

Aspects of NVH Integration in Hybrid Vehicles

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ABSTRACT

NVH refinement is an important aspect of the powertrain development and vehicle integration process. The depletion of fossil-based fuels and increase in price of gasoline have prompted most vehicle manufacturers to embrace propulsion technologies with varying degrees and types of hybridization. Many different hybrid vehicle systems are either on the market, or under development, even up to all-electric vehicles. Each hybrid vehicle configuration brings unique NVH challenges that result from a variety of sources. This paper begins with an introductory discussion of hybrid propulsion technologies and associated unique vehicle NVH challenges inherent in the operation of such hybrid vehicles.

Following this, the paper outlines a two-dimensional landscape of typical customer vehicle maneuvers mapped against hybrid electric vehicle (HEV) operational modes. Overlaid on this map are NVH issues such as those associated with global powertrain vibration, driveline vibration, HEV component-specific noise, motor/generator whine, accessory noise, gear rattle, and noise pattern changes. The remainder of the paper focuses on specific examples from case studies illustrating key HEV NVH issues such as engine start/stop behavior, motor/generator whine, and

influence of electric machines on powerplant integration issues. The use of advanced time-domain methods such as vehicle interior noise simulation (VINS) to understand and optimize HEV vehicle NVH behavior is shown. Finally, the findings from the discussed studies are summarized and appropriate conclusions are drawn with respect to understanding, characterizing, and solving unique hybrid vehicle NVH issues.

INTRODUCTION

The depleting supplies of fossil based fuels and associated increase in the price of fuel has prompted the automotive industry to focus efforts on development of fuel efficient vehicle technologies. While the development of fuel efficient propulsion technologies such as downsized/boosted internal combustion engines (ICE) and use of direct injection technology is expected to continue, there is increasing focus on the development of varying degrees of hybrid technology. Figure 1 provides a view of the tradeoffs between fuel consumption and cost of complexity for varying degrees of hybridization (shown for port fuel gasoline and directed injected Diesel engine based HEV's). As the costs related to added complexity from the hybrid system go down, the degree of hybridization can be expected to go up to fully realize the potential to reduce overall vehicle fuel consumption.

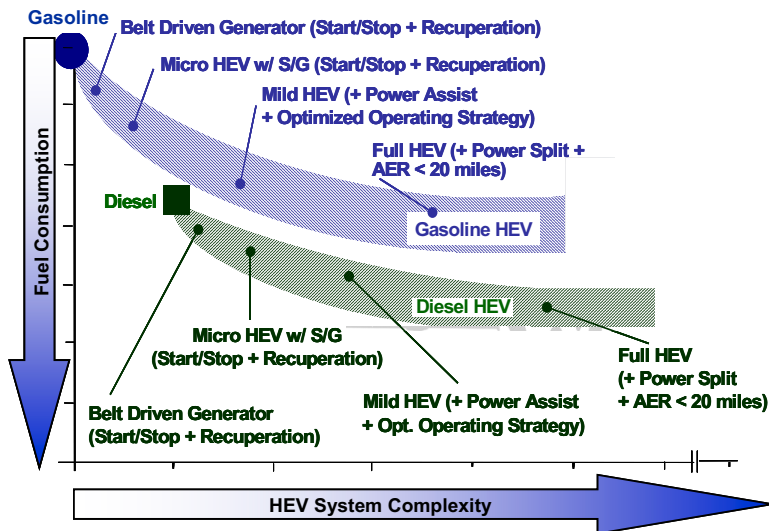


Figure 1: HEV Concepts and Tradeoffs

For a given degree of hybridization, HEV's can also be classified based on power flow as series, parallel and split hybrid vehicles, as shown in Figure 2. In series hybrid vehicles, the ICE power is converted completely into electric power that is used to propel the vehicle so that there is no direct connection between the ICE and the vehicle driveline. In parallel hybrid vehicles, the ICE and electric motor are both connected to the vehicle driveline, with many variants possible in both front wheel drive and rear wheel drive combinations. Split hybrids typically involve the use of power-split devices that direct the power either in a series or parallel fashion from the ICE and/or electric motor to the vehicle driveline.

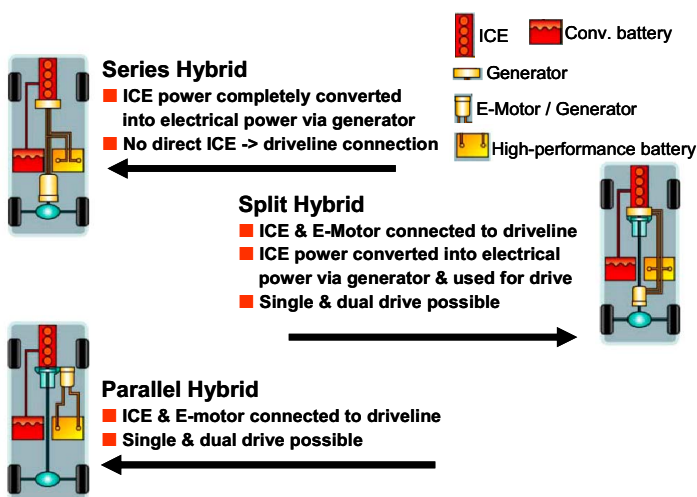


Figure 2: HEV Classification based on Power Flow

In addition to hybrid vehicles, many OEM's are developing electric vehicles (EV) where the prime mover is an electric motor that's coupled to the driveline through an appropriate transmission. With all variables remaining the same (vehicle type, drive profile, accessory loads, etc.) an EV will require only 25-35% of

total cost for energy when compared to a conventional ICE powered vehicle. This reduction in energy cost is possible primarily due to significant differences in energy efficiency of the prime movers. In general, electric motors can operate at energy efficiency above 90% for much of the functional operating range, as compared to only 20-30% energy efficiency for an ICE.

Based on currently available battery technology, EV's are expected to be limited to approximately 40 miles of driving on a fully charged battery. In order to provide customers with the flexibility of driving longer distances, developments are ongoing to add an ICE to the EV concept that would extend the driving range of the vehicle. Such vehicles are hence called range-extended electric vehicles (ReEV), electric range-extended vehicles (E-REV) or plug-in hybrid vehicles (PHEV) and can be developed in both series and parallel hybrid configurations. Figure 3 shows a schematic of a series ReEV vehicle.

While all the concepts discussed in this paper are designed to reduce fuel consumption and overall cost of vehicle ownership, they come with significant NVH challenges. Typically, customers' perception of vehicle quality closely parallels the NVH characteristics of the vehicle. Drivers of conventional ICE powered vehicles have come to expect a high level of refinement in vehicles and will continue to demand similar levels of refinement in all HEV variants. NVH refinement is an important aspect of the powertrain development and vehicle integration process. In particular, HEV's and ReEV's present unique NVH challenges during the vehicle integration process.

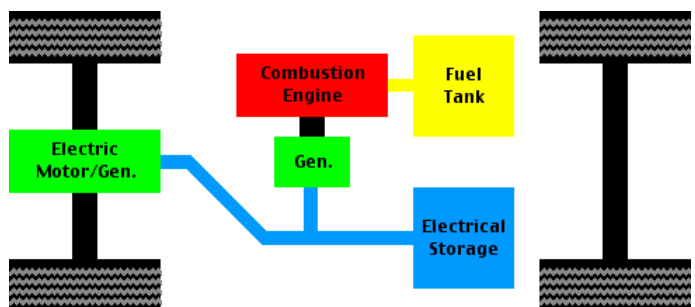


Figure 3: Schematic of a Series ReEV

Figure 4 shows a two-dimensional landscape of typical customer vehicle maneuvers mapped against range extender electric vehicle operational modes. Overlaid on this map are NVH issues such as those associated with global powertrain vibration, driveline vibration, HEV component-specific noise, motor/generator whine, accessory noise, gear rattle, and noise pattern changeover. From the point of view of customer acceptance of the end product, the plot shown in

Figure 4 should be customized to a given vehicle program, so that a focused plan can be developed to address each NVH item systematically.

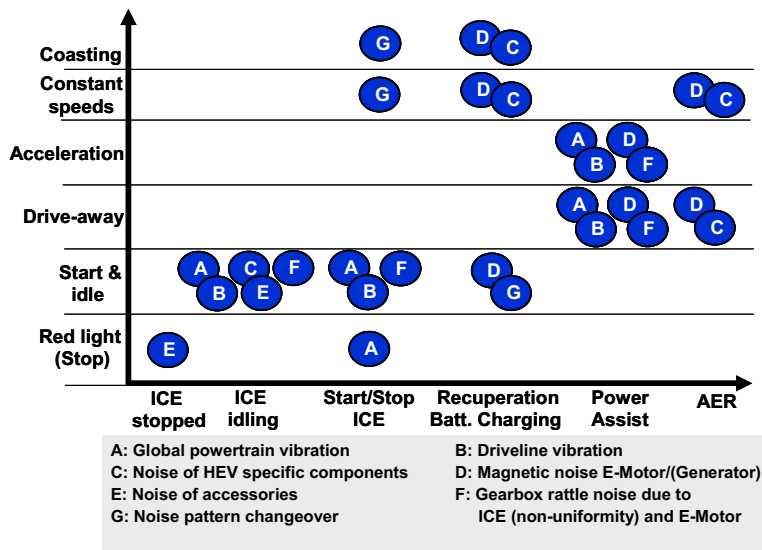


Figure 4: Unique HEV and ReEV NVH Challenges

Clearly, ReEV's combine the NVH integration challenges of conventional hybrid electric vehicles and all electric vehicles. The remainder of this paper includes specific case studies from various ReEV and HEV development programs.

ICE START/STOP VIBRATIONS

It is important for the engine start/stop behavior to be transparent to the driver from both a tactile (vibrations) and acoustic (noise) standpoint. Figure 5 shows an example of seat track vibrations measured during ICE start-up conditions on a ReEV vehicle. As discussed in previous publications [e.g., 1], the start-up event can be split into the engine cranking phase and initial start of combustion.

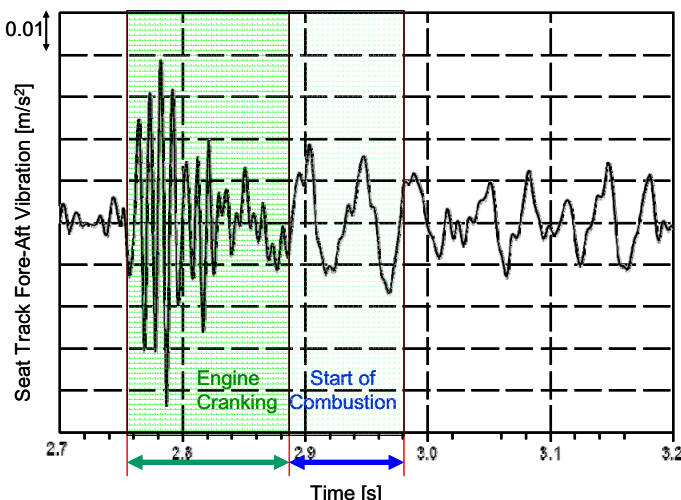


Figure 5: Vibrations during ICE Start-up

Although the vibration behavior might seem generally similar to the starting phase of a conventional ICE powered vehicle, the ICE start-up vibration for HEV and ReEV can be more important. In a conventional ICE powered vehicle, the ICE start-up occurs only at the beginning of vehicle operation and the resulting vibration feedback (in response to cranking the engine to start the vehicle) is expected from the driver of the vehicle. For HEV and ReEV, the start-up of the ICE is linked to factors such as the state of charge of the battery and driver torque demand, which can result in "unexpected" vehicle vibration. Depending on the layout of the driveline, the start-up vibrations for HEV can be further complicated by the fact that the start-up of the ICE does not occur in neutral [1], causing excitation of driveline torsional modes (in addition to powertrain rigid body modes).

A proven metric to describe vibration during transient events such as ICE start-up is the VDV (Vibration Dose Value). The VDV is defined as [2]:

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

The VDV is typically based on the low-frequency content of the vehicle's fore-aft acceleration signal during the transient event of interest [3]. The VDV results in a single number metric, which can be used for vehicle benchmarking, target setting, and to track the ICE start/stop performance of a vehicle during the HEV and/or ReEV development phase.

Figure 6 shows VDV numbers for the seat track vibration (longitudinal direction) during ICE start-up calculated for five different hybrid electric vehicles. Three of the HEV's tested (called Vehicle 1, Vehicle 2, and Vehicle 3, in Figure 6) were evaluated under two loads, i.e., ICE start from all electric drive under *moderate* pedal input and *aggressive* pedal input. As shown, the VDV metric captures the expected trends relative to driver input, i.e., the *aggressive* pedal ICE start-up vibrations are higher than those for the *moderate* pedal inputs. However, the difference in VDV's (Figure 6) among the five vehicles tested also shows that there can be a wide range of ICE start-up behavior among HEV's and it is important to develop production vehicles towards a not-to-exceed target line as shown on Figure 6.