A review of current sensor technologies and applications within automotive and traffic control systems

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Abstract: This paper reviews the current practice in sensors and sensor applications for automotive and traffic control systems. Sensors to control engine fuelling, ignition and transmission (known as the powertrain) are reviewed, and the likely course of future development is discussed in the light of regulatory and market requirements as well as trends in sensor design and manufacture. Sensor needs for suspension, braking and traction control are also reviewed, and the likely introduction of wheel and tyre sensors to enhance driving safety is discussed. The recent trend towards vehicle-mounted devices to sense the vehicle environment (such as radar, optical, ultrasound, capacitive and image-based systems) is discussed, and the sensor implications of the introduction of safety-critical automotive systems such as adaptive cruise control (ACC) are discussed. Sensors for initiating the deployment of safety systems such as airbags are reviewed, together with transducers for disconnecting fuel pumps and vehicle batteries in the event of a crash. The paper includes a brief discussion of highway-based sensors for measuring vehicle speed and presence, and concludes with a discussion of the likely future developments in the field.

Keywords: automotive, highway traffic, transducers, sensors, telematics, control

1 INTRODUCTION

The problems of congestion associated with increasing vehicle ownership and use are well known. Throughout the world, the climate of opinion is turning against unfettered mobility. In most developed countries, government transport policy places increasing emphasis on the efficient management of existing roads, and recognizes the difficulty of satisfying demand by building new roads. The use of a combination of information technology (IT) and electronic systems to advise drivers and reduce their workload is being seen as offering at least a partial solution to current and projected traffic problems, since it has been shown to smooth the traffic flow [1]. Telematics also offers the possibility of safely reducing the gaps between vehicles (the ‘headway’), thus increasing the number of vehicles that can use a particular stretch of road.

The combination of IT, vehicle and highway-based electronic systems has become known as automotive telematics. All telematic systems rely heavily on sensors and measurement techniques, and this is especially true of those applications that are safety critical. Many research projects are currently underway in this area, which is particularly challenging for the sensor designer in the light of typical automotive cost constraints. As a rule of thumb, at 1999 prices a vehicle manufacturer will normally only tolerate a ‘measurement cost’ of around $10 per measurand, including all the signal conditioning required. If an automotive sensor costs significantly more than this, the extra cost has to be justified in terms of additional functionality, perhaps because the measurement information can be used for several purposes.

Highway sensor costs are much higher than those of automotive devices. There are two main reasons for this:

1. The volumes are much lower—many highway sensors are almost custom-made for a particular application, and volume production runs of any particular configuration are rare.
2. The cost of the associated ground work has to be taken into consideration.

These factors mean that the cost of installing (for example) a loop detector (see Section 3.1) is typically several thousand pounds.

To succeed commercially, automotive sensors have to be very robust. They must tolerate an environment that includes temperatures from \(-40\) to \(+140\) °C, possible exposure to boiling water, battery acid, fuel, hydraulic fluid, road salt, etc., as well as very high shock and vibration loads, which can exceed 1000 g on the unsprung side of the vehicle suspension.

Highway sensors also have to be robust. They too can suffer the full range of climate conditions, and may also occasionally be exposed to fluids originating from motor vehicles. However, in general the shock and vibration environment is less demanding, and the cost constraints are usually less extreme.

The major telematic topics currently under investigation by the road transport industry include the following:

1. Vehicles under some form of automatic or ‘telematic’ control have to monitor others in their immediate environment, normally using some combination of radar, image processing, laser rangefinders, ultrasound and vehicle-vehicle communications. The sensor and signal processing requirements for this task are very challenging in view of the low budgets available for on-vehicle equipment and the safety-critical nature of the task.

2. Highway operators use a variety of sensing techniques to monitor traffic flow and detect incidents (breakdowns and accidents). In the near future, many countries are likely to implement systems that charge for road use. Both applications may require on-board or infrastructure-based sensors for vehicle type, speed, weight or even emissions.

3. Many navigation and traffic congestion warning systems (e.g. the Trafficmaster system available in the United Kingdom) use highway sensors [2] to monitor and collect information, which is then used to optimize driver’s route choice in the light of prevailing traffic conditions. A variety of sensing techniques are used, including optical systems (e.g. IR speed sensors), Doppler microwave devices and image-based systems (using analysis of video pictures), as well as more conventional roadway-based transducers such as inductive loops.

4. So-called ‘drive-by-wire’ systems are becoming widespread in automotive engineering. This is not as big a step as may at first be supposed: many of the direct mechanical links between the driver and the vehicle controls (such as the brakes, throttle, steering, etc.) have been supplemented by electronic connections for some time. Examples include diesel engine management systems, antilock braking (ABS), traction control systems and cruise control, all of which can and do intervene in the operation of the vehicle.

A number of high-performance vehicles (such as the Jaguar XK8 [3]) make use of a drive-by-wire throttle. The reasons for this move are cost and convenience: it makes the job of the vehicle designer much easier if large, fixed-geometry components such as steering columns or brake and throttle cables are replaced by wiring harnesses, particularly in the crowded dashboard area. However, reliance on telematic drive-by-wire systems does add to the safety-critical nature of many vehicle functions.

5. Convoy driving [4] is increasingly being seen as offering the most promising means of improving road usage (i.e. the number of vehicles per kilometre of highway). Convoy driving involves setting up electronic ‘trains’ of vehicles, which run close together (i.e. with reduced headway) under autonomous control. Vehicles taking part in convoys will have to have better condition monitoring systems than at present, since the consequences of mechanical or electrical failure (such as a tyre bursting) on a participating vehicle operating at a reduced headway could be catastrophic.

The engineers responsible for producing telematic systems that directly affect the vehicle controls must be extremely careful to ensure that their designs are fail safe and fault tolerant. It is curious that society appears to be happy to accept the fact that over 50 000 deaths a year are caused by human drivers in Europe alone, but if an electronic system were to be responsible for even one such death per year, it would cause an immediate outcry. To function safely and to be generally acceptable, therefore, vehicles that are even partly controlled by telematic systems are likely to be very heavily dependent on sensors: it has been noted that these have to be both very cheap and very robust.

2 VEHICLE-BASED SENSORS

A complex electronic/electromechanical system such as a modern motor vehicle has to be operated in intimate varying interaction with its driver and with an outside world of considerable complexity. For any such system to operate satisfactorily, the need for effective, accurate, reliable and low-cost sensors is very great. Electronic measurement systems can be applied very widely within a motor vehicle, as shown in Fig. 1. The complexity can range from the interactive control of engine and transmission to optimize economy, emissions and performance, to the simple sensing of water temperature and fuel level.
2.1 Powertrain sensors

The complexity of the control task involved in powertrain management is demonstrated by Fig. 2. Table 1 lists typical required specifications for the powertrain sensors. The accuracy and temperature range over which these devices have to operate should be noted, and it also must be remembered that they have to be of minimal cost and high reliability. A typical automotive sensor has a design life of up to 10 years and should require no initial setting up or maintenance within that time. A fully comprehensive powertrain control system would contain most of the devices listed in Table 1, although the really critical devices are those that measure engine timing, inlet manifold mass air flow, manifold vacuum pressure, exhaust gas oxygen content, transmission control valve position, transmission input and output speed and throttle and accelerator position.

2.1.1 Ignition control

The ignition timing sensors available at present normally use Hall-effect [5] or other electromagnetic transducers to detect the movement of a magnet or metallic projection attached to the flywheel. The major inaccuracies in ignition timing arise from mechanical vibration and torsion in the geared drive to the distributor from the engine crankshaft. This problem is likely to be partially overcome in future vehicles, where the timing will be taken directly from the crankshaft, although this will then require an additional sensor on the camshaft to determine the correct timing for each cylinder in the four-stroke cycle. Crankshaft sensing itself may suffer from wind-up errors due to the main engine torque and the influence of the differing operating conditions in each cylinder.

The measurement of inlet manifold vacuum pressure was the first measurement made in early ignition control systems [6], and it continues to be a very important parameter. It provides a relatively good measurement of engine torque, since, as the engine slows down under load, the inlet manifold vacuum pressure moves closer to atmospheric pressure. This effect is accentuated by the driver (who is part of the control loop) pressing the accelerator and opening the throttle further.

It would be much better to measure the engine torque directly, if a reliable low-cost way to do this could be found. The search for a low-cost, non-contact method of torque measurement is currently the subject of a great deal of automotive research, as discussed in Section 2.1.6.

The inferred measurement of load by sensing manifold vacuum has been used for controlling ignition advance from a very early stage in the development of the internal combustion engine. For many years the preferred approach was mechanical. The load-related control was achieved through the use of an aneroid vacuum capsule connected to the manifold. The varying vacuum altered the aneroid capsule shape, producing a force that physically rotated the distributor to alter the ignition advance angle. At the same time, a centrifugal weight system further controlled the ignition advance angle according to the rotational speed of the engine.

In an ignition system with electronic control, these functions are taken over by a pressure transducer connected to the manifold and a measurement of engine rotational speed derived from a sensor connected to the crankshaft. The pressure and speed signals provide the
Fig. 2  Typical powertrain management system
<table>
<thead>
<tr>
<th>Sensor/type</th>
<th>Sensing method</th>
<th>Range</th>
<th>Accuracy (%)</th>
<th>Thermal range (°C)</th>
<th>Response time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet manifold absolute or differential</td>
<td>Piezoresistive silicon strain-gauged diaphragm or capacitive silicon</td>
<td>0–105 kPa</td>
<td>±1 at 25 °C</td>
<td>–40 to +125</td>
<td>1 ms</td>
</tr>
<tr>
<td>pressure sensor (petrol engines)</td>
<td>diaphragm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet and exhaust manifold pressure sensor</td>
<td>As above</td>
<td>20–200 kPa</td>
<td>±3</td>
<td>As above</td>
<td>10 ms</td>
</tr>
<tr>
<td>(diesel engines)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric absolute pressure sensor</td>
<td>As above</td>
<td>50–105 kPa</td>
<td>±3</td>
<td>As above</td>
<td>10 ms</td>
</tr>
<tr>
<td>Transmission oil pressure sensor</td>
<td>Differential transformer and diaphragm, or capacitive diaphragm (often stainless</td>
<td>0–2000 kPa</td>
<td>±1</td>
<td>–40 to +160</td>
<td>10 ms</td>
</tr>
<tr>
<td>Inlet manifold air temperature sensor</td>
<td>Metal film or semiconductor film</td>
<td>–40 to +150 °C</td>
<td>±2 to ±5</td>
<td>–40 to +150</td>
<td>20 ms</td>
</tr>
<tr>
<td>Coolant temperature sensor</td>
<td>Thermistor</td>
<td>–40 to +200 °C</td>
<td>±2</td>
<td>As above</td>
<td>10 s</td>
</tr>
<tr>
<td>Diesel fuel temperature sensor</td>
<td>Cr/Al thermocouple</td>
<td>–40 to +200 °C</td>
<td>±2</td>
<td>+40 to +200</td>
<td>10 s</td>
</tr>
<tr>
<td>Diesel exhaust temperature sensor</td>
<td>Thermistor</td>
<td>–40 to +750 °C</td>
<td>±2</td>
<td>–40 to +750</td>
<td>10 s</td>
</tr>
<tr>
<td>Ambient air temperature sensor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributor mounted timing/ speed/trigger</td>
<td>Hall effect or optical or eddy current or variable reluctance</td>
<td>Zero to maximum engine</td>
<td>±1</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>sensors</td>
<td></td>
<td>speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crankshaft mounted timing/ speed/trigger</td>
<td>As above</td>
<td>As above</td>
<td>–40 to +180</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>sensors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road speed sensor: speedo</td>
<td>Optical or Hall effect or reed switch</td>
<td>As above</td>
<td>±1</td>
<td>–40 to +125</td>
<td>N/A</td>
</tr>
<tr>
<td>cable/gearbox fitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed-over-ground sensor</td>
<td>Optical or radar</td>
<td>Zero to maximum vehicle</td>
<td>±1</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Inlet manifold air mass flow (unidirectional)</td>
<td>Vanometer or hot wire or hot film</td>
<td>10–400 kg/h and 20–400 kg/h</td>
<td>±2</td>
<td>–40 to +125</td>
<td>35 ms</td>
</tr>
<tr>
<td></td>
<td>(two ranges)</td>
<td></td>
<td></td>
<td></td>
<td>for vanometer,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 ms for others</td>
</tr>
<tr>
<td>Inlet manifold air mass flow (bidirectional)</td>
<td>Ultrasonic or corona discharge or ion flow</td>
<td>±200 kg/h</td>
<td>±2</td>
<td>–40 to +125</td>
<td>1 ms</td>
</tr>
<tr>
<td>Accelerator pedal position sensor</td>
<td>Potentiometer</td>
<td>0–5 kΩ from minimum to</td>
<td>±1</td>
<td>–40 to +125</td>
<td>N/A</td>
</tr>
<tr>
<td>Throttle position sensor</td>
<td>Potentiometer</td>
<td>maximum pedal travel</td>
<td>±1</td>
<td>–40 to +125</td>
<td>N/A</td>
</tr>
<tr>
<td>Gear selector position sensor</td>
<td>Microswitch or potentiometer</td>
<td>0–5 kΩ from closed to open</td>
<td>±3</td>
<td>–40 to +125</td>
<td>N/A</td>
</tr>
<tr>
<td>Gear selector hydraulic valve position</td>
<td>Optical encoder</td>
<td>position selection or</td>
<td>±2</td>
<td>–40 to +125</td>
<td>N/A</td>
</tr>
<tr>
<td>sensor</td>
<td></td>
<td>0–5 kΩ</td>
<td>±2</td>
<td>–40 to +125</td>
<td>N/A</td>
</tr>
<tr>
<td>EGR* valve position sensor</td>
<td>Linear displacement potentiometer</td>
<td>0–10 mm</td>
<td>±2</td>
<td>–40 to +125</td>
<td>N/A</td>
</tr>
<tr>
<td>Closed throttle/full throttle sensors</td>
<td>Microswitches</td>
<td>N/A</td>
<td>–40 to +125</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Engine knock sensor (petrol engines)</td>
<td>Piezoelectric accelerometer</td>
<td>5–10 kHz, up to 1000 g</td>
<td>N/A</td>
<td>–40 to +125</td>
<td>Depends on</td>
</tr>
<tr>
<td>Engine knock and misfire sensor</td>
<td>Ionization measurement in cylinder or exhaust manifold</td>
<td>?</td>
<td>?</td>
<td>–40 to +150</td>
<td>resonant</td>
</tr>
<tr>
<td>Exhaust gas oxygen content sensor</td>
<td>Zirconium dioxide ceramic with platinum electrodes or titanium discs in</td>
<td>50–150% stoichiometric</td>
<td>?</td>
<td>+300 to +850</td>
<td>50 ms</td>
</tr>
<tr>
<td></td>
<td>aluminium</td>
<td>air-fuel ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust gas oxygen content sensor for</td>
<td>Zirconium dioxide oxygen pumping device with heater</td>
<td>14 : 1–30 : 1 air-fuel ratio</td>
<td>?</td>
<td>+300 to +850</td>
<td>50 ms</td>
</tr>
<tr>
<td>lean-burn operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Exhaust gas recirculation.
inputs to a microprocessor, which is programmed to look up the optimum advance angle from a three-dimensional table relating speed, load and advance angle stored in the microprocessor memory (see Fig. 3 for an example). By this means, significant improvements in engine operation and economy can be obtained. A number of designs of manifold pressure sensor have been used for this system, including devices based on capacitive, inductive and potentiometric [7] techniques. The most widely used approaches are to employ a silicon diaphragm with integral silicon strain gauges, or to use a capacitive deflection sensing method [8]. In both of these sensors a disc of silicon is etched to form a thin diaphragm (see Fig. 4) to which the pressure is applied. The strain gauges are integrated on to the disc, or a second capacitive plate is added. This technique produces a reliable low-cost device with a good resistance to the high-temperature, high-vibration conditions under which it has to operate.

2.1.2 Knock sensing

When an ignition system with electronic advance control is optimized for best performance and economy, it can, under some conditions, be set sufficiently far advanced to cause a condition known as ‘knocking’. Under these conditions, premature high-rate combustion (‘detonation’) takes place which, because of the rapid pressure

![Fig. 3 Look-up table relating engine speed and load to ignition advance angle](image)

![Fig. 4 Silicon capacitive pressure transducer structures used in automotive engineering](image)
increase, can quickly cause physical damage to vulnerable structures within the combustion chamber, such as the piston crown. In an engine with conventional mechanical ignition timing control, the advance angle is normally retarded sufficiently to avoid this condition, but considerable loss of efficiency results. For this reason it is desirable to operate an electronically controlled ignition as close to the knock limit as possible while retaining the ability to retard the ignition within one or two engine cycles to a safe level. This requires a method of rapidly sensing the knock condition, and to date this has usually been achieved by the use of a piezoelectric accelerometer, known not surprisingly as a knock sensor (see Fig. 5). An automotive knock sensor is usually mechanically tuned to be sensitive to the characteristic knock ringing frequency, which in normalized engines is in the region of 8 kHz. The transducer is positioned on the engine block in a place shown by extensive vibration analysis to give the best knock signal from all cylinders.

It has been proposed that measuring the ionization current across the spark plug after normal firing could provide an alternative method for obtaining this knock signal [9]. This could be done by applying a small voltage to the plug, sufficient to maintain an ionization current across the plug electrodes. This current has been shown to exhibit a superimposed ringing signal during knock, which can be distinguished and used to control ignition retard. This oscillation in ionization current appears to be due to the variations in plasma density caused by the pressure resonance initiated by the knock condition.

2.1.3 Fuel control

The principle of using a three-dimensional look-up table as a means of describing optimized engine operation has been taken further with the electronic control of engine fuelling. Most modern vehicles use electromagnetic fuel injectors, where the major parameters are again load and speed, but with the amount of fuel required being determined by the injector opening time as the controlled parameter. In this system both the total quantity of fuel and the ratio of air mass to fuel injected into the engine are critical. Under these circumstances, the ideal measurement to be made is the mass air flow into the engine manifold. Measuring inlet manifold vacuum pressure, and then calculating the swept volume of the engine from the rotational speed can derive this [10]. However, because of the compressibility of air, and the significant volume of the manifold, this is a difficult calculation to make accurately, particularly under transient conditions. Many attempts have been made to develop a low-cost sensor to measure air mass flow rate directly, but it has always been a difficult measurement to make. The vane air meter, in which a pivoted vane is placed in the air stream and attached to a single potentiometer as the measuring device (see Fig. 6), was the first sensor to be used in production and has been very widely applied.

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**Fig. 5** Knock sensor

**Fig. 6** Bosch moving-vane air meter
Fig. 7 Hot-film air mass flow rate sensor

Its performance suffers from the fact that it measures air velocity rather than mass, and therefore the signal requires processing with a further signal representing air density to obtain air mass flow. The transducer also has significant mechanical inertia under transient conditions, and there is a reduction in engine efficiency caused by the flap partially blocking the air flow into the manifold. However, the device has proved to be a very valuable sensor for a generation of fuel-injected engines and is still in production.

An alternative device is now in common use and is based on the hot-wire or hot-film anemometer (see Fig. 7). It measures mass air flow directly, is fast in response (1–2 ms) and does not significantly obstruct the manifold. The sensor does, however, require a correction for air temperature, and is also susceptible to contamination of the hot surface. The contamination is often dealt with by an automatic burn-off operation, which heats the wire to red heat on each occasion the vehicle is used. Hot-film transducers also suffer from inaccuracies under pulsed flow conditions, owing to their inability to differentiate the direction of flow.

Several other sensors for the measurement of mass air flow into the manifold have been developed, notably the vortex shedding flow meter [11, 12] and the ion drift flow meter [13]. This latter device has the major advantage of being able to measure direction of flow as well as its quantity. However, neither of these devices has proved entirely successful, although a vortex-shedding device has been used in at least one Japanese production vehicle.

2.1.4 Emission control

In most developed countries, severe restrictions are placed on exhaust emissions. This makes the requirement to control the air–fuel ratio provided to the engine very critical. With current engine technology, the only way to meet the emissions regulations is to use a so-called ‘three-way catalyst’ in the exhaust system to reduce the levels of the critical pollutants [carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx)]. For its correct operation, such a catalyst requires that the air–fuel ratio supplied to the engine should always be as close as possible to the optimum stoichiometric level of 14.7:1. This is only achievable by the use of a feedback control system in which this air–fuel ratio is sensed by means of an exhaust gas oxygen sensor in the engine exhaust manifold.

This sensor (see Fig. 8) makes use of the fact that the migration of oxygen ions across a suitable membrane or filter from one gas to another is only dependent on the partial pressure of oxygen in the two gases. At the stoichiometric air–fuel ratio, the partial pressure of oxygen in the engine exhaust gas equals that in ambient air. If suitable electrodes are attached to each side of the ceramic filter used in the sensor, a positive or negative voltage is generated by the ion migration when the air–fuel ratio is below or above stoichiometry. A rapid voltage change occurs over the transition between those two conditions. This voltage transition is ideal for use as a feedback signal to control the amount of fuel injected and therefore the air–fuel ratio.
low levels of engine emissions, rather than by the use of the expensive three-way catalyst with a stoichiometric engine and with consequent poor fuel economy and performance. Lean-burn operation requires effective control of the engine at air–fuel ratios between 14:1 and 22:1 while still maintaining adequate driveability. If this is to be done by feedback methods, then the availability of a lean-burn exhaust gas oxygen (EGO) sensor becomes critical. Prototype sensors are now available using a technique known as ‘oxygen pumping’ [14–16], which is outlined in Fig. 9. The oxygen pumping approach relies on the fact that applying a voltage across a filter forces oxygen ions to migrate to or from a small pumping cell, which positively controls the oxygen partial pressure within the sensor. A conventional EGO sensor is used to compare the increased partial pressure of oxygen in the cell with the increased partial pressure of oxygen in the exhaust gas stream from a lean-burn engine. The output voltage change at balance behaves like that from a conventional exhaust oxygen sensor. The current required to produce the balance condition in the pumping cell is a measure of the increase above stoichiometry in the air-fuel ratio being supplied to the engine. A lean-burn oxygen sensor of this type still suffers from a response time that is long compared with the rate of change in engine conditions, and the associated control system therefore continues to require open-loop compensation for transient conditions.

The imposition of US-level exhaust emission regulations in Europe has left lean-burn technology unable to meet the very low emissions levels now required. However, proposals have been made for mixed-cycle engines which run at stoichiometry when necessary to meet instantaneous emission levels, and under lean-burn conditions at other times (such as in high-speed driving). These mixed-cycle engines are reputed to give excellent fuel consumption and may bring back the need for a lean-burn oxygen sensor. Such developments could also increase the need for specific exhaust gas sensors for CO, HC and NOx levels to permit fine control of
the switchover between stoichiometric and lean-burn operation.

2.1.5 In-cylinder combustion measurement

In an internal combustion engine, a finely atomized fuel spray is dispersed in air, compressed within the cylinder and ignited. The resulting explosion of hot gases drives the piston down and is the source of the power produced by the engine. In a spark ignition engine, the combustion is initiated by an electric arc from a spark plug. In a compression ignition (or diesel) engine, the heating effect of compression causes combustion. In both cases, combustion starts at a point (in diesel engines, often a ‘hot spot’ on the piston crown), and the flame front spreads across the cylinder at the speed of sound.

In an ideal world, control of the process described above would be based on measurements of some meaningful property of the combustion process in the cylinder itself, undertaken quickly enough to allow the operation of the engine to be controlled accurately on a cycle-to-cycle basis. Three methods have been developed for meeting this requirement. The first approach is based on measurements of the pressure variations within the combustion chamber. The second method relies on detecting the arrival time of the flame front by means of an ionization detector. The third technique assesses the optical output from the combustion process (i.e. its colour and intensity) by means of an optical sensor.

High-cost, laboratory-grade, instrumentation-type piezoelectric pressure sensors have been available to the engine developer for many years. The problem in applying them to production vehicles has been to reduce the price to a level that will permit the economic fitting of a pressure sensor in each combustion chamber of the engine in mass production. The task is made more difficult by the extremely hostile environment within and close to the cylinder. This goal has now been approached by some sensor manufacturers, such as Texas Instruments [17], and a suitable piezoelectric sensor with a flush diaphragm (see Fig. 10) has been developed for production use. Good correspondence has been shown between laboratory-quality high-cost instrumentation pressure sensors and these low-cost devices. (These sensors also offer the capability of detecting knock conditions in a combustion chamber; this is because knock is a ringing effect caused by a rapid pressure increase in the combustion chamber.)

In the case of an ionization sensor, the idea is to detect the arrival of the flame front of the burning air–fuel mixture on the far side of the combustion chamber from the point of ignition. This provides two pieces of information. Firstly, the time it takes for the flame to arrive after the firing of the spark plug gives an indication of the suitability of the ignition timing and can therefore be used as a feedback signal to correct that timing. Secondly, the scatter of arrival times between successive firings gives an indication of the air–fuel mixture weakness, because a weak mixture produces a greater variation in arrival times. This information can therefore be used as a measure of air–fuel ratio, and, when integrated over a number of engine cycles, can be used as a feedback signal to control the combustion process. These ionization measurements can also give an indication that knocking is taking place, as can measurements of the ionization across the spark plug electrodes themselves after firing is complete.

An ionization sensor consists of a simple insulated electrode projecting into the combustion chamber in an appropriate location. A low voltage is applied between the electrode and the body of the engine. When the flame with its large supply of ions arrives, it reduces the resistance through the gas between the electrode and the surrounding metal and generates a large and easily measured step-voltage change.

The third type of in-cylinder sensor is optical, and a number of studies have been done in this area. The approach most commonly adopted is to insert a quartz rod into the combustion chamber, which is viewed at the outer (cold) end by a photoelectric sensor. The parameters of interest are the variation in brightness and timing of the combustion; these data provide similar

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Fig. 10 Piezoelectric diaphragm sensor for in-cylinder combustion pressure measurement
information, including some on knock, to that supplied by the pressure sensor. It is likely that at least one of these measurement techniques, combined with feedback, will be used for the adaptive and interactive control of engines in the twenty-first century.

2.1.6 Engine speed and torque measurement

After the measurement of engine speed and timing, engine torque is probably the quantity of most interest to automotive engineers. The measurement of speed and timing has always been essential, since the control of even the very early engines required some events, such as ignition and valve opening, to take place at the correct time in the engine cycle. At present, the distributor, which normally uses a self-generating electromagnetic pick-up in the breakerless ignition systems found on most vehicles, provides engine speed data. However, with the advent of distributorless ignition systems, the use of digitizer discs on the main crankshaft and electromagnetic or optical sensors matched to these is expected to increase rapidly.

Low-cost methods of measuring engine torque have not so far become available for automotive use, and existing control systems have had to function without this important parameter. However, a number of new developments in low-cost torque measurement and its telemetry from moving to stationary parts of the vehicle have been made, and torque measurement may become important for the future of engine control. This will be essential if predictions on the use of embedded simulation come to fruition, since the accurate measurement of engine torque and speed and the comparison of these measurements with a good computer simulation should provide all the information necessary to control an engine effectively.

The engineer faced with the problem of measuring torque normally uses a torque transducer that has been made by applying strain gauges to a shaft to measure the shear strain caused by torque. This type of transducer is widely used and probably forms the most common type of torque sensor. The major disadvantage of this approach for automotive applications is that additional equipment is usually required to transmit power to the rotating shaft and energize the strain gauge bridge, and also to retrieve the data. This apparatus can take the form of a set of slip rings, rotary transformers or battery-powered radio telemetry equipment. Regardless of which is chosen, the need for some form of power and/or data transmission system makes the measurement of torque more expensive than, say, that of pressure or temperature. In addition, slip rings (and, to some extent, rotary transformers) can be unreliable when operated in a dirty environment and may be prone to radio frequency interference (RFI). All the above problems normally make strain gauge-based methods of torque sensing unsuitable for automotive applications. A number of other methods are potentially available, however, as described below.

**Torsion bars.** Torque in a shaft leads to elastic deflection. The resulting strain can be measured by strain gauges as described in the preceding section, or alternatively the gross relative motion between the ends of the shaft may be used to indicate the torque. Just as in the case of strain gauge systems, a major difficulty is the necessity of being able to measure the deflection while the shaft is rotating. However, there are several advantages in using shaft deflection.

1. The need for precise location and orientation of the strain sensors is avoided.
2. Since the effect of an applied torque is integrated along the length of the shaft, the influence of any local variation in material properties or shaft geometry is reduced.
3. The (relatively) larger displacements available when movements of the two ends of a shaft are compared make it possible to design a variety of non-contact torque measurement systems that avoid the need for slip rings.

Figure 11 shows a typical torsion-bar torquemeter using an optical method for deflection measurement. The relative angular displacement between the ends of the torque-transmitting member is read from the position of the pointer on disc 2 relative to the calibrated scale fixed to disc 1. The ‘persistence’ of human vision and the stroboscopic effect of intermittent viewing make it possible to operate this system from about 600 r/min (10 Hz) upwards.

A number of torsion-bar systems have been demonstrated for automotive use. In a study reported in reference [18], an automotive driveshaft was fitted with a concentric sleeve of dielectric material as shown in Fig. 12. The sleeve is fixed to the shaft at one end and rests on a rubbing bearing at the other end. When torque is applied to the shaft, it causes relative motion between the surface of the shaft and the free end of the concentric tube. This motion is used to vary the capacitance between two opposing patterns of conducting strips, one of which was applied to the shaft and one to the tube.

The capacitive torque sensor is connected to an inductor coil wound around the shaft. The resulting passive circuit thus has a resonance frequency that depends on the applied torque. The passive resonant circuit rotates with the driveshaft and is excited from an adjacent stationary location by inductive coupling using a second inductor coil driven by an oscillator as shown in Fig. 13. The problem of torque measurement then becomes one of measuring the frequency at which resonance occurs. When the oscillator frequency is the same as that at which resonance occurs in the passive
circuit, an increased current is drawn. If the frequency at which this occurs is measured, it can be used to indicate the torque. The advantage of this arrangement is that no physical connection between the rotating shaft and the vehicle body is required.

An optical torsion-bar sensor intended for use as part of an electric power-assisted steering (EPAS) system has also been proposed by the Lucas Advanced Engineering Centre in Birmingham [19]. The sensor uses a pair of slotted discs positioned at the ends of a torsion bar as shown in Fig. 14. Light from a light-emitting diode (LED) passes through the slots in the discs and is received by a photodetector. Torque variations cause the amount of overlap between the discs to vary, and hence the output from the photodetector. However, the Lucas system exhibits a number of refinements that are intended to make it more suitable for automotive use. The most important of these is the use of a ratiometric technique to cancel out the effect of any variation in the source illumination intensity. A common LED as shown in Fig. 15 illuminates the slotted discs. The amount of light emitted by the diode will vary if the supply voltage changes. Even if a well-regulated supply is available, the light output from an LED decreases by up to 40 per cent as the device ages. The ratiometric effect is achieved by arranging for each slotted disc to carry two tracks of slots, positioned so that as torque is applied in one direction the light intensity transmitted through the outer track, $A$, increases, while that passing through the inner track, $B$, decreases. A pair of photodiodes measures the light passing through each track.

![Fig. 11 Torsion-bar torque transducer](image)

![Capacitive torque transducer for the automotive driveshaft](image)

![Rotating resonant circuit excited by inductive coupling](image)
The torque is calculated by measuring the outputs from photodiodes \( A \) and \( B \) and then evaluating the expression

\[
\text{Torque} = \frac{A - B}{A + B}
\]

The magnitude of the result gives the torque, and the sign gives the direction (i.e. clockwise or anticlockwise) in which it is applied. Provided both channels are affected equally, this technique ensures that the torque measurement is independent of the source intensity. Furthermore, for a given source intensity, the quantity \( A + B \) should be a constant that is independent of torque, and this value can be used to check that the sensor is operating correctly. If \( A + B \) moves outside preset limits, an appropriate warning may be given. A self-test facility of this kind is obviously essential in a safety-critical system such as vehicle steering.

The main problem with the Lucas system appears to be that the geometry of the photodetectors and their location with respect to the slots on the discs are critical if ripple in the sensor output is to be prevented as the discs rotate. Variations in the output can only be avoided if the sensitive area of the light detectors corresponds exactly to an even multiple of the slot area. Reference [19] proposes the use of masks to give the correct detection area and to collimate the light source. The ripple amplitude after these improvements is reported to be better than 10 per cent of the full-scale measurement range. Although this level of accuracy would not be acceptable for a laboratory torque sensor, it is probably adequate for power steering applications.

Work on measuring the twist or ‘wind-up’ along the cranks of an engine using slotted discs at each end has also been reported [20]. However, it was found that the high levels of torque variation that result from multi-cylinder operation made it difficult to obtain accurate results.

**Non-contact magnetic methods.** A number of torque sensors utilizing the magnetostrictive effect have been reported. A good example of this approach is a device described in reference [20] and shown in Fig. 16. Magnetostriction is an effect that occurs in ferromagnetic materials such as steel, where the magnetic permeability is affected by stress. The stress in a shaft is proportional to the applied torque, i.e.

\[
\tau = \frac{Tr}{J}
\]

where \( \tau \) is the maximum shear stress at the shaft surface, \( T \) is the torque, \( r \) is the shaft radius and \( J \) is the polar moment of inertia. It follows that torque must change the permeability of the shaft if it is made of a magnetic material such as steel. The effect is small but can be measured by an arrangement such as that shown in Fig. 17. The torque sensor consists of five coils arranged as shown, wound on to a common five-armed core. The centre coil can be thought of as the primary winding of a transformer, and the four circumferentially positioned coils act as secondaries. Magnetic coupling between the primary and the secondaries is provided by the steel shaft, which is positioned close to the sensor as shown. The primary coil is excited by an a.c. current and produces an oscillating magnetic field within the shaft. The

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**Fig. 14** Lucas EPAS ratio metric torque sensor

**Fig. 15** SAW devices used as a driveshaft torque transducer
Fig. 16 Magnetostrictive torque transducer

Fig. 17 Engine torque/speed curves with specific fuel consumption
four secondary coils are connected together in a Wheatstone bridge arrangement and are positioned so that they lie over the lines of principal stress, which follow a helical path at 45° for a cylinder in torsion. When the shaft is not under torsion, equal currents are induced in the four secondaries and the bridge out-of-balance voltage is zero. When torque is applied to the shaft, the permeability in the tension and compression directions will change by equal but opposite amounts, and the amplitude of the resulting bridge output voltage will be proportional to the applied torque.

There are four main problems with this type of torque sensor:

(a) inhomogeneity of the shaft material,
(b) sensitivity to changes in the sensor/ shaft gap,
(c) thermal effects and
(d) variations in the sensor output due to changes in the shaft rotation speed.

The first of these effects is the most serious. The permeability of the material from which the shaft is made can vary by up to 50 per cent around the circumference of the shaft. For a constant torque the output signal from the sensor can ‘ripple’ as a result at a frequency equivalent to the rotation rate. This characteristic makes it very difficult to measure instantaneous torque levels around a rotating shaft. However, the use of smoothing circuits allows the device to be used for measuring the average torque in the shaft integrated over several revolutions.

Surface acoustic wave torque transducers. Surface acoustic wave (SAW) devices are based on a theory propounded by Lord Rayleigh in 1885 [21], which showed that waves (known as surface waves or Rayleigh waves) could propagate along the surface of an isotropic elastic medium. Surface acoustic waves can be excited and detected using piezoelectric transducers etched with a pattern of interdigitated electrodes as shown in Fig. 18. The frequency at which the SAW device operates is determined by the electrode geometry. For torque measurement, two SAW devices are attached to the shaft undergoing torsion. The shear strain resulting from torque changes the geometry of the electrodes and hence the operating frequency of the device. At a frequency of 500 MHz, 1000 με (microstrains) will alter the SAW frequency by 500 kHz [22]. The two transducers are positioned on the shaft at 45°, as shown in Fig. 15. Each transducer forms part of the feedback loop in an oscillator, such that the output frequency is a function of the SAW geometry. The two SAW transducers are used in a half-bridge configuration, one undergoing tension and the other compression. The resulting two frequencies are added or subtracted: the difference in frequency gives a measure of torque, and the sum can be used to estimate temperature [22].

The SAW devices can be driven without the need for any electrical connection if capacitive or inductive pick-ups are used [22]. This feature makes SAW-based systems particularly attractive for automotive torque measurement, since (as discussed at the start of this section) telemetry based on slip rings or rotary transformers can be a source of unreliability and is probably too expensive for use in mass-produced vehicles. Consideration of engine torque leads naturally on to the device that transmits that torque to the road wheels—the transmission or gear box.

2.2 Transmission control

The function of the transmission in a road vehicle is purely that of a power-matching device between the power source (the engine) and the load. With a conventional manual transmission, the driver acts as the
feedback loop, sensing speed and load and adjusting the transmission ratio within the mechanical limitations of the vehicle to what he or she perceives as being the best operating condition. One of the main feedback parameters used is engine speed, in the form of the pitch and noise level perceived by the driver. Unfortunately, this gives a rather poor representation of engine power output. Although the driver’s gear changing may optimize subjective acceleration and driveability, it does not give anything like optimum operation for economy and performance. In fact, consideration of the torque–speed curves for a typical engine (Fig. 17) shows that the optimum economy is obtained by keeping the engine at the lowest speed possible for as long as possible during acceleration and changing the gear ratio to increase vehicle speed, only increasing engine speed (to produce more power output) when a wide-open throttle condition is reached. By this means, the best possible economy is attained. Good acceleration performance will require some modification to this strategy. Operating the transmission in this way requires the use of either an automatic stepped transmission with electronic control and smooth changes and sufficient steps to give an adequate range of gear ratios [23], or an electronically controlled continuously variable transmission (CVT) with an adequately wide ratio.

The transmission ideally needs to be variable in ratio throughout the operating range, and, in a fully integrated powertrain (engine and transmission) control system, to be controlled interactively with the engine. The sensors required are for engine speed, transmission output speed, and vehicle speed and, assuming that the transmission ratio is hydraulically controlled, hydraulic valve position and hydraulic oil pressure. The first of these parameters is normally available from existing sensors on the engine. Vehicle speed is often available from an inductive sensor used on the transmission to provide a signal for an electronic speedometer. If a stepping motor actuates the hydraulic control valve, a separate sensor may not be required. If a sensor is required, an encoder disc and electromagnetic or optical sensor is attached to the end of the valve shaft. For some types of transmission, accurate control of the hydraulic system pressure is essential. In this case a diaphragm-operated linear variable differential transformer (LVDT) has been used with some success experimentally. In production systems, a pressure sensor based on etched-silicon technology is likely to be the best device from the standpoint of cost and reliability.

### 2.3 Suspension control

In a conventional automotive suspension, two incompatible requirements have to be reconciled by achieving a compromise between good vehicle handling characteristics and the provision of a comfortable ride. The conventional approach to suspension design uses steel springs to carry the vehicle body, and dampers (shock absorbers) connected in parallel with the springs to absorb energy put into the system when the wheels encounter bumps in the road. With this approach it is possible to achieve good ride characteristics or good handling characteristics, but not both simultaneously.

In racing cars and other high-performance vehicles a different approach has been used. The system adopted is known as an active suspension. With this approach, either the vehicle springs or the dampers, or both, are replaced by controllable devices with variable characteristics. This allows the suspension characteristics to be altered to suit the current driving conditions.

There are two major types of controllable suspension. In one type, known as active suspension (developed particularly by Lotus), the vehicle springs are replaced or substantially augmented by hydraulic jacks. These jacks are electronically controlled to maintain the body of the vehicle as level as possible irrespective of the road surface being traversed by the vehicle. This can lead to an expensive system that requires large amounts of power to operate, and its use is normally restricted to racing vehicles.

An alternative (and much cheaper) system is known as adaptive damping. In this system the stiffness of the shock absorbers is controlled, either continuously or in a series of steps, by an electronic control system which can react to bumps in the road, turning movements of the steering and speed changes. A particularly noteworthy example of this was introduced on the Ford Mondeo. The use of adaptive damping provides a soft, comfortable ride for low-speed straight-line driving, with a progressively harder ride and improved handling characteristics during high-speed driving and rapid turning movements. Because of the lower costs, the adaptive damping system is more likely to be used in production vehicles, and it seems probable that it will become common during the next few years.

Figure 19 shows the layout of a typical adaptive damping system. The most notable feature is the large number of sensors required. The gearbox speed sensor is usually already provided to pass information about the speed of the vehicle to the transmission and engine control system. The throttle position sensor is also already provided for use by the engine control system. Suspension control requires further sensors for steering wheel position and velocity, to inform the suspension control system when the driver initiates a turning manoeuvre. The most likely sensor for this purpose is an optical digitizer disc, with the digital information obtained being processed electronically to give information on both position and rotational velocity. Some prototypes used potentiometer sensors for steering wheel movement sensing, but problems of wear were experienced and the optical set-up is more likely to succeed in practice.
At least one accelerometer is required to provide information on vertical acceleration of the vehicle body. Improved performance is obtained by using four accelerometers, one at each corner of the vehicle. In some systems these may be augmented by a further lateral accelerometer placed at the centre of the vehicle. These accelerometers are likely to be constructed using piezoelectric or etched-silicon devices, perhaps combined with thick-film technology [24].

The measurement of static and dynamic wheel-to-body displacement poses particular problems because of the large ranges of both displacement and velocity to be measured. One promising approach is to use an inductive system, in which the shock absorber piston moves vertically within a coil of wire. Effectively, this turns the shock absorbers into a simple form of LVDT [25]. Other workers have used linear potentiometers, normally fitted within the shock absorbers, but experience showed that this approach suffered from problems of noise and wear.

Finally, to achieve optimum performance, wheel accelerometers are also required, in addition to body accelerometers, to measure the vertical acceleration at the wheel hubs (i.e. on the unsprung side of the suspension). Once again, it is likely that these accelerometers will be constructed from micromachined silicon.

From this brief description it can be seen that a diverse range of sensors is required to provide sufficient input information for active and effective control of the vehicle suspension in response to all the various inputs from the road to the vehicle. In the longer term, embedded simulation may be used to allow the sensing requirements to be reduced. The target of this approach is suspension control using only one major vertical and one lateral acceleration measurement, together with steering wheel motion input to give predictive information.

2.4 Sensors for antilock braking and traction control

The final major powertrain control system fitted to most vehicles is that concerned with antilock braking and anti-spin traction control. Antilock brakes work by sensing whether, on braking, one wheel starts to slow down towards a locked condition faster than the other wheel. If this is detected, hydraulic braking pressure is taken off that wheel, which is then allowed to speed up until it is again rotating at the speed of the other wheels. Braking pressure is then reapplied. Antispin or traction control is the exact reverse of antilock. It is intended to retain traction when a wheel spins on a slippery surface (such as ice). When a wheel starts to speed up towards spin, braking is applied to that particular wheel, and backing off the (electronic) engine throttle through the engine control system reduces engine power.

It is clear that, if a vehicle already has electronic engine control with electronic throttle and electronic antilock braking, then the provision of an antispin system can be provided at almost no extra cost (see Fig. 20). This is a classic example of the benefits of integrating different electronic control systems around the vehicle.

The critical sensors involved in antilock/antispin systems are those used for sensing wheel rotation speed. A range of electromagnetic devices is currently used in production vehicles, including variable reluctance and Hall-effect devices, both of which detect the passage of ferromagnetic teeth on a steel digitizer ring mounted on each wheel. Because of the exposed position and the inevitable contamination from salt water and mud, inductive or magnetic sensing techniques are essential. These sensors are therefore unlikely to change dramatically in the future. However, they are likely to be among the first automotive sensors to benefit from the ignition of ‘intelligence’ at the sensor. At present,
the train of relatively high-frequency pulses from the wheel sensor is passed through the vehicle wiring system to a central control unit. This process is always at risk of electromagnetic interference in the severe automotive environment. The information actually required, however, is not wheel speed but the change in wheel speed, and this is essentially a very low-frequency event in electronic terms. Sensing the change in rotation rate could easily be handled by a suitable smart sensor, and the data provided would potentially be much more suitable for transmitting over the multiplexed data buses that are already beginning to appear on many vehicles.

2.5 Tyre and wheel sensing

Vehicle tyres and wheels are probably the last remaining major parts of the mass-produced motor vehicle that have not to date benefited from electronics. However, the wheels and particularly the tyres of a road vehicle represent the final and probably the most critical link in the chain by which engine power is used to create vehicle motion. The tyre is a key component in conventional ground vehicles. With the exception of wind resistance and gravity, all external forces are transmitted through the tyre–road contact patch.

If sensors can be applied to the tyres of a vehicle, a number of benefits may be obtained. Continuous monitoring of the coefficient of friction between the tyre and road could enhance both vehicle safety and performance. A number of studies are currently underway in this area.

Tyre temperature can also be measured and has been shown to be a good predictor for tyre blowouts. Work undertaken at Southampton University [26] demonstrated that most high-speed tyre blowouts result from prolonged running on under-pressure tyres. The resultant heating can raise the tyre temperature by up to 50 °C, and failure ultimately results from heat-induced softening of the tyre material and structure.

The Southampton study also demonstrated that it is feasible to measure tyre pressure while a vehicle is in motion. Once again, tyre pressure can be used as an important indication of imminent failure. As noted above, most tyre bursts are the result of prolonged running on under-pressure tyres. It is a sad fact that most car drivers do not check their tyres on a regular basis, and a dashboard tyre monitoring system would offer real safety advantages. In the case of both tyre pressure and tyre temperature, suitable sensors are readily available. The major problem in manufacturing tyre pressure, temperature or strain measurement systems is that of powering the measurement system and recovering sensor signals from the rotating wheel at an economic cost. A number of different methods have been used with varying degrees of success. Some manufacturers have incorporated batteries within the wheel hub to energize the measurement circuits, and have used radio telemetry to recover the data. Other studies have reported the successful use of inductive coupling across air gaps of up to 10 mm. The Southampton study [26] made use of inductive coupling for both energizing the measurement circuit and for data retrieval. As described in reference [26], power was fed from the chassis to the wheel at a frequency of 1 MHz, and encoded data were passed in the other direction through the same inductive link at a carrier frequency of 100 kHz.

A second study undertaken by the Southampton group made use of a purely mechanical sensor, in which pressure changes were used to alter the separation of a pair of permanent magnets. The magnet positions
were sensed from the vehicle chassis by a Hall probe [27]. The device incorporated a mechanical temperature compensation system and thus avoided any need to pass power to or retrieve data from the rotating wheel.

2.6 Vehicle-based external sensors for driver support

The term used by the automotive industry for driver support equipment is integrated driver support (IDS). The first commercial application of IDS is the adaptive cruise control (ACC) system, initially introduced on up-market vehicles. ACC uses a vehicle-based range-finding system as described in the next section.

The exclusivity of IDS systems such as ACC is likely to be short lived. Most European car manufacturers are developing the feature for vehicles based on high-volume platforms that will start to appear within the next 2–3 years. A number of Japanese and Korean manufacturers are also planning to include ACC on new models for both the domestic and export markets.

Other IDS systems likely to appear in the next decade are targeted at making the roads safer for both vehicle occupants and other road users. These include collision warning and collision avoidance systems, as well as sensors that trigger external protection devices [such as external airbags, or side protection curtains fitted to heavy goods vehicles (HGVs)] to reduce or prevent injury to vulnerable road users.

2.6.1 Sensors for adaptive cruise control and collision avoidance

ACC makes automatic adjustments to the speed of a car to ensure that a constant headway is maintained between vehicles. As a consequence, traffic flow is smoothed and the more comfortable progress of the car reduces fatigue and stress for the driver.

Like standard cruise control, ACC is capable of maintaining a cruising speed at a preset level, but it is also able to adjust the speed to maintain a safe distance from the vehicle in front. This is possible through automatic control of the accelerator and brakes, which then allows pedal-free progress and so alleviates some of the work associated with long-distance travel over motorways and urban expressways.

Quite apart from being seen as a convenience feature, ACC appears to be able to help reduce traffic congestion by keeping the traffic moving. Simulation flow tests in Sweden showed that, if just one car in ten has ACC installed, traffic flow is dramatically improved [1].

ACC is the first of a generation of driver support systems that will ultimately lead to convoy driving, collision avoidance and perhaps even the electronic chauffeur. Driver acceptance of the technology will evolve as the systems are brought to market, and there is little doubt that the benefits of IDS features in general will win wide recognition over the next decade.

The sensor requirements of ACC consist in the main of range finding. Most of the systems that have been or are about to be launched use a radar sensor fitted to the front of the vehicle, often behind the vehicle registration plate, to measure the speed and closing distance of the vehicle in front. Frequency-modulated continuous wave (FMCW) radar is normally used, operating at a frequency of 77 GHz [28]. The first-generation ACC systems have been found to suffer from poor angular coverage (typically 10°) and a near-range cut-off (typically 5 m) which limits their use in dense or slow-moving traffic. On even moderately curved roads the narrow beam width necessitates some form of beam steering. However, these first-generation systems function well on motorways and urban expressways.

A number of laser-based optical range-finding (LIDAR) systems for ACC have also been proposed [29, 30]. Most of the proposed systems adopt a pulsed mode of operation and use infrared to achieve better penetration in mist or rain. The system described by Lissel et al. [30] is typical and has a wavelength of 1.55 µm and a pulse duration of 50 ns. This type of sensor has better resolution than the radar systems and is capable of detecting objects as small as 0.1 m at ranges of 100 m. However, unlike radar, the performance of LIDAR systems is markedly degraded by dirt, mist or rain, as well as road spray.

On a demonstrator car produced by LucasVarity and Thomson CSF, an additional refinement allowed the vehicle to accelerate as soon as the indicator or turn signal switch was activated [28]. The project participants believed that this feature encouraged proper use of the indicators, in addition to assisting the vehicle in lane-changing manoeuvres.

2.6.2 Sensors for the vehicle environment

The use of transducers to sense obstacles close to the vehicle is not restricted to ACC. A number of studies have proposed systems that can warn the driver of the presence of pedestrians or other obstacles during reversing, as well as monitoring the ‘blind spot’ during overtaking manoeuvres. Visibility of the road around a vehicle has always been problematic even on bright and sunny days. A number of vehicle manufacturers are studying the idea of replacing mirrors with video cameras to eliminate blind spots. This approach has the added advantage of improving the car aerodynamics, reducing wind noise and increasing fuel economy.

Ultrasound. Ultrasound offers an inexpensive method by which the presence, distance and direction of objects close to the vehicle can be measured. A number of manufacturers already offer ultrasonic parking/reversing aids, often using an audio signal for driver feedback.
Ultrasonic distance measurement is normally based on a pulsed, time-of-flight approach, and distance can be measured to an accuracy of a few millimetres or better [31]. The resolution depends primarily on the precision with which the speed of sound is known, which varies with local air properties. The beam width of an ultrasonic transducer is typically 20–30°, but the relatively low cost means that it is usually feasible to employ more than one device in a given application. The repetition rate is normally no more than 10 Hz because of the relatively low speed of sound compared with optical/radar pulses. Thus, ultrasound systems are restricted in their application to low-speed manoeuvring and other applications where the relative velocity is low. While most surfaces and objects are good reflectors of ultrasound, one study noted that pedestrians wearing fur or heavy wool coats provided little or no attenuation [32].

Vision- and image-based systems. The image from a charge coupled device (CCD) camera consists of a two-dimensional picture generated in a form that may be stored and processed by computer. The images are typically produced at a 25 Hz frame rate [33] and are stored as a matrix in computer memory. The digitized image can then be processed, displayed and searched for recognizable features using a model-specific filter. Maximum response locations are used as the initial search points for the model matching process, possibly supported by other features such as shape, symmetry or the use of a bounding box. In principle, image processing techniques can be used to give information about the presence of humans at close ranges, i.e. less than 0.3 m and up to 50 m. As humans vary a great deal in size and shape, image analysis systems find it difficult to distinguish between a tall adult standing 10 m away and a small child standing 2 m away. This could be overcome by combining image processing with a ranging system, e.g. ultrasound [32].

It has been shown that, by combining ultrasound and image processing, a typical CCD camera can give an accuracy of 1.5 mm for distance estimation, 2° for bearing and a recognition rate or success rate of 90 per cent in the presence of clutter. A combined system of this type was described in a study by Zhang and Sexton [34].

An alternative to the use of visible-light images is passive infrared (PIR). Infrared (IR) sensors use the fact that all objects with a temperature above absolute zero emit black body radiation. Different objects emit light of different wavelengths. The human body emits IR radiation in the wavelength region 8–14 μm.

A PIR camera uses an array of detectors to image the radiation of a warm body, which can be significantly higher than the background temperature. In most commercial PIR devices the radiation passes through anti-reflection coatings (to minimize the reflection losses caused by the large change in the refractive index from

![Table 2  Summary of vehicle external environment transducer characteristics](image-url)
Capacitive proximity sensors. Capacitive sensors have been used for many years in industrial environments to detect the presence of non-metallic objects and for liquid level measurement [35]. They have also been considered for detecting obstacles in low-speed manoeuvres such as parking. Transducers of this type operate by sensing the change in dielectric constant that occurs when an object with dielectric properties different from those of air approaches a sensing electrode. Capacitive sensors can accurately measure distance up to a range of 2 m and can determine the size and shape of the detected object [36]. Capacitive sensors do not contain any mechanically moving parts, are insensitive to dirt and will work in the absence of light. The associated circuitry is simple and the devices low cost, all of which appears to make them ideal candidates for use with automotive telematic systems. The fact that they have not (to the authors’ knowledge) been introduced in spite of extensive trials is most probably due to the fact that (like other high-impedance devices) capacitive sensors are prone to RFI. Table 2 summarizes the characteristics of various forms of vehicle-mounted sensor for measuring the vehicle environment.

2.7 Vehicle-based safety sensors

Until about a decade ago, in-vehicle safety systems were entirely mechanical. Two approaches to occupant protection were adopted: the use of harness restraint systems to prevent passengers moving during a crash, and a structural design approach in which energy-absorbing regions (‘crumple zones’) were incorporated within the vehicle body.

The introduction of airbags has brought a third element into play: the use of electrically fired devices to cushion the driver and other occupants. Airbags, together with fuel cut-off switches, battery disconnect systems and seat belt pretensioners, require sensors for their correct operation. These transducers sense the rapid deceleration associated with a crash, but must also discriminate between a crash and ‘legitimate’ manoeuvres, such as driving over kerbs, hitting potholes or heavy braking. Since the firing of an airbag is very much a ‘last resort’ as far as safety systems are concerned, and also because airbag operation has occasionally been found to be hazardous, airbag sensors are relatively insensitive and require decelerations in excess of 20 g sustained for at least 20 ms before they are deployed. Figure 21 shows a typical set of airbag sensors.
deceleration/duration requirements, from which it can be seen that the transducer has to respond to high-intensity, short-duration impacts as well as longer-intensity, lower-duration events. Essentially what is being transduced is the energy dissipated in an impact, which can be calculated from the integral of the acceleration–time function. Most crash sensors are therefore inertia switches. Since the required function is one of switching rather than deceleration measurement, conventional accelerometers are not normally used.

One form of inertia switch consists of a weight, often in the form of a steel ball or cylinder, which is fixed to one end of a spring. The weight and spring are contained within a tube. When the assembly is accelerated or decelerated along its axis, inertia forces cause the weight to compress or extend the spring. The deflection of the weight is proportional to acceleration and is sensed by placing an appropriate sensor in the side of the tube. An alternative design that has the advantage of being equally sensitive to any deceleration in a (normally horizontal) plane uses a ferromagnetic sphere, retained at the bottom of a conical or dish-shaped ‘saucer’ by a permanent magnet. A simplified form is shown in Fig. 22. Rapid deceleration causes the ball to break free from the magnet, and it rolls towards the rim of the saucer where it closes a switch.

Fuel cut-off and battery disconnect sensors operate in a similar fashion to airbag sensors, but are normally made more sensitive, with switching thresholds in the range 8–12 g. The likelihood of unintended operation during the vehicle lifetime means that a somewhat more complicated mechanical arrangement is normally used, in which motion of the seismic mass disturbs an over-centre mechanism. Resetting the transducer requires external intervention, often through the medium of a reset button located in the boot or elsewhere in the vehicle, which the driver has to press. An argument frequently advanced for this arrangement is that the requirement to open the boot prior to resetting the fuel pump cut-off forces a driver to walk around the car following a minor collision, thus enabling him or her to observe any fuel leakage from damaged pipes or tank. It is noteworthy in this context that the frequency of post-crash fires has decreased markedly since the widespread introduction of fuel pump cut-off switches. Other reported applications for crash switches include seat belt pretensioners, activation of hazard warning lights, mobile phone distress beacons, door lock releases and antitheft devices.

Some crashes do not result in a deceleration severe enough to trigger inertia switches of the types described above, but are nevertheless life threatening. Most incidents of this kind involve the vehicle turning over, and a range of rollover switches has been developed with the purpose of firing airbags, switching off fuel pumps, etc., in the event of this type of accident occurring. Figure 23 shows a typical design, in which a ball is contained within a V-shaped enclosure that requires rotation to more than 60° before the device operates by breaking a light beam.

3 HIGHWAY-BASED SENSORS FOR TELEMATICS

The subject of highway (road and roadside) sensors for vehicle telematics is very large, and space allows only a short overview to be presented in this paper. Vehicle detection systems have been used for many years to monitor and control traffic. The first pneumatic tube-based vehicle detectors were used as long ago as the 1930s for traffic signal control, and some pneumatic systems are still in use today. However, induction loops were first introduced in the early 1960s and rapidly became the dominant detection technology [37].

3.1 Loop detectors

Loop detectors consist of one or more loops of wire buried in the road surface, as shown in Fig. 24. The loop forms the inductive part of an LC resonant
circuit. At resonance, the fundamental frequency of oscillation is

$$f = \frac{1}{2\pi\sqrt{LC}} \frac{R^2}{L^2}$$

and variation in the inductance, $L$, the series resistance, $R$, or the capacitance, $C$, will cause a change in frequency. Loop detector circuits are designed to be relatively insensitive to small changes in $R$ or $C$ and automatically tune to resonance within a prescribed frequency band. Two detection systems are used. Probably the least error-prone approach is one in which a phase shift between the loop oscillator circuit and a fixed reference frequency is detected. However, an alternative approach is used by some systems that detect the change in frequency occurring when a variation in loop inductance takes place. In either case the circuit output is monitored by a microprocessor-based system scanning a number of channels.

As a vehicle is introduced into the inductive loop in the road, three effects occur:

1. Magnetic and eddy currents are induced in the vehicle which oppose the main field of the coil and therefore reduce the loop inductance.
2. The magnetic flux density increases because of the iron content of the vehicle, which increases the loop inductance.
3. The loop capacitance increases owing to the proximity of the vehicle.

The eddy current-induced inductance change is by far the greatest effect, and is the one that makes this system of vehicle detection viable. The other two effects are usually neglected.

One problem with this system is that it can be unreliable for detecting bicycles. The low metallic content of a bicycle means that only small eddy currents are induced in the structure of the bicycle. If a cyclist crosses the loop wires at right-angles to the direction of travel, eddy currents will only be induced across the width of the bicycle, and the resulting inductance change will normally be too small to be detected. If bicycle detection is required, loops must be installed at an angle to the cyclist’s direction of travel. This results in the production of two orthogonal magnetic vector components, one of which opposes the magnetic field of the loop and is large enough to ensure bicycle detection. Bicycles with small wheels and/or non-metallic frames can be very hard to detect, however, and the problem is not easily solved by increasing detector sensitivity since this is often accompanied with an increase in false detection signals.

3.2 Infrared detectors

Infrared (IR) detectors have been used as an above-ground vehicle sensor that avoids some of the problems (such as bicycle sensing) inherent in loop detectors. IR detectors may operate in active or passive modes, but whichever is used the essential difference between these devices and the inductive loop systems described earlier is that IR detectors can only detect movement within their zone of coverage, while loop detectors sense the presence of a vehicle.

As discussed in Section 2.6.2, passive infrared (PIR) detectors consist of an optical system that focuses infrared energy on to a transducer. The transducer incorporates one or more ceramic pyroelectric elements behind a silicon window and is sensitive to radiation in the 6–14 μm region of the electromagnetic spectrum. This waveband corresponds to the emissions peak from targets such as motor vehicles and people. The detection algorithms used rely on sensing changes in radiation intensity as targets move in and out of the detection zone.

In contrast, active infrared detectors operate by transmitting encoded beams of infrared light on to a region of the road, normally from an overhead gantry. Reflections from vehicles travelling through the illuminated zone, which is limited to a small area, are focused on to a sensor matrix. Real-time processing of the output signal and comparison with the encoding data are used to indicate the presence of a vehicle in the target area.
Active IR detectors can also be used for speed measurement. The normal arrangement used is shown in Fig. 25, where it can be seen that two detection zones per lane are used. The time at which a target vehicle enters each zone is noted, and the vehicle speed can then readily be calculated as long as the installation geometry is known.

3.3 Microwave detectors

Microwave vehicle detectors (MVDs) use the microwave part of the electromagnetic spectrum. They operate by radiating a microwave beam in the X (10.587 GHz) or K (24.2 GHz) frequency bands. When the beam strikes a moving metallic object, a reflection is returned at a slightly different frequency (the Doppler effect). As the MVD relies on detecting this Doppler shift, it cannot detect stationary or very slow-moving vehicles. For an X band system detecting a vehicle travelling at 50 km/h, the Doppler shift is of the order of 1 kHz.

Some studies of MVDs have shown that their performance can be erratic. In work described in reference [37] it was shown that some MVDs failed to detect around 3.5 per cent of all vehicles, and that HGVs were detected an average of two seconds earlier than cars. This could lead to timing problems for traffic signal controllers.

3.4 Piezoelectric detectors

Piezoelectric (PE) cables have been used to provide an accurate axle (rather than vehicle) detector for vehicle classification and speed surveillance applications. Piezoelectric cables use the well-known piezoelectric effect [38], in which lateral compression of a cable made from a piezoelectric plastic material such as polyvinylidene fluoride (PVdF) results in the generation of a small charge which can be amplified and detected. In use, the piezoelectric cable is placed in a precut slot in the carriageway so that vehicles drive over it. After conditioning, the output usually takes the form of a pulse corresponding to each axle. PE systems of this type are very sensitive, allowing detection of vehicles such as motorcycles and slow-moving bicycles. By measuring the time interval between pulses from consecutive piezodetectors it is possible to measure speed accurately in addition to axle counting. Piezoelectric detection systems have the disadvantage that they cannot provide any information about lane occupancy, since outputs are only provided as a wheel crosses the PE cable.

3.5 Video image processing

Although not strictly a sensing system, video image analysis is included in this section for completeness. Video image processing techniques are increasingly being applied to detect the presence and speed of vehicles in real time, as well as for vehicle identification through number plate recognition. A great deal of research is currently underway in this area, principally because the rapidly falling cost of image analysis hardware is now making it feasible to design systems for highway use. Existing systems range from relatively low-level devices in which an image is divided into a number of windows, and changes to the ‘scene’ in each window are assumed to indicate the presence of a vehicle, to more sophisticated approaches in which vehicle types and number plates are automatically identified and classified.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

In conclusion, this article has attempted to show the breadth of sensing and transduction techniques currently in use for automotive telematics. From the preceding
discussion it can be seen that the field of automotive engineering is very active, with research pushing forward on several fronts. Drive-by-wire systems are in the late stages of development by a number of vehicle builders and component manufacturers, and it is almost certain that during the coming decade many or all of the mechanical links between driver and vehicle will be partially or completely replaced by electrical connections. The electronic systems currently incorporated in a motor vehicle account for 15–20 per cent of the cost of building the vehicle, and industry sources estimate that by 2005 this will rise to over 30 per cent. A large part of this increase will be the result of increased sensor use (and the associated signal conditioning systems).

Although few new sensing techniques are likely to be developed for automotive or highway use, sensor fabrication methods continue to develop as part of the drive to reduce automotive manufacturing costs. The advent of silicon micromachining techniques has meant that much greater intelligence can be incorporated within a sensor, with many of the signal conditioning and compensation circuits being fabricated on the same wafer as the sensor. Micromachining has also brought about improvements in reliability, principally as a result of the reduction in the number of device interconnections.

Another fabrication technique finding automotive applications is the use of thick-film processing [39]. Thick-film techniques, while leading to larger package sizes than those produced by silicon methods, are cost effective at much smaller volumes (thousands or even hundreds of devices against hundreds of thousands for silicon).

It is interesting to note that, in many cases, the sensor technology required for telematics already exists, or at least can be easily developed from today’s systems. Most of the problems that have to be addressed before vehicle telematics can be widely introduced centre on legal issues (such as liability in the event of an accident), customer acceptability or unwillingness on the part of vehicle manufacturers or highway authorities to make the necessary investment. Part of the problem is to do with the perception of risk. Considerable effort will have to be put into persuading drivers that surrendering some of their authority over a vehicle is acceptable. For some reason, society tolerates the fact that human drivers cause several thousand deaths a month in Europe, but there would be an enormous outcry if it were found that telematic systems were causing even one fatality a year.

In a current vehicle the most likely consequence of serious electronic systems failure is that the engine stops. While there is no doubt that this can be dangerous, in most circumstances it is merely inconvenient. However, the drive to increase road usage, combined with the rise in traffic levels, implies that driving will become increasingly automated (or ‘telematic’). In the process, more and more sensors and monitoring systems will be needed as the electronics on a vehicle become increasingly safety-critical. The engineers responsible for producing telematic systems that directly intervene with the vehicle controls must therefore be extremely careful to ensure that their designs are fail safe and fault tolerant. Systematic techniques are needed to produce technology that ‘degrades gracefully’, to use an industry-current expression. In software this aim is partly achieved by the use of lean formal methods (LFM). However, similar formal design techniques will also be required for safety-critical hardware systems, and hardware/software interactions will require particularly close scrutiny.

Convoy driving (perhaps using specially designated highway lanes) is currently under active consideration as a means of improving the traffic density and usage of motorways. Trials of the technology needed to achieve convoy driving have been undertaken in the United States, Europe and Japan. The aim is to improve the traffic flow and density through the use of vehicle-to-vehicle communications. Convoys of electronically linked vehicles travelling with reduced headway are expected significantly to improve road usage and reduce fuel consumption, journey time and driver stress.

Convoy driving systems are the logical extension of the autonomous cruise control (ACC) systems now being deployed. However, it seems likely that safety concerns will require vehicle-based sensing to be backed up by vehicle–vehicle data communications links. For convoy driving to be fail safe, each vehicle will have to communicate its status (such as speed, intended lane changes, etc.) to its neighbours.

In theory, elimination of at least part of the human response from the control loop should allow vehicles to travel closer together than at present (headway reduction), with improved safety. The introduction of telematics systems such as ACC brings the advent of convoy driving much closer. However, the safety of convoy driving in the event of full or partial systems or mechanical failure on one of the convoy vehicles has not been examined in depth, and further research in this area is urgently required.

Highway systems are also becoming more safety critical. Real-time traffic control has already been undertaken, and in some parts of the United Kingdom variable speed limits have been in place for several years [40]. Consideration is currently being given to passing these speed limits to vehicles, initially for driver assistance in the form of a dashboard display. However, the possibility of direct control of vehicle speeds by the highway authorities is also being investigated, and the safety implications of failure in such a system are clear. It is likely that enhanced sensing and monitoring systems will be required if current patterns of vehicle use are to be maintained. It seems clear that the use of sensors and measurement systems on both road vehicles and highways will increase considerably during the next decade.
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