Hybrid Powertrain with Methane Engine – the consequent Evolution

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1 Motivation

Never before have the challenges for future propulsion systems been more demanding than these days. It is important to consider the very complex goals in terms of primary functionality, environmental compatibility and cost efficiency to a balanced extent. Based on a detailed analysis the 48V technology turned out as the most effective approach considering the trade-off between CO_2 and cost (Figure 1).

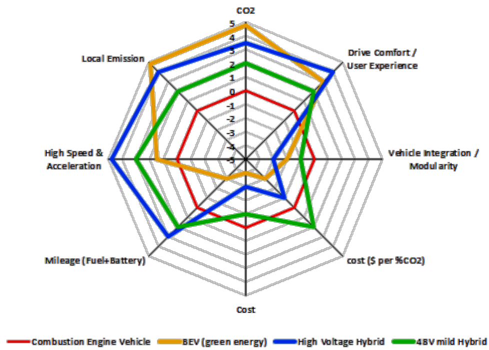

Figure 1: Hybrid system concept selection for best CO_2 and cost trade-off

The modern internal combustion engine (ICE) is approaching its theoretical limits in terms of efficiency. The conversion of fuel-bound chemical energy into effectively usable power by combustion is largely defined by the fuel properties. In particular, the combustion process and the implicit phenomena such as "knocking" combustion limit further efficiency increases.

The use of a knock-resistant fuel such as methane is leading to a significant raise in the average combustion pressure and total engine efficiency. This requires a base engine architecture that is specially designed to the increased thermal and mechanical requirements so that the positive fuel properties can be fully exploited.

Further improvement of the energy balance is achieved by utilizing the kinetic energy stored in the vehicle by means of electrical recovery.

In addition to the system related challenges such as the additional costs and weight, the space required for the installation of electrical components, in particular, the interaction of the electric drive with the conventional elements, especially the internal combustion engine, is of high importance [6,12].

The aim is a continuous delivery of the entire system capability with no negative affect on the drivability and comfort. In this context the restart of the internal combustion engine after an electrical driving situation is the most critical and challenging maneuver.

The concept presented below exploits the advantages of an electrified powertrain, making use of the vehicle's recovered kinetic energy in combination with a highly efficient internal combustion engine that is dedicated to the exclusive use of methane.

2 EcoBoost Engine with CNG Direct-Injection

Most vehicles today are equipped with spark ignition (SI) engines operated with gasoline as fuel. Although the gasoline quality has been significantly improved over the recent decades, the efficiency potential of gasoline engines is still limited by the knock sensitivity of this fuel. In order to exploit the full thermodynamic potential of a spark ignited engine a future fuel with significantly higher knock resistance is required as well as an engine architecture optimized for the knock resistant fuel. Therefore, a high knock resistant future fuel needs to be identified, which allows to gain the remaining efficiency potential. However, beside the high knock resistance, such a future fuel needs to fulfil further requirements. It should be available in sufficient amounts, economically affordable, support zero-impact emission capability and – finally yet importantly – long term it should enable sustainable transportation on a large scale [1].

Considering the European and German greenhouse gas (GHG) reduction targets, a significant reduction until 2050 (vs. 1990) needs to be achieved. In the transport sector, such a reduction is not possible with the further use of fossil fuel as the main source of transportation energy. Such a reduction can only be achieved by sustainable energy harvesting. In this context, the use of so-called e-fuels (aka PtX fuels) is of considerable importance as a future energy source for the on-road transportation sector. E-fuels are synthesized out of sustainable hydrogen and CO2 removed from the atmosphere. As illustrated in Figure 2 sustainable hydrogen itself is produced by water electrolysis, using GHG-neutral electrical energy from wind- or solar power. The carbon used in e-fuels is recycled from the ambient and thus has no direct fossil origin [2]. In contrast to crop based bio-fuels, which are limited in quantity by the constraint of arable land, e-fuels have the potential to replace 100% of the fossil transportation energy used today [2].

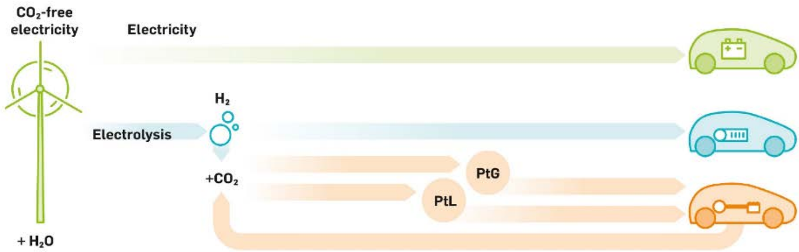

Figure 2: Sustainable pathways of transportation: e-fuels used in vehicles with combustion engines vs. direct use of electricity in battery electric vehicles and hydrogen used in fuel cell electric vehicles [2].

As shown in Figure 3 [2], promising candidates among the most cost efficient e-fuels are e.g. methane and methanol. Both of them are very suitable for fuelling a spark ignited combustion engine, since they are very knock resistant and therefore are enablers for a dedicated engine design for highest efficiency.

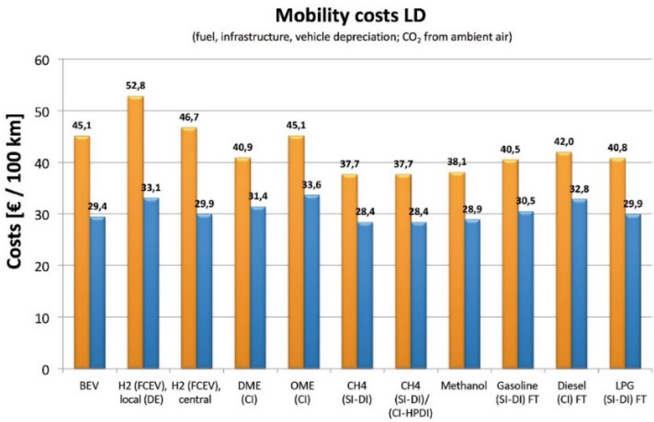

Figure 3: Minimum and maximum boundary e-fuel mobility costs of passenger cars and light duty vehicles vs. direct use of electricity [2]

Based on those considerations, methane – respectively CNG, which mainly consists of methane - has been chosen a representative future fuel for a further investigation of high efficient engine technology. Beside the high knock resistance and e-fuel production efficiency, it has further advantages, such as the very clean combustion, stoichiometric combustion capability in an SI engine and offers unrestricted mixing capability with gaseous fuels of fossil (natural gas) and agricultural (bio-methane) origin. Furthermore, methane has a very advantageous C/H-ratio. Just by this effect an approximately 25% CO_2 reduction vs. gasoline can be achieved, even when methane of fossil origin (CNG) is used as a fuel.

Therefore, in a first development step a dedicated methane engine (MTDI) has been developed in the framework of an EU Horizon 2020 project called “GasOn” (H2020-GV.3 – 2014; GA No. 652816) [3]. The GasOn engine is based upon the 2nd generation of the multi-awarded Ford 1.0l-3-cylinder Ecoboost engine [5] and is optimized for the dedicated operation with methane. In order to exploit the maximum efficiency, the peak combustion pressure capability is increased considerably compared to a usual gasoline engine, by the enforcement of nearly all moving engine parts. The high mechanical combustion pressure capability in combination with the high knock resistant fuel allows an engine design with a high compression ratio (CR 13) in combination with high boost pressure levels (improved downsizing capability), while still keeping an early combustion phasing even at loads of 30 bar BMEP, as shown in Figure 4.

In order to improve the downsizing capability - which is the enabler for a high on road and cycle efficiency, in particular at part load operation conditions - high engine torque over a large rpm range is achieved by the application of a new methane direct injection system and an advanced parallel-sequential twin boost system [13]. The second turbocharger of the twin boost system is activated by a continuously variable valve lift system

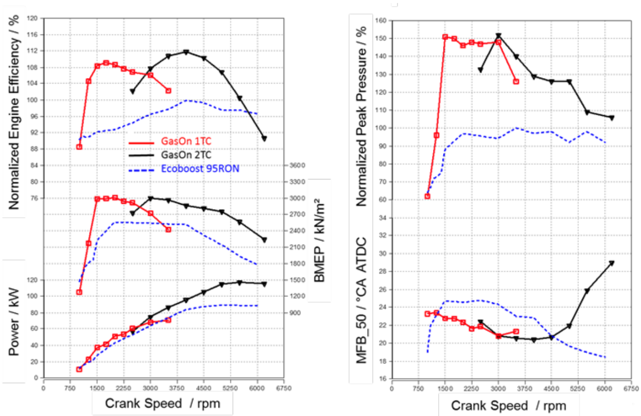

Figure 4: MTDI Engine: Power, Break Mean Effective Pressure (BMEP), Combustion Phasing (MFB 50), Normalized Efficiency and Peak Pressure [3]

on the exhaust side. The same system is applied to the intake side in order to further improve part load efficiency by de-throttling the engine. As shown in Figure 5, the maximum achieved engine efficiency exceeds 38%. More important for superior on road fuel saving is the very wide speed-load-range of the engine map, in which an efficiency of more than 30% is achieved.

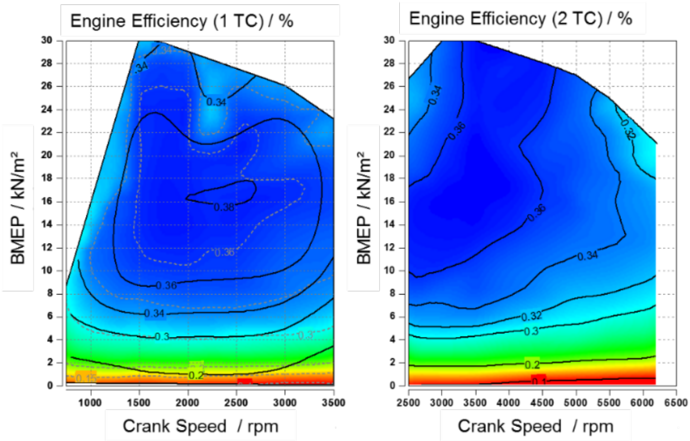

Figure 5: MTDI Engine: Efficiency Map [3]

The second evolutionary step to further improve fuel economy and reduce GHG emissions of a dedicated methane engine is the electrification (hybridization) of the powertrain. Therefore, a methane hybrid propulsion system has been developed. This has been carried out in the framework of a complementary project to GasOn, namely the EU Horizon 2020 project called “Thomson” (EU H2020 GA 724037); [15].

The hybridization of the powertrain complements the requirements on the low end torque capability and responsiveness of the engine under several operation conditions. The MTDI engine as used in the mHEV-powertrain thus can be simplified in comparison to the pure ICE approach based MTDI derivative, which is only optimized for the usage in a non-hybridized vehicle. Subsequently, the mHEV powertrain based MTDI engine has been derived from the pure ICE based MTDI engine by the deletion or replacement of some technologies to address feasibility and cost challenges.

One of the turbochargers of the MTDI engine is replaced by an e-booster, which is supported by the 48V electrical system architecture of the hybrid vehicle and will subsequently be able to provide boost-pressure on demand. The deletion of the second turbocharger furthermore allows the deletion of the variable valve lift system on the exhaust side, which is no longer required for the turbo charger actuation.

3 mHEV Powertrain Technology (48V)

The Thomson powertrain comprises the advantages of mild hybridization with a highly efficient internal combustion engine. The usage of fuels with a high H/C ratio enable another important opportunity to significantly reduce anthropogenic CO_2 emission from the transportation sector. Hence a dedicated direct injection gas (methane) engine has been combined with a P2 approach based mHEV module [14].

3.1 Powertrain topology

The P2 powertrain is implemented into the vehicle is an axial-parallel P2 configuration (Figure 6), [14]. The hybrid module (Figure 7) is the key component that enables the powertrain operation in the typical hybrid specific modes [12]:

- standard/hybrid/low speed pure electrical driving,
- start/stop coasting and sailing and
- recuperation mode.

The hybrid module is located between the ICE and the manual transmission (Figure 6). It comprises for the e-machine and two electronically controlled clutches (C0, C1). The e-machine is connected to the drive line via the clutches and a belt drive. A standard climate compressor is integrated into the belt drive as well. Hence the compact and highly integrated hybrid module enables not only an installation in east-west direction but as well to delete the standard ICE front end accessory drive provided the cooling pump is electrified as well. Electrifying the cooling pump offers improved fuel economy by enabling smart “cooling on demand” strategies that enhances engine warm up. Controlled cooling pump speed optimized for cooling demand further reduces parasitic powertrain losses.

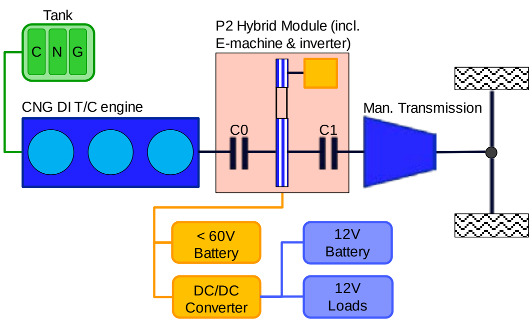

Figure 6: Thomson powertrain architecture

The e-machine is connected to the Li-Ion battery via a 48V power net. A DC/DC converter connects the 48V net with the standard 12V board net.

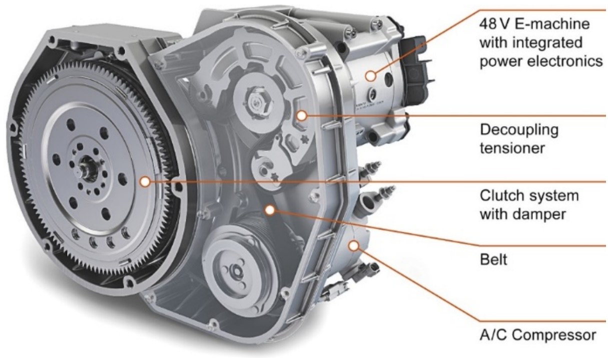

Figure 7: Thomson hybrid module

3.2 Operational Strategies and fuel consumption

A powertrain comprising a P2 mild hybridization in combination with a combustion engine requires an optimized operation strategy to harvest the maximum the fuel saving potential. In the P2 hybrid architecture (Figure 6) "normal driving" is realized by closing the clutches C0 and C1. For efficiency optimization the drive strategy supervisor operates the powertrain in advanced propulsion modes via the clutches C0 and C1. Figure 8 shows the operation strategy for the P2 mild hybrid vehicle in the WLTP utilizing following modes [12]:

- hybrid driving (C0 closed, C1 closed, e-machine providing pos. torque),
- sailing/e-driving (C0 open, C1 closed, e-machine providing pos. torque),
- start/stop coasting (ICE shut down, C0 and C1 adapted for opt. engine restart) and
- recuperation (C1 open, C1 closed, e-machine in generator mode).

Electrical energy generation by load point shifting actually is only marginally used in the WLTP for the envisaged ICE since the engine is mostly operated in the engine map area (Figure 9) with best efficiency. Only vehicles with less efficient combustion engines might benefit from load point shifting as long as the efficiency chain in the electrical path can be over-compensated by the ICE efficiency improvement shift. The energy harvested in the recuperation phases is limited to the dissipated brake energy at the friction brakes. The most efficient usage of recuperated electrical energy is the direct consumption in the board net. Excess recuperated energy is stored in the battery. It is used for e-driving to replace inefficient ICE operation in map areas with low engine speed and load. Since the electrical energy is limited it is primarily spent for vehicle launch and gentle accelerations at low vehicle speed. Electrical energy may be used for sailing (driving at constant speed) as well (however constant speed driving is not represented in the WLTC). Since the e-drive capability is only employed at low e-machine power it is obvious that the mild hybrid concept balances the limited available electrical energy perfectly with the relatively low installed electrical power of the 48V e-machine.

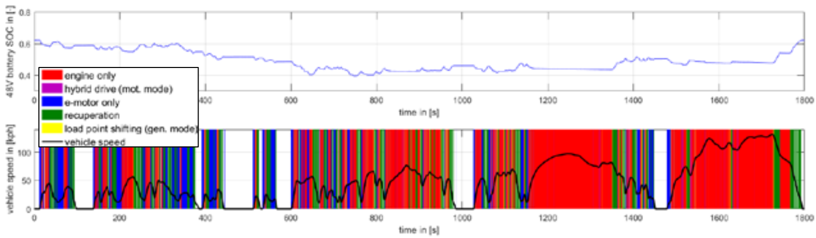

Figure 8: WLPT operation strategy of a compact-class vehicle with the P2 mild hybrid topology and 1.0l dedicated CNG engine

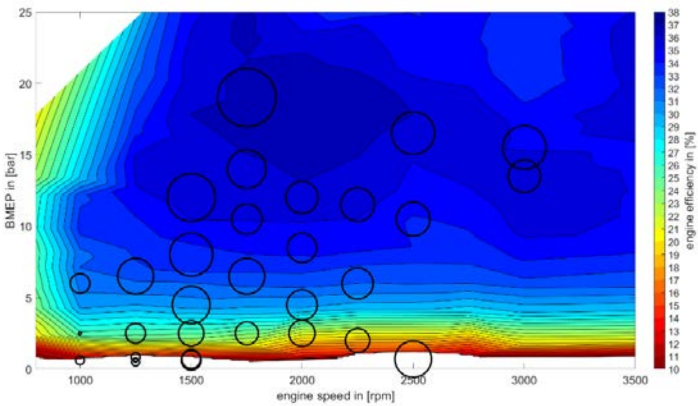

Figure 9: CNG combustion engine efficiency and WLTP residency points

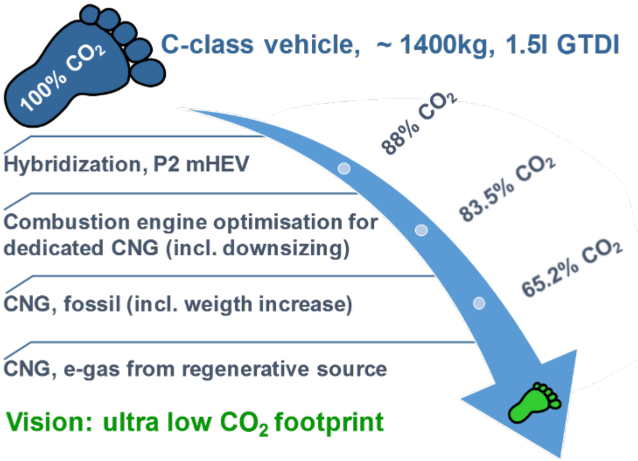

Figure 10: Vehicle concept CO_2 reduction walk by technology

With the powertrain concept that has been discussed a substantial CO_2 reduction can be achieved (Figure 10). While a reduction of 35% can be realized in the mid-term with technology that is basically available the CNG based concept also provides a long-term future perspective towards ultra-low CO_2 emission from light duty vehicles. Apart from political decisions that need to be taken, future powertrain concepts as outlined in this paper have to appear attractive to the customer. The powertrain of this concept has been evaluated upfront with a novel approach consisting of a CAE toolchain.

4. Driveability, Performance and NVH

In order to address all positive effects brought by the combination of CNG-DI (MTDI) operation and a P2-mHEV architecture, and bring the synergies to an optimum regarding the attributes, a thorough trade-off analysis is worthwhile getting conducted. For instance, it is not worth to increase torque response even further, when the anti-jerk control on the other end limits the transient response, as the powertrain-vehicle system is not yet optimised concerning low frequency response sensitivity. Same is as well valid for the

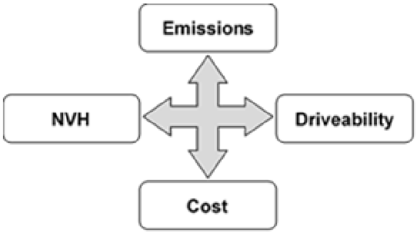

Figure 11: Trade-off between the individual disciplines

aspect of start and stop operation of the ICE during driving or at stand-still on hybrid powertrain systems, especially when it is based on a lay-shaft-transmission architecture. A generic trade-off between the individual disciplines is depicted in Figure 11.

In most cases different re-start and engagement methods are feasible, however, owed to the fact that the powertrain system is a flexible system, for each gear, speed and load point the most appropriate ICE-re-start approach needs to be identified to satisfy the requirements on driveability performance and NVH. In order to do this, a simulation tool chain was used to perform a corresponding up-front analysis to encompass among others the relevant manoeuvre “tip-in from coasting” (Figure 12).

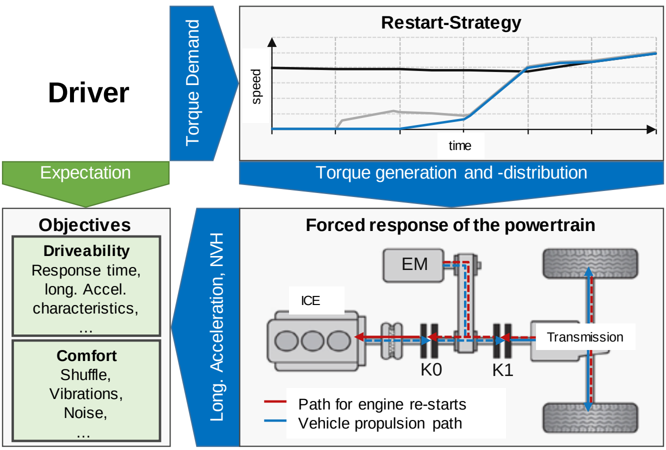

Figure 12: Simulation approach for engine start-stop optimization [9]

The relevant parameters out of the simulation were fed into a driveability evaluation tool [11], while setting the target score to 100%. A relevant score out of the manoeuvre “tip-in” was then drawn versus the target inputshaft of the transmission. Clearly, it can be observed in Figure 13 that different re-start strategies result in a different quality of driveability. Furthermore, when drawing the target line at 100%, the size of the window the vehicle

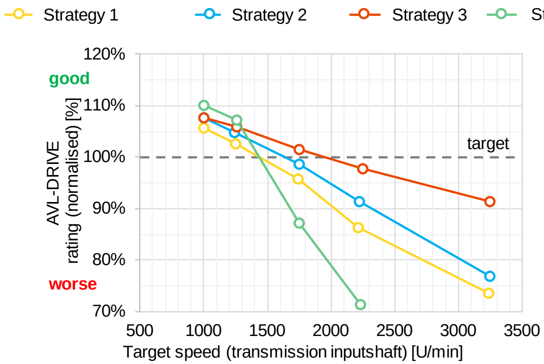

Figure 13: Feasibility of re-start strategy versus target rotational speed (full load, 3rd gear engaged)

will be able to coast is contoured. In the example given here, depicting results out of a full-load request (tip-in) from coasting in 3rd gear, reveals a maximum target-speed of the inputshaft of approximately *2100rpm* is revealed and defines the upper limit that would still satisfy the targeted driveability requirement. However, this performance and driveability can only be achieved when applying the *strategy#3*. By contrast, the most appropriate re-start strategy in the lower target speed range revealed to be *strategy#4*. Subsequently the window size of the operational range of the engine start-stop coasting and the recommended re-start strategy are then incorporated into the hybrid strategy, supporting an optimum trade-off between driveability, performance and fuel economy.

Making use of the knock-resistive fuel properties of CNG, the level of power/torque densitiy can be brought to an enhanced level [7], in this case supported on top by the addition of electric propulsion. Subsequently, this results in an altered level of transient performance of the vehicle, as it can drawn from Figure 14 for an representative driving manoeuvre, addressing the elasticity while reducing the time to 60 to 100km/h in 5th gear by almost 15% versus the base powertrain configuration.

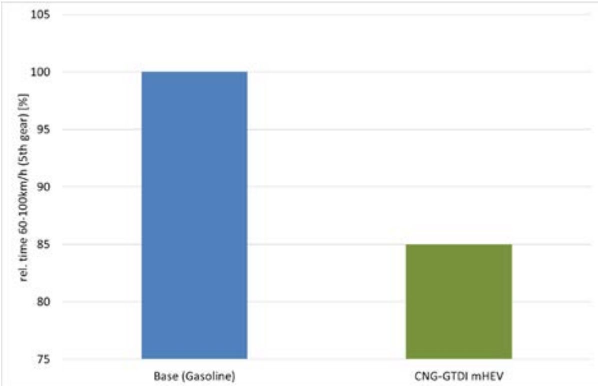

Figure 14: Improvement in performance (60-100km/h, 5th gear, full-load request) by introduction of a MTDI engine

Owed to the altered level of maximum peak cylinder pressures and higher cylinder pressure rise rates to make efficient use when combusting CNG in a DI combustion system, the engine and powertrain NVH within the mHEV system should deserve closer attention. First, an analysis of the direct combustion noise at $n_{ENG}=1500rpm$, $bmep=25bar$ reveals an increase of about 6dB (unweighted!) of the direct combustion noise excitation (Figure 15). However, this is caused mainly by an increase in the low frequency content (lower 100Hz), brought be the increased level of peak pressures [7].

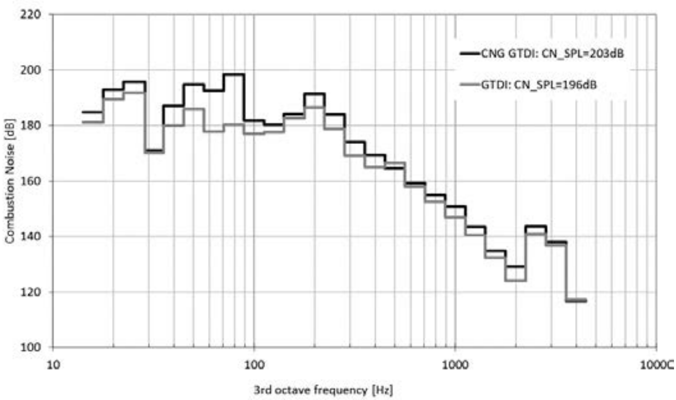

Figure 15: Direct combustion excitation – GTDI vs CNG DI at 1500rpm, 25bar BMEP

Operating with CNG DI will not increase the level of torsional vibrations significantly, even though the level of peak pressure will rise significantly. This can be explained by the location of the maximum peak pressure of an efficient CNG-DI combustion, which is located nearby the top-dead centre (TDC). Moreover, torsionals can be as well re-

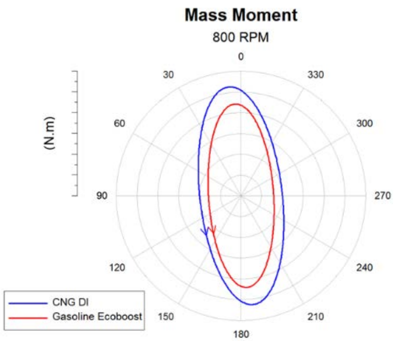

Figure 17: Engine couple during idle – GTDI vs CNG-DI

duced by an appropriate torque arbitration strategy between combustion engine and e-motor [10]. A final question was whether even at idle the increased excitation characteristics could deteriorate the comfort, even though this is rarely the case on a mHEV powertrain. However, if required, the engine operating in idle shall be hardly noticeable,

but due to fuel economy reasons the application of a balancer shaft has to be avoided. Figure 17 shows the resulting mass moment trajectory for a conventional GDTI versus the MTDI. The increase brought by the reinforced cranktrain (oscillating masses) to provide appropriate peak-pressure capability and power densitiy can be considered as negligible, i.e. a minor effect by the MTDI design can be observed.

5 Summary and Outlook

The concept of a mild hybrid powertrain presented in this report, consisting of a combustion engine specially developed for the use of methane, a semi-automated transmission and a 48V electrification module in a compact P2 design, was able to achieve its ambitious goals. This applies both to the significant reduction of climate-relevant exhaust gases and to the overall cost level. The combination of a highly efficient MTDI engine, with a fully variable intake valve on the intake side and an electric compressor and an electric motor integrated in the drivetrain, also meets all emission-related criteria and vehicle-related targets in terms of drivability and comfort.

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