In-Situ Torque Measurements in Hybrid Electric Vehicle Powertrains

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Abstract

For several years, ANL has taken a leading role in the benchmarking of various advanced hybrid vehicles for the US FreedomCAR industry-government partnership. Early designs provided highly desirable direct engine torque measurement (with telemetry for non-contact signal acquisition) for steady-state and transient operation in an operating Prius powertrain. Newer designs have done away with a sizable spacer and left the powertrain configuration intact. This was made possible by creating a new flywheel damper unit that incorporates the torque sensor, thus the powertrain fits back together without body modifications. Tradeoffs such as signal dynamic range and filtering are challenges that have been addressed by newer generation designs. Close proximity to the stator coils in the Accord HEV prompted the use of a digital telemetry for noise immunity. In all, there are seven (7) unique designs that have been specified and built through the sensor vendor and installed in advanced hybrid electric vehicles. Along with the axle torque measurements and other measurements the power flows of the powertrain system can be tracked for nearly every component from the engine to the chassis dynamometer. This data is key to benchmarking in great detail the potential of advanced technology for use in passenger cars.

Keywords: Hybrid Vehicle, In-Situ, Torque Measurement

1. INTRODUCTION

The Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (ANL) handles the U.S. DOE's technology validation and benchmark testing of advanced vehicle technologies. ANL tests new hybrid electric vehicles (HEV) to provide data that are used to update DOE-funded vehicle simulation tools, such as PSAT. The data are also used to provide DOE and auto industry engineers with benchmark specifications that aid in forecasting future technology developments.

Of key interest is engine operation during these tests. ANL has pioneered the use of in-vehicle torque measurement and engine mapping during vehicle operation on a chassis dynamometer [1]. Working with the instrument supplier, ANL has produced an engine torque sensor that requires no vehicle modifications, except for the replacement of the flywheel itself.

2. BACKGROUND

The need for engine torque information in hybrid vehicle analysis is at the core of understanding where power is flowing within the highly active set of subsystems in the Prius. Conventional vehicles have one power source of interest: the engine. Hybrid vehicles can have several electric motors and an exponentially increasing number of power flow paths. Modeling software for hybrid vehicles is only as accurate as the validity of the assumptions used in the model. At ANL, an integrated system development process that links data collection to modeling to development projects, as illustrated in Figure 1.

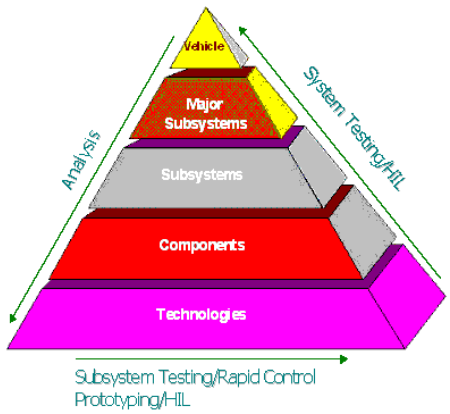

Figure 1: Integrated Systems Development Process

The systems analysis effort at ANL starts with subsystem testing, which encompasses various technologies. This testing leads to system testing, which covers technologies, components, subsystems, major systems, and the vehicle itself. All of this information feeds the model (PSAT) as validation of the previous modeling results, which subsequently leads to more insights into the direction and benefits of subsystem improvements. Engine torque information is essential for model validation at the vehicle and component level and for analysis of the entire hybrid system.

Several engine-torque-sensing technologies have been demonstrated. In 1996, a solenoidal magnetoelastic torque sensor was applied to the surface of the engine crankshaft [2]. All ferromagnetic materials contain magnetoelastic properties where the magnetic permeability of the material changes with mechanical stress. This phenomenon is similar to magnetostriction, in which the unstressed material changes shape with magnetization. This non-contact stress-measurement technique uses a high-frequency magnetic field that causes an induced voltage in the sense coil. Changes in this voltage reflect changes in permeability of the sensor as a result of stress on the shaft.

This technique requires that the shaft be encircled by the primary (excitation) coils and secondary (sensing) coils, which take up physical length in the powertrain and need to operate at engine temperatures. The two main limitations with this type of torque sensor are linearity and temperature stability.

With the release of the first production HEV, an off-the-shelf disk torque sensor was implemented in this vehicle between the flywheel/damper and the input to the then-new power split hybrid transaxle in 2000 [1]. Figure 2 shows that the torque sensor and non-contact receiver are mounted to the flywheel/damper on the engine.

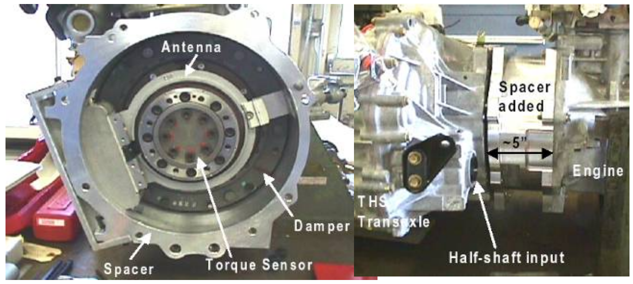

Figure 2: Torque Sensor Installed with Spacer Mounted to Flywheel/Damper on the Engine

Inserting this sensor between the engine and transmission required the addition of a 5-in. spacer. The extra powertrain length in this transverse-mounted application was accommodated by moving the engine/mounts over and cutting into the vehicle's chassis to provide clearance. The chassis modifications limited the vehicle to non-road (dynamometer) testing.

Since the sensor is indirectly connected to the crankshaft, the torque-sensing element is subject to operating temperatures near 100°C. External cooling air needed to be forced into the cavity for the sensor. Another limitation caused by using an off-the-shelf part was the overload rating of the sensor itself. This was a concern, but not a critical factor because of (1) its location after the flywheel/damper and (2) the torque limiting/regulation characteristics of the power split topology. This demonstration produced quality results with bandwidth in the range of 1000 Hz.

A clutch disk torque sensor was demonstrated in a manual transmission application in 2001 [3]. This demonstration took advantage of the deflection of the clutch disk damper springs (following Hook's Law) as a torque-sensing element. The angular displacement measurement requires two additional sensor rings (on the friction plate and center output shaft hub) to provide a saliency for the non-contact magnetic reluctance sensor. Signal processing hardware was used to generate a set of gating signals. The sensor rings had posts every 60 degrees, offset by 30 degrees from each other. The displacement angle, which was due to the applied engine torque, was calculated by determining the ratio of the time interval between pulses to the difference between the inner and outer sensor. The engine torque is estimated as a linear relationship of spring displacement angle and the spring constant ($Torque = k * \theta$).

Although simple, passive, and uses a low-cost sensing element, this technique appears to be limited by the assumption that the clutch disk damping springs have linear force vs. displacement. The usable signal bandwidth is unknown for this demonstration. Filtering noise may be difficult as well as a result of aliasing caused by the instantaneous torque pulses much higher than the sensor ring resolution.

A disk torque sensor was also demonstrated in 2002 on an automatic transmission application [4]. The goal of this demonstration was to validate an engine torque model. Similar to the sensor used in the 2000 [1] experiment, this torque sensor also used an inductively coupled power source, digital telemetry, and a short-coupled sensing element. The acquisition system averaged five revolutions worth of torque samples and produced smooth torque information to the vehicle ECM. The torque sensor was installed between the crankshaft and the flywheel, necessitating filtering and averaging of the individual torque spikes before the flywheel mass. Because the sensor was compact and easily installed and the change in powertrain length was minimal, the vehicle could be road-tested and tested on the dynamometer.

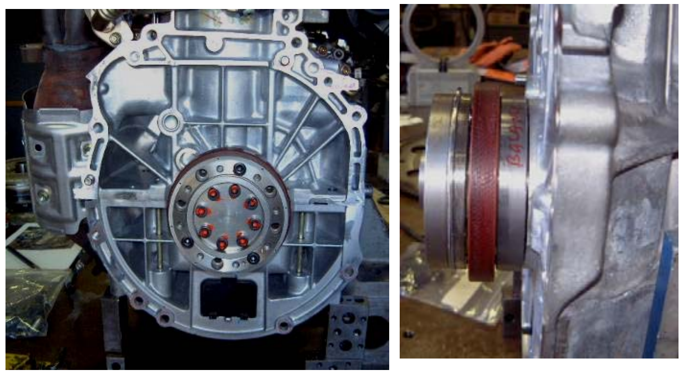

Figure 3: Toyota Opa Crankshaft Torque Sensor [5]

In 2003, a CVT in-vehicle torque sensor demonstration [6] used the same technique as in the 2000 experiment [1]. In this case, signal quality and sensor robustness were of concern because the torque sensor was directly attached to the crankshaft, before the flywheel. Figure 3 shows the sensor installed in a Toyota Opa gasoline direct-injection vehicle with a CVT. The sensor failed shortly after testing began, under normal operating conditions. Suspected contributing factors include higher than expected peak torque values (beyond the component rating), start-up/cranking torque impulse, and overheating of the sensor electronics at high load.

Two other techniques have also been successfully used to measure (calculate) engine torque. For automatic transmissions, the input and output speed of the torque converter turbine can be used to infer crankshaft torque. By using a crankshaft speed sensor of adequate resolution, variations in engine speed velocity can be used to calculate engine torque.

Throughout the rest of this paper, it is understood that torque from the output side of the engine will be discussed. The only belt-driven accessory load on the 2004 Toyota Prius is the water pump. Power steering, air conditioning, and 12-V system loads are all tied into the high-voltage system, which is fed by the generator connected to the flywheel end of the engine.

3. TORQUE SENSOR IMPLEMENTATION

The key constraint of the torque sensor implementation is to be non-intrusive. By developing a “bolt-in-replacement” part, thousands of dollars and weeks of fabrication shop time were saved. The cost of the vehicle modifications can often exceed the sensor cost (and possibly the vehicle cost). Maintaining stock vehicle conditions was also important to avoid skewing the results of vehicle testing. The prototype matched the stock flywheel inertia to within 2.5%.

3.1 FLYWHEEL TORQUE SENSOR DESIGN

As expected, the torque sensor design started by reviewing the published engine specifications, which are shown in Table 1.

Table 1: Maximum Ratings of 2004 Toyota Prius Engine

Displacement	Max output	Max Torque
1497cm^3 (4 cylinder)	57 kW/5000 rpm	111 Nm/4200 rpm 82 ft-lb/4200 rpm

This bolt-in replacement flywheel torque sensor design was inspired by Teledyne Instruments' FPT-100 flex-plate torque sensor product for vehicles with automatic transmissions. The Toyota Prius does not use a torque converter but a more conventional flywheel with torque limiting clutch (limits torque transients).

The space constraints for a non-intrusive torque sensor were tight. Fortunately, in this application, there was a stock opening in the engine casting directly below the crankshaft main bearing. The antenna for the telemetry fit in this space well, as shown in Figure 4.

Figure 4: Telemetry Antenna Mounted in Original Opening in Engine Flange

Figure 5 shows a CAD representation of the stock flywheel and a fabricated replica with torque-sensing elements. Bonded foil strain gage elements were added to each of the 6 spokes on the 17-4 stainless-steel replica flywheel.

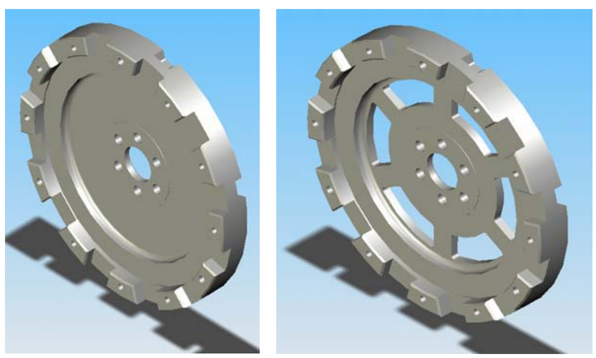

Figure 5: CAD Model of Stock and Replica Flywheel with Force-Sensing Spokes

Figure 6 shows the finished flywheel with the inductive power/telemetry system attached to the rotor. The compact stator and signal-conditioning unit are also shown. The rotor was spin balanced and inertia measured (within 2.5% of stock).

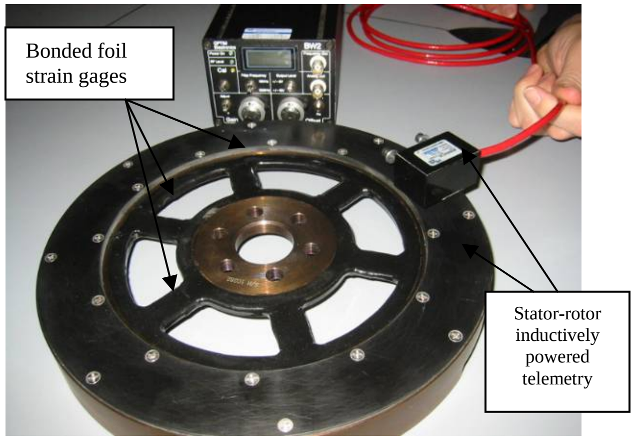

Figure 6: Finished Flywheel and Telemetry

The 450ft-lb rating allows 4.5X-rated engine torque to be measured. The torque-sensing elements are exposed to the full crankshaft pulsating torque since it is before the flywheel mass. This was one of the undesirable consequences of a "bolt-in-replacement" sensor. The assembled sensor (damper/slip clutch assembly removed for clarity) is shown in Figure 7. Specifications for the sensor are given in Table 2.

3.2 Flywheel Torque Sensor Specifications

Table 2: FPT-100P Torque Sensor Characteristics

Torque Range	+/- 610 Nm (450 ft-lbf) full-scale sensitivity
Safe Overload	2 X full scale
Engine Speed	Range 0–6000 RPM
Temp. Range	-40 to 120°C
Temp. Compensated	-40 to 120°C
System Frequency Response	User-selectable toggle switch 100 or 1000 Hz (-3dB)
Overall System Accuracy	0.5% Full scale
Calibration	NIST-traceable with remote shunt calibration toggle
Rotating Inertia	0.07755 kg-m^2 (265 lb-in.^{2})
Mass	5.9 kg

Figure 7: Finished Sensor Mounted in Place of Stock Flywheel

4. BRIEF REVIEW OF POWERSPLIT TOPOLOGY

Before test results are discussed, a brief overview of the power-split topology is given here to orient the reader to the flow of power from the engine to the wheels. Figure 8 shows the location of the torque sensor and various parts of the power split transmission [7].

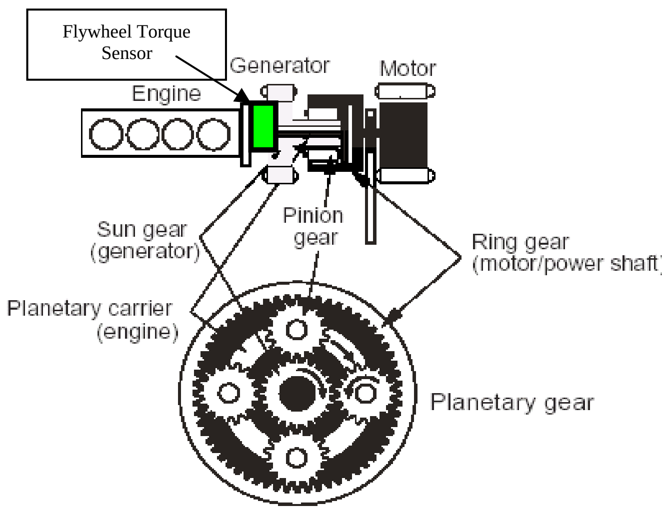

Figure 8: Power-Split Topology and Torque Sensor [7]

Figure 9 shows that with the engine off, the power-split hybrid topology can run as an electric vehicle (motor drives wheels, no engine power/engine stopped). With the engine running in hybrid mode, some of the power is "split," via the planetary gearbox, between (1) the electrical path - the generator/inverter/motor and (2) the direct mechanical path to the axles.

4.1 Prius CVT Functionality

One key feature of the Prius power-split design is that the gear ratio between the engine and the road is infinitely variable within the speed and torque limits of the engine, generator, and motor. At any given power point, the hybrid system can select a ratio best suited for the engine and the rest of the system. This sophisticated operation is key information for benchmarking the system enabled by measuring the engine torque directly.

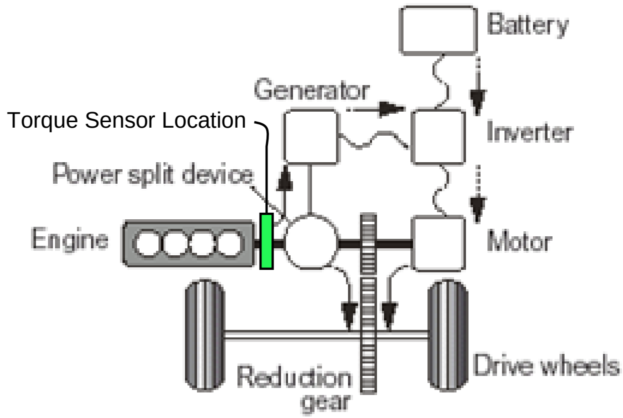

Figure 9: Power-Split Topology [7]

4.2 STEADY-STATE DATA AND ANALYSIS

Advancements made in engine efficiency for a vehicle like the Prius are important parameters to assess for making a thorough accounting for all vehicle losses and, just as importantly, for feeding modeling studies that will use the current achievements as accurate benchmarks.

Similar telemetry-based axle torque sensors are also used in the vehicle to measure torque to the wheels. By using the engine and axle torque sensors in conjunction with conventional speed sensors, power from the engine and electric motors and power to the road can be mapped for various operating conditions. Future on-road "real world" testing is also planned for this vehicle to compare lab test results with less-controlled but more realistic test conditions.

4.2.1 Engine Mapping

A very important part of engine analysis is the representation of the efficiency across the entire range of engine operation. This “map” is the primary input for engine modeling, and, in the case of the Atkinson-cycle Prius engine, it is interesting to compare it to more conventional engines.

To map the engine in the vehicle, it is helpful to have a motoring chassis dynamometer set to speed control mode. The operator then varies the load by using the accelerator pedal. Figure 10 shows the operation points of such a test. Unfortunately, for the sake of a complete engine map, the Prius will not operate outside of a narrow band. Varying the SOC can sometimes bring the engine operation away from the “best operation” line, but not to a large extent.

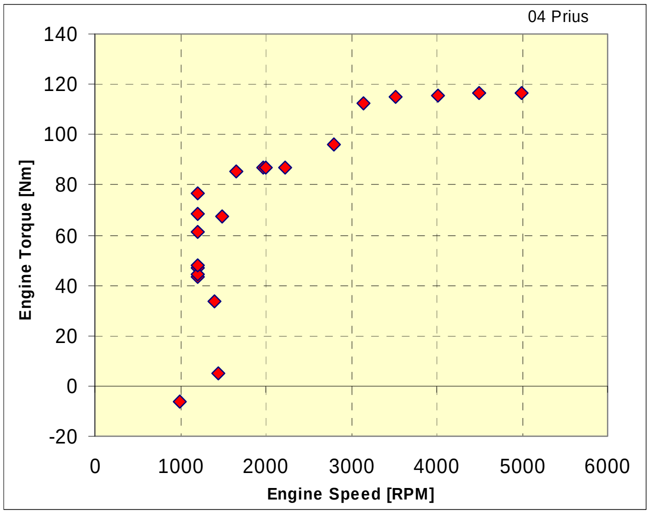

Figure 10: Engine Operating Point Mapped for Efficiency

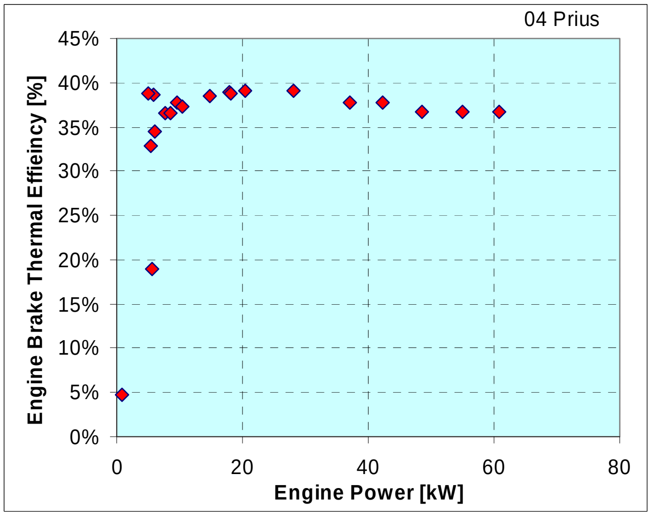

Figure 11: 2004 Prius Engine Efficiency vs. Power

The same data collected in Figure 10 is plotted according to efficiency in Figure 11. Anecdotally, Prius engine efficiency is claimed to be around 37%. During testing, it was discovered that rising engine temperatures provide a more positive bias to the output signal of the torque sensor over time. Without frequent re-zeroing the output (at a stop while in neutral gear), the torque (and thus the efficiency) is shown to be too high.

4.2.2 Cruise Conditions

An analysis of steady cruise (in dynamometer road load mode) conditions is possible by using measured signals and calculating power flows. Fuel is measured by using either the measured emissions or direct fuel measurement, and main battery power is measured by using voltage dividers and shunt resistors; the dynamometer power (or axle power from additional torque sensors) is also collected. Four sample steady-cruise load points were collected on the dynamometer in a hot-stabilized condition and the data shown in Figure 12. The fact that four different load points were measured for the same steady-state cruise condition illustrates the highly active control system.

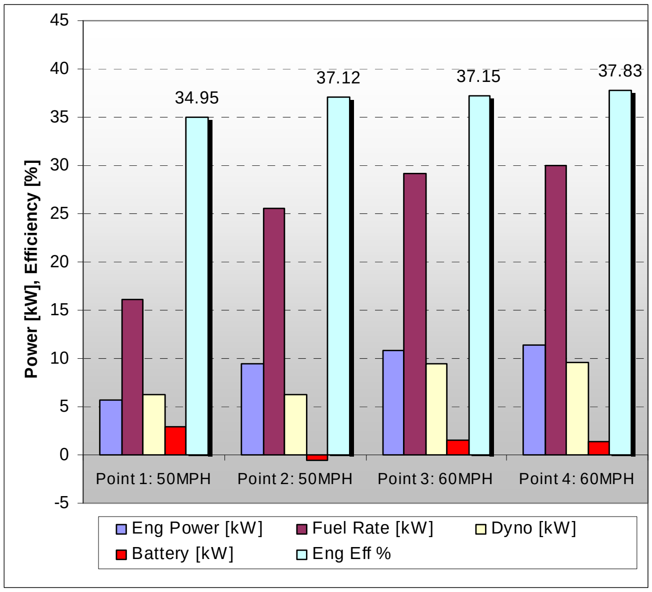

Figure 12: Four Cruise Conditions of Varying Engine Loads

The Prius's varying range of operation is well illustrated in the data by looking at two of the test points depicted in Figure 13. At Point 1, the battery is providing motive power. At Point 2, it is being slightly charged. The load point at Point 2 is higher and thus the fuel rate is higher. As expected at the higher load, the efficiency is also improved (see Figure 12).

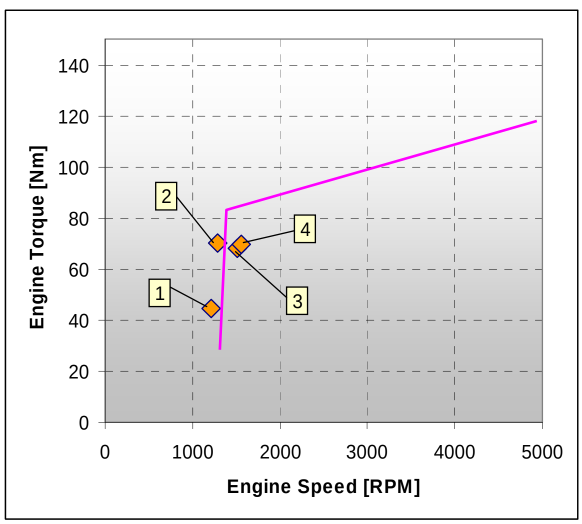

Figure 13: Four Cruise Conditions Located on an Engine Map with Operation Line Shown

4.3 TRANSIENT TEST DATA AND ANALYSIS

The new location (upstream of the flywheel damper) has brought new challenges to analyzing the net engine torque. Figure 14 shows an easy-to-view engine torque signal of the previous design [1] during engine start of a relatively low-speed acquisition. The starting torque and over shoot (perhaps rebound in the damper springs) are clearly seen in the data sampled at 10 Hz, with a corner frequency of 4 Hz. By using the same data acquisition setup with the new system, the torque required to start the engine is harder to pinpoint, and the dynamics of the signal are quite large. As a consequence, three separate signal conditioners were used with different low-pass corner frequencies.

For 10Hz data collection, the 4Hz conditioners were used. In Figure 15, the 4Hz trace is shown with the data from a custom 30Hz signal conditioner. There is evidence of aliasing in the highly dynamic signal. For closer dynamic analysis of the test cycles, the sample rate was increased to 100 Hz. An engine start at this speed is shown in Figure 16. Even though the signal conditioner should filter out frequencies higher than the Nyquist criteria dictates, single points are shown at the peaks of the trace. Further investigation of the magnitude of the torque dynamics was needed. By using 10kHz wide-bandwidth signal conditioners and a high-speed oscilloscope the magnitude of the engine torque pulses can be seen to dominate the "carrier" net torque signal, as seen in Figure 17.

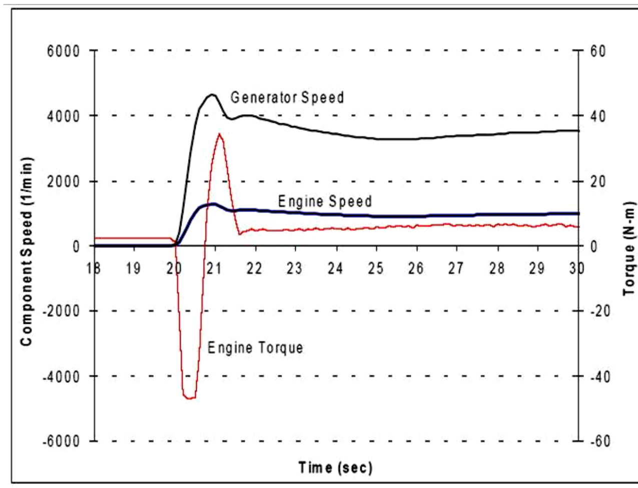

Figure 14: Engine Start of Earlier Design Engine Torque Sensor with 4Hz-Bandwidth Signal Conditioners [1]

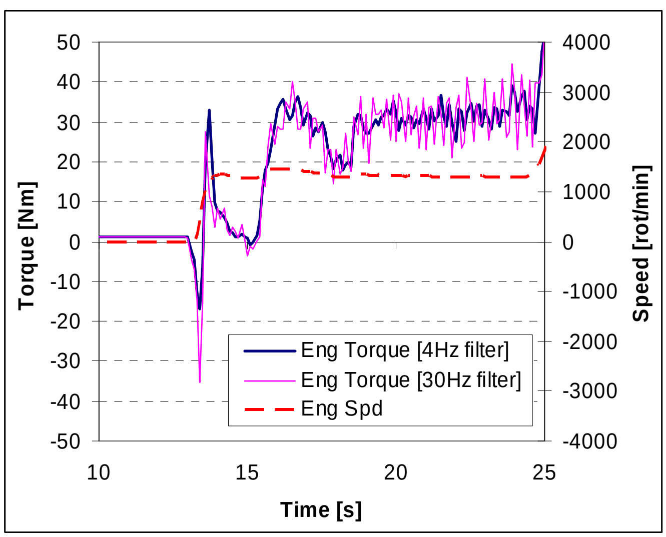

Figure 15: Engine Start Capture Using 10Hz Acquisition with 4Hz and 30Hz-Bandwidth Signal Conditioners

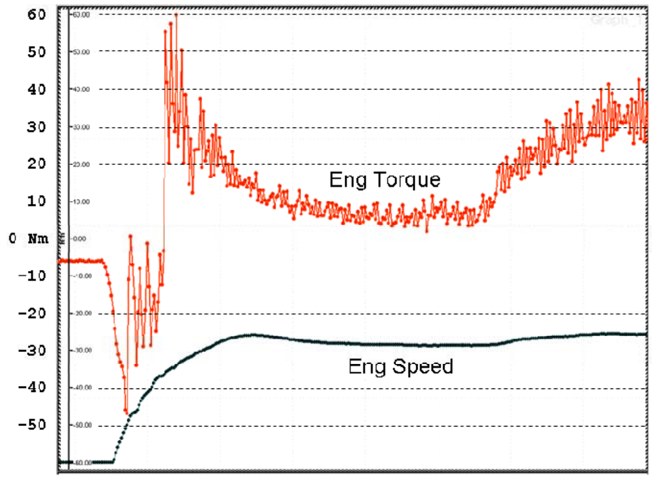

Figure 16: Engine Start Using 100Hz Acquisition and 30Hz-Bandwidth Signal Conditioners

In Figure 17, engine torque (top trace), #1 injector trigger (2nd trace), and #1 top dead center pulse (3rd trace) are shown. The engine spins about three revolutions before the #1 injector fires, and combustion takes place thereafter. The transition from net negative torque to positive torque is subtle but detectable in the next couple revolutions.

This graph illustrates the highly dynamic torque signal that is present. Obviously, if the mean torque value output is desired, filtering (analog or post-processing) must be used. This high-speed data coupled with other signals such as injector and engine revolution allow close examination of the engine start event. As seen in Figure 17, the injector's first injection pulse is markedly larger than the subsequent injector pulses. Further analysis may include fast-response hydrocarbon emission measurements that will show the emissions implications of the small time-scale events.

The engine start is of special interest, considering that in hybrid electric vehicles, the engine starts and stops over 30 times during one 12.1-km Urban Driving Dynamometer Cycle (UDDS).

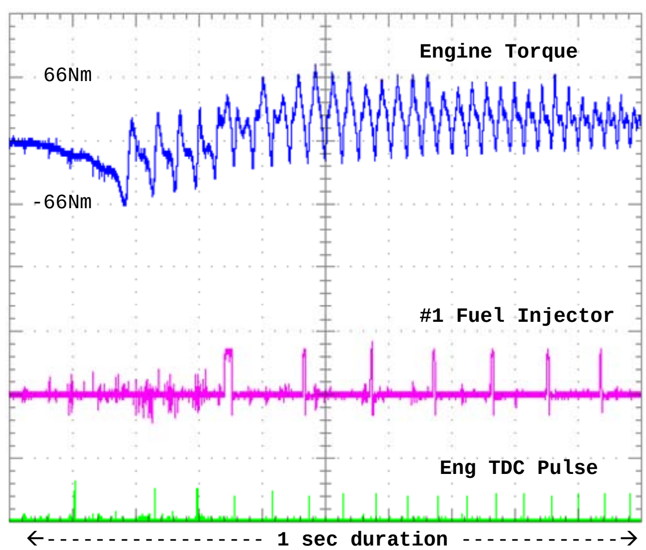

Figure 17: Engine Start Using High-Speed Oscilloscope

Figure 18: Engine Torque Sensor and Toyota THS

The non-intrusive flywheel torque sensor design [8], presented in this paper is shown in Figure 18, next to the Prius powertrain removed from the vehicle.

5. Evolution of Telemetry and Sensor Location

One of the key limitations to non-contact sensors is wireless telemetry that provides both power for the sensor elements as well as conveys undistorted torque measurement information. Environmental concerns, such as significant amounts of electromagnetic interference from the HEV electric motors (right next to the flywheel) prompted a shift to digital telemetry. The Honda Accord and Civic hybrid vehicles utilize a pre-transmission parallel hybrid motor, directly connected to the engine crankshaft. The rotor of the electric machine in these vehicles acts as flywheel damper mass. The sensors for these vehicles, shown in figure 19, are mounted on the drive plate, downstream of the damper mass for lower pulsating torque measurements. The sensors use digital telemetry for noise immunity from the large magnetic fields of the electric motor.

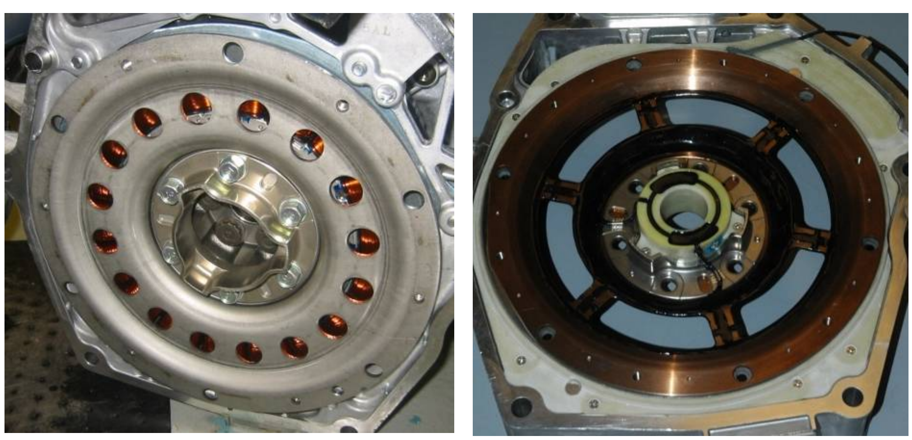

Figure 19: Honda Civic Stock (left) and Instrumented (right) Engine Torque Sensor on Drive Plate Adjacent to Motor Stator

6. Future Work

Another standard method for measuring/estimating engine torque is via an indicated power meter, based on an in-cylinder pressure transducer. This system uses a crank shaft position sensor (720 pulse-per-rev) to correlate the rise in cylinder pressure to the theoretical power produced by combustion. This indicated power estimate is in-cylinder power, not net power out of the engine, with valve-train, friction and other losses from accessory loads. Nonetheless, by estimating those losses, a comparison will be made between the measured mechanical output torque of the engine, and the indicated power produced in the cylinder.

Another future-work item is to utilize the in-situ torque signal during on-road testing of the Prius, Escape, Civic, Accord and Camry hybrid vehicles.

Design work is currently under way to use a different measurement point for engine torque measurement. Internal shaft gauging of the transaxle input shaft. In this case the center of the transmission shaft will be drilled out and strain gauges added **inside** the shaft. This sensing location is post-damper and flywheel mass, yielding the lowest engine torque ripple signal, as well as furthest away from the engine heat.

7. Summary

ANL has developed methods to benchmark advanced hybrid vehicles for the US FreedomCAR industry-government partnership. Direct engine torque measurement (with telemetry for non-contact signal acquisition) for steady-state and transient operation in an operating Prius powertrain can be challenging. A new flywheel damper unit, identical in dimension to the stock part, incorporates the torque sensor, and allows the powertrain to fit back together without body modifications. Tradeoffs such as signal dynamic range and filtering are challenges that have been addressed by newer generation designs. Close proximity to the stator coils in the Accord HEV prompted the use of a digital telemetry for noise immunity. Over time, seven (7) unique designs have been designed and built for the various production hybrid vehicles on the market today.
Data collected as part of this benchmarking effort offers insights into the potential for future improvement of subsystems in these advanced technology vehicles.

8. Acknowledgments

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Technical contribution, fabrication, and calibration of sensor hardware were provided by M. Sullivan and J. Haglund of Teledyne Instruments, Marion, MA.

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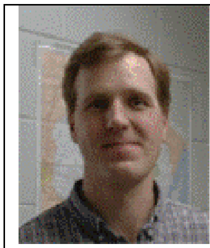	**Theodore Bohn**, Electrical Engineer, Argonne National Laboratory 9700 South Cass, Argonne, IL, USA e-mail:tbohn@anl.gov Mr. Bohn is the lead electrical engineer in ANL's Advanced Powertrain Embedded Control Systems lab. His primary focus is on power electronics, electric machines, and control systems for hybrid electric vehicles. He has 25+ years experience in electrical engineering in industrial and research environments including 16 years of experience in HEV-related design projects. Mr. Bohn has a Masters of Science in Electrical Engineering from University of Wisconsin-Madison.
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