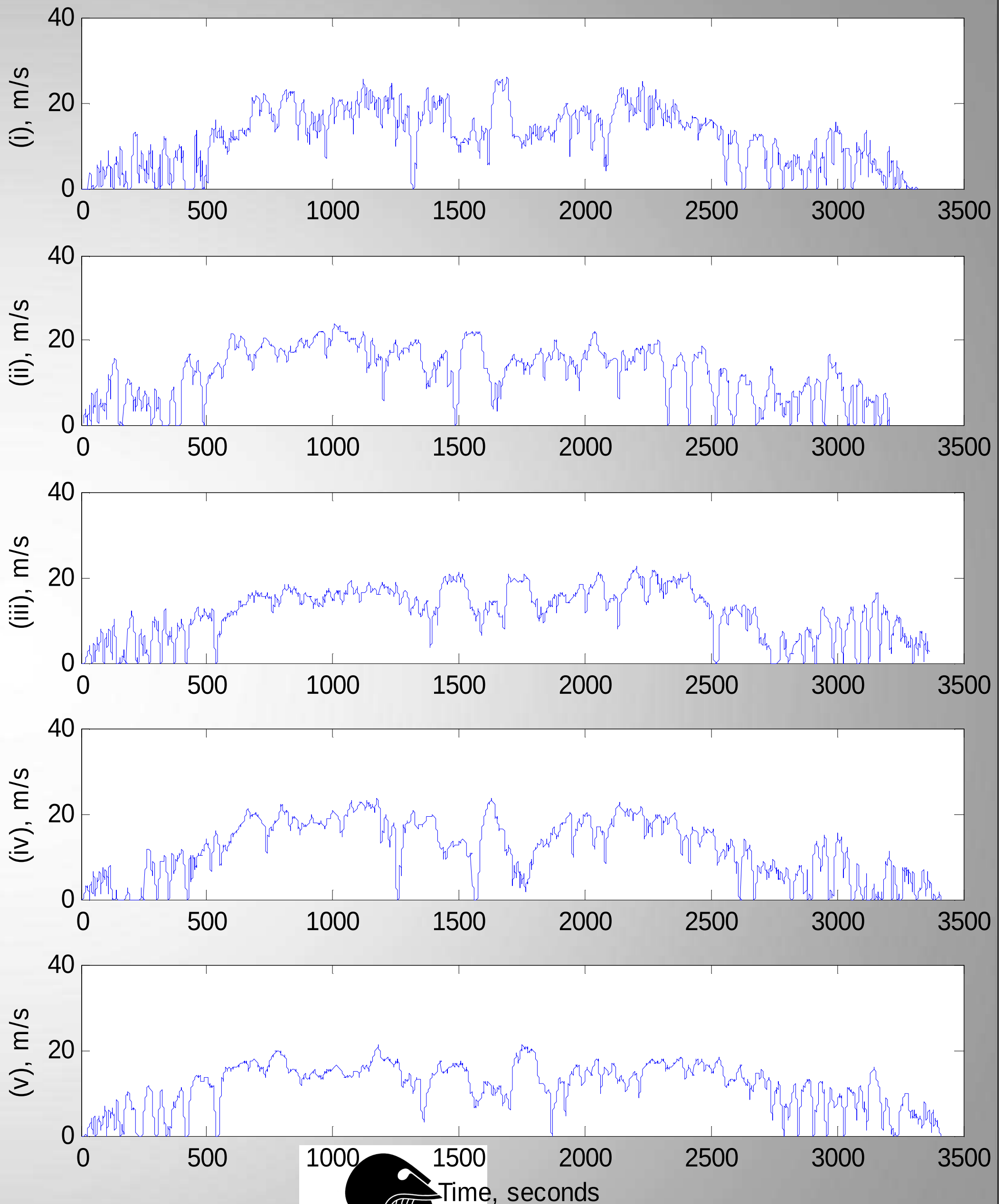
5 Example Trials

5 Different drivers

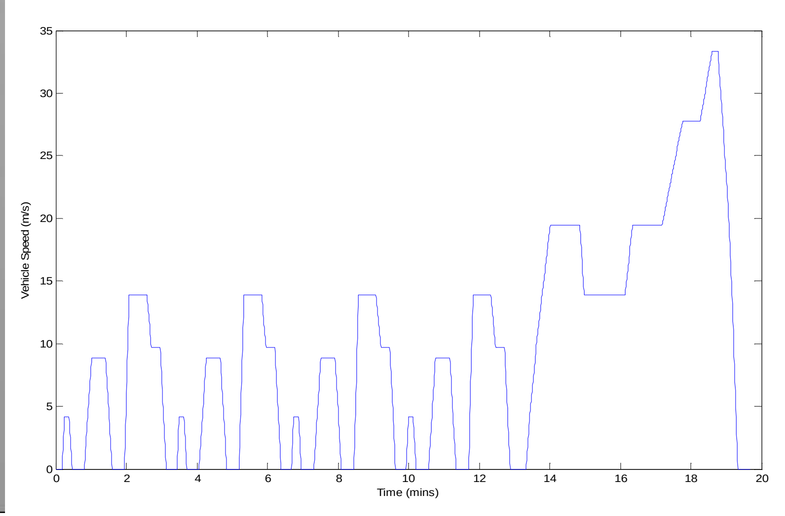
Velocity profiles

All trials take ~57mins

{Not in chronological order}



NEDC



Net energy consumption (%SoC) of each trial (measured at battery)

Trial	Final %SOC	Mean Power (kW)
(i)	43	5.47
(ii)	50	5.33
(iii)	53	4.95
(iv)	54	4.70
(v)	61	4.21

Integrate Power

5.3kWh

~32.5% difference

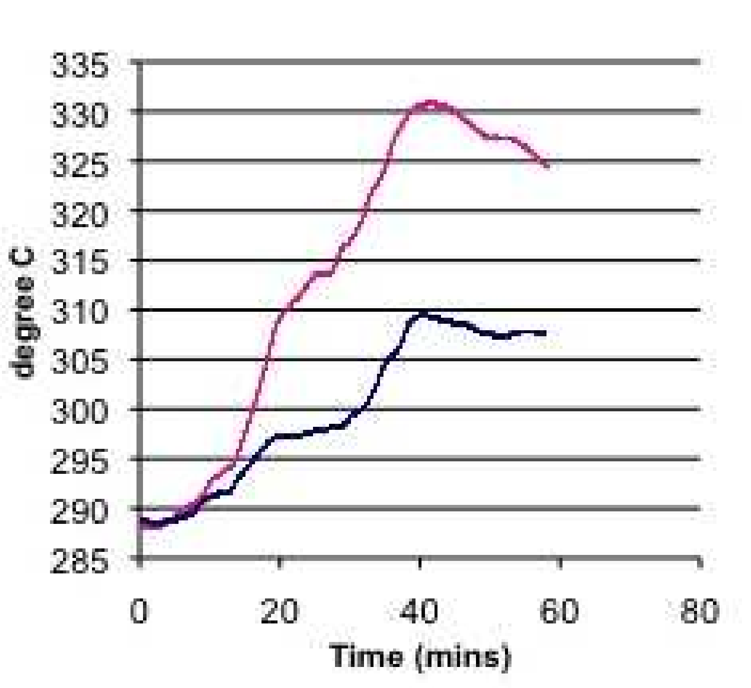
4.0kWh

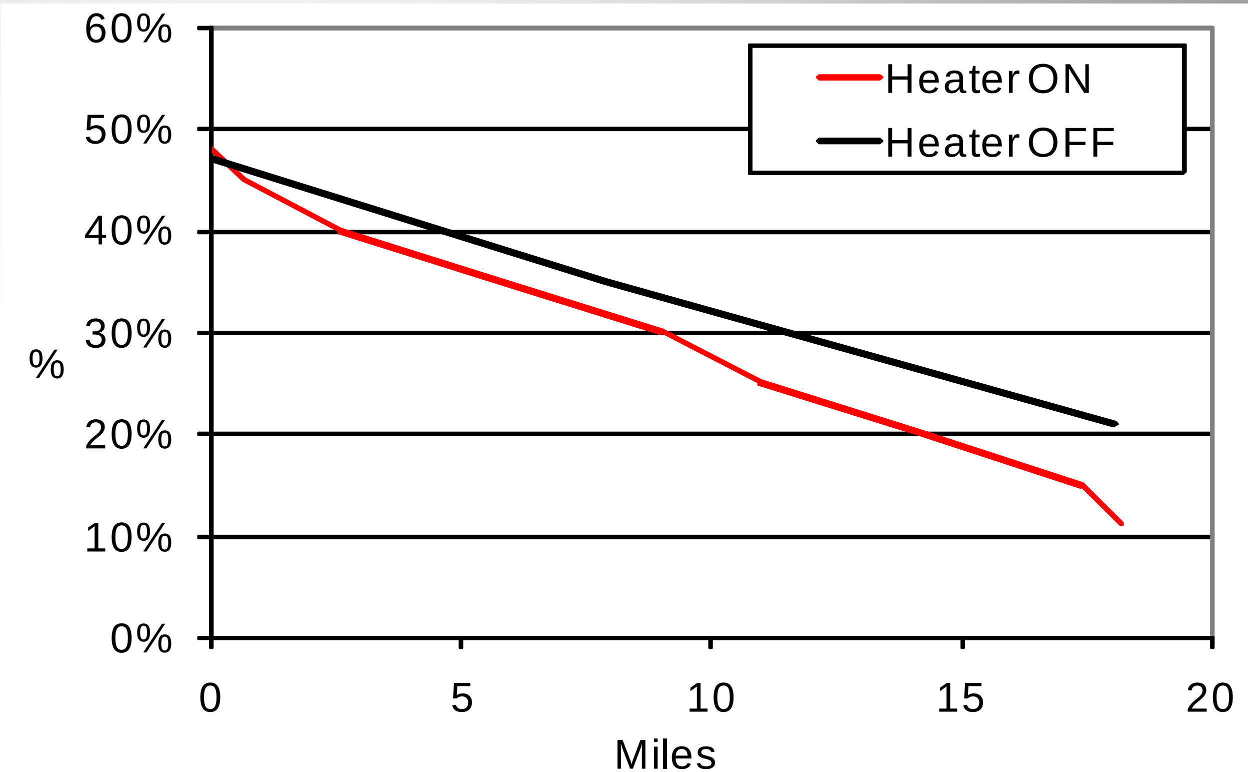
A saving of ~30g/km (equivalent UK grid mix)

0.537kg/kWh

Hotel Loads: CHP for Vehicles ?

Energy consumption related to journey time rather than journey distance





Zebra

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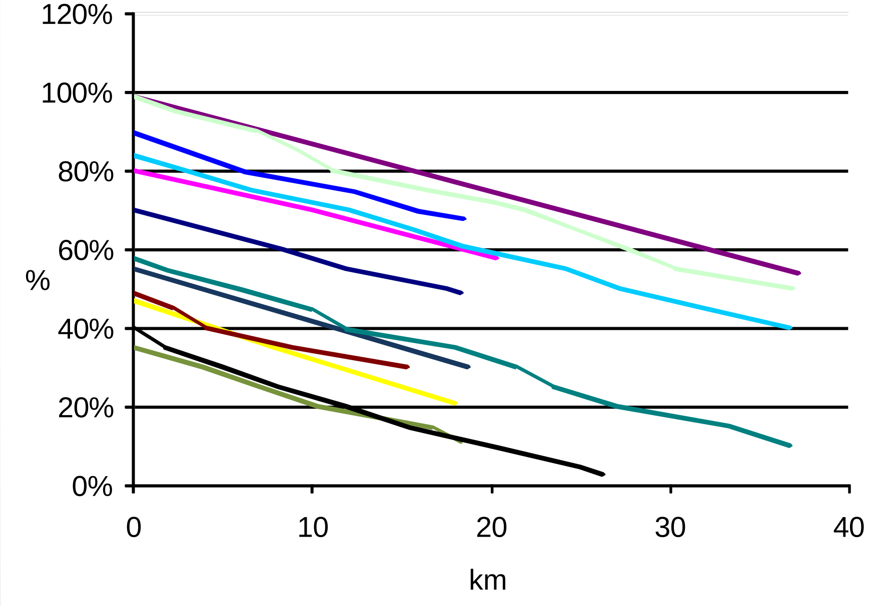
‘Re-charging Behaviour’ (user perspective)

- Initially charged over night on regular basis
- Behaviour migrated towards ‘opportunist charging’ as confidence in range grew:
- Remaining range vs. remaining %SoC readily predictable
- Problems associated with grid infrastructure may not be as acute as perceived !
- Can be controlled by Tariffs !



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Industrial Power and Energy

‘Crystal Ball’ on the Future-Energy Storage and Infrastructure

Development in supercaps to supersede batteries in some applications

-lifetime/fit-and-forget/improve energy density (insurance for EVs/HEVs!)

Harvesting technologies (solar, excess heat) supported by local storage (robustness).

-Need efficient power conversion at source.

Localised islanded/network issues on vehicle:

-Minor technological retro-fits to systems can require significant legislation accommodation eg. connectors

-Don’t know impact on control yet! (a story for another day)

-Battery (possibly Pb)/supercap hybrids supporting CHP

-Harmonic/power quality control for EV/PHEV to support grid

Challenges:

-Be transparent to user/social acceptance/demonstrable benefit

-Security/stability

-TECHNOLOGY RELIABILITY

-Energy Management—efficient power integration and conversion

Management of user behaviour could provide biggest relative benefits !