Alain LEFEBVRE
RENAULT POWERTRAIN DIVISION
LARDY TECHNICAL CENTER
alain.a.lefebvre@renault.com

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GT Power simulations on a small two-stage turbocharged engine

GT Power user conference - Frankfurt – October 2005

Presentation overview

Introduction

- Why a two-stage turbocharged engine ?
- Engine and model description

Engine performances at full load

- Influence of the LP turbocharger on power
- Influence of the LP turbocharger on low end torque
- Influence of the LP turbocharger under transient conditions

Engine design at part load

- Calculation methodology
- Influence of the HP turbocharger on EGR rates

Conclusions

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Use of a two-stage turbocharged engine

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ACEA agreements …

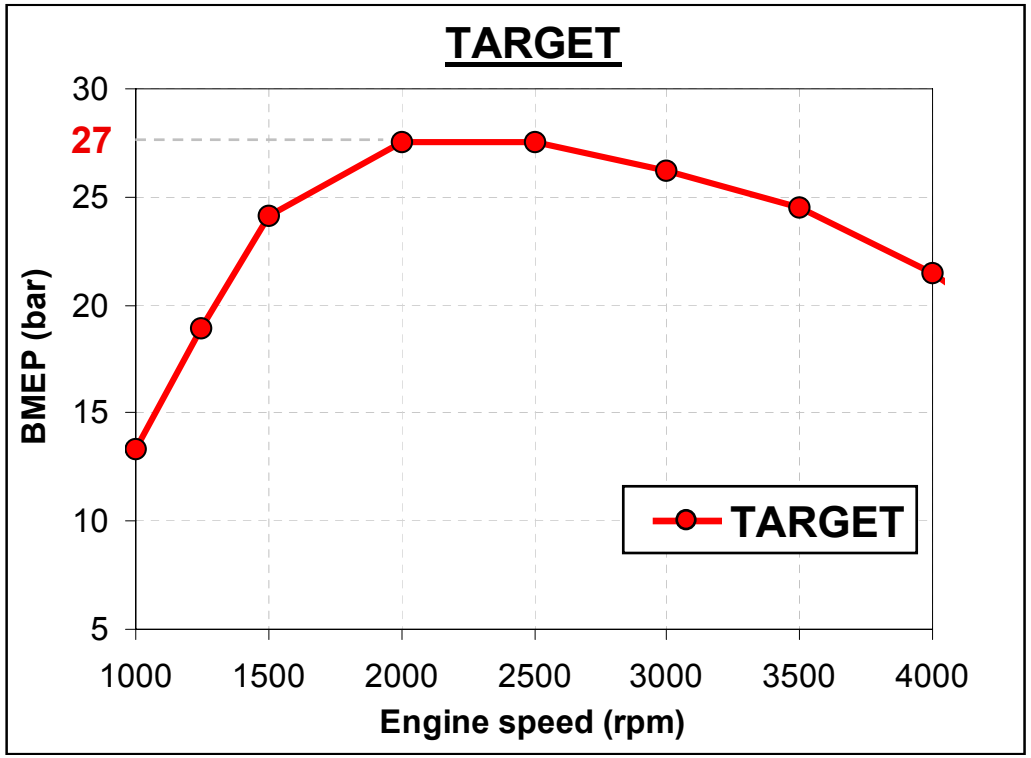
- ACEA agreement : CO_2 emissions should be reduced to
  140g/km in 2010
  120g/km in 2012
- A way to reduce the engine consumption is to reduce the size of the engine. This solution is called ***downsizing***
- turbocharger is used to keep engine performances in spite of a lower engine capacity under ***steady-state and transient conditions***
- ***two-stage turbocharging*** can be a response for the ***high downsizing*** of a Diesel, already turbocharged engine

… and european norms

g/km	Euro 1 (1993)	Euro 2 (1996)	Euro 3 (2000)	Euro 4 (2005)	Pollutant Emissions	Euro 5 (2008)	Euro 6 (?)
CO	2.72	1	0.64	0.50	↓ -82%	0.50	
NO_x			0.50	0.25		0.20	?
$HC+NO_x$	0.97	0.7	0.56	0.30	↓ -69%	0.25	
Soot	0.14	0.08	0.05	0.025	↓ -82%	0.005	

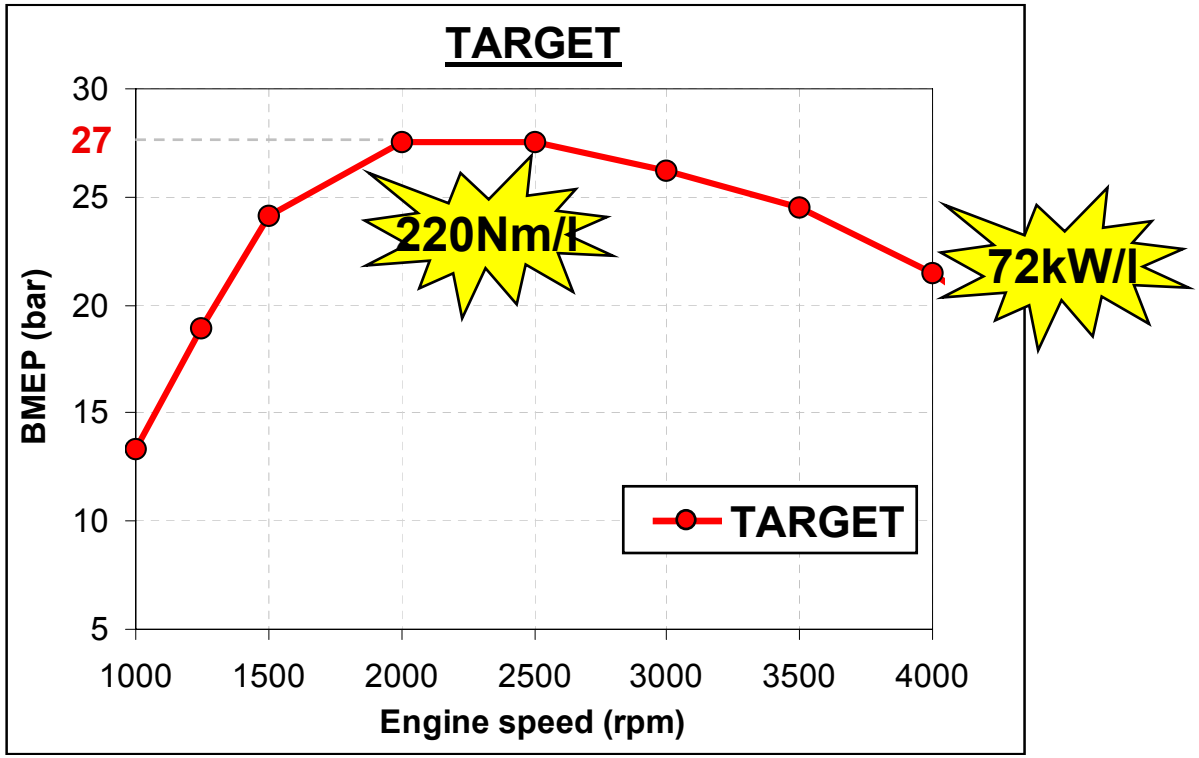
- Polluant emissions have been drastically reduced since the beginning of the 90's and will have to be still reduced in the coming years
- NOx emissions will have to be decreased
- One way to ***reduce NOx emissions*** is to ***increase the EGR*** rates
- ***two-stage turbocharging*** is one way to reach such ***high EGR levels***

Small two-stage engine target



- RENAULT's target : to reach 72kW/l and 220Nm/l with a smaller engine capacity (downsizing level=25%)

Small two-stage engine target



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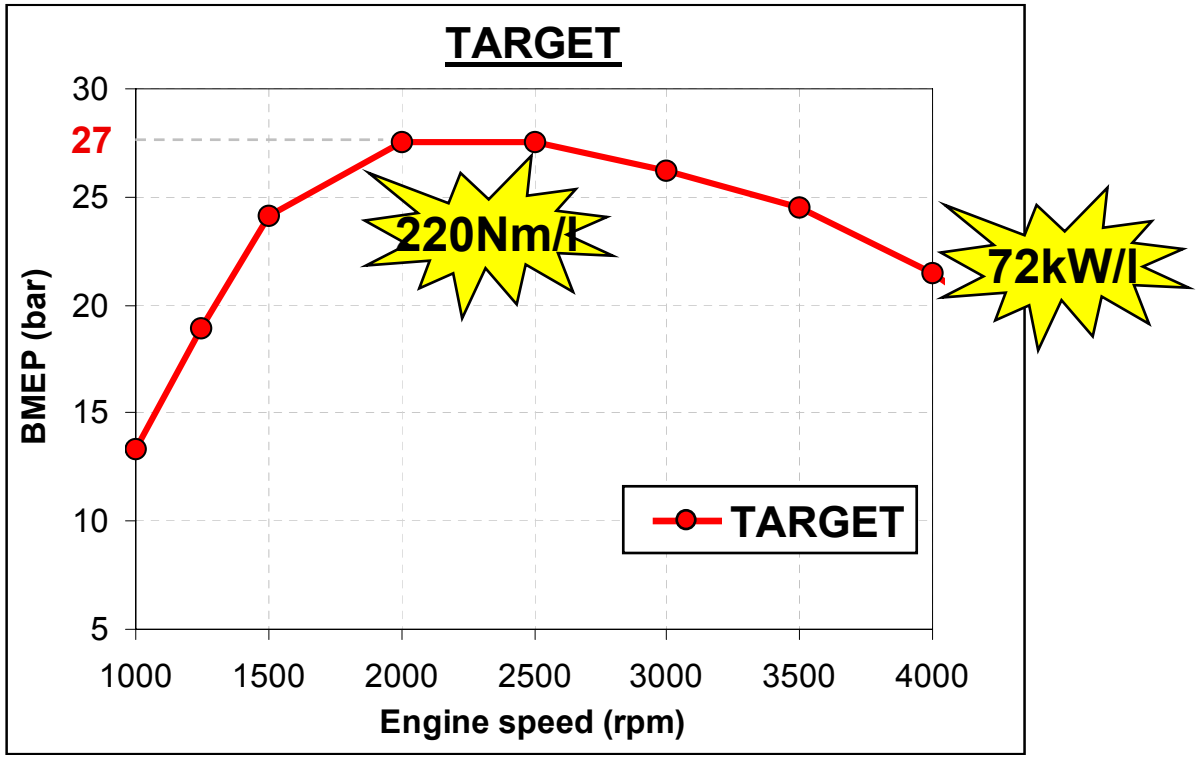
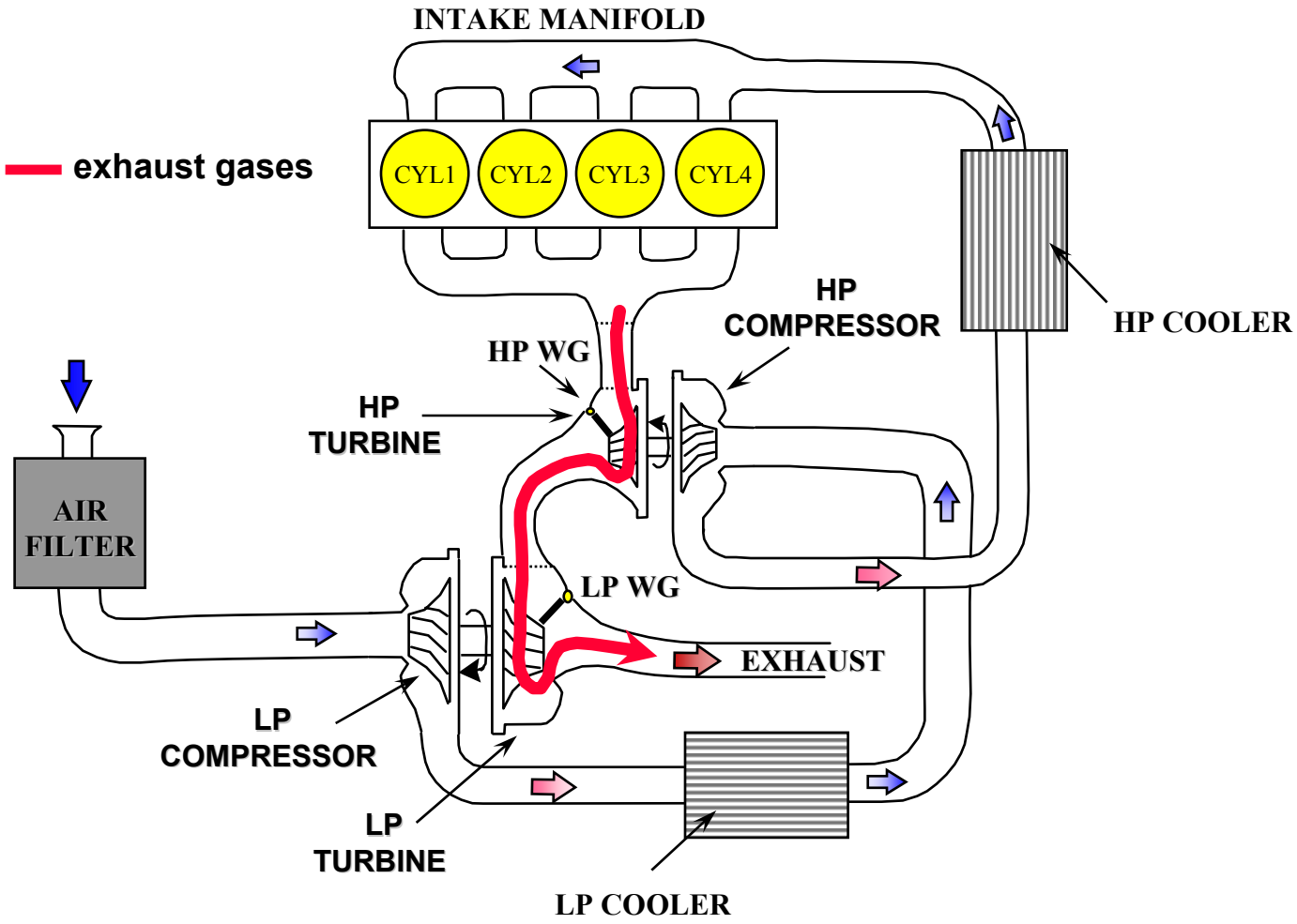


- RENAULT's target : to reach 72kW/l and 220Nm/l with a smaller engine capacity (downsizing level=25%)
- To reach ***performances similar*** to the engine to replace, under ***steady and transient*** conditions, in spite of a lower engine capacity and smaller turbochargers with ***lower*** turbine and compressor ***efficiencies***

Small two-stage engine schematic



- Exhaust system in ***serial mode*** *type*

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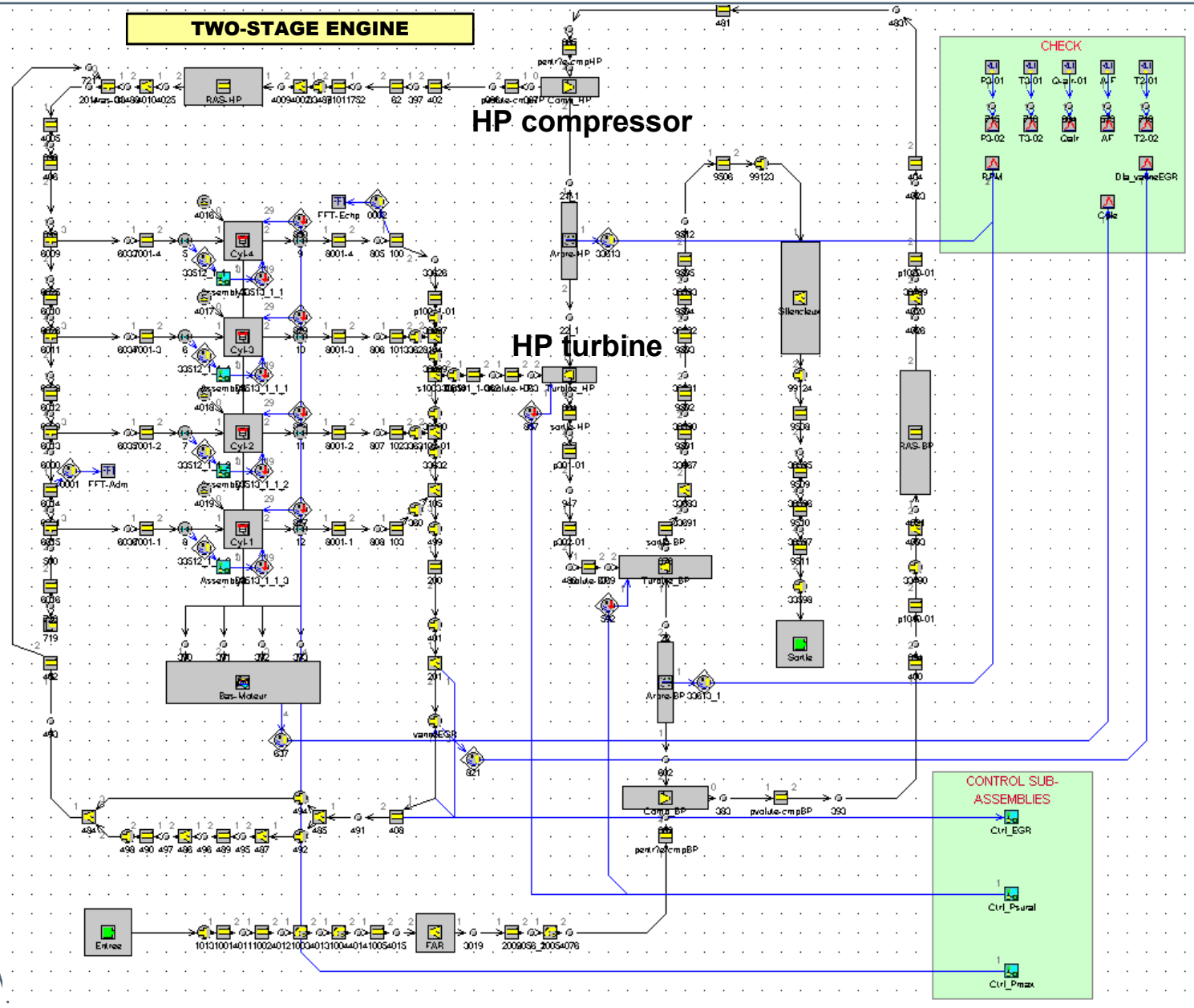
Small two-stage engine
GT Power model



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TWO-STAGE ENGINE

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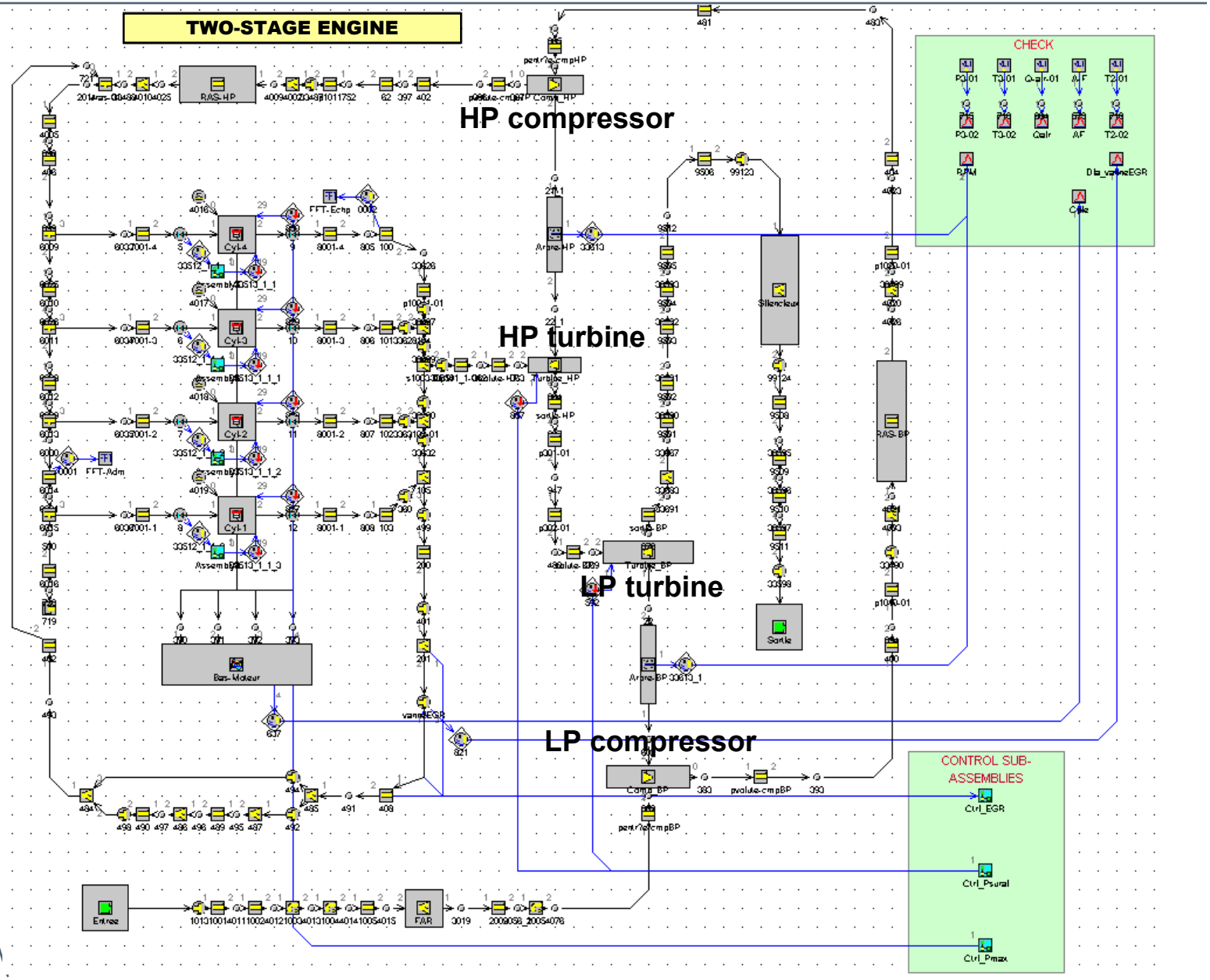
Small two-stage engine
GT Power model



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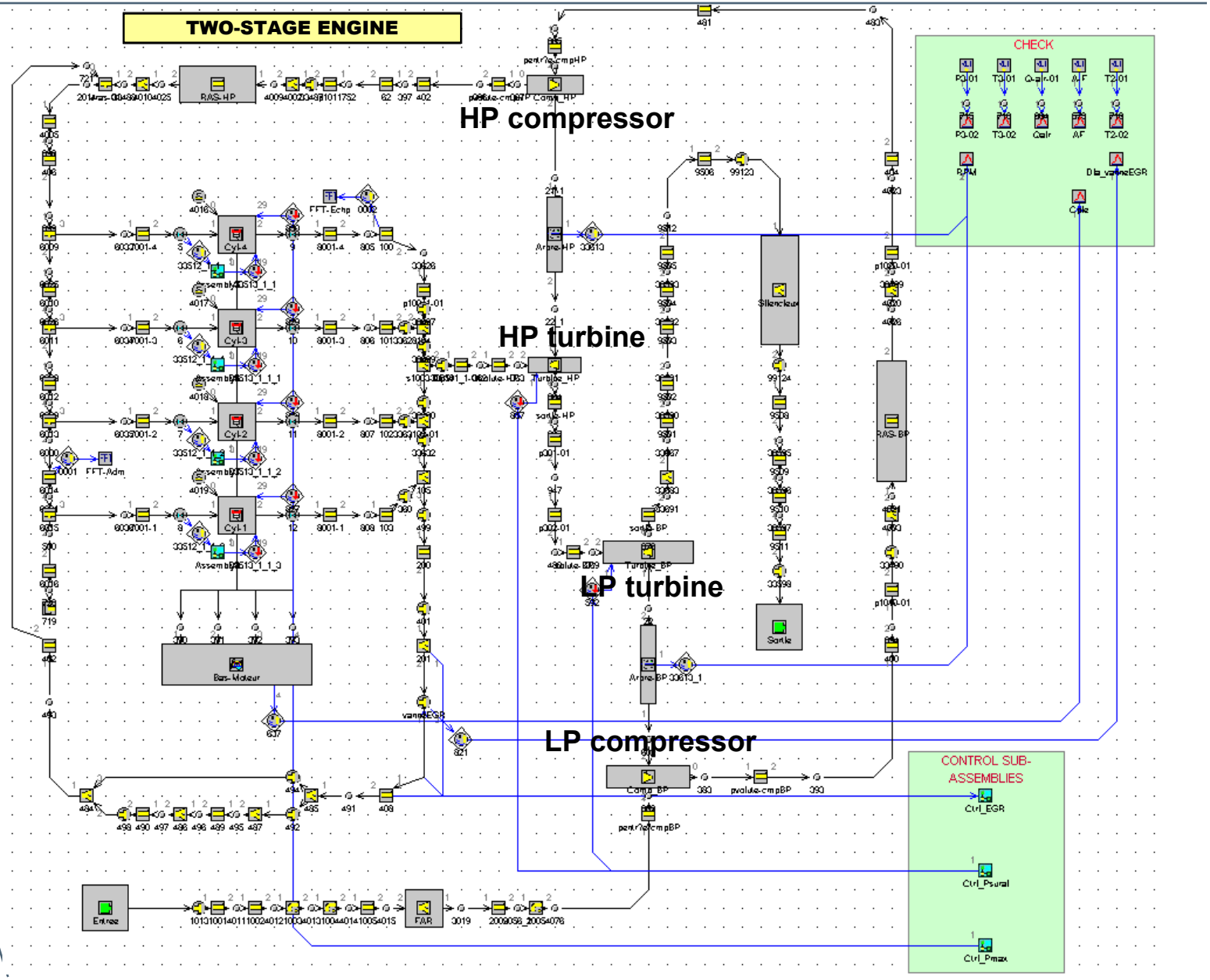

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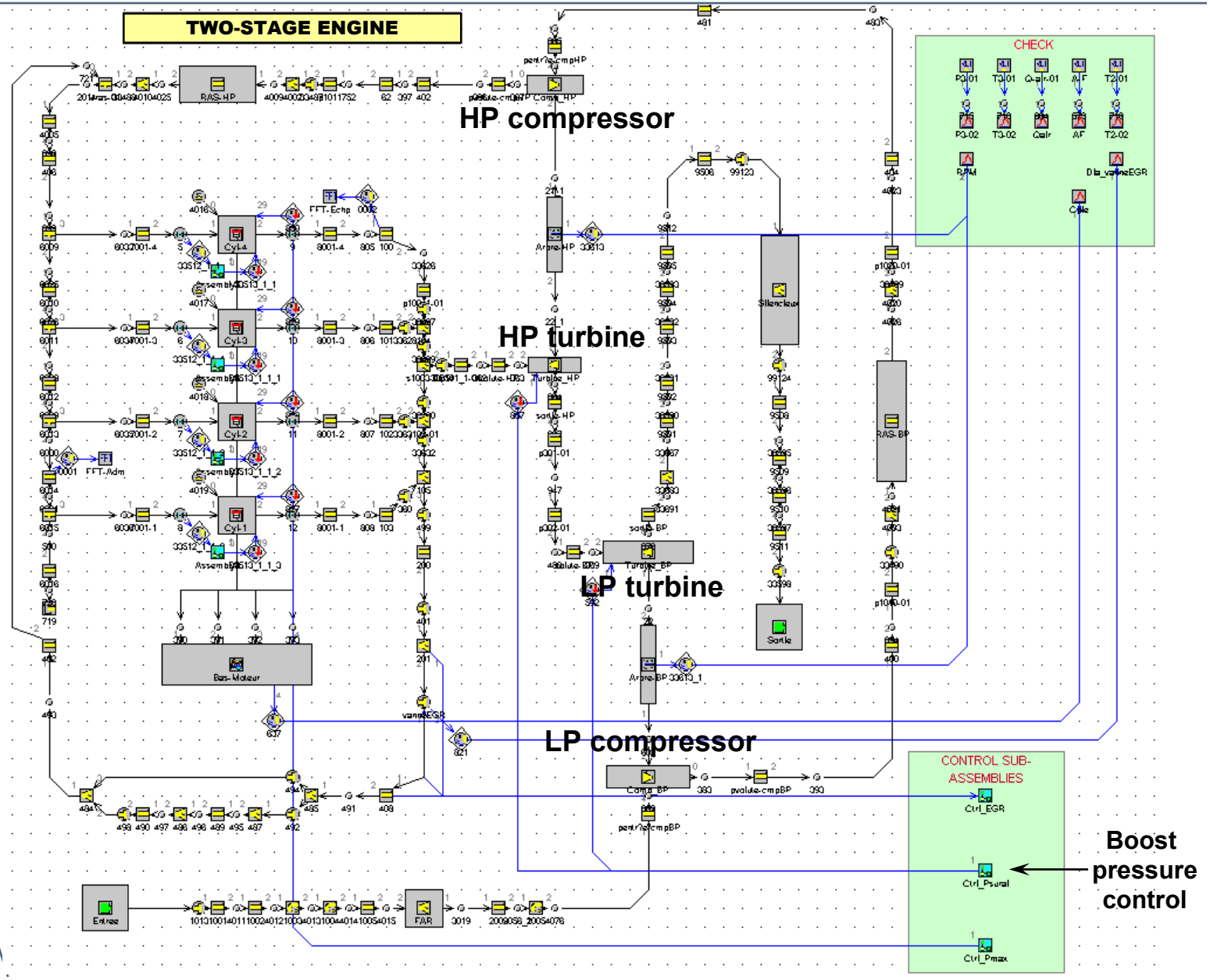

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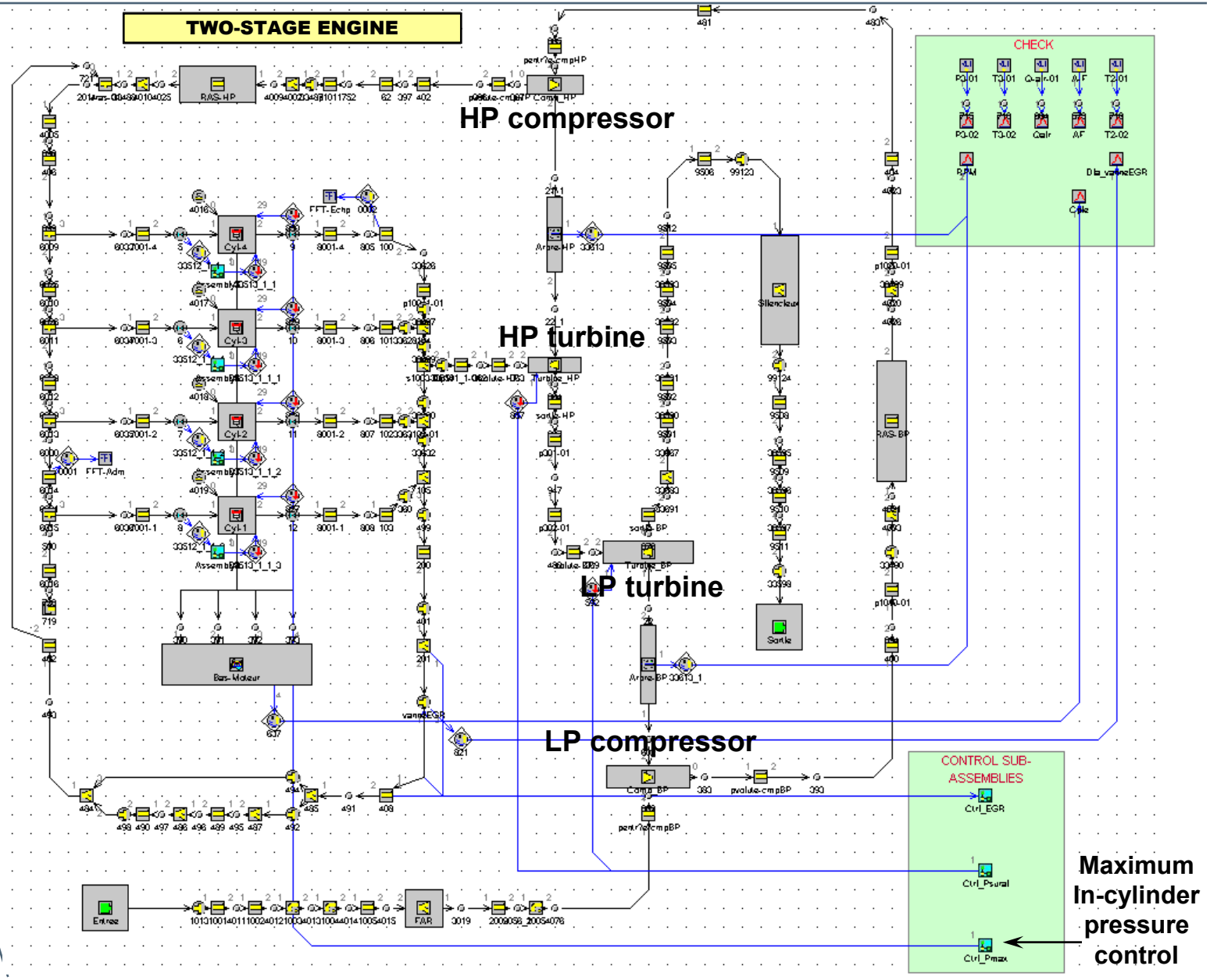

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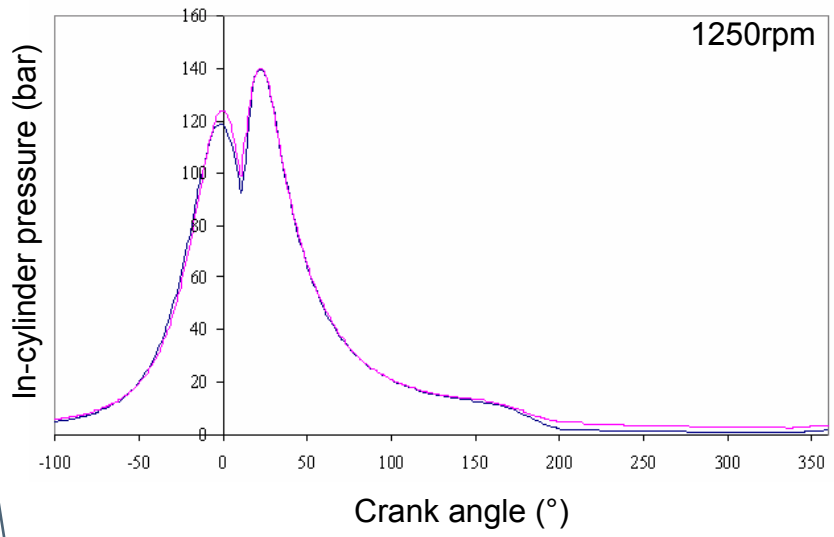
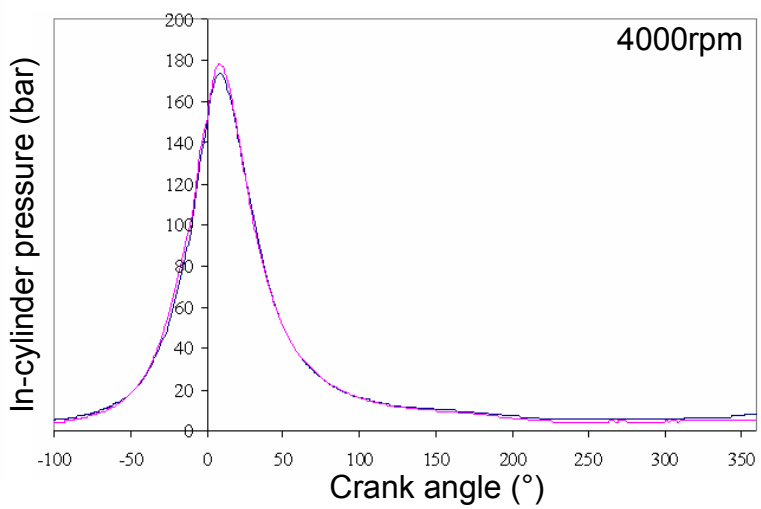
Small two-stage engine
GT Power model

- GT Power model tuned at full load and steady state
  - pressure losses
  - combustion parameters
  - heat transfer coefficients (in-cylinder and exhaust)





- Good agreement on the entire speed range and especially at low and high engine speeds

Full load simulations

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Full load simulations

Influence of the LP turbocharger – 4000rpm

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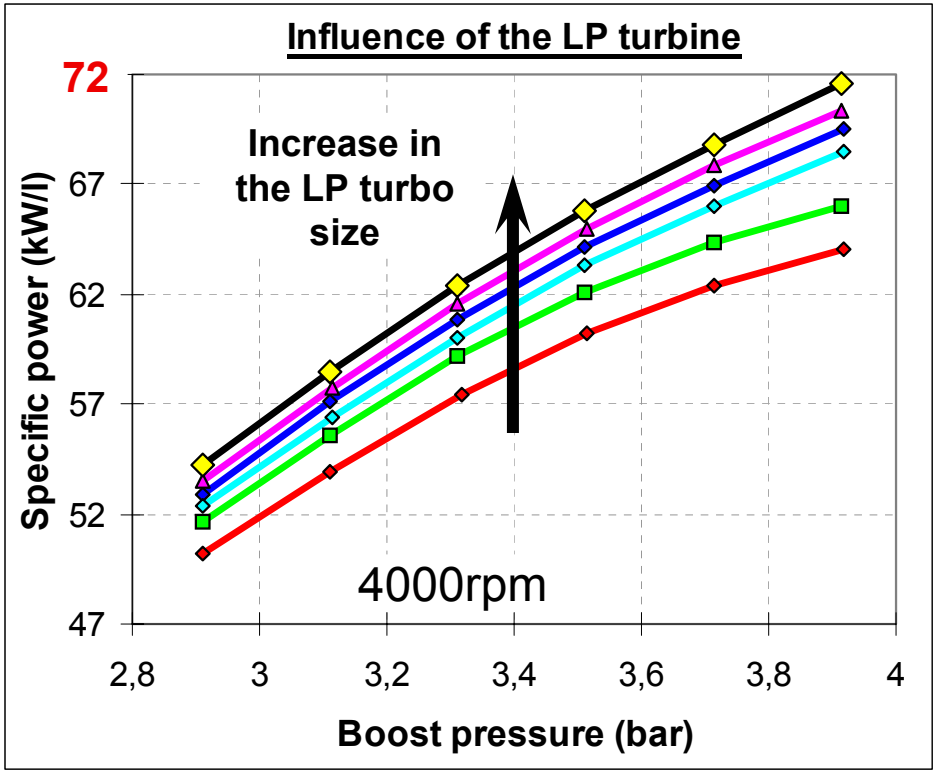
Full load simulations at 4000rpm
Influence of the LP turbocharger

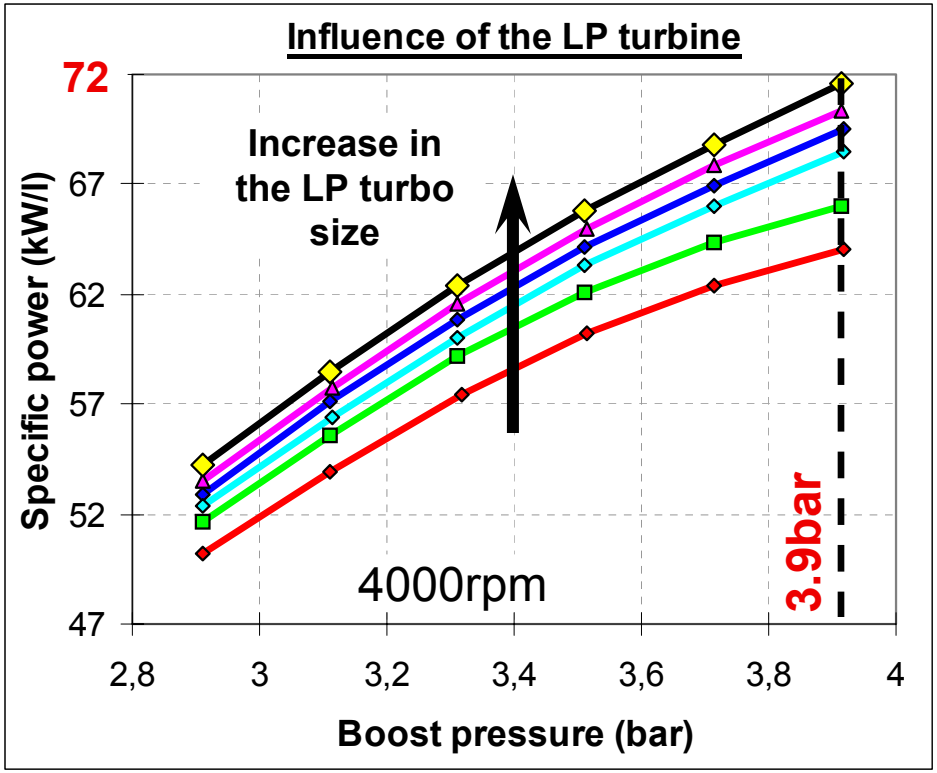


- maximum in-cylinder pressure = 180bar
- same air-fuel ratio

Use of a higher LP turbocharger size

72kW/l reached

Full load simulations at 4000rpm
Influence of the LP turbocharger



- maximum in-cylinder pressure = 180bar
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Use of a higher LP turbocharger size

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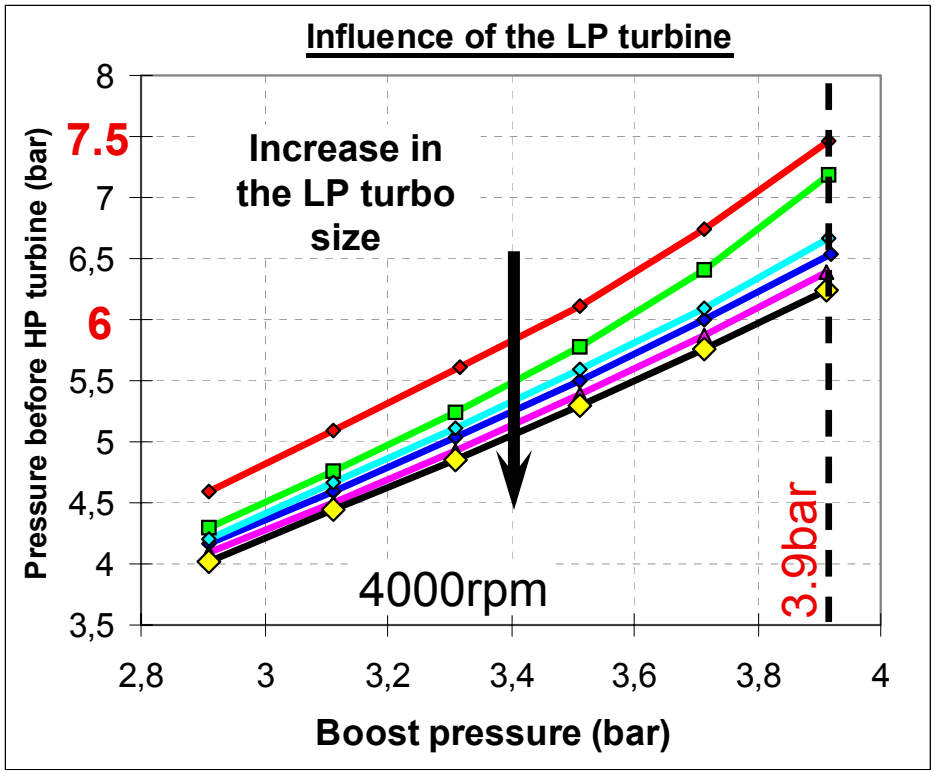
72kW/l reached

↓

but at the price of high boost pressures

Full load simulations at 4000rpm
Influence of the LP turbocharger



Use of a higher LP turbocharger size

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but at the price of high boost pressures

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high pressure before turbine levels

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Full load simulations at 4000rpm
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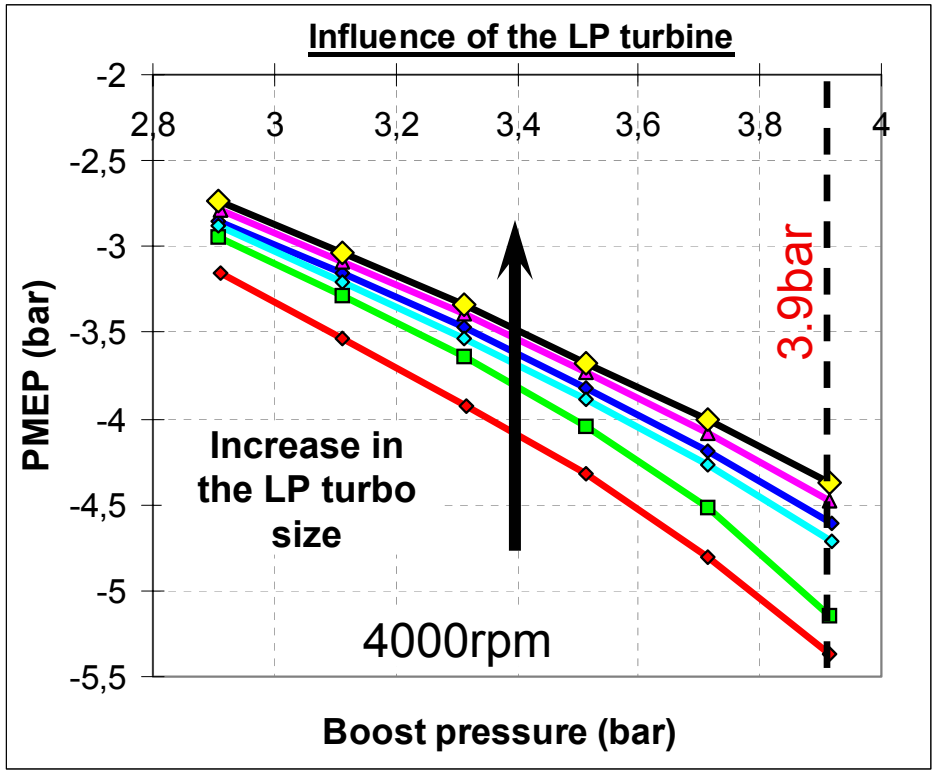

Use of a higher LP turbocharger size

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72kW/l reached

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but at the price of high boost pressures

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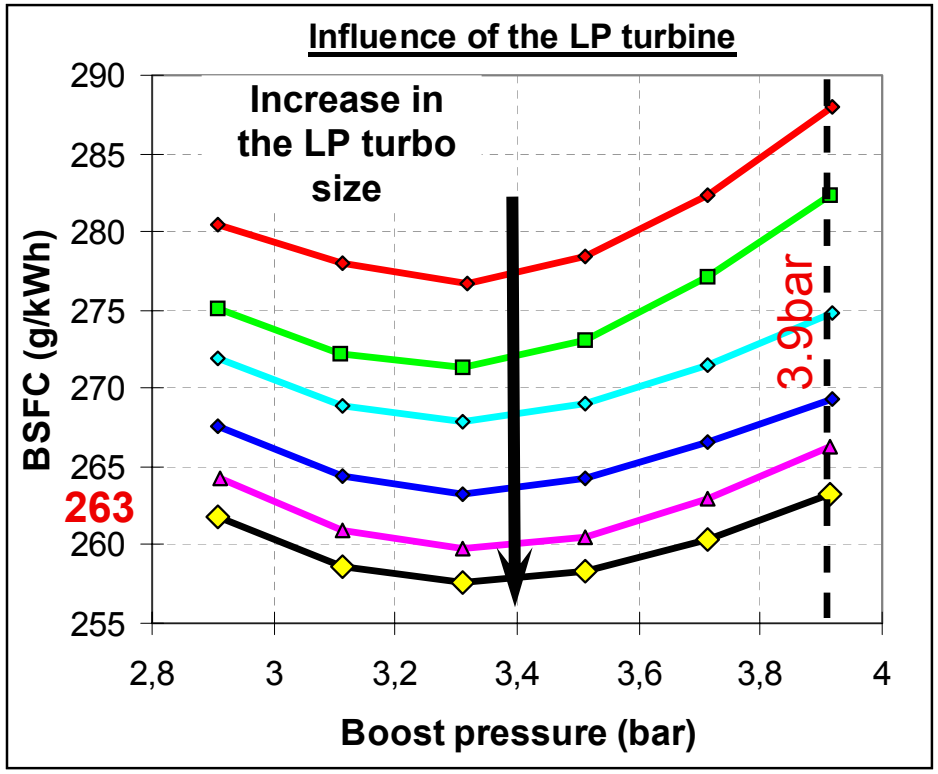
high pressure before turbine levels

↓

High pumping losses levels

Full load simulations at 4000rpm
Influence of the LP turbocharger



Use of a higher LP turbocharger size

↓

72kW/l reached

↓

but at the price of high boost pressures

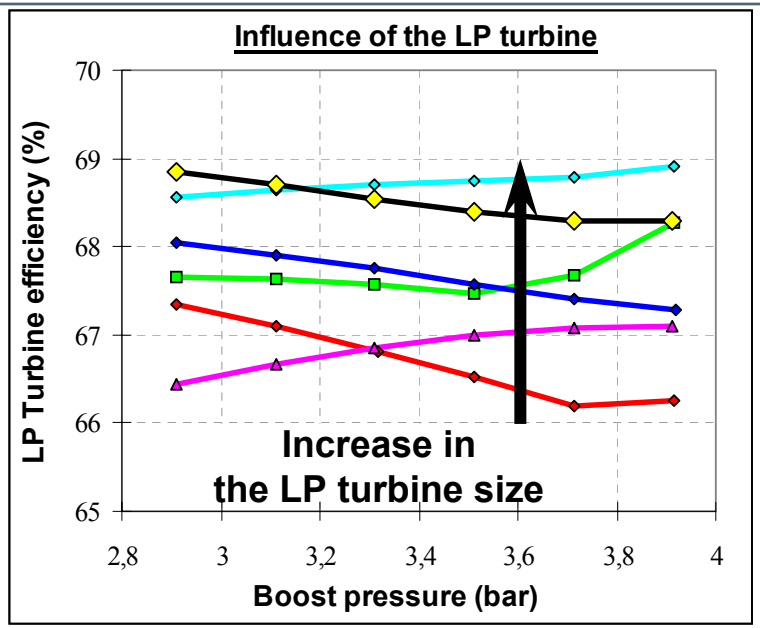
↓

high pressure before turbine levels

↓

Penalty in specific fuel consumption

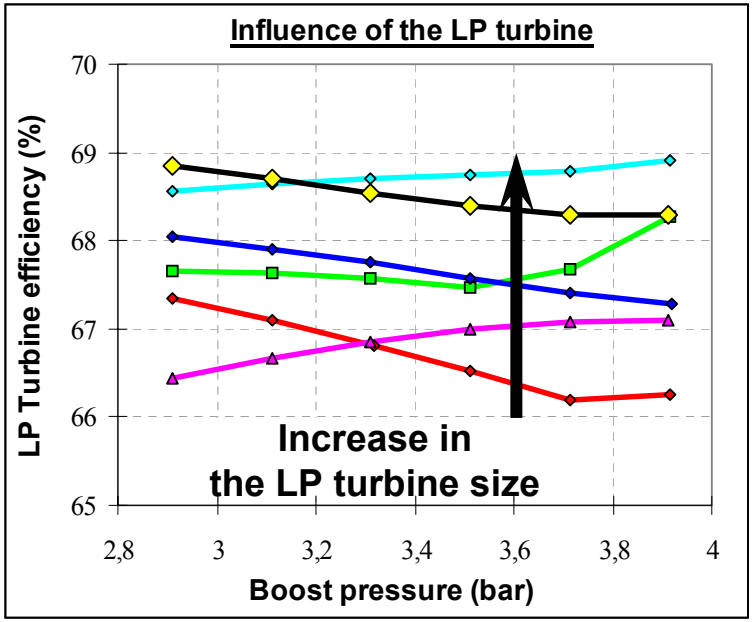
Full load simulations at 4000rpm
Influence of the LP turbocharger

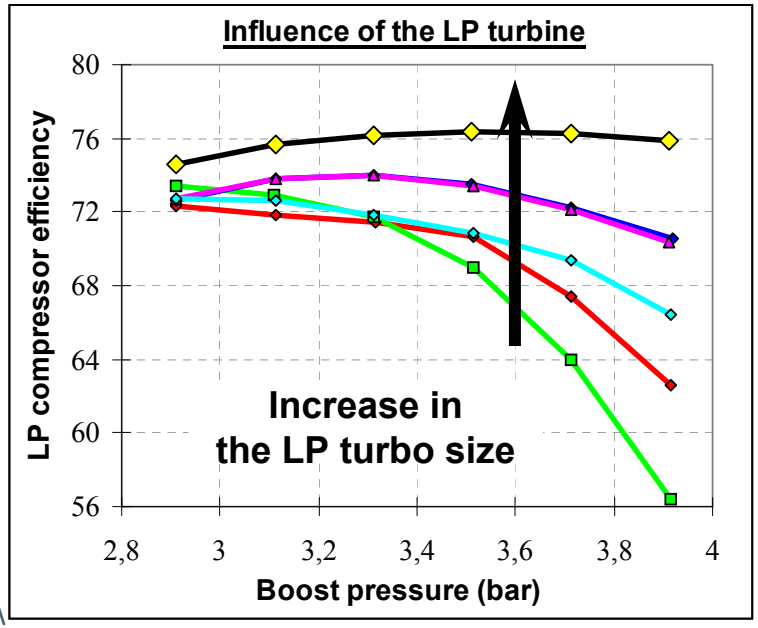


Positive effect of a higher LP turbocharger size

due to LP ***turbine efficiency***…

Full load simulations at 4000rpm
Influence of the LP turbocharger





Positive effect of a higher LP turbocharger size

⇩

due to LP ***turbine efficiency***…

⇩

…and LP ***compressor efficiency*** improvement

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Full load simulations
Influence of the LP turbocharger – low end

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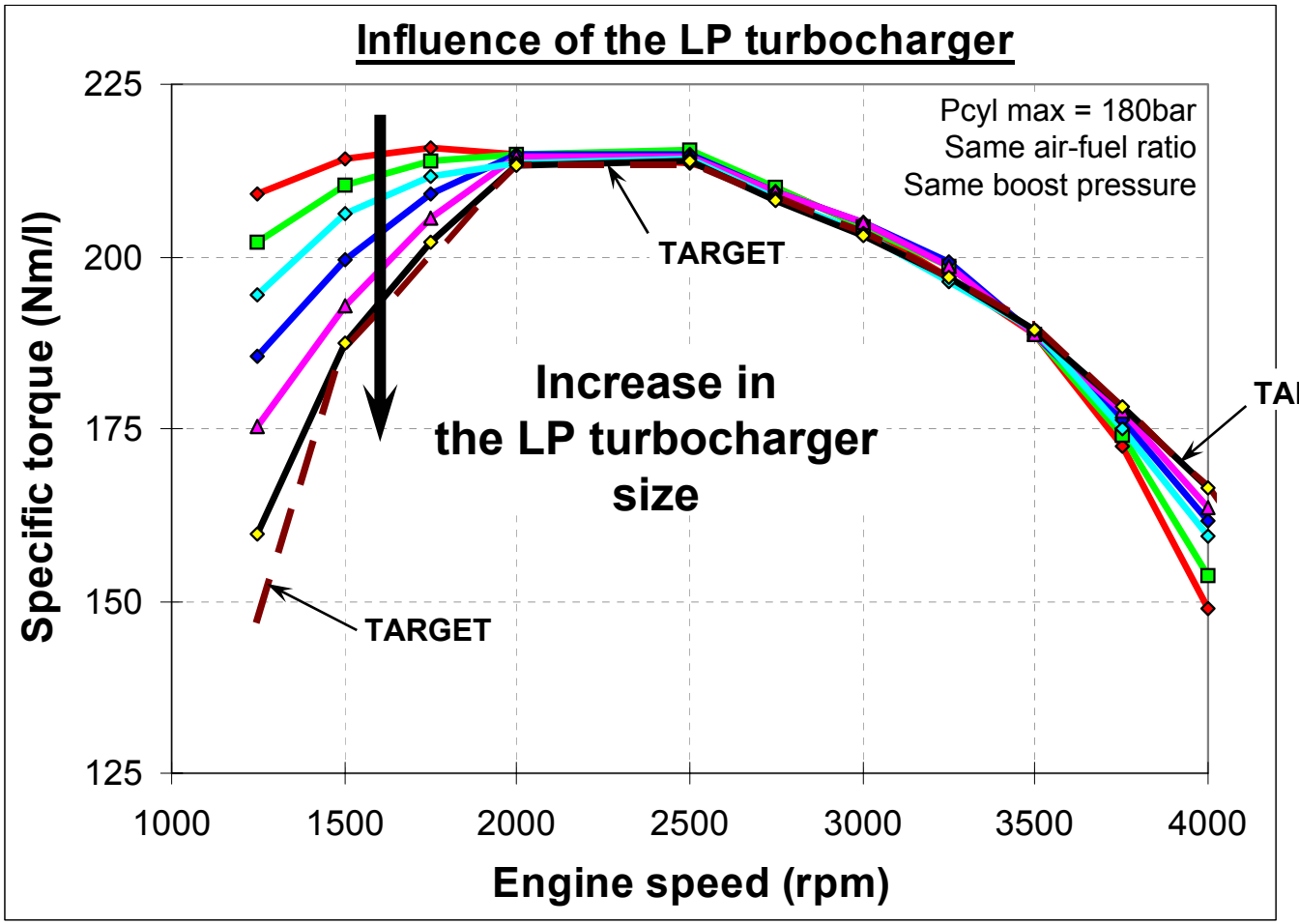
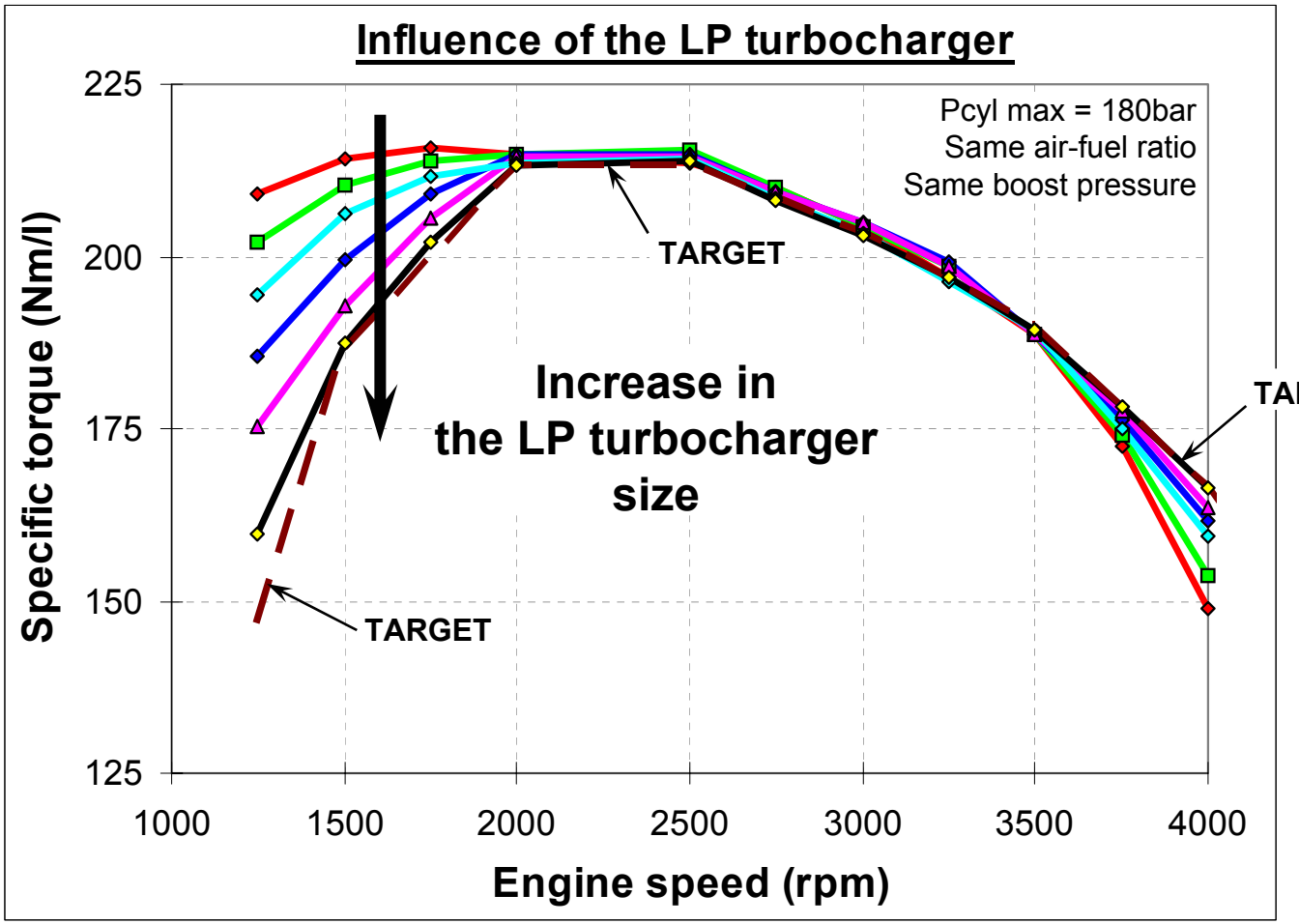
Full load simulations at low end
Influence of the LP turbocharger



- LP turbocharger size has also a strong ***effect on the engine performances even at low speed***

Full load simulations at low end
Influence of the LP turbocharger



- LP turbocharger size has also a strong ***effect on the engine performances even at low speed***
- ***Target reached*** on the entire speed range

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Full load simulations

Influence of the LP turbo – transient conditions

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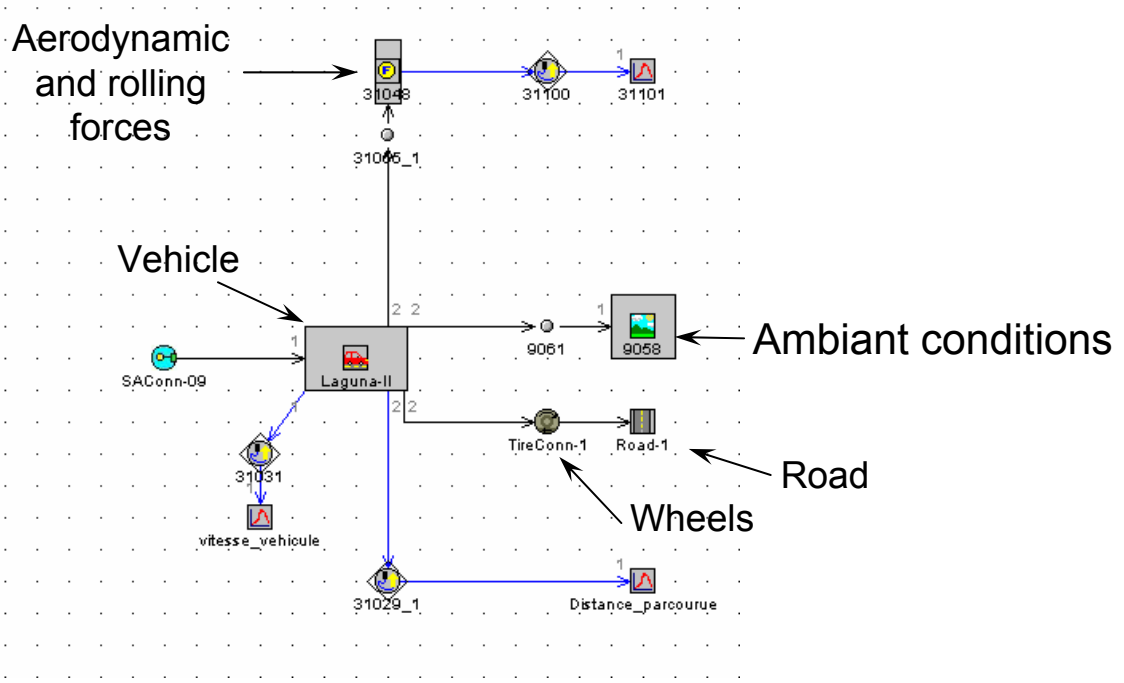
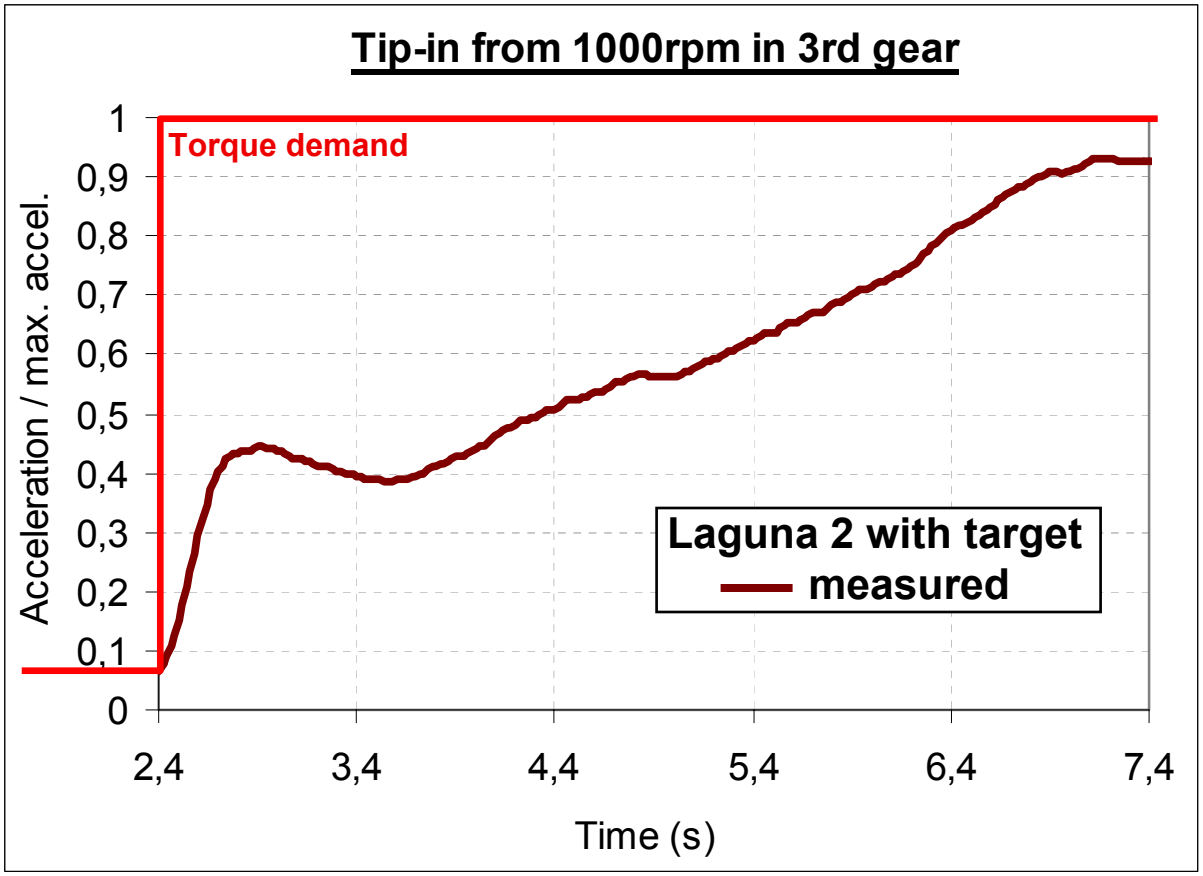
Transient simulations
Modelling

- GT Power model already tuned at full load and steady state
- Adapted according RENAULT's experience under transient conditions :
  - combustion parameters
  - in-cylinder heat transfer coefficients
- Vehicle model based on a *LAGUNA 2* with the engine to replace (target engine)

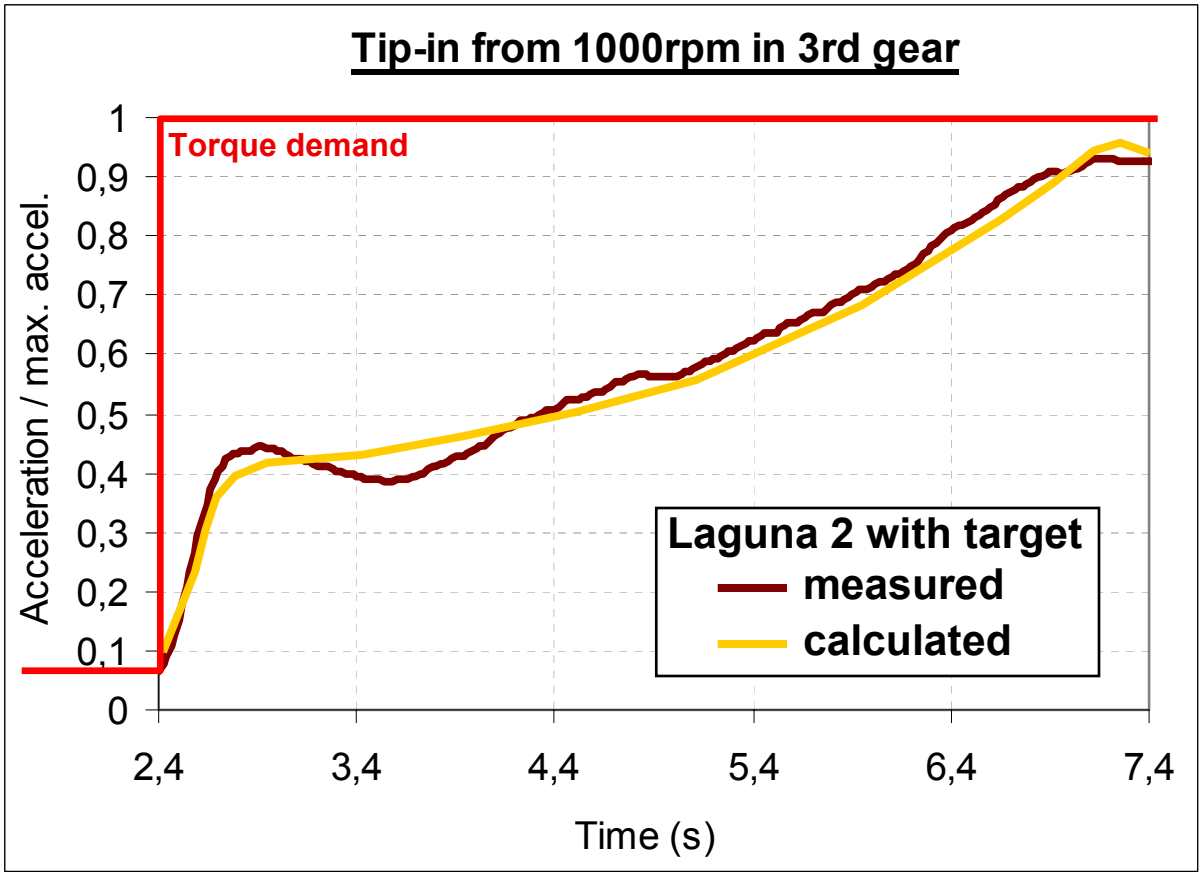


Transient simulations
Influence of the LP turbocharger



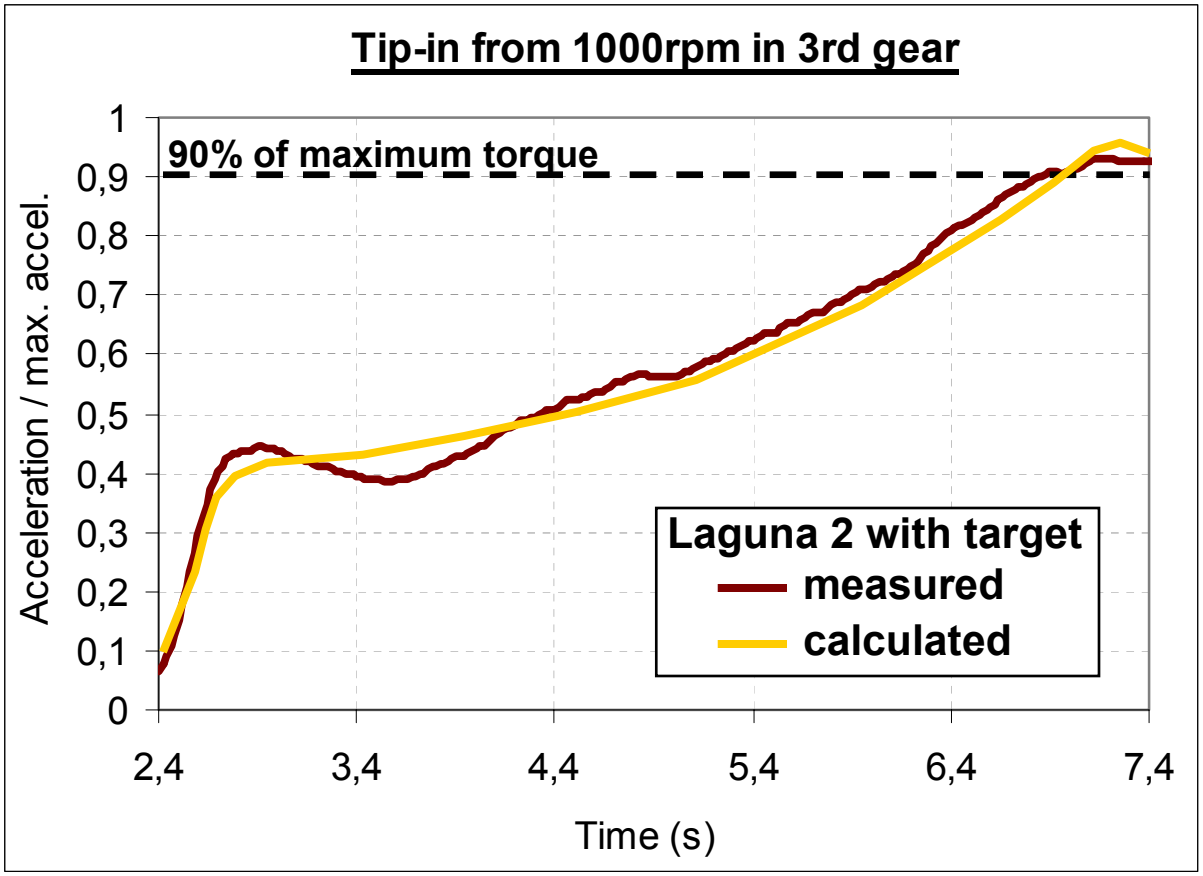
- Transient performances ***measured*** on a Laguna 2 vehicle with target engine on a tip-in from 1000rpm in 3rd gear after part load conditions (constant vehicle speed)

Transient simulations
Influence of the LP turbocharger



- Transient performances ***calculated*** on a Laguna 2 vehicle with target engine on a tip-in from 1000rpm in 3rd gear after part load conditions (constant vehicle speed)
- ***Good agreement*** between ***calculations and tests***

Transient simulations
Influence of the LP turbocharger



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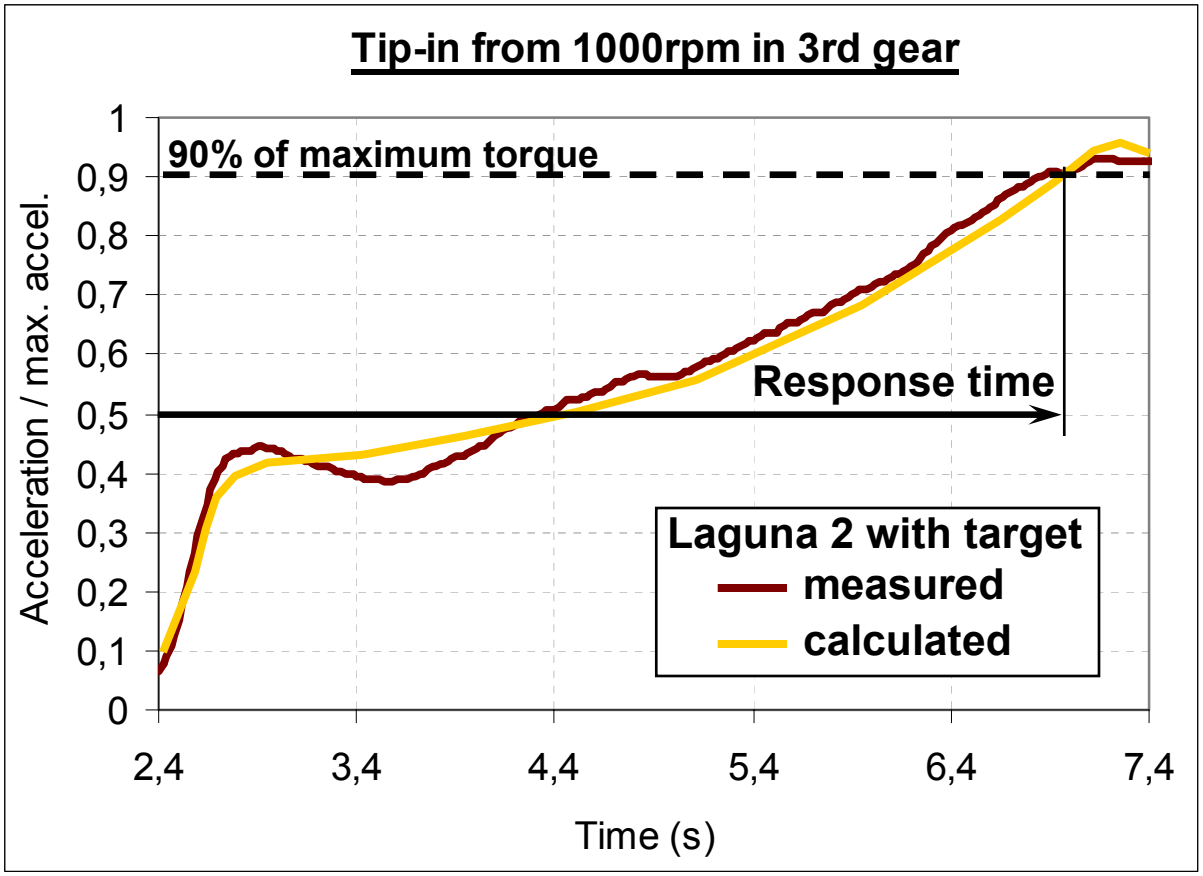

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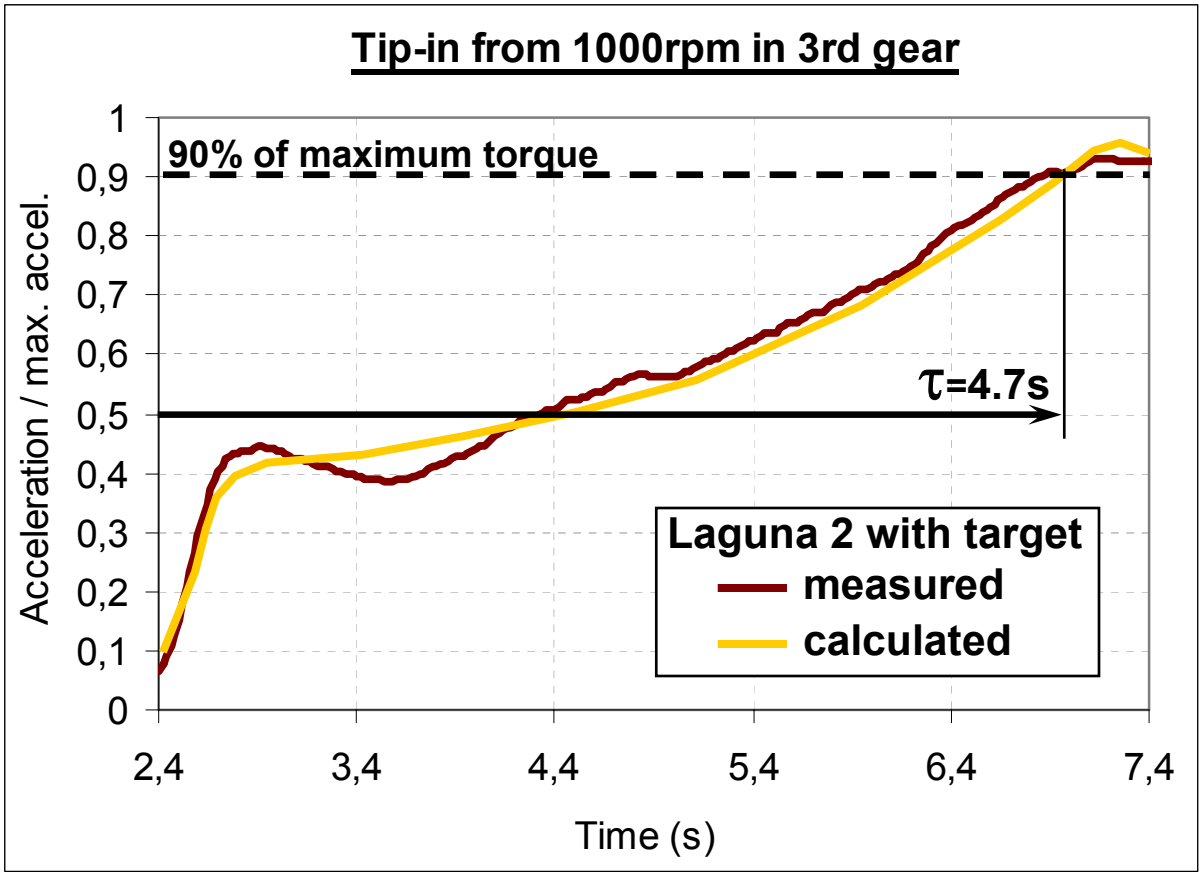

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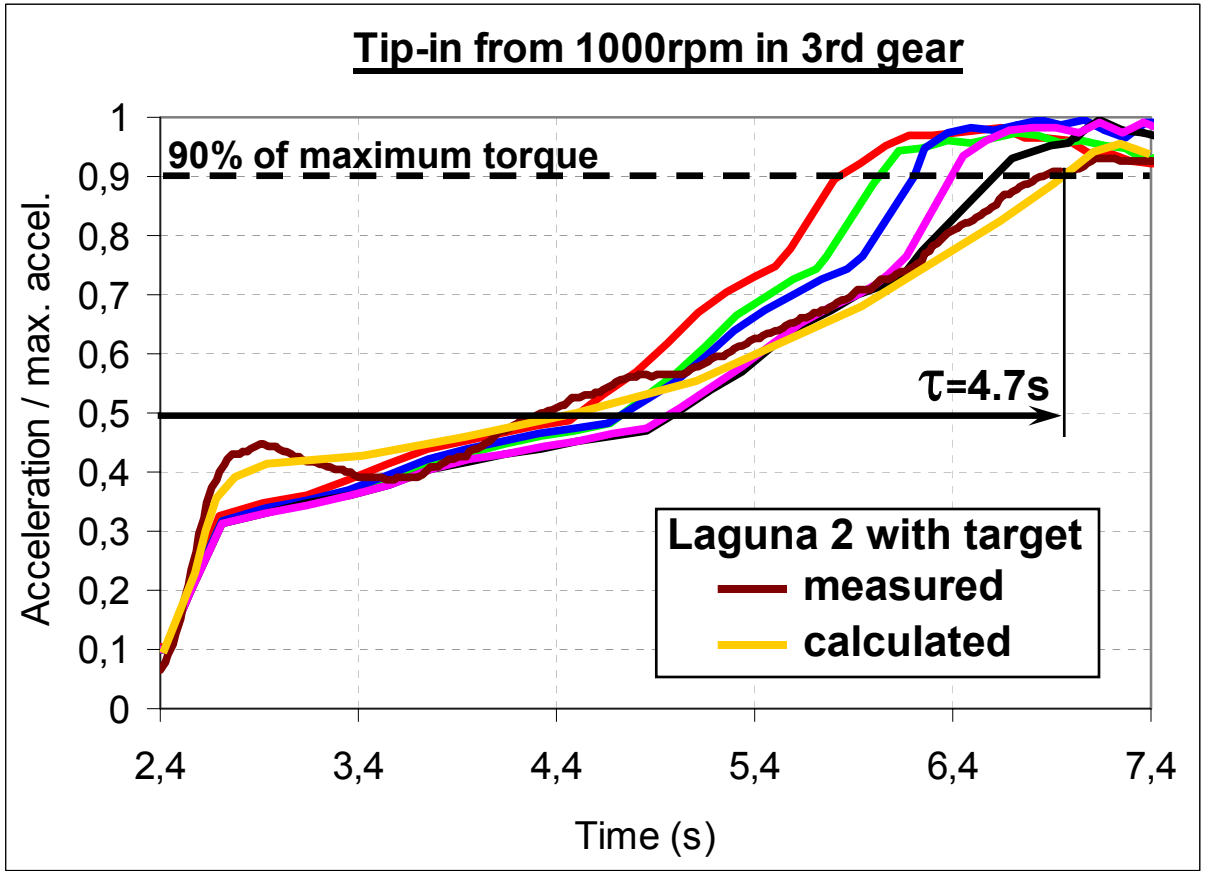
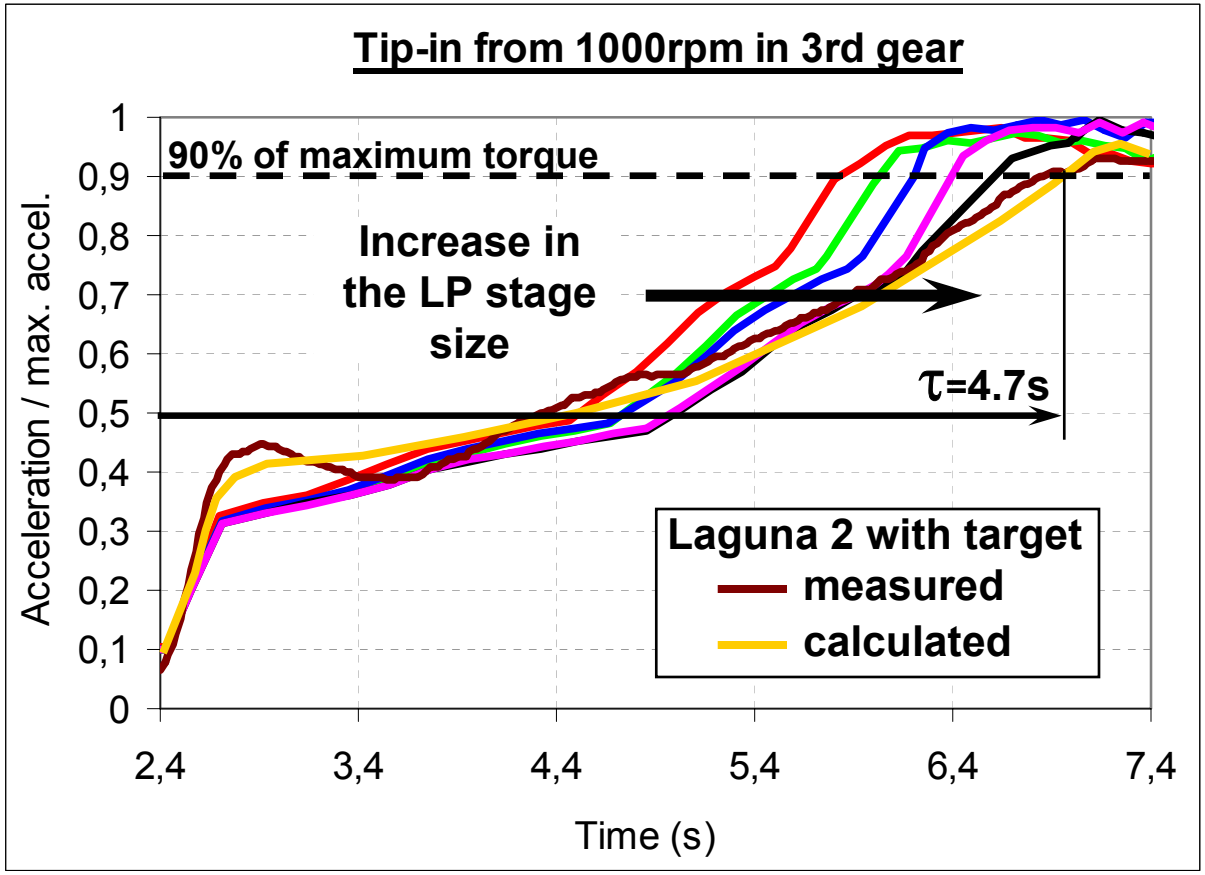
Transient simulations
Influence of the LP turbocharger



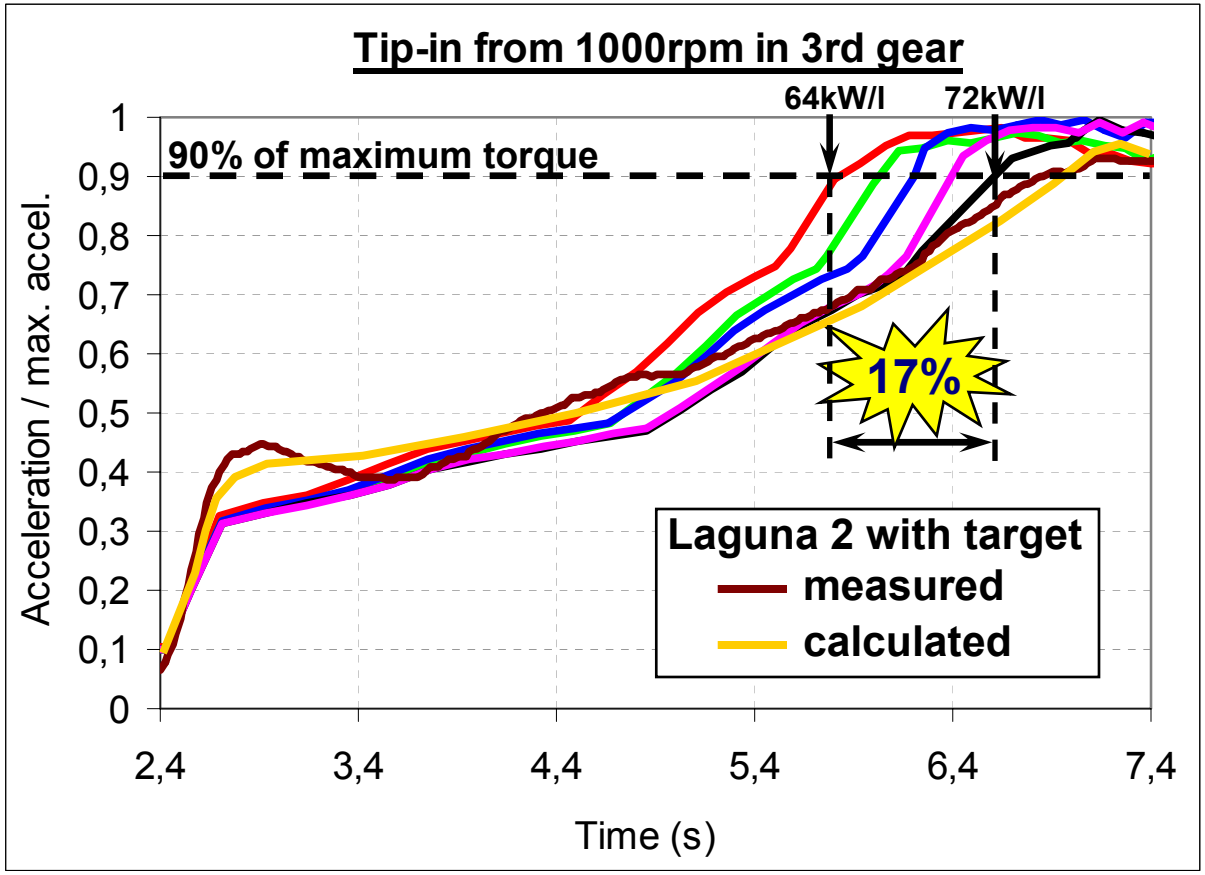
- The vehicle with the small ***two-stage engine*** has a ***similar acceleration*** to the target engine with single turbocharger

Transient simulations
Influence of the LP turbocharger



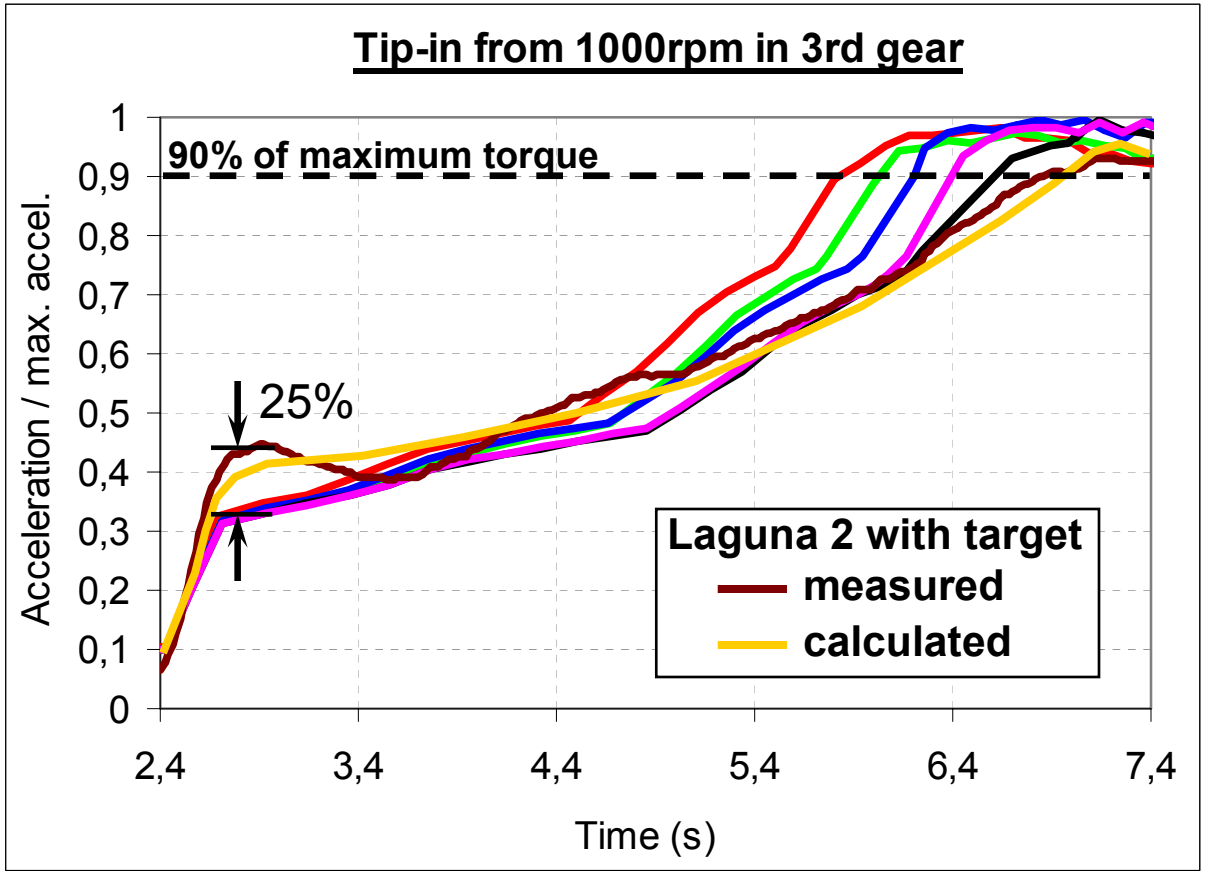
- LP turbo has a strong effect on the transient performances

Transient simulations
Influence of the LP turbocharger



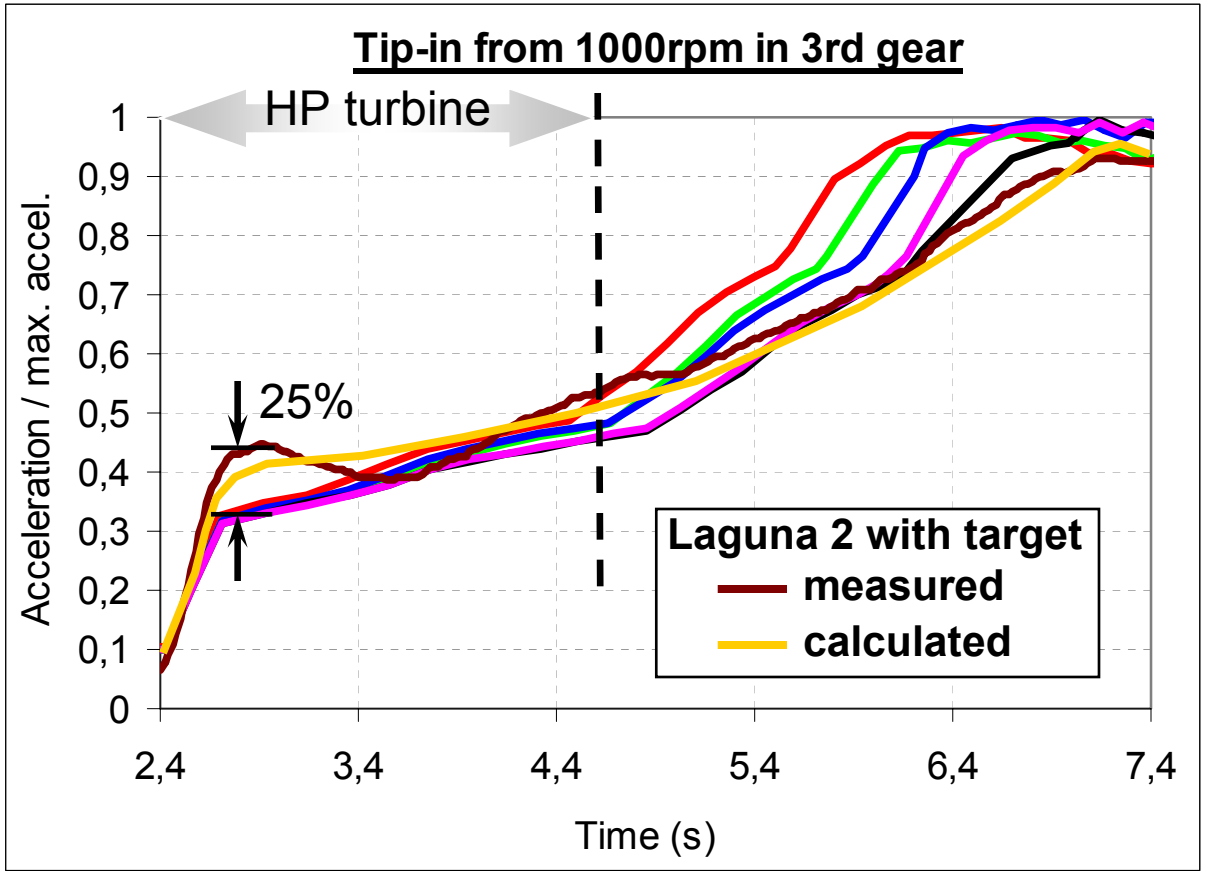
- LP turbo has a strong effect on the transient performances
- 17% on the response time between the larger LP turbo (72kW/l) and the smaller HP turbo (64kW/l)

Transient simulations
Influence of the LP turbocharger



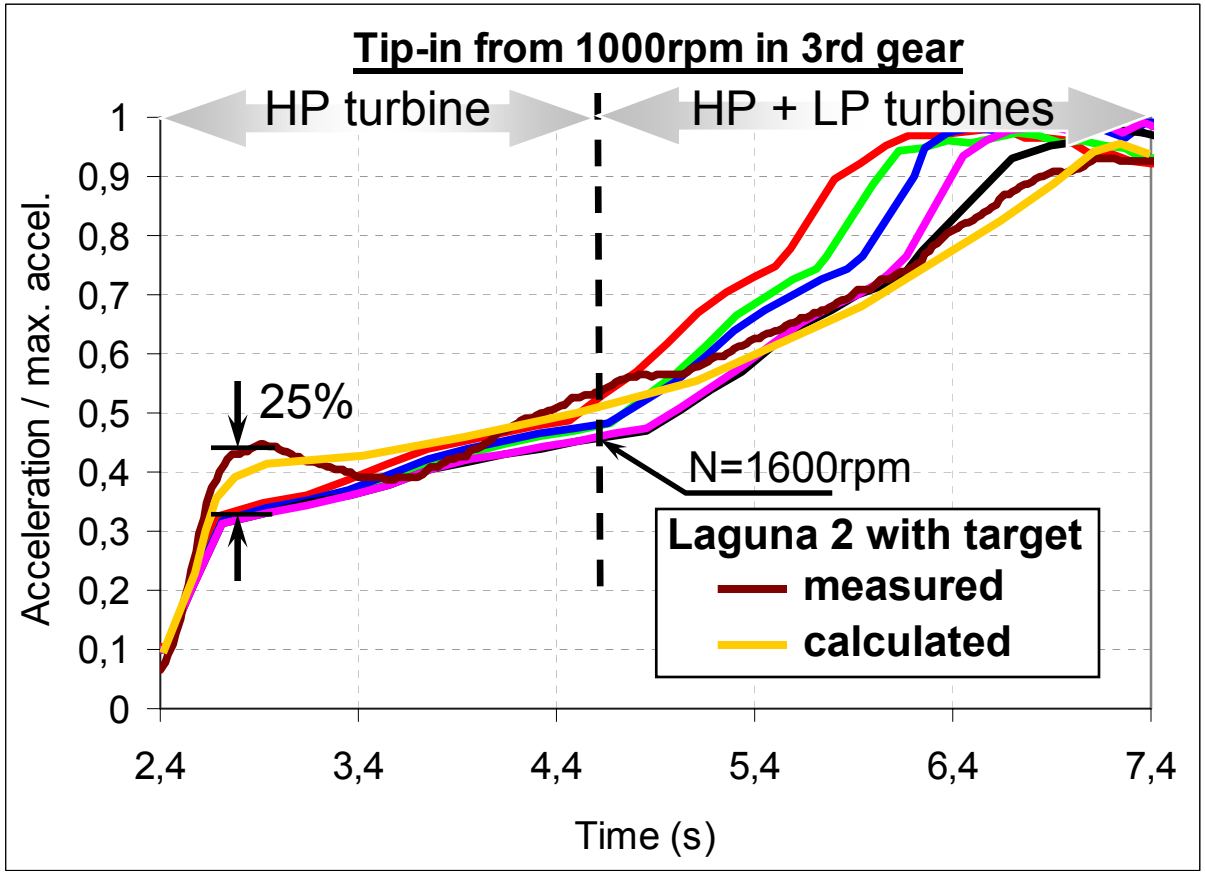
- Advantage for the Laguna 2 with the target engine at the beginning thanks to its capacity

Transient simulations
Influence of the LP turbocharger



- Advantage for the Laguna 2 with the target engine at the beginning thanks to its capacity
- At the beginning of the transient, HP turbine is mainly used

Transient simulations
Influence of the LP turbocharger



- Advantage for the Laguna 2 with the target engine at the beginning thanks to its capacity
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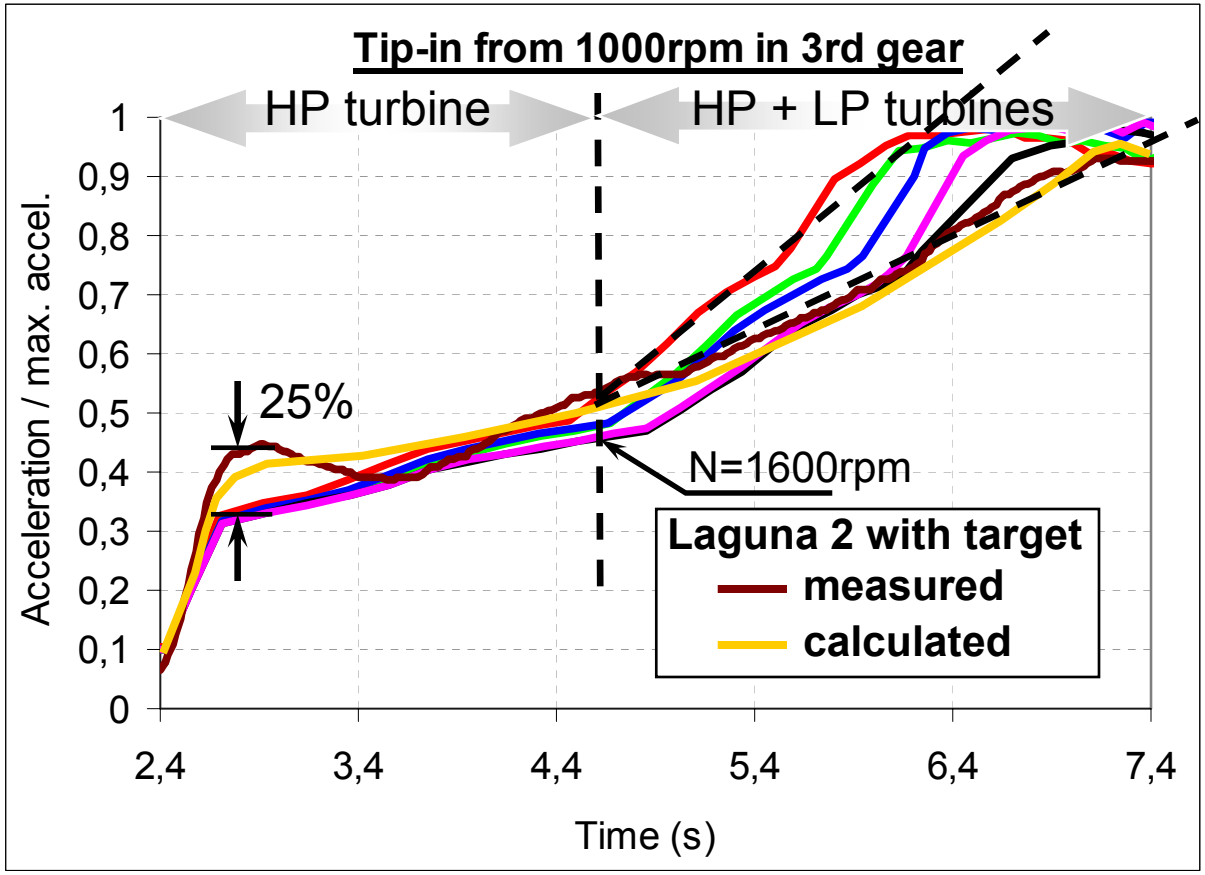
- LP turbine has an effect only after 2.5s, when the engine reaches 1600rpm

Transient simulations
Influence of the LP turbocharger



- Advantage for the Laguna 2 with the target engine at the beginning thanks to its capacity
- At the beginning of the transient, HP turbine is mainly used
- LP turbine has an effect only after 2.5s, when the engine reaches 1600rpm ➡ change in slope

Full load simulations
Conclusions

GT Power calculations show that :

- it is ***possible to reach the target*** engine performances with a smaller two-stage engine ***under steady-state and transient conditions***

- Balance between low and high engine speeds has to be found especially for the ***LP turbocharger***

- The use of ***larger LP turbochargers*** has a negative impact even on ***low end torque*** and on the vehicle acceleration under ***transient conditions***

- On the contrary, the use of too small HP turbochargers will have a negative influence on the power target (not presented here)

Part load simulations

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Part load simulations
Principle

- Main engine parameters during ***tuning tests***

- HP boost pressure
- LP boost pressure
- EGR vane opening
- A/F ratio…

Part load simulations
Principle

- Main engine parameters during ***tuning tests***
- HP boost pressure
- LP boost pressure
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- A/F ratio…

- Parameters to optimize
- Polluant emissions (to minimise)
- Specific fuel consumption (to minimise)

Part load simulations
Principle

- Main engine parameters during ***tuning tests***
- HP boost pressure
- LP boost pressure
- EGR vane opening
- A/F ratio…

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- Polluant emissions (to minimise)
- Specific fuel consumption (to minimise)

- GT Power ***calculations*** outputs
- effective section and dimensions of the EGR circuit
- ***maximum EGR rate*** available

Part load simulations
Principle

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- LP boost pressure
- EGR vane opening
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- Operating points representative of the NMVEG cycle :

1500rpm – BMEP=8bar
1750rpm – BMEP=8bar
….

Part load simulations
Principle

- Main engine parameters during ***tuning tests***
- HP boost pressure
- LP boost pressure
- EGR vane opening
- A/F ratio…

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- effective section and dimensions of the EGR circuit
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- Operating points representative of the NMVEG cycle :

1500rpm – BMEP=8bar
1750rpm – BMEP=8bar
….

We decided to use the new GT Power ***DOE and Design Optimizer tools***

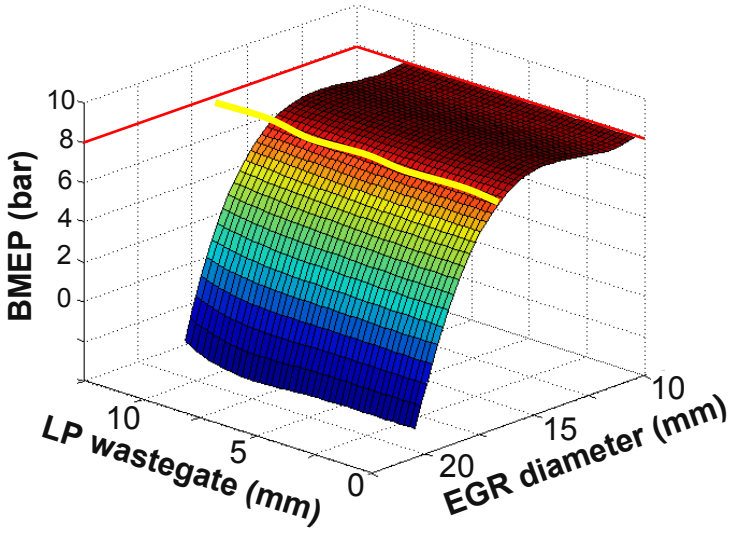
Part load simulations
Modelling

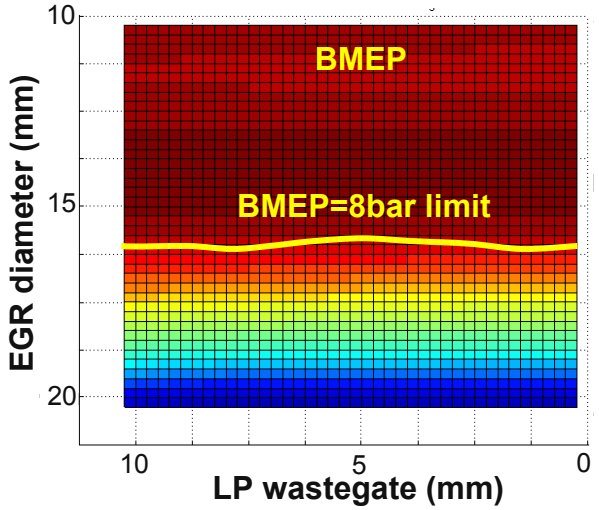
- GT Power model already tuned at full load
- Adapted according RENAULT's experience at part load on engines with EGR :
  - combustion parameters
  - in-cylinder heat exchanges coefficients
- PID regulation on A/F ratio with BMEP target
  A/F ratio limitation (smoke limit)
- DOE model based on :

- WG diameters (LP WG diameter, HP WG closed) : 5 positions
- EGR vane diameter : 5 positions
  (no regulation on wastegates and vanes)

- For each case (1500rpm –BMEP=8bar,…) : ***25 cases***

Part load simulations
1500rpm-BMEP=8bar





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TWO-STAGE ENGINE

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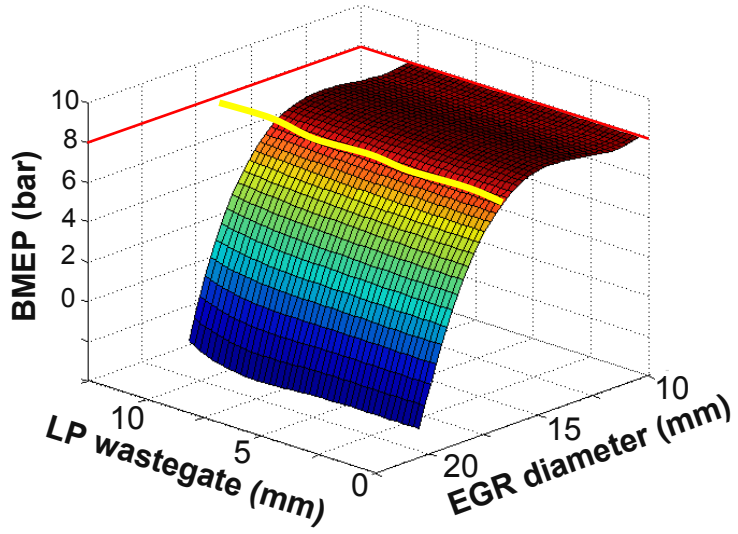
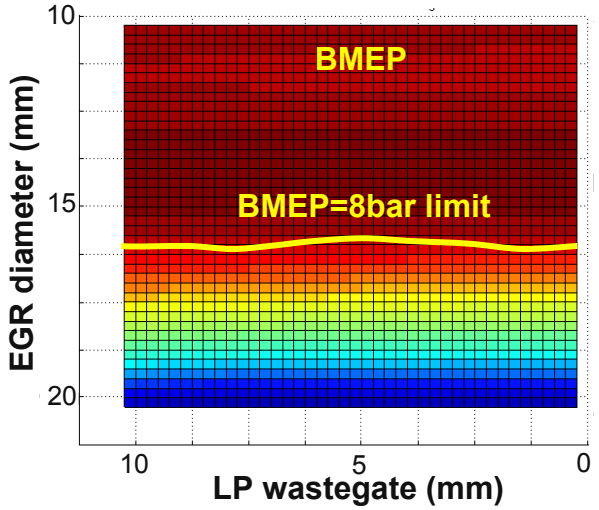
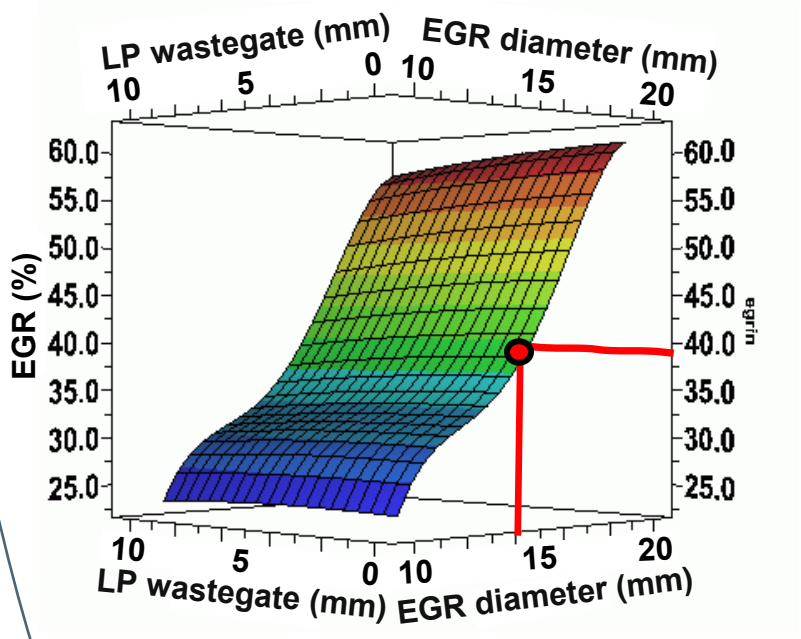
Part load simulations
1500rpm-BMEP=8bar







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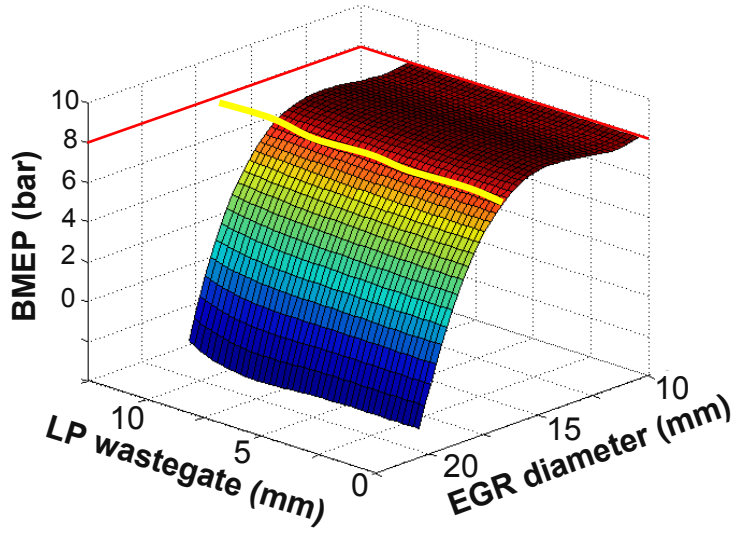

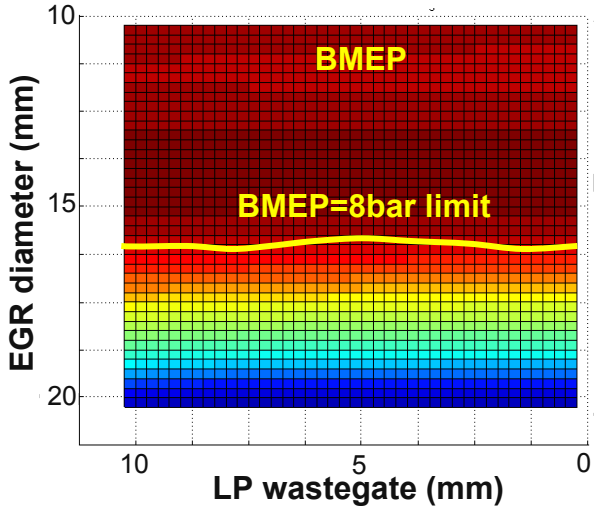

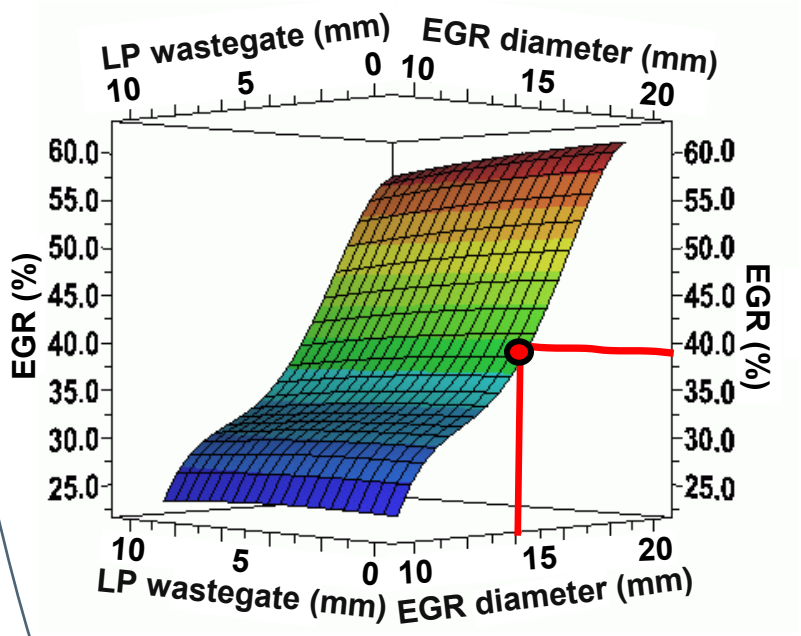

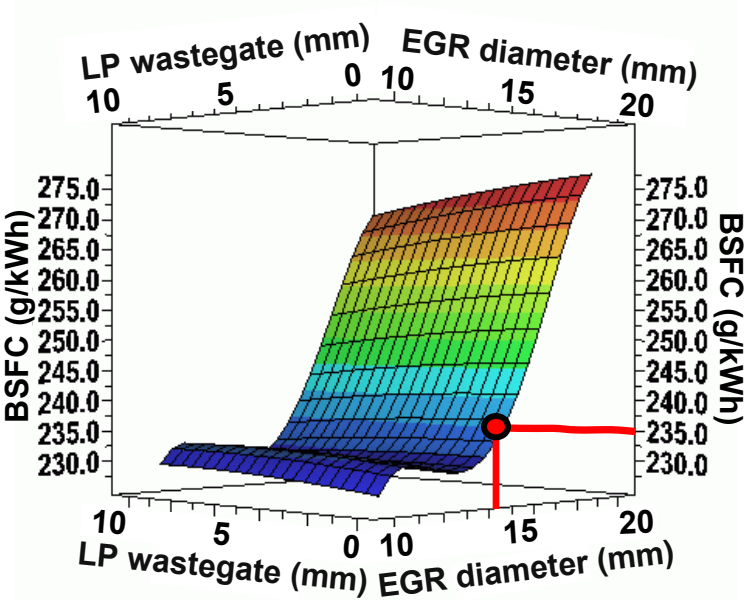

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Part load simulations
1500rpm-BMEP=8bar

EGR vane opening

↓

Increase in the EGR rate

↓

Increase in the air mass flow

↓

Turbocharging system limits
(WG closed)

↓

Increase in the BMEP thanks to air fuel ratio

↓

Air fuel ratio limitation
(BSFC and smoke limits)

↓

Maximum EGR rate

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Maximum EGR rate

Optimisation results
Base HP turbocharger

BMEP	8bar
N	1500rpm
BSFC (g/kWh)	233
EGR diameter	15.2mm
A/F ratio	15.1
EGR (%)	**38**

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☺ Close to the RENAULT Eu06 estimated target

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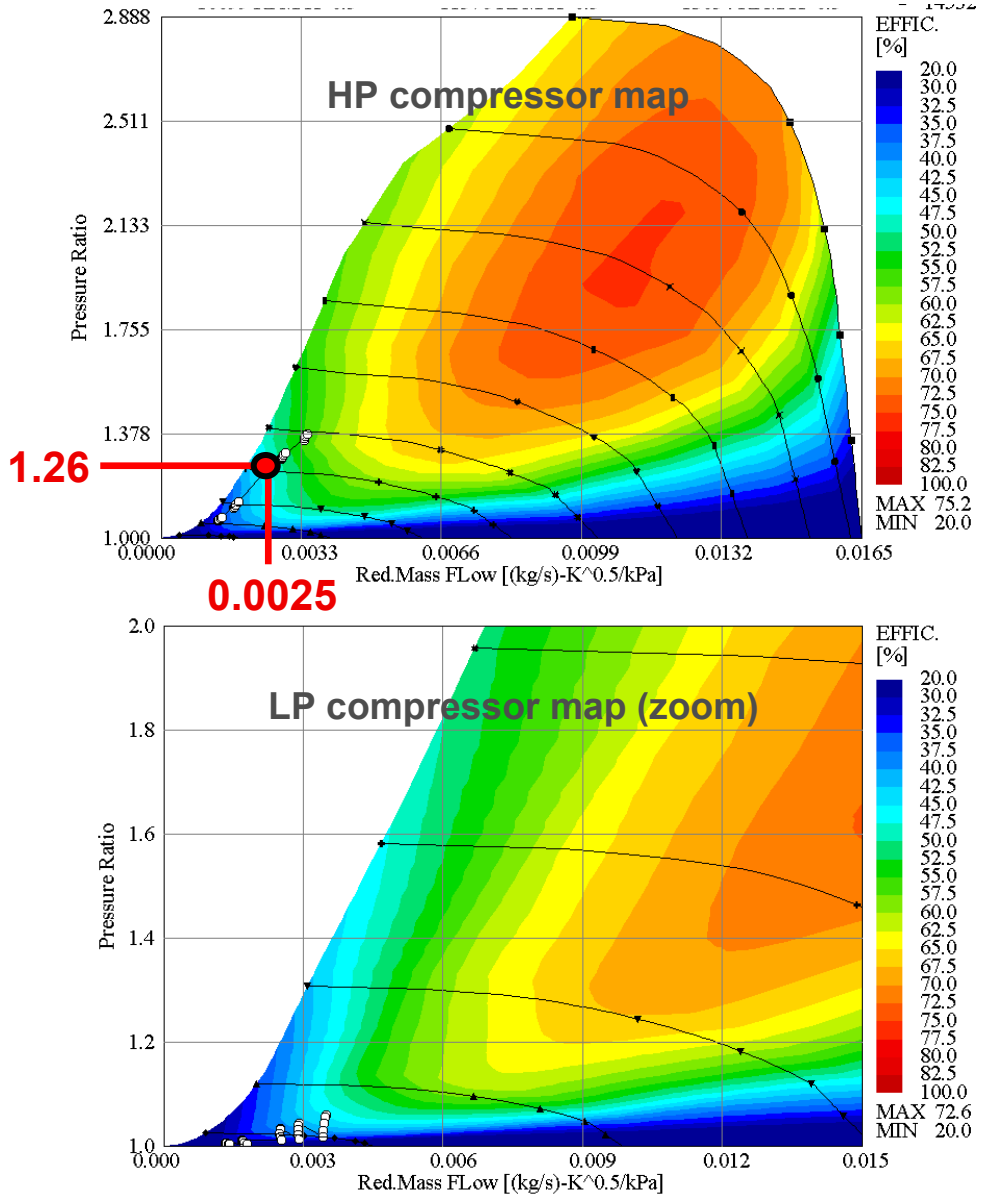
Part load simulations
1500rpm-BMEP=8bar

Operating points far away from the ***surge line*** in the HP and LP compressor maps



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Part load simulations
Influence of the HP turbocharger

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Part load simulations
Influence of the HP turbine

Optimisation results
Lower HP turbocharger

(max. mass flow rate -10% at π_t=2.5)

BMEP	8bar
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Optimisation results
VGT HP turbocharger

(max. mass flow rate -30% at π_t=2.5)

BMEP	8bar
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EGR diameter	**10.3mm**
A/F ratio	15.1
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- Interest to use a ***lower HP turbocharger*** (but compromise to find with the maximum power)
- Limited interest of a ***VGT HP turbine,*** due to ***lower turbo-charger efficiencies***

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Conclusions

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Small two-stage engine
Conclusions

- GT Power calculations were used to optimize the engine design at ***full load***
  - to choose the turbocharger matching for HP and LP stages
  - to evaluate the response times under transient conditions
  - ***target engine performances*** can be ***reached with a smaller two-stage engine***
- GT Power DOE tools were used to estimate the maximum EGR rates at ***part load***
  - DOE is a good tool to have quick estimations on a large field
  - new interpolation methods have to be developed
  - Two-stage turbocharged engine is a good way to reach high EGR rates and to reach our estimated targets for Eu06
  - Interesting influence of the HP turbine effective area (like on a classical single-stage turbocharged engine)
  - Poor impact of the VGT turbine on the EGR rates
- Turbocharger matching is also compromise between part and full load, like on a single stage engine

Thank you for your attention…

…Your questions

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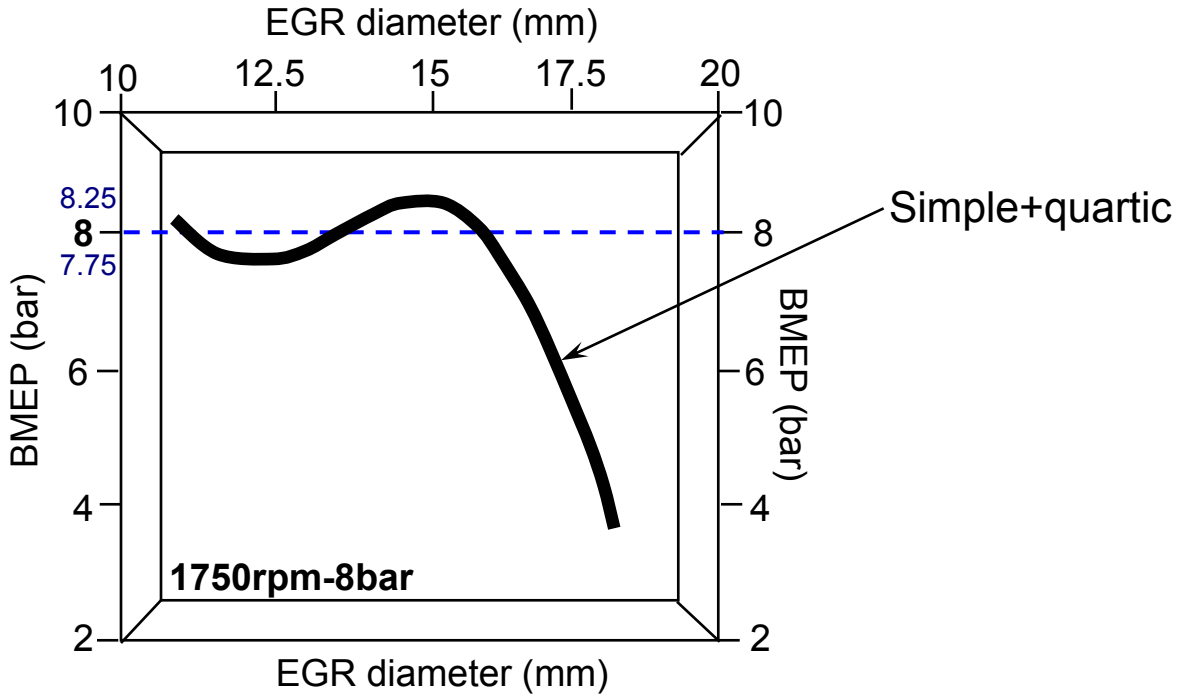
Part load simulations
DOE tool



Sometimes difficult to have a good fit with the available interpolation methods (simple + quartic resolution model generally giving the best results)

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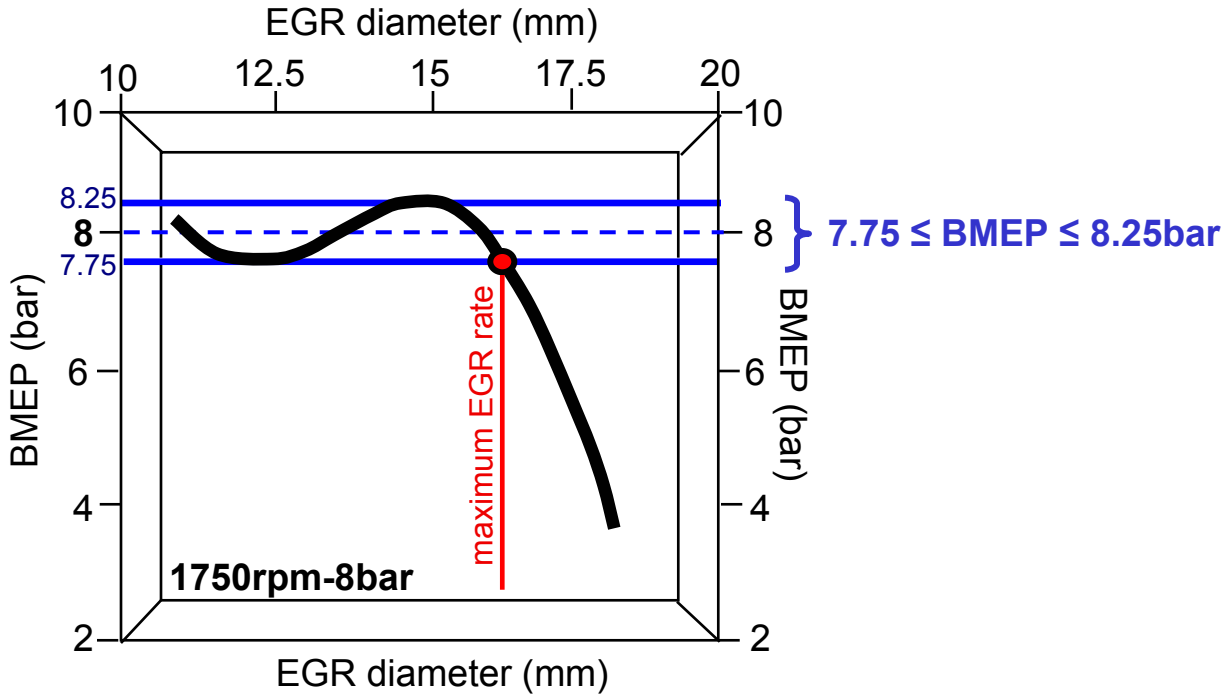

- Sometimes difficult to have a good fit with the available interpolation methods (simple + quartic resolution model generally giving the best results)
- But possibility to fix constraints on the BMEP in the DOE