

Influence of Automatic Engine Stop/Start Systems on Vehicle NVH and Launch Performance

Thomas Wellmann and Kiran Govindswamy
FEV North America, Inc.

Jeff Orzechowski and Sudharsan Srinivasan
FCA US LLC

ABSTRACT

Integration of automatic engine Stop/Start systems in “conventional” drivetrains with 12V starters is a relatively cost-effective measure to reduce fuel consumption. Therefore, automatic engine Stop/Start systems are becoming more prevalent and increasing market share of such systems is predicted. A quick, reliable and consistent engine start behavior is essential for customer acceptance of these systems. The launch of the vehicle should not be compromised by the Stop/Start system, which implies that the engine start time and transmission readiness for transmitting torque should occur within the time the driver releases the brake pedal and de-presses the accelerator pedal. Comfort and NVH aspects will continue to play an important role for customer acceptance of these systems. Hence, the engine stop and re-start behavior should be imperceptible to the driver from both a tactile and acoustic standpoint.

This paper describes the details of various powertrain calibration factors for the engine start process. The key phases of an engine start event are described in detail, and their influence on the vehicle vibration investigated. The engine stop behavior is analyzed with respect to crank position and possible engine “roll back” and its influence on vehicle vibration. Unconventional start systems such as assisted direct starts are investigated with respect to engine start time and associated NVH behavior. Case studies are utilized to illustrate the influence of cylinder pressure, spark, and injection system parameters on the engine start process. In addition, key parameters of torque converted equipped planetary automatic transmissions with respect to the engine start behavior are analyzed. Comparisons of different Stop/Start systems are conducted and their influence on engine start, launch delay, and “change-of-mind” engine re-start are summarized.

CITATION: Wellmann, T., Govindswamy, K., Orzechowski, J., and Srinivasan, S., "Influence of Automatic Engine Stop/Start Systems on Vehicle NVH and Launch Performance," *SAE Int. J. Engines* 8(4):2015, doi:10.4271/2015-01-2183.

INTRODUCTION

In order to comply with fuel economy and greenhouse gas emissions regulations, various vehicle and powertrain related technologies are being evaluated. The implementation of automatic engine Stop/Start systems is one such technology aimed at reducing overall fuel consumption. The use of such systems can cut the engine idle time significantly and the fuel economy benefit is estimated to be in the 3-5% in the FTP75 or NEDC test cycles [1,2]. The most common engine start system is a 12V-based ring gear starter. Such a basic engine Stop/Start system offers an attractive benefit-to-cost ratio compared to other enablers for fuel economy savings [3].

Integration of a conventional 12V-based automatic engine Stop/Start system typically requires modifications including the use of a starter that can accommodate the durability requirements associated with an increased number of Stop/Start cycles. High current draw from the engine starter can cause a significant voltage drop during re-start events. Hence, DC/DC converters, capacitors, or secondary 12V batteries are necessary for assuring the stability of the electric system

during engine re-start events. Changes in the engine, transmission and vehicle controls are often necessary and engine Stop/Start enablers must be implemented to assure vehicle safety and passenger comfort criteria [4]. The use of automatic engine Stop/Start systems with automatic transmission requires additional countermeasures to ensure that the transmission line pressure is maintained at a given level or can be built up quickly so that the lack of transmission readiness does not result in a launch delay [5,6].

Disadvantages of 12V-based automatic engine Stop/Start systems include reduced engine cranking speeds (as compared to belt starter generator (BSG) systems) and limitations associated with change of mind engine restarts [1,7]. These drawbacks are primarily related to increased vibration during engine re-starts and delay/hesitation during vehicle launch. While permanently engaged starter systems can compensate for some of these drawbacks, such systems come with increased complexity and cost. Therefore, it is desirable to achieve customer acceptance of automatic engine Stop/Start systems utilizing conventional 12V-based ring gear starter architecture.

Key metrics to characterize the NVH and launch performance of a vehicle with automatic engine Stop/Start systems such as the vibration dose value (VDV), energy spectral density (ESD), engine start time, and launch delay have been reported in prior publications [1,8,9]. This paper discusses measures that can be utilized to improve the NVH behavior of automatic engine Stop/Start systems with a focus on conventional ring gear starter systems. Additionally, the launch behavior is investigated with focus on engine re-start time and launch readiness of automatic transmission systems.

12V-BASED RING GEAR STARTER SYSTEM

Figure 1 shows test results from an engine start example for a vehicle with a conventional ring gear starter system. The pinion of the engine starter has to be engaged with the ring gear for the engine start, shown by the starter solenoid voltage in Figure 1. Once the pinion is engaged, the starter motor is powered, drawing a significant current for the time of the engine start. The engine speed increase during an engine start event can be separated into two distinct phases; the cranking phase and the start of combustion. The engine starter accelerates the engine during the cranking phase to a rotational speed that is sufficient to allow for a stable start of engine firing event that further increases the engine's rotational speed. Once the combustion process is started, the engine speed shows a high initial speed increase, but combined with significant speed fluctuations.

Figure 1 also shows engine starter engagement and voltage drop measured at the starter battery. The voltage during cranking falls to approximately 9.5V, showing the need for an additional system assuring voltage stability during engine re-start.

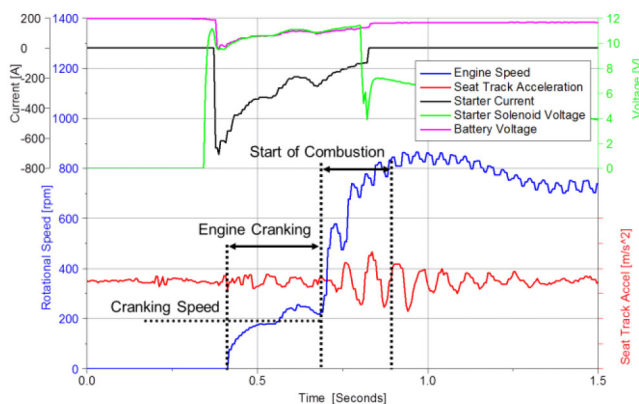


Figure 1. Engine Start via Ring Gear Starter on a Vehicle with a Longitudinally Mounted Engine [1]

ENGINE STOP AND RESTART FOR STOP/START SYSTEMS

The exact crank angle location of the engine must be known for controlling the exact timing of fuel injection and ignition thus allowing the first combustion during engine start. Crank angle position is typically determined via sensors at the crankshaft ("crank position sensor") and cam shaft ("cam position sensor"), both utilizing a tone-wheel with a defined gap. Depending on the tone wheel profile, it can take up to 360° crank angle rotation on some systems (but not all) for the engine to detect the crank angle location. Engine

synchronization time is defined as the time the engine controller requires for identifying the crank angle location and enabling the first combustion process. The synchronization time can be reduced when changing the profile of the camshaft tone wheel to a more unique profile with several unequal length gaps and teeth. The repeated synchronization time for each engine restart can be avoided altogether if the crank angle location is stored in the ECU during the engine stop phase. However, this cannot be achieved with conventional Hall Effect position sensors as they do not detect a possible crankshaft reversal during engine stop (see details in the following section). If the position sensor is capable of detecting the rotation direction, the exact crank angle position of the engine can be determined during the engine stop phase. The rotation direction can be detected with speed sensors that utilize at least two Hall-Effect sensors with a slight offset; the phase information between these signals enables the detection of rotation direction.

Figure 2 illustrates an automatic engine stop and restart event transformed in the crank angle domain. The engine in this case is a 4 cylinder gasoline engine with direct injection. In the first shown engine cycle (0-720°) the engine is still operated at idle. Within the next cycle combustion is shut off, and the injector for Cylinder 1 is deactivated. The engine rotates approximately 2 cycles from idle speed before coming to a full stop. Cylinder pressure records show the pressure fluctuation of the engine pumping during shut off.

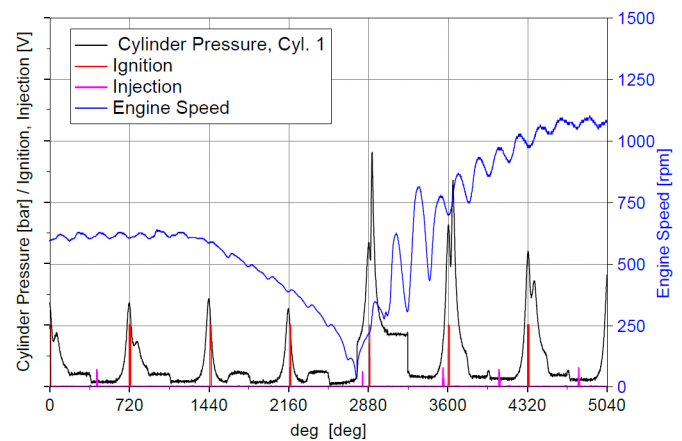


Figure 2. Engine Stop and Restart in Crank Angle Domain

The first firing event during engine restart is executed by Cylinder 1 in the shown example. The crank angle rotation from engine stop to spark time of Cylinder 1 is nearly 135° CA. The engine in this example utilized a speed sensor capable of detecting rotational directivity; hence no synchronization is necessary. Without the need for a new synchronization, the time to enabling the first injection and firing is mainly determined by the duration of starter engagement required to achieve the necessary cranking speed in time to get into the next possible 'window' of injection/ignition.

The first combustion reveals the highest peak pressure, indicating a nearly unthrottled combustion since intake manifold pressure during engine stop increases to ambient pressure. Upon the initial firing, the engine speed displays high fluctuation. These fluctuations correlate to a driveline torsional resonance, which is excited by the high excitation of the (nearly) unthrottled combustion events. The

resonance is typically related to the Dual Mass Flywheel (DMF), which allows setting this frequency below idle excitation [1,10,11]. Ideally the start of combustion would occur past the range of excitation (from the engine firing order) of the driveline resonance as well as powertrain rigid body modes. While this could be achieved with higher cranking speeds achievable with a BSG system, conventional 12V ring gear starters have a limitation in this area.

INFLUENCE OF CRANK ANGLE POSITION DURING ENGINE STOP EVENTS

Although the engine start typically shows relatively high vibration levels due to the combustion excitation, the engine stop can also cause noticeable vibration and NVH concerns. Compression forces can lead to high excitations during the engine stop process. Figure 3 compares the seat track acceleration during engine stop events of two different vehicles. While both vehicles reveal a low frequency vibration (vehicle shuffle) due to the vehicle stop event, Vehicle A shows a high acceleration peak during the engine stop phase, causing a significantly higher Vibration Dose Value (VDV) than that of Vehicle B. Engine speed in these examples is measured with a one pulse/revolution signal, causing the 'digitized' engine speed and associated inaccuracies during the engine stop event. As no combustion excitation occurs during the engine stop event, the excitation during engine stop is caused by rotational oscillation of the crankshaft and compression forces [12]. Rotational oscillation is mainly influenced by the crankshaft inertia, forces from compression/decompression, and friction. While inertia and friction are fixed for a given system during engine stop, the compression and decompression forces can be influenced via throttle position (most common), as well as cam phasing and valvelift, if applicable. When closing the throttle, air is restricted and hence compression forces are reduced. In addition to the NVH during engine stop, other criteria such as possible positioning of the crankshaft during engine stop (see following section) are important items to consider as well. These aspects of throttle control can have conflicting targets, resulting in a compromise between NVH, preparing the engine re-start with respect to start time, robustness of restart, and emissions.

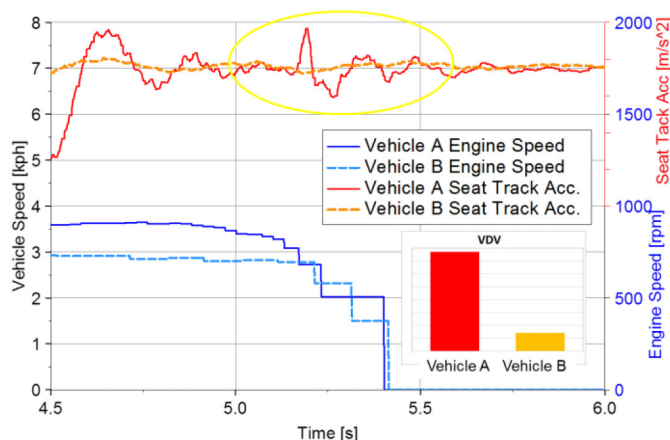


Figure 3. Seat Track Vibration during Engine Stop

Figure 4 illustrates the crank angle position distribution of a V6 engine during the engine stop phase (from multiple stop events). The stop position, in this example, is not entirely random. Three areas of

high occupancy can be identified. For a V6 engine with even firing order, these peaks are distributed by 120° crank angle increments. It should be noted that crank angle position in this plot does not indicate whether the top dead center (TDC) corresponds to the firing or gas exchange cycles. Although the engine stop position (in this example) reveals higher occupancy at certain positions (approx. 60° before TDC Cylinder 1) in the histograms, numerous outliers can be detected where the crankshaft position seems random.

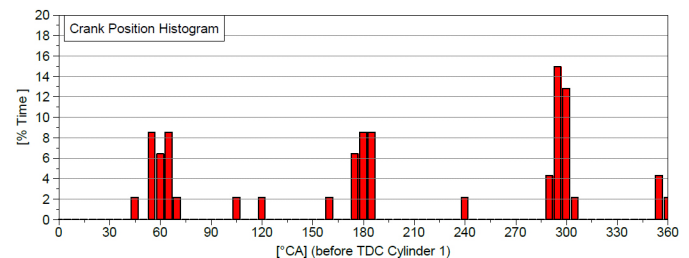


Figure 4. Crankshaft Position during Engine Stops (30 runs)

The engine crankshaft often rolls back during the end of the engine stop due to the compression forces. The higher the compression forces are, the more likely the engine changes its rotation directivity at engine stop since the compression forces act like an air spring. Compression forces can be influenced by throttling the engine during engine stop, resulting in a more controlled engine position at engine stop and hence, reduced vibration [13]. When investigating the VDV and crankshaft rollback of the same test vehicle in Figure 4, it can be noted that the VDV and rollback angle do not necessarily correlate, as shown in Figure 5. However, the throttle was always nearly fully closed during this evaluation so that the differences are driven by run-to-run variability. While the compression forces are assumed to be fairly constant due to the same throttle control during engine stop events; for unthrottled engine stops, the vibration levels will be noticeably higher.

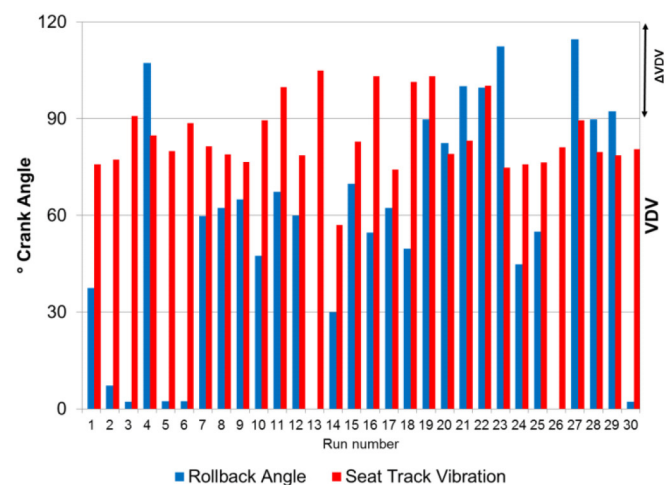


Figure 5. Crankshaft Rollback Angle and Seat Track Vibration (VDV) at Engine Stop with closed Throttle Position

For enabling quick and consistent engine restart times, it is desirable to have the engine stopped in a certain crank angle position, with a known crank angle. The crank angle position should ideally fall in an area such that the cranking phase directly ends in