Gasoline (Otto) Engine Control

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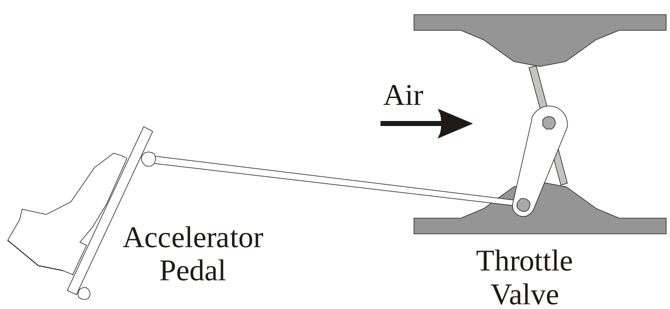
(revised 26 July 2007)

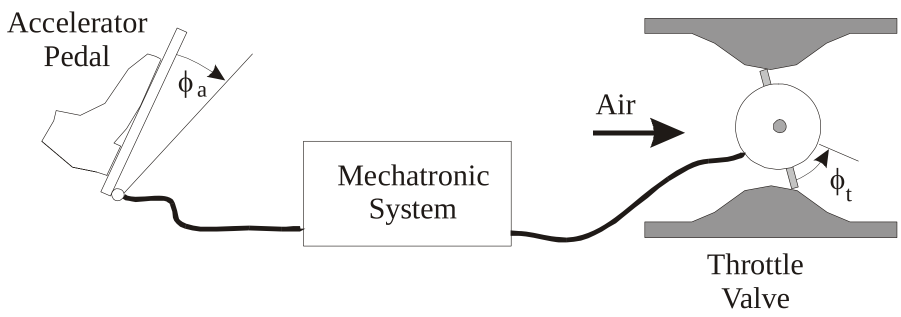
Introduction

The automobile of today is quite different than that of a decade ago or two decades ago. The introduction of electronics and the development of the fields of mechatronics and specifically automotive mechatronics have wrought huge technological changes on the autos of today. The refinement of automotive technology has been helped along by electronic and mechatronic development. These improvements have been in response to customer demand and satisfaction and also in response to ever more stringent demands for energy efficient cars and emissions reduction.

Central to this is the development of engine control systems. In autos that predate the electronic era, there was a direct, mechanical coupling between the accelerator pedal and the engine intake throttle valve. Pressing on the accelerator opened the throttle valve directly, which resulted in a greater flow of air and gas into the engine. In today's cars this direct connection has been severed. A mechatronic system stands between the accelerator pedal and the engine throttle valve. The demand for more power, expressed by a change in the accelerator pedal angle, can be met in a variety of ways and can be met while taking account of the engine operating condition and in a manner that maximize fuel economy. So through the mediation of a mechatronic engine control system the operation of the engine is improved through intelligent control.



Non-Mechatronic System, direction connection between accelerator and throttle valve



Mechatronic System mediates engine power changes

This decoupling of the driver demand and the throttle valve enabled many other changes that improved engine operation. The purpose of this section is to use this example, a primary example in automotive mechatronic technology to give you an idea of how mechatronics has changed the way a car works.

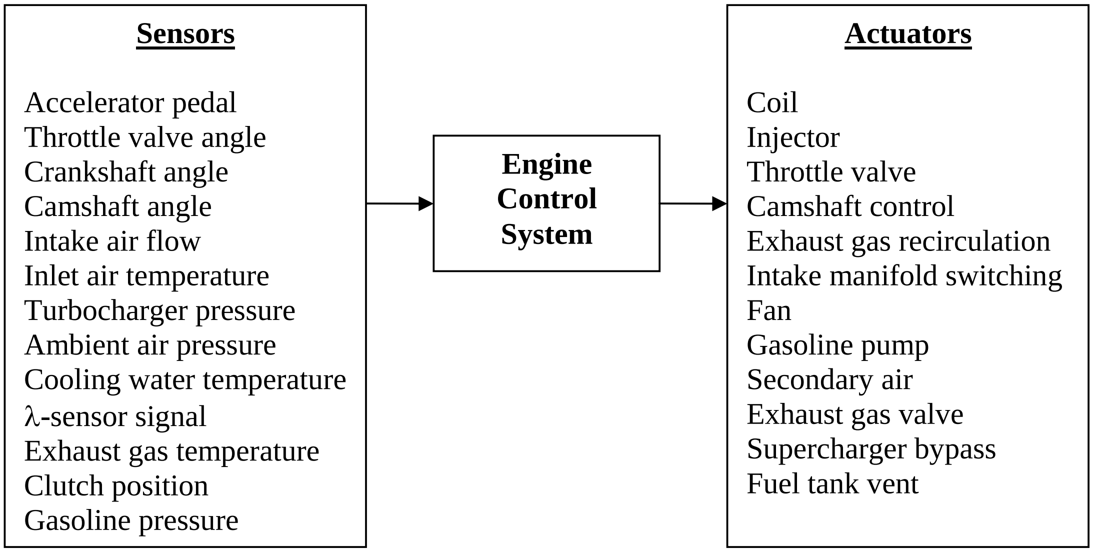
Electronic engine control was initially introduced in the 1970s and has grown significantly since then. The demands of emissions control, first in the U.S., particularly in California, and then later in Europe, led to the replacement of mechanical linkages with electronic controls. Nowadays engine control takes place in an atmosphere of conflicting interests: customers want more power, comfort, and economy, while air control agencies want more emissions reductions. Nowadays great emphasis is placed on emissions monitoring and on engine diagnostics in engine control systems. Air/fuel mixture and amount are the primary factors in affecting emissions. Spark timing also plays an important role in emissions control. In the fully mechatronic car of today, the spark can be set off at a time determined by the engine control unit.

One other important mechanical decoupling found in many modern automobiles is the elimination of the camshaft, which governs valve timing. The age-old manner of valve actuation is through the camshaft, which opens and closes the valves. The camshaft is driven through a belt or a chain from the crankshaft. So the point at which an intake or exhaust valve opens is fixed. The length of time it is open is also fixed by the shape of the cam.

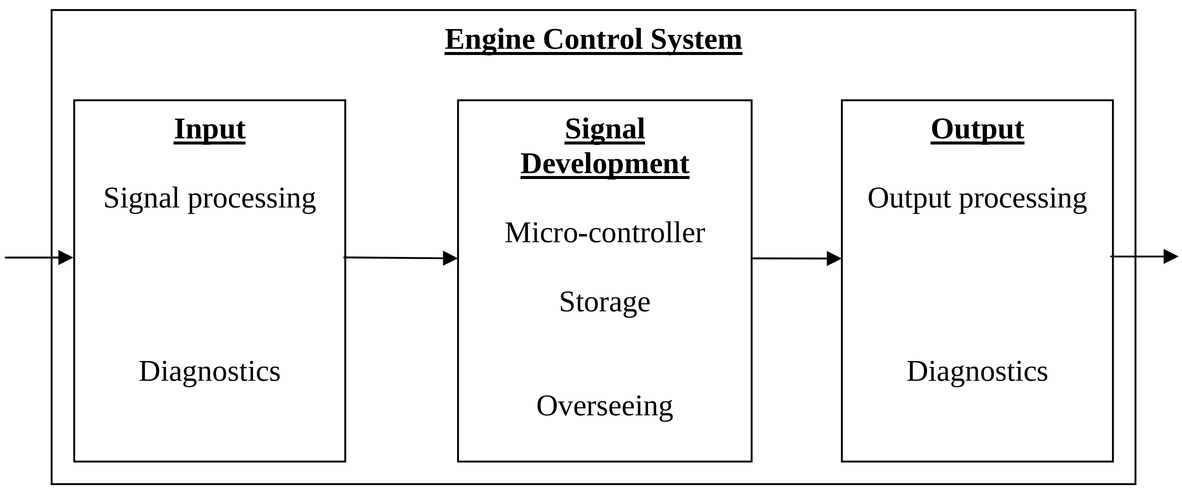
Instead of cams driving the valves open, in a fully mechatronic car the valves are opened using electrical solenoids controlled by the engine control unit. So when a valve opens during a piston's cycle can be altered to fit the engine control strategy. How long the valve remains open is also controllable in a crankshaft-less engine. So the possibilities of engine operation are greatly expanded with these mechanical decouplings. This allows emissions reduction, fuel economy, engine protection, etc.

System configuration

The mechatronic unit that governs engine operation takes input signals for the system sensors, makes decisions based on this input information, and then issues commands to the system actuators. The actuators take action based on the wishes of the driver, input through the gas pedal, and based on the current situation of the engine as perceived by the sensors. As you can see, what was done mostly through mechanical connections prior to the days of automotive mechatronics is now a complex orchestration managed by the mechatronic brain in the automobile.



The engine control system is subdivided as shown in the drawing below:



The input signals from the sensors can be analog, digital 1/0 states, or pulse sequences from instruments. The purpose of the input module is to convert these signals into digital bit sequences that are understandable by the micro-controller. On the output side such real-world signals (voltages, digital voltage levels, pulses) have to be generated to drive the actuators. The output module takes the commands generated in the micro-controller and converts them into signals that drive the actuators.

So the brain of the unit is the micro-controller. The engine control program runs in the micro-controller and implements the engine control strategy developed by the engine manufacturer. The micro-controller's programs are stored in a Flash-EPROM which retains the program even in the absence of electrical power. That the program is stored in a writeable device enables the engine control software to be updated as improvements are made in the software.

Control Strategy

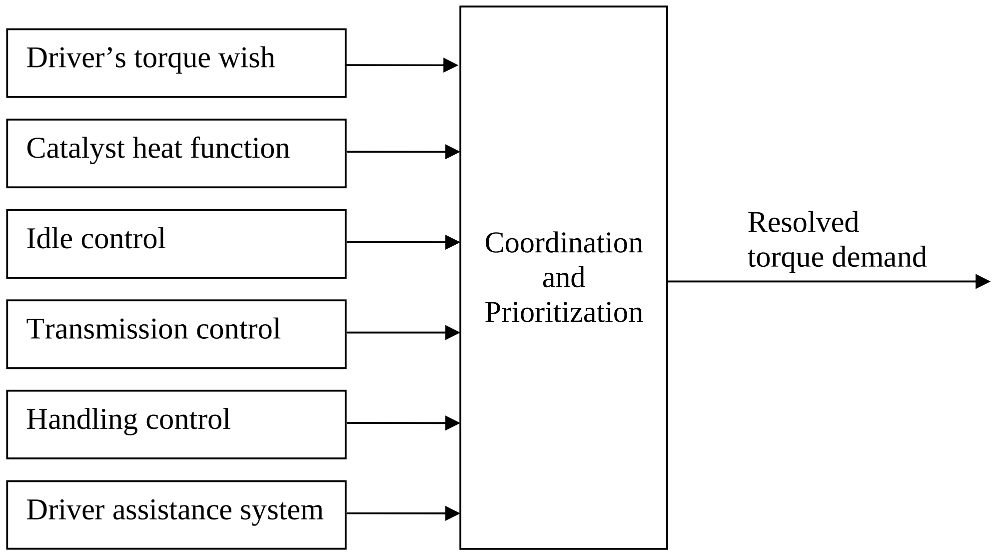
As you will see in the following description of the engine control system, there is a lot going on. There are dozens of control loops to take care of orchestrating the complex sequence of events that bring the right amount of air with the right amount of fuel into the cylinder, where at the right moment a spark ignites the mixture. Another thing that you will notice is that in controlling the air, the spark timing, etc., a base control signal is developed. But then this signal is modified in taking into account other constraints within which the engine operates. So the development of a command signal to an actuator is a two-stage process: 1) development of the base signal and 2) modification from this base to take other things into account.

Current engine control can be characterized as a torque management strategy and is called torque-based control. The driver expresses his or her wish for more torque by pressing on the gas pedal. The system perceives the state of the car, including the load on it. The torque wish can then be met in a variety of ways. This all takes place under the heavy constraint of meeting emissions demands.

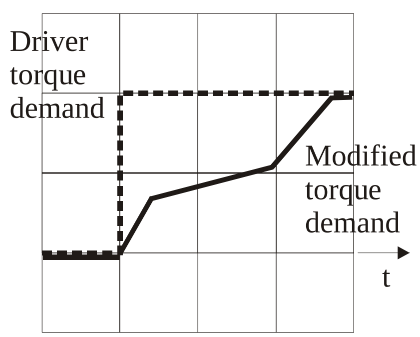
Torque-based control is divided into three different functions:

- The coordination and prioritization of the various torque demands
- The filtering and correction of the demand according to drivability criteria
- The coordination of the torque delivery through various operation methods

<u>Coordination of torque demands</u> – Besides the torque demand expressed by the driver through the gas pedal, other demands impinge on this wish. Part of the torque delivered by the engine is diverted by belt drives to supply power to other devices, like the air-conditioning compressor. Also modern mechatronic cars have handling control systems and driver-assistance systems. The driving condition of the car must also be taken into account by an engine control system. For example if a car is on the verge of shifting into a higher gear (automatically), it is the job of the shift control system to remove torque delivery from the engine while the gearshift is actuated. So the torque demand expressed by the driver cannot be immediately and directly met without taking account of all these other demands and prevailing conditions. The driver's wish for more torque must be coordinated with other demands. All these demands are prioritized and converted into a tuned demand that includes all these considerations. The figure below graphically expresses this situation.



<u>Filtering and correction of torque demand</u> – At this stage the torque demand of the driver has been reconciled with all the other competing demands. The resulting resolved torque demand must now be matched with the actual driving situation. If torque is delivered too suddenly to the drive train, it will actually cause an oscillation in the drive train that can damage it. The torque must be delivered more gradually to avoid this oscillation. The figure below shows a possible scenario for torque demand. The driver presses on the accelerator pedal which represents an immediate step increase in torque demand (dotted line). This demand is modified , so that the torque demand is expressed more gradually (solid line).

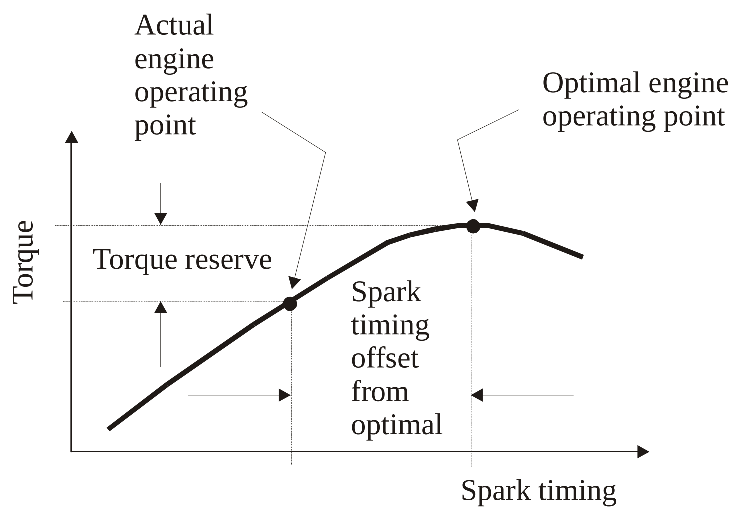


<u>Coordination of torque implementation</u> – This is the third phase of torque control, the delivery of the torque wish onto the actuators that deliver air, fuel, and spark to the engine. These actuators are divided into a so-called "slow path" and a "fast path". The slow path is associated with the air flow. Here there are time constants on the order of 100 ms. The fast path is the fuel injection and the spark. These three must be well coordinated because the timing is short and critical, both for power, reaction time, and emissions control.

In direct-injection engines the gasoline is injected directly into the cylinder. It is possible in such engines to *stratify* the charge. This means that the mixture in the cylinder is not uniform or homogeneous. Rather the mixture is lean and in fact may just be air at the far reaches of the cylinder away from the spark plug. But near the spark plug the mixture is richer and, especially important, ignitable. Thus in a stratified charge engine, the mixture is rich near the spark plug and then leaner and leaner the farther way it is from the spark plug. Thus the spark can ignite the mixture, which then ignites the ever leaner mixture as the flame front propagates through the cylinder. A direct-injection, *stratified charge engine* thus can burn a leaner mixture and save around 15% of the gasoline burned in an engine with only homogeneous charges.

One problem that results from this is that NOX production results from lean burning. NOX is also produced by high-temperature burning. In a stratified charge the mixture at the far reaches of the engine may be only air. Thus the expanding flame front of the lean burn encounters this and is cooled, leading to low NOX production. As we shall see, NOX control is a primary goal of emissions control A primary purpose of the catalytic converter is to remove NOX from the exhaust gas.

Another strategy that can be implemented in a firing strategy for an engine allows overcoming the slowness associated with air flow control. Even though a time constant of 0.01 seconds may seem fast, quick response is very important to the driver, who gets a primary *feel* for the car from its response to a sudden torque demand. There are driving regimes where the likelihood of a sudden increase in demand is high, for instance at idle. Here it is possible to run the engine with non-optimal spark timing. If a sudden torque demand is expressed by the driver, the spark timing can be immediately switched to optimal to get a optimal burn and to get an immediate torque response. In such non-optimal spark timing the difference between non-optimal torque and optimal torque is called *torque reserve*.



Inlet air control – Intake flow and composition in filling the cylinders is primary in determining the resulting torque as well as the accompanying fuel economy and emissions control. Part of this also is *exhaust gas recirculation* (EGR), where part of the exhaust gas (5-15%) is recirculated back into the inlet to become part of the air/fuel cylinder charge. This has various effects, but the primary effect that results from introducing an inert (non-burning) content into the inlet mixture is to reduce the burn temperature in the cylinder. This leads to NOx reduction, because NOx is the result of burning a mixture of oxygen and nitrogen (such as air) at high temperatures.

So EGR is also a part of inlet flow control. Exhaust gasses can be "circulated" internally or externally. Internal recirculation is really not recirculation. The exhaust valve timing is controlled so that part of the just-burned mixture actually remains in the cylinder. So mechatronically the exhaust valve timing controls inert-gas content of the cylinder charge. External EGR involves controlling the flow through a flow path that connects the exhaust manifold with the intake manifold.

Intake valve control is used to control the flow of air into the cylinder. If the valve opening is kept small, this increases the turbulence if the intake charge, which promotes mixing in the cylinder. In a supercharged engine, the intake air pressure can be increased to increase the amount of air that enters the cylinder at a given intake valve opening. In non-supercharged engines it is possible to change the effective length of the inlet manifold. This can be done with controllable baffles in the inlet manifold or with telescoping sections of the inlet manifold. This allows setting up a pressure resonance within the inlet manifold that helps load the cylinder with air. The needed resonance varies with flow so must be controlled depending on the operating level of the engine.

Other settable parameters for the engine that depend on operating level are spark timing, throttle valve angle, exhaust recirculation, and the valve stroke (how far the valve moves). These are set for various operating levels using either an on-line model (equations that model the engine in the engine control micro-controller) or by look-up tables stored in the micro-controller.

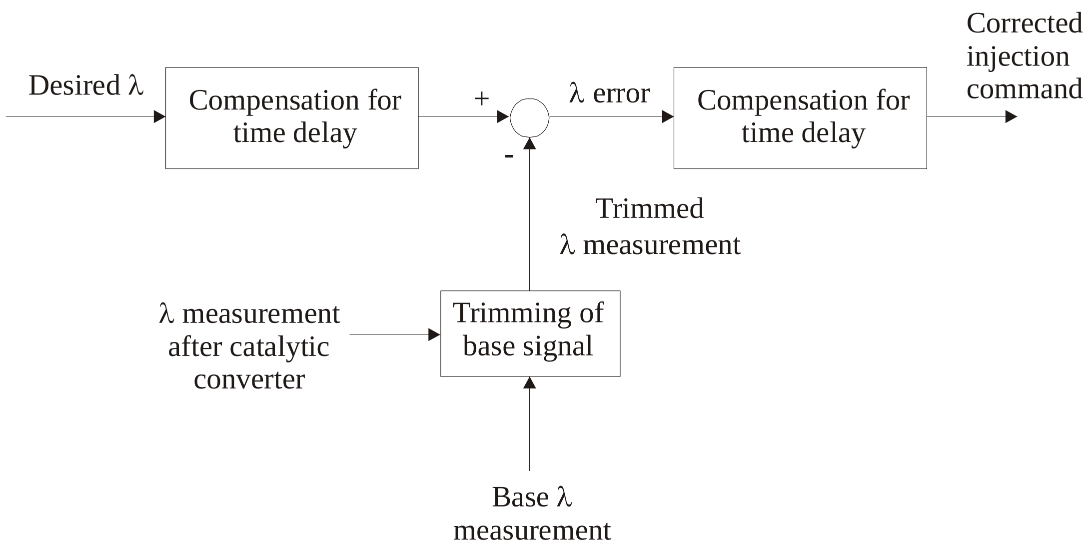
The cylinder air charge is very important in engine control. This changes with operating levels and conditions. Flows are notoriously hard to measure, especially in compressible flows under transient conditions. So a good deal of effort is expended trying to measure or estimate *flow* through mathematical models of the cylinder charge. As the car ages the charge changes too. The inlet suction created by the piston becomes gradually less as the piston rings wear. This can be detected through measurements and the mathematical models in the micro-processor can be adjusted to compensate for this aging. If a car has an exhaust-driven turbocharger, the inlet model also has to include part of the exhaust system to be complete.

<u>Mixture control</u> – The purpose of mixture control is to provide the right amount of fuel at the proper time for burning, at all operation levels and also in transient conditions. This is critical to torque generation and fuel economy as well as to emissions control. Mixture control has three parts:

1. Calculation of correct fuel charge. This is calculated from the air charge and the engine speed. This is a base calculation. The result is then tuned to account for transient effects, like *wall-film-compensation* and transient states like starting or warm-up.

2. Control of fuel/air ratio. This is the so-called λ control, named after the sensor that measures exhaust gas content. The exhaust gas is analyzed to measure the oxygen remaining in it. This is measured by two sensors, one in the exhaust stream just downstream of the engine and one after the catalytic converter. The main measurement comes from the λ sensor immediately downstream of the engine. But because this is a very hot, hostile environment, the sensor is crude. A

second l sensor is placed after the catalytic converter, where the conditions are more benign, so a more accurate sensor can be used. This sensor's reading is used to trim the main λ measurement.

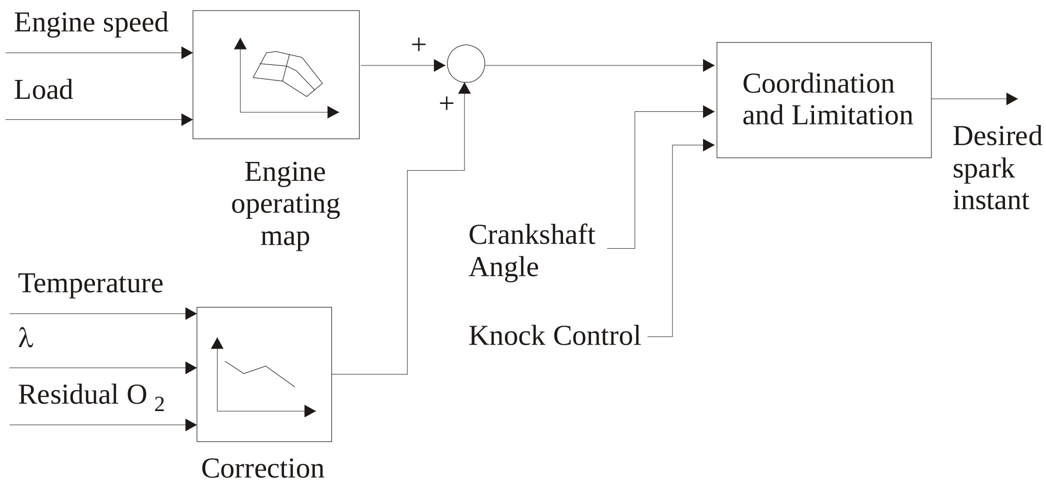


Notice also that this measurement has time delays associated with it. This must be taken into account as shown above by noting that the current λ reading is old and that any resulting change will not take effect until a little time has passed. The result of analyzing the exhaust flow will be an adjustment in the fuel injection command.

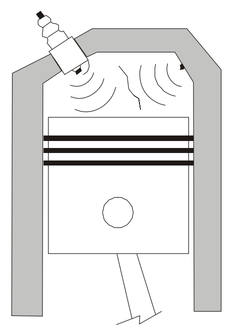
Because of the time delays associated with this sensor, it doesn't work very well in transient operations. So the control scheme associated with exhaust gas measurement can be disabled or simplified for transient operations. With a mechatronic system it is possible to adjust the control scheme for transient operations, something impossible to do with non-mechatronic engine control.

3. Time coordination of the injection. The time that the injection valve remains open can be controlled in an engine with solenoid-operated valves. As previously mentioned in a stratified charge engine, there needs to be an ignitable charge in the vicinity of the spark plug. Also the amount of gas injected into the engine depends on the pressure in the fuel supply system. This has a separate control loop to maintain the pressure at a specified value.

<u>Spark timing control</u> – The figure below shows the two-tiered development of the spark timing decision. Again the strategy of developing a base signal (from the engine RPM and from the load) and then tuning it to take account of other considerations (engine temperature, exhaust gas content, and residual oxygen) is followed. The engine operating map is empirical data developed on an engine test stand to cover all operating conditions and levels of an engine. Once the tuned spark timing wish is developed, this signal is further modified to take account of the crankshaft angle and to avoid knocking (see below). The resulting signal from all this development and then account taking is used as the control signal to the ignition coil.



Knock control – *Knocking* or *pre-ignition* happens when two flame fronts collide in a cylinder. One flame originates at the spark plug. The other often originates at a hot spot in the cylinder, often where a speck of exhaust residue adheres to the cylinder head. Knocking results when the spark is set off too early. It is advantageous to set the spark off early to give the mixture time to burn. This results in better fuel economy. So knocking takes place when this desire for complete burning is overly aggressive. The engine control system wants to make the spark early but not early enough to cause knocking. Knocking and the violence associated with it can be damaging to the engine if it is not controlled.



In a modern engine knocking can be sensed. A piezo-electric sensor supplies the signal. So stresses caused by knocking in the sensor are converted to an electrical signal. This signal is very dirty, because the engine is normally subjected to stresses that cause the sensor to output an electrical signal. What is done is that a *measurement window* is taken around TDC on the power stroke. This noisy signal is then filtered, and then a decision is made on whether knocking is present or not.

In a modern engine control system, each and every firing can be evaluated for the presence of knocking, the electronics are so fast. If knocking is detected, the spark timing is retarded. Actually an over-compensation takes place. Knocking causes elevated temperatures in the cylinder, which make further knocking more likely. So the spark timing is retarded considerably and then slowly advanced thereafter to avoid further knocking.

Balancing output from cylinders – On top of all the control described heretofore, the engine control system also looks at the contribution of each cylinder to the entire engine torque output. Unequal cylinder output causes vibration and also less-than-optimal operation of the engine. Unequal cylinder contributions are detected by a careful measurement of the engine's rotational speed. If all cylinders are contributing equally, what should be seen is a set of equal pulses with two revolutions of the crankshaft. If the speed pulses are unequal, that indicates unequal contributions from each cylinder. The pulses can be tied back to individual cylinders through the corresponding crankshaft angle. Then measures can be taken to equalize the contribution of the deviating cylinder(s).

Exhaust and emissions control – Emissions control is a primary function of the engine control system, now stringently mandated by law. The catalyst in the catalytic converter must also be protected from overtemperature. Secondary air can be introduced into the exhaust system upstream of the catalytic converter for this purpose. It is also necessary to regenerate the catalyst on a regular basis, when it becomes saturated with NOx.

Most emissions occur in the first few seconds after the engine is started. The catalyst is still full and therefore not effective. It is desirable to bring the catalyst to the reaction temperature as quickly as possible. Warmed secondary air can be introduced into the catalyst to speed up its heating.

NOx saturation of the catalyst results from lean burning, which is a by-product of stratified charges. If the catalyst gets NOx-saturated, the firing control can be temporarily switched to homogeneous, richer burning. This allows the catalyst to regenerate itself. The NOx in the catalyst converts to N_2 and CO_2. Once the catalyst has regenerated itself, the engine control can switch back to stratified charging. There is also a procedure to flush the catalyst of sulpher if it become saturated with it. The catalyst is brought to an elevated temperature for a period of time. All of this takes place automatically, under the control of the engine control system and is not perceived by the driver.

Diagnostics – There is an extensive diagnostic system built into such a mechatronic engine control system. The health of the system must be watched, the functioning of the sensors, which feed the mechatronic brain with information, must be secure and certain. This allows also an assessment of the physical condition of the engine and its degradation with age.

Summary

As you can see, the operation of a modern engine is a complicated orchestration of a number of control loops and reconciliation with competing and conflicting demands. The replacement of mechanical linkages, especially the mechanical connection between accelerator pedal and throttle valve, has allowed modes of operation and selective tuning that were impossible in pre-mechatronic cars. Emissions control is a primary consideration, mandated by law. The engine control system plays a decisive role in assuring more efficient and economic operation of a modern engine, while meeting the demands of air pollution control agencies.

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