

Impact of the Future Fuel Economy Targets on Powertrain, Driveline and Vehicle NVH Development

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ABSTRACT

The automotive industry continues to develop new technologies aimed at reducing overall vehicle level fuel consumption. Powertrain and driveline related technologies will play a key role in helping OEM's meet fleet CO₂ reduction targets for 2025 and beyond. Specifically, use of technologies such as downsized engines, idle start-stop systems, aggressive torque converter lock-up schedules, wide-ratio spread transmissions, and electrified propulsion systems are vital towards meeting aggressive fuel economy targets. Judicious combinations of such powertrain and driveline technology packages in conjunction with measures such as the use of low rolling resistance tires and vehicle lightweighting will be required to meet future OEM fleet CO₂ targets. Many of the technologies needed for meeting the fuel economy and CO₂ targets come with unique NVH challenges. In order to ensure customer acceptance of new vehicles, it is imperative that these NVH challenges be understood and solved.

This paper will begin with an introduction of the legislative framework with respect to fuel economy and CO₂ targets for light duty vehicles. Key megatrends of engine, transmission, driveline, and electrified propulsion systems will be examined, following which the NVH behavior of each sub-system will be illustrated. A combination of experimentally measured data and simulations will be used to demonstrate key NVH challenges such as high levels of combustion noise, increased driveline torsional excitation, start-stop refinement, shift quality, and high-frequency whine noise from motors/generators in electrified propulsion systems. Examples of component-level and system-level NVH countermeasures will be discussed. Finally, the use of advanced test and simulation-based methodologies for smooth NVH refinement of future propulsion systems will be illustrated using case study examples.

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INTRODUCTION

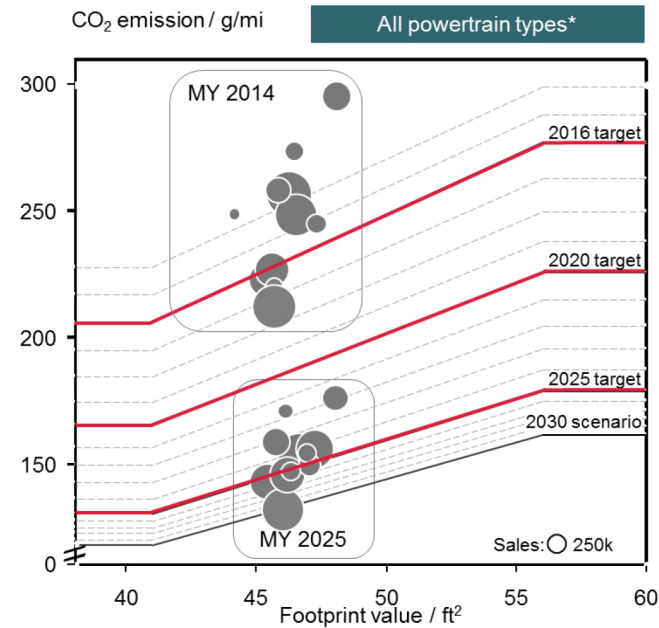
For reducing overall greenhouse gas emissions of passenger vehicles and light trucks, fleet CO₂ targets for OEM's have been defined with incremental CO₂ reduction over time. US fleet compliance targets are based on the vehicle "footprint", which takes the vehicle size into account, and have milestones defined for the year 2020 and 2025. Based on these targets, fuel economy improvements on the order of about 40% (relative to today) are needed to meet the requirements for 2025.

While full electric vehicle or fuel cell powered vehicles can achieve the future targets, these technologies have currently only a very small market share due to customer acceptance of the electric range or insufficient infrastructure for hydrogen as well as cost for such systems.

For Internal Combustion Engines (ICE) propelled vehicles, individual measures for improving fuel economy such as use of engine start/stop systems, improved combustion systems or disconnect units for AWD

applications have already been introduced by multiple OEM's. In order to comply with future fuel economy and greenhouse gas emissions regulations ([Figure 1](#)), further efficiency improvements in powertrains and vehicle systems are necessary. Various vehicle and powertrain related technologies must be evaluated as numerous technologies have to be utilized in order to meet these targets [[1](#)].

The combination of different fuel economy enablers has to be evaluated with consideration of vehicle class, feasibility, cost and level of electrification of the vehicle. For example, it might be sufficient to have a more conventional combustion engine in combination with a full hybrid electric powertrain for certain vehicle applications, while more advanced combustion systems will be vital towards meeting the CO₂ targets with non-electrified powertrains.



* Including: ICE-only, Micro Hybrid, MHEV, HEV, PHEV, BEV, FCV, Other; Source: EPA 2014, FEV

Figure 1. US Fleet CO₂ emission targets

With all propulsion concepts, energy management for the complete vehicle becomes a critically important aspect for fuel economy improvements. As an example, optimized energy management can result in “mode changes” during vehicle operation. Such mode changes are typically accompanied by the change of the noise characteristics inside the vehicle, which are typically undesirable from the standpoint of customer acceptance. As “out-calibrating” these changes is not an option with respect to achieving stringent fuel economy targets, NVH development has to be an integral part of the vehicle energy management process.

Furthermore, the use of conventional NVH enablers such as additional sound package treatments (absorption and barrier materials) and dampers conflicts with the need to develop lightweight vehicles. With shorter development times as well as demand for both cost and weight reduction, advanced simulation tools are indispensable for NVH development.

This paper describes some of the NVH challenges associated with the use of enablers for improved powertrain and driveline efficiency. Technologies such as engine downsizing, downspeaking, idle start/stop systems, aggressive torque converter lockup, and powertrain electrification are described and their impact on NVH evaluated. Examples from relevant case studies are illustrated and the NVH challenges that come with these technologies discussed in detail. Interactions between different technologies are investigated as for a successful NVH integration the entire system understanding is

necessary. In addition to case studies based on hardware evaluations, the use of simulation-based processes is illustrated. Through these examples, the challenges for NVH integration of advanced powertrains driven by demand for fuel economy improvement are illustrated and the use of potential NVH enablers for achieving refined NVH behavior is discussed.

ENGINE DOWNSIZING AND DOWNSPEEDING

An effective approach for improving fuel economy of combustion engines can be through downsizing and downspeaking of the engine. Smaller engines with reduced number of cylinders have lower friction losses. Furthermore, downsized engines operate closer to the most efficient operating point in the BSFC (brake specific fuel consumption) map during part load conditions. As seen from the example of an engine BSFC map in Figure 2, downspeaking helps move the operating point for a given power level closer to the optimal efficiency. The red curve in the BSFC map shows an example of the hyperbolic curve for constant power.

In order to not compromise power and performance when downsizing and downspeaking, these engines are typically turbocharged, which result in higher indicated mean pressures of such engines compared to naturally aspirated engines. Figure 3 compares the torque curves for a 3.0L V6 naturally aspirated and a 2.0L I4 turbocharged DI engine [2]. While the peak power for both these engines is equal, the turbocharged DI engine achieves its performance with smaller displacement, lower cylinder numbers, and boosting. The turbocharged DI engine has its peak power at a lower speed. Torque, and in particular “low-end” torque, is significantly higher with the boosted engine, despite the smaller displacement. This increased torque allows the engine to be operated at lower rotational speeds in conjunction with modified transmission and final drive ratios without compromising vehicle performance and driveability [3].

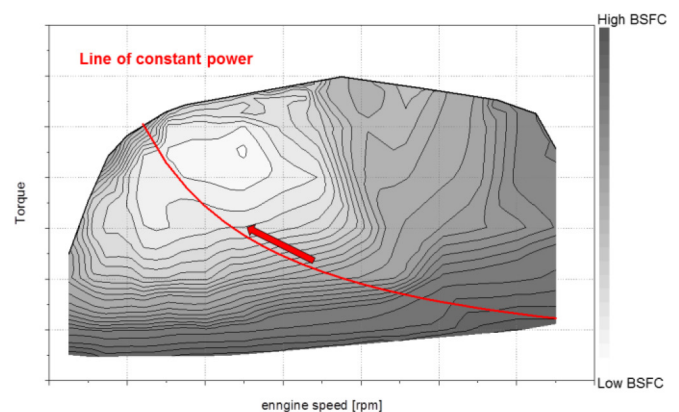


Figure 2. Engine BSFC map example

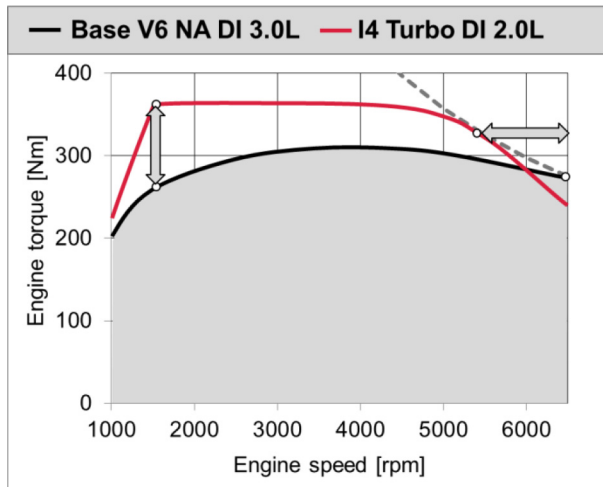


Figure 3. Engine torque curve comparison [2]

With the higher specific output torque and hence engine BMEP (brake mean effective pressure), the torsional speed fluctuation due to the cyclic combustion process is also higher than lower BMEP engines. A comparison of torsional fluctuation for inline 4-cylinder engines based on different combustion systems (i.e., naturally aspirated gasoline, turbocharged gasoline, and turbocharged Diesel) is shown in Figure 4 [4]. Highly boosted gasoline DI engines can exhibit torsional fluctuations in the range of some Diesel engines. In addition to higher excitation due to the higher cylinder pressures, reducing the number of cylinders can also result in a significant increase in torsional fluctuations as shown in Figure 5.

When downsizing a combustion engine, the effects of torsional vibration increase due to higher gas excitation (Figure 4). In addition, the use of reduced number of cylinders (Figure 5) results in a significant increase in transmission and driveline excitation, making the NVH refinement for boosted combustion engines with 4 or less cylinders challenging.

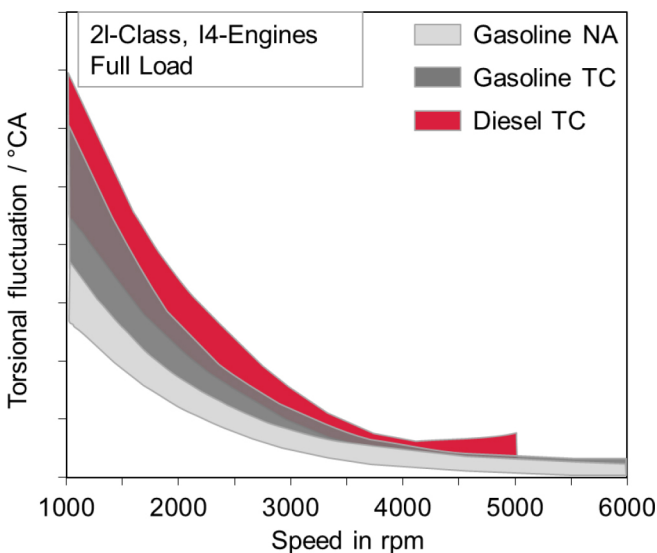


Figure 4. Engine torsional fluctuations for different combustion systems [2]

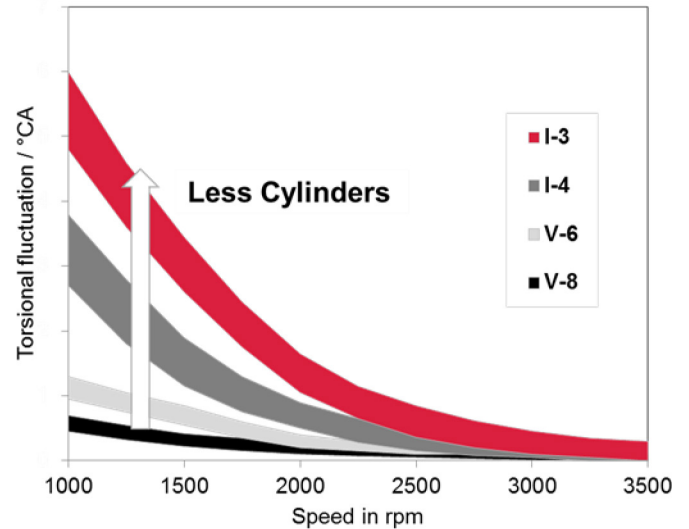


Figure 5. Engine torsional fluctuations for different cylinder counts [2]

In order to show the effect of overall (mean) engine torque and torsional vibration, simulations were conducted using multi-body systems tools. Specifically, multi-body system models for V8, V6, and I4 engines were created (Figure 6 shows examples of the Virtual Engine models) using engine parameters for typical V8, V6, and I4 engines (see Table 1).

As for cylinder pressure, measured data from state-of-the-art PFI (port fuel injection) and GTDI (gasoline turbo direct injection) engines have been applied as excitation in the Virtual Engine models. The results of mean torque and torsional vibration for the naturally aspirated V8 engine and the turbocharged DI engine in V8, V6, and I4 configurations are compared in Figure 7 and Figure 8 respectively. Based on the mean torque it becomes obvious that even with reduced displacement the same torque (or higher) can be achieved with a GTDI engine relative to a PFI engine. This composite effect of increase in cylinder pressure excitation and reduction of cylinder count is a significant increase in engine-out torsional fluctuations (Figure 8).

Despite some differences between bores and strokes between the simulated engine architectures, this comparison reveals clearly the performance potential of downsized combustion engines, but also shows the NVH challenges with respect to torsional excitation of the driveline. Additionally, higher peak pressures and pressure rise rates of downsized and boosted engine result in higher combustion noise excitation [5] and hence additional NVH challenges with respect to integration of these engines into vehicles.

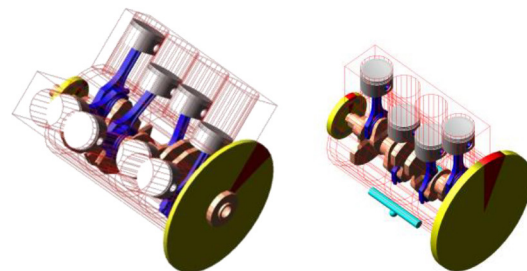


Figure 6. MBS models of the V8 and I4 engines

Table 1. Main engine parameters used for the Virtual Engine models

Engine Type	Bore [mm]	Stroke [mm]	Displacement [L]
V8	105.8	90.2	6.3
V6	86.7	92.5	3.3
I4	86.0	86.0	2.0

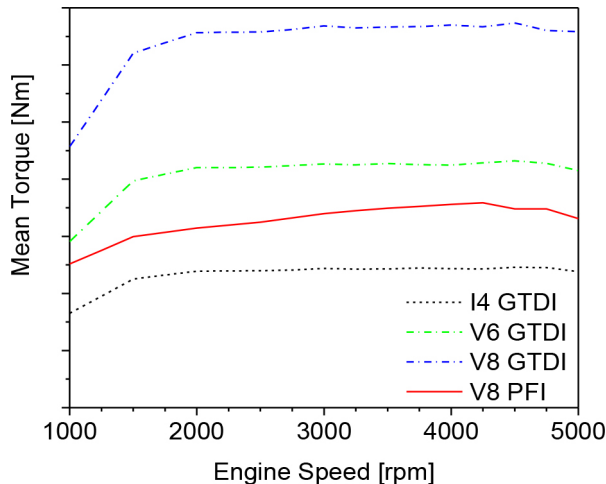


Figure 7. Engine torque for different engine architectures and cylinder pressure excitations

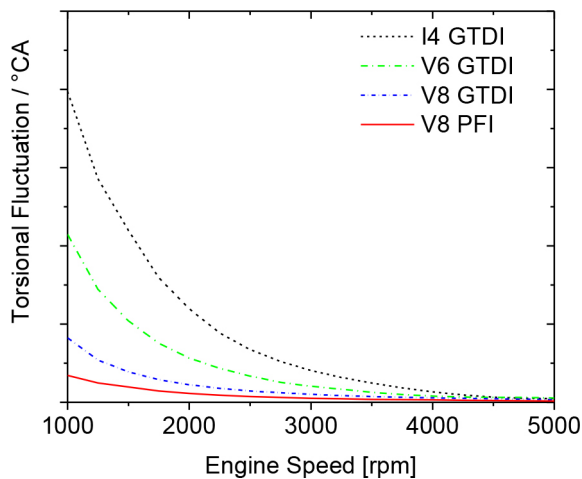


Figure 8. Torsional vibration for different engine architectures and cylinder pressure excitations

TRANSMISSION AND DRIVELINE NVH CHALLENGES WITH DOWNSIZED ENGINES

Engine torsional vibrations are known to cause challenges for transmission and driveline NVH integration. In particular, driveline boom noise and gear rattle are driveline phenomena that get excited by engine torsional vibration [e.g., 6, 7]. While gear rattle is primarily an NVH concern for manual transmissions, AMT (automated manual transmissions) and DCT (dual clutch transmissions), driveline boom noise is related to the excitation of the fundamental torsional driveline modes in the frequency range from approximately 30 Hz - 250 Hz, which also occurs with planetary automatic transmissions under torque converter lock-up conditions. Hence, driveline boom

could be avoided for torque converter equipped vehicles when the torque converter remains unlocked for a wide operating area. It is, however, desirable to lock up the torque converter as early as possible for reducing losses in the torque converter system.

To minimize fuel consumption, the automatic transmission applications focus on maximizing the lock-up area of the torque converter. When the torque converter is locked, it can also be operated under “controlled slip” conditions. The slip adds damping to the resonant excitation of the driveline modes and hence, can be employed to minimize boom noise inside the vehicle. The example shown in Figure 9 shows the interior noise of a vehicle with boom noise prevalent in the vicinity of 1800 engine rpm. This corresponds to a frequency of 120 Hz (V8 engine application). As shown, the boom noise can be effectively minimized by employing controlled slip in the torque converter clutch. It is interesting to note that the difference in interior boom noise between 25 rpm and 50 rpm slip is marginal. Hence, even a small amount of slip can be effective in reducing torsional vibration at the transmission input side. Reducing slip is desired for minimizing driveline losses and the minimum slip that can be set is typically limited by the characteristics of the friction material of the lock-up clutch as well as the capabilities of the lock-up controls.

For vehicle calibration, the torque converter lock-up strategy can be described similar to transmission shift lines as a function of vehicle speed and accelerator pedal position. An example of applied torque converter slip overlaid with the shift lines for a conventional torque converter automatic transmission is shown in Figure 10. As shown, the torque converter exhibits slip control past a certain threshold vehicle speed for a given load (pedal position) condition. It can also be noted that at higher pedal positions some micro-slip is utilized to avoid NVH concerns. In addition, the micro-slip is reduced in the higher gears (4th gear and above) in order to minimize losses related to clutch slip. Figure 11 shows the engine torsional vibrations (overlaid with the shift lines) as a function of accelerator pedal position and vehicle speed (for the same vehicle). As shown in the plot, relatively high levels of torsional vibrations are noted at the low pedal positions. At first, this behavior appears counter intuitive, but this characteristic is related to the lower engine speeds for these operating conditions.

Engine downspeeding and the general behavior of high torsional vibration at low engine speeds (e.g., shown in Figure 5) can cause driveline NVH concerns. For fuel economy reasons it is also desirable to operate the engine (even for low pedal positions) at relatively high engine load. This is accomplished by shifting early to higher gears such that the engine operates closer to its best BSFC point (e.g., Figure 2). The corresponding torsional vibration (to Figures 10 and 11) for the transmission input speed is shown in Figure 12. In comparing Figure 10 and Figure 12, it becomes very obvious that the torsional vibration on the transmission input side increases in 4th-6th gears when the torque converter is fully locked. For low pedal positions the torsional vibration levels at the transmission input are relatively high and can result in driveline NVH issues. Since engines spend a significant portion of their duty cycle in this range, it is very important to optimize their operation for both overall vehicle fuel economy and NVH.