Advances in Dynamic Skip Fire: eDSF and mDSF

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Summary

Global CO_2 mandates require a substantial increase in vehicle fuel efficiency over the next several years. Electrification will clearly play an increasing role for the vehicle propulsion system. An important segment of electrified powertrains are mild hybrid vehicles, which are expected to comprise the majority of electrified vehicles produced globally in 2025. However, efficiency improvements to the internal combustion engine must continue, since the majority of vehicles will continue to have engines for many years to come.

Delphi Technologies and Tula Technology have built and tested a demonstration vehicle that combines Dynamic Skip Fire (DSF) with 48V mild hybridization (which when coupled together is called eDSF) in a 4-cylinder turbocharged gasoline direct injection vehicle. DSF is an advanced cylinder deactivation strategy providing independent control for each cylinder on a cylinder-by-cylinder and cycle-by-cycle basis. The reduction in pumping losses provided by DSF offers a hybrid system additional available kinetic energy for recovery through regenerative braking. Test results show greater than 15% fuel consumption reduction with DSF and mild hybridization in the demonstration vehicle.

Tula Technology is also developing a novel concept designated as mDSF, which integrates Dynamic Skip Fire and Miller cycle engines, and is projected to reduce drive cycle CO_2 emissions by 10-12%. In mDSF, individual cylinders dynamically switch among three operating states: high charge firing (high cylinder load), low charge firing (with aggressive Miller cycle) and deactivation. The mDSF concept provides enhanced control over engine firing frequency and torque waveform compared with DSF, which helps to mitigate NVH issues that currently limit its efficiency improvement potential. mDSF also minimizes the efficiency-power tradeoff commonly required in Miller cycle engines and maximizes the best fuel consumption area through cylinder deactivation.

1 Introduction to Dynamic Skip Fire

Dynamic Skip Fire optimizes the operation of conventional engines by only firing the cylinders events required to meet the torque demand. As can be seen in Figure 1, as torque demand increases, a larger fraction of cylinder events is fired. As torque demand decreases, fewer cylinder events are fired. When torque demand is zero, for example during deceleration events, no cylinders are fired. This eliminates the penalty of saturating the catalyst with oxygen that conventional engines have. In contrast, rather than merely shutting off fueling, DSF deactivates both intake and exhaust valves in a cylinder.

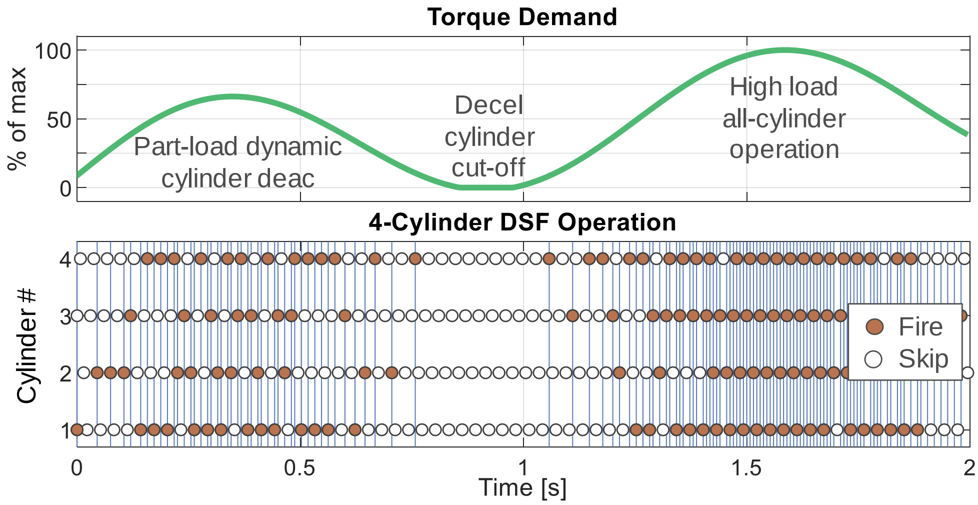

Fig. 1: DSF in a Transient Maneuver

1.1 Dynamic Skip Fire Valvetrain Deactivation Hardware

To enable the individual cylinder deactivation required for DSF, an experimental cylinder head was designed and fitted with Delphi Technologies deactivation roller finger followers (dRFF) on the intake and exhaust valves of all cylinders. The experimental head can be seen in Figure 2.

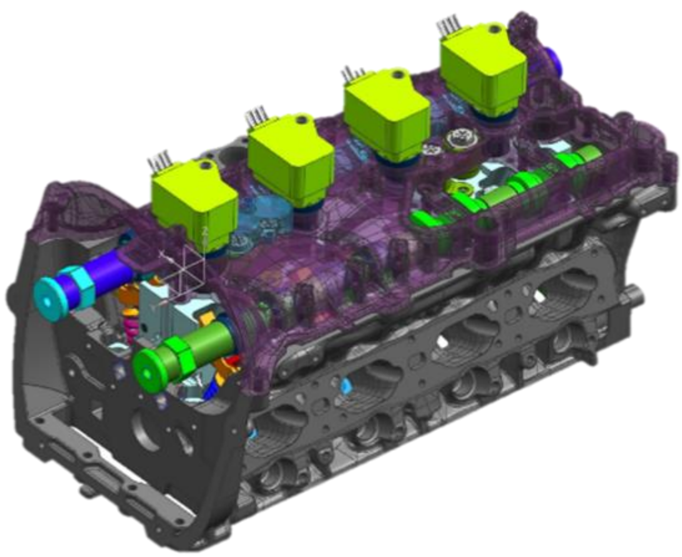

Fig. 2: Development DSF cylinder head with project specific hardware installed (modified casting, Deactivation Roller Finger Followers, Deactivation Control Valves, intake and exhaust camshafts and machined cam cover)

Deactivation roller finger followers shown in Figure 3 vary valve actuation between full and zero lift to enable cylinder deactivation by switching between a standard cam profile and a base circle cam profile. A hydraulic circuit, controlled by an oil control valve, uses oil pressure to move a pin that engages / disengages a lost motion device in the body of the dRFF. One deactivation control valve was used for each engine cylinder to control dRFF operation for both intake valves and both exhaust valves for that cylinder. To deactivate a cylinder, a signal is sent to the appropriate oil control valve so that the dRFFs for that cylinder move in lost motion as they ride along the cam profiles; consequently, the valves remain closed. To reactivate the cylinder, the oil control valve releases the oil pressure, a spring forces the pin back into engagement, and the dRFF behaves like a normal type-2 roller finger to open the valve as it rides along the cam profile. Figure 4 provides a schematic view of the dRFF in activation (left) and deactivation (right) modes, respectively.

Fig. 3: Deactivation Roller Finger Follower (dRFF) on left and Deactivation Control Valve on the right. Shown in the figure are production level designs (mule level designs were used during testing)

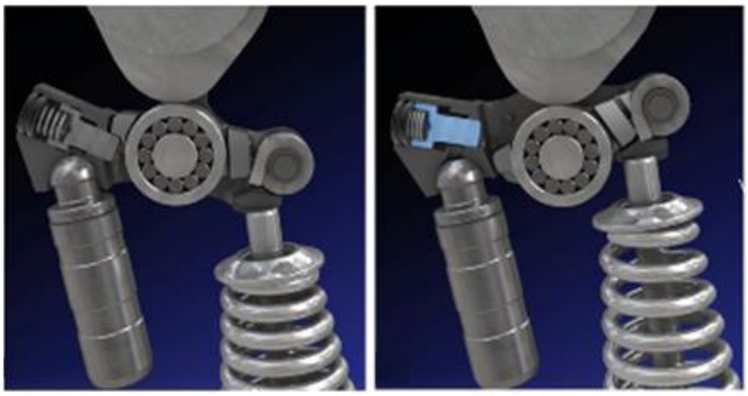

Fig. 4: Deactivation Roller Finger Follower at peak cam lift, in Activated (left) and Deactivated (right) states

1.2 Vibration Management

A great deal of effort has been put into algorithms and calibration to precisely meter torque output while increasing efficiency and deactivating cylinders. In general, repetitive excitations at low frequencies are avoided. Dynamic Skip Fire calibration is adjusted subject to a weighting function similar to the W_d and W_k standards found in

ISO 2631 and shown in Figure 5. Detail about basic NVH response methods were shown in prior work [1]-[3].

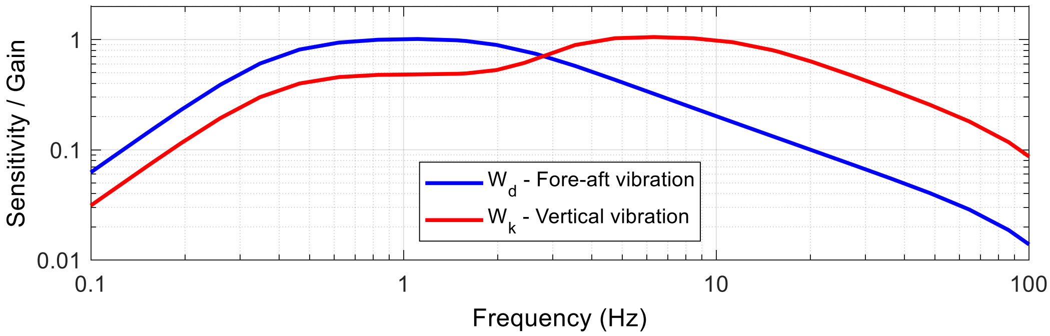

Fig. 5: ISO 2631 Standard Weighting Functions for Human Sensitivity to Vibration

2 eDSF: Synergies with Mild Hybridization

Mild hybrid systems are gaining increased acceptance with automotive manufacturers because of the high value of this architecture and the fuel consumption improvements due to kinetic energy recovery. An architecture that is quickly gaining acceptance in the automotive community is a P0 dual voltage architecture that uses a belt driven high torque 48V Motor Generator Unit (MGU) on the front of engine accessory drive (FEAD). In addition to traditional generator functions, this system can provide additional torque to the engine, through the motoring function of the MGU, plus offers significant improvements to the stop/start function.

Energy recovery during vehicle operation is accomplished during vehicle decelerations. The MGU operates in generating mode and vehicle kinetic energy is recaptured through the FEAD and converted to stored energy in the battery. If the required deceleration rate is greater than can be accomplished solely via torque absorption through the MGU, additional braking is provided by the vehicle’s mechanical (friction) brakes.

Stored battery power can be used by applying torque from the MGU to the drivetrain through the FEAD, or can be used to drive vehicle electrical loads.

Of particular interest for this project, DSF allows for all cylinders to be shut off when the torque required from the engine is at or below zero. While this strategy of Deceleration Cylinder Cutoff (DCCO) avoids saturating the catalyst with oxygen during deceleration, it also significantly reduces engine pumping losses (engine braking) during decelerations. By reducing or eliminating engine braking, more of the vehicle's kinetic energy is available for regeneration by the hybrid system. Therefore, mild hybrid and DSF technologies combine to recuperate more kinetic energy than has traditionally been available.

2.1 Synergies of Mild Electrification and DSF

Mild hybrid torque delivery or absorption generally occurs during high-load (torque assist) or no-load (regenerative braking) conditions. Since DSF is a part-load technology, there is little competition for fuel consumption improvement between mild hybrid and DSF; the gains are largely additive, and the functions are very good partners.

In addition, there are situations where the benefits are more than additive. eDSF achieves three major synergies by operating DSF in conjunction with hybrid systems: enhanced regeneration during deceleration, expansion of DSF operation with torque assist, and expansion of DSF operation with torque smoothing.

2.1.1 Enhanced Deceleration Regeneration

DCCO completely avoids pumping losses that normally occur during vehicle deceleration compared to all-cylinder operation with deceleration fuel cutoff (DFCO). For a given desired vehicle deceleration profile, the resulting reduction in engine braking allows greater regenerative braking by the 48V generator.

2.1.2 Expansion of DSF Operation through Torque Assist

Standard mild hybrid strategies provide torque assist with the electric motor primarily under high load conditions (e.g. vehicle launch). This creates a responsive drivability feel, which is especially important for downsized turbocharged engines. Because electric torque supplements the combustion engine torque, it can also provide additional opportunity for DSF operation. DSF has better fuel consumption at low loads compared with all-cylinder operation, so implementation of mild hybrid control strategies that account for this can provide better overall fuel consumption.

2.1.3 Expansion of DSF Operation through Torque Smoothing

Skip fire operation increases cylinder torque pulse magnitude for fired cylinders, and spaces the fired cylinder torque pulses farther from each other in time than all-cylinder operation. This introduces more low-frequency content in the torque excitations on the drivetrain and thus of the vehicle's chassis. An advanced function of eDSF is to use an electric motor-generator unit (MGU) to counter the low frequency excitation.

A countering torque waveform can be generated as conceptually shown in Figure 6. Here the large, wider-spaced torque pulses from combustion are partially captured by an MGU negative (generating) torque pulse, and stored in an energy storage device such as a battery or capacitor. During skipped cylinder events, this energy is reapplied on the powertrain in the form of a positive torque pulse or wave. In practice, the electric torque pulses only partially reproduce the missing combustion torque pulses, due to MGU torque and power limitations.

Lower magnitude pulses or waveforms that reproduce some of the characteristics of the skipped combustion torque pulses are used. In this manner, the lower frequency components of the resultant combined torque waveform are reduced as shown at right in the figure. The torque excitation spectral components are shifted to higher frequencies where vehicle attenuation characteristics are generally better, and vibrations are less perceptible by humans. Figure 5 showed human whole-body vibration perception characteristics [3], in which the frequency range 0.5 to 12Hz is the most perceptible in various directions of vibration.

This smoothing torque is used optimally to obtain the maximum benefit of reducing perceived accelerations while minimizing energy losses in the process of storing and providing torque/power from the MGU to provide the best fuel consumption reduction at each operating condition.

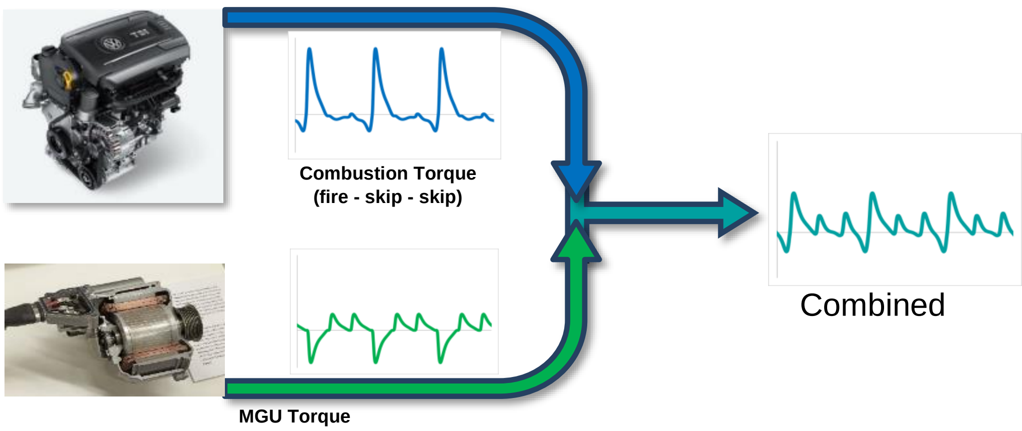

Fig. 6: Torque Smoothing Principle

2.2 eDSF Test Results: Simple Implementation

Vehicle testing described here considered a simple implementation of eDSF. No active torque smoothing was employed by the 48V hybrid system. This mechanization allows determination of CO_2 reduction benefits including synergies due to enhanced regeneration and expansion of DSF operation through torque assist. Data shown represents the status of development at the time of this writing. Work continues and further refinement and CO_2 reductions are expected.

A 2016 Volkwagen Passat, shown in Figure 7, with a 1.8L TGDi EA888 Gen 3 engine was upfitted to a P0 48V mild hybrid configuration including a Delphi Technologies DC/DC converter. Figure 8 shows a schematic diagram of the 48V system in the project vehicle. Also included in the P0 architecture are an engine mounted MGU and a 48 Volt Lithium-Ion battery with 8 Ahr working capacity. This P0 configuration adsorbed up to 13 kW during regeneration and delivered up to 10kW as an electric motor. An electric pump was added to maintain transmission pressure during stop/start operation. To increase kinetic energy recovery, vehicle braking was accomplished preferentially through regeneration by the MGU and supplemented, as required, by the production hydraulic friction braking system.

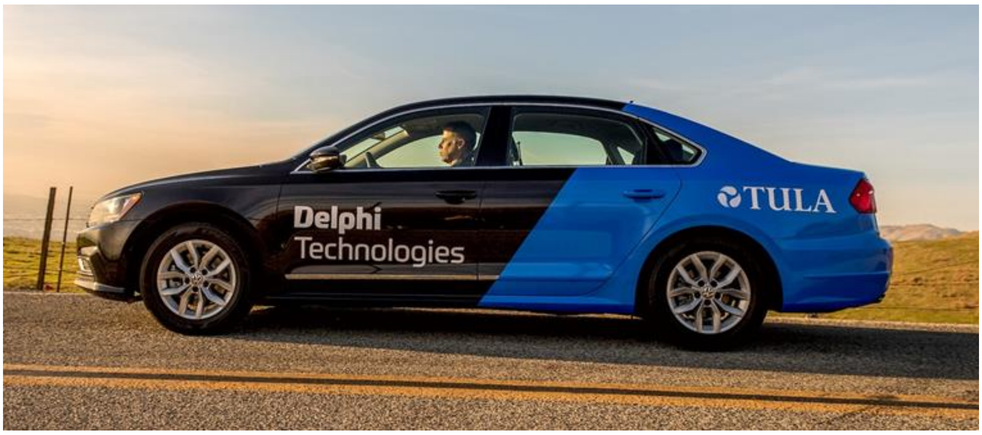

Fig. 7: 48V with eDSF Development Vehicle

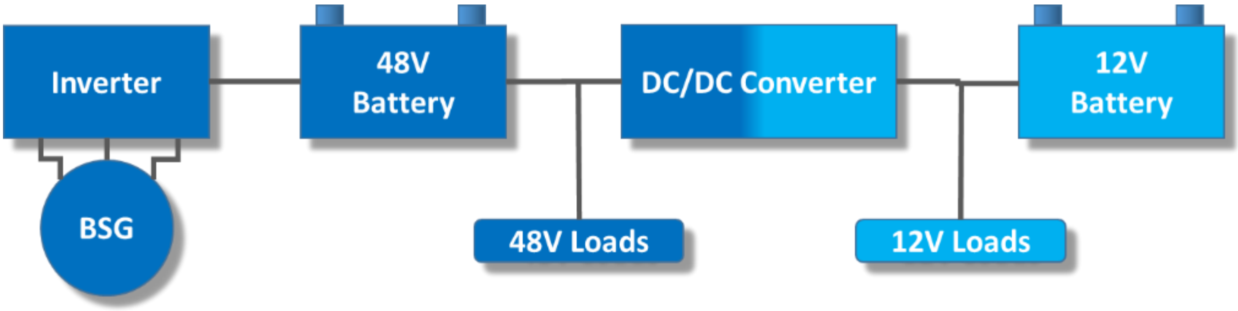

Fig. 8: Schematic Diagram of the 48V Mild Hybrid System Mechanization

System control was accomplished using a Delphi Technologies engine management system (EMS) in a production Delphi Technologies controller that included 48V mild hybrid functionality and Tula Technology's DSF algorithms. The Delphi Technologies transmission control module (TCM) allowed enhanced control of shift schedules and converter slip. To reflect the current industry trend toward higher injection pressures the fuel system was converted to a Delphi Technologies production-level 350 bar GDi fuel system.

Testing was conducted in the vehicle emissions laboratory at Delphi Technologies in Auburn Hills, Michigan, USA. The vehicle test cell utilizes a chassis dyno simulating road load, and is held at a controlled temperature and relative humidity. Test cycles included the US EPA 2-cycle test (FTP-75 + HWFET).

The technology package of 48V mild hybridization with eDSF offers complementary modes for CO_2 reduction. A 48V mild hybrid reduces CO_2 mostly due to energy recuperation during decelerations, reducing the total energy demand from the engine during a test cycle. DSF improves the efficiency of engine operation by firing fewer engine cylinders at higher load for reduced engine pumping losses and improved thermodynamic efficiency.

It is the reduction in pumping losses provided by DSF that leads to the synergistic improvement afforded by implementing both technologies. During light vehicle decelerations, when no torque is required from the engine, DCCO prevents any air from being pumped through the engine. The resulting reduction in engine braking allows greater kinetic energy recovery by the 48V generator to achieve a given vehicle deceleration profile.

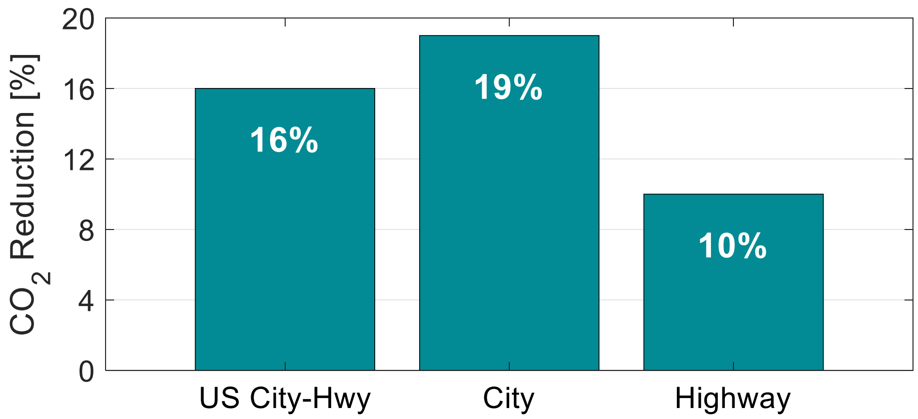

Fig. 9: Test results showing percentage CO_2 reduction results of 48V mild hybrid with eDSF system compared to the baseline vehicle

As shown in Figure 9, 48V with eDSF delivered 19% CO_2 reduction for the city cycle and 10% over the highway test cycle, resulting in a combined benefit of 16%. CO_2 reduction from 48V with eDSF was better under the city cycle. Frequent engine operation under light engine loads enables significant benefit from DSF. Additionally, that test cycle includes a substantial number of decelerations affording significant energy recuperation by the 48V mild hybrid system.

Nevertheless, the technology package offers substantial benefit over the highway cycle. Though regenerative braking occurs more infrequently over the highway cycle than during city testing, the recuperated energy still substantially reduced the overall engine torque required to drive the 12V electrical loads. This reduced engine torque directly reduced CO_2 emissions. Also, with DSF, the reduction in required torque increased the fraction of time that the engine operated within the DSF fly zone to deliver improved engine efficiency and additional CO_2 reduction.

2.3 Torque Smoothing

2.3.1 Torque Smoothing Hardware Requirements

Work is currently ongoing at Tula Technology to develop torque smoothing benefits for eDSF.

The eDSF torque smoothing function may pass a significant amount of power bidirectionally through the MGU, inverter and energy storage system (ESS) in a round-trip path from negative (generating) torque pulses through the MGU, inverter and ESS, and back out to positive (motoring) pulses on the crankshaft or drivetrain.

So that energy/power losses in this roundtrip are small enough to result in a fuel consumption benefit in performing the torque smoothing function, all components in the path should have high efficiency, and their bandwidth of operation should be high enough to cover the frequency content of the smoothing waveforms.

The following subsections discuss these considerations of efficiency and bandwidth.

2.3.1.1 Motor Generator Unit

MGUs are designed for high efficiency within cost constraints of the target application. There are several technologies of automotive traction MGUs in the current market, including permanent magnet synchronous machines (PMSM), AC induction machines (ACIM), and switched reluctance machines (SRM). Generally, PM machines have higher power to volume ratio than other types and thus for P0 applications are more easily packaged underhood in today's vehicles' engine bays, if at somewhat higher cost due to the rare earth magnets typically employed.

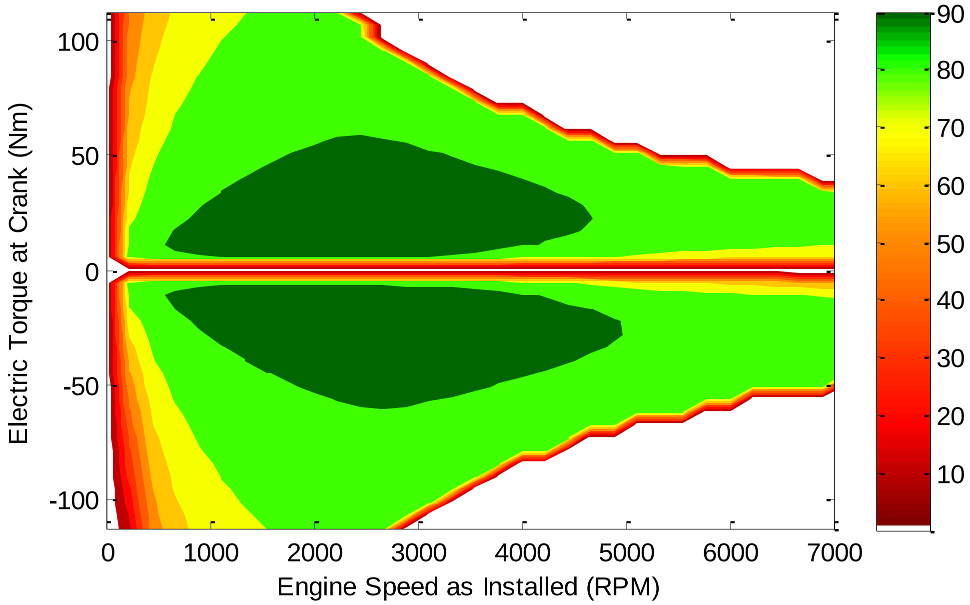

Fig. 10: PMSM Inverter Integrated Efficiency Map Example

Figure 10 shows a conceptual map of MGU one-way efficiency vs. torque and speed, integrated with inverter, expressed at the crankshaft. The stator winding arrangement and construction affects the shape of this map, in particular the corner speed between torque limited operation and power limited operation. Depending on the planned duty cycle of the MGU, an appropriate stator winding arrangement, and pulley ratio for belt driven applications, should be chosen, so that the torque and speed operating range has high efficiency.

The combined MGU and inverter efficiency shown in Figure 10 demonstrates a high efficiency range well suited for eDSF. The areas most relevant to torque smoothing operation achieve efficiencies in the neighborhood of 90%.

The open-loop rate of change of current, and thus torque, in a PM machine is related to the stator inductance to resistance ratio. With closed-loop current control in the inverter, however, the current dynamics can easily meet the requirements for eDSF torque smoothing application as described in the next section.

2.3.1.2 Inverter

Controlling the inverter appropriately is critical for eDSF. Modern vector control, or field oriented control (FOC) algorithms provide high performance, high bandwidth, low loss torque control, when properly configured with correct machine parameters.

For torque smoothing control the bandwidth should not be artificially limited to a response rate less than 5-10Hz which is sometimes done in automotive propulsion inverters. Thus, a challenge of using common commercial inverters is overcoming artificial limitations that were intentionally or unintentionally introduced in inverter software. Care should be taken to avoid low sampling rates or filtering of the input torque requests, which make the inverter software less capable of achieving the modest bandwidth requirements of eDSF torque smoothing. The electronic hardware components are rarely the bandwidth limiting factor; switching control is commonly employed at frequencies greater than 10kHz.

High performance inverters fortunately already perform very well in terms of efficiency. Losses in the inverter hardware consist of the Rds(on) of the power FETs under load and FET driver switching losses when idle. Automotive inverters commonly employ MOSFETs which typically achieve > 96% efficiency.

2.3.1.3 Energy Storage System

Because of the oscillating positive and negative power demands, the energy storage system efficiency is critical for torque smoothing. Generally, capacitors have lowest round trip losses in the range 97-99% at 48V. Super-capacitors, having many low voltage modules in series may have higher equivalent series resistance (ESR) and thus marginally lower efficiency.

Battery design has also advanced, and efficiencies of well above 90% have been reported. An important constraint of these batteries is their capacity to source and sink current, depending on the battery chemistry, construction and temperature.

Optimized configurations including combinations of capacitors and batteries can be contemplated. For the simulations presented here, a 48V lithium iron phosphate battery was assumed.

2.3.1.4 Front of Engine Accessory Drive

In a P0 configuration, the MGU is attached to the crankshaft at the FEAD. The high-magnitude, reversing torques applied to the belt require that the FEAD be adequately engineered to maintain consistent belt contact between the driven and drive pulleys over the full eDSF operating range.

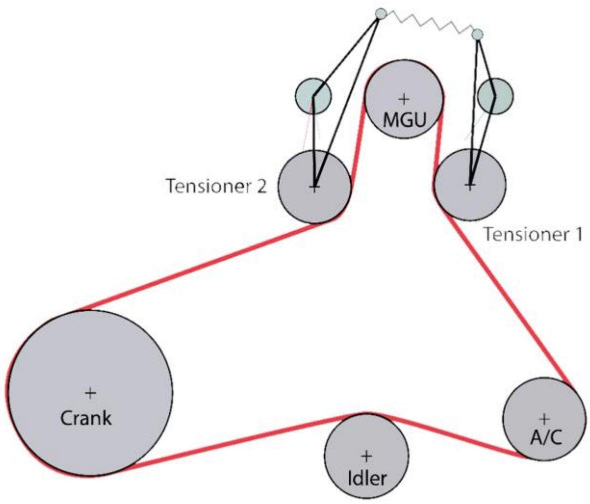

Fig. 11: Bidirectional FEAD Tensioner Arrangement

A typical FEAD tensioner system consists of two pulleys, one on either side of the MGU that are spring loaded and to some degree coupled to each other as shown in Figure 11. This arrangement keeps the belt adequately wrapped and ideally in non-slipping contact around the MGU pulley.

The FEAD system can be simulated by creating a multibody, planar representation of the belt, pulleys, and tensioner masses, spring constants, and damping factors. The combustion torques and/or rotational speed of the crankshaft and torque waveforms of the MGU are used to drive a dynamic simulation which can predict tensions in each span of the belt, slipping at the driven pulleys, and other quantities needing to comply with engineering constraints.

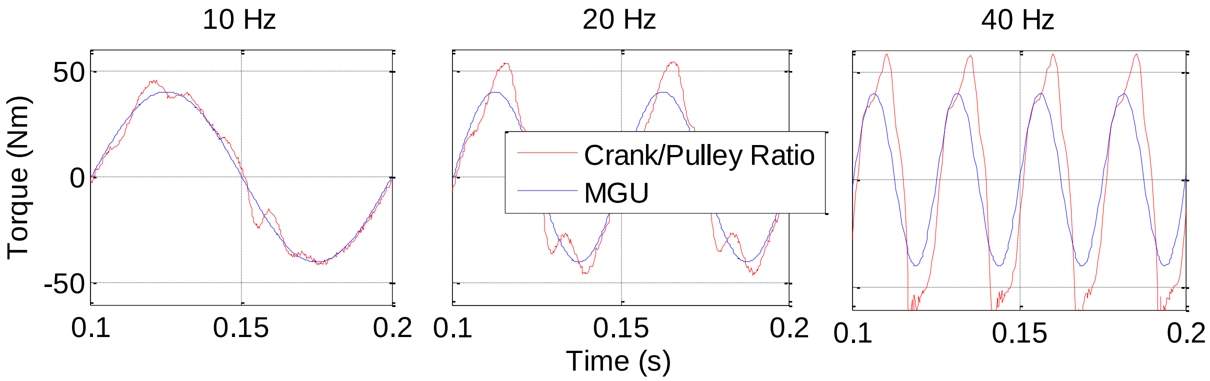

Fig. 12: Crankshaft Torque Responses to Sinusoidal MGU Torque Inputs at Various Frequencies

Figure 12 shows example responses of torque at the crankshaft to torque applied at the MGU, adjusted by pulley ratio, with the tensioner system parameters set at values typical for a mild hybrid application. There is some distortion and phase lag of the torque due to the dynamic response of the FEAD, which is fundamentally a collection of springs, masses, and dampers. These effects need to be adequately accounted for in the torque smoothing controller as described in the next section.

Variation of parameters can be explored in simulation to optimize the belt and tensioner configuration. Parameters include the static pretension of the belt, belt number of ribs, belt stiffness, tensioner spring constant(s), and tensioner geometry. Reference [5] describes these methods in more detail.

2.3.2 Control Considerations

2.3.2.1 Energy Management

The simplest energy management strategy for torque smoothing with eDSF, conceptually, is a charge maintaining strategy in which no net storage or depletion of battery charge occurs over time. In this mode, charge in the energy storage device is maintained by an increase in combustion engine torque mean value to account for losses in the MGU, inverter, and ESS.

DSF and eDSF have several synergies with mild hybrid functions such as torque assist and decel regeneration as described earlier. More sophisticated energy management strategies can be contemplated that optimize drive cycle fuel consumption through more intelligent choice of the storage and release of energy from the ESS.

2.3.2.2 Torque Smoothing

In a drive cycle, skip-fire sequences are continually changing, along with the electric torque smoothing waveform. Torque smoothing waveforms are bandwidth limited to the low frequency range that is most important from response and perception. As described previously, the frequency range 0.5 to 12Hz is the most perceptible in various directions of vibration. For implementation a practical maximum required torque frequency response of the MGU system of 35Hz can be chosen.

Torque smoothing algorithms extend DSF operation by allowing skip-fire sequences that have noise or vibration characteristics exceeding NVH targets to become acceptable. Fuel consumption is improved due to greater utilization of skip-fire operating conditions that have lower fuel consumption. Thus, the torque smoothing algorithms calculate the lowest fuel consumption combination of firing density and torque smoothing magnitude. This can largely be precomputed and incorporated in the controller in the form of calibrations.

One method of creating torque smoothing waveforms of appropriate bandwidth is to model the combustion torque at each operating condition and create a countering MGU waveform antiphase to it, as described in the introduction. The waveform should have zero mean mechanical torque or power, and should only include frequency content that has most impact on vehicle/powertrain vibration response and perception, in order to have best fuel economy improvements.

Figure 13 shows a simple example of a countering waveform constructed from harmonics of appropriate magnitude and phase. This example is relevant for a firing sequence that repetitively fires once and then skips twice. Summing the three harmonics shown in the upper plot creates a target torque waveform to be supplied by the MGU shown in the middle plot. Limiting the overall countering waveform to the first three harmonics of engine operation results in the required mitigation waveform with the lowest frequency content, which is important for practical implementation purposes. The bottom plot shows the original combustion engine torque in blue and the modified combustion plus electric torque in green. This modified flywheel torque has less content at the lowest frequencies and more content at higher frequencies that are outside the range of perceptibility.

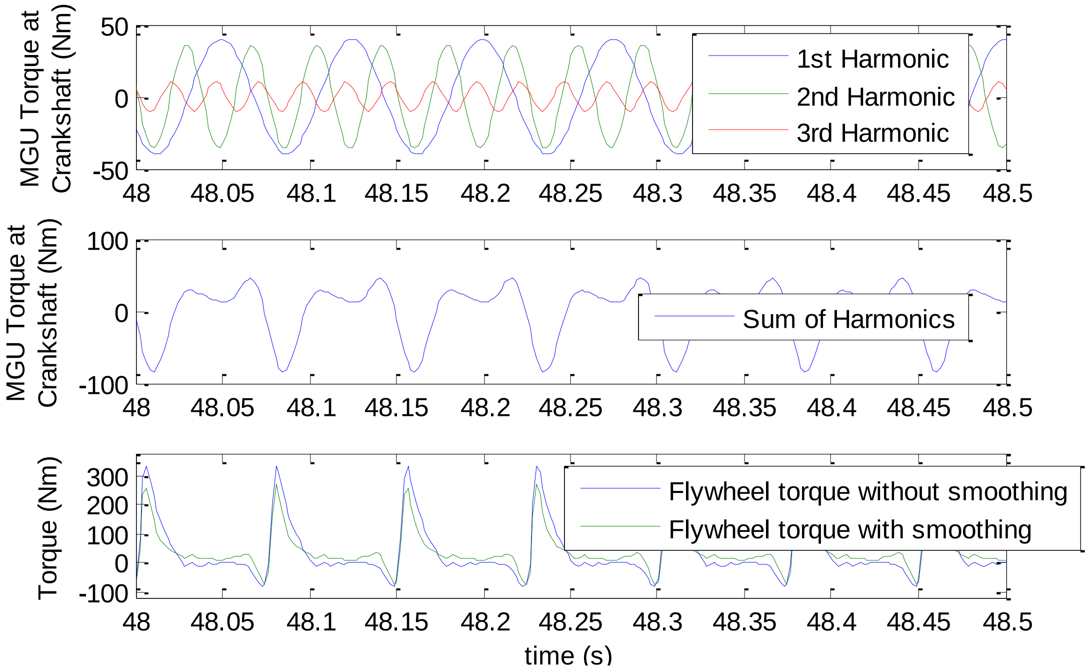

Fig. 13: Torque smoothing target waveform harmonics (top), sum of harmonics (middle), and flywheel torque before and after application of torque smoothing (bottom)

When a target torque waveform desired to be applied to the crankshaft is constructed, an MGU waveform that properly accounts for the phase and magnitude response of the FEAD system must be derived. One method by which this can be done is with modeling of the frequency response characteristics of the FEAD and reduction to appropriate tables and functions in the controller, that will then be inverted to introduce appropriate phase lead and gain for the current FEAD conditions.

A simpler approach is to include a feedback or adaptive controller that automatically ensures that the torque at the crankshaft is at appropriate phase and magnitude. This system has been implemented successfully and results are presented in the next section.

There is a varying amount of engineering effort and ECM resources needed to implement predictive, model based approaches versus adaptive/feedback strategies.

2.3.3 Vehicle Vibration Improvement with Torque Smoothing

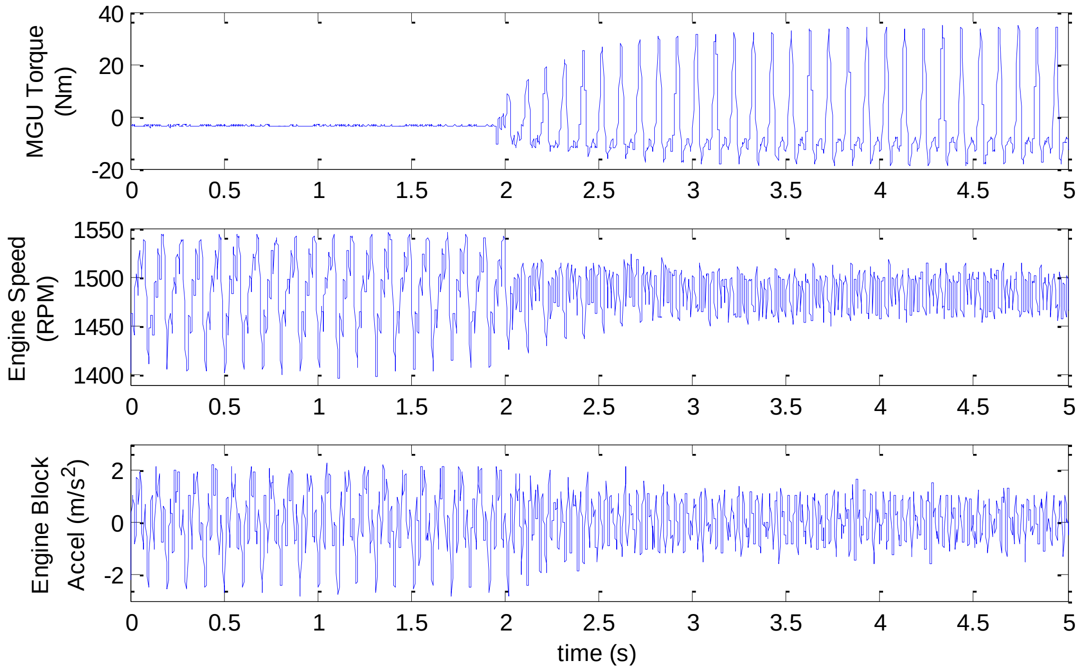

Fig. 14: eDSF Crank Torsional Variation Reduction Example, Time Traces

Figure 14 shows example experimental data for engine speed oscillation reduction when MGU torque smoothing is turned on, measured on vehicle on a chassis dynamometer. Here, engine speed variation magnitude is reduced by roughly half through application of a 25 Nm amplitude torque waveform.

Figure 15 shows the corresponding reduction in engine speed harmonics amplitude before and after application of the MGU torque smoothing. Dramatic improvements are seen, with a reduction in acceleration at the critical 10Hz region of greater than 30 dB, which represents a reduction in the absolute scale of over 97%.

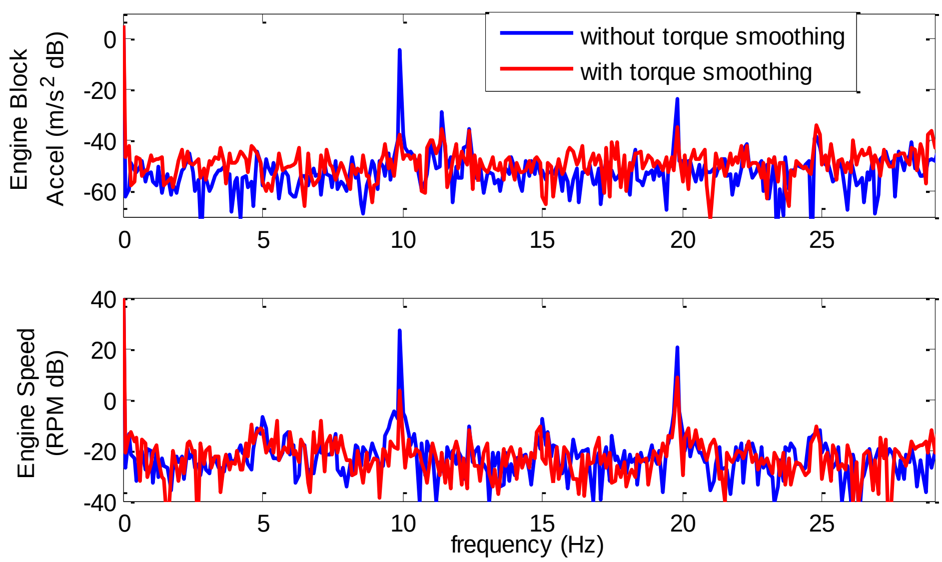

Fig. 15: eDSF Crank Torsional Variation Reduction Example, Spectra

2.3.4 Fuel Consumption Projections

2.3.4.1 Powertrain and Vehicle Model

A drive cycle fuel economy prediction model was created consisting of an engine/vehicle model combined with an engine/transmission controller model.

A vehicle model representing a VW Jetta with DSF 1.8L turbocharged engine was developed for drive cycle fuel consumption projection. Table 1 shows specifics. Inertias and mechanical efficiencies of powertrain components are accounted for.

Tab. 1: Target Vehicle and Powertrain

Vehicle	2015 Volkswagen Jetta SEL with US EPA test weight class and retarding force coefficients.
Engine	1.8L GTDI EA888
Transmission	6-speed automatic with torque converter and torque converter clutch

Important model outputs are the combined hybrid powertrain torque, vehicle acceleration, fuel consumption, and ESS state of charge.

As a routine part of powertrain integration with OEM vehicle platforms, noise and vibration related hardware is optimized, particularly with respect to torsional mitigation, exhaust system design and engine mounting hardware. Devices may be included such as centrifugal pendulum absorbers, dual mass flywheels, and tilgers. For simulation purposes, it was assumed that a vibration mitigation hardware device was incorporated in the powertrain in addition to the stock torque converter and torque converter clutch. The same mitigation hardware was assumed for all simulations presented here.

2.3.4.2 Hybrid System Model

Tab. 2: Target Vehicle Hybrid System

MGU	12kW power constraint, 44Nm torque constraint P0 with 2.2 pulley ratio
ESS	48V, 8Ah Lithium-iron-phosphate battery

Data sheet information for the MGU and battery were used to create models containing MGU motoring/generating efficiency maps and battery charge/discharge efficiency maps. With these models the state of charge of the battery is tracked.

2.3.4.3 Controller Models

The torque demand is provided by a driver model which incorporates vehicle and powertrain characteristics to calculate accelerator pedal and brake pedal inputs and corresponding powertrain and brake system torque demands to follow the vehicle speed target trace for each test cycle within +/-3 km/h.

Control strategy models calculate commanded firing density, cylinder torque, and MGU torque to satisfy demanded powertrain torque, along with transmission gear and TCC slip. The MGU torque level is used to modify torque commands to the combustion engine and friction brakes.

The controller model minimizes fuel consumption for a given engine torque, subject to constraints on predicted noise and vibration. In the fuel consumption minimization, losses in the MGU, inverter and ESS are accounted for by an increase in the mean-value engine torque command. This is extremely simplified, as intelligent charging would normally be used to replace the energy losses in the battery rather than always increasing the engine torque. To simplify this calculation in the controller model, a constant value of 75% roundtrip efficiency is used.

Regarding operation of the mild hybrid functions, simple models for regenerative braking and torque assist were included. For regenerative braking, the maximum regeneration was applied, subject to MGU power and torque constraints, and battery charge current constraints.

Torque assist is applied when battery state of charge (SoC) is above 40%, subject to MGU torque and power limits, and battery charge current limits. For each simulation a 48V battery SoC initial condition is used that matches the final SoC.

Sophisticated energy management strategies that optimize drive cycle fuel consumption through intelligent choice of the storage and release of energy from the ESS were not included in this simulation study.

A transmission controller model following the stock vehicle shift schedule was included, and for this study a constant TCC slip target was used for all conditions.

2.3.4.4 Fuel Consumption Simulation Results

Figure 16 shows predicted CO_2 reduction for the eDSF system versus DSF without electrification and all-cylinder operation with mild hybrid electrification, on US City-Highway, NEDC, WLTC and JC08 test cycles. The reduction in CO_2 of the eDSF system over base all-cylinder operation ranges from 18% to 28% depending on drive cycle. The reduction of fuel consumption of eDSF over 48V mild hybrid operation ranges from 8.4% to 10.8%. The synergy between eDSF and mild hybrid vehicles results from increased coast regeneration and regenerative braking, made possible with the near elimination of engine pumping losses, and the increased operating region of eDSF over base DSF.

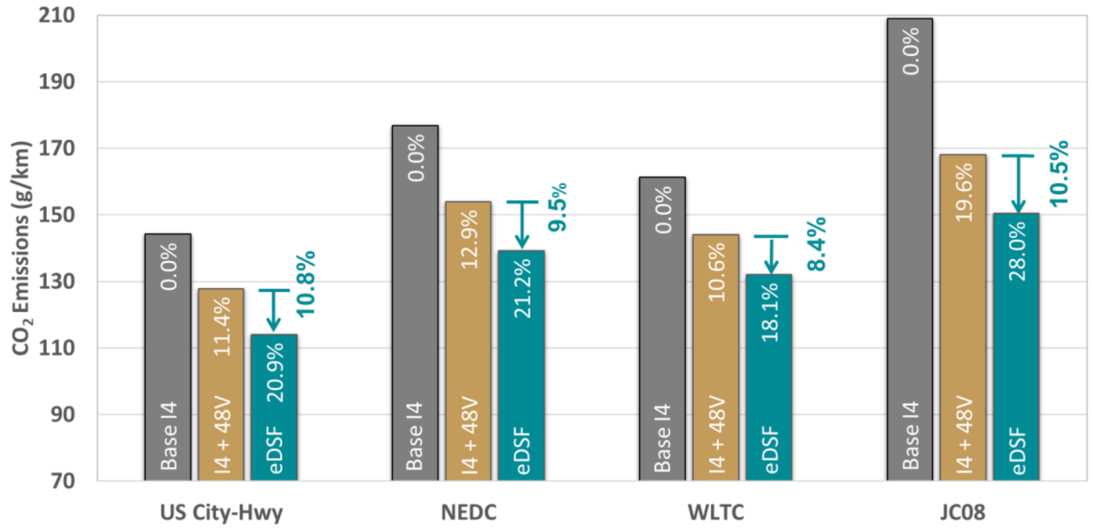

Fig. 16: CO_2 Emissions Reduction by Drive Cycle for DSF, All-cylinder with Mild Hybrid and eDSF vs. Base All-Cylinder Operation without Electrification

Of particular note is the improvement over the vehicle tests (shown earlier as 16%), which in this simulation improves to 20.9%. Tula believes that result is now within reach, due primarily to three areas that are currently being optimized:

1. Test results shown earlier did not yet incorporate the torsional smoothing aspect of eDSF. As mentioned, torsional smoothing allows DSF to have a greater range of operation and thus higher efficiency.
2. The eDSF flyzone was conservatively created, assuming there would be no changes to vehicle hardware from the production vehicle. Tula's experience on other vehicles, in particular the similar VW Jetta, has shown that a calibration that incorporates a simple torsional mitigation system will improve fuel consumption a further 2%.
3. A full optimization of all mild hybrid functionality coupled with eDSF has not yet been undertaken.

Of course, the simulation results are dependent on vehicle chosen. MGU and battery constraints, component efficiencies, mild hybrid strategy, battery capacity, and other factors will impact the final numbers achieved. However, Tula feels these results are representative of the mid-size sedan market.

3 mDSF: Synergies with Miller Cycle Engines

Despite the positive outlook for eDSF, not all powertrains offered are currently outfitted with mild hybrid powertrains. Additionally, the potential for DSF can be limited in smaller, heavily loaded three- and four-cylinder engines due to overall lower firing frequencies which deteriorate NVH. The proposed mDSF technology unlocks DSF's potential for fuel efficiency improvement, while strengthening alignment with global automotive trends.

Miller cycle gasoline engines – achieved through a combination of early or late intake valve closing (EIVC or LIVC), higher compression ratios, moderate displacement increases and intake air boosting – have demonstrated sizable reductions in vehicle fuel consumption from reduced pumping losses and increased expansion work [6]-[9]. The Miller cycle can deliver benefits throughout the usable engine operating range and has made it into several production applications. Comparing the previous generation Audi 1.8L EA888 Gen. 3 engine with the current generation 2.0L Miller cycle engine designated as the EA888 Gen. 3B [10], the brake specific fuel consumption (BSFC) was reduced by 5% to 15% depending on engine speed and load. This includes friction improvements enabled by lower specific loads in the upsized engine.

The combustion system for the Miller cycle requires detailed consideration, since the EIVC strategy impacts charge motion and subsequent combustion behavior. Typically, the intake ports and combustion chamber must be redesigned to enhance and conserve tumble intensity through the spark ignition event. This can be achieved through steeper intake port angles, valve masking and piston crown shaping [10].

The airflow restriction resulting from lower lift, shorter duration intake valve events typically leads to a detrimental compromise between maximum power and best efficiency. With a 2-step intake valve lift system, more optimal low power and highpower configurations can be designed to maximize part load efficiency and deliver the target peak torque. At low speeds and loads, the low lift (shorter duration) Miller configuration delivers better fuel consumption. At higher speeds and loads, the high lift (longer duration) configuration increases flow area and allows sufficient airflow to meet rated torque and power targets. In current production applications, however, the low lift Miller cycle follows a relatively mild design so it can have enough torque capacity for most normal driving conditions. This minimizes the fuel consumption penalty of mode transitions, but limits the potential efficiency benefit of the Miller cycle engine.

3.1 mDSF Concept

Tula Technology is developing a novel concept designated as mDSF, which intelligently combines DSF and 2-step Miller cycle engine technologies. mDSF aims to simultaneously address the NVH constraints and efficiency-power tradeoffs that limit the fuel efficiency improvement potential of these technologies. mDSF improves upon DSF by allowing individual cylinders to dynamically switch among three operating states: high charge firing (high cylinder load), low charge firing (low cylinder load, using aggressive Miller cycle) and deactivation. This strategy provides enhanced control over engine firing frequency and torque waveform, which can be used to more effectively mitigate NVH issues. mDSF also enables a more aggressive Miller cycle strategy by employing novel DSF based control algorithms during mode transitions, which reinforces the synergistic benefits with 2-step Miller cycle engines.

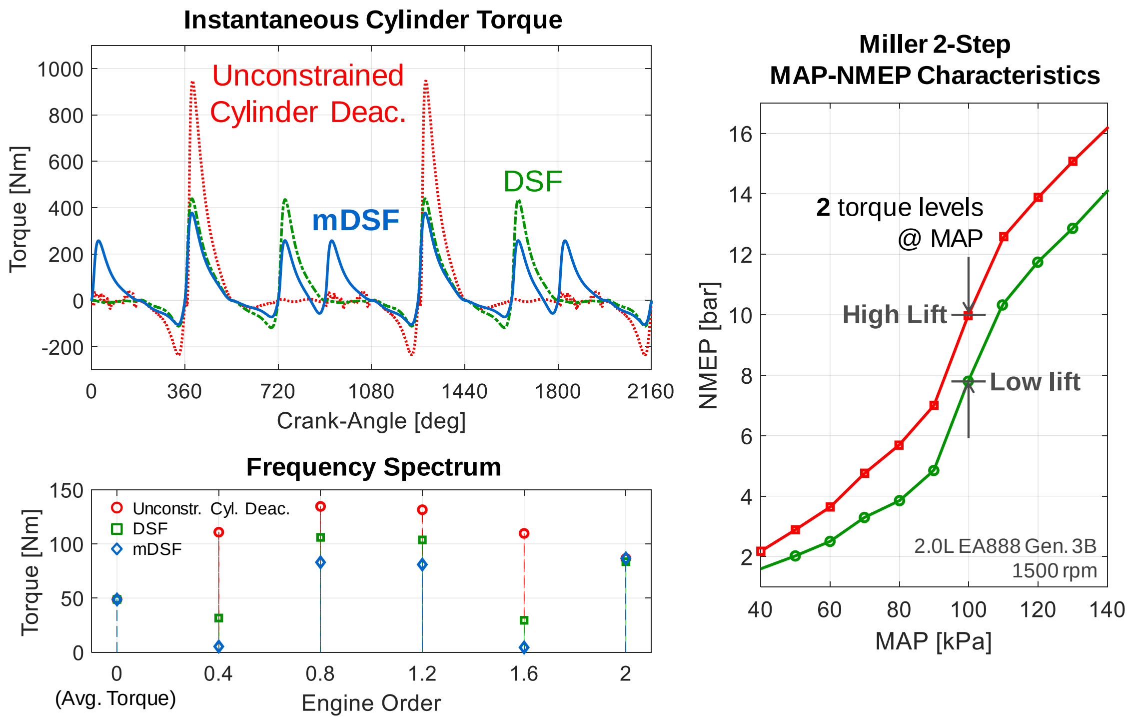

Fig. 17: NVH improvement opportunity presented by a 2-step Miller engine and exploited by mDSF to expand "flyzone" and maximize fuel efficiency benefit

Figure 17 (top-left panel) shows a series of torque waveforms delivering the same average torque for various cylinder deactivation strategies. Best efficiency in an ideal, unconstrained dynamic cylinder deactivation strategy would be achieved by operating at the lowest firing density possible, but the resulting low frequency and high amplitude torque waveform would result in unacceptable NVH. This can be appreciated from the low frequency torque amplitude shown in the frequency spectrum chart in Figure 17 (bottom-left panel). Tula's proprietary algorithms manage these undesired excitations in DSF operation to maintain production quality NVH using higher firing frequencies where necessary, but at the inevitable expense of fuel efficiency. Through an innovative application of the 2-step Miller cycle strategy, mDSF takes advantage of the multi-level air charge and torque characteristics at a given manifold pressure (MAP), as shown in Figure 17 (right panel), to produce torque waveforms with excitation characteristics that can be used to expand the viable firing density "flyzone". mDSF is also capable of operating at higher overall firing frequencies with lower impacts to fuel consumption. mDSF can therefore deliver synergistic benefits between two highly capable engine technologies with potentially significant impact to short- and mid-term vehicle fuel efficiency and emissions.

Figure 18 shows one possible mDSF firing history for a 4-cylinder engine (bottom panel) as a function of driver torque demand relative to maximum engine torque (top panel). The additional firing state in mDSF provides enhanced NVH control, while maintaining all the key functions that make DSF such a powerful technology, including improved combustion stability, fast torque control and DCCO. Furthermore, mDSF allows full optimization of 2-step Miller cycle engines by enabling smooth and efficient transitions between low and high charge modes, which effectively eliminates the Miller cycle efficiency-power tradeoff.

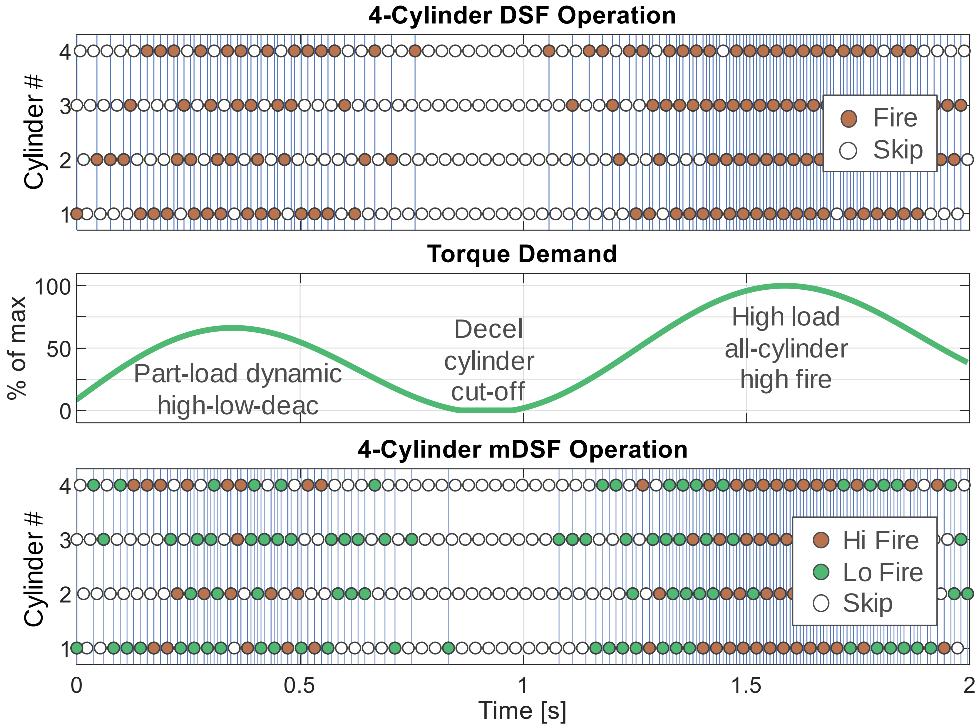

Fig. 18: Representative DSF and mDSF firing histories on a 4-cylinder engine for a changing torque request capturing low load, deceleration and high load operation

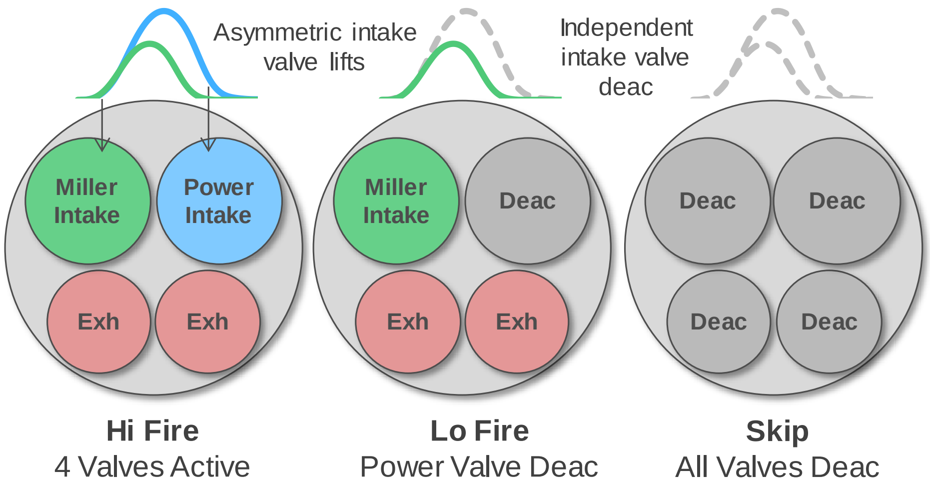

Fig. 19: Cost effective 3-state mechanization approach for mDSF using asymmetric intake ports and independent intake valve deactivation

The most cost effective valvetrain configuration proposed for mDSF employs asymmetric intake valve lifts and port flows, which only requires independent control of the two intake valves in addition to the valve deactivation hardware needed for DSF. Figure 19 illustrates the three valve actuation states for high charge fire, low charge fire and deactivation or skip. The power intake valve, defined by higher lift and longer duration events, only operates in the high charge fire mode. Upon deactivation, the aggressive Miller cycle intake valve, defined by low lift and short duration (EIVC) events, remains open. Finally, all valves become inactive and remain closed during a skip. This could be implemented mechanically using deactivatable roller finger followers (dRFF), controlled either hydraulically or electronically. Hydraulic systems are a production ready solution described in Section 1.1. Packaging can be challenging due to the four additional oil control valves (OCV) required for independent intake valve deactivation, but it has proven feasible for Tula's demonstration platform and a prototype cylinder head is currently being developed jointly with FEV. A solid model of the design is shown in Figure 20.

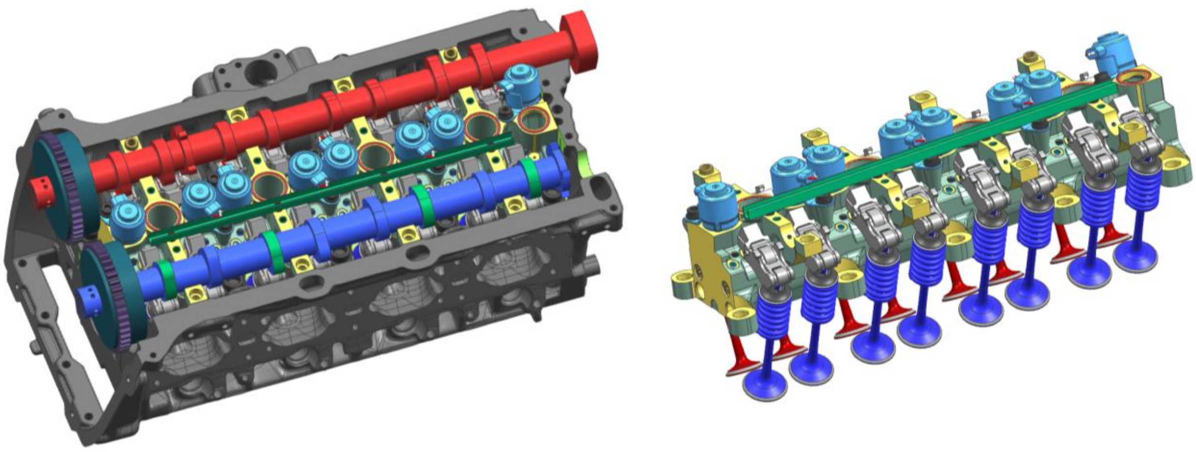

Fig. 20: Solid model of mDSF cylinder head using DSF cylinder deactivation hardware with 4 additional OCVs for independent intake valve control

Electronically deactivating dRFFs would be the ideal solution, but the hardware is currently still in early development. Other alternatives using sliding cam elements, deactivatable lifters / lash adjusters, or suitable combinations of all the above are also be feasible.

Achieving the maximum fuel efficiency potential with mDSF requires an optimized combustion system and valvetrain design. This is particularly true with the configuration described in Figure 19, which is expected to have an impact on combustion and power due to the asymmetric intake valve lifts and port flows, which disturbs charge motion and reduces overall flow areas. This is of notable concern to OEMs and one of the primary risks associated with the mDSF technology. Single port operation, however, has been shown to offer some benefits in efficiency and emissions control [11], [12]. Reference [12] also demonstrates the possibility of an optimized asymmetric port design, where one of the intake ports maximizes tumble motion and reduces swirl motion in single port operation, and the second port acts as a charge port. This design delivers maximum airflow and power in dual port operation. Unconventional port geometry and valve masking played key roles to achieve the air flow and charge motion targets.

The torque management control functions affected by mDSF are not significantly different than with standard DSF, with additional calibrations and actuator controls for multi-step intake lift or air charge. The logic to determine the appropriate combinations of high fire, low fire and skip, which maximize fuel efficiency and mitigate NVH, requires novel algorithms and advanced digital signal processing based control strategies operating in real time.

3.2 Engine Test Results and Projections

The Audi EA888 Gen. 3B engine was chosen as the development platform for mDSF. The key specifications are shown in Table 3. The optimized Miller cycle combustion system ensures combustion quality and efficiency. The 2-step sliding cam valve lift system also provides the capability to do initial investigation of dynamic low lift / high lift switching. The base engine calibrations were reverse engineered from a 2017 Audi A4 Ultra, and implemented in a rapid prototyping dSPACE engine controller with the capability to drive all relevant engine actuators. A custom camshaft was created to realize the asymmetric valve lift / port configurations shown in Figure 19. The stock low lift and high lift cam lobes were retained.

In addition to the OEM sensors, engine instrumentation included pressure and temperature sensors throughout the air handling system, a Coriolis fuel flow meter and high speed in-cylinder pressure transducers. The engine was operated at constant engine speed using an Eddy Current dynamometer. No full cylinder deactivation capability was available during this initial development phase.

Tab. 3: Specifications of Audi EA888 Gen. 3B Inline 4-Cylinder GTDI Engine.

Displacement (Bore x Stroke)	1984 cm3 (82.5 mm x 92.8 mm)
Compression Ratio	11.7:1
Valve Lift Control	2-Step Sliding Cam Elements (AVS)
Low Lift Valve Profile	Duration: 140° CA / Max Lift: 6.9 mm
High Lift Valve Profile	Duration: 170° CA / Max Lift: 8.5 mm
Combustion Chamber	Tumble Ports w/ Valve Masking Tumble Conserving Pent-roof & Piston
Test Fuel	Gasoline 93 ON

Figure 21 shows engine test results comparing the high load NMEP (top panel) for the stock camshaft with symmetric intake valve lifts and the custom camshaft with asymmetric intake valve lifts at the same manifold pressure. The low charge (Sym. Lo, Asym. Lo) and high charge (Sym. Hi, Asym. Hi) data demonstrate similar trends at speeds below 2500 rpm. At higher speeds, the flow restriction created by the single port configuration causes a steeper drop in torque compared with the dual port configuration. The asymmetric high charge configuration produces 3-8% lower torque throughout the speed range. This is consequential since this configuration is expected to deliver rated torque and power in the mDSF engine. Tula is confident the torque loss can be mitigated through optimization of the combustion system, including valve lifts, turbocharger and ports.

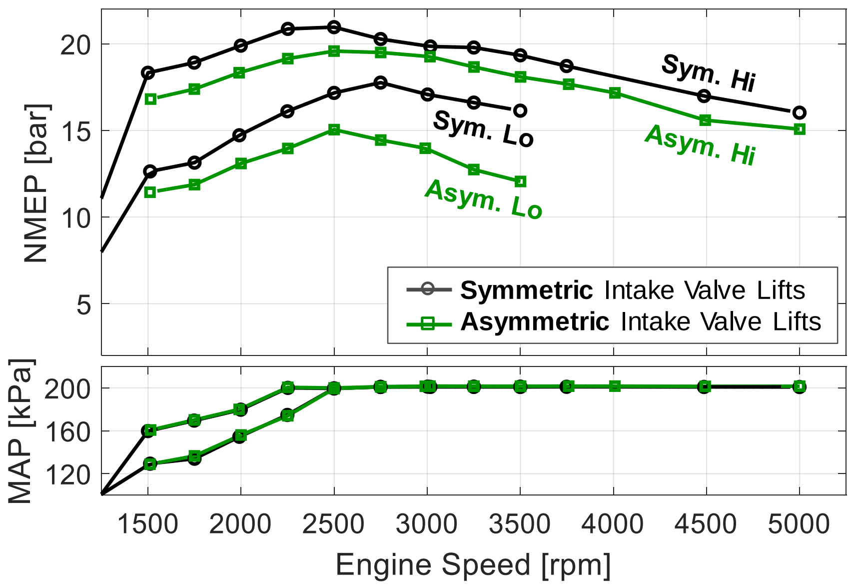

Fig. 21: Comparison of net torque output (NMEP) from symmetric and asymmetric intake valve lifts at constant manifold pressure (MAP)

The mDSF engine was calibrated for best fuel consumption at 1250, 1500, 2000 and 3000 rpm. In stock Miller 2-step configuration, the engine calibrations extracted from the vehicle were minimally adjusted to address differences in ECU controls and dyno installation. The BSFC data versus brake torque at 1500 rpm are shown in Figure 22. The stock Miller 2-step engine and mDSF engine in all-cylinder operation show similar fuel consumption throughout the low to mid load range. This is an important finding given the charge motion disturbance caused by the single port configuration in mDSF.

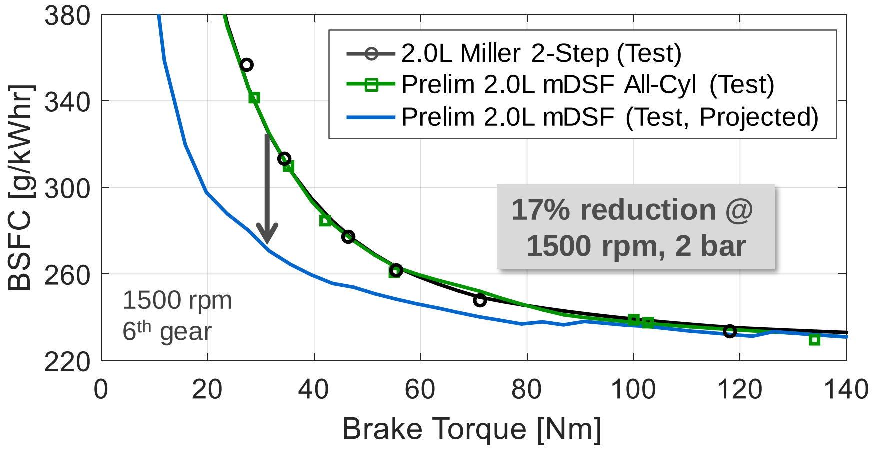

Fig. 22: mDSF engine fuel consumption compared with baseline Miller 2-step and mDSF all-cylinder (asymmetric valve lifts) at 1500 rpm, 6th gear

mDSF engine fuel consumption was projected using the all-cylinder test data and firing density "flyzones" based on the measured NVH characteristics of Tula's current demonstration 2015 VW Jetta. A passive torsional NVH mitigation device was assumed. At 1500 rpm, 2 bar BMEP, mDSF improves the fuel consumption from the baseline Miller 2-step engine by 17%. These results are preliminary, and further benefits could be expected with improved understanding of NVH characteristics in mDSF operation and a more aggressive Miller cycle implementation.

3.3 Vehicle Fuel Consumption Projections

Vehicle simulations were carried out for the US City-Highway (FTP75), WLTC Class 3, NEDC and JC08 drive cycles to project the fuel consumption benefits of mDSF. A 1D vehicle model in GT-SUITE was used in conjunction with steady-state engine fuel consumption maps. The model was calibrated against Tula's 2015 VW Jetta demonstrator vehicle and assumes stop/start functionality. The engine maps were created from Tula's engine dynamometer data and projections as described in the previous section.

The results of the vehicle simulations for the baseline Miller 2-step engine and mDSF engine are presented in Figure 23. These initial projections indicate mDSF can improve CO_2 emissions by 7.5% to 9.5% from the Miller 2-step, which already delivers class benchmark efficiency. These efficiency gains from mDSF are expected to be even more robust to NVH constraints or sensitive platforms compared with standard DSF, and could increase further through optimized engine design that better aligns with the mDSF strategy.

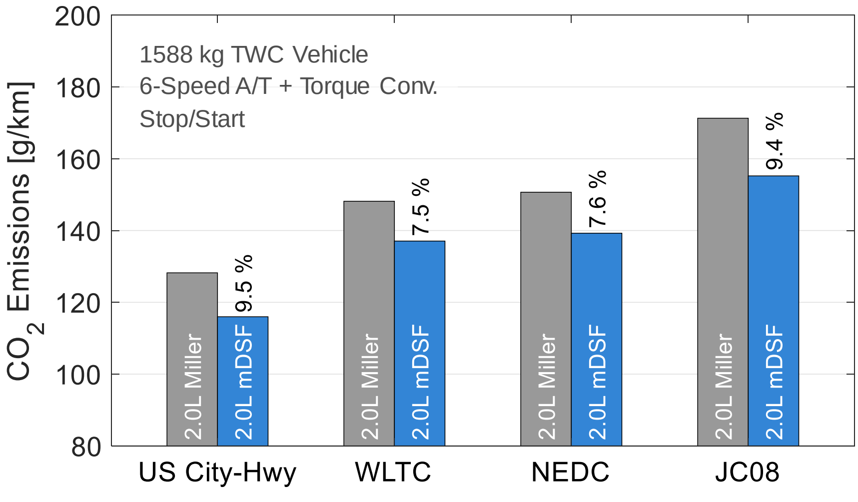

Fig. 23: mDSF vehicle CO_2 emissions in four certification drive cycles compared with baseline Miller 2-Step engine

The fuel efficiency gains delivered by mDSF become more impressive when the cost is factored in. Assuming a Miller cycle combustion system is available, the incremental OEM on-cost for mDSF from DSF is very low. In the current configuration, this would consist primarily of four additional OCVs. The mDSF technology, therefore, offers one of the best values for gasoline engine powertrains in the market with relative short-term viability.

4 Conclusions

Dynamic Skip Fire offers remarkable improvements to automotive powertrains.

Vehicle testing implementing 48V mild hybridization and eDSF without torque smoothing shows 16% CO_2 reduction (combined results over the US EPA 2-cycle test). Vehicle work continues and further benefits with this configuration are expected. Simulations at Tula Technologies indicate that full optimization of the system, including implementing NVH hardware, implementing torque smoothing, and optimizing the strategy of coupling eDSF with mild hybrid predict a 20% gain over a TGDi baseline may be possible.

In addition, mDSF couples DSF with Miller cycle engines, and can improve upon those engines substantially. Vehicle level simulations, backed up by engine level test results, show improvements of 7% to 9% over already optimized Audi EA888 Gen. 3B powertrains. A demonstration vehicle is currently in development and combustion system optimization for mDSF will begin soon.

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