

Integration of Engine Start/Stop Systems with Emphasis on NVH and Launch Behavior

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ABSTRACT

Automatic engine start/stop systems are becoming more prevalent and increasing market share of these systems is predicted due to demands on improving fuel efficiency of vehicles. Integration of an engine start/stop system into a “conventional” drivetrain with internal combustion engine and 12V board system is a relatively cost effective measure to reduce fuel consumption. Comfort and NVH aspects will continue to play an important role for customer acceptance of these systems. Possible delay during vehicle launch due to the engine re-start is not only a safety relevant issue but a hesitating launch feel characteristic will result in reduced customer acceptance of these systems. The engine stop and re-start behavior should be imperceptible to the driver from both a tactile and acoustic standpoint. The lack of masking effects of the engine during the engine stop phases can cause other “unwanted” noise to become noticeable or more prominent. Other comfort related criteria like a stable 12V board supply during the engine start phase or A/C usage during the engine stop phase need to be considered as well.

This paper provides an overview of start/stop systems and starter concepts. The requirements for different transmission types and the associated start/stop challenges are described. The phases of an engine start are described in detail, and their influence on the vehicle vibration investigated. NVH related metrics for describing the engine start/stop and vehicle launch are introduced. Key design parameters of the powertrain and driveline on the start/stop NVH behavior are studied. In addition, the impact of engine start on the vehicle's launch behavior is analyzed. Comparisons of different start/stop systems are conducted and results from case studies on the influence to launch delay and “change-of-mind” engine restart are provided. Finally, the effect of missing masking noise during the engine stop phases is discussed.

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INTRODUCTION

Automatic engine start/stop systems are one possibility to improve fuel efficiency of vehicles with internal combustion engine. Idle time is avoided by shutting the combustion engine off; it automatically re-starts when the driver releases the brake pedal or presses the clutch pedal in vehicles with manual transmissions. Figure 1 shows a comparison of engine speed profiles during the FTP75 emission cycle for a vehicle equipped with a four-cylinder turbocharged direct injected gasoline engine operated with- and without automatic start/stop feature. Without the start/stop system, the vehicle remains at idle for nearly 20% of the test cycle duration. This results in a fuel efficiency benefit for FTP75 or NEDC emission cycle of approximately 3-5% for vehicles with start/stop system enabled [1, 2]. Due to these fuel efficiency benefits, the market share of vehicles equipped with start/stop system is expected to increase rapidly. It is estimated that by 2017 about 65% of the vehicles in the

European market and 38% of vehicle in the North American market will be equipped with engine start/stop systems [3].

In comparison to full hybrid systems, it seems relatively easy to integrate start/stop systems into conventional vehicles. However, there are numerous challenges inherent in the integration of start/stop systems. For example, the starter motor and battery need to be designed for significantly higher duty cycles. Additional items include aspects such as ensuring that engine re-starts happen under all circumstances while addressing safety concerns with error states such as unintended engine starts.

With respect to passenger comfort, the A/C system requires modifications since most A/C compressors are driven via the front end engine accessory belt and hence do not operate during the engine stop phases. Additionally, the 12V electrical system must be stable even during the event of the engine re-starts.

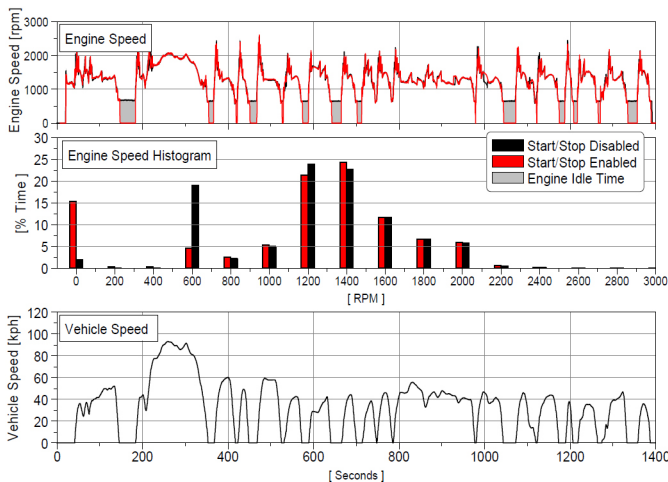


Figure 1. Engine speed histograms for an FTP75 emissions cycle with start/stop disabled and enabled

The engine stop and re-start NVH quality is critical to the refinement of the vehicle. While a vehicle key start and stop is initiated by the driver and happens only once during each vehicle operation, the automatic engine start/stops occur at each vehicle stop and are not initiated by the driver. Engine starts can also occur without driver request; e.g., during vehicle launch and due to conditions dependent on A/C settings or battery state-of-charge.

Repeated engine start after each vehicle stop can result in a higher sensitivity of the driver to the disturbance of the engine stop and start. During the engine stop phase, “unwanted” noise; e.g. from the HVAC system or electric auxiliary pumps can become more prominent due to absence of engine noise. Additionally, the engine start could result in a higher launch delay of the vehicle and hence an objectionable launch perception. It is hence necessary to have quick reliable engine re-starts and no delays in the transmission functionality related to the engine start/stop feature.

The most common starter system is a 12V operated ring gear starter. This system is well proven and has a very high market share. Conventional ring gear starters require the least complex modifications of a given vehicle architecture to implement a start/stop system. Disadvantages of this system are limited cranking speed as well as the lack of “change-of-mind” re-start capability. The engine must not be spinning before the starter pinion can be engaged in the ring gear, resulting in a rather long delay of engine re-start for a “change-of-mind” event. Enhanced ring gear starters are permanently engaged and avoid delays for engine “change-of-mind” re-starts [4]. Belt starter generators (BSG) allow for a higher cranking speed for engine start and ramp down of engine speed during stop, resulting in improved NVH behavior [5]. Full hybrid vehicles allow even more possibilities to start and stop the engine, but the start can be subjectively more critical since it can also occur during normal driving events (i.e., not only during vehicle launch)

[6]. This paper is mainly focused on conventional 12V start/stop systems utilizing ring gear starters and BSG systems.

ENGINE START PROCESS WITH RING GEAR STARTER SYSTEM AND EVALUATION METRICS

Figure 2 shows an example of an engine start for a vehicle (transversely mounted four cylinder engine) utilizing a ring gear starter system. The pinion of the engine starter needs to be engaged with the ring gear for the engine start, which is shown by the starter solenoid voltage in Figure 2. Once the pinion is engaged, the starter motor is powered, drawing a significant current for the time of an 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. In the cranking phase the engine starter accelerates the engine to a rotational speed that is sufficient to allow for a stable combustion event that further increases the engine's rotational speed. In the shown example (Figure 2), the cranking speed is approximately 270 rpm. Once the combustion process is started, the engine speed not only shows a high initial speed increase, but also exhibits significant speed fluctuations. This phase is typically most critical for NVH concerns during engine starts [5]. Seat track vibration shows the highest amplitudes in the region of the combustion start, followed by decaying resonant response.

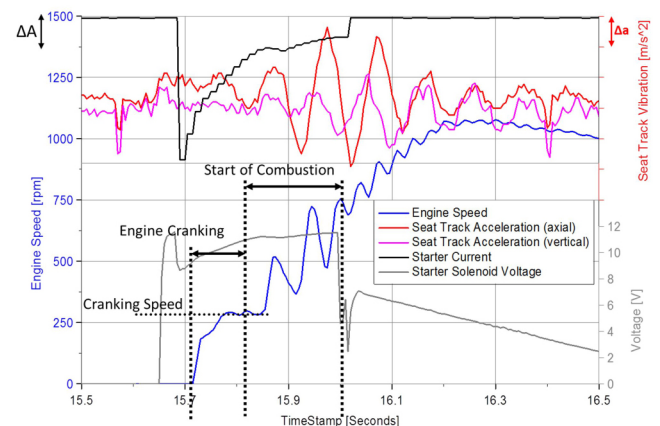


Figure 2. Engine start via ring gear starter on a vehicle with a transversely mounted engine

Figure 3 shows the spectral information for the same engine start process described in Figure 2. The seat track vibration is dominated by a frequency peak around 10 Hz, which is within the expected frequency range for the rigid body powertrain modes. These modes are excited due to the reaction forces of the engine cranking torque as well as the highly non-linear engine rotational speed ramp up during engine start. Torsional vibration measured at the engine starter ring gear clearly show the firing order (2nd engine order for the 4 cylinder engine in the given test vehicle). Throughout the engine start process, the 2nd order frequency

content increased from approximately 9 Hz (cranking speed) to 36 Hz (1080 rpm peak engine speed at engine start). Engine speed reveals a torsional resonance at 26 Hz, which is excited by the engine firing order during the combustion phase of the engine start process. This frequency correlates well with a torsional driveline mode in conjunction with a dual mass flywheel (DMF).

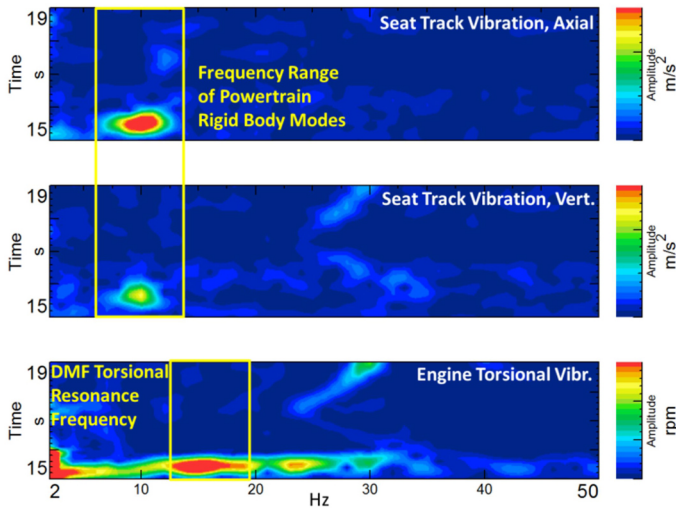


Figure 3. Engine start via ring gear starter on a vehicle with a transversely mounted engine

The examples in [Figure 2](#) and [Figure 3](#) show the seat track vibrations for a front wheel drive (FWD) vehicle with a transversely mounted engine. Seat track vibrations in axial (vehicle fore-aft) direction show highest amplitudes for this vehicle, suggesting that the powertrain roll mode (about crankshaft axis) is excited during the engine start process. [Figure 4](#) and [Figure 5](#) show similar information for a vehicle with a longitudinally mounted four cylinder engine. In this case, seat track vertical vibrations (measured at the outboard location) reveal higher seat track vibration response than the axial direction. Since the high engine torsional fluctuations during engine start excite engine roll around the engine crankshaft axis, the engine orientation has a significant influence on the seat track vibration response. In either case the powertrain rigid body modes get excited, which correlate well with the frequency range of the measured seat track response.

Seat track vibration is a proven objective measurement for describing the customer-perceived vibration disturbance during engine start and stop events. A proven metric for describing vibration during a transient event like engine start and stop is the Vibration Dose Value (VDV). The VDV describes the vibration disturbance as a single number metric, which allows for easy comparisons of the vibration response from different vehicles [7, 8]. The VDV is defined as:

$$VDV = \sqrt[4]{\int_{ts}^{te} a^4(t) dt}$$

where “a” is the measured seat track acceleration (typically filtered to include content below 30 Hz), while “ts” and “te” refer to the start and end times respectively of the transient event (e.g., engine start).

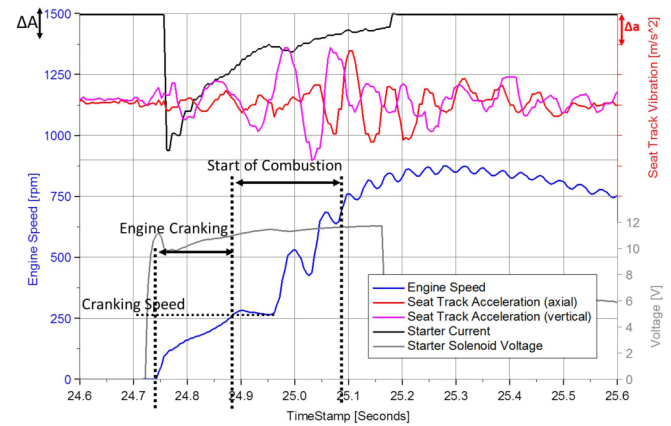


Figure 4. Engine start via ring gear starter on a vehicle with a longitudinally mounted engine

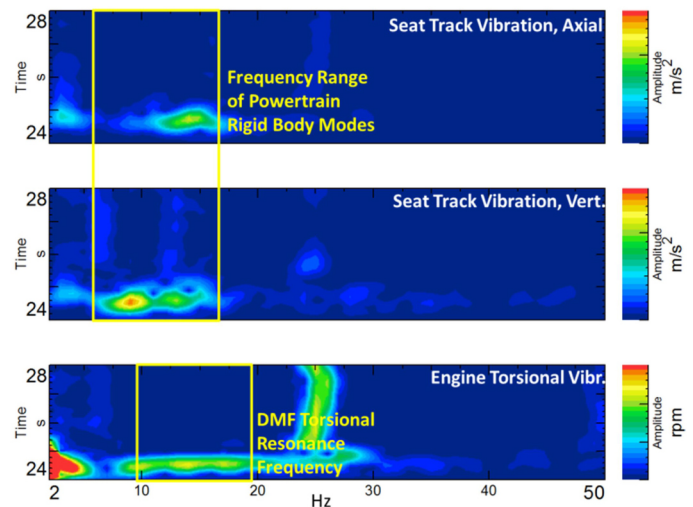


Figure 5. Engine start via ring gear starter on a vehicle with a longitudinally mounted engine

[Figure 6](#) compares VDV's for engine starts measured on various vehicles with start/stop systems. The engine re-starts were measured upon brake pedal release (engine start trigger) and vehicle launch with different accelerator pedal positions. For most vehicles, the vibration response is relatively independent of the accelerator pedal position at launch. The relatively high VDV values for Vehicle B at 50% and 100% pedal position launches are related to a higher engine speed after initial engine start. [Figure 7](#) compares a 15% pedal and 100% pedal (WOT) launch including engine start for this vehicle. As shown in [Figure 7](#), under a WOT launch, Vehicle B starts to accelerate (launch) during the engine start process. The DC acceleration of the vehicle (as measured by the seat track accelerometer) can influence the VDV calculation and

provide an incorrect assessment of the engine start up vibration. In such cases, additional analysis is often necessary to understand and optimize the engine start NVH behavior of the vehicle.

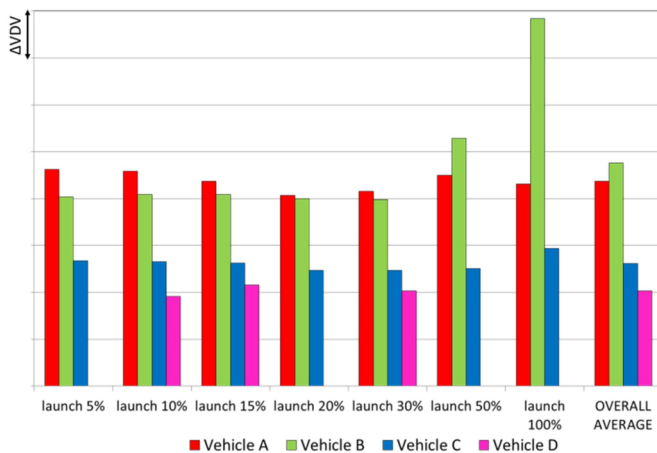


Figure 6. Engine start Vibration Dose Values (VDV)

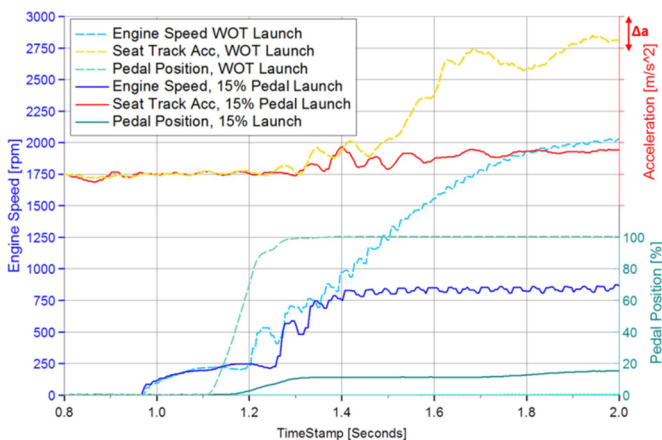


Figure 7. Launch pedal position influence on seat track acceleration for Vehicle B

While the VDV is useful for target setting and assessment of the engine start/stop behavior, it does not provide additional insights that might be needed to focus development efforts. Another useful metric that can help with engine start/stop refinement is the ESD (Energy Spectral Density) of vehicle seat track vibration. The ESD is defined as [8]:

$$ESD = \frac{G_s(\omega)}{\Delta f} \Delta T$$

where $G_s(\omega)$ is the auto power spectrum, Δf the frequency resolution and ΔT the time period for ESD calculation.

The ESD based analysis can provide insights into the engine start/stop vibration since it allows for determining the frequency content of the seat track (or steering wheel) disturbance, while the VDV is a single number metric. Figure

8 shows the ESD for the seat track vibration response measured for engine re-starts with start/stop system for the same vehicles for which the VDV values were shown in Figure 6. Generally, the ESD enables target setting, as well as identification of the frequency range of concern. The ESD information given in Figure 8 reveals relatively high vehicle sensitivity in the 5-15 Hz frequency range.

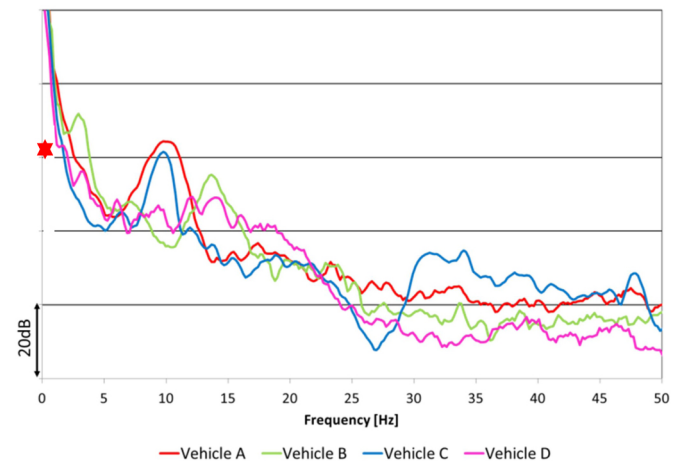


Figure 8. Engine start Energy Spectral Density (ESD)

Vehicle vibrational response can be minimized with a relatively quick engine start, resulting in limited duration of powertrain and driveline resonance excitation. The torque of the engine starter and the cranking speed has to be sufficient to enable a quick start. It is also critical for the engine to produce adequate energy during the initial combustion to further accelerate the engine speed and quickly pass through the driveline resonance. It is important for the cranking speed to be high enough so that the combustion energy can accelerate the engine to its idle rotational speed instead of increasing the vehicle vibration during this process [9]. Ideally the start of combustion would occur past the range of excitation (from the engine firing order) of the driveline resonance. While this could be achieved with higher cranking speeds, conventional 12 V ring gear starters have a limitation in this area.

An important criteria regarding acceptance of start stop systems is a fast and imperceptible engine start behavior. For a quick engine re-start, the engine crankshaft position must be known prior to the re-start, or the engine camshaft position sensor wheel has to be equipped with a profile which enables a quick start. In this case, the engine does not need a full revolution to determine its crankshaft position relative to a cylinder's top dead center (TDC). Figure 9 shows an example of an engine re-start event including cylinder pressure and engine encoder measurements. In this example, the first cylinder (Cylinder 1) of a four cylinder gasoline engine was instrumented with a cylinder pressure sensor. At the shown engine re-start, Cylinder 1 is the first cylinder that shows a combustion event. This is particularly obvious as the engine rotational speed rapidly increases after the combustion event