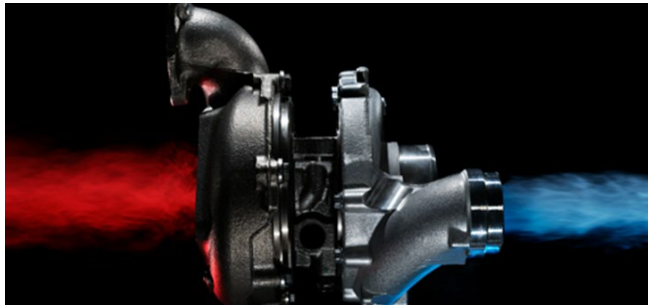

Electric Turbo Whitepaper | A key Technology for EU7

Garrett Motion – Electric & Hybrid Technologies

Garrett
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CONTEXT

The Automotive world is undoubtedly in a period of flux. Urban Air Quality and Climate Change are the key drivers and new technologies such Zero Emission, Connected and Autonomous Vehicles are causing significant changes in the mobility landscape. Full Electric Vehicles (EV's) are growing quickly on a percentile basis but require significant monetary and "in kind" incentivization such as preferential city access, parking and exemption from Life Cycle CO_2 counting, to stimulate adoption, at least in the short term.

Legislation is also evolving rapidly. Real Driving Emission (RDE), the Clean Vehicle Directive (CVD), CO_2 monitoring and the still to be published Euro 7 emission targets are being designed to transition the European fleet to one that can be measured and monitored firstly in terms of real world emission and ultimately in Life cycle CO_2 footprint.

CONTEXT

Change is not only taking place in Automotive however. In the Energy Sector, the Renewable Energy Directive (RED II) and the Gas Market Design are the instruments with which the EU Commission will steer the primary Energy Industries such as Electricity and Natural Gas towards the goal of 90% reduction in CO_2 by 2050.

All these actions will take time to shape the individual Industries but convergence will be well advanced by 2025 and by 2030 it should be possible to start comparing based Life Cycle CO_2 in a meaningful way.

CONTENTS

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Garrett is a cutting-edge technology provider that enables vehicles to become safer, more connected, efficient and environmentally friendly.

We lead the development of innovative and differentiated solutions which empower the transportation industry to redefine and further advance motion.

1 Garrett at a glance

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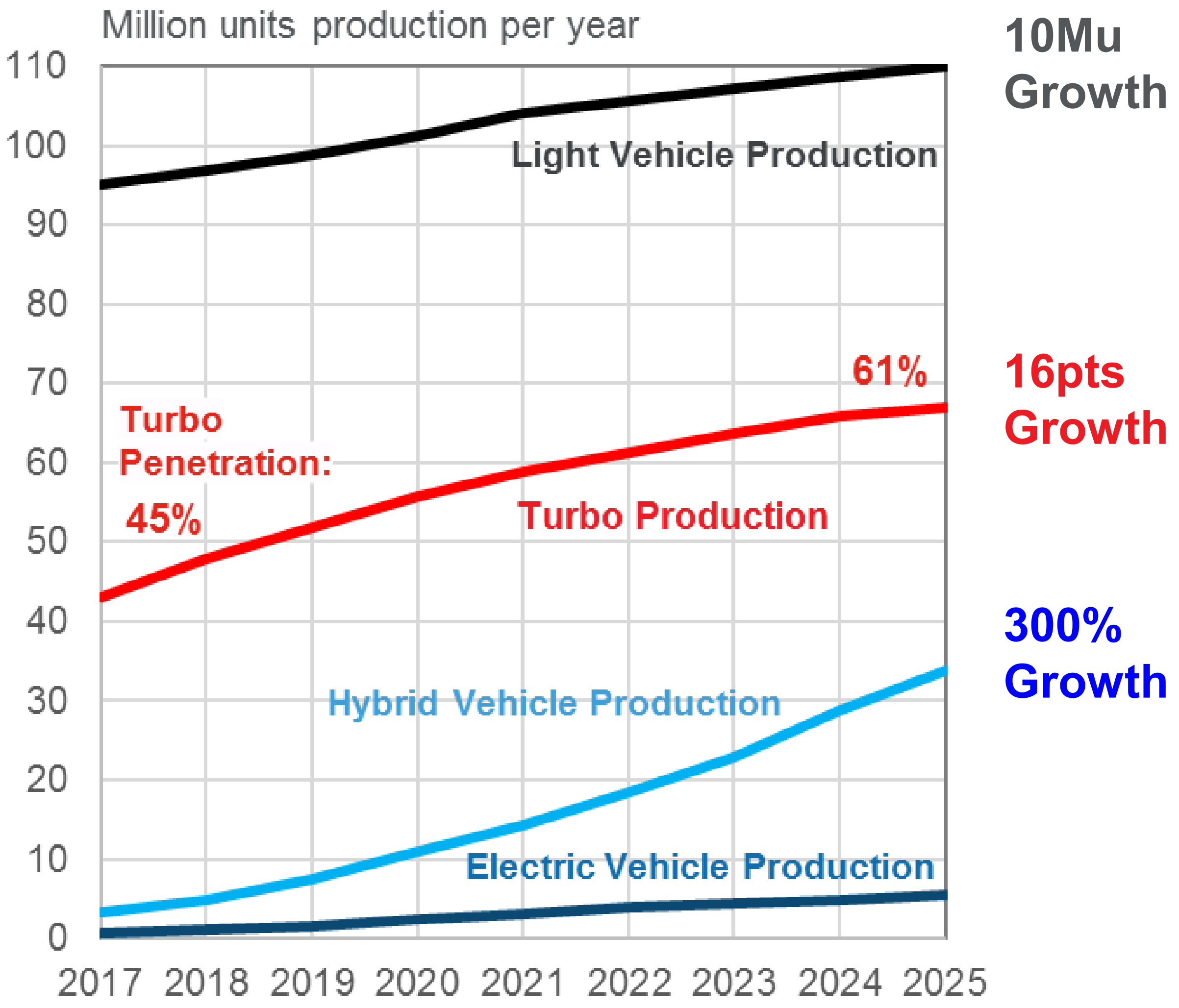
$3.4B 2018 Revenue	**5** R&D Centers	**13** state-of-the-art manufacturing facilities
~7,500 Employees	**13** “Close-to-Customer” engineering centers	**50,000+** Turbos / day
~1,200 Engineers	**100+** New applications annually	**100M+** Garrett turbos in use globally
40 OEMs served globally	**1,400+** Patents issued or pending	GTX LISTED NYSE

2

Market Development



Source :IHS

3

Gasoline Combustion Changes

Gasoline and Diesel Combustion Trends

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	Clean Diesel Combustion	Gas. Stoich GDI + Miller (+LP EGR)	Lean GDI (+ Miller or LP EGR)	Gasoline Low Temp. Combustion (HCCI + derivatives)
FE Potential	High	Medium	High	Best
Three Way Catalyst	NA	✓	✓	-
Lean NOx converters	✓	NA	✓	✓
Oxi Catalyst	✓	NA		✓
HC Traps	By Application	By Application	By Application	✓
Passive NOx Adsorbers	✓	By Application	By Application	✓
Particulate filter	✓	✓	✓	✓
Multifunction Devices Systems	✓	-	✓	✓
Complexity & Cost	Medium / High	Low / Medium	High	Very high
Turbocharging	✓	✓	✓	TBD
Exh. Heat Recovery	✓	✓	✓	TBD

Trend mainly turbocharged and with heat recovery potential

Combustion System Evolution

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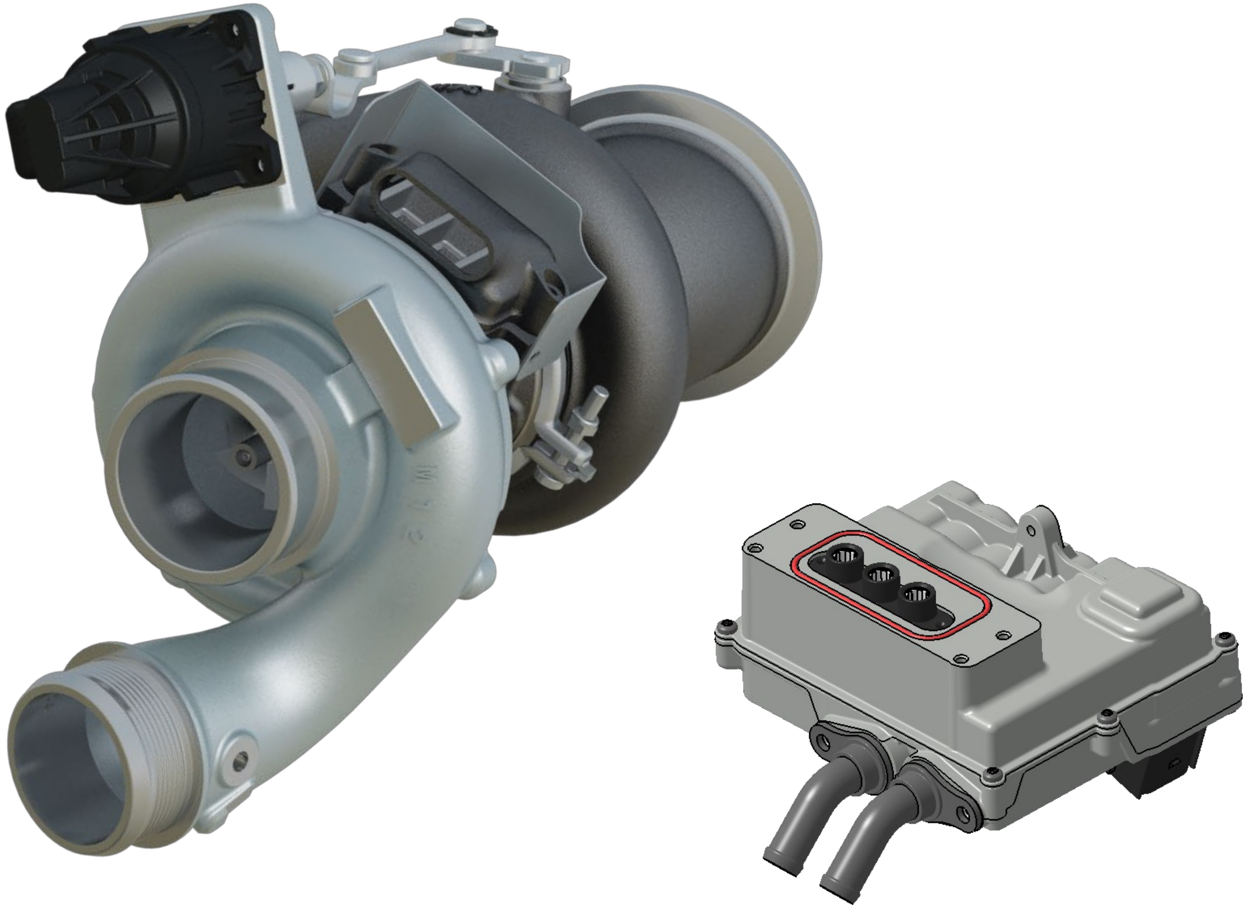
Electrifying a turbocharger removes the constraint of needing a small turbine with excellent efficiency to drive the compressor at low flow rates. Instead, it allows us to right size the turbine for Lambda 1 rated power. Any penalty in inertia can be more than compensated for by an E-Motor and the addition of a wide range compressor can result in both improving low-end and stretching high-end performance simultaneously.

A "right-sized" electrified turbocharger therefore can deliver CO_2 reduction by supporting down-sizing and down-speeding at the same time. It might be thought that an electrified turbocharger is a consumer and a potential drain on a vehicle electrical system (VEN). This is not the case and it will be shown that in urban driving the turbocharger can recuperate more kinetic energy in the lift off, gear change and braking phases than is used to boost it in city driving.

4

Electrification of the Turbocharger

- New Functionalities



Electrified Turbocharger

New Functionality

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Performance

Downspeeding
CO_2 / Fuel savings
Shift Strategies

Downsizing
e.g. 1.5L vs 2L
or 3 vs 4 vs 6 vs 8 cyl

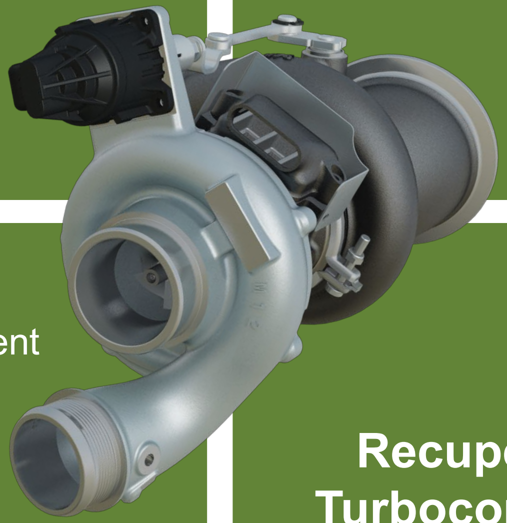
Advanced Combustion

Enable λ1

Transient λ Control

Enable Millerization

Enable Lean



Special Functions

Part-Load Supercharging
Drive electrically when turbine inefficient

TwoStage
Rematching & Transition

Thermal Mgt
Cold start assist

Energy Management Strategy

Energy Management
Charge battery vs eHorizon

Recuperation & Turbocompounding
Based on “cost of energy”

4 Major Function Groups – Multiple Valuable Functions and CO_2 Levers

5

2L Gasoline Case Study

5 2L Gasoline Case Study

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	Series Car	Garrett Electric Turbo Demo Car	Delta (Abs)	Delta (%)
Homologation	EU6	EU7*	-	-
T3 Max (°C)	980	980	0	-
Turbo Frame Size	GT17 (equiv)	GT25	3	-
Power kW	185	215	30	16
λ @ Rated Power	0.85	1.00	0.15	-
Torque Nm	380	420	40	10.5
λ @ Rated Torque	1.20	1.00	-0.20	-
Transient Torque Nm/l.s**	**~20**	**~80**	**60**	**~4x**

* EU7 intent, best known as per 2018

Audi — **Q7 Vehicle**, inclusive of 2L EA888 Gen 3 EU6 & 48V Network
Garrett — **GT25 Electric Turbo**, inclusive Power Electronics & Software
IAV — **System Integration**, inclusive Facilities & Expertise

Electrification enables λ1 through Right Sizing of the Turbo

Improvement in all Performance Vectors @ EU7 Boundary Conditions

5.1

2L Gasoline Case Study

- Engine Dyno

2L Gasoline Case Study

Engine Test | Full load - Steady-state

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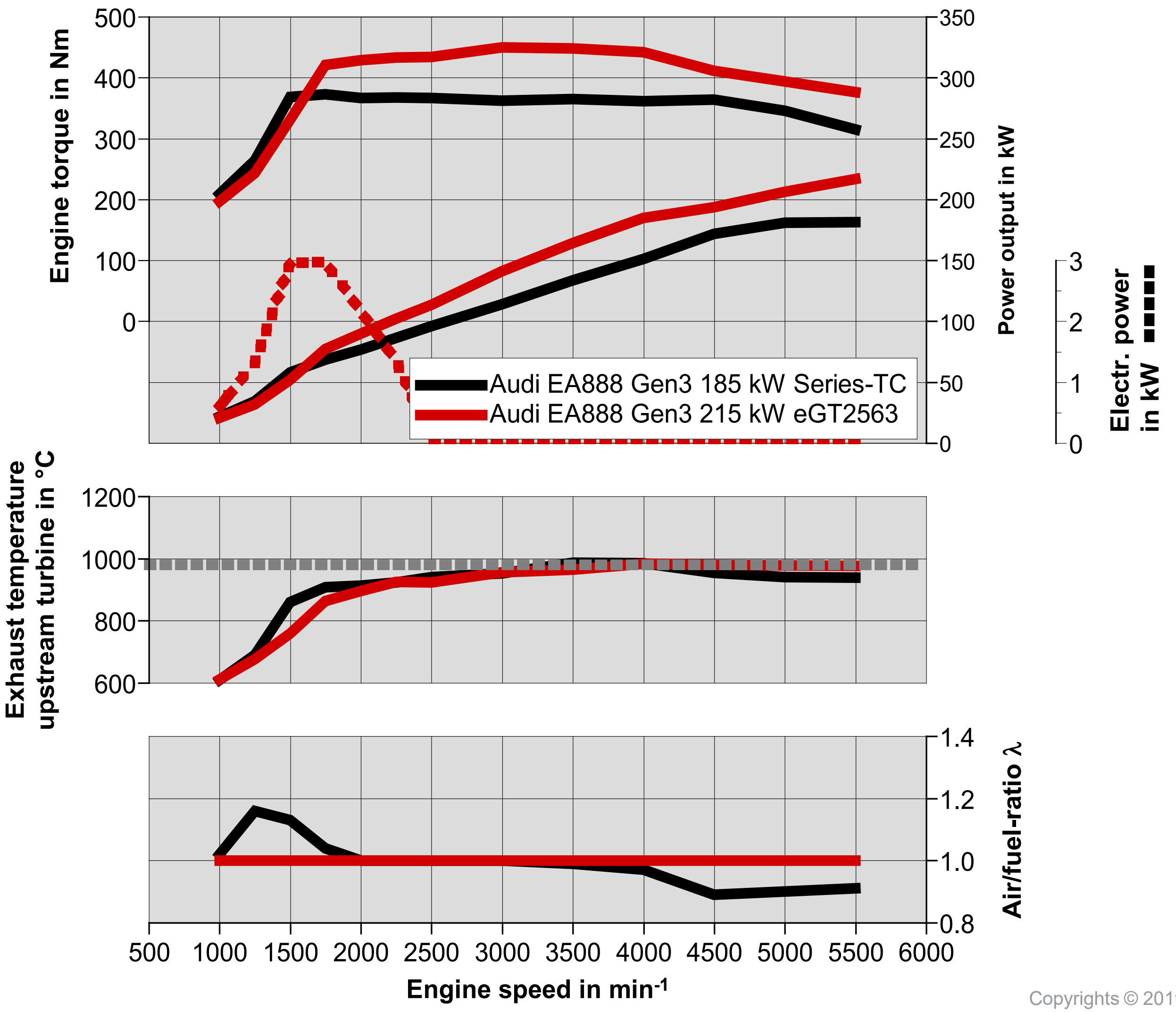
- **Baseline GT17 equiv.**
  - 380Nm & 185kW
- **eGT25 (3kW$_e$)**
  - Same LET
  - 420-450Nm mid range
  - 215kW rated power

@

  - λ1
    - no Scavenge
    - no Fuel Enrichment
    - while respecting T1T 980°C

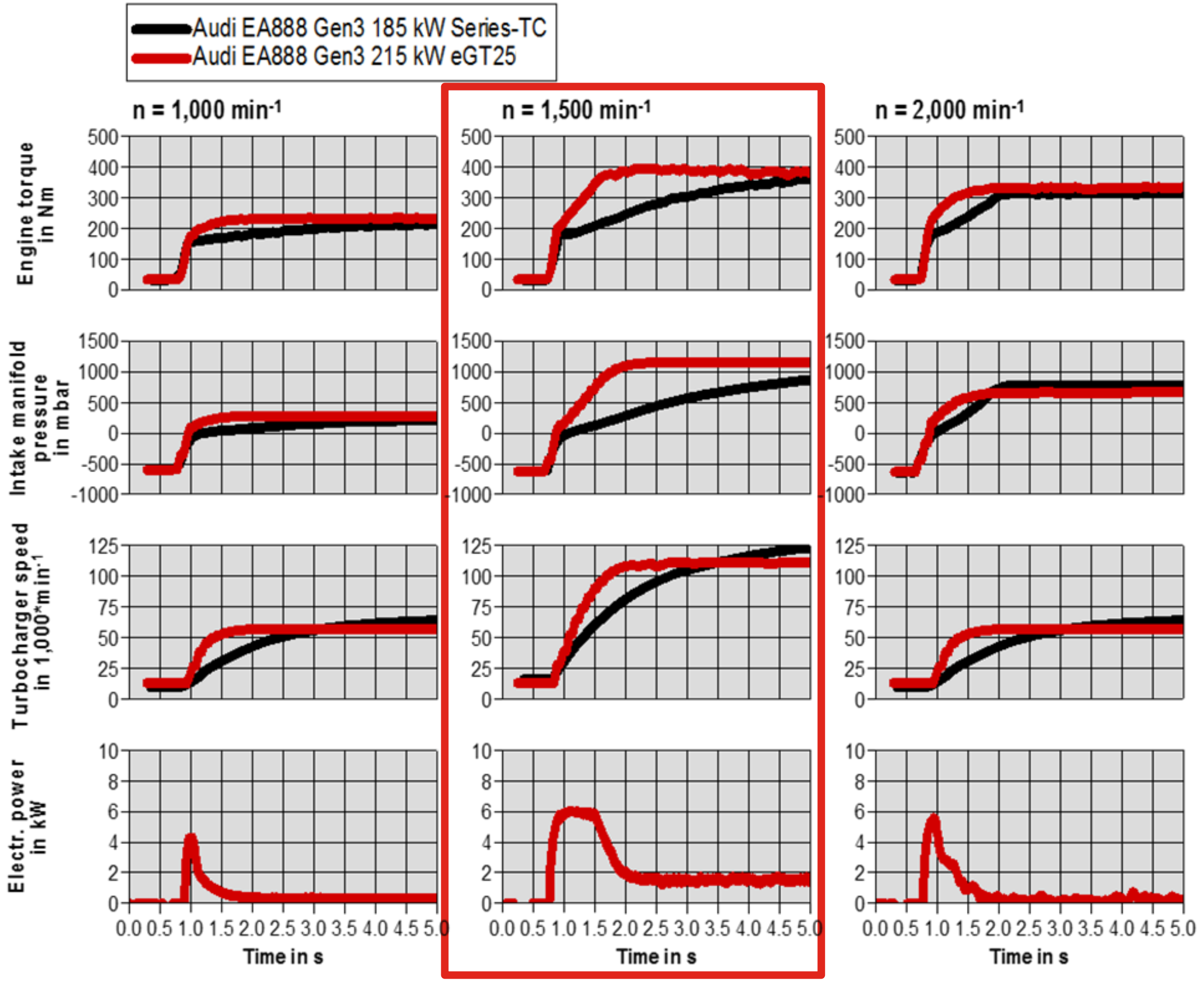


Same LET but more Torque & more Power @ λ1

2L Gasoline Case Study

Engine Test | Transient Load Steps

- **1500 rpm**
  - **Baseline equiv. GT17 @**
    - 20Nm/l.s @ 1500 rpm
    - t_{90} 4,5s
  - **eGT25 (6kW$_e$)**
    - 80Nm/l.s @ 1500 rpm
    - t_{90} 1s



Quasi NA load acceptance from Electric Turbo

5.2

2L Gasoline Case Study

- Demo Vehicle
  - Agility
  - Hill Climb

Audi Q7 2L EA888 with Garrett GT25 Electric Turbo

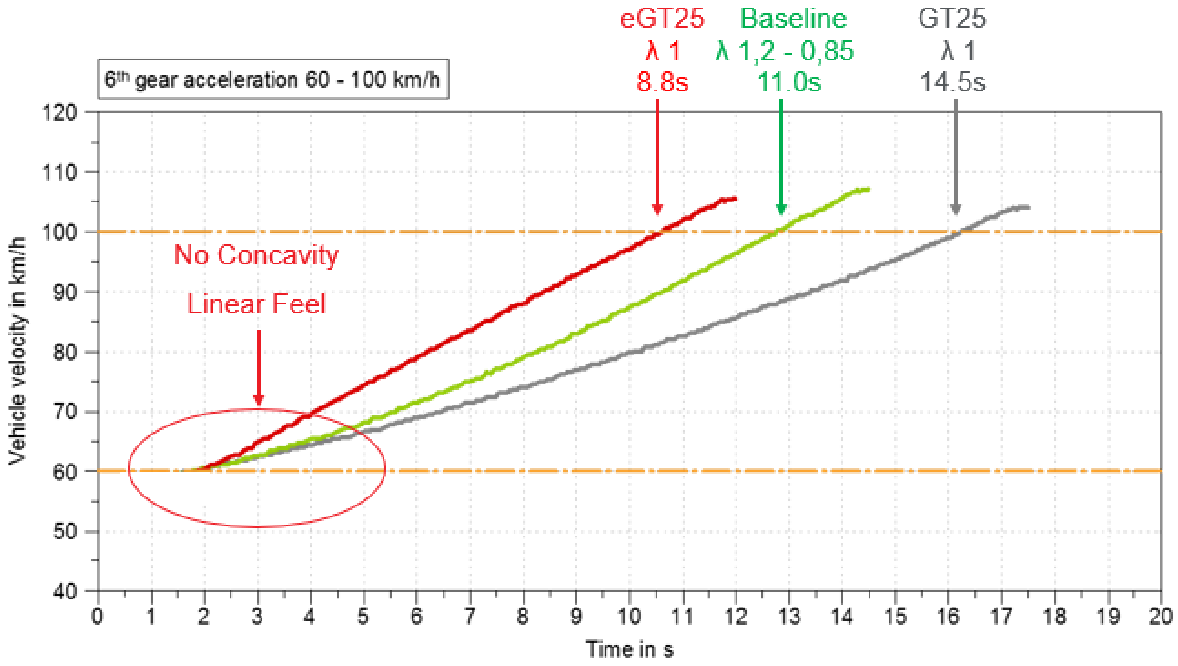
CENEX LCV, Millbrook, England | 11th September 2018

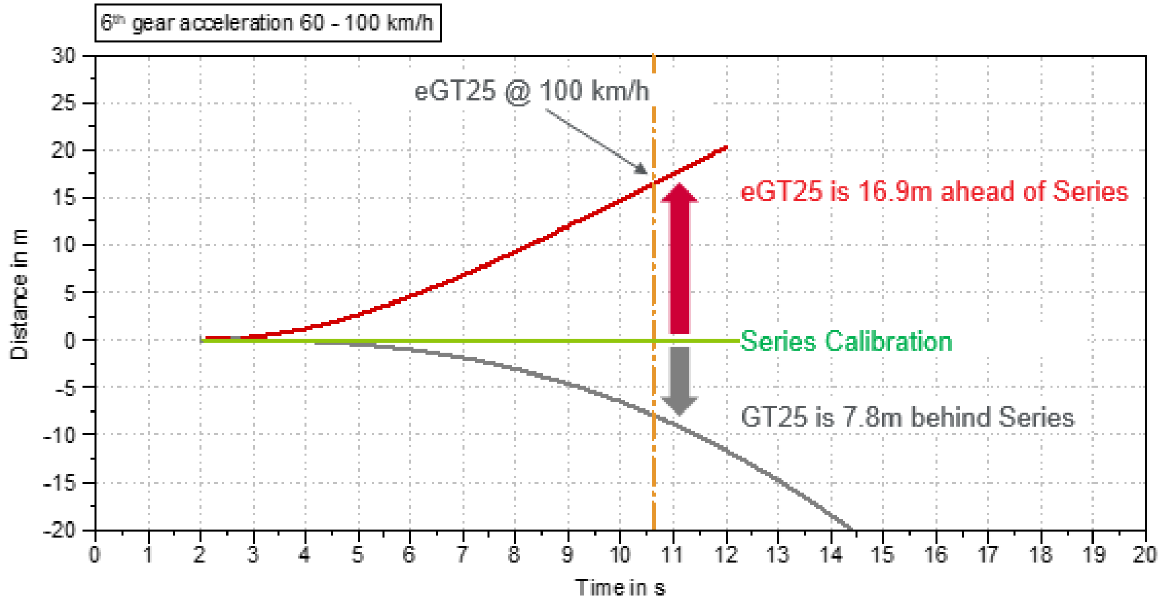
2L Gasoline Case Study

CENEX Millbrook | Fixed Gear Accelerations

2L Gasoline Case Study

CENEX Millbrook | Fixed Gear Accelerations





Significantly better Agility → 100km/h reached 17m ahead of Series Car

5 | 2L Gasoline Case Study

CENEX Millbrook | Fixed Gear Accelerations

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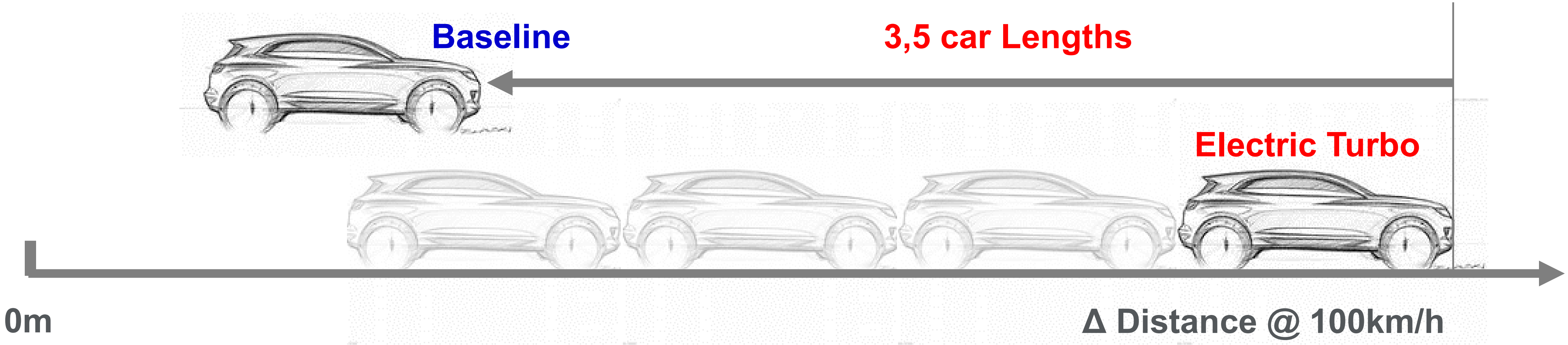
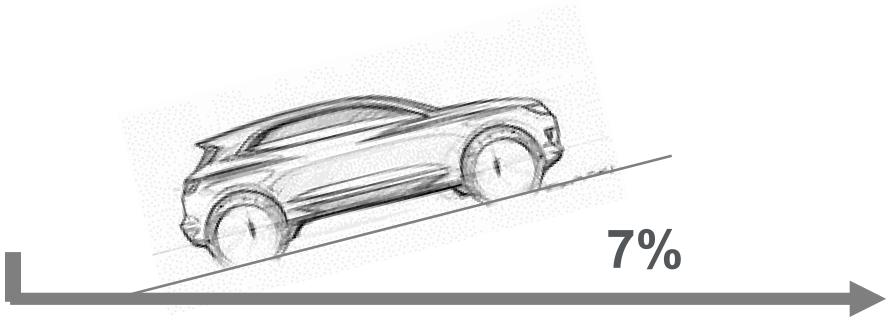
- High Speed Track 60-100 km/h in Manual 6 (M6)

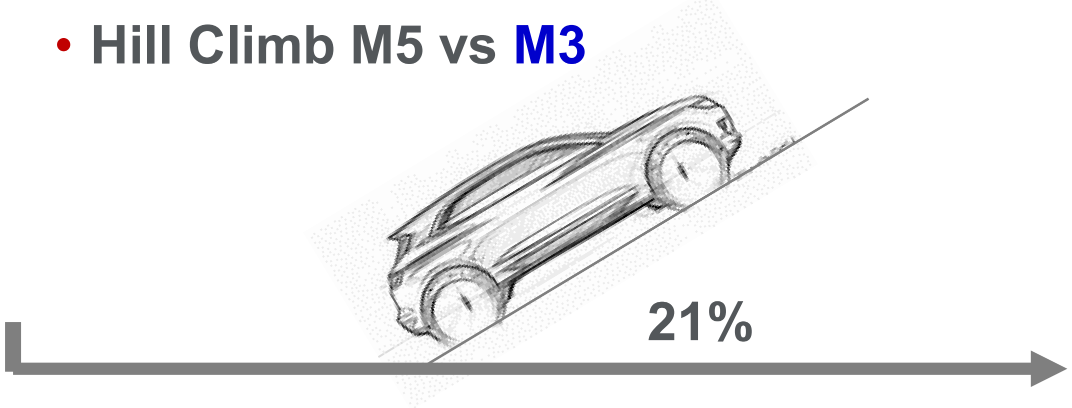


- Hill Climb M6 vs M4



17m is approximately 3,5 Car lengths

- Hill Climb M5 vs M3



Ability to accelerate in a higher gear | Highway & Mountains

5.3

2L Gasoline Case Study

- Demo Vehicle
  - Torque Consistency
  - Kinetic Energy Recovery

Torque Consistency

1500 vs 3250 rpm

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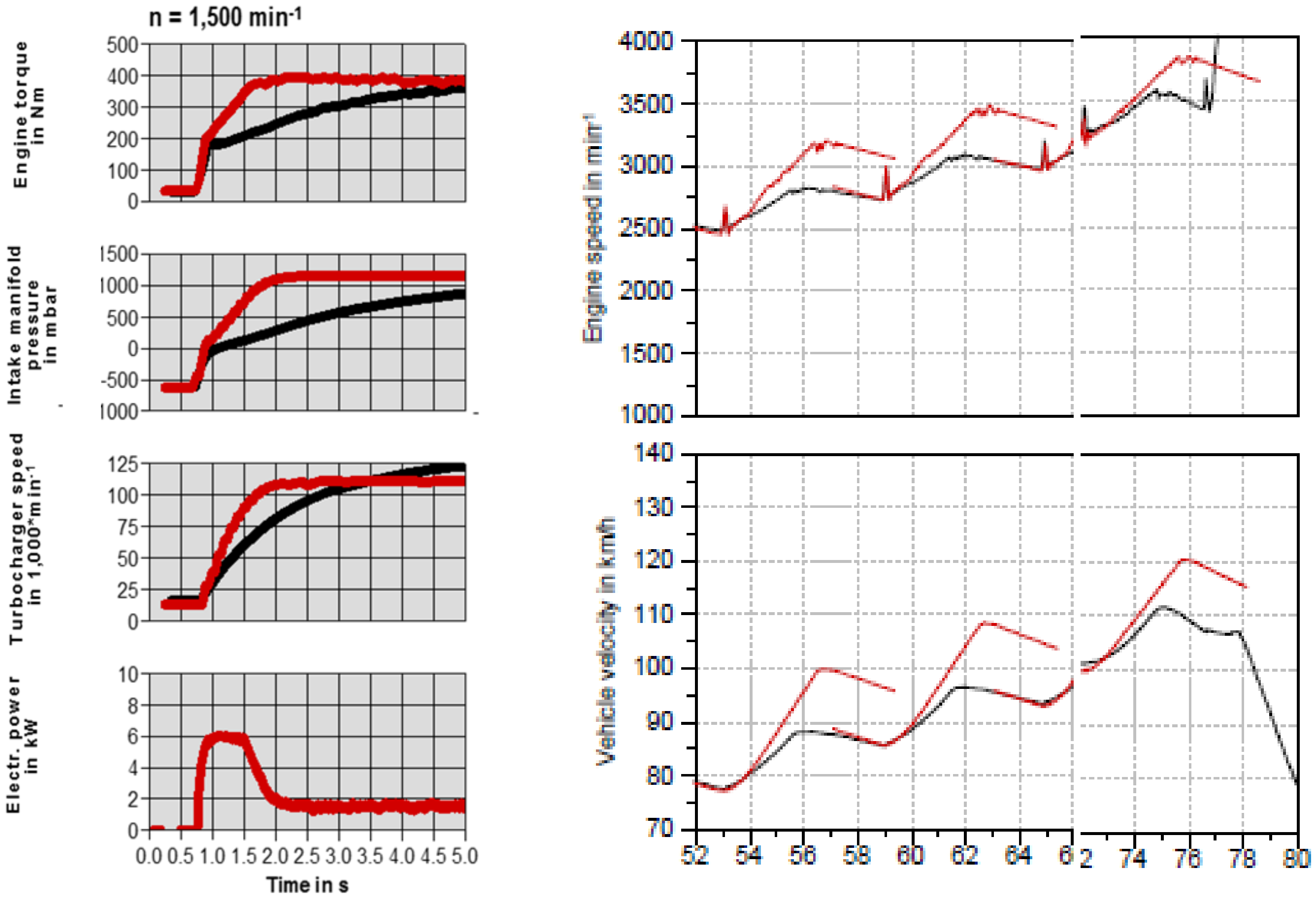
- < 2500rpm VIC Closed
- > 2500rpm VIC Open

- Electric Turbo boosts at 1500rpm

- Excellent acceleration at 2500rpm through to 3250rpm

- 6kW/Turbine Power becomes smaller as speed increases

Engine | **Vehicle**



Able to add eMotor Power across the full speed range

5 Kinetic Energy Recuperation

Tip in / Tip out

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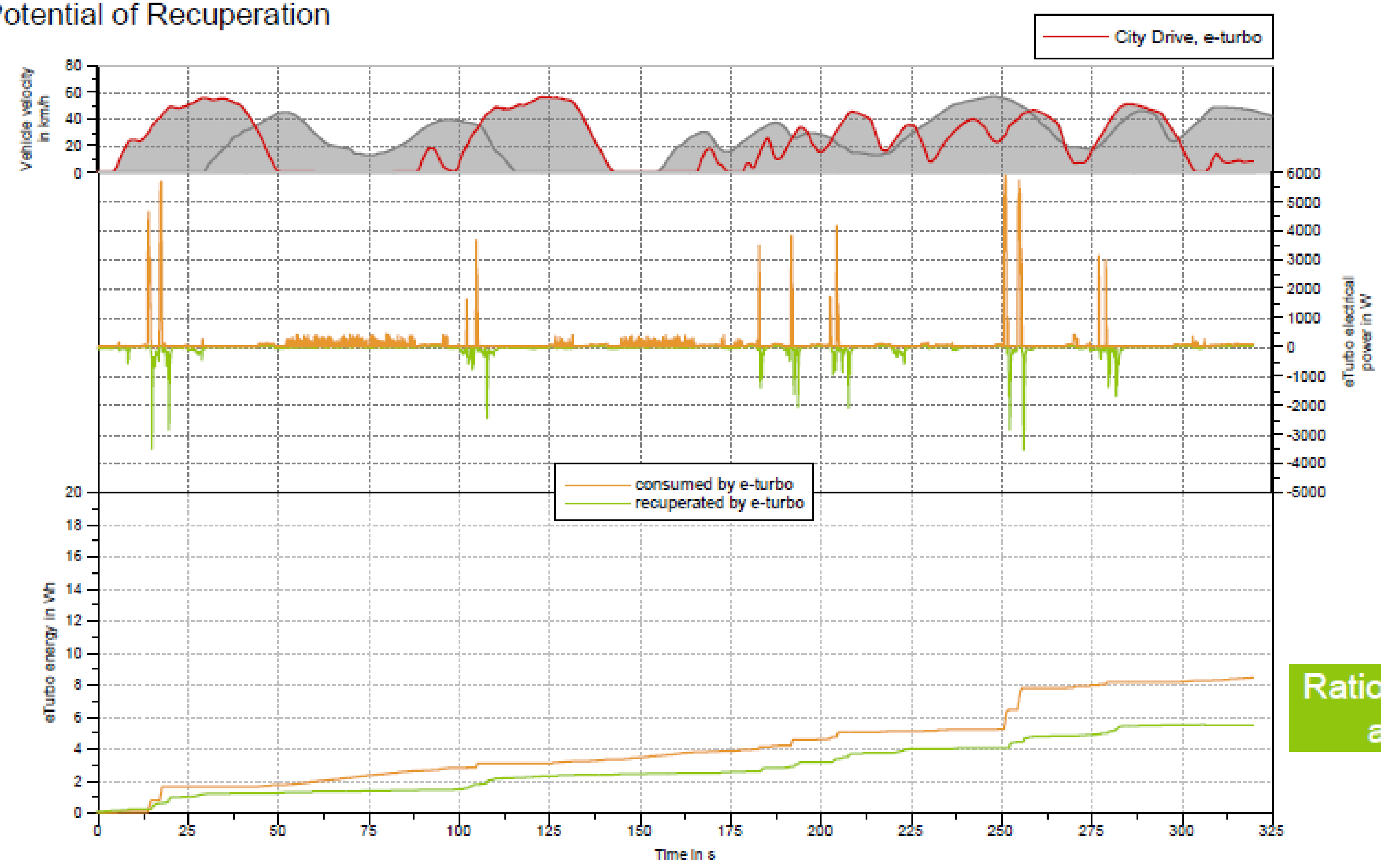
48V System – Potential of Recuperation

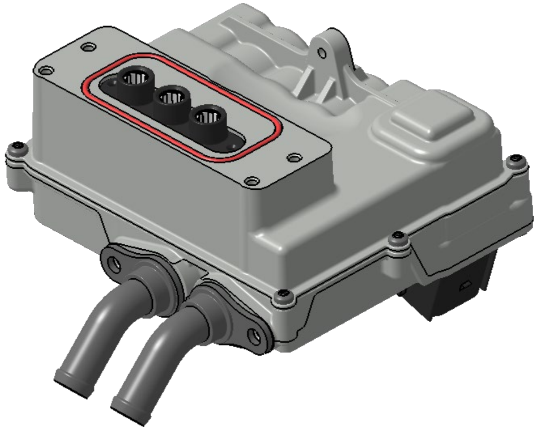


Ratio of recuperation: approx. 60 %

Current Status - 60% of Energy Input recovered in City Driving (more potential)

6

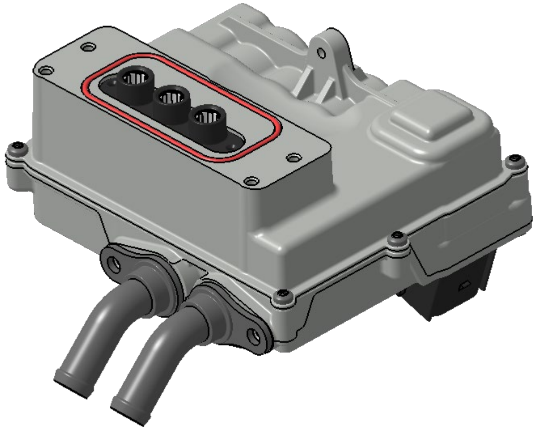
Conclusions & Next Steps



6 Conclusions

EU7 Mainstream Concept

- Lambda 1980°C Full Map
- 16% Power vs Baseline
- 10,5% Torque vs Baseline
- 4x Torque Gradient at 1500 rpm
- Torque Consistency across Speed Range
- > 60% Kinetic energy recovery in a Tip Out



Conclusions

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It has been shown that a correctly sized electrified turbocharger can provide a route for OEM's to meet the engineering challenges of EU7, particularly the requirement to respect Lambda 1, while still improving the performance of their powertrains further.

The benefits shown here are additive to any tendency to convert such vehicles to Mild or Plug-in hybrids.

An electrified turbocharger can therefore be considered as a complementary technology to hybridization, which essentially is a plug & play technology on top of vehicle hybridization, it is compatible with millerization, Variable Geometry Turbines and EGR solutions.

The technology will not be a consumer of electricity from the Vehicle Electrical Network, on the contrary, it will become a net contributor to SOC.

GTX Portfolio

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GT15-17	GT22-30	GT35-45
3.5/1.75kW – 48V	**6.0/3.0kW 48-400V**	**15-35kW 400-700V**
1.2 - 1.5L Gas	2.0L - 3.0L Gas	Heavy Duty On-Highway
2.0L Diesel	3.0L Diesel	Medium Duty On-Highway
Light Commercial Vehicle	LCV & Small Off-Highway	Off-Highway

Expanding Portfolio to new sizes and segments

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Thank you for your attention !