

Optimizing 12 Volt Start - Stop for Conventional Powertrains

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ABSTRACT

A cost effective means of achieving fuel economy gains in conventional powertrain is to utilize a 12 volt start/stop (S/S) system to turn the engine off and on during periods of vehicle idle. This paper presents powertrain integration issues specific to a 12 volt S/S system and the powertrain hardware content and calibration strategies required to execute a 12 volt S/S system for start ability, reduced noise and vibration (N&V) and vehicle launch. A correlated lumped parameter modeling methodology is used to determine engine startup profiles, starter hardware and intake cam park position requirements based upon vehicle level response to the startup event. Optimization of the engine startup is reported for a multitude of powertrain configurations, including transverse and longitudinal arrangements with manual, automatic and dual clutch transmissions. Details are provided on the level of hardware and calibration necessary to satisfy a set of prescribed performance metrics, particularly seat track vibration and smooth vehicle launch.

INTRODUCTION

Automotive hybrid systems with only start/stop functionality at idle typically provide a 4 to 10% improvement in fuel economy over a combined EPA cycle, see [1 and 2], and approximately comparable percentage reduction in CO₂ emissions, [3]. Unlike S/S systems with motor-generators running off the engine accessory drive referred to as belt alternator-starters, BAS or BSA, a 12 volt S/S system utilizes a conventional starter on flexplate/flywheel ring gear with no regeneration benefit. The 12 volt S/S system simply shuts off the engine during periods of zero vehicle speed and restarts the engine once the driver performs a lift foot of the brake (automatics - AT's, automated manual transmissions - AMT's and dual clutch transmissions - DCT's) or presses the clutch

pedal on manual transmissions - MT's. The level of performance required in certain markets will require the 12 volt auto start system to be as transparent as possible, meaning imperceptible N&V at driver interfaces (steering wheel, seat track and interior noise) with no compromise to vehicle launch performance for automated transmission applications.

N&V CONSIDERATIONS

The basic source-path-receiver model for a conventional automotive powertrain startup event is shown in [Figure 1](#). With this basic model, the source is engine torque pulsations from compression and/or combustion. The path is vehicle sensitivity, defined as the ratio of driver seat track acceleration to torque at the powertrain mounts. The receiver is the driver, quantified by the level of peak-to-peak acceleration at the driver's seat. Source level vibrations are produced by the slider crank mechanism of the reciprocating internal combustion engine and are a result of block force reactions to instantaneous cylinder pressures. The engine speed spin-up profile will have a significant influence on the severity of the receiver response at the seat track depending on how the frequency content of the torque pulsations align with vehicle sensitivity.

For 12 volt S/S, either source level vibrations originating from the engine can be reduced or path sensitivity can be reduced to produce auto starts that are nearly transparent to the driver and vehicle occupants. At a source level, the engine speed spin profile can be managed through cranking speed and combustion to avoid dwelling at engine speeds that align with high vehicle sensitivity. Peak cylinder pressures, whether motoring or firing, can be reduced since this will lead to a reduction in net block torque acting on the powertrain mounts, see [5, 6, 7]. However, a cylinder pressure reduction strategy is complicated by other metrics,

such as cold start-ability, start-ability at altitude and emissions. Managing engine park position during the auto stop can reduce force input from the powertrain to the vehicle as shown previously by [6]. Without a controllable motoring device, such as in strong or mild hybrid powertrains, this strategy can be difficult to accomplish by relying on the engine to self park at a particular crank angle degree (CAD) that results in a partial compression and minimal forces upon auto restart. Although, statistically, the engine will tend to park itself at a minimum energy point, such as the start compression of any one of the cylinders. The path can be modified through powertrain mount locations, mount property selection (stiffness, damping, passive or active, etc.). Modification to these parameters alter the frequency response as well as help to reduce the seat track acceleration to powertrain block torque (A/T) amplitude, see [7]. The focus of this paper will be on modifications to the source level vibrations, particularly through powertrain hardware and the approach to engine controls during engine startup.

The receiver, driver's pk-pk seat track vibration is an appropriate means of quantifying the level tactile vibration that is tolerable before becoming objectionable for auto starts. Govindswamy et al [6] and Kuang et al [5] have reported and used seat vibration as the metric for assessing auto starts and stops for hybrid vehicle applications. Testing and evaluation by [6] have shown that the disturbance at the seat track is most noted by the driver during engine starts up due mainly to human sensitivity to low frequency vibrations around 10 Hz.

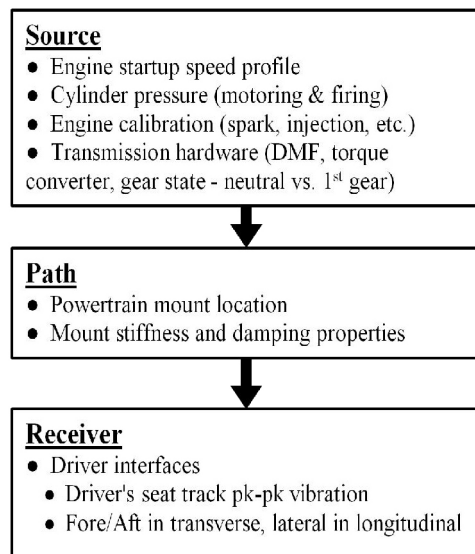


Figure 1. Source-path-receiver model for 12V auto starts.

Figure 2 shows a typical mean engine speed auto start for a direct injected (DI) in line 4 cylinder (L4) engine using a 12 volt S/S system. The startup process is initiated by a 12 volt

cranking motor engaged to the ring gear of the flexplate or flywheel attached to the engine crank. After the first compression pulse and the engine controller is synchronized with the position of the crankshaft, fuel can be injected and combusted to accelerate the engine to idle speed. Unlike, port fuel injected (PFI) engines, DI engines eliminate the required manifold mixing dynamics of developing a combustible mixture in the manifold before spark can be added, enabling combustion to start on the second compression as opposed the third or fourth compression, see [8]. This not only reduces time to reach idle and vehicle launch times, but it reduces time spent in an engine speed range that N&V is problematic. For an L4 engine, the speed range that produces N&V issues is generally between 150 and 450 rpm (5 to 15 Hz). This speed range can be separated into two distinct regions, powertrain torsional modes, between 5 and 15 Hz and vehicle modes, between 9 and 15 Hz. The powertrain torsional modes include dual mass flywheel (DMF) resonance, driveline rigid body mode on the half shafts, known as surge, chugge, or judder and other low frequency drivetrain modes that may occur within the powertrain subsystems. The main vehicle mode is the rigid body mode of the powertrain on the mount system about the axis of the crankshaft. In the case of a transverse powertrain configuration, the fore-aft direction of with respect to the vehicle is of most concern in terms of the powertrain rigid body mode of vibration. For longitudinal powertrains, it is the lateral, or cross car direction that is of most concern for causing objectionable vibration in vehicle and at the driver interfaces during auto starts.

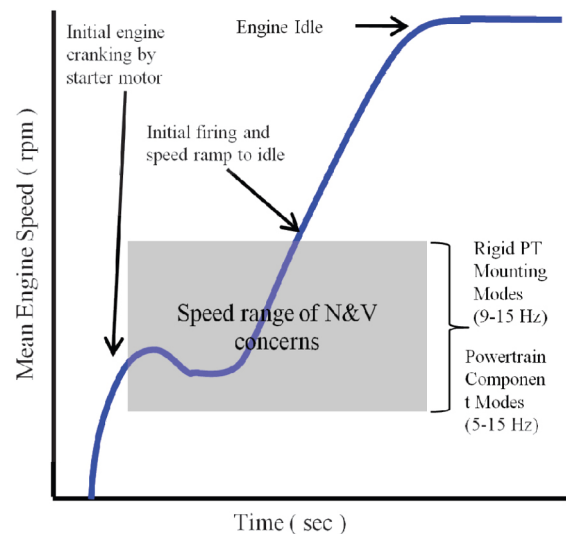


Figure 2. Typical L4 DI engine speed spin up profile for auto start for 12 volt S/S system.

The speed range that N&V is a concern cannot be avoided during a 12 volt auto start, but the time spent operating within this speed range can be reduced. Figure 3 shows engine speed profiles for auto starts events, one a 42 volt-belt-alternator starter (BAS) and the other two 12 volt S/S configurations.

Figure 4 contains the corresponding time history of seat track fore/aft vibration. For the 42 volt BAS system, an engine speed of 450 rpm is achieved in approximately 100 ms, spending little time in the N&V zone, resulting in a seat vibration of 0.4 m/s^2 . The ability to spin up the engine with this profile is accomplished with a 5 to 7 kW electric machine with advantageous ratio through the engine accessory drive, providing peak cranking torques of 100 to 120 Nm; see [2 and 3]. Twelve volt starter motors in the 1 to 2.5 kW range are typical in passenger vehicle applications. Peak cranking speeds tend to be around 200 to 250 rpm, as shown in Figure 3 for the two 12 volt S/S applications. For the L4 DI engine, about 250 ms is spent in the N&V zone, cranking to just over 200 rpm and firing occurs on the second compression pulse. With the engine controls minimizing peak combustion pressure through spark retard engine speed drops after the first combustion, before increasing to 80% of engine idle speed after the second combustion. The measured seat track vibration was 0.6 m/s^2 . The L4 diesel with DMF measured highest of the three applications at 2.8 m/s^2 . This was due to the time spent in the N&V zone, higher geometric compression ratio and high combustion pressures leading to higher block reaction forces to the powertrain mounts.

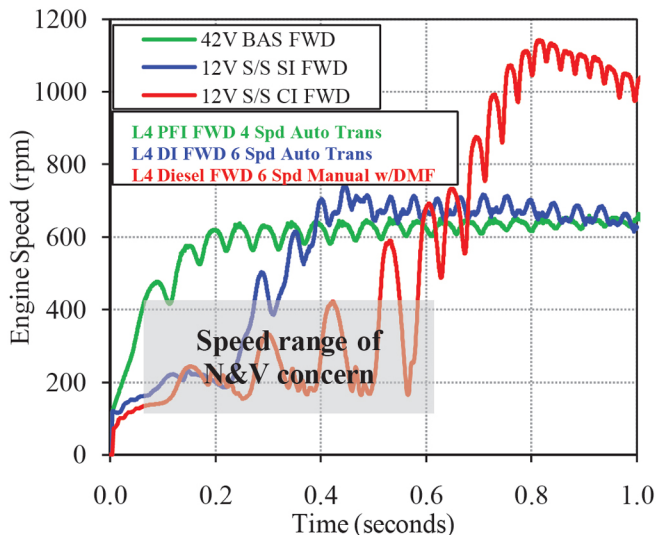


Figure 3. Typical engine speed auto start profiles for various mild hybrid auto starts.

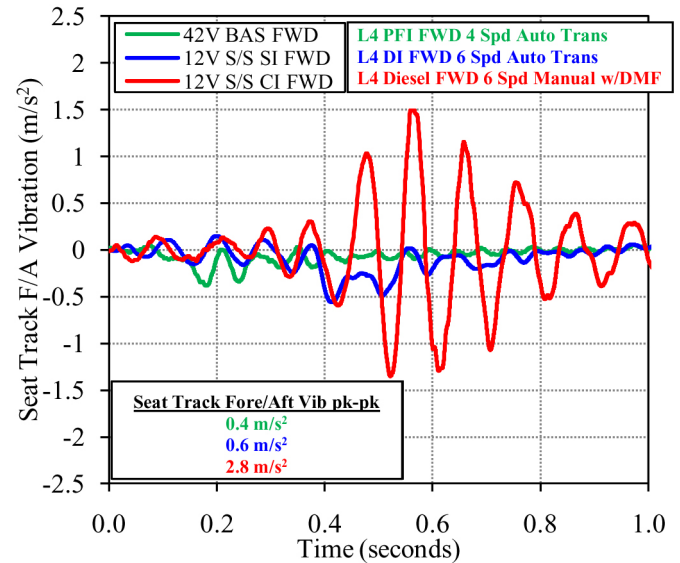


Figure 4. Seat track fore/aft vibration pk-pk for various mild hybrid auto starts.

Further insight into the mechanics behind high seat track vibration during 12 volt auto starts by examining the time history traces of engine speed, seat track vibration and cylinder pressures for the L4 diesel, 6 speed FWD manual with a DMF, shown in Figures 5 and 6. Figure 5 contains engine speed and seat track fore-aft vibration for the 12 volt auto start and Figure 6 engine speed and individual cylinder pressures. A peak cranking speed of 190 rpm is achieved, with cranking pressures in 3 MPa and seat track pk-pk vibration already exceeding the 0.3 to 0.5 m/s^2 threshold of acceptable disturbance. To accelerate the engine from 190 rpm cranking to 800 rpm idle target, fuel is gradually phased in over six combustion events of increasing pressure 5 to nearly 8 MPa, overshooting idle by 300 rpm. The maximum pk-pk seat track vibration of 2.3 m/s^2 occurs after the first combustion event where engine speed peaks at 600 rpm and drops back to the cranking speed of 190 rpm. The drop back to cranking speed is a direct result of the motion of the DMF secondary mass having high angular displacement due to the engine operating at or near DMF resonant speed. The second combustion event elevates engine speed beyond the N&V zone. The amplitude of seat track vibration decreases only when peak combustion pressures reduce to around 4 MPa and steady state idle speed is approached. The combination of high motoring and firing cylinder pressures along with engine speed oscillating at a region of high vehicle sensitivity between 190 and 400 rpm during cranking produce the excessive disturbance at the seat track. Later discussion will show the direct influence of DMF secondary mass motion on engine speed.

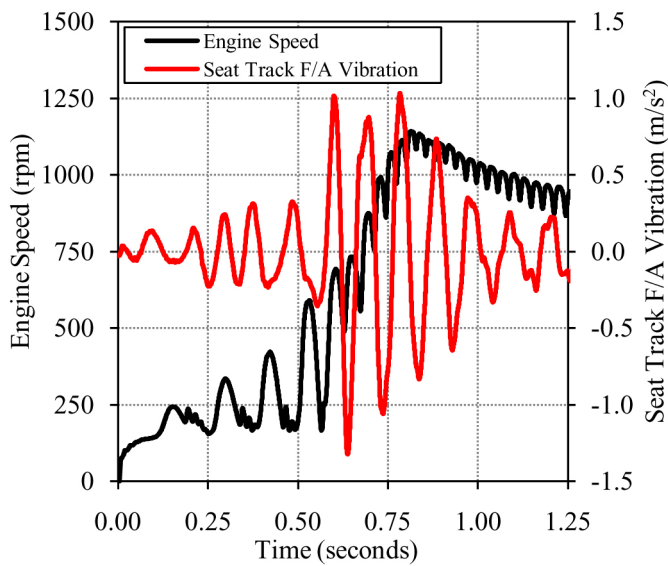


Figure 5. Engine speed and seat track fore/aft vibration.

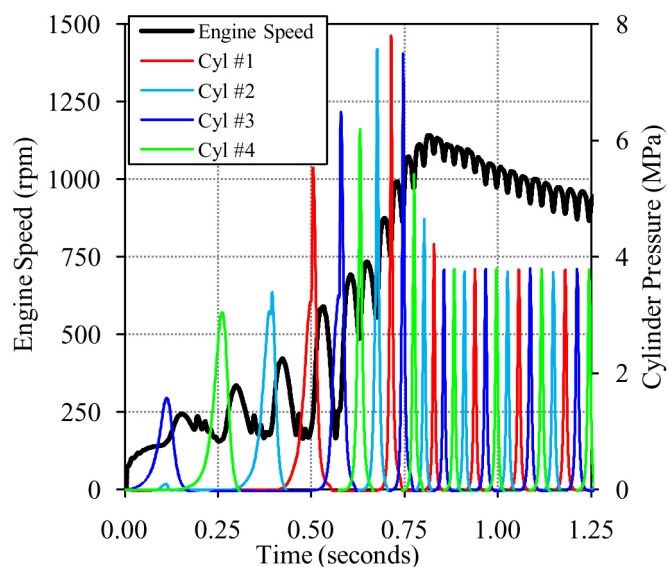


Figure 6. Engine speed and cylinder pressures for L4 diesel, 6 speed FWD manual transmission 12 volt auto start.

START/STOP MODELING TECHNIQUE

To explore the design space of powertrain hardware and calibration changes that improve 12 volt S/S N&V and vehicle launch performance a lumped torsional modeling technique was developed that utilizes measured cylinder pressures from existing engine hardware or analytically generated cylinder pressures based upon future engine hardware designs. Measured cylinder pressures enable validation of the modeling technique and more detailed analysis of a particular 12 volt auto start profile. Analytical

cylinder pressures allow the flexibility to investigate effects such as effective compression ratio, peak cranking speed, cranking time and overall calibration of the 12 volt S/S event. The engine model, when driven by analytical cylinder pressures operates off a throttle-opening request and a motoring-firing Boolean input. Comprised within the engine model are gas and inertia torques, engine friction and accessory drive loads. The engine is cranked via a conventional starter motor incorporating speed-torque characteristics, internal gearing, the one-way clutch, and tooth counts for the pinion and flexplate/flywheel ring gear. The dynamic response of the starter motor for initial cranking is tuned to produce peak cranking torque in 20 to 25 ms. Engine valve timing is also included within engine model calculations, but assumes a fixed position for intake and exhaust cams. This assumption should be accurate for auto start simulations, as phasing for variable valve timing (VVT) camshafts does not typically occur at or above engine idle speeds.

Downstream of the engine, the torsional model includes, details of the launch device (single mass flywheel inertia, DMF inertia damper properties or torque converter speed ratio dependent properties). For automated transmissions, AT's, AMT's and DCT's, clutch pressure profiles are included to capture vehicle launch performance and assess any adverse driveline torsional dynamics that may occur during auto starts. All reaction torques from the powertrain are summed at common node and are imposed upon a single degree of freedom (SDOF) representation of the powertrain inertia in either the fore-aft or lateral direction on the powertrain mounts. The spring rate of the SDOF powertrain mount is tuned to the natural frequency measured in vehicle or analytically computed in the direction of interest with respect to the powertrain architecture (transverse or longitudinal).

Model correlation for keyed and auto starts for a 12 volt cranking system is contained in [Figures 7](#) and [8](#), respectively. Measured cylinder pressures drove the correlation models, with engine speed serving as the correlation variable to determine the sufficiency of the model to accurately capture the physics of engine startup. In both cases, reasonably good correlation is achieved with only minor discrepancies in engine speed amplitude and only minor shifts with respect to crank angle.