Results shown in this presentation shall indicate the value of GT-POWER along with 3D CFD in the creation of new powertrain applications. When we eventually decided to really build this demonstrator vehicle with a two-stage turbocharged engine, there were just about 5 ½ months until the date to exhibit the car on the 18th Aachen Colloquium "Automobile and Engine Technology". This period included the summer vacation season, which usually limits the available human resources required for such a project. Hence, a strongly motivated crew and efficient virtual engineering tools such as GT-SUITE were indispensable to cope with this challenge.

At this point I wanted to thank my co-authors at BorgWarner, at the RWTH Aachen University and at FEV for their support and for giving me the honor to present the results of the work.
My presentation will start with the motivation and targets for this project. Next the engine concept will be outlined. Details of the thermodynamic layout will be presented, followed by a short insight into the narrow package, and the rapid prototyping. Model predictions will be displayed before the presentation ends with brief conclusions.
Content

Motivation and Targets
Concept
Thermodynamic Layout
Package
Model Validation
Conclusions
Introduction
Global Warming

The temperature records of the past 130 years indicate a more or less continuous rise of temperatures in the past (\(\ast\)) 40 years, which coincided with increasing energy consumption of industry, households and traffic.
Introduction
Coincidence with increasing molar fraction of CO2

Taking a closer look at these last four to five decades, we see also a continuous increase of the year average carbon dioxide mole fraction in the atmosphere. It is widely accepted that this increase originates from combustion of fossil fuels, and that the greenhouse effect caused by enriching the atmosphere with CO2 and other gaseous emissions like N2O and CH4 contributes to global warming.
Moreover, the availability of oil is limited. While most of the oil wells in the USA have already seen their peak oil in the early seventies, other oil producers have been facing declining oil delivery rates in the following decades. And there are rumors about Saudi Arabia and other OPEC countries, that they could not produce more oil in 2008 even though the crude oil prices were very attractive.
In view of these scenarios, politicians react, and the European Commission sets a mandatory average CO2 emission of 120 g/km in NEDC for all new passenger cars an OEM sells in 2012. Because 10 g/km may be attributed to fuel-side measures such as bio-fuel blends, new passenger cars shall not produce more than 130 g/km of CO2 in operation using traditional fuels. This applies in the same way to conventional motor cars as well as hybrid powertrain vehicles.

Today, the focus of my presentation is on motor technology and on downsizing aiming to operate the engine in higher specific loads and hence better brake efficiency.
The idea of downsizing is not new. But recent trends in the market toward downsizing take a more rigorous approach. E.g. BMW will no longer sell its new 7 series with a V8 diesel. This engine will be replaced by a 2-stage turbocharged straight six. [1]

Consequently, other market segments will probably see six cylinder engines replaced by four cylinders. But it will be difficult to convince a six cylinder client to step back from his prestigious and smoothly running acquaintance toward a small straight four. This engine will have to offer him something, that makes her or him want this prime mover.

Aiming at a 3.5 liter V6, it takes significantly higher targets for the downsized engine than those for our previous SGT engine, which was a 1.8 l GDI engine with single turbo and central injector. The targets for this GT² engine (for Gasoline Twin Turbo) are 26 bar BMEP for most of the speed range and a specific power output of 120 kW/liter.

With this downsizing engine, the same car shall emit 17% less CO₂ in the European test cycle, and its acceleration from 0-100 km/h as well as from 80-120 km/h in 6th gear shall be improved compared to the V6 car.
Introduction
Limits of 1-Stage-Charging

This target decision leads to new technical challenges. (*) A single-stage turbo has enough compressor flow range for a specific power of 90 kW/l along with pressure ratio for satisfactory low end torque. (*) Also, exhaust backpressure complies with turbine layouts. Now, the new target of 120 kW/l requires (*) higher boost pressure ratio and a larger compressor flow range to enable the target low end torque at engine speeds as low as 1500 rpm. In a single stage turbo layout, this may lead to (*) pressure ratios across the turbine that can be considered (*) critical. The step to a two-stage turbocharger overcomes these limitations.
Now, let me discuss a few turbo concepts for such a high performance.
This slide shows engine systems with two turbochargers, both compressing the charge air in a single stage. The first system is a bi-turbo layout with both turbines fed continuously from a set of three cylinders each. Also the concept on the right hand side employs the turbos in parallel arrangement to compress the air in a single stage. The one displayed here was used in the Porsche 959 [2]. A similar solution has been presented by Ford at the Aachen Colloquium as boosting concept for the new Jaguar V6 Diesel [3]. That Parallel-Sequential Turbocharging uses a VGT turbocharger, which is assisted by a fixed geometry turbo only at higher engine speeds.
Two Stage Turbocharging Architectures

Concept

System specific actuators:

- **High-Pressure-Turbine bypass**
  - on/off bypass (active), no control function
  - at low speed complete mass flow through turbine
  - from low/mid speed on complete mass flow bypassed

- **High-Pressure-Compressor bypass**
  - on/off bypass (active)
  - complete mass flow bypassed

- **External Bypass (Overall-Bypass)**
  - conventional function of turbine control but both turbines simultaneously affected

2-stage turbocharging is called like this, because the boost air is compressed in two sequential stages. This picture displays an interesting concept suggested by Reiner Wohlberg.

The exhaust gas propels the HPT first before driving the LPT with the remaining pressure ratio. Boost pressure is controlled at any time using an external bypass. Because the wastegated mass flow also bypasses the LPT, the latter contributes less to boosting. Hence, the HP turbine delivers a larger share of turbo power, and its compressor operates at high specific work and favorable efficiency in the low speed range. At a certain point the HP bypasses open, the LP TC speeds up, and the external bypass now controls the low pressure turbocharger.

The system has advantages in compressor outlet temperature, because the compressors operate near optimum efficiency. But there are several challenges related to this system, too:

1) transient control in acceleration: The HP turbo is controlled using the external bypass. Its gas flow does not propel the LP turbo. When opening HP turbine bypass at higher full load speeds, the LP turbo starts revving up from rather low speeds.

2) Additional package space is required for the external bypass.
Because of the availability of prototype parts and the tight schedule and also because of the narrow package of the target vehicle, we chose a more conventional 2-stage turbo architecture for our concept car in the first step. This system is similar to what is in production in the BMW 123d, but its application to gasoline engines is quite new.

The system features a controlled bypass for the HPT, a switchable bypass for the HPC and a large wastegate turbocharger as low pressure stage. While the HP bypass has a vacuum actuator, default open, the LP wastegate works on positive pressure, default closed.
Concept  
**GT² (Gasoline Twin Turbo) Demonstrator Data**

- Serial sequential 2-Stage Turbocharging System
- Turbochargers by BorgWarner Turbo Systems designed for 1.8ltr-I4 SI-Engine:
  - Rated Power: 216 kW (120 kW/ltr)
  - Max. Torque: 375 Nm @ 1500 rpm
- Fuel Economy Target:
  - Fuel consumption -17% or
  - Mileage +20%, respectively
  vs. 3.5ltr-V6 NA reference engine

Accordingly, our gasoline twin turbo concept demonstrator car features a serial-sequential 2-stage turbocharger, the turbo machinery of which was generously provided by BorgWarner Turbo Systems in Kirchheim-Bolanden. They also helped us finding the appropriate compressor wheels and trim to match our boost and mass flow requirements for the performance targets of 120 kW/liter and more than 200 Nm/liter from 1500 to 5500 rpm. The CO2 footprint of that engine shall be 17% less than a 3.5 liter V6 breathing from atmosphere.
This slide gives you some more details about the engine geometry parameters, the flexibility in valve timing, and fuel supply. The vehicle for the GT² concept demonstrator car is a used Ford Focus ST along with other production parts. A KP35 turbine is used on the high pressure stage, and K04 turbine as low pressure stage.
In order to upgrade the previous SGT engine to the GT² engine, we took two measures against mega-knock and pre-ignition: To be on the safe side, the compression ratio was reduced from 9.8 to 8.5, which will be revisited in future investigations. FEV’s CMD process predicted further advantages in combustion speed from enhancing tumble, so the intake ports were modified. The GT-POWER knock model told us these measures were safe. Luckily, this statement did not become invalidated by experimental work. Otherwise, we hadn’t had the demonstrator car ready for the Exposition.

For the first proof of concept, we tried to make the engine work without a larger charge air cooler but without intercooler between the stages. Eventually, we created a rapid prototype control for knock and boost pressure based on dSPACE equipment.
Next, we get to the thermodynamic layout.
Comparing the compressor maps of the SGT engine in blue to the low pressure stage of the GT² engine in gray, it is obvious, that the new T/C delivers higher mass flow rate and higher boost pressure (*) at same speed lines, although the compressor wheel diameter is equal. Our partners at BorgWarner exchanged the compressor wheel type “E” having 4 full and 4 split blades by a 6+6 blade “D” type wheel allowing higher boost pressure ratio. Then, (*) they adjusted the flow capacity by increasing the trim from 75 to 83%.
The GT-POWER model is an air-to-air model with limited details of exhaust mufflers. (*) It features air cleaner, turbocharger, charge air cooler and several control blocks.

For simulation of vehicle transients, a (*) vehicle model has been linked to the crank train object of the GT-POWER model.
The turbo subassembly includes the two turbochargers and the bypasses of the high pressure stage and the pop-off or diverter valve modeled separately. Just the wastegate of the LP turbine has been modeled the traditional way for simplicity.
GT-POWER Model of the GT² Engine

Model features

Model used first for *prediction* of future engine
- EngSITurb Combustion model
  - Model parameters adopted from previous SGT engine model
  - Employing STL data of target combustion chamber
- EngKnock Knock Model
  - Model parameters adopted from previous SGT engine model
  - Wiebe combustion model using parameters evaluated from EngCombSITurb predictions
- Draft geometry data stepwise updated with packaged geometry from CAD
- Heat transfer and wall temperatures using heat conduction objects in steady-state and transient applications
- Transient vehicle simulations employ full detailed engine model

The modeling approach included the validation of turbulent combustion and knock models using measured data from the previous engine. For the more time consuming parameter variations of the system architecture, Wiebe models were applied using mapped heat release profiles of the turbulent combustion model.

The design work was supported by stepwise exchange of information and advice between design and simulation.

Eventually, the transient vehicle simulations employed the full detailed engine model in order not to miss any effect of pulsating flow on turbo efficiency, pressure response, heat transfer, etc.
### Concept Layout

**Modes of Turbo Operation**

- LP stage can provide boost for $\geq 2500$ rpm with HP stage bypass fully open
- HP-Stage delivers required boost for full load below 2500 rpm
- Efficiency trade off shifts boundary for single LP stage operation to higher engine speeds
- Transient control runs HP stage in larger map areas

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For high torque at engine speeds of 2500 rpm and higher, just the new enhanced LP stage would be sufficient, (*) as indicated here in operation with bypasses of HP compressor and turbine fully open. However, this would leave the customer with the impression of (*) a very weak starting torque and also result in poor drivability. Therefore, the small T/C in the HP loop is required to (*) fill the gap for the lower speeds.
The stationary operation map of the engine can be divided into the following areas: In the lower part load, so-called naturally aspirated operation, the wastegate of the low pressure stage is closed in lack of positive pressure for its actuator. Increasing load involves boost pressure control by firstly opening the LP wastegate and gradually closing it again towards higher load. For speeds below 2500 rpm there exists a boundary curve (3), where the LP wastegate is closed, and the HP stage bypasses are just still open. Exceeding this curve will close the HP compressor bypass and employ the vacuum actuator for the HP turbine bypass to increase the boost pressure in area 2, until also the HP turbine bypass is fully closed for full load speeds below 1500 rpm, which is indicated as mode 1.
When the engine operates transient, the area of 2-Stage charging is much larger, because the HP-TC speeds up much faster and responds better than the LP-TC. While the present calibration was focused to make the car drivable until the Colloquium, future work will explore the limits of the transient 2-stage operation in more depth.
The presence of the HPC increases mass flow at low engine speeds. Therefore, also the LPT speeds up and delivers higher boost pressure below 1700 rpm than if operating alone.
Now come a few pictures how the turbocharger was integrated with the engine.
This is the front view on the engine. Slight modifications were done to the design when building the prototype by further reducing the distance between turbine outlet pipe and generator for the sake of a smoother bend.
The view from the right side shows the exhaust downpipe well aligned with the engine envelope.
Admittedly, the engine compartment is very narrow for such an application. The insulations between hot parts and parts to be protected will look different in a production vehicle, and the clearances would be larger, too.
Nevertheless, the car ran smoothly during vehicle calibration; and its performance was appreciated on many test drives during the Aachen Colloquium one month ago. When dismantling the engine thereafter, no damages or wear were observed. The car was reassembled and is available for test drives to interested clients in Aachen until further notice.
Since the GT-POWER model was used as a predictive tool for the layout of an engine, measurement data of the target engine became available only after the required simulations were done. Therefore, the validity of the model could only be checked a posteriori.
As expected, not every experimental result looked like its model prediction. By taking into account feedback signals from sensors and actuators in the car, the model was then used to understand, what caused the differences. This simulation of a tip-in from 25 km/h takes into account measured bypass flap positions and feeds them into the model. We found, that unintentionally the flaps were not fully closed, which resulted from exhaust backpressure and still to be improved closing forces of actuators. The torque rise after tip-in and the acceleration of the vehicle are affected by this behavior and are expected significantly better after the holding forces will be adjusted.

But nevertheless imposing the flap positions in the model leads to a good match of the TC-Speeds.
The calculated boost pressure build-up also nearly fits to the measurement data, so that the GT-POWER/GT-Drive Model seems to predict the behavior of the engine and vehicle in an appropriate way.
Looking at the steady state operation points in all compressor (*) maps, we plot the points of the (*) high pressure stage in red, the low pressure stage (*) in blue, and the overall result of both stages (*) in green. The (*) diagram shows that the HP stage fades out after reaching the target torque and the low pressure stage takes over. After the HP stage bypass is completely open, the total pressure ratio is equal to the one of the low pressure stage.

The picture shows, that the coordination of both compressor stages can be improved to make them work at better efficiencies in 2-stage operation. Possible measures include revised bypass control of both turbines and/or resized high-pressure turbine and compressor.
To conclude my presentation, we can say the feasibility of a gasoline engine with two stage turbocharging has been demonstrated, although a lot of improvement work is yet to be done.

The concept has been evaluated using GT-POWER, and the simulations were indispensible to create this demonstrator car in the very narrow schedule.
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