

# Design and Benefits of Dynamic Skip Fire Strategies for Cylinder Deactivated Engines

Mark Wilcutts, Joshua Switkes, Mark Shost and Adya Tripathi  
Tula Technology, Inc.

## ABSTRACT

Cylinder deactivation is a fuel consumption reduction technology for throttled internal combustion engines and other engines with thermal efficiency loss at part cylinder load. Recent production implementations, deactivating fixed sets of cylinders under part-load operating conditions, have had limited “fly zones” due to issues with drivability and noise, vibration and harshness (NVH). Dynamic skip firing, which in its ultimate form incorporates anytime, any-cylinder deactivation, continuously varies the number of firing cylinders, along with cylinder load, obtaining flexible control of acoustic and vibrational excitations from the engine, and allowing an expanded operational envelope with fewer drive ability/NVH issues. This paper outlines design considerations of dynamic skip fire operational strategies, discusses implementation of the system on a vehicle, and presents benefits to fuel economy and NVH.

**CITATION:** Wilcutts, M., Switkes, J., Shost, M. and Tripathi, A., "Design and Benefits of Dynamic Skip Fire Strategies for Cylinder Deactivated Engines," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-0359.

## INTRODUCTION

Selective firing of engine cylinders has been used for load control going back at least to the late 19<sup>th</sup> century in agricultural engines common at the time regulated by a governor which cut off cylinders to maintain constant speed. In automotive applications, engine torque production is demanded by the vehicle driver in an often highly transient manner. The basic concept of Dynamic Skip Fire technology is to manage torque production in response to the driver command via selectively engaging or disengaging torque production from engine cylinders rather than by throttling. The operation of each firing cylinder can be optimized for best thermal efficiency, subject to possible constraints such as air-fuel mixture ratio, peak pressures or temperatures (durability), and other factors.

Dynamic skip fire technology is a good match for throttled, spark ignited engines in which full load combustion in each cylinder has excellent fuel conversion efficiency, controllable peak pressures and temperatures, and emissions manageable via modern catalytic converter technology. Mechanically it is a good fit with today's hydraulic-mechanical cylinder deactivation technology which has reached a high level of durability and refinement in production vehicles.

The benefits of dynamic skip fire engine operation which will be described further in this paper include:

1. Fuel economy improvement via removal of pumping losses and optimization of combustion. For each engine speed, a sweet spot of thermal efficiency for operating cylinders exists which is at high load for throttled engines due to minimized pumping loss. With combustion occurring preferentially in this regime, the engine combustion system can potentially be optimized to match this operating area. Finally, with intake or exhaust (or both) valve deactivation in place, inactive cylinders are prevented from pumping air through the engine, which enables effective use of three-way catalyst technology.

2. Wide authority over generation of vibrational and acoustic excitations. In normal throttled operation of an engine, excitation spectra are tied to the engine speed, and magnitude is determined by the level of throttling, whereas with dynamic skip fire technology the spectra are additionally controlled by the number and sequence of firing cylinders. Full dynamic control of firings and non-firings of engine cylinders means that noise, vibration and harshness (NVH) can be dealt with algorithmically, in a flexible and systematic way.

## HISTORY OF SKIP FIRE OPERATION AND CYLINDER DEACTIVATION SYSTEMS

Use of selective firing of cylinders as a means to regulate engine torque production goes back to the late 19<sup>th</sup> century in single-cylinder portable engines widely manufactured and broadly employed for various tasks in agriculture and manufacturing. The “hit and miss” regulation mechanism varied the “hit” or “miss” of engine cycles based on the applied load. In one such system [1], when load removal caused the engine speed to climb, a mechanical governor held open the exhaust valve following the exhaust stroke. The subsequent intake stroke then pulled fresh air from the open exhaust port at atmospheric pressure leaving the intake valve closed, creating a “miss” engine cycle with no combustion. As load caused engine speed to decrease the mechanism allowed the exhaust valve to close. The intake stroke of the piston then created vacuum in the cylinder opening the intake poppet valve, held closed by a light spring, drawing in air and fuel. The subsequent compression and power strokes generated the “hit” engine cycle. These systems generally relied on a large inertial flywheel to buffer cylinder and load torques, and a low speed of operation permitting use of the light intake valve spring operated by cylinder vacuum.

Application to computer-controlled automotive engines dates back at least to 1978 when Ford advanced engineering implemented cylinder deactivation via hydraulic rocker deactivation developed by Eaton [2,3].

Production automotive release of cylinder deactivation began in 1981 with the Cadillac “Modulated Displacement” also known as V8-6-4 [4]. The application used lost-motion rocker arm studs controlled by solenoids that deactivated intake and exhaust valves. The system demonstrated the fuel economy benefit of operating on 6 or 4 cylinders under light to medium load conditions but the response time to re-engage all cylinders with the limited computing power and system diagnostics of the time led to poor consumer acceptance.

In 1982 Mitsubishi introduced a 1.4L, 4 cylinder variable displacement engine named Orion-MD [5] which deactivated intake and exhaust valves on cylinders 1 and 4 using an engine oil hydraulic operated rocker arm which provided for lost motion at the valve tip rocker pallet interface by means of a moveable stopper plate. The system utilized a cam-driven auxiliary oil pressure boost pump and accumulator to maintain operation. Mitsubishi demonstrated 20% reduction in fuel consumption in the Japanese 10-mode driving cycle and 11% on the EPA city schedule. In the EPA city test 2 cylinder operation was used for 54% of the driving schedule.

DaimlerChrysler introduced cylinder deactivation on its production 5.7L Hemi V8 in the 2004 model year [6]. The system utilized deactivating valve lifters with hydraulically actuated latching pins on 4 cylinder positions providing for V8 operation with firing order 1-8-4-3-6-5-7-2 or V4 with firing order 8-3-5-2.

General Motors released a similar system for its 5.3L OHV V8 for the 2005 model year. In 2007 GM applied the system to its OHV 3.9L 60° V6 engine with variable valve timing [7]. In the V6 configuration the right bank cylinders 1-3-5 are equipped with deactivation lifters. In a 2007 Impala the V6 with AFM achieved 5.5% fuel economy increase over the 2006 on the city schedule and 7.5% improvement highway.

In 2005 Honda introduced Variable Cylinder Management (VCM) providing 6 and 3 cylinder operation of its V6 engine. For 2008 model year Honda introduced its new 3.5L i-VTEC Variable Cylinder Management (VCM) which added a 4 cylinder mode, allowing 6, 4 and 3 cylinder modes [8]. In 3-cylinder mode all cylinders on bank 1 are deactivated, and in 4 cylinder mode one cylinder on each bank is idled. This system requires four hydraulic circuits passing through the rocker shafts. The new 3.5L V6 increased EPA highway fuel economy by 10% (29 vs. 26 mpg) and city by 6% (19 vs. 18 mpg) over the 3.0L V6 of the 2007 model year. The VTEC VCM mechanism is oil-pressure hydraulic linked rocker arms controlled by spool-valve solenoids to apply pressure to shuttle a lock pin linking the cam following rocker arm to the valve activating rocker arm.

Recently Mercedes introduced AMG Cylinder Management for its 5.5L V8 using lost-motion lash adjusters to operate in V4 mode[9], and new for 2013 Lamborghini's Cylinder Deactivation System (CDS) to turn off one bank of its V12 [10].

The 2012 Audi S8 applied Cylinder on Demand to the V8 using selectable cam lobes (Audi Valvelift System) [11] to produce zero valve lift to go from V8 to V4 mode. This system will see Audi 4-cylinder applications in 2013.

VW has introduced for 2013 Active Cylinder Management Technology (ACT) on its new 1.4-liter TSI 4-cylinder with direct injection and turbo charging in the Polo, which develops a power output of 103 kW [12], with a combined fuel consumption of just 4.6 l/100 km (51 mpg US), equivalent to 107 g/km CO<sub>2</sub>). The mechanism introduced on the Audi V8 is applied to cylinders 2 & 3 on this engine to deactivate in light to medium loads (25-75 N·m) over speeds from 1400-4000 rpm, covering approximately 70% of the NEDC, reducing fuel consumption by about 0.4 l/100 km.

As can be seen in the above list of recent and upcoming applications, the basic cylinder deactivation technology has seen wide acceptance for production by major automotive OEMs.

One common characteristic of production automotive cylinder deactivation systems is that they tend to exit variable displacement operation to conventional all-cylinder operation any time the driver requests non-trivial additional torque by further depressing the accelerator pedal. Often this happens even though the engine is capable of delivering the desired torque using only the reduced number of cylinders that were being used in the variable displacement mode. It is believed that the reason that variable displacement operation is exited

so readily is due to the difficulty of controlling the engine to provide substantially the same output regardless of which subset of cylinders is being used.

Another common characteristic of production automotive cylinder deactivation systems is that they switch to one or at most two reduced cylinder sets, such as eight to four cylinders or six to four to three. Over the years, a number of skip-fire engine control arrangements have been proposed which do not simply switch back and forth to reduced cylinder sets, but skip working cycles of cylinders.

Daimler-Benz patented a concept for skipping working cycles in fixed patterns, with distributions approximately uniform in time [13]. In this system a fixed amount of fuel was fed to the firing cylinders so that they worked near their optimum efficiency. Although the distribution of the skipped working cycles varied based on the load, a discrete number of different firing patterns were contemplated so the power output by the engine would regularly not match the desired load precisely. The authors recognized a risk of introducing resonant vibrations into the engine crankshaft in some patterns, and proposed a second embodiment utilizing a random distribution of cylinder firings to reduce this possibility. That approach has the disadvantage of introducing larger variations in torque, which the authors appear to have recognized, and proposed the use of a more robust flywheel than normal to compensate for the resultant fluctuations in drive energy.

The dynamic skip fire approach described in this paper and disclosed in a series of U.S. Patents [14, 15, 16, 17, 18, 19, 20] does not rely on fixed cylinder deactivation as in current-production cylinder deactivation systems, or on switching between fixed patterns, but rather varies the firings and skips continuously with load demand.

## CONCEPT AND DESIGN CONSIDERATIONS OF DYNAMIC SKIP FIRE OPERATION

Fundamentals of Dynamic Skip Fire Operation. The basic concept of dynamic skip fire operation is to use firings or non-firings of engine cylinders to satisfy engine torque demand rather than throttling or other torque reduction mechanisms which reduce thermal efficiency. Figure 1 shows this conceptually; in proportion to the torque demand, the occurrence of firing cylinders increases.

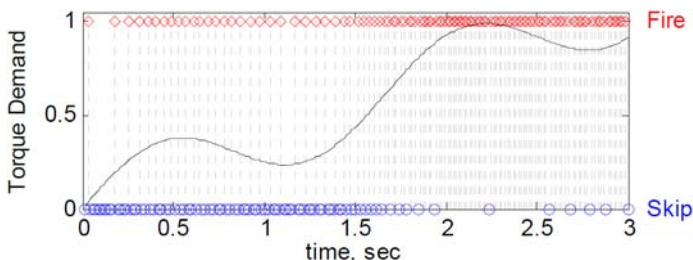


Figure 1. Dynamic Skip Fire Concept

In the Tula DSF system, fire/no fire decisions are made at each firing opportunity, dictated by engine speed and cylinder count, to keep pace with the continuously varying input torque demand. That is, sets of cylinders are not pre-programmed into patterns but rather the decision whether or not to fire each individual cylinder is made as it comes along in the firing order.

Realization of fuel consumption benefits is achieved by reduction of thermal efficiency losses, primarily pumping losses and combustion inefficiency. Operation with high manifold pressure achieves reduction in pumping work, whereas combustion is generally more complete and can be more optimally phased in relation to the piston motion with larger cylinder air-fuel charge. The availability of cam phasing or other cylinder charge reduction mechanism provides a third control input which can be manipulated to achieve even higher optimization of fuel conversion efficiency gains and tradeoff with NO<sub>x</sub>/HC emissions.

As discussed later in this paper, NVH considerations modify the basic concept of firings in proportion to torque demand described above. With full control over which firing opportunities are realized as firings, there is wide control over the vibrational and acoustic excitations; fires may be rearranged in time to obtain favorable vibration and acoustics.

Additional factors may enter into the choice of when to fire and skip, for example if need exists to not deactivate cylinders for long periods of time. Such factors can be incorporated in the algorithmic design to meet constraints while still meeting the driver's torque demand.

Although dynamic skip fire operation can be achieved via fuel shutoff alone, valve deactivation enables effective use of three-way catalysts as well as further reducing pumping losses. Full dynamic skip fire operation in conjunction with cylinder deactivation implies any-cylinder, anytime deactivation. This is achievable with modern hydraulic-based deactivation hardware. The charge trapping strategy needs to be selected appropriately in order to achieve favorable fuel consumption benefits with dynamic skip fire operation. Even in the case that only certain cylinders have deactivatable valves, dynamic skip fire can still be operated although with reduced NVH performance.

An inbuilt advantage of dynamic skip fire operation is that in contrast to current production cylinder deactivation systems, the cylinders being deactivated are not always restricted to the same set, but rather deactivation is uniformly distributed among the cylinders, avoiding any differential wear concerns.

## Thermodynamic Considerations

Fuel consumption benefits in dynamic skip fire engine operation are achieved by reduction of thermal efficiency losses in the engine. This section discusses the factors relating to thermal efficiency affected by cylinder deactivation and in particular by dynamic skip firing where the deactivation system is used to its full potential.

### Pumping Loss

The main thermodynamic effect of dynamic skip fire operation is removal of pumping loss. In DSF operation the engine can be operated with high manifold pressure since the skipped cylinders do not create torque. PV work during a pumping loop is directly related to intake manifold pressure; idealized, the pumping loop plot is rectangular with one side at intake manifold pressure, and the other at exhaust pressure, thus the work expended in gas exchange is

$$W_p = (P_e - P_i)V_d$$

With intake pressure approaching atmospheric pressure, the pumping work is significantly reduced. In applications including valve deactivation, a further benefit is realized in that the skipped cylinder pumping loss is completely removed.

### Friction

Friction in piston engines consists of sliding and viscous losses in the crank train and valve train. In the crank train, firing cylinders have higher piston skirt and ring side forces in DSF operation due to higher cylinder combustion loading, whereas non-firing cylinder side forces depend on the gas trapping strategy. Low-pressure gas trapping, taking place if valve deactivation occurs after the exhaust stroke, will have small side forces. High-pressure gas trapping, when valve deactivation occurs before the exhaust stroke, will have much larger side forces. With low-pressure gas trapping strategy the total crank train frictional losses will be roughly the same as in throttled operation.

With valve deactivation, valve train friction is significantly reduced in the portion of the valve train no longer having loading on its sliding surfaces. For example in a pushrod engine with deactivatable lifters, the deactivated valve spring force is removed which reduces loads on all bearing surfaces of the lifter, rocker, and cam connected to that cylinder, including portions still operating in lost motion.

### Combustion and Heat Transfer

In cylinders firing at low load, the heat transfer as a fraction of the total energy fuel energy released in combustion can be large. In DSF operation, with combustion events occurring at higher load, less heat transfer loss as a proportion of the fuel energy can be realized, depending on the in-cylinder charge motion. With larger cylinder air-fuel charge, combustion is more stable and can be more optimally phased in relation to the piston motion. Higher residual fraction can also be tolerated which allows better NO<sub>x</sub> emissions via increased cam retard and/or external EGR.

## NVH Considerations

### Vibration Considerations

Full-authority dynamic skip fire operation gives wide control over excitation spectra. Excitation spectra management goals include avoiding

- Frequency bands particularly perceptible by humans (vibration of body, hand, foot, or auditory)
- Coupling with mechanical resonances (mirror, steering wheel)
- Coupling with acoustic modes (exhaust system, cabin)

The first design consideration listed above is human body vibration perception/comfort. ISO2631 [21] is an international standard defining methods of quantifying whole-body vibration in relation to human comfort and likelihood of vibration perception. Figure 2 shows frequency weightings from the standard to be applied in evaluating vibration. Table 1 and Figure 3 define the locations and directions to which the weighting factors are to be applied.

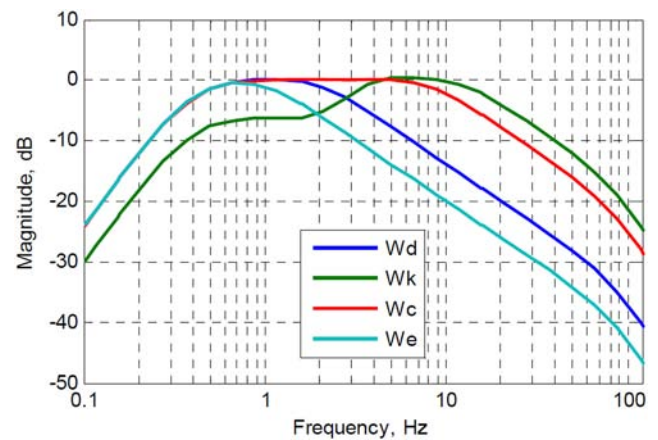


Figure 2. Comfort/perception frequency weightings from ISO 2631

Table 1. Applicability of comfort/perception weighting factors to locations on the body and directions of acceleration

Location, Direction	Weighting
Seat surface, x-axis	W <sub>d</sub>
Seat surface, y-axis	W <sub>d</sub>
Seat surface, z-axis	W <sub>k</sub>
Seat surface, r <sub>x</sub> -axis	W <sub>e</sub>
Seat surface, r <sub>y</sub> -axis	W <sub>e</sub>
Seat surface, r <sub>z</sub> -axis	W <sub>e</sub>
Seat back, x-axis	W <sub>c</sub>
Seat back, y-axis	W <sub>d</sub>
Seat back, z-axis	W <sub>d</sub>
Feet, x-axis	W <sub>k</sub>
Feet, y-axis	W <sub>k</sub>
Feet, z-axis	W <sub>k</sub>

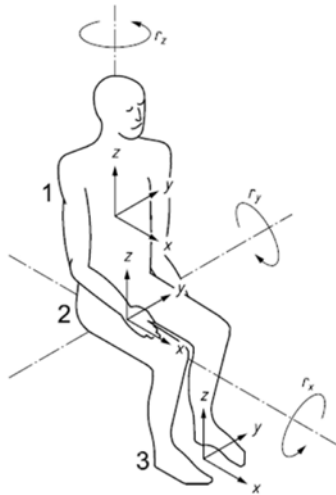


Figure 3. Definitions of axes (taken from [21])

Of particular interest in propulsion system design are the axes relating to longitudinal motion such as the x-axis and  $r_y$ -axis. Weighting factors for those axes for various locations on the body emphasize frequency content in the 0.4Hz to 11Hz range. A design goal, then, from the whole-body vibration perception perspective, is to exclude excitations which introduce accelerations of the body in that frequency range.

A method of preventing excitation of such frequency ranges in engine torque generation is to utilize firing sequences whose resulting torque history have little content in the low frequency range of interest. For a given number of firing events commanded over a given number of firing opportunities, evenly-spaced firing sequences have more content at higher frequencies and less at lower frequencies than other choices.

Another useful controlled item in modern vehicles for reduction of torque pulsations is the controlled-slip torque converter clutch (TCC). Having information about the vibratory characteristics at each operating point, the controller is able to manage the slip setpoint of the TCC appropriately.

### Acoustic Considerations

When operating in dynamic skip-fire mode, the acoustic excitations can be far less systematically related to engine speed and load than those of all-cylinder operation.

Skip fire operation may excite frequency ranges of exhaust system acoustic modes and other system resonances which would not normally be excited by all-cylinder operation. Also, in the case of asymmetric exhaust systems banks, low frequency acoustic modulation may result. As in the case of vibration, the acoustic excitations can be managed through appropriate sequencing of fires and non-fires among cylinders.

Also, since vehicle acoustics are influenced by exhaust system design, cabin design and the mechanical and acoustic couplings between the two [22], many acoustic effects can be

addressed through appropriate design and tuning of passive systems such as dimensional configurations of the exhaust manifold and y-pipe, as well as acoustic attenuation characteristics of mufflers and resonators.

## COMPATIBILITY AND SYNERGY OF DYNAMIC SKIP FIRE OPERATION WITH MODERN AUTOMOTIVE ENGINE TECHNOLOGIES

### Cylinder Deactivation

Selective actuation of intake and exhaust valves is commonly implemented in modern production vehicles via control of hydraulically deactivatable elements in the valve train. The GM and Chrysler systems mentioned in previous sections utilize deactivatable lifters, the Honda system uses deactivatable rocker arms, and the VW/Audi system uses a laterally movable cam lobe containing two profiles, one producing zero lift.

With rocker arm or lifter deactivation systems, the deactivatable element has a spring-loaded lock pin that in the absence of hydraulic pressure is in position to operate the valves as normal. As hydraulic pressure is applied to the pin it moves out of lock position and allows part of the valve train to operate in lost motion.

The timing of hydraulic pressure application to the lock pin must be carefully managed to achieve pin movement while the cam lobe is on the base circle, so as to avoid high loading on the pin when it is only partially engaged, which would be a possible durability issue. The application of hydraulic pressure to locking pins is normally controlled by individual solenoid valves so as to achieve this correct timing.

For skip fire operation, individual cylinder deactivation is easily achieved by this type of mechanical-hydraulic arrangement, and control of individual deactivatable elements is typically fast enough to implement dynamic skip fire.

### Direct Injection

Direct injection is coming into prevalence in spark ignited engines due to its ability to extend knock limits to higher cylinder loads and higher compression ratios which are favorable for efficiency. In an engine operating with dynamic skip fire, direct injection avoids fuel puddles in intake runners possibly evaporating and being drawn into other cylinders during deactivation, thus avoiding concerns of compensating for this effect during a variable amount of deactivation time.

In applications not incorporating cylinder deactivation, direct injection avoids pass-through of intake runner fuel puddles during non-firing cylinder events.

### Hybridization

Skip fire is a natural combination with electric hybrids where high-bandwidth electric motor control allows the combustion engine and electric motor to work in concert to



apply favorable torque excitation spectra, achieving high vibration refinement and obtaining more flexible noise-vibration tradeoff. An additional benefit is that since full-authority cylinder deactivation can completely remove the pumping portion of engine braking, during deceleration the hybrid system can introduce artificial engine braking utilizing the full energy for regeneration.

### Other Technologies

Turbocharged, downsized engines may still obtain fuel consumption benefits from skip fire operation. The combination of turbo charging with deactivation appears in the new VW 1.4L TSI engine mentioned in the introduction. A regime of increased efficiency operation with reduced cylinder counts and under boost can exist, depending on the engine and turbocharger design.

In diesel engines, although the potential for pumping loss reduction is substantially reduced, deactivation may have secondary benefits in the form of improved combustion characteristics via optimized injector design or injection strategy design, transient benefits due to optimized turbocharger design or operating strategy design, or in the thermal management of after treatment devices.

## IMPLEMENTATION

For development and demonstration of dynamic skip fire operation, the system was deployed in a model year 2010 GMC Yukon Denali full size sport-utility vehicle. The production engine for this vehicle includes GM's Active Fuel Management (AFM) system, which deactivates intake and exhaust valves on four of the eight cylinders under appropriate operating conditions. The specifics of this engine are listed in [Table 2](#).

**Table 2. GM L94 Engine Specifications [23]**

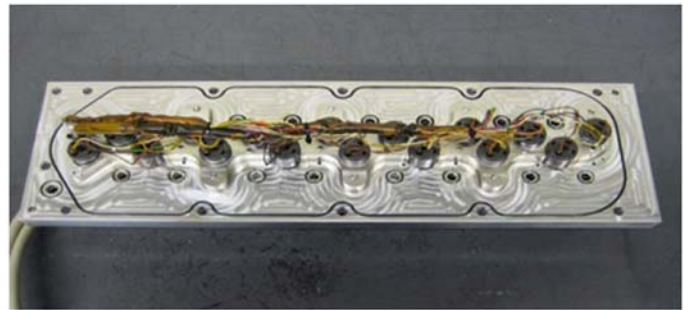
Type	V-8
Displacement	6162 cm <sup>3</sup>
Bore & stroke	103.25 mm x 92 mm
Block material	cast aluminum
Cylinder head material	cast aluminum
Valvetrain	overhead valve, two valves per cylinder, variable valve timing
Deactivation system	Intake and exhaust valve lifters, oil pressure actuated, cylinders 1,4,6,7
Ignition system	coil-near-plug ignition
Fuel delivery	sequential fuel injection
Compression ratio	10.4:1
Power (peak)	301 kW @ 5700 rpm
Torque (peak)	565 Nm @ 4300 rpm
Fuel	premium recommended; or E85
Maximum speed	6000 rpm
Emissions controls	close-coupled catalytic converter, 58X ignition, returnless fuel rail, fast-response O <sub>2</sub> sensor

## Engine Modification

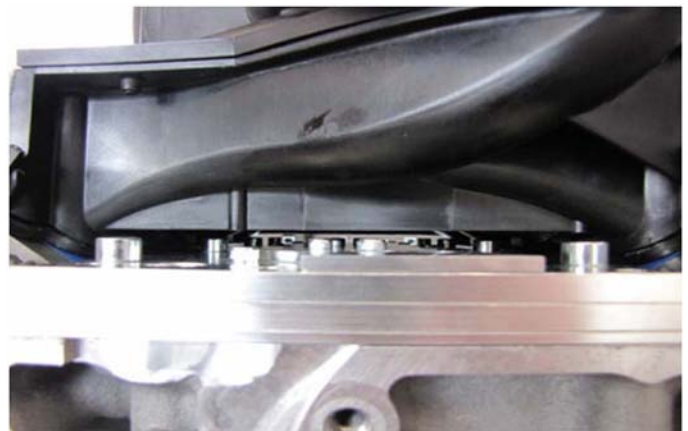
To incorporate full-authority valve deactivation the engine was modified via

- Addition of deactivatable lifters to intake and exhaust valves of cylinders 2, 3, 5, and 8
- Modification of the engine block to incorporate additional galleries directing oil pressure to the additional deactivatable lifters
- Fabrication of a new lifter oil manifold assembly (LOMA) containing 16 solenoid valves to direct oil pressure to the oil galleries

Packaging of the extended functionality LOMA was achieved within the dimensional constraints between the block and production intake manifold. The new LOMA design is shown in [figure 4](#) and as installed in [figure 5](#). The deactivation system was operated from the original production oil pump and oil pressure relief valve.



**Figure 4. New LOMA, solenoid side**



**Figure 5. New LOMA installed between engine block and intake manifold, side view**

The constraints for proper hydraulic operation of the new cylinder deactivation system were determined on a test rig consisting of modified block and new LOMA and controllable oil pump. After installation in an engine the

hydraulic operating envelope was fully characterized and calibrated into the control system.

For the NVH evaluations that follow in this paper, no modifications were made to the production vehicle mechanicals beyond the engine modifications described above. In particular no changes were made to the exhaust system, engine mounts, or any other NVH related mechanical components. The vehicle was not put through any N&V mechanical tuning to adjust it to the completely different engine operating strategy

## Control Development

For fast control system bring up, a commercial rapid prototyping controller system was fitted. This system allows easy iterative development of control functions. Control software was developed for full-authority control of deactivation oil control solenoids along with electronic throttle, cam phaser, fuel injectors, and digital ignition modules.

The base engine control was built up, and a number of calibrations were obtained via aftermarket tools capable of viewing the OEM engine control module tables.

Selective fire algorithms were then developed for full authority cylinder control. New algorithmic features to manage vibrational and acoustic excitations were developed, respecting the design considerations outlined in previous sections of this paper. Features were validated in simulation as well as tuned and calibrated via seat time in the vehicle.

Because of the continuously-variable nature of dynamic skip fire operation, air, fuel and exhaust dynamics become even more important than they are in all-cylinder or fixed-cylinder deactivated operation and special attention to modeling and calibrating these phenomena must be taken in the fuel and spark control subsystems. One-dimensional thermofluid simulations as well as carefully designed tests on an engine dynamometer were used to gain insight, create control oriented models, and generate calibration data.

The final production computing requirements of DSF algorithms have not yet been determined with respect to the capabilities of next-generation engine control units. Current production software architectures generally need some adaptation to accommodate the cylinder-event based firing decision and associated estimation algorithms needed for DSF.

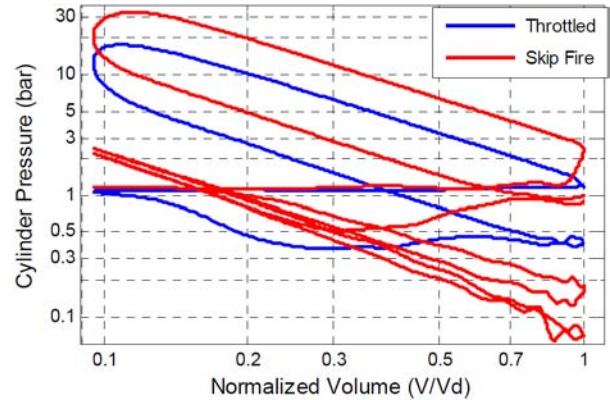
## OPERATIONAL CHARACTERISTICS

### Thermodynamic Cycle Analysis

Figure 6 shows pressure-volume traces for throttled engine operation, and for a DSF firing cycle followed by a deactivated engine cycle in DSF operation, both at 2 bar BMEP. In this case the deactivated cycle employs low-pressure exhaust gas trapping. The gas exchange pumping loop is significantly reduced in area for skip fire operation.

A set of measured thermodynamic characteristics is presented in table 3 for dynamic skip fire operation and

throttled operation at a 2bar BMEP, 1500 RPM operating condition. At this operating condition, the engine is firing 41% of working cycles in DSF operation. The reduction in pumping work is reflected in the engine average PMEP reduction from 0.64 to 0.12 bar.



**Figure 6. PV Diagrams for Throttled Operation and Deactivated Operation, 2 bar BMEP**

Engine friction is slightly higher in skip fire operation, with 0.61 bar FMEP vs. 0.55 bar for throttled operation.

The effects outlined above conspire to bring about an 18% reduction in brake specific fuel consumption at this operating condition.

**Table 3. Thermodynamic Characteristics of Skip Fire Operation vs. Throttled Operation at 2 Bar BMEP, 1500rpm**

	Throttled Operation	Skip Fire Operation
BMEP, (bar)	2.04	1.96
IMEPg, firing (bar)	3.26	6.61
IMEPg, EA (bar)	3.23	2.68
PMEP, EA (bar)	-0.64	-0.12
FMEP, EA (bar)	0.55	0.61
Brake Thermal Efficiency (%)	22.8	28.2
ISFCn, EA (g/kWh)	273	219
BSFC (g/kWh)	347	286

Figures 7, 8, 9 show measured trends of BSFC, PMEP, and thermal efficiency with BMEP for throttled operation vs. skip fire operation for a fixed RPM of 1500. Figure 8 shows the substantial reduction in pumping work and its near elimination at the lowest loads. This is because the skipped cylinders experience no pumping loss, and so pumping loss is approximately linear with the fraction of cylinders firing. The resulting substantial gains in BSFC and thermal efficiency are reflected in figures 7 and 9.

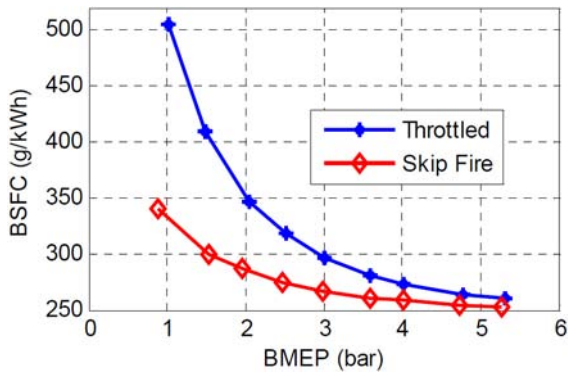


Figure 7. BSFC vs. BMEP for Throttled vs. DSF Operation, 1500 RPM

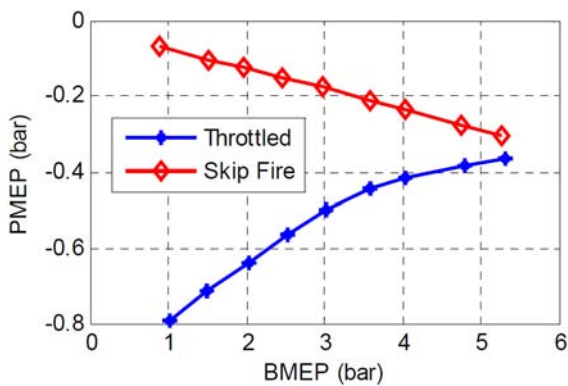


Figure 8. PMEP vs. BMEP for Throttled vs. DSF Operation, 1500 RPM

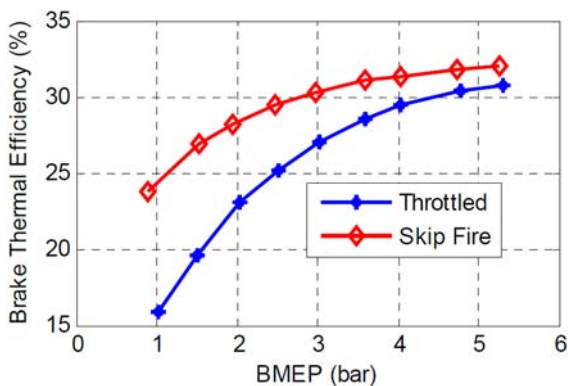


Figure 9. Brake Thermal Efficiency vs. BMEP for Throttled vs. DSF Operation, 1500 RPM

## Drive Cycle Analysis

With the operational concept described above, the dynamic skip fire strategy runs the engine with fewer than all cylinders whenever possible to meet the torque demand and advantageous to fuel efficiency. In order to ease the interpretation of the number of cylinders that are currently firing, we define the firing fraction as the number of fired

cylinders as a fraction of the number of cylinder firing opportunities. The distribution of this firing fraction during a drive cycle is, of course, dependent on a number of considerations, among them the vehicle speed, weight, aerodynamic properties, and rolling resistance, and the DSF control calibration embodying the NVH properties of the powertrain and vehicle.

Figure 10 shows, for one DSF calibration set, operating-time-based histograms of firing fraction during the FTP and HFET drive cycles, for the vehicle described in the previous section. Operation below 900 rpm and in 1<sup>st</sup> gear is excluded from the FTP cycle histogram to clarify the operation, since with this calibration the engine was operated with all cylinders at idle and 1st gear, and idle takes up a large portion of the FTP.

In DSF operation the engine often operates with fewer cylinders than the stock V4 deactivation, with high likelihood of operating with 30%-40% firing fraction both on the FTP and HFET cycles. For reference the AFM system was observed to operate the same vehicle in V4 mode 43% of the FTP (excluding RPM<900 and 1<sup>st</sup> gear) and 54% of the HFET.

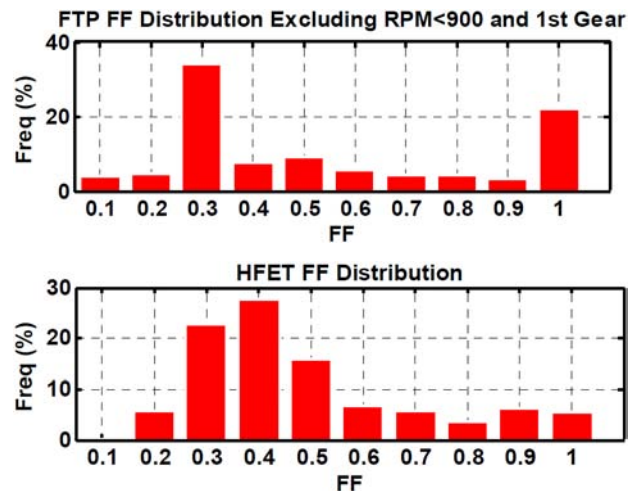


Figure 10. Operating Time Histograms of DSF Firing Fraction for FTP and HFET Drive Cycles

## Fuel Economy Benefits

Drive-cycle fuel economy was measured on a 48" roll chassis dynamometer in a CARB-certified laboratory by standard methodology. The dynamometer target loading coefficients were selected based on coefficients of a similar vehicle model since coefficients for this exact vehicle were not available in the EPA database. The automatic transmission was operated in tap-up, tap-down manualized mode, following prescribed gear schedules vs. time, since modification of the automatic transmission shift strategy according to the new engine operating principle was not available at the time. Hot running starts were used for ease of testing.



Table 4 shows fuel economy test results for dynamic skip fire operation as well as all-cylinder (V8) throttled operation, over U.S. federal test procedure (FTP) and highway fuel economy test (HFET) cycles. Also presented is the composite fuel economy according to the 2-cycle CAFE formula [24].

The table shows results for several different gear shift schedules. The first is a generic schedule used by the test lab as a default in testing vehicles with 6-speed manual transmissions. The second is a shift schedule captured by operating the stock vehicle in normal automatic shifting, with the AFM system active. The stock automatic shift schedule generally operates in higher gears more often than the generic manual transmission schedule.

Also presented are results for two different DSF algorithm calibrations: one an initial calibration with very little accommodation of vibration and acoustic phenomena, and the second a later calibration and algorithmic modifications recognizing vibrational and acoustic factors as described in the next section of this paper.

With the generic manual transmission schedule, the composite fuel economy figures show a 21% improvement of the initial dynamic skip fire operation over V8 throttled operation. On the stock automatic transmission schedule, the initial DSF calibration showed fuel economy improvement of 17%, with the reduced improvement on FTP mainly due to better fuel economy of the baseline V8 operation. This is because with the stock automatic shift schedule generally operating in higher gears than the generic manual transmission schedule, the pumping loss penalty for V8 operation is reduced.

With accommodation of vibrational and acoustic characteristics in the DSF calibration, the composite fuel economy benefit was 14% on the automatic transmission schedule. With this calibration, excellent noise and vibration characteristics were achieved as described on the next section.

**Table 4. Measured Fuel Economy (Hot Running Start) Improvements of DSF Operation**

	FTP mpg	HFET mpg	Composite mpg	Improvement over V8
<b>Generic 6-Speed MT Gear Schedule</b>				
V8	16.6	26.6	20.0	
DSF without N&V features	20.4	31.6	24.3	+21%
<b>Vehicle Production AT Gear Schedule</b>				
V8	17.3	28.1	20.9	
DSF without N&V features	20.2	33.2	24.5	+17%
DSF with N&V features	19.5	32.4	23.8	+14%

These fuel economy gains are significant. For reference, General Motors has advertised that the AFM system achieves 6% fuel economy improvement on standardized tests [25].

Our measured fuel economy gains should be discounted somewhat with respect to the AFM advertised gain because the AFM gain likely included cold start, which delays utilization of the deactivation system until oil temperatures are suitable for reliable operation.

### Noise and Vibration Performance

NVH has been one of the primary concerns to deployment of cylinder deactivation in highly-refined production vehicles. Since the DSF system operates over a wide range of torque and speed, as well as being continuously variable, there are fewer concerns regarding a noticeable switch in and out of such operation. Generally the switch into dynamic skip fire operation will occur right off of idle when conditions for proper operation of the hydraulic-mechanical deactivation hardware are suitable. The switch out of dynamic skip fire operation generally happens when RPM drops low on no-pedal decelerations.

NVH subjective ratings were performed in the vehicle in steady driving on public roads. Tables 5 and 6 show the jury ratings in all-cylinder mode and DSF mode, respectively. The ratings of four vehicle occupants were averaged for each operating condition.

Table 5 shows ratings for V8 throttled operation. In this evaluation the torque converter clutch was left completely disengaged. This was expected to be the best NVH obtainable from the vehicle.

Table 6 shows ratings for DSF operation with algorithmic features managing vibrational and acoustic characteristics, corresponding to the 14% fuel economy gain presented in Table 4. Here the torque converter clutch was operating in controlled slip mode, with TCC slip setpoint modified from the OEM TCM tables but never exceeding the maximum value of the OEM tables.

The overall NVH subjective ratings were nearly always the same or better for DSF operation. The surprising conclusion is that the flexibility of the DSF system can in certain cases improve the N&V subjective experience with respect to V8.

**Table 5. Combined Noise & Vibration Subjective Ratings for V8 Operation, Open TCC**

RPM	Gear				
	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>
1250	8	7	7		
1500	7	6	6	7	7
1750	7	7	8	8	7
2000	7	8	7	7	
2250	7	7	7	7	
2500	6	7	7		
2750	7				
3000	6				
3250	5				

**Table 6. Combined Noise & Vibration Subjective Ratings for Dynamic Skip Fire Operation, Controlled Slip TCC**

RPM	Gear				
	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>
1250	8	8	7	7	7
1500	7	8	8	8	7
1750	7	7	7	8	
2000	7	7	7	8	
2250	7	7	7		
2500	7	6	7		
2750	7	6			
3000	6	7			
3250	6				

In short, DSF vibration ratings were on par with V8 operation, even with the disadvantage of controlled-slip TCC mode versus an open TCC. Acoustic ratings revealed that some acoustic issues remained at higher engine speeds, related to modulation and roughness. However, nearly all of the acoustic issues were removed when a large auxiliary muffler was attached to the tailpipe of the vehicle, indicating the potential to address acoustics through exhaust system mechanical changes.

The vehicle was not put through an N&V mechanical tuning design cycle which would normally accompany production release with a new engine, or one operating in a completely different manner. It is common for car manufacturers to tune exhaust systems not to produce minimal sound but to emphasize certain sounds while attenuating others, often for model or brand image reasons, and this tuning may not be appropriate for a completely different engine operating strategy. Despite this potentially significant disadvantage the vehicle showed excellent NVH characteristics, which were obtained solely via careful design and calibration of operating algorithms. The ratings above show that vehicle NVH, even implemented without acoustic mechanical tuning, is within striking distance of commercial acceptance. Trained NVH evaluators from the automotive industry have agreed with this assessment.

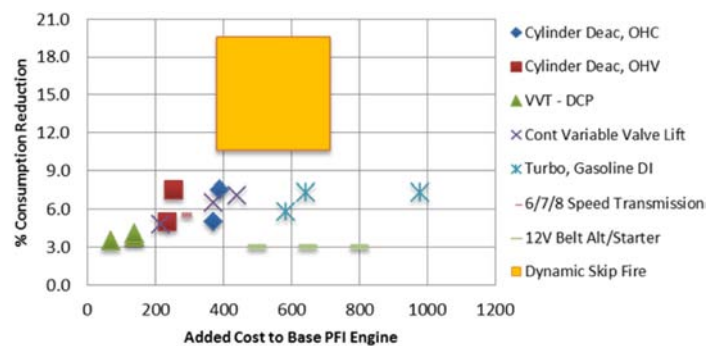
## SUMMARY/CONCLUSIONS

The dynamic skip fire system incorporating anytime, any-cylinder deactivation is able to achieve impressive fuel economy benefits without compromising the driving experience. Near-production NVH levels were achieved, even without vehicle modification relative to the NVH tuning done for the two-mode fixed-cylinder deactivation application. The deactivation hardware implementation is a straight forward extension of existing, production-proven systems, thereby minimizing the capital investment required to implement.

The benefits and costs of dynamic skip fire operation are disruptive compared with other systems incorporating industry-accepted, productionized hardware. Figure 11 shows a comparison of fuel economy gains of various advanced

engine technologies [26], including conventional cylinder deactivation on half of the cylinders, VVT with dual cam phasers, continuously variable valve lift, turbo charging with direct injection, 6/7/8 speed transmissions, and belt alternator start/stop systems.

DSF gains and costs are represented as an area because they depend on the base engine and what cylinder deactivation hardware is already in place, the base ECM I/O capabilities, and other factors related to the final costs of the DSF system implemented in production on a particular engine. The fuel economy gains of the DSF system claimed in Figure 11 have been adjusted downward from results presented in previous sections due to hot starts having been used for those tests. The substantial fuel economy gains of dynamic skip fire operation and reasonable costs provide a strong value proposition, especially on engines which already incorporate partial cylinder deactivation.



**Figure 11. Comparison of DSF Fuel Economy Gains and Costs with Competing Technologies**

The operational concept is applicable to automotive engines with 4, 6, 8, or more cylinders, and the careful excitation management approach may even find application in ultra-downsized 2- and 3-cylinder engines. The excitation management issues become easiest with engines with more rather than fewer cylinders, and pumping loss improvement potential is greatest on those with large displacement relative to their application vehicle loading requirements, related to mass and aerodynamic characteristics.

We expect the technology to be synergistic with other fuel savings technologies, including electrification. The authors believe dynamic skip fire technology can be a key enabler for meeting upcoming fuel economy standards such as the 2025 U.S. corporate average 54.5mpg mandate.

## REFERENCES

1. See U.S. Patent 543,157, 1895, for an example.
2. Bates, B., Dosdall, J., and Smith, D., "Variable Displacement by Engine Valve Control," SAE Technical Paper 780145, 1978: doi: [10.4271/780145](https://doi.org/10.4271/780145).
3. Mueller, R. and Uitvlugt, M., "Valve Selector Hardware," SAE Technical Paper 780146, 1978: doi: [10.4271/780146](https://doi.org/10.4271/780146).
4. "Cadillac's Revolutionary 3-in-1 V8", Popular Science, Oct. 1980, pp. 121-122.
5. Fukui, T., Nakagami, T., Endo, H., Katsumoto, T. et al., "Mitsubishi Orion-MD - A New Variable Displacement Engine," SAE Technical Paper 831007, 1983: doi: [10.4271/831007](https://doi.org/10.4271/831007).

6. Falkowski, A., McElwee, M., and Bonne, M., "Design and Development of the Daimler Chrysler 5.7L HEMI® Engine Multi-Displacement Cylinder Deactivation System," SAE Technical Paper 2004-01-2106, 2004; doi: [10.4271/2004-01-2106](https://doi.org/10.4271/2004-01-2106).
7. Stabinsky, M., Albertson, W., Tuttle, J., Kehr, D. et al., "Active Fuel Management™ Technology: Hardware Development on a 2007 GM 3.9L V-6 OHV SI Engine," SAE Technical Paper 2007-01-1292, 2007; doi: [10.4271/2007-01-1292](https://doi.org/10.4271/2007-01-1292).
8. Fujiwara, M., Kumagai, K., Segawa, M., Sato, R. et al., "Development of a 6-Cylinder Gasoline Engine with New Variable Cylinder Management Technology," SAE Technical Paper 2008-01-0610, 2008; doi: [10.4271/2008-01-0610](https://doi.org/10.4271/2008-01-0610).
9. Eichler, F., Gindele J., Hart M., Ramsteiner T., Thater G., "The New AMG 5.5 1 V8 Naturally Aspirated Engine with Cylinder Shut-off", 20<sup>th</sup> Aachen Colloquium Automobile and Engine Technology, 2011.
10. "2013 Lamborghini Aventador Adds Cylinder Deactivation and Stop-Start", Car and Driver, Oct 2011.
11. Huber, R., Klumpp, P., and Ulbrich, H., "Dynamic Analysis of the Audi Valvelift System," *SAE Int. J. Engines* 3(1):839-849, 2010; doi: [10.4271/2010-01-1195](https://doi.org/10.4271/2010-01-1195).
12. Hadler, J., Neusser, H.-J., Szengel, R., Middendorf, H., "The New TSI", 33rd International Vienna Motor Symposium, April 2012.
13. Förster, H.J., Lübbing B.E., Letsche U., "Process and Apparatus for Intermittent Control of a Cyclically Operating Internal Combustion Engine", U.S. Pat. No. 4509488, 1982.
14. Tripathi, A. and Silvestri C., "Internal combustion engine control for improved fuel efficiency", U.S. Patent 7,577,511, 2009.
15. Tripathi, A. and Silvestri C., "Internal combustion engine control for improved fuel efficiency", U.S. Patent 7,849,835, 2010.
16. Tripathi, A. and Silvestri C., "Internal combustion engine control for improved fuel efficiency", U.S. Patent 7,886,715, 2011.
17. Tripathi, A. and Silvestri C., "Internal combustion engine control for improved fuel efficiency", U.S. Patent 7,954,474, 2011.
18. Tripathi, A. and Silvestri C., "Internal combustion engine control for improved fuel efficiency", U.S. Patent 8,099,224, 2012.
19. Tripathi, A. and Silvestri C., "Internal combustion engine control for improved fuel efficiency", U.S. Patent 8,131,445, 2012.
20. Tripathi, A. and Silvestri C., "Internal combustion engine control for improved fuel efficiency", U.S. Patent 8,131,447, 2012.
21. International Standard ISO 2631-1: "Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements", Second edition 1997-05-01, ISO Reference number ISO 2631-1: 1997(E).
22. Harrison, M., *Vehicle Refinement: Controlling Noise and Vibration in Road Vehicles*, Elsevier, 2004.
23. <http://media.gm.com/media/us/en/gmc/vehicles/yukon/2010.tab1.html>
24. U.S. Code of Federal Regulations, Title 40, *Protection of Environment*, section 600.206-12, 2012.
25. <http://gmpowertrain.com/VehicleEngines/PowertrainProducts.aspx>
26. Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, National Academies Press, 2011.

## CONTACT INFORMATION

The first author can be reached at  
[mark@tulatech.com](mailto:mark@tulatech.com)

## ACKNOWLEDGMENTS

The authors would like to commend the entire Tula Technology Inc. team on making the technology a success.

Particular Tula Technology contributors to this paper include

Li-Chun Chien, Geoff Routledge, Xin Yuan, Steven Carlson and Chris Chandler.

## DEFINITIONS/ABBREVIATIONS

**AFM** - Active Fuel Management

**AT** - Automatic Transmission

**BSFC** - Brake Specific Fuel Consumption

**CAFE** - Corporate Average Fuel Economy

**CARB** - California Air Resources Board

**DSF** - Dynamic Skip Fire

**EA** - Engine Average

**FMEP** - Friction Mean Effective Pressure

**FTP** - Federal Test Procedure

**HFET** - Highway Fuel Economy Test

**IMEPg** - Gross Indicated Mean Effective Pressure

**IMEPn** - Net Indicated Mean Effective Pressure

**ISFCg** - Gross Indicated Specific Fuel Consumption

**ISFCn** - Net Indicated Specific Fuel Consumption

**LOMA** - Lifter oil manifold assembly

**mpg** - Miles per gallon

**MT** - Manual Transmission

**NEDC** - New European Driving Cycle

**OEM** - Original Equipment Manufacturer

**PMEP** - Pumping Mean Effective Pressure

**TCC** - Torque Converter Clutch

**TCM** - Transmission Control Module