Basic considerations for sensors in the powertrain

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Designing a better powertrain is the most significant way to reduce automotive emissions.

Whether it's improving the efficiency of a combustion engine or designing electric vehicles (EVs) or hybrid electric vehicles (HEVs), electrification is powering a massive evolution of the powertrain as we know it. This white paper examines the future of powertrain sensors through the electrification of a vehicle in internal combustion engines (ICEs) and sensors in EVs and HEVs, and their importance in optimizing the powertrain for effectively managing the battery, inverter and motor building blocks.

Powertrain sensing explained

Within the powertrain, shown in **Figure 1**, highly precise electrical sensors monitor conditions to boost efficiency.

A powertrain system comprises several modules; each module operates individually, with different types of sensors and feedback control mechanisms. A vehicle's efficiency mainly depends on accuracy, precision and the response time of powertrain sensors and actuators.

These sensors facilitate the closed-loop operation necessary for communicating sensing information for engine management and transmission control, as outlined in **Table 1**. The main driving factors for a powertrain system are economy and emissions, which impact performance and drivability.

In engine and transmission systems, sensors and their feedback-control mechanisms facilitate efficiency by accurately monitoring the stimulus thereby reducing the emissions by increasing the efficiency of combustion process.

Sensors and their feedback-control mechanisms promote the overall efficiency of engine and transmission systems by accurately monitoring stimuli to boost the efficiency of the combustion process.

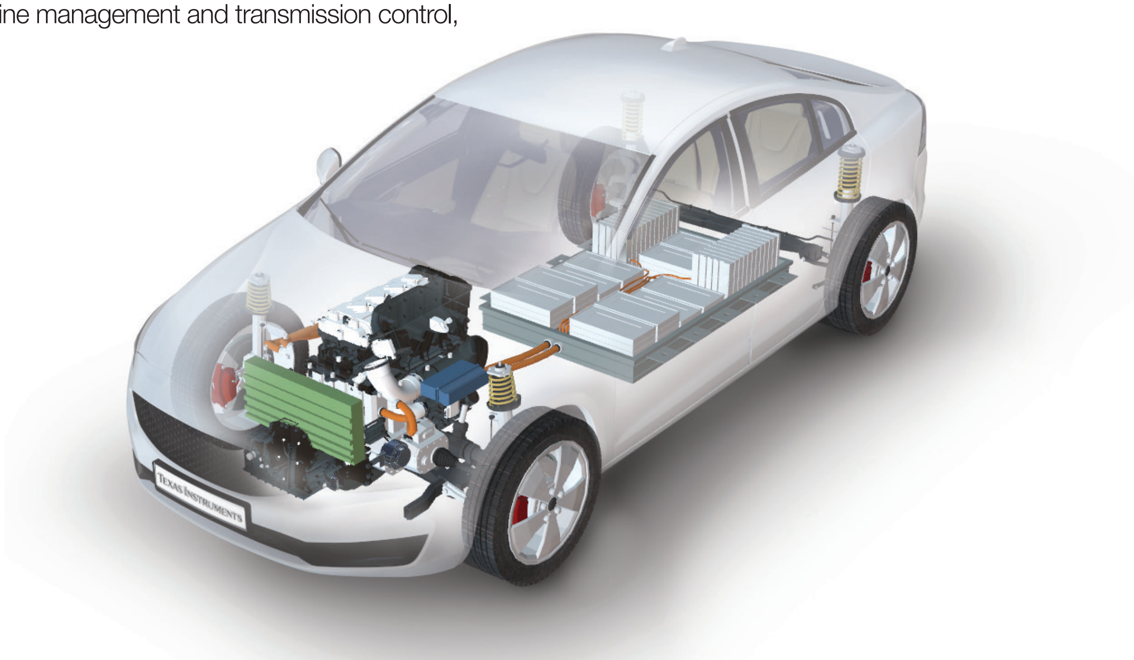

Figure 1. *The powertrain system in an HEV.*

	Economy	Emissions	Performance
Design goal	Powertrain Best use of energy		Drivability
Automotive processes relying on sensors	Engine Combustion-based feedback control, ultra-low emission, variable valve timing, cylinder deactivation	Transmission Seamless gear shifting, shift-by-wire, continuously variable gears	Power steering onboard diagnostics Engine misfire, deterioration, oxygen-sensor degradation

Table 1. *The anatomy of a powertrain system: how it relates to key building blocks and achieves top-level design goals.*

In EVs and HEVs, increased electrification within vehicles is requiring engineers to reimagine the powertrain architecture and controls.

Powertrain sensors play an equally important role in ICE vehicles. As shown in **Figure 2**, the electrification of a vehicle starts from the smart sensors. The main tool to reduce emissions in ICE vehicles is through the powertrain sensors and their performance.

An overview of powertrain sensors

Powertrain sensors are categorized according to the measurement functionality that they provide, as outlined in **Figure 3**.

Powertrain sensors should generally provide the following features:

- Low power (~10 mA).
- High accuracy implies precise control mechanisms.
- High sensitivity to the stimulus changes.
- Robustness within the automotive environment.
- Electromagnetic interference (EMI electromagnetic compatibility.

Appendix A lists the types of sensors and their definitions, based on the end equipments.

> The "Automotive High-Temperature Sensor (HTS) Reference Design" provides a high-density, low-cost and high-accuracy thermocouple analog front end.

Powertrain temperature sensors

There are three main types of temperature sensors in a powertrain:

- **Thermocouple.** The demand for high-temperature sensors has been increasing with the advent of new diesel engines because the exhaust system is right below the engine. This configuration requires temperature detection with high accuracy, high resolution and high integration. Exhaust system temperature sensors capable of withstanding and detecting high temperatures mostly operate using thermocouple-based principles, with multiple thermocouple temperature sensors and one stand-alone module to control them.

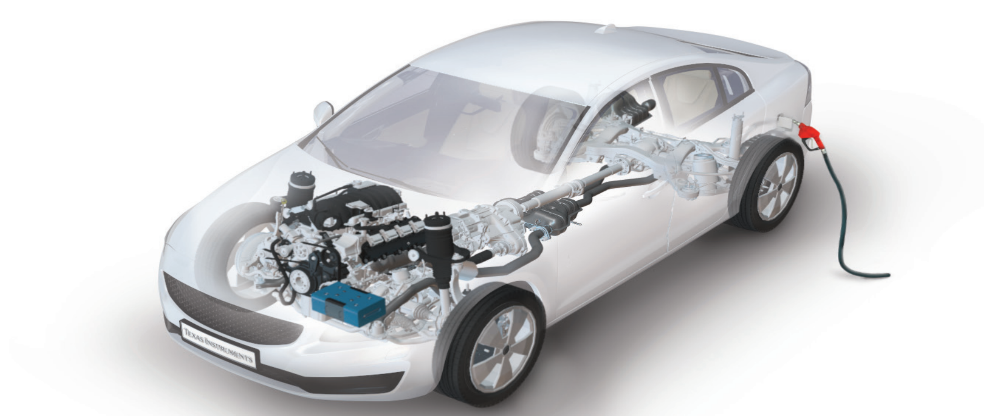

Figure 2. *A traditional internal combustion engine.*

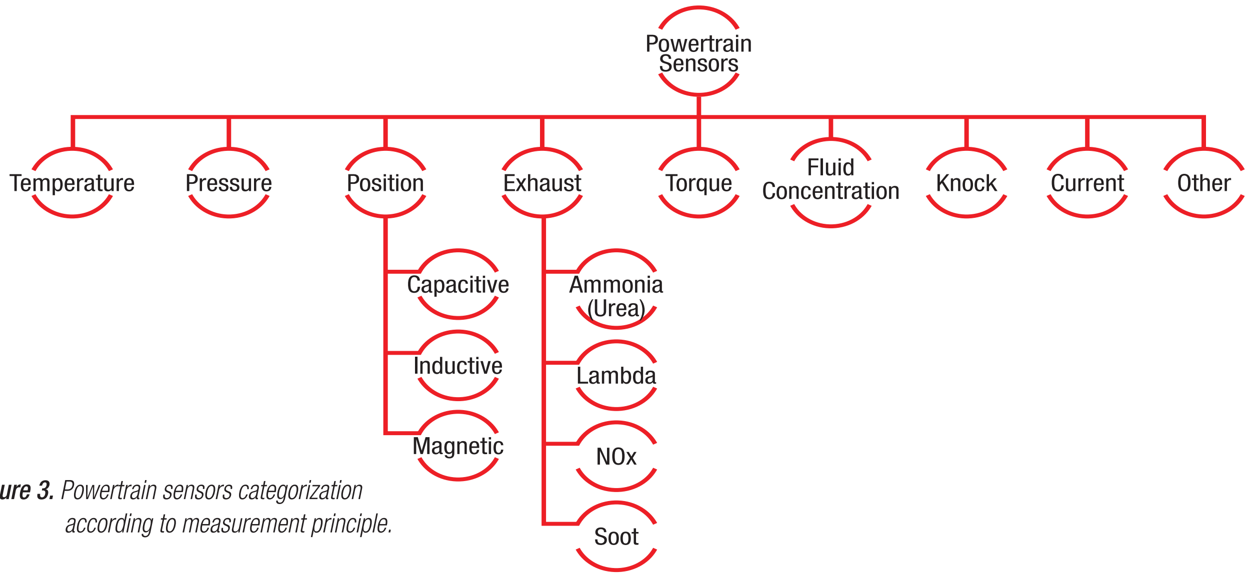

Figure 3. *Powertrain sensors categorization according to measurement principle.*

- **Thermistor.** New thermistors on the market are available with high temperature ranges to fit the needs of high-temperature sensors. Silicon based linear thermistors to replace the standard negative temperature coefficient and positive temperature coefficient types are also trending. With these new smart thermistors, it's possible to achieve high linearity over a large dynamic range, which is a particular need in automotive powertrains.
- **Silicon.** Silicon temperature sensors are playing a major role in HEV/EV and ICE vehicles because of these advantages:
  - Higher linearity over wide temperature ranges.
  - The ability to maintain accuracy throughout the range of supported temperatures.
  - High resolution and Grade 0 qualification for the temperature sensor.
  - Digital output interfaces to facilitate the digital transfer of data.
  - Alert triggering functionality to make control operations much more efficient.
  - Lower costs and easier implementation.

Powertrain pressure sensors

Integrated powertrain pressure sensors operate on capacitive- and resistive-based principles. Signal conditioning – along with amplifiers, analog-to-digital converters, a microcontroller and a digital-to-analog converter/digital interface – are on one chip. In general, pressure sense elements are prone to nonlinearity over temperatures, so a conventional pressure sensor signal-conditioning circuit contains temperature and linearity compensation mechanisms.

Because pressure sensor module wires require several wiring harnesses, it is always good practice to protect the module from harness faults such as overcurrent, overvoltage or short circuits.

The "Automotive Resistive Bridge Pressure Sensor Reference Design" and "Automotive Capacitive Pressure Sensor Reference Design" can help you avoid harness faults.

Basic considerations for powertrain pressure sensors include:

- Higher absolute maximum ratings on the signal-conditioning element.
- Tolerance to harness faults.
- Highly sensitive, Piezo-resistive pressure sensors given increased demand.

In automotive applications, the signal conditioning of powertrain pressure sensors in such a way that the sensors should be operate in extremely harsh environments, withstanding a wide range of vibrations, temperature fluctuations, various electromagnetic conditions and shocks.

Powertrain fluid level and concentration sensors

Powertrain fluid level and concentration sensors mostly operate on ultrasonic, capacitive-based principles. The level must be measured at several places inside the vehicle: for example, the water, fuel, hydraulic fluid, oil and urea tanks are all situated in the vehicle's powertrain. Monitoring the level and concentration of these liquids is necessary for efficient control-loop operations.

Using an ultrasonic method to sense these liquids provides these advantages:

- Faster measurement times.
- The ability to drive a variety of transducers over a wide detection range.
- Adaptability to various mediums, tank sizes and distances.
- The potential to interface with a high-voltage circuit and thus drive the transducer to penetrate deeper tanks.
- The ability to integrate protection stages.
- The ability to use the Controller Area Network (CAN) interface.

In an exhaust system, adblue injection happens after the diesel particulate filter (DFP) to reduce ammonia concentration in emissions. The fluid concentration and level sensors are playing an important role in measuring the fluid concentration and level of adblue.

Powertrain position sensors

Position sensors are another important category serving ICE, HEV and EV powertrain systems. They measure speed, angle, velocity and on/off positions in critical operations such as electric power steering, traction inverters, automatic transmissions and anti-lock braking systems.

These ultrasonic parameters are supported by TI's ultrasonic sensing analog front end for level, concentration and flow sensing and automotive ultrasonic signal processor and transducer driver. Learn more in the "Automotive Ultrasonic Fluid Level/Quality Measurement Reference Design."

Position sensors mainly operate on magnetic (Hall-based and magneto-resistive) and inductive principles depending on the application. Considerations and requirements for powertrain position sensors include:

- Robustness, given their critical locations.
- More sensitivity to detect the smallest change.
- High bandwidth for speed sensing.
- An integrated digital output.
- Low noise at the input.
- Array sensors or different axes of sensitivity.
- Temperature and vibration tolerance.
- A nonlinear magnet.
- The ability to achieve high-bandwidth position sensing.

	Hall	LDC	FG	RF absolute position
Sensor element	Magnet + hall	Magnet + hall	Magnet + FG	Metal
Temp range limiter	Magnet & hall limited	Coil limited	Magnet & FG limited	Metal melting point limited
Failure possibilities	Magnet, hall, AFE + ADC	Coil, AFE + ADC	Magnet, FG, AFE + ADC	AFE + ADC
Shielding	Magnetic shield + enclosure	Enclosure	Magnetic shield + enclosure	Enclosure
Absolute position	Need array of sensors & control electronics	Need array of sensors & control electronics	Need array of sensors & control electronics	Scalable sensor
Measurement range	0.1 mm to few cm (array)	1 um to few cm (array)	0.01 mm to few cm (array)	0.1 um to 6000 mm
Resolutions	10-16 bits	10-16 bits	10-16 bits	16-24 bits (>24 bits is possible)

Table 2. *Position sensor types based on principle of use.*

Inductive-based position sensors offer more robustness at the cost of less maintenance and higher accuracies.

Powertrain exhaust sensors

Exhaust sensors are employed in all ICE vehicles including hybrid electric vehicles. With the new norms on emissions, the requirements on exhaust sensing have increased with limits actually mandated in a growing number of countries.

As shown in **Figure 4**, there are different types of sensors in the exhaust system of a vehicle. Conventionally, these sensors operate on chemical-based principles, with two electrodes and sensing based on electrode potential principles. These types of chemical-based sensors can have higher maintenance and response times.

New radio frequency (RF) based exhaust sensors offer shorter response times, lower maintenance costs and higher accuracy. These sensors operate on the principle that each gas has its own absorption frequency where the resonance occurs with one transmitting antenna; one receiving antenna serves the whole purpose of sensing the gases.

To help reduce emissions, the "Automotive RF Soot Sensor Reference Design" demonstrates the ability of RF sensors to detect various gases in automotive exhaust systems.

Exhaust sensing needs:

- Grade 0-qualified products.
- The CAN protocol to communicate with the main electronic control unit, since there is a separate module for each and every exhaust sensor.
- High accuracy.
- Minimal maintenance costs.
- Robustness and tolerance for higher temperatures. The temperature range of an exhaust sensor is almost 1,500°C because these exhaust sensing systems sit under the hood of the engine.

Powertrain current sensors

Current sensors are among the most prominent in a vehicle powertrain, whether it's a combustion engine, HEV or EV. Shunt, magnetic-based principles serve the needs of current sensing in a vehicle. You can select the right principle based on where the sensor is. Current sensing in combustion vehicles is mainly 12 V; in HEV/EV vehicles it is 48 V and in EVs it ranges from 400 V to 600 or 800 V.

The "Automotive Resolver-to-Digital Converter Reference Design for Safety Application" is a complete resolver solution based on a system-on-chip sensor interface.

Here are critical requirements of current sensing by subsystem:

- **ICEs.** Current sensors in an ICE are used for 12-V batteries where accuracy and higher levels of integration are key factors. The current sensor in this case should be capable of handling accuracy over higher temperatures. Temperature and compensation algorithms maintain accuracy over wide temperature ranges to protect the stand-alone current sensor from harness faults.
- **HEVs.** Current sensors are placed in HEVs for 12- and 48-V batteries, DC/DC converters and

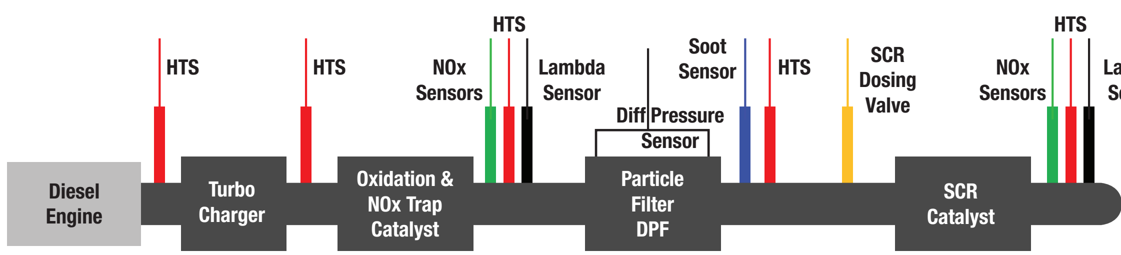

Figure 4. Types of sensors in an automotive exhaust system.

motor control. Especially in batteries current sensing in the milliampere range to kiloampere range is necessary where higher common-mode voltage current-shunt sensors are required to tolerate 48-V batteries. Accuracy at lower currents is required in battery current sensing for SoC and SoH calculations. DC-DC converters current sensing needs higher bandwidths to act quickly on the faults. Motor control current sensing needs higher slew rates and lower response times.

- **EVs.** Current sensors are needed in EV onboard chargers, DC/DC converters, traction motors and high-voltage batteries from 400 V to 800 V. Isolation for current sensing is also needed to handle the high voltage. Magnetic- or reinforced-type isolations and isolation with high accuracy and high linearity are possible with shunt-based resistors. Designs with lower power dissipation and isolated amplifier-based current sensing are popular. In EV high-voltage batteries, low-side current sensing is preferable where high accuracy at lower currents, high integration and wider dynamic range current sensing are required for state-of-charge and state-of-health battery calculations.

When precision sensing is critical, the "Automotive Shunt-Based ±500 A Precision Current Sensing Reference Design" provides a full scale range accuracy of <0.2% over a temperature range of -40°C to +125°C in battery-management systems, motor currents and other automotive applications.

- **Other uses.** Solenoids and several valves also need current sensing for high accuracy over the entire temperature range, so needs to have less temperature drift and less offset and have a lower shunt tolerance. An integrated shunt is preferable in these cases.

For the high-capacity batteries inside EVs and HEVs, the "Automotive, mA-to-kA Range, Current Shunt Sensor Reference Design" demonstrates how to detect current from the milliampere-to-kiloampere range using a busbar-type shunt resistor.

Conclusion

The emergence of new automotive technologies and continued vehicle electrification are impacting powertrain sensors and their accompanying electronics. In HEVs and EVs, there is a significant increase in design requirements for current and position sensors.

Highly accurate signal conditioners and high-precision operational amplifiers play a vital role in enabling powertrain sensors to operate in harsh automotive environments reliably. The challenges that sensor signal-conditioning electronics can help counter include high-temperature and vibration conditions, EMI protection and compliance with automotive safety standards.

Access design resources, reference designs and product information at TI.com/powertrain.

In the final analysis, powertrain sensors are ready for one of the greatest technology disruptions of this era: vehicle electrification. But you should carefully review the basic design considerations when selecting powertrain sensors and their accompanying signal-conditioning electronics.

Appendix A. Engine management sensors.

Principle	Sensor name	Significance/importance
Pressure	Manifold	Provides instantaneous manifold pressure information to the engine's electronic control unit.
	Barometric	Senses subtle changes in the barometric absolute pressure (atmospheric air pressure). The sensor is vented directly into the atmosphere.
	Cylinder	Detects abnormal combustion cycles in the engine (inside cylinder) and facilitates closed-loop combustion to reduce exhaust emissions.
	Mass airflow	Measures the volume and density of the air entering the engine. Computers calculate how much fuel is needed to maintain the correct fuel mixture.
	Fuel pressure vapor	Measures the vapor pressure in the evaporative emission control system. May be located on the fuel tank, near the charcoal canister assembly or in a remote location.
	Fuel rail	Measures the pressure of the fuel near the fuel injectors. This signal is used by the powertrain control module to adjust the fuel injector pulse width, and to meter fuel to each combustion cylinder.
	Engine oil	Detects the amount of (mechanical) oil pressure in the engine and relays this amount in the form of a voltage reading/value to the powertrain control module.
	Differential pressure (particulate) filter	Measures the difference in pressure of the exhaust gas. Situated across the diesel particulate filter.
Fluid concentration/ quality	Urea concentration	Measures the quality and concentration of urea/AdBlue solution and instructs the electronic control unit to give the right amounts to mix with exhaust gas in order to reduce nitric oxides.
	Oil concentration sensor	Measures oil concentration and quality and instructs the system on when to change the oil for better efficiency.
Position	Exhaust gas recirculation valve position sensor	Monitors the position of the exhaust gas recirculation valve pintle and converts the mechanical movement of this pintle into an electrical voltage signal that is relayed to the powertrain control module.
	Camshaft	Provides camshaft position informationwhich is used by the powertrain control module for fuel synchronization.
	Crankshaft	Provides crankshaft position informationwhich is used by the powertrain control module for fuel synchronization.
	Throttle	Determines the opening angle of the butterfly valve, which in turn determines the amount of air aspired by the engine, and sends this information to the powertrain control module.
	Throttle pedal	Detects the position of the pedal and conveys this information to the electronic control unit to take necessary action on opening and closing of the throttle. The throttle is actuated directly by the driver through the gas pedal.
	Fuel level	Used for precision fuel level measurement in all kinds of vehicle tanks, mainly for defining vehicle fueling volumes and remote tank monitoring.

Appendix A. Engine management sensors. (Continued)

Principle	Sensor name	Significance/importance
Temperature	Intake air	Measures the temperature of the air into the engine and conveys this information to the electronic control unit to accomplish optimal combustion. The electronic control unit takes necessary action to optimize the fuel delivery so that the air-to-fuel ratio produces efficient combustion.
	Exhaust gas/high-temperature sensor	Detects the exhaust gas temperature and converts it into a voltage, which is then fed back to the electronic control unit with the voltage signal in order to control engine conditions and effectively reduce emissions. The exhaust gas/high-temperature sensor is located in front of the diesel oxidation catalyst and/or in front of the diesel particulate filter.
	Exhaust gas recirculation valve temperature sensor	Helps control the function of the exhaust gas recirculation valve to help reduce engine emissions. These systems route gases from the exhaust to the intake to reduce combustion temperatures, thereby reducing nitrogen oxide emissions.
	Engine coolant	Measures the temperature of the engine coolant in an internal combustion engine. The readings from this sensor are fed back to the electronic control unit, which uses this data to adjust the fuel injection and ignition timing. On some vehicles, this sensor may also switch on the electric cooling fan.
	Engine oil	Calculates the temperature of the engine oil. The measuring range is generally from -40°C to +170°C.
Exhaust	Soot or particulate matter	Detects soot in the exhaust gas. A diagnosed diesel particulate filter fault will trigger an onboard diagnostic fault and control the filter's regeneration.
	Nitrogen oxide	Detects nitrogen oxides in exhaust pipes and sends this information to the electronic control unit to take necessary action. Typically situated after the catalytic converter and particulate filter.
	Lambda/ oxygen	It is an oxygen concentration sensor which measures the residual oxygen content of the exhaust gas and then transmits a signal to the engine control unit in the form of an electric voltage. The oxygen sensor voltage allows the control unit to detect whether the mixture is too lean or rich. If the mixture is too rich, the control unit reduces the quantity of fuel in the A/F ratio and increases it if the mixture is too lean.
	Ammonia	Measures the ammonia levels in the exhaust of vehicles equipped with a selective catalytic reduction after-treatment system. The sensor output can provide feedback to such systems, helping reduce nitrogen oxide emissions.
Knock	Knock	Detects engine knock (detonation), which occurs when the combustion of air/fuel in a cylinder

Transmission management sensors

	Sensor name	Location
Speed	Front wheel	Measures the speed of wheels to convey information to the anti-lock brake system, traction control system and electronic stability program control units, which individually control the brake force at each wheel.
	Rear wheel	Measures the speed of wheels to convey information to the anti-lock brake system, traction control system and electronic stability program control units, which individually control the brake force at each wheel.
	Intermediate shaft	Detects the rotation speed of the counter gear. By comparing the counter gear speed signal with the direct clutch speed sensor signal, the electronic control unit detects the shift timing of the gears and controls the engine torque and hydraulic pressure according to various conditions in order to facilitate smooth gear shifting.
	Transmission input shaft	Measures the input shaft speed of the transmission. The electronic transmission control module uses the information provided by the turbine shaft sensor to determine the amount of torque converter clutch slippage.
	Vehicle speed sensor	Reads the speed of a vehicle's wheel rotation and measures the transmission/ transaxle output or wheel speed. The electronic control unit uses this information to modify engine functions such as ignition timing, the air-to-fuel ratio and transmission shift points, and to initiate diagnostic routines.
	Diesel fuel pump	Uses tooth wheel sensor principles to estimate the speed of the fuel pump and send this information to the electronic control unit to control the exact position and speed of the pump.
Position	Gear lever	Provides information about the position of the gear rod to the electronic control unit, which controls the gear shifting mechanism. Also used to suggest the next gear.
	Clutch	Measures the piston position of the clutch master cylinder. Used in cruise control, engine management, interlock and electrical park brake applications, among others.
Temperature	Automatic transmission fluid temperature sensor	Provides input to the transmission control module, which uses this sensor to monitor the temperature of the transmission fluid. Located in the valve body or oil pan of the transmission or transaxle.
Pressure	Automatic transmission fluid pressure sensor	Monitors the transmission fluid pressure inside the transmission box (to which it is attached), responds to changes in fluid pressure and conveys this information to the transmission control unit.

Electric power steering

	Sensor name	Location
Torque	Steering wheel/rod torque	Estimates the rotational force of the steering column and conveys this information to the electric motor so that based on the amount of torque the actuators assists the wheels.
Position	Steering wheel angle	Uses magnetic position sensors to estimate the angle information of the steering wheel and sends this information to the electric motor.
Speed	Electronic power steering motor speed	Estimates the motor position/angle/speed to adjust the brushless DC motor's pulse-width modulation cycles to get precise control over the wheels.
Temperature	Transmission temperature sensor	Monitors the temperature of the transmission control unit and clutch and gear shift controllers.

HEV/EV

	Sensor name	Location
Position	Motor control position	Estimates the traction motor position using a resolver to control brushless DC operation.
	Motor control angle	Estimates the traction motor angle using a resolver to control brushless DC operation.
	Motor control speed	Estimates the traction motor speed using a resolver to control brushless DC operation.
Current	Onboard charger current sensor	Located on the primary as well as the secondary side for control-loop operations and protection from overcurrent faults. current sensing in Power factor correction schemes improves the ON/OFF sequences.
	DC/DC current sensor	Located mainly on the primary side as well as the secondary side for protection purposes on the primary side and for control-loop operations on the secondary side.
	Battery-management current sensor	Stand-alone and onboard current sensors are required in battery management systems for state-of-charge and state-of-health calculations.
	Traction motor current sensor	Located on the hot side for protection purposes and on the low side or in phase of the field-effect transistors for motor drive operations.
	Motor current sensor	For various kind of motors in the vehicle, current sensors on the low side used for motor diagnostics and control loop operations.
	Transmission current sensor	Proportional solenoids use current sensing to accurately monitor current and send the information to the microcontroller, where the PWM duty cycle percentage is adjusted to make the solenoid drive more efficient.
Voltage	Onboard charger voltage sensor	The voltage sense monitors the voltage magnitude of the DC/DC input/ output. A resistive divider is normally used to divide the high voltage. Galvanic isolation is normally needed to prevent electric hazards from the high voltage.
	DC/DC voltage sensor	The voltage sense at the primary side monitors the voltage magnitude of the high voltage battery. A resistive divider is normally used to divide the high voltage.
	Battery-management voltage sensor	Battery monitoring ICs measure cell voltages along with ,current and temperature and perform cell balancing to monitor and protect the cells.
Temperature	Onboard charger temperature sensor	Temperature monitoring circuitry maintains the health of the power transistors during their active operation by checking the case or internal temperature depending on where the sensor is positioned. It immediately shuts down the system once the temperature is above the threshold.
	DC/DC temperature sensor	Temperature monitoring circuitry maintains the health of the power transistors during their active operation by checking the case or internal temperature depending on where the sensor is positioned. It immediately shuts down the system once the temperature is above the threshold.
	Battery-management temperature sensor	Battery monitoring ICs measure temperature and perform cell balancing to monitor and protect the cells
	Traction motor temperature sensor	IGBTs temperature is monitored to protect the system from over temperature faults.

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