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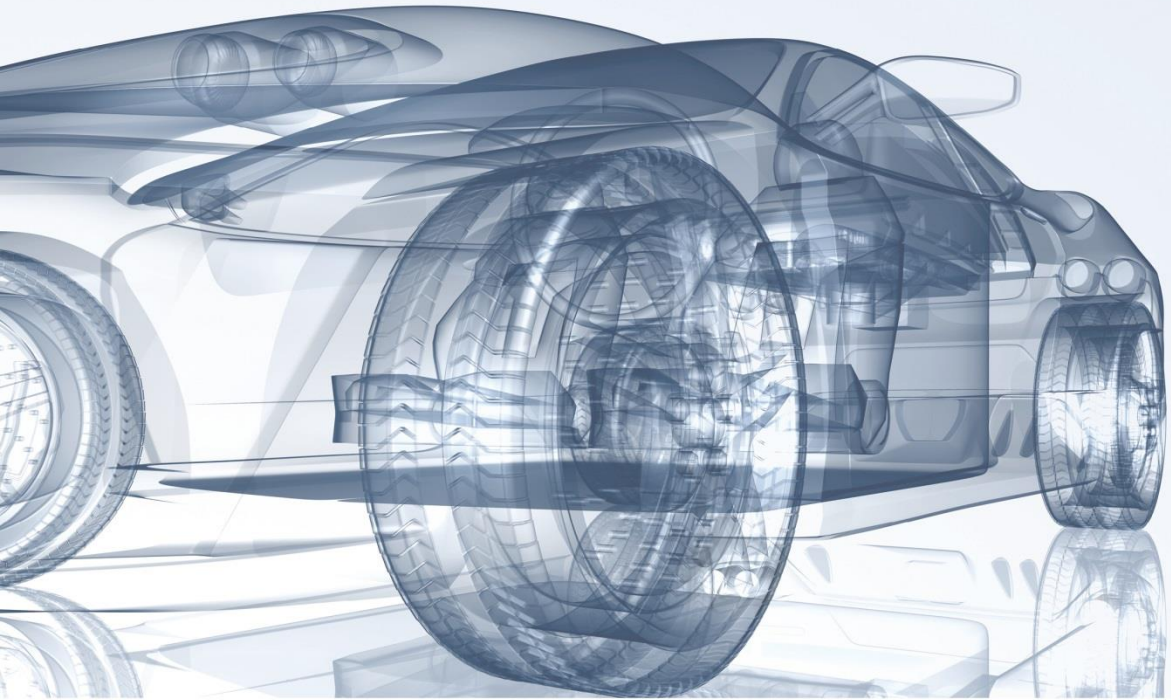

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The MAHLE Range Extender Engine

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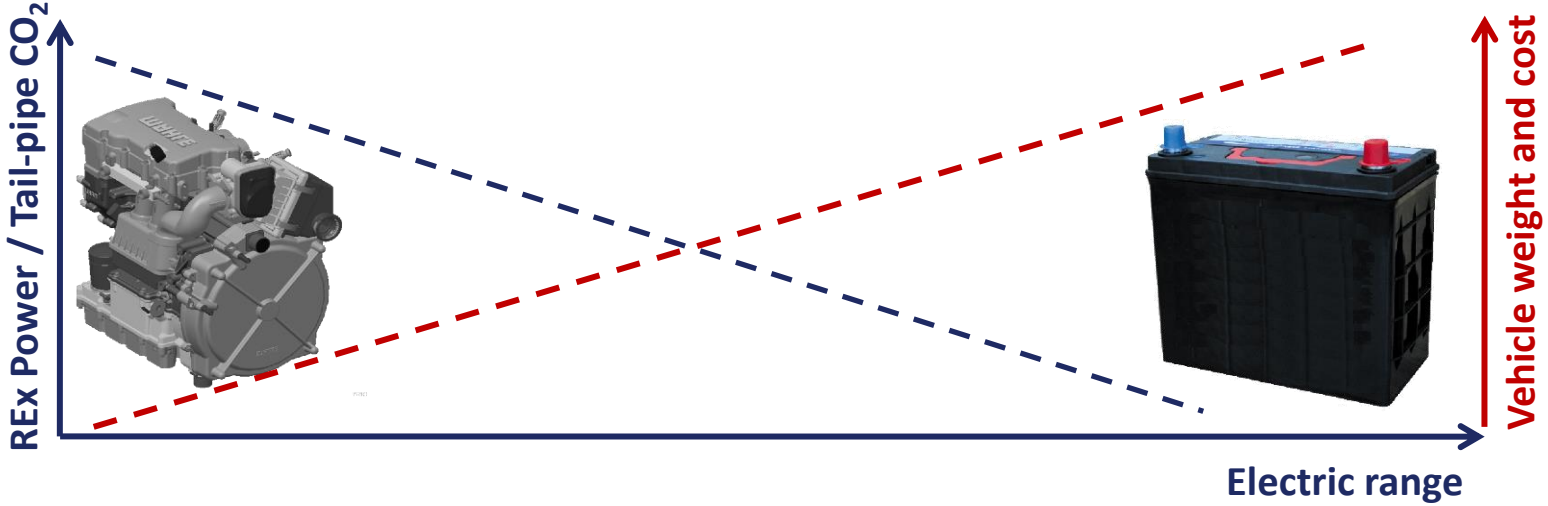
The MAHLE Range Extender Engine

Agenda

- Introduction
- Range extender power requirements
- MAHLE range extender specifications
- Test results
- Dynamic generator control
- Demonstrator vehicle
- Vehicle control strategy
- GPS based control system
- Engine family
- Conclusions

Introduction

- Battery provides load-levelling of driver demand
- REx power needed dependent on battery capacity
  - No battery – REx must provide instantaneous power
  - Limitless battery – REx not required



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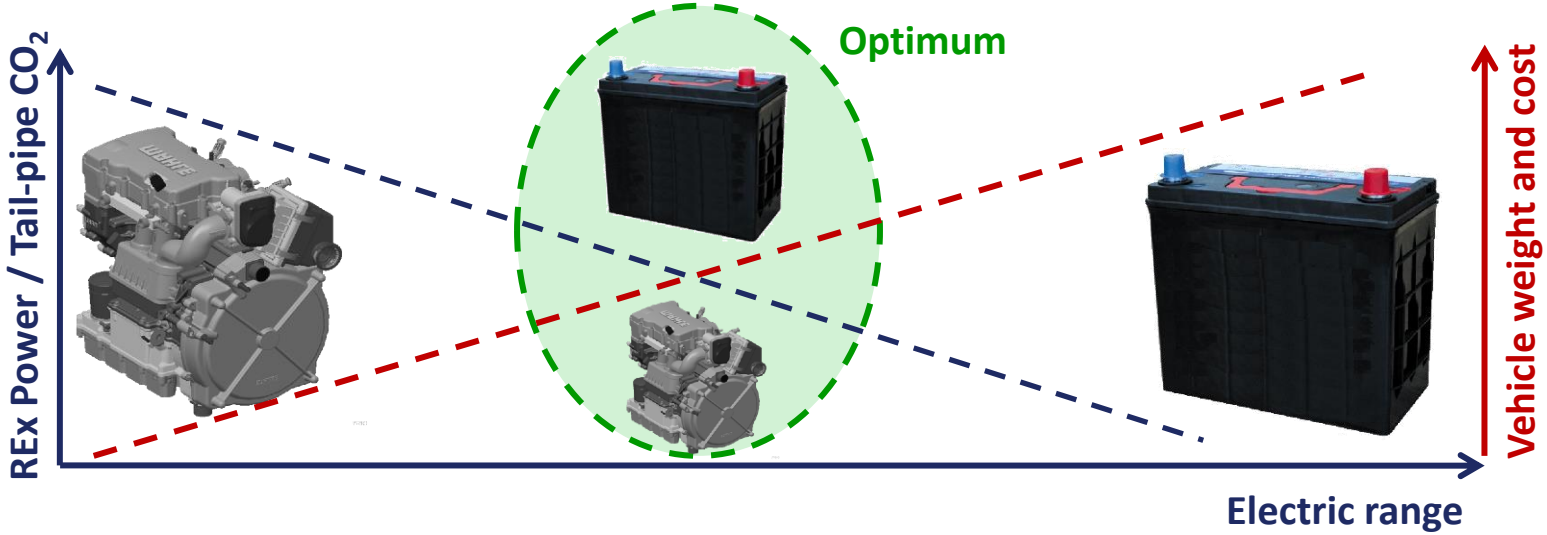
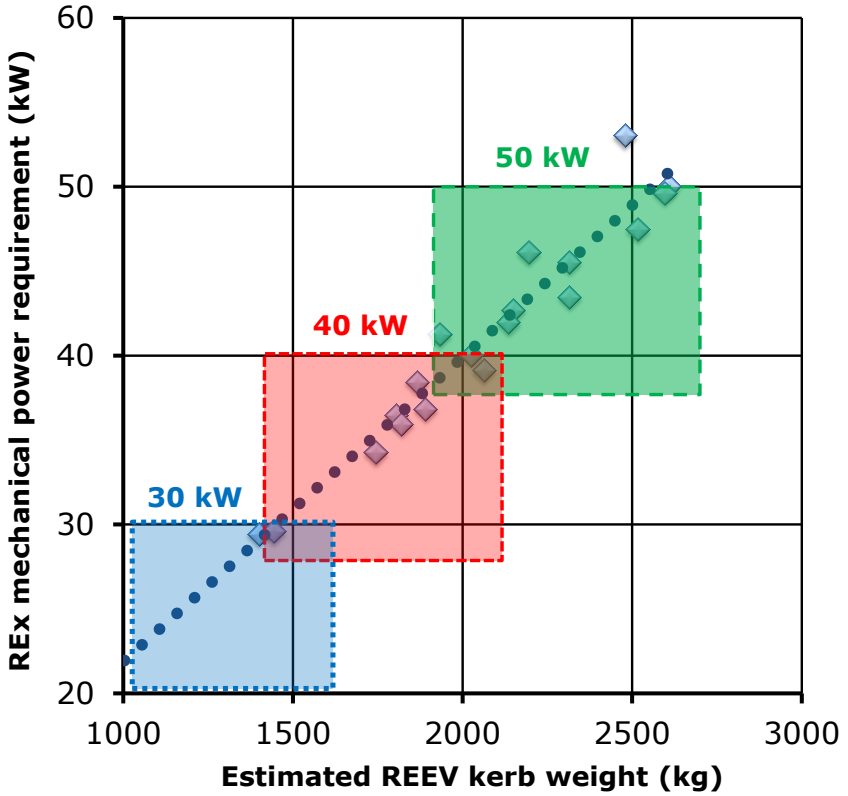


Range Extender Engine Family Concept

Power Requirements

- Increasing power required with vehicle weight:
  - Compact car
    ➔30 kW required
  - Mid / Large car
    ➔40 kW required
  - SUV / Van / Delivery Vehicle
    ➔50 kW required



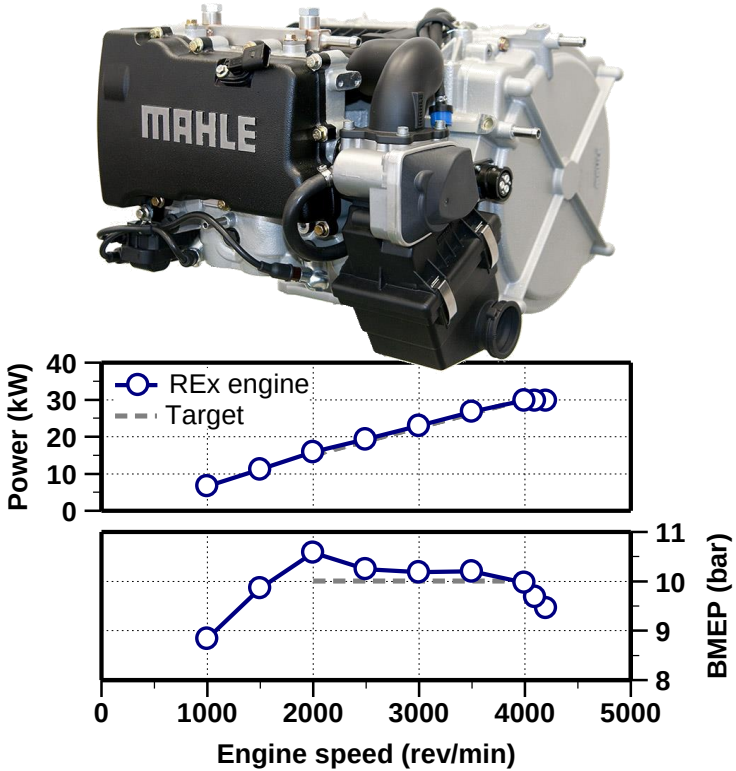
MAHLE Range Extender Specifications

Range Extender Unit Specifications

- 900 cc, in-line two cylinder, four stroke gasoline
- 30 kW peak power at 4000 rev/min
- Port-fuel injection (λ = 1)
- 0°/180° TDC firing angles
- Flexible installation (vertical to horizontal)
- Fully integrated permanent magnet axial flux generator

Range Extender Engine Testing

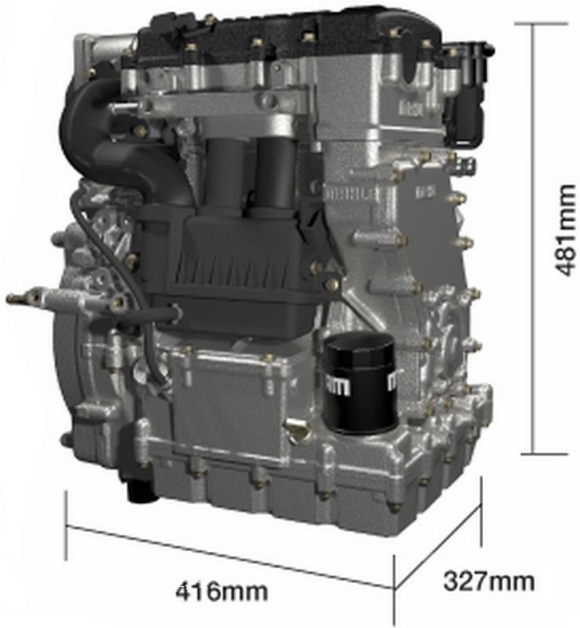
- Achieved 30 kW at 4000 rev/min
- 10 bar BMEP from 2000 to 4000 rev/min
- **Engine performance targets met**



Size, Weight & Cost Optimised

Dimensions

- L x W x Height: 416 x 327 x 481 mm
- Volume (Box): 65 litres*
- Weight: 50 kg (engine only)
  70 kg (inc. generator)



*IATA Hand baggage guidelines 63 litres

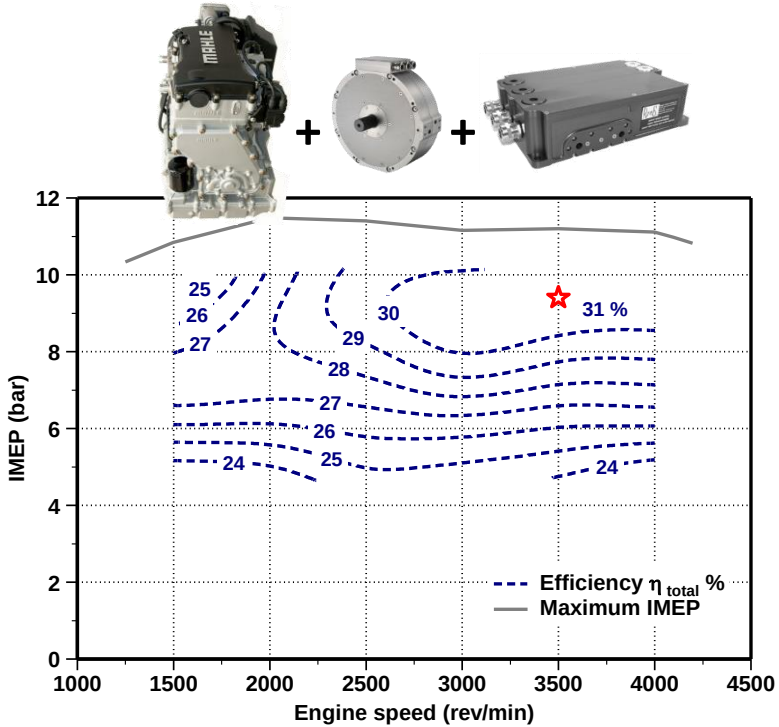
System Efficiency

Range Extender System

- Engine
- Generator
- Inverter

Power Generation System Efficiency

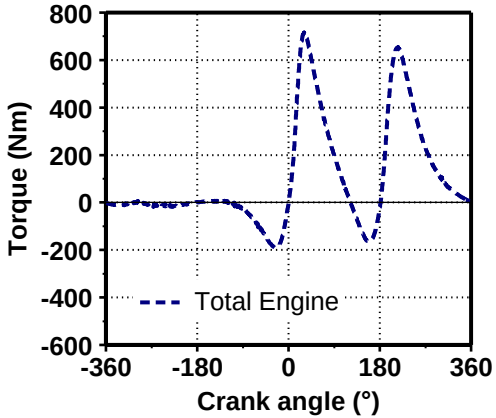
- $\eta_{total} = \eta_{engine} \times \eta_{generator} \times \eta_{inverter}$
- Efficiency almost constant with varying engine speed
- Efficincy predominantly engine load dependent
- **Maximum efficiency ≈ 31 %**



Range Extender system efficiency
(measured at 350 V system voltage)

Dynamic Generator Control

- No primary out of balance forces (0°/180° firing)
  - No balancer shaft required
- Two bearing crankshaft
  - Low cost and low friction
- Flywheel located between cylinders
  - Small package volume
  - Low rotational inertia
- Uneven torque profile
  - All torque from single crank revolution
  - No torque from other revolution
- **Challenge: Cyclic speed fluctuations**



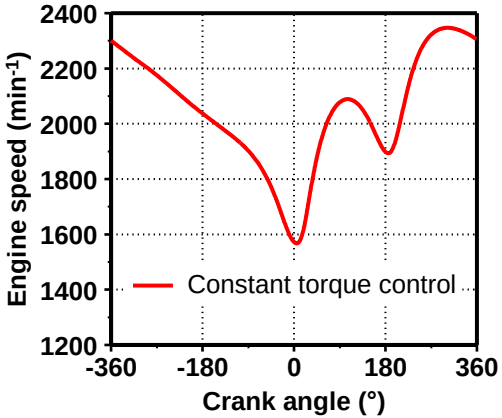
Cyclic Torque Variation
(2000 rev/min, 8 bar BMEP)

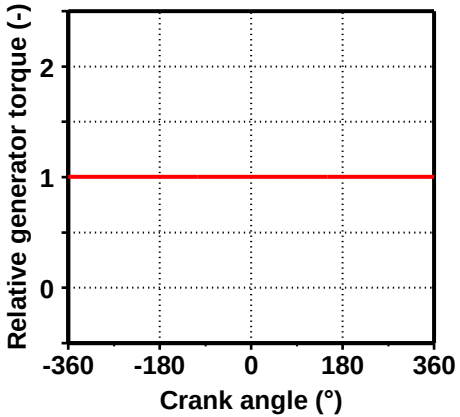
Dynamic Generator Control

Dynamic Control

- Constant generator torque:
  - ±400 min^{-1} speed fluctuation

- **Low cranktrain inertia ➔ High cyclic speed fluctuation**



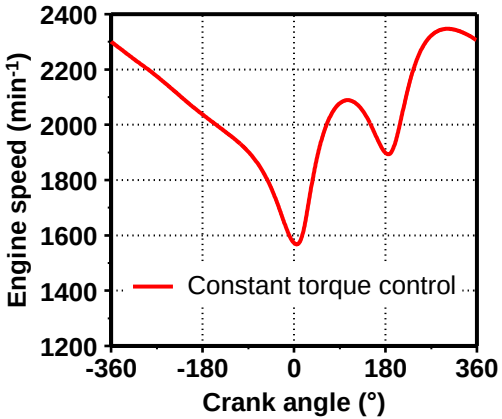


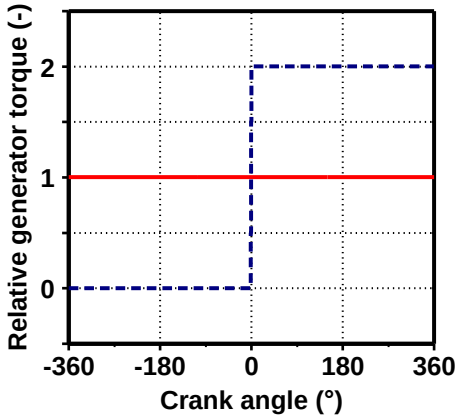
Dynamic Generator Control

Dynamic Control

- Constant generator torque:
  - ±400 min^{-1} speed fluctuation

- **Low cranktrain inertia ➔ High cyclic speed fluctuation**
  - Solution ➔ Dynamic generator control

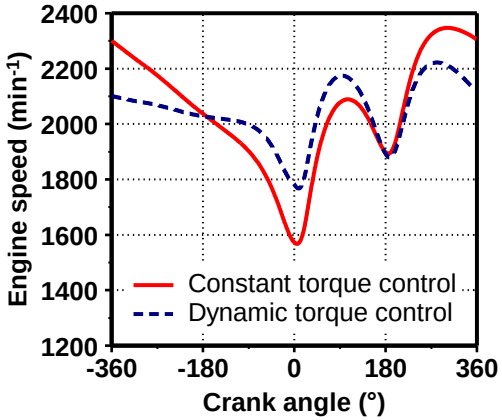


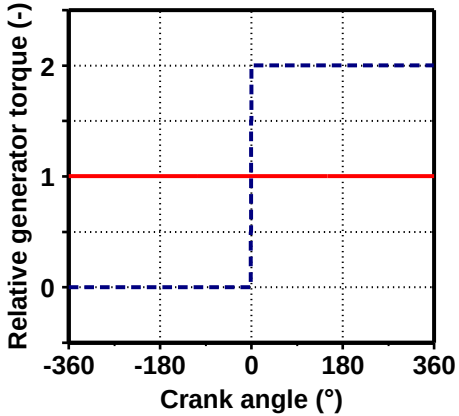


Dynamic Generator Control

Dynamic Control

- Constant generator torque:
  - ±400 min^{-1} speed fluctuation
- Dynamic generator torque:
  - Reduced speed fluctuation down to ±200 min^{-1}
  - Smoother engine operation
  - No large flywheel requirement





MAHLE Range Extender Demonstrator Vehicle

B-Segment Demonstrator Vehicle

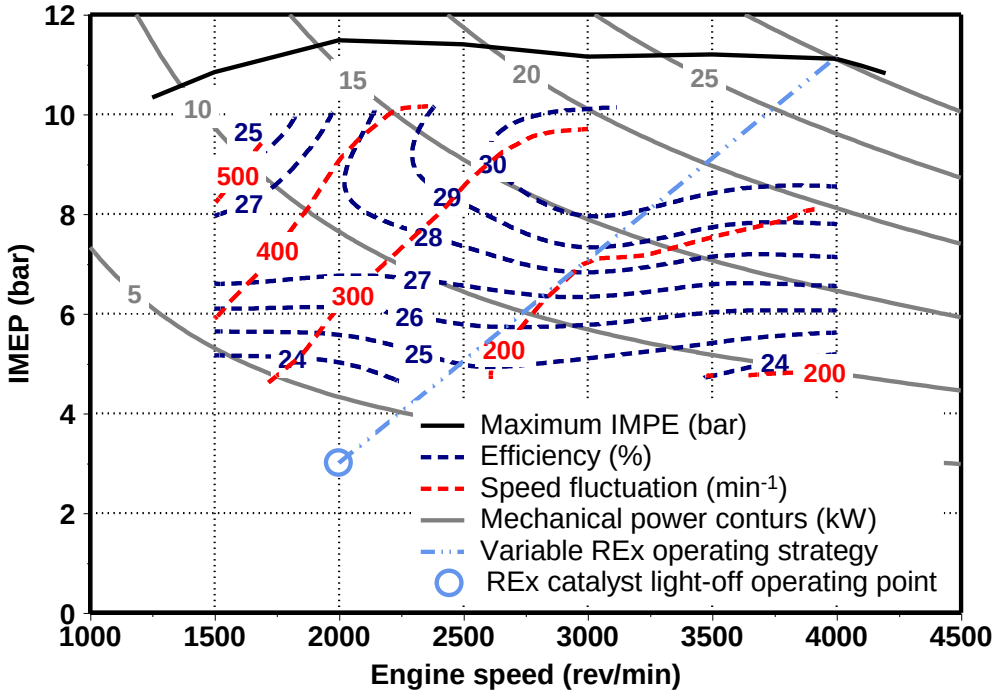
- Total range 500 km

  (70 km pure electric range with 14 kWh battery)
- 42 g/km CO_2 Tail-pipe emissions for NEDC
- Charge sustaining speed of 120 km/h
- Dynamic performance comparable to baseline vehicle

B-Segment Demonstrator Vehicle
(Picture from the Bertha Benz Challenge 2013)

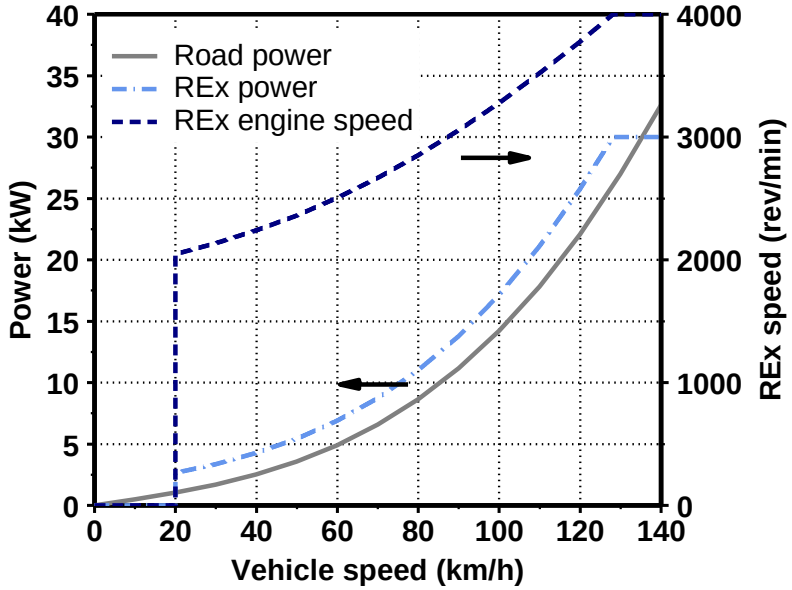
Operating Strategy

- REx efficiency
- NVH
  - Speed fluctuations
- Operating line represents a good compromise



Range Extender Vehicle Operating Strategy

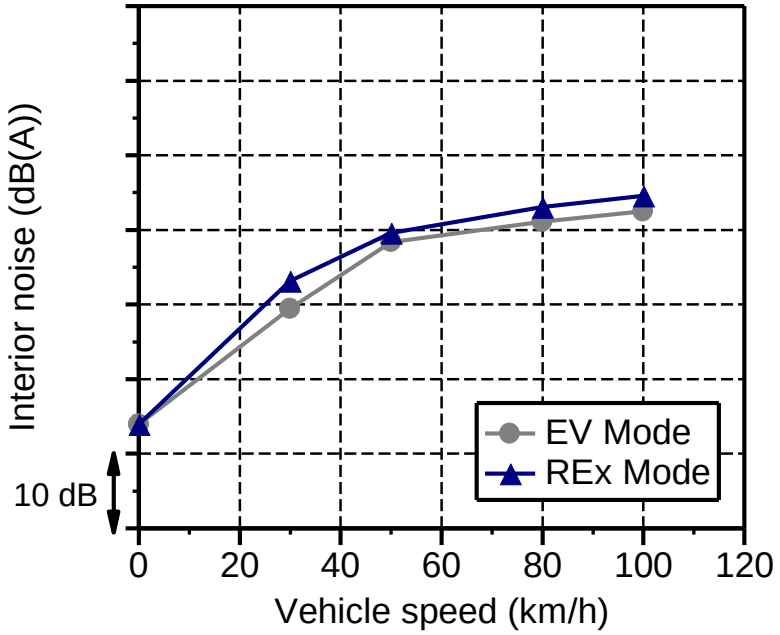
- Deplete battery
  - Maximise EV range
- Load follow
  - SOC sustaining
  - Engine speed/load follows vehicle speed
  - Minimise noise and fuel consumption
  - Vehicle noise masks REx operation
- REx off at low vehicle speeds
  - Unless SOC critically low



Range Extender Operating Strategy (Example)

Vehicle Interior Noise Measurements

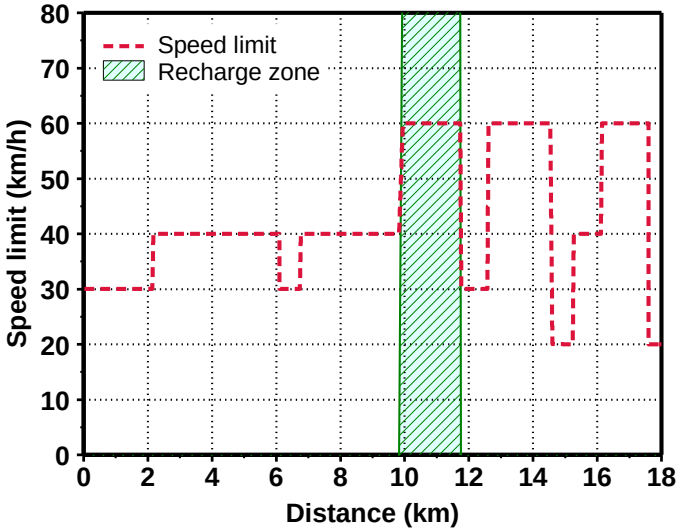
- REx operating strategy developed to enhance passenger comfort pack
- REx speed follows vehicle speed
- Road noise helps mask REx
- Interior noise in REx mode only marginally louder than in pure EV mode
- REx operation barely perceptible to vehicle occupants

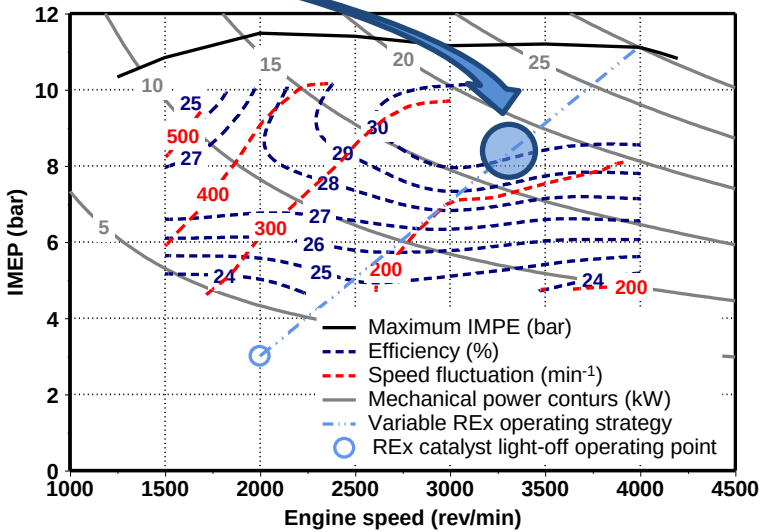


Demonstrator vehicle interior noise measurements in EV mode and REx mode

GPS Based Operating Strategy

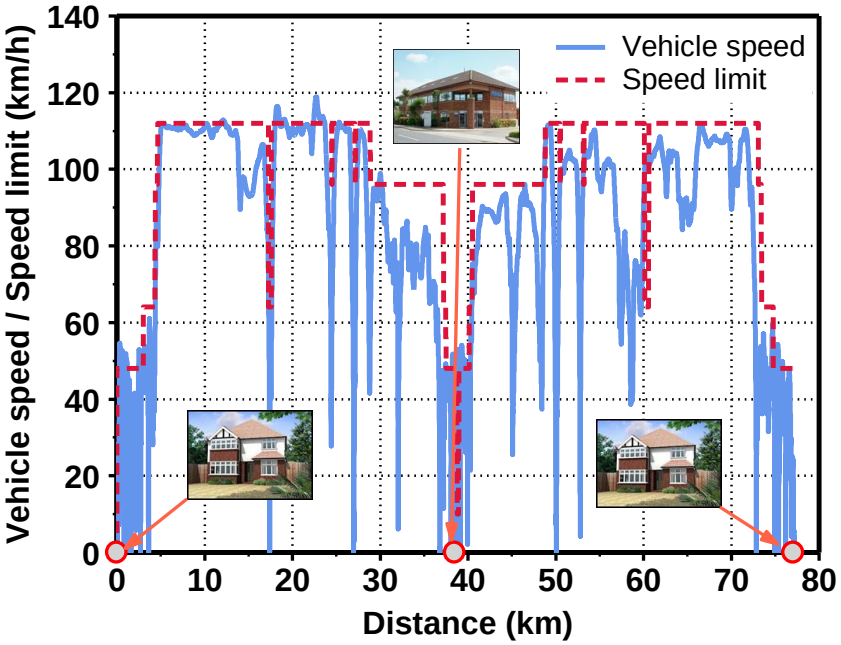
- If route is known, we can
  - Plan when to operate REx for best efficiency
  - End journey with desired SOC
  - Charge early

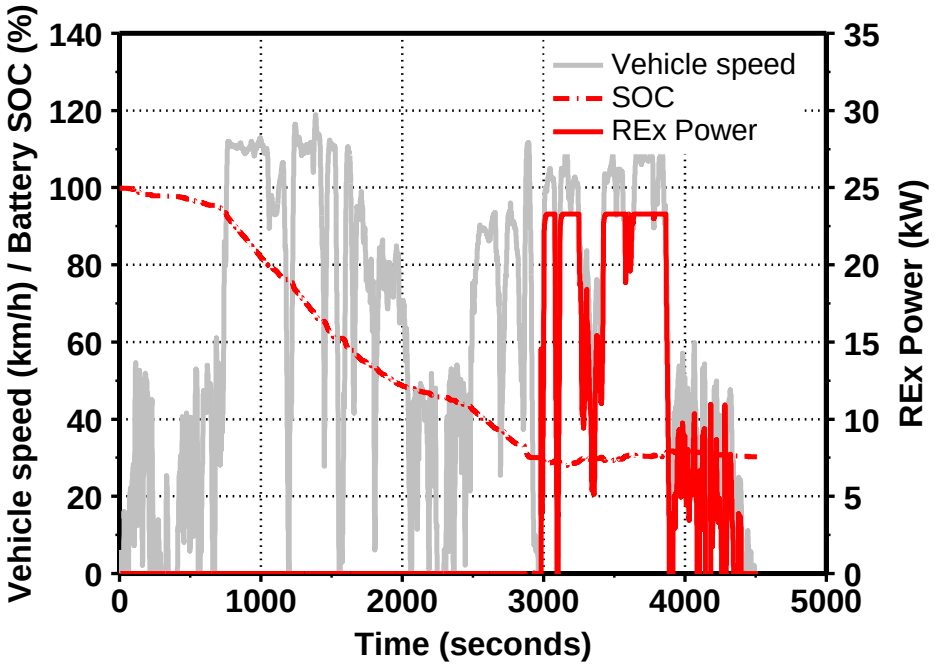




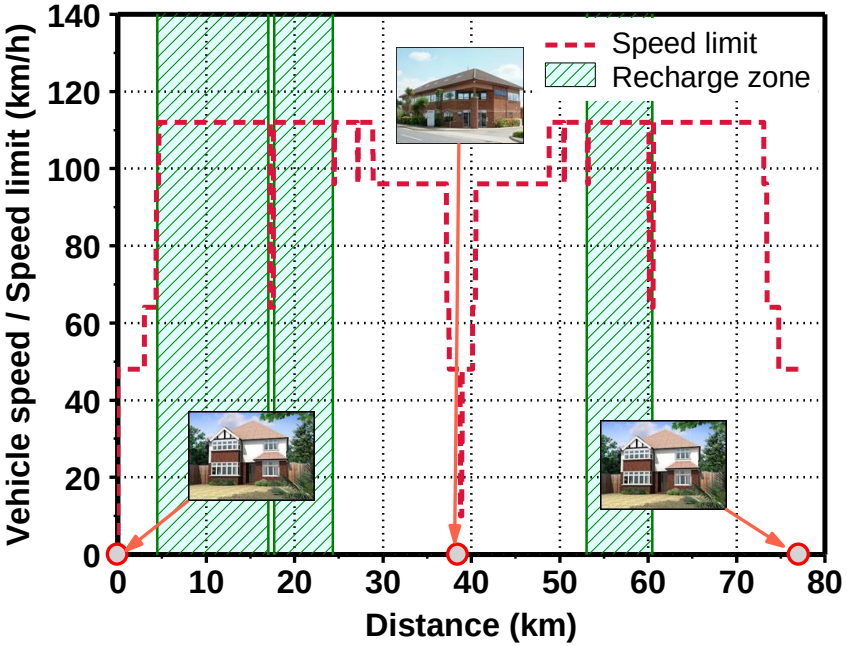
GPS Based Operating Strategy Vehicle Implementation

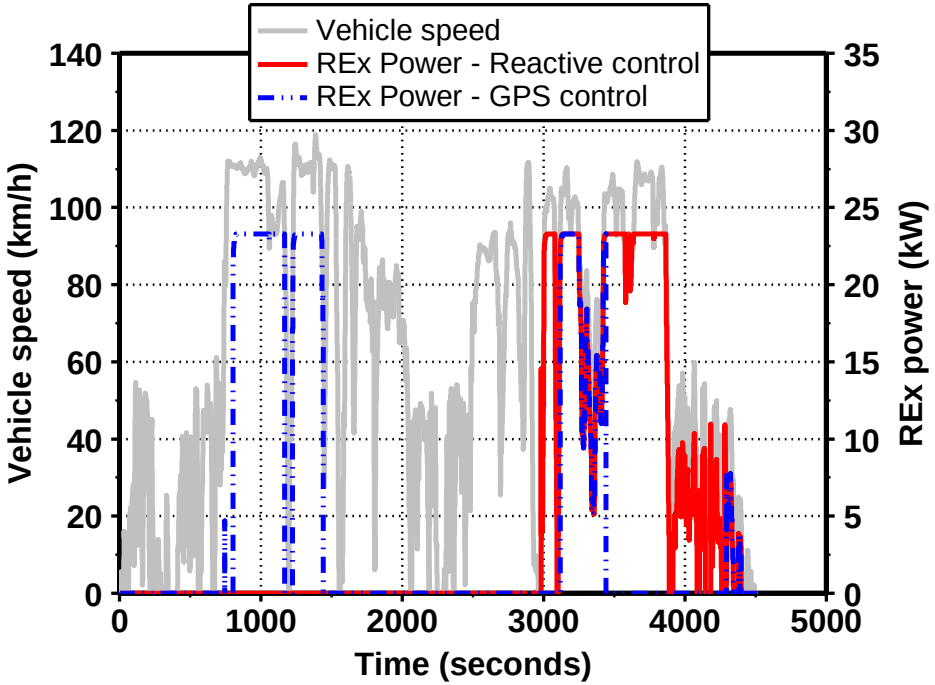
Route Speed Profile and REx Charging



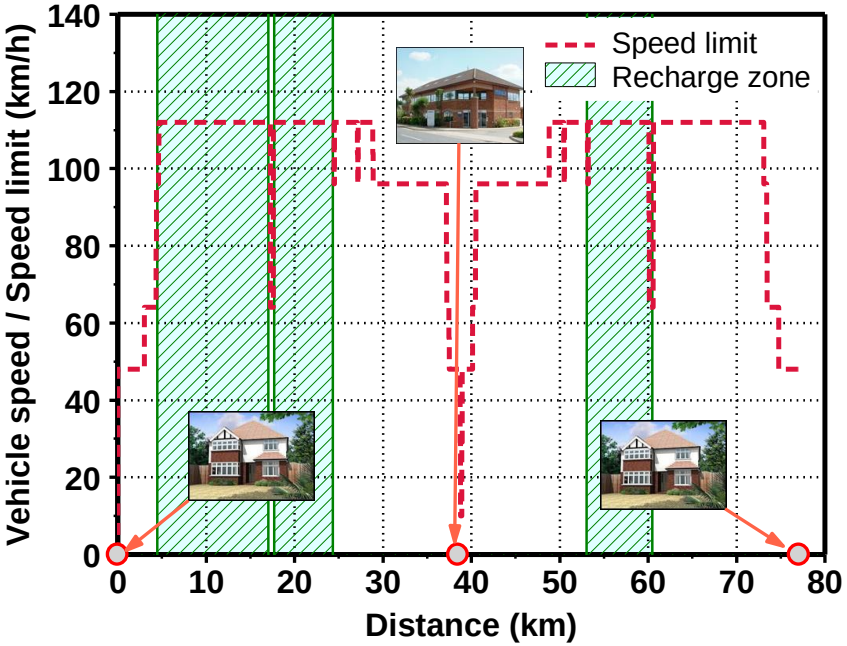


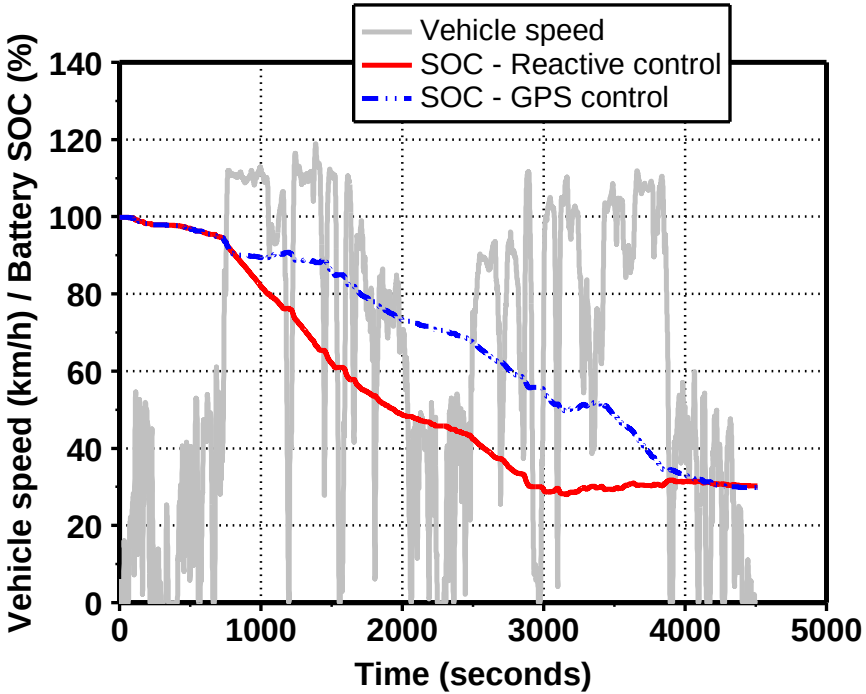
Route Speed Profile and GPS Controlled Charging Points





GPS Controlled Charging Points and Battery SOC





Fuel saving of >4%

Range Extender Engine Family Concept

Power Requirements

- Increasing power required with vehicle weight:
  - Compact car
    ➔30 kW required
  - Mid / Large car
    ➔40 kW required
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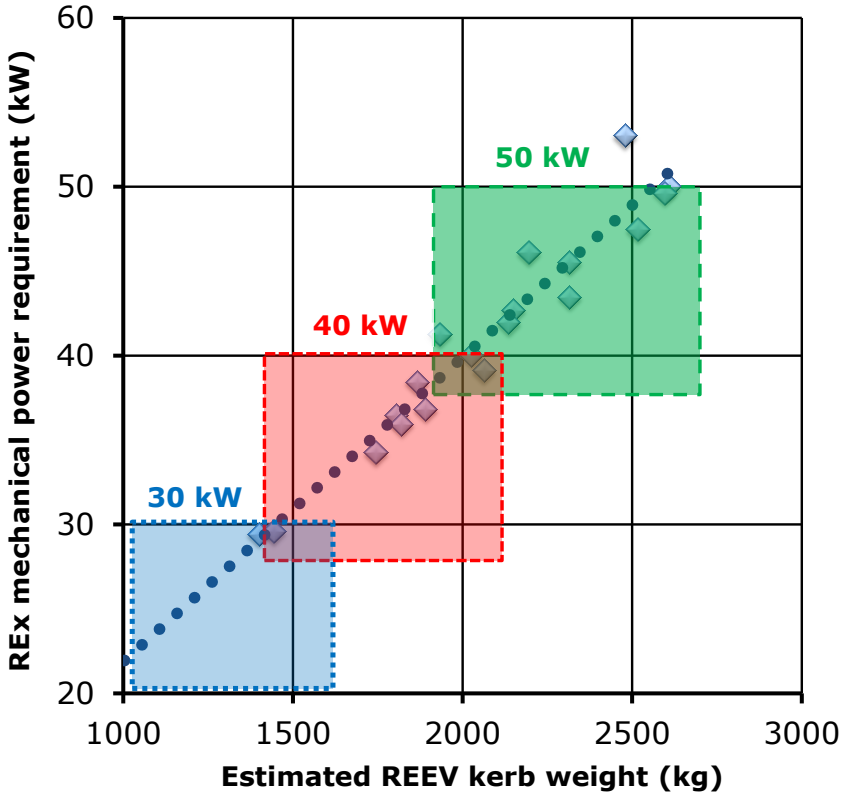

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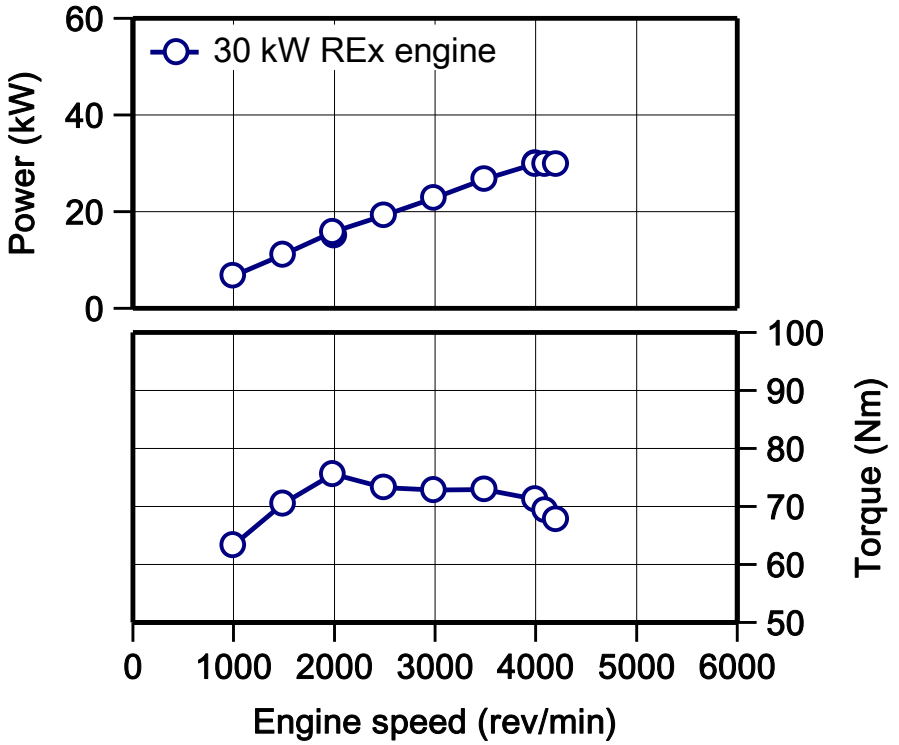

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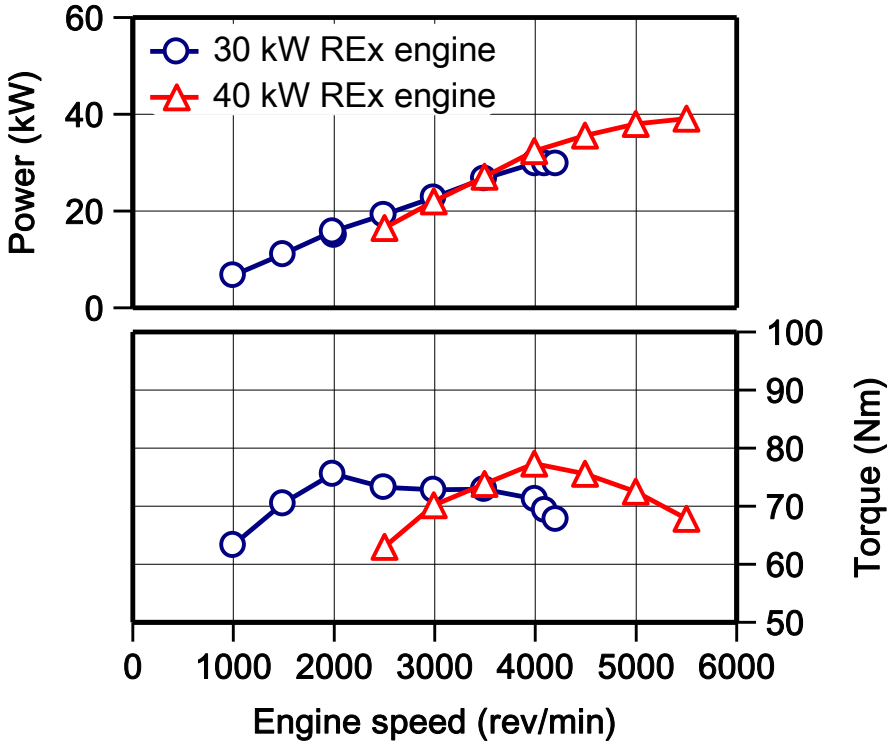

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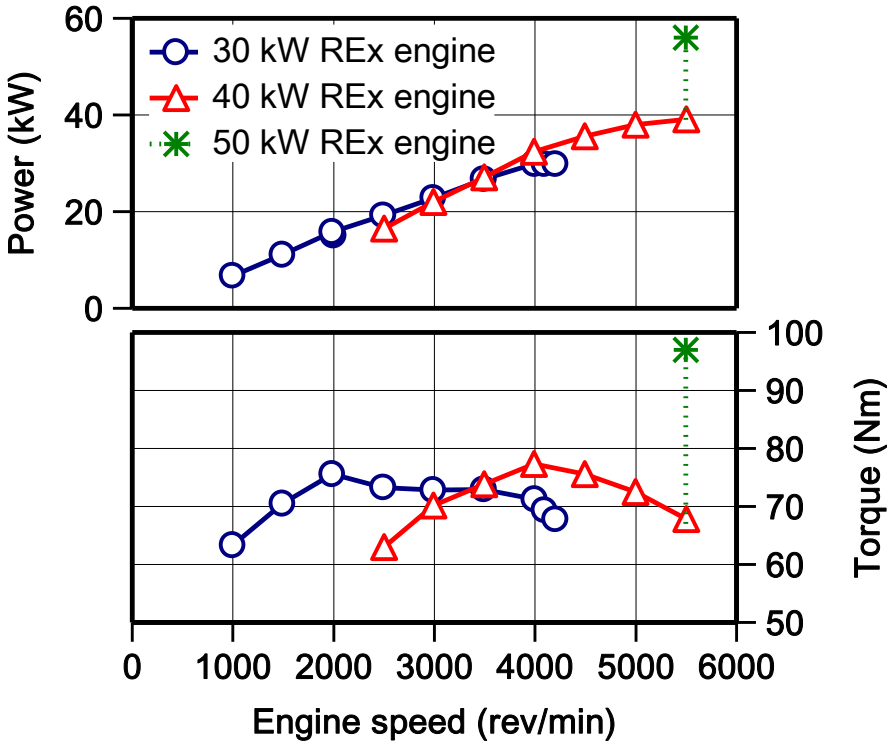
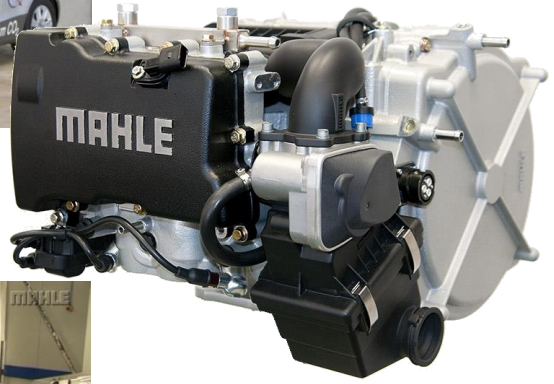


Conclusions

- Compact and light weight REx unit developed
  - Low cost
  - Light weight
  - Compact
  - Efficient
  - Quiet
- Plug-in series hybrid drivetrain system integration and vehicle conversion
  - Fully-fledged B-segment REEV demonstrator vehicle with 500 km range and 42 g/km CO_2
- PHEV controller developed using GPS and road topographical data
- Range extender family suited to a range of vehicles



Thank you