Investigation into the Potential Fuel Savings from the use of Hydraulic Regenerative Systems in Heavy Vehicles.

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Presentation Outline.

- Introduction.
  - What are Hybrid Vehicles?
  - Who are Permo-Drive?
- Model Development
  - Vehicle and Hydraulic System Simulation.
  - Permo-Drive Fuel Trials.
  - Model Validation.
- Research at Monash University
  - Fuzzy Logic Controller.
  - Optimisation.
- Vehicle Braking Analysis.

Introduction.

- What are Hybrid Vehicles?

- Definition:

  "A hybrid road vehicle is one in which propulsion energy, during specified operational missions, is available from two or more kinds or types of energy stores, sources or converters."

- Most hybrids combine the Internal Combustion Engine (ICE) with a secondary renewable power source.

Introduction.

- Types of Hybrid Vehicle:
  - Hybrid Electric Vehicle (HEV).
  - Uses Batteries or Ultra-Capacitors.
    - Toyota Prius / Honda Insight.

  - Mechanical Hybrids.
  - Uses Flywheels.
    - Volvo flywheel buses.

Introduction.

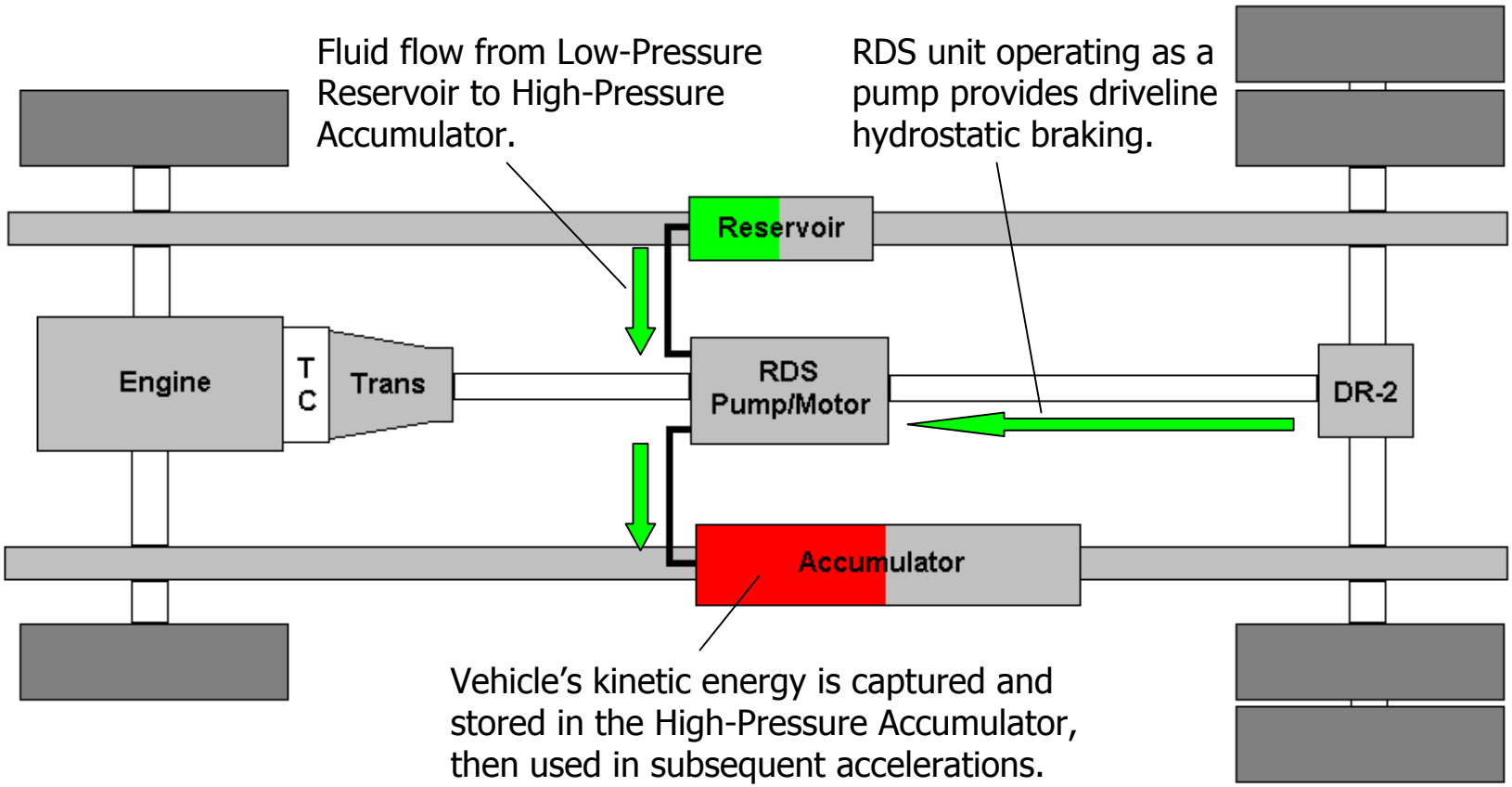
- Hybrid Vehicles are an attractive solution because:
  - They increase the vehicle's fuel economy without sacrificing on vehicle performance.
  - They reduce harmful vehicle emissions resulting from combustion.
  - They present opportunity to downsize existing driveline components.
  - They increase the life of vehicle driveline components.

Introduction.

- This research is focused on the Hydraulic-Hybrid Vehicle (HHV).
  - The HHV uses a variable displacement pump/motor unit as an energy conversion device, and
  - High-pressure accumulators to store energy.

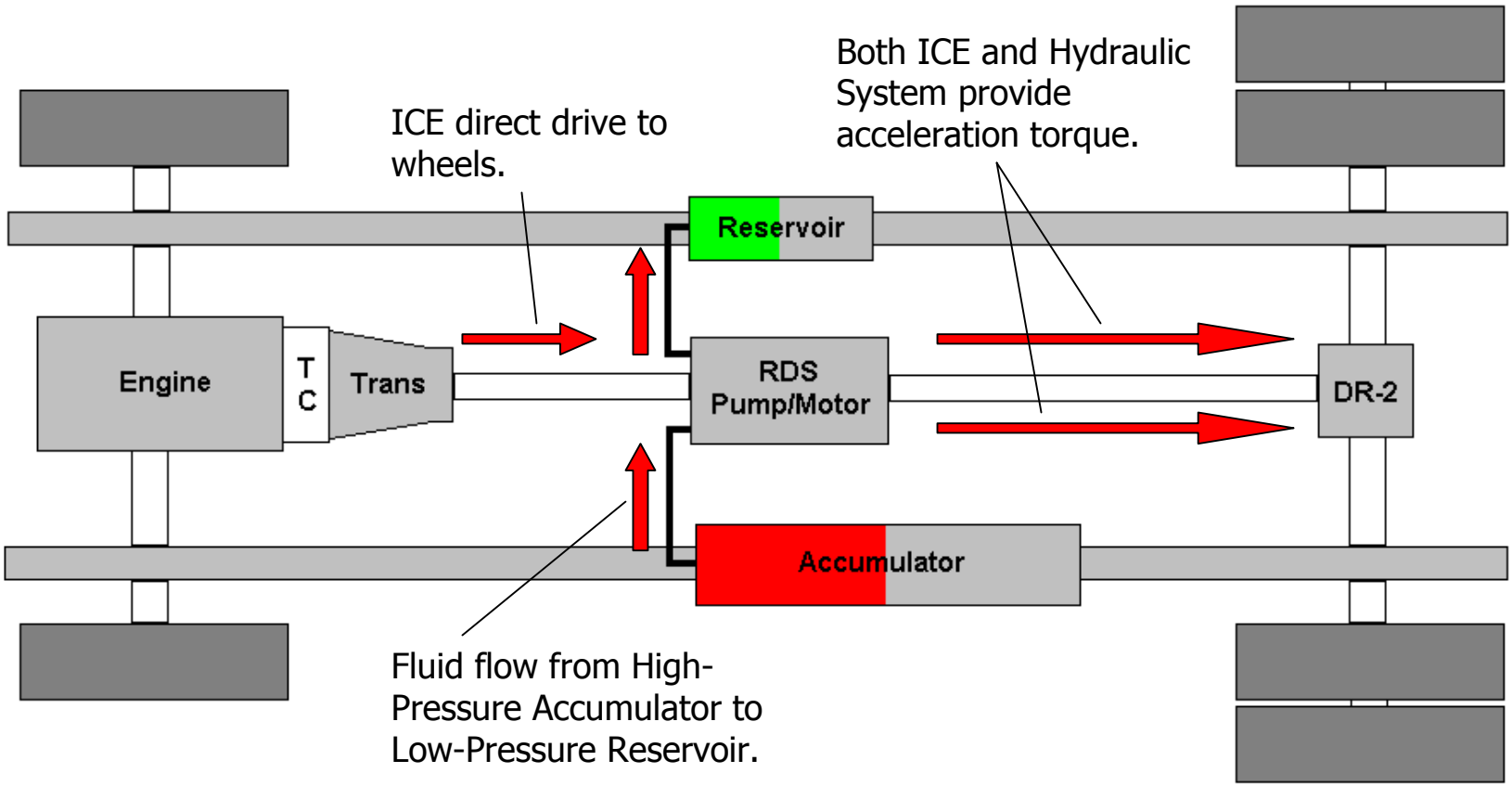
Introduction.

- During Braking:



Introduction.

- During Acceleration:

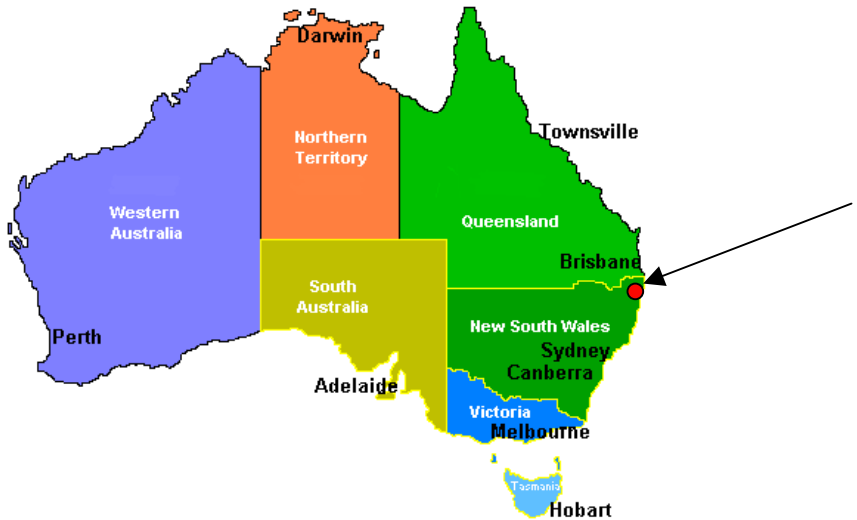


Introduction.

- Why Trucks?
  - Diesel transport industry is a large consumer of fossil fuels.
  - More mass – greater opportunity for regenerative braking.
  - Greatest potential in urban environment.
  - Diesel more efficient than gasoline engine.
- Why Hydraulic Hybrid?
  - Mature technology.
  - Good component efficiency levels.
  - High power density compared to other hybrid systems.
  - Accumulator has low energy density.
  - Not affected by water or humidity.

Introduction.

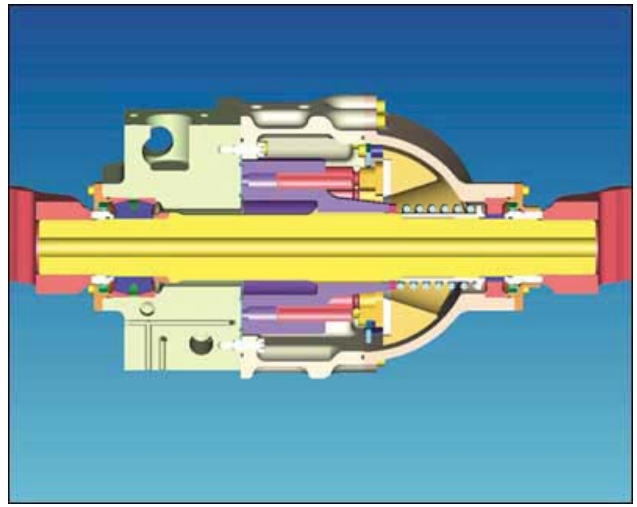
- Who are Permo-Drive?
  - An Australian Research and Development company focused on the development of the Permo-Drive Regenerative Energy Management System (PDREMS).
  - Go to www.permo-drive.com



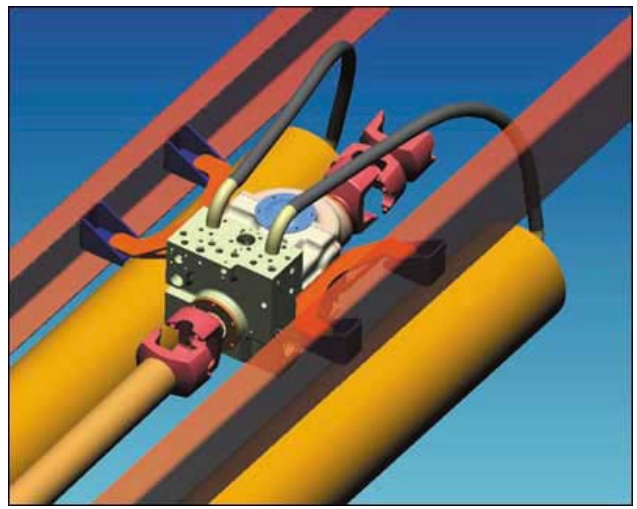
Permo-Drive are based in the northern NSW town of Ballina.

Introduction.

- The main thrust of the R&D effort has been on the pump/motor unit, known as the Regenerative Drive Shaft (RDS).



- The RDS unit sits coaxial with the vehicles drive shaft, in between the transmission and the differential, thus reducing the amount of driveline component losses for regenerative braking.



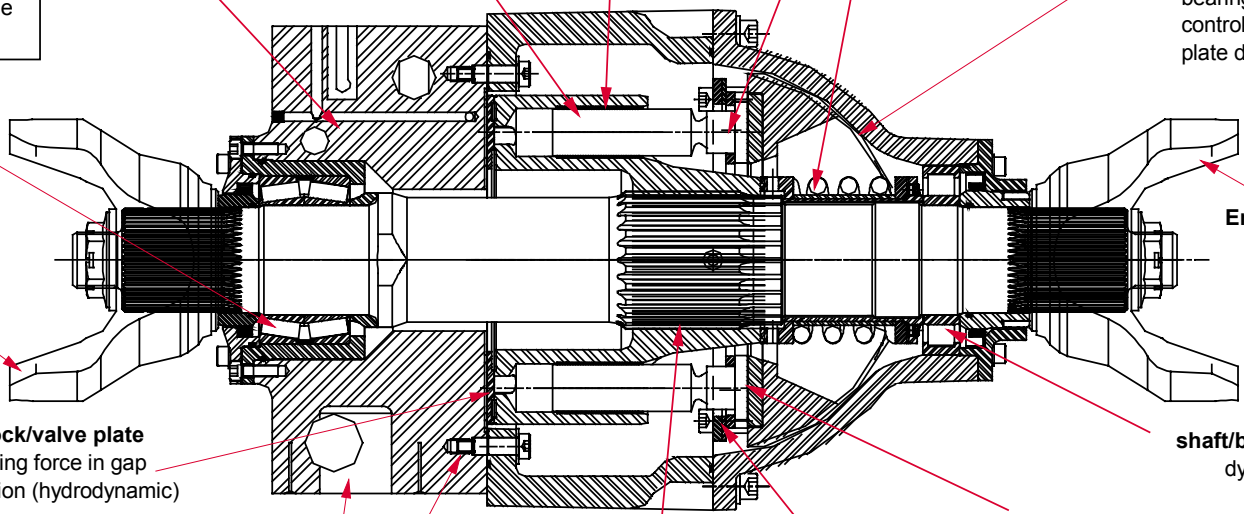
Introduction.

- Issues regarding RDS development:

- Materials selection for tribological pairs
- Hydrodynamic phenomena occurring within pump
- Dynamic interactions within pump
- Dynamic interactions between pump and vehicle

The RDS unit has virtually been developed from scratch, since pump manufacturers do not make standard units capable of dealing with the high pressures and flow rates associated with heavy vehicle regenerative braking.

Introduction.



Operating parameters
torque/velocity
fluid temperature
bulk modulus
swash plate angle
control signals

Manifold
pressure/flow characteristics
pressure losses
rigidity
heat distortion
valves responses

cylinder block/piston
load on piston -pressure
load on piston -suction
contact stresses
friction forces
inertial forces
piston deformation
piston skewness

bush/cylinder block
contact forces

piston/slipper
interface forces

spring/cylinder block
dynamic response

swash plate/housing
loads - dynamic
control forces
gap -lubrication
separating force
bearing forces
control moments
plate dynamics

shaft/bearing
dynamic loading

Vehicle/RDS
torque/velocity
vehicle inertia
acceleration
deceleration
vehicle dynamics

Engine/RDS
torque/velocity
acceleration

cylinder block/valve plate
separating force in gap
lubrication (hydrodynamic) forces
force balance block/valve plate
moment balance block/valve plate
leakage rate through gap
pressure distribution in the gap
cylinder pressure
gap dimension
skewness (block/plate)
suction conditions - cavitation
block dynamics

shaft/bearing
dynamic loading

slipper/swash plate
dynamic gap
slipper loading
lubrication (hydrodynamic) lift
hydrostatic lift
temperature distribution

control circuit/RDS
pressure/flow dynamics
control responses
valves responses

Slipper/retainer plate
interface forces
contact forces

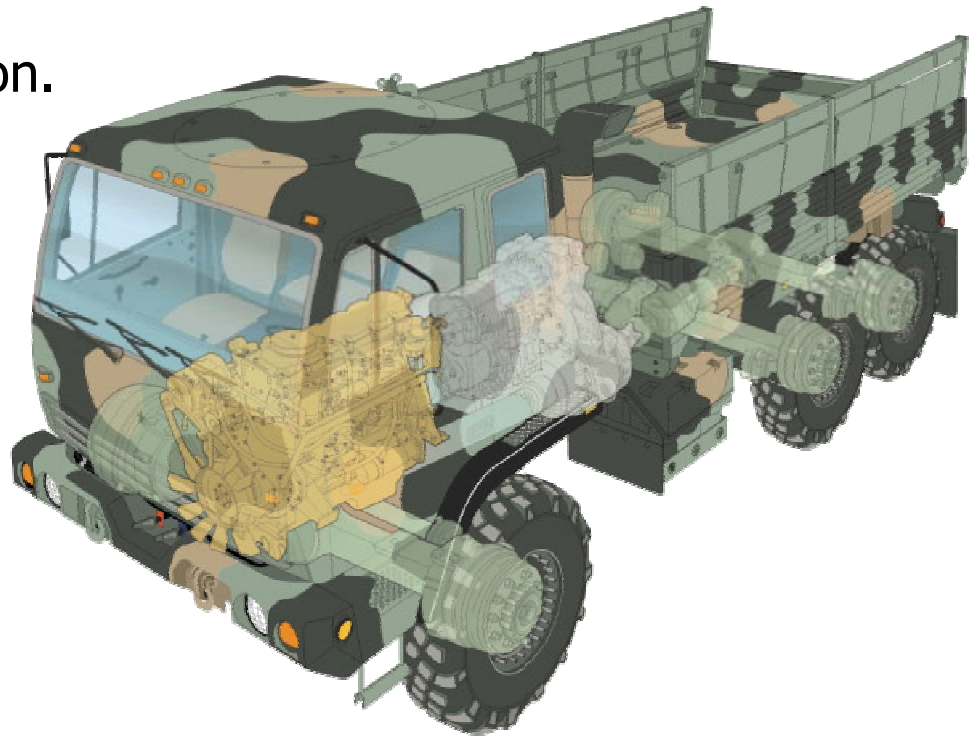
accumulators/RDS
pressure/flow dynamics
piston dynamics

cylinder block/shaft
torque x-axis
deflection
clearance (effect on leakage)
skewness of the block z-axis
moment y-axis

Introduction.

- US Army FMTV M1084 A1 Tactical Vehicle.

- 246 kW Diesel Engine.
- 7-Speed Automatic Transmission.
- ABS Brakes.
- Full Time All-Wheel-Drive.
- GVW = 15,790 kg.



Graphic courtesy of Stewart & Stevenson

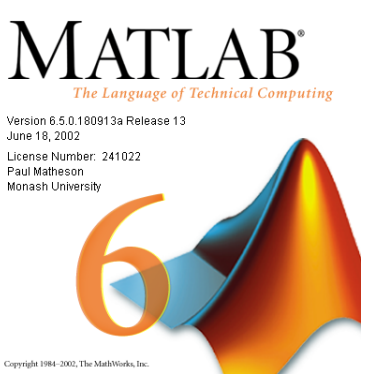
Introduction.

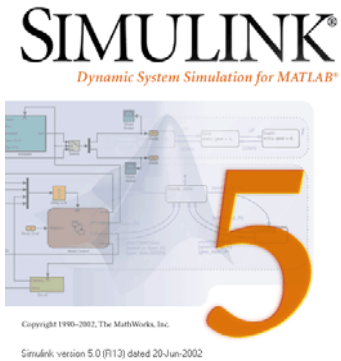
Introduction.

Introduction.

Model Development

- Monash research has been focused on developing a PC-based simulation of the Hydraulic Hybrid FMTV vehicle.
- PDREMS model developed in the Matlab/Simulink environment – Implemented into ADVISOR software



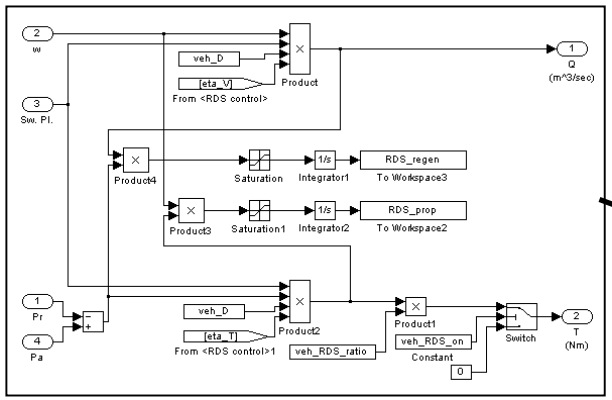


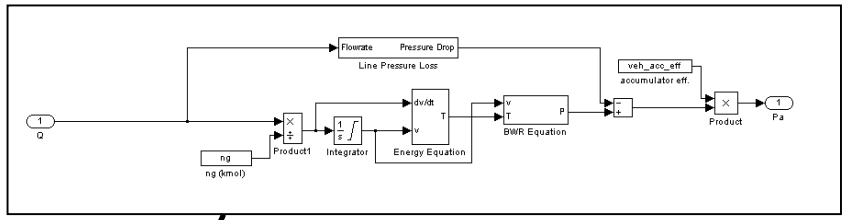
Model Development

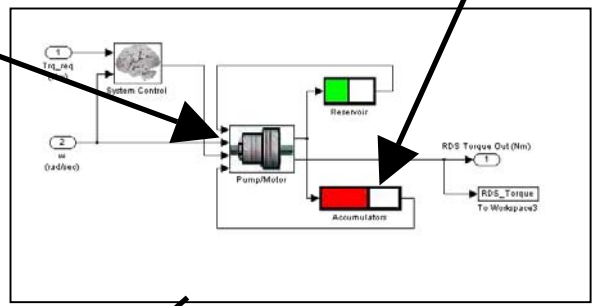
- The NREL's Advanced Vehicle Simulator (ADVISOR) was used to simulate the Hydraulic-Hybrid FMTV.
- ADVISOR is a set of script and model files for use within the Matlab / Simulink environment.
- Initial use was for the US Department of Energy hybrid propulsion program.
- ADVISOR available as shareware over the internet.

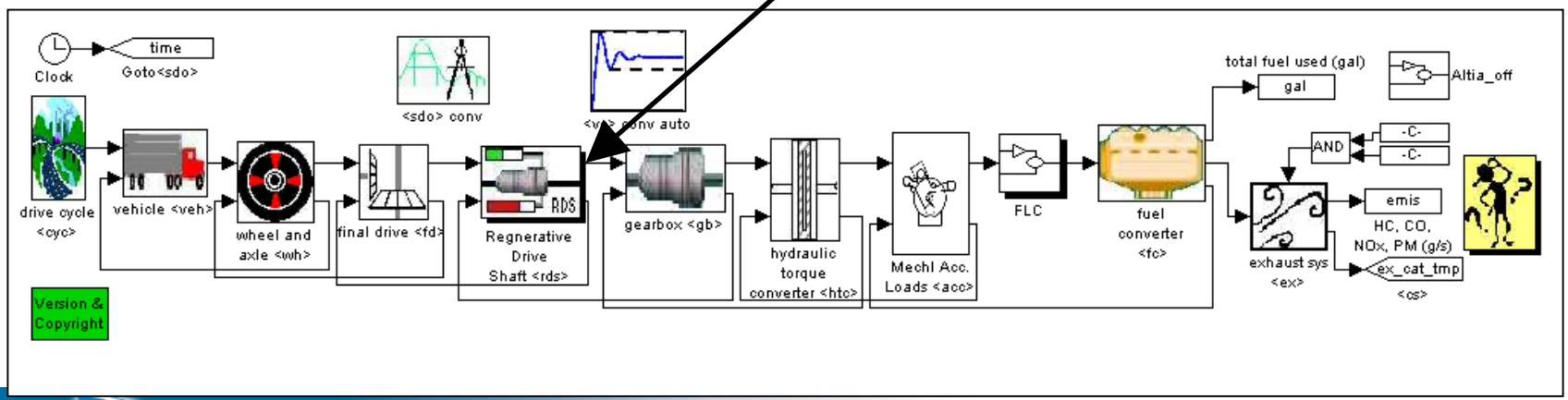
Model Development

PDREMS Simulink models were implemented into the top-level ADVISOR driveline model.



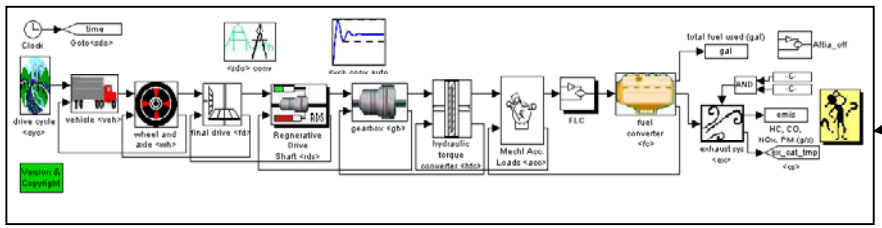




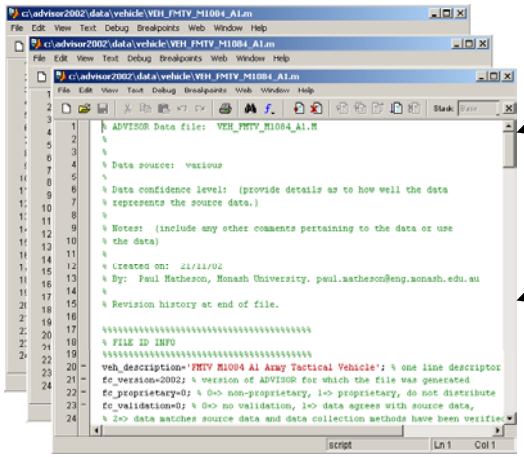


Model Development

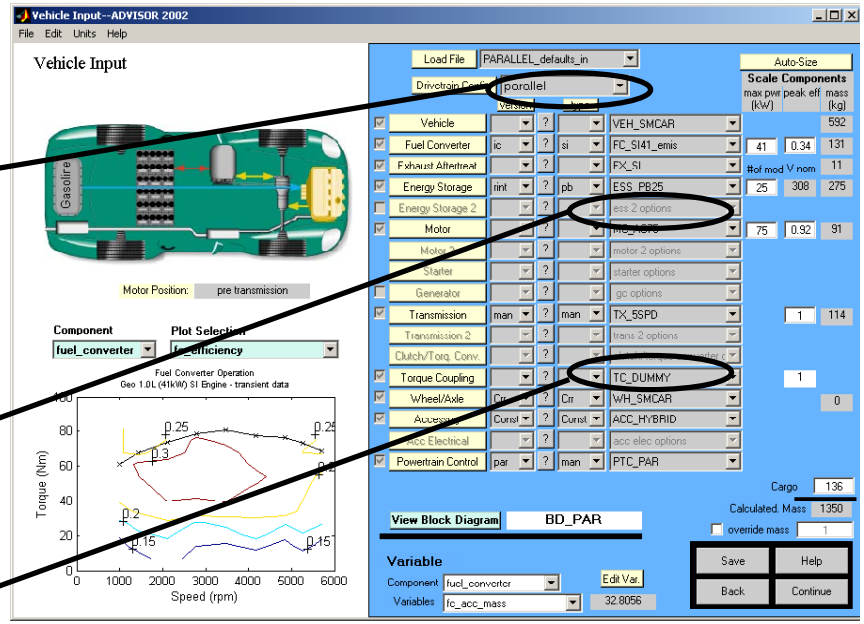
The FMTV vehicle was then simulated in the ADVISOR package.



Simulink model



Matlab script file

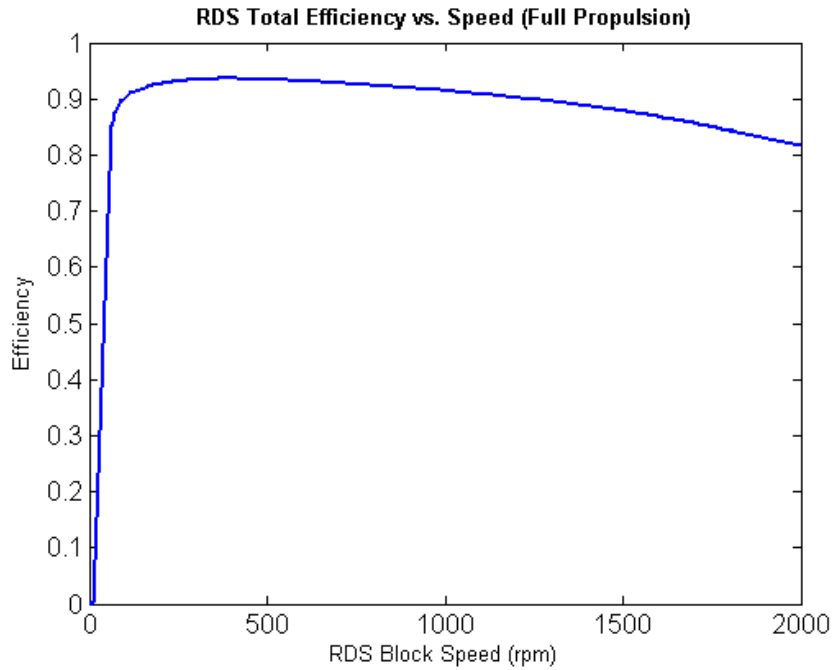


Setup GUI

Model Development

RDS (Variable Displacement Pump/Motor Unit)

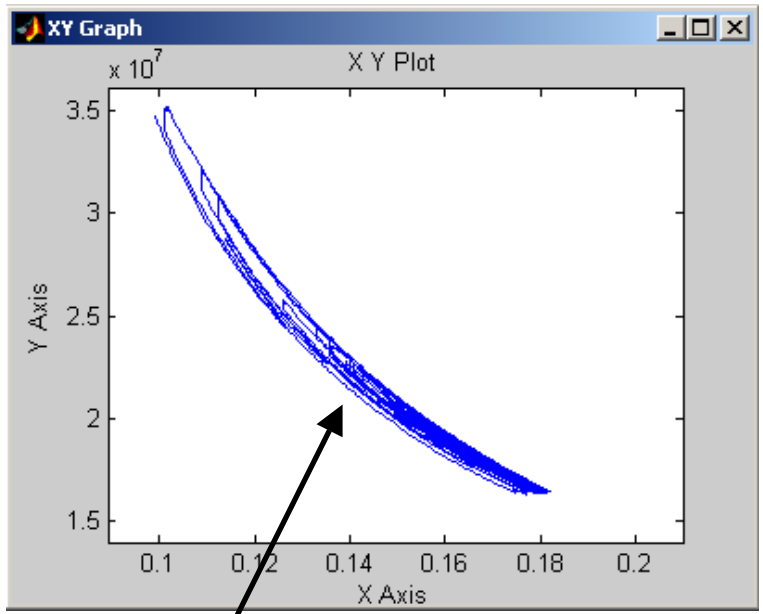
- Modified Wilson's Pump Theory.
- Calculates pump flow rate and torque.
- Considers volumetric and mechanical losses.
- Coefficients must be found via experiment.



Model Development

Hydraulic Accumulators

- Modeled using Otis Time Constant Theory.
- Accounts for irreversible heat transfer between the charge gas and environment.
- Assumed to be accurate over the entire superheated gas region.



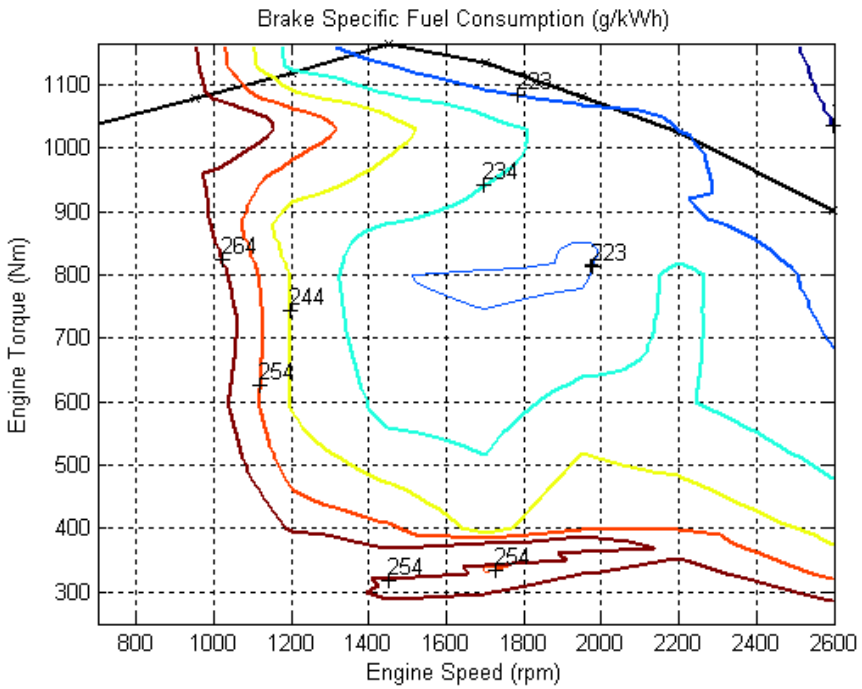
Energy lost to surrounding environment.

Model Development

Baseline FMTV modeling

Changes were made to the standard ADVISOR simulation technique for some components – such as:

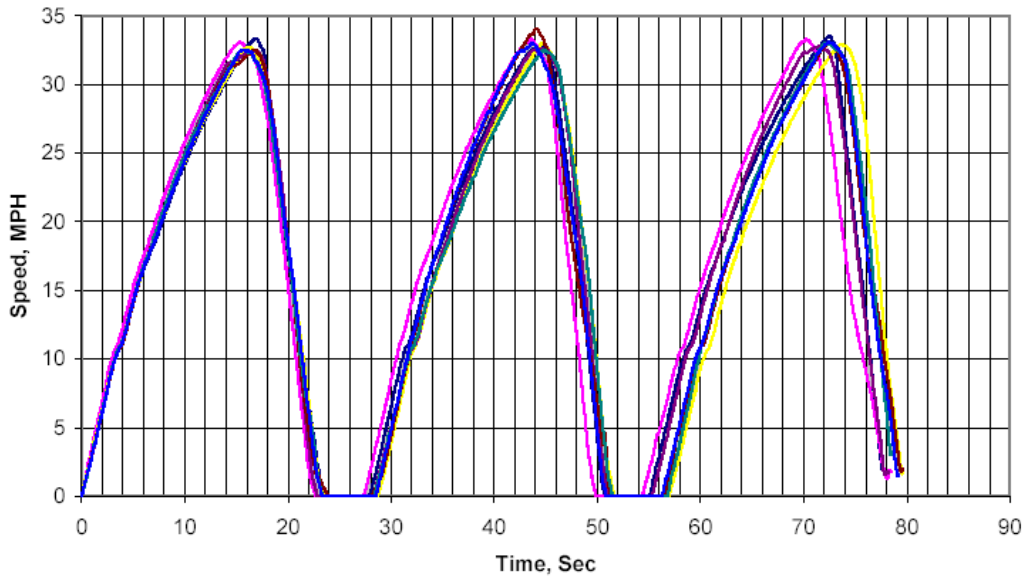
- 6x6 driveline configuration
- Engine fuel use map
- Smoke control
- Torque converter
- Transmission shift points



Model Development

Hybrid FMTV Fuel Trials.

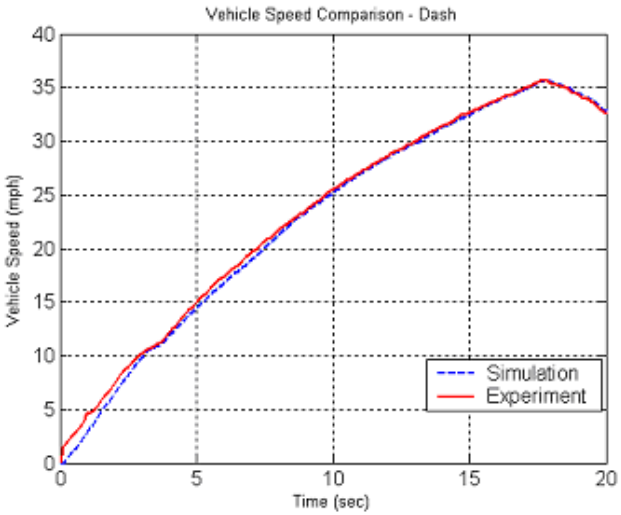
- Aimed to quantitatively measure the effectiveness of the HH system.
- Recreate aggressive urban driving (garbage truck).
- Also included maximum acceleration tests.



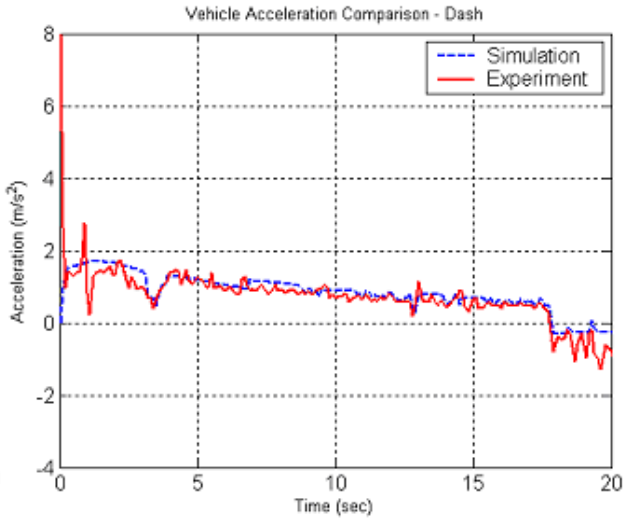
Model Development

Model Validation – PDREMS off.

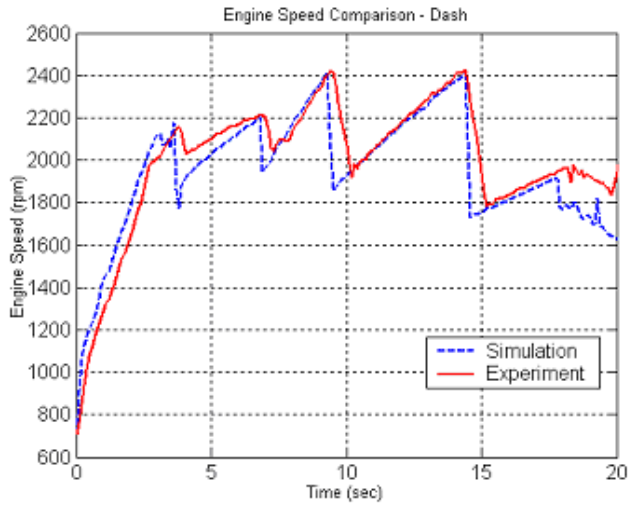
Vehicle Speed



Vehicle Acceleration



Engine Speed

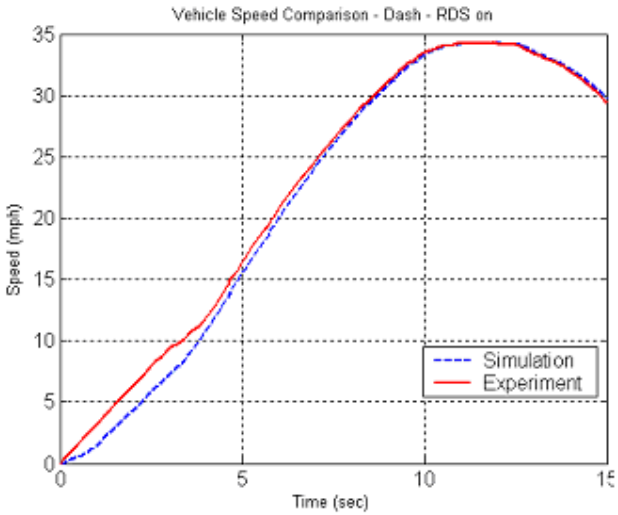


Fuel consumption estimate within 2.6%

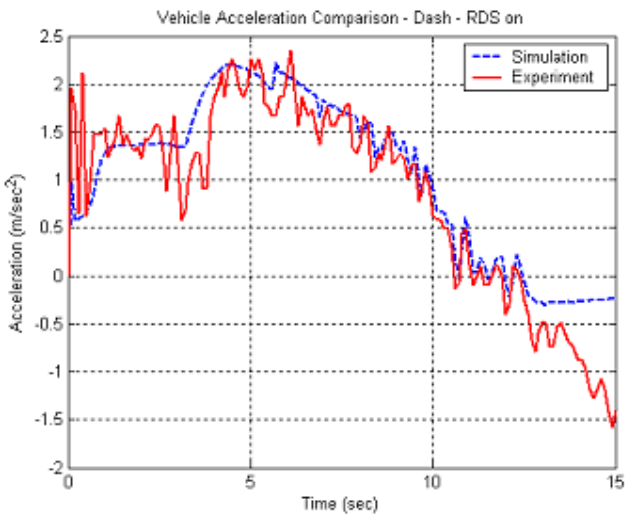
Model Development

Model Validation – PDREMS on.

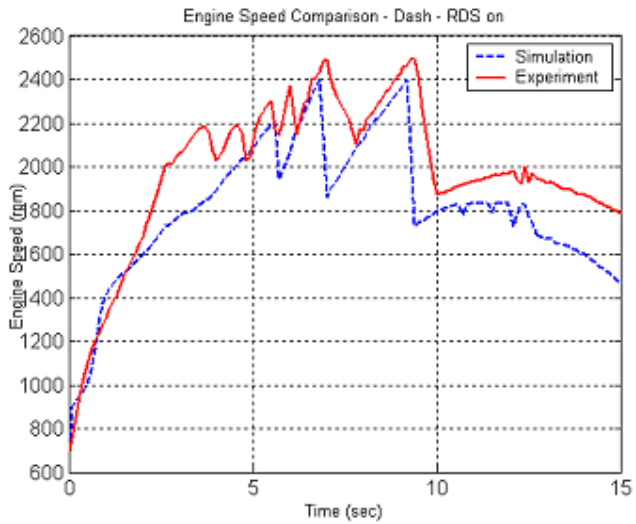
Vehicle Speed



Vehicle Acceleration



Engine Speed



Fuel consumption estimate within 2.0%

Monash Research.

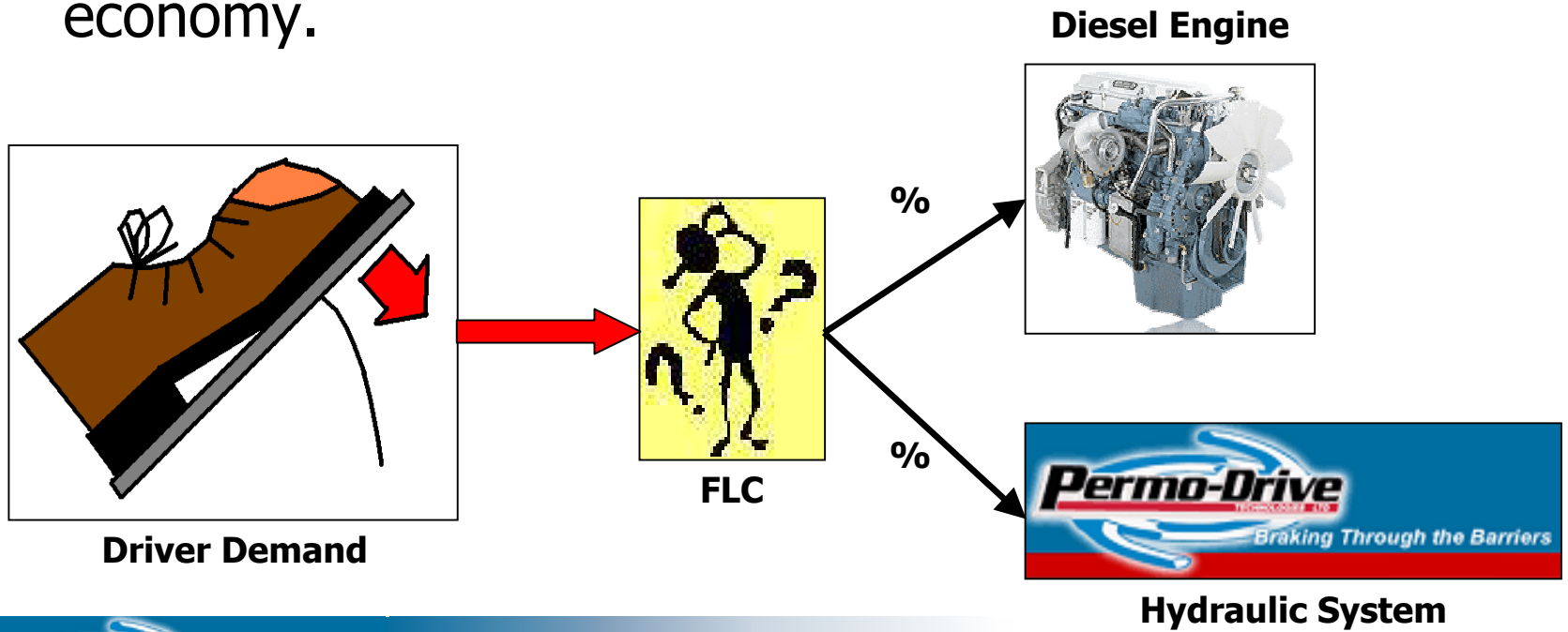
Fuzzy Logic Controller (FLC).

- One of the main research goals was to investigate the potential benefits from using Fuzzy Logic to control the hybrid driveline.
- Fuzzy Logic was chosen due its ability to control dynamic multi-variable systems that involve decision making.
- Fuzzy Logic has been used successfully in many automotive engineering applications – including automatic transmission control.

Monash Research.

What does the FLC do?

- The main goal of the FLC is to distribute the driver's demand for power between the two power sources (ICE and PDREMS) at any point in time which maximises fuel economy.



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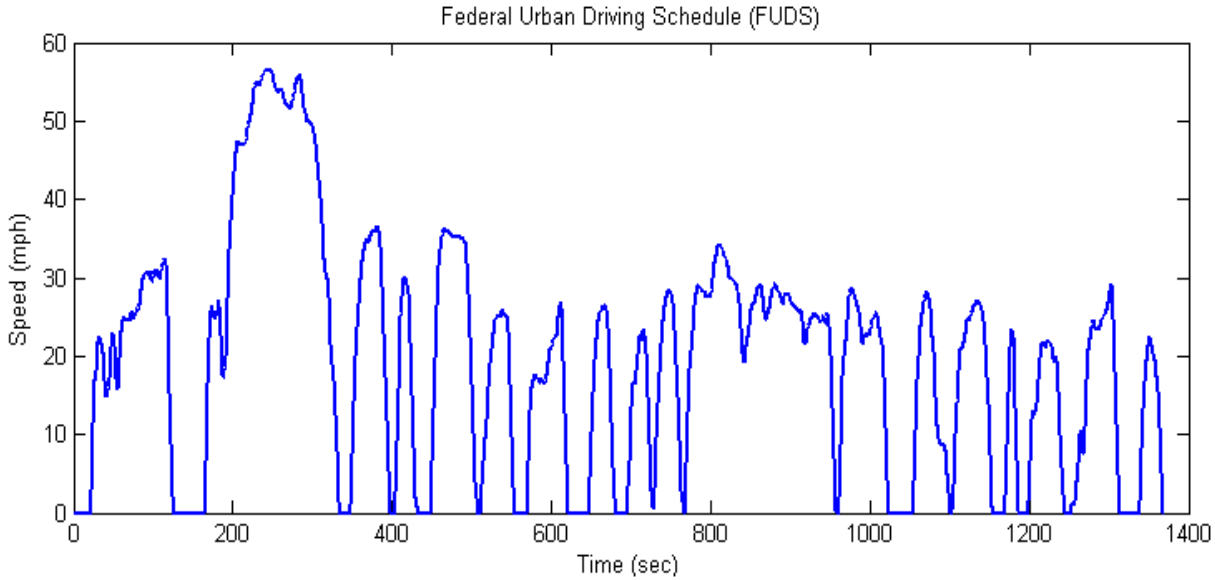
Results of Comparison.

- A model of the baseline control strategy was compared to the FLC when run over the Federal Urban Driving Schedule.



- The FLC produced a 3% improvement on the baseline control strategy.

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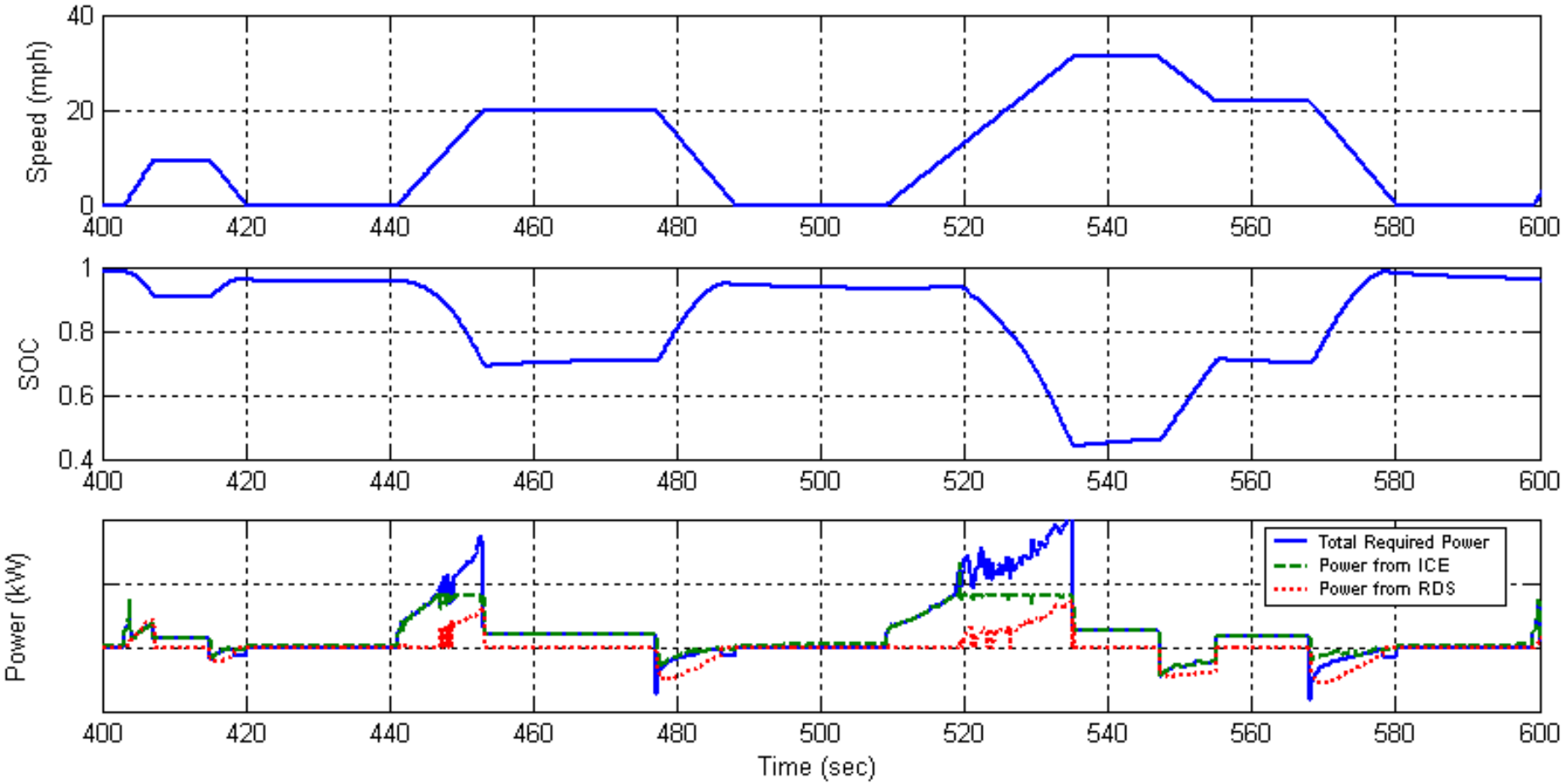
NEDC Analysis.



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Advantages of Fuzzy Logic:

- The design engineer has greater control over when to use the stored accumulator energy.
- Professional advice can be directly translated into control commands.
- Greater degree of control without the use of complex mathematics.
- Ability to produce 'seamless' operation.

Monash Research.

Hybrid System Optimisation.

- The other focus of the research was on the Hydraulic System Optimisation.
- Aimed to find the ideal combination of system parameters which maximise fuel economy for a given duty cycle.
- Primarily focused on the PDREMS components due to retrofitting – can be focused on entire vehicle driveline (ICE size, gear ratios, etc).

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Hybrid System Optimisation.

Objective Function = ADVISOR fuel economy (maximise).

Constraints = Acceleration performance (0 to 30 mph < 10 sec).
= Accumulator size (50-300 litres).
= Pump/Motor size (200-550 cc/rev).
= Pre-charge (50-300 bar).

Performed over the FUDS. All constraints are varied until an optimum configuration is reached.

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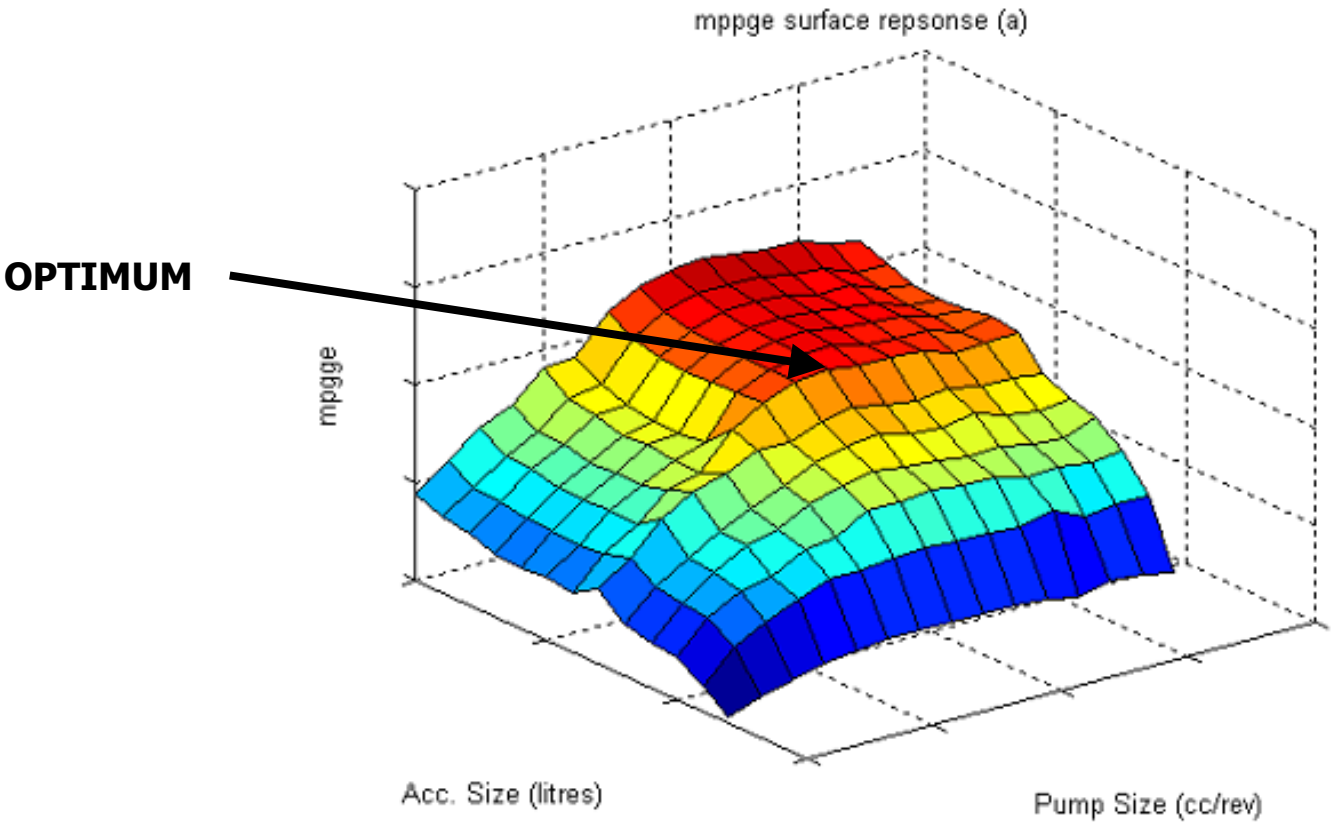
Hybrid System Optimisation - Visualisation.



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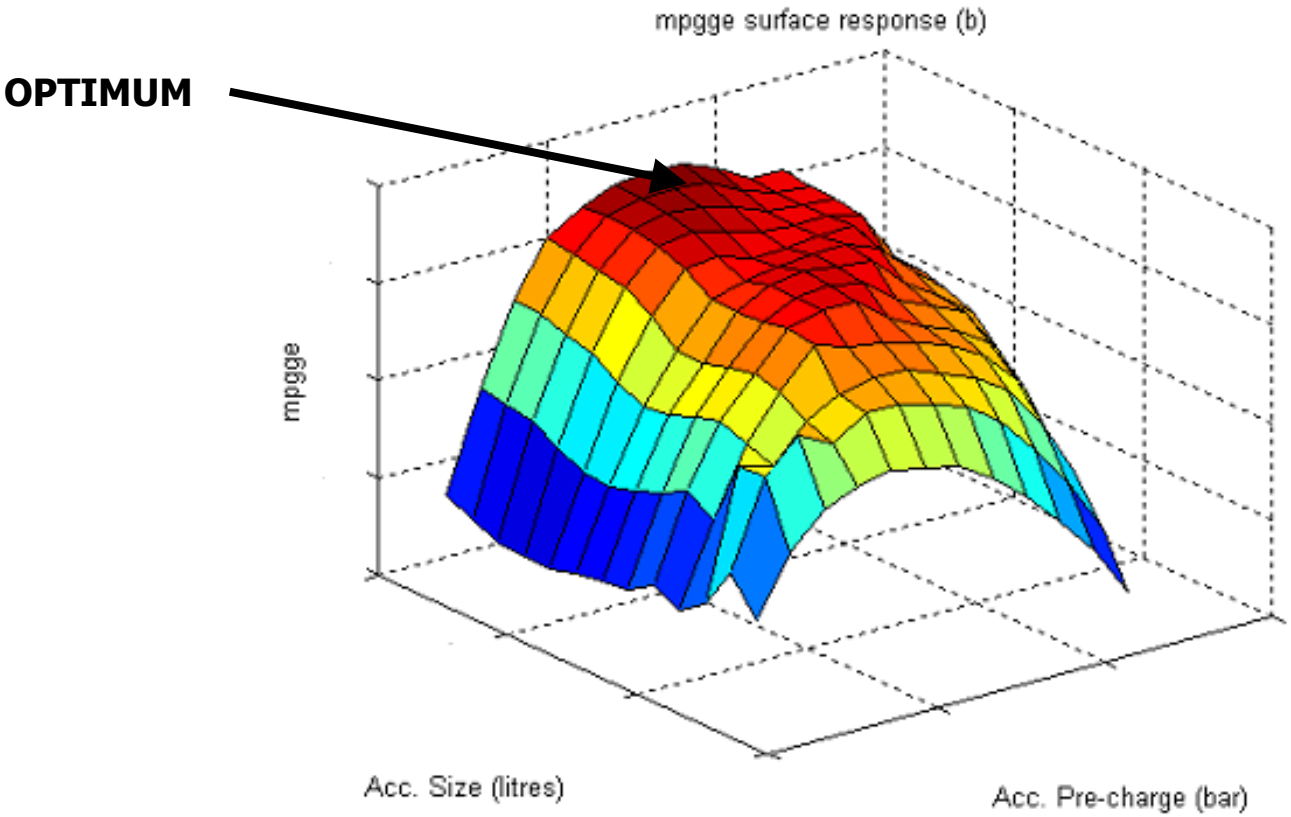
Hybrid System Optimisation - Visualisation.



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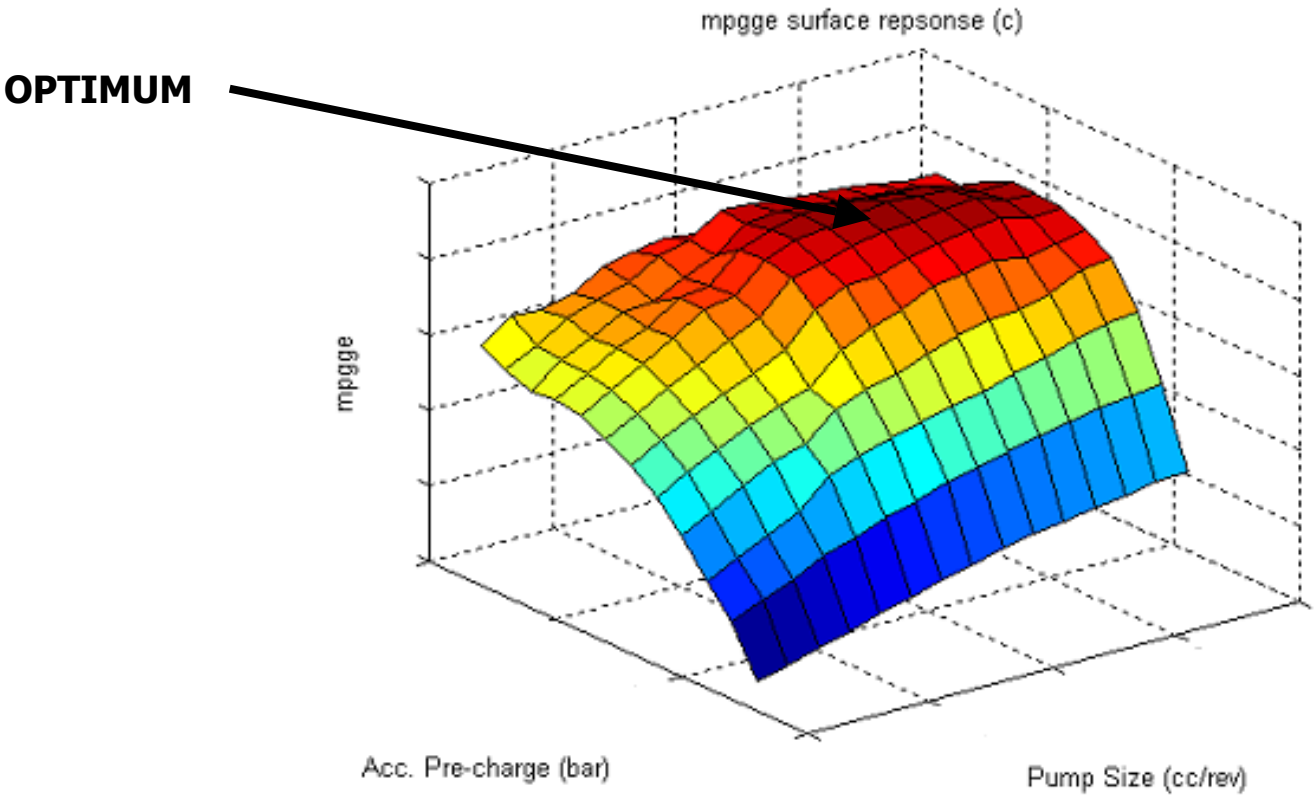
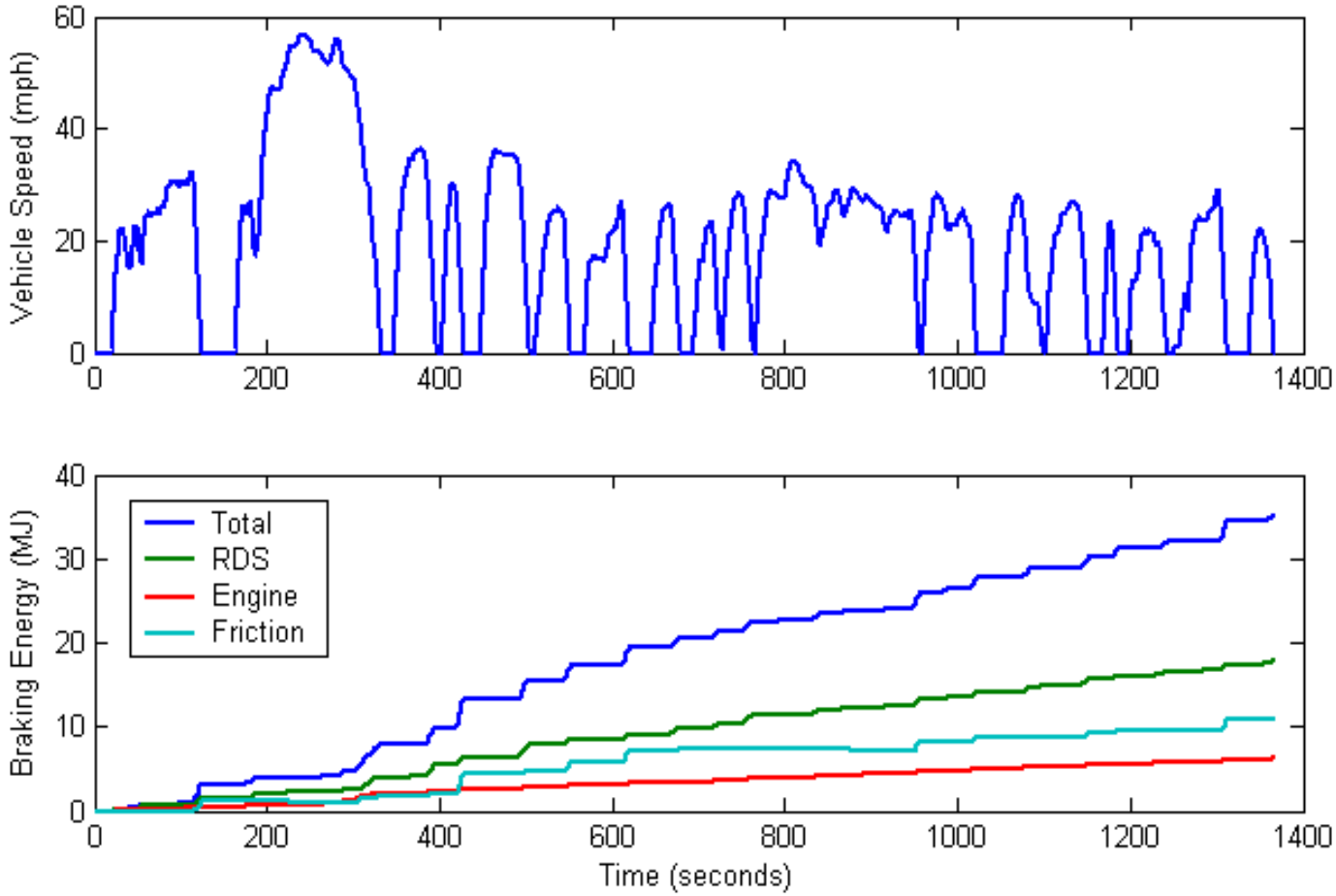
Hybrid System Optimisation - Visualisation.



Braking Analysis.

Braking Analysis on FUDS.



Braking Analysis.

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Braking Analysis on FUDS.

Total required energy for braking over cycle = 35.04 MJ.

Engine braking = 6.19 MJ (17%).
Friction braking = 10.97 MJ (31%).
RDS braking = **17.87 MJ (51%).**

Without the RDS, the friction brakes would have to do an additional 51% of the total braking.

Conclusions.

- This presentation shows the potential benefits from the use of Hydraulic Regenerative Systems for heavy vehicles.
- Hybrid systems are of most benefit in stop-start (urban) driving. (Garbage, urban delivery, buses).
- The benefits of Fuzzy Logic Control were investigated on a validated computer simulation.
- PDREMS component sizes were optimised using ADVISOR.
- RDS braking dramatically reduces load on friction brakes.

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Thanks For Listening.