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Electronic Throttle Control (ETC): A Cost Effective System for Improved Emissions, Fuel Economy, and Driveability

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Electronic Throttle Control (ETC): A Cost Effective System for Improved Emissions, Fuel Economy, and Driveability

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ABSTRACT

This paper shows that the functional integration of Electronic Throttle Control (ETC) into the engine control strategy allows improvements of emissions and fuel economy without making compromises in respect of driveability. A cost effective way for realizing ETC is the integration of the control electronics into the engine control unit (ECU). The paper describes the consequences of such an integration for the ECU hardware and software. Special attention is given to the ETC related safety aspects. Another chapter discusses different technologies for the throttle actuator drive. This is followed by a brief description of a suitable control strategy for a throttle actuator. Finally the paper gives also an overview about current status and development trends of accelerator pedal sensors necessary for ETC.

1. INTRODUCTION

Electronic Throttle Control systems have been in production since 1986. These were add on devices to conventional engine management systems including fuel injection and spark control. Such an add on system comprises an accelerator pedal sensor, a separate electronic control unit, and a throttle valve with integrated electric drive and position sensors. ETC replaces the mechanical link between accelerator pedal and throttle valve and also eliminates the idle speed actuator, because ETC controls the idle speed via the main throttle valve. The major reasons for introducing ETC at that time were traction control, programmable engine response characteristics, and cruise control.

Costs of these add on systems were relatively high due to the separate ECU and due to an actuator design which was not optimized for mass production. Therefore application was limited to high performance vehicles with traction control.

In January 1995 Bosch started the production of a new ETC generation. This generation is the first ETC system having the electronics of ETC and of the conventional engine control functions integrated into the same ECU with one microcontroller. The integrated electronics and a new actuator design which is suited for high production volume result in a sharp decline of system costs.

Within the last few years additional requirements for engine and powertrain control functions have evolved in order to improve emissions, fuel economy, and driveability. These new requirements, combined with the reduction of system costs have expedited the introduction of ETC in a large and steadily growing number of cars.

Until 1998 a large variety of vehicles with engine displacements between 0.6 litres and 6 litres will have ETC. It is expected that in the year 2000 the penetration of ETC in engine management systems sold in western Europe will reach a very high level.

2. ETC FUNCTIONS

2.1 STANDARD FUNCTIONS

2.1.1 PROGRAMMABLE ACCELERATOR PEDAL CHARACTERISTIC - For cars with conventional mechanically driven throttle there is one fixed relation between pedal position and throttle position. For a given engine speed it is possible, even with a mechanically driven throttle valve, to vary the relationship between engine torque and pedal position within certain limits by specifying a mechanical progression between pedal position and effective throttle opening area. But for a given pedal position the relationship between engine speed and engine torque cannot be varied with a mechanically driven throttle. If the driver accelerates with a constant pedal position, the acceleration starts with a high torque. Torque and acceleration decrease with increasing engine speed (fig. 1, upper diagram). The course of this decrease is fixed and may or may not fit the desired acceleration characteristic for the specific vehicle. With ETC however the throttle position depends not only on the pedal position, but also on engine speed and other parameters (fig. 1, lower diagram). With this it is possible to realize any desired acceleration characteristic within the limits of the engine power. For example good acceleration control at low engine speed (e.g. for stop and go driving) can be combined with sportive pedal response at higher engine speed. An additional feature is the selection of different response characteristics by a switch or in future by an adaptive "driver recognition function". A very smooth characteristic, as soon as the reverse gear is engaged, is also a standard function.

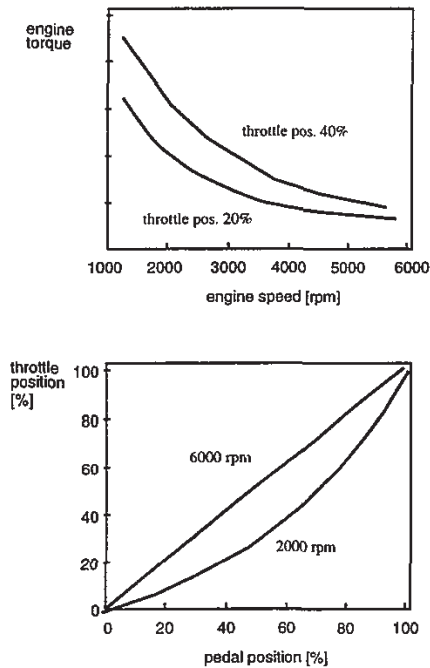


Fig. 1: Upper diagram: engine torque versus engine speed for constant throttle position. Lower diagram: variable throttle opening for different engine speeds.

2.1.2 CRUISE CONTROL - In a conventional system without ETC the throttle position is controlled mechanically by the driver during normal operation. For **cruise control** however, an additional actuator and electronics for the control function and for safety is necessary. In an ETC system the only additional part needed for cruise control is the cruise control lever. The actuator and the electronics, including safety features, are already part of the system. Therefore ETC is especially cost effective if cruise control is a standard function. Depending on the type of actuator, which is used for a conventional cruise control realization, a cruise control function realized by ETC has advantages in respect of better comfort during transitions from normal driving to cruise control mode (set / resume function).

2.1.3 TRACTION CONTROL - The **traction control** ECU sends a torque request to the engine control ECU via a serial data bus or via PWM interfaces. This request is realized by a coordinated control of throttle position and spark advance. By using ETC for traction control, low emission levels are achieved also during traction control activity. Negative influences on catalyst ageing are excluded.

2.2 NEW ETC FUNCTIONS

Recent requirements for further emission reduction and improved fuel economy have produced additional need for ETC.

2.2.1 CATALYST HEATING / CATALYST PROTECTION

One major key measure to comply with LEV or ULEV emission legislation is a **fast catalyst warm up** and the reduction of raw emissions. To provide this, various combinations of single measures have to be combined to different strategies. Fig. 2 shows 6 different proposals of such strategies. All the strategies use improved catalyst technique. A low level of raw emissions is required as well. The concepts 1 to 4 use rich mixture during warm up, electrically heated catalyst (EHC) or burner or HC adsorber in combination with secondary air. Instead of rich warm up, strategy 5 uses a lean mixture during warm up and a HC adsorber. In order to ensure good driveability during lean warm up, a continuous air fuel ratio control is necessary. For engines with a good lean burn performance and vehicle designs which allows a close coupled catalyst, strategy 6 [1][2], which is briefly described in the following, is a very interesting alternative. It comprises of a close coupled catalyst or precatalyst, continuous air fuel ratio control, and electronic throttle control. The advantages of this approach are minimum system costs and minimum weight.

Measures		Strategies					
		1	2	3	4	5	6
• Engine Management System							
Warm-up:	Improved mixture preparation	○	○	○	○	●	●
	Lean λ -closed loop					○	○
	Extremely retarded ignition					○	○
	Electronic throttle control	○	●	○	○	○	●
Mixture Control:							
	Continuous λ -closed loop	○	○	○	○	○	○
• Exhaust Gas Aftertreatment							
Catalyst resp.							
Precatalyst:	Improved technique (Trimetal)	●	●	●	●	●	●
	Close coupled		●	●	●	●	●
	Electrically heated			●			
	Burner heated				●		
HC-adsorber						●	
							●
Sec. Air System:							
	With rich mixture	●	●	●	●	○	○

○ necessary measure
● supporting measure

Fig 2: Different possible strategies for emission reduction.

In order to achieve a fast catalyst warm up the engine efficiency is deteriorated as much as possible by **retarded ignition**. This measure increases the exhaust gas temperature and therefore the heat energy which flows into the catalyst. A positive side effect is, that retarded ignition reduces the raw emissions of NO_x and also slightly those of HC. At the same time, the **idle speed is increased** in order to have a higher exhaust gas mass flow. This also increases the heating power for the catalyst.

As a result of the retarded ignition the engine efficiency is considerably reduced. In a conventional system the driver therefore will notice poor driveability as long as the warm up function is active, because the engine torque at a given pedal position is much lower than it is during normal operation. With **electronic throttle control** the decoupling

between throttle position and pedal position allows compensation for the lack of driveability, so that the engine torque response versus pedal position remains unchanged. An example is shown in Fig. 3. The first diagram displays the engine torque versus pedal position for different operating conditions. The upper solid line shows the situation for warm engine with stoichiometric air fuel ratio and normal spark advance. During catalyst heating the engine torque at a given pedal position is considerably reduced due to late ignition timing and lean mixture (lower solid line). This reduction in engine torque can be compensated by a higher throttle opening during catalyst heating (dashed line). The corresponding throttle positions are displayed in the second diagram. During catalyst heating wide open throttle is reached already at partly depressed accelerator pedal. To achieve further torque increase at higher pedal positions, the ignition timing is adjusted towards normal ignition timing for higher pedal positions (third diagram). Also the air fuel ratio is adjusted towards stoichiometric mixture.

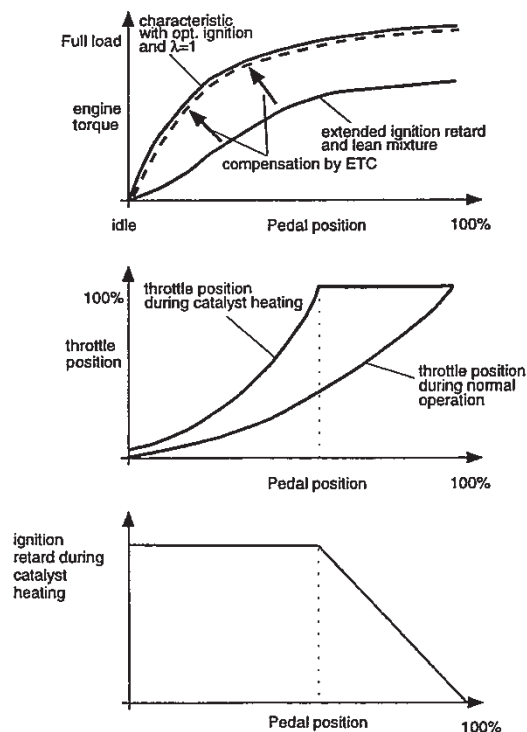


Fig 3: First diagram: engine torque characteristic versus pedal position with and without retarded ignition in the case of a mechanically driven throttle valve (solid lines) and in the case of ETC (dashed line). Second diagram: throttle position versus pedal position in the case of ETC. Third diagram: ignition retard during catalyst heating.

A **close coupled catalyst** is also important for a fast heat up. On the other hand, the close coupling gives additional stress to the catalyst. Therefore **electronic throttle control** is used for **catalyst protection** under special operation conditions. These operation conditions include engine speed limitation, vehicle speed limitation, and traction control where ETC ensures that neither unburned hydrocarbon nor excess oxygen stresses the catalyst.

Depending on engine characteristic, vehicle weight and other circumstances, it may be necessary to apply different strategies for different applications. However, vehicle tests with a 1500 kg vehicle and 2.5 litre production engine have indicated that the proposed strategy can comply with LEV and even ULEV standards (fig. 4).

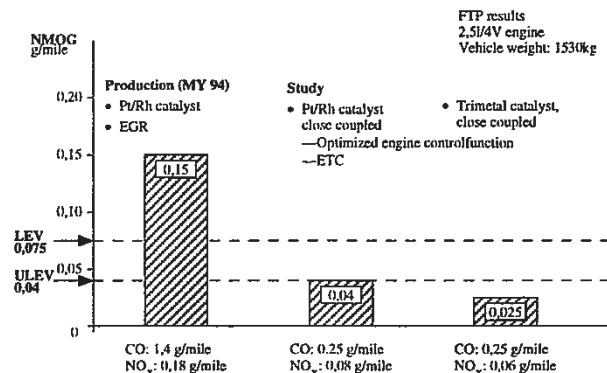


Fig. 4: Emission levels reached with the proposed strategy 6 for a vehicle with 2.5 litre engine

2.2.2 MASTERSHIFT - Gear shifts of an automatic transmission at constant throttle position usually result in a change of tractive force. The amount of change depends on vehicle speed and on the throttle position at which the shift occurs. The amount of change is higher at higher throttle positions and lower engine speeds. If maximum fuel economy is required, gear shifts typically are in this range of high throttle positions and low engine speeds. This means, that these changes in tractive force are especially high in combination with maximum fuel economy shift patterns. This results in a conflict between driveability and acceleration control on one hand and fuel economy on the other hand. ETC contributes to solve this conflict by having a throttle position depending not only on pedal position, but also on the actual gear ratio. Fig. 5 shows an example for a coordination between throttle control and transmission control, also known as **Mastershift** [3][4].

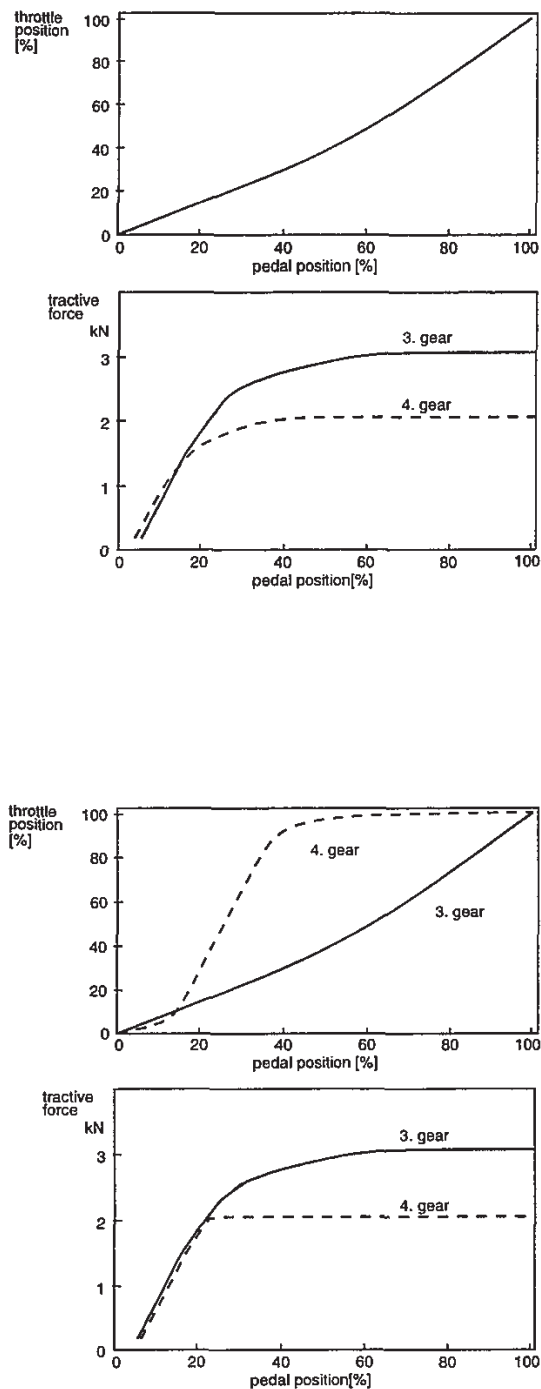


Fig. 5: Throttle position versus pedal position and resulting tractive force versus pedal position at constant vehicle speed. Upper diagrams: conventional system, lower diagrams: compensation of different transmission ratio by selecting a gear dependent throttle position.

The first diagram in fig. 5 shows a conventional characteristic of throttle position versus pedal position. This characteristic results in a certain relation between pedal position and tractive force for a given gear and vehicle speed. The 2nd diagram displays that relation for a vehicle with a 4.2 litre V8 engine. Except for one certain pedal position, gear shifts result in a change of tractive force at constant pedal position. At pedal positions above 18%, tractive force in the 4th gear is always lower than in the 3rd gear. This means, if a tractive force between 1.5 and 2 kN is desired, a higher pedal position is required in the 4th gear than it is in the 3rd gear. If, for fuel economy reasons, the 4th gear is engaged at that operation point, the vehicle response to pedal movements is not as sensitive as it would be in the 3rd gear. ETC solves this conflict between fuel economy and driveability by including the actually engaged gear into the computation of the throttle set position as shown in the 3rd diagram. In this case there are different characteristics for the throttle opening versus pedal position in the 3rd and in the 4th gear. The result can be seen in the 4th diagram. In a wide range of operating conditions the tractive force at a certain pedal position does not depend on the gear any more. The one result is, that pedal response in higher gears is improved, the other result is, that gear shifts in part load do not affect the tractive force any more, which improves ride comfort.

2.2.3 LEAN BURN TORQUE CONTROL - Lean burn engines are usually operated with lean mixture during idle and lower part load, but with stoichiometric mixture at upper part load and full load. The transition between lean and stoichiometric operation should be discontinuous to avoid high NO_x emissions during slightly lean operation. To avoid a discontinuous jump in engine output torque during this transition, the throttle position must be adjusted simultaneously by ETC like shown in fig. 6: In the range of lean operation the throttle opens as a function of the desired engine torque until wide open throttle position is reached. For further torque increase the mixture is changed to stoichiometric. This change is done by reducing the throttle position. Because the engine efficiency is lower at stoichiometric operation, it is necessary to increase simultaneously the amount of fuel injected in order to avoid a jump in engine torque.

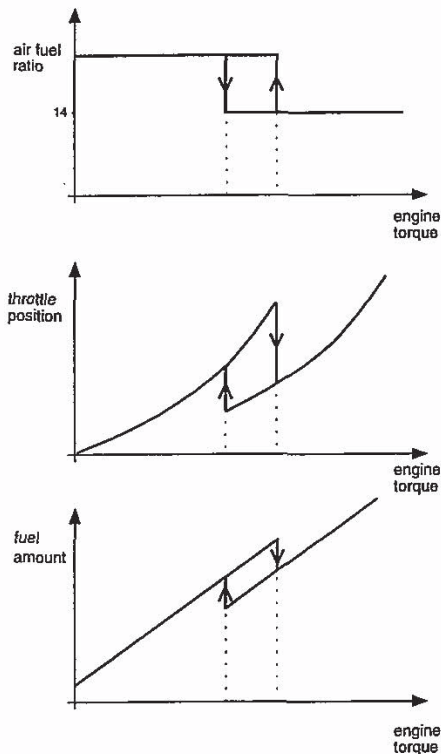


Fig. 6: Air fuel ratio, throttle position and amount of injected fuel as a function of engine torque for a lean burn engine.

2.2.4 CYLINDER BANK SHUT OFF TORQUE CONTROL - A similar function is the compensation of torque impact by **cylinder bank shut off** [5]. During idle and lower part load operation the engine efficiency is poor. One reason for this are high pumping losses. They can be reduced if the valve train is disengaged for half the number of cylinders. Then the remaining active cylinders are operated with higher load and therefore with reduced pumping losses. Fig. 7 shows an example for the relationship between engine torque and throttle position for operation with all cylinders and for operation with half the number of cylinders (one common manifold and throttle valve for all cylinders is assumed). In the lower part load range the mass airflow is only a function of the throttle position and is therefore independent of the number of active cylinders. In this range the engine output power and consequently the engine torque is higher in the case of half the number of cylinders active due to the improved efficiency. At higher load however the mass airflow depends not only on the throttle position, but also on the intake manifold pressure. In the case of not all cylinders being active the manifold pressure is higher because of reduced pumping of the engine. Higher manifold pressure at constant throttle position results in reduced mass airflow. The reduction of the mass airflow dominates the effect of increased engine

efficiency in this operating range and therefore engine power and engine torque are lower compared to the case of all cylinders being active. With electronic throttle control this effect can be compensated by having different throttle positions for the case of normal operation or shut-off operation.

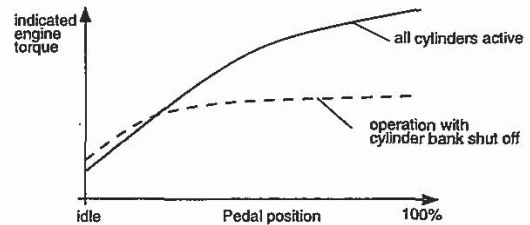


Fig. 7: Engine torque versus throttle position for normal engine operation and engine operation with half the number of active cylinders.

2.2.5 ANTI JERKING FUNCTION - A transition between coasting and part load or full load and vice versa can cause jerking of the vehicle because of the backlash in the powertrain. This is shown in fig. 8 for a vehicle with manual transmission. The vehicle is coasting and the engine speed decreases from about 2500 rpm down to 1200 rpm. When 1200 rpm are reached the driver suddenly presses down the accelerator pedal. In the upper diagram the throttle blade opens simultaneously to the pedal position. A strong jerking can be seen on the engine speed signal after this. With ETC throttle position and pedal position are decoupled by an **anti jerking function**. The lower part of fig. 8 shows that the throttle valve begins to open with a limited opening speed until the transition from negative to positive torque is completed. After that the throttle opening speed is increased. There are almost no oscillations in the engine speed signal any more, which indicates that there is almost no jerking. This function is especially important for manual transmissions where there is no torque converter which acts as a damper.

In the future the anti jerking function is likely to become more and more interesting, also for cars with automatic transmission, because for fuel economy reasons the lock up zones of the torque converter clutch are extended to operating points which are more critical in respect of jerking. When the torque converter is locked up, there is no damping by the converter any more.

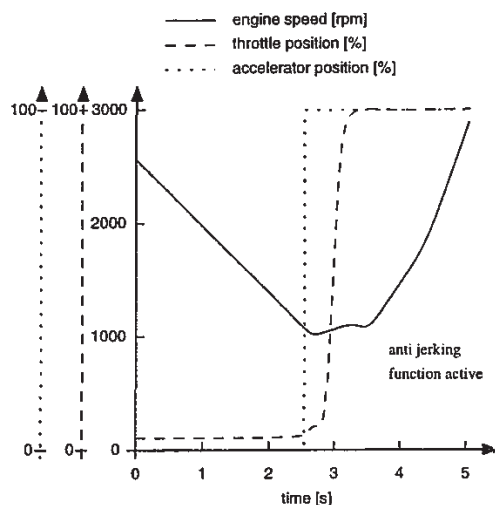
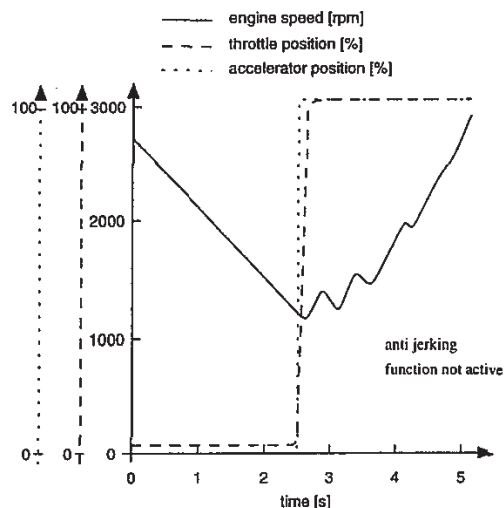


Fig. 8: Transition between coasting and full load without and with anti jerking function active.

3. INTEGRATED ECU

3.1 HARDWARE ASPECTS - In the integrated ECU all engine control functions are coordinated by one single microcontroller. This is one key for an optimal coordination of all engine management functions. For an integration of ETC electronics into an engine control ECU following supplements are necessary compared to a system without ETC: For the accelerator pedal sensor 2 **analog inputs** and a **sensor voltage supply** are required. The actuator drive needs an **H-bridge power stage**. H-bridge power stages are already used in many ECUs for controlling a bypass idle speed actuator, but these bridges are usually designed for lower current. For safety reasons an additional **safety module** must be integrated into the ECU (see chapter 3.3). For improved diagnoses and limp home performance in case of throttle position sensor failure it is helpful to have

an additional **analog input** for a second throttle position sensor.

3.2 SOFTWARE ASPECTS - Additional software modules compared to a conventional system are the **detection of pedal position**, including plausibility checks between the redundant sensor elements, a digital **closed loop position control** for the actuator drive, and a **coordination block**, which coordinates the requests of idle speed control, traction control, cruise control, and the driver. Furthermore there are some **diagnostic and safety functions**, which are described in chapter 3.3.

With above mentioned software extensions it is possible to introduce ETC into an existing ECU. If, however, full advantage shall be taken from ETC, a software structure based on an **engine torque model** is suitable. In such a structure the application effort for all the new ETC functions mentioned in chapter 2 is considerably reduced compared to a conventional structure without torque model. Engine torque requests from all functions are realized by a coordinated response of throttle position, spark advance control and fuel injection. Such a coordinated control allows an optimization of both emissions and dynamic response in comparison to a control strategy, where torque requests are realized either only by throttle position or by fuel injection and ignition.

3.3 SAFETY CONCEPT - In an ETC system there are several components of which a failure could result in uncommanded acceleration, if no failure detection mechanisms are implemented. Therefore a consistent safety concept is absolutely necessary. For failure detection there is redundancy in safety relevant input signals. This redundancy can either be realized by using two sensor elements instead of one (e.g. accelerator pedal sensor or throttle position sensor), or it can be realized in some cases by plausibility checks between different existing signals. For example the **throttle position sensor** can be cross-checked with a signal from a mass airflow meter or an intake manifold pressure sensor and engine speed. Failures can occur not only in peripheral elements, also the microcontroller itself could be affected by failures. Therefore an additional external safety module, which checks the correct function of the microcontroller is necessary. For this check two solutions are possible. The first solution is the **"direct method"**, which comprises of a direct permanent check of the relevant microcontroller modules (e.g. arithmetic logic unit, bus,...). The safety module randomly generates input data which are transmitted to the microcontroller. Every safety relevant program module in the microcontroller must modify these input data in several different computation steps. At the end of every program cycle, the final result is transmitted back to the safety module. For every input data there is only one correct solution. The safety module checks the received solution in respect of correctness and timing. In the **"indirect method"** safety relevant input signals, e.g. pedal sensor, throttle position sensor and others are connected directly to the safety module. With these informations the safety module performs a plausibility check between driver's request and a model based computed engine torque. This method is called **"indirect"** because failures are detected by their effects on engine parameters.

4. THROTTLE ACTUATOR

4.1 ACTUATOR HARDWARE - Compared to preceding generations today's throttle actuators are designed for a cost effective mass production with a low number of assembly steps. The number of parts has been reduced considerably.

A question which has been discussed very often is the question about the best drive concept. In addition to the well established DC motor drive with gearing, stepper motors and direct drive rotary actuators can be considered as a possible alternative. The answer to this question is closely related to the question, how much torque is necessary for a proper function of the actuator. For a proper operation, the drive must first compensate for the return spring and for the friction. Additionally to this the airflow generates an aerodynamic torque in closing direction. The amount of this torque, which has its maximum value at throttle positions of about 45 degrees, depends on throttle diameter and engine power. In some applications, maximum dynamic peak values of about 0.4 Nm have been observed. Beyond this, it is necessary to have an excess torque for acceleration and deceleration of the throttle blade for reasonable dynamic response and for complying with ambient conditions like icing or oil and dust deposits at the throttle blade. The amount of excess torque necessary depends on the concrete application. If a high excess torque is required, a DC drive with gearing has important advantages, because this solution gives the best torque to weight ratio and the best torque to current ratio. Beside this, the DC drive is a very cost effective solution. Potential problems with the brushes and the gearing can be avoided by carefully selecting the materials for the typical ETC operating conditions. Long field experience with ETC actuators based on DC drive supports this drive concept. Fig. 9 shows an example of an ETC actuator with DC drive and 2 step gearing.

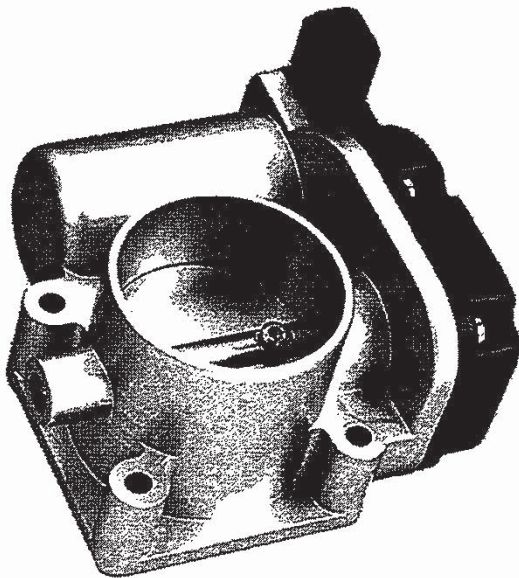


Fig. 9: Example for a throttle actuator with DC-drive and 2-step gearing. This family offers bores from 30mm up to 86mm.

4.2 POSITION CONTROL OF THE ACTUATOR -

Among several alternatives a digital nonlinear PID controller is a suitable control strategy for an ETC actuator with DC drive. The nonlinearity is necessary in order to optimize both response time during transient operation and stability during stationary operation. The coefficients for the P-, I-, and D-parts are functions of the difference between target throttle position and actual position. Input for the P- and I-part is the difference between target position and actual position, while the D-part is only a function of the actual position gradient.

5. ACCELERATOR PEDAL SENSOR

Instead of a Bowden cable, in an ETC system the accelerator pedal is connected to the accelerator pedal sensor. For safety reasons there is redundancy in the sensor elements and in the return springs.

According to different mounting conditions different basic types of sensors are used. There are solutions which contain only the sensor element itself. These solutions can be mounted to existing accelerator pedal mechanics. Another solution is a pedal sensor with integrated return springs and friction element. The friction element gives a defined hysteresis in the pedal operating force. This type of sensor is widely used in today's applications for ETC and for electronic diesel control. Another development step are integrated accelerator pedal modules, where the customer specific accelerator pedal, return springs, friction element, and the sensor elements form one pre-calibrated unit. A calibration between accelerator pedal and sensor element during the car manufacturing process is no longer necessary. Fig. 10 shows an example of such an accelerator pedal module.

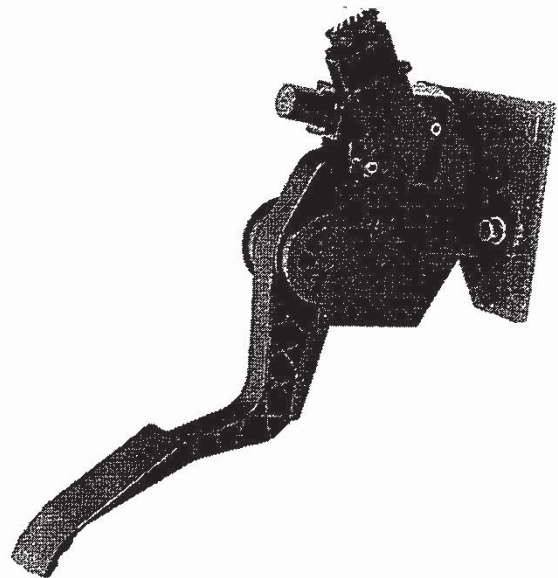


Fig. 10: Example of an integrated accelerator pedal module.

6. CONCLUSIONS

Electronic Throttle Control is a system which is expected to have a very high market penetration in the near future for several reasons.

Increased demand for improved ride comfort is supported by functions like cruise control, anti jerking functions, software definable accelerator pedal characteristic and improved shift comfort by Mastershift.

ETC, in combination with other measures, is one possibility to comply with future emission standards without reducing driveability.

Improvements of fuel economy can be achieved for example by lean burn engine technology, cylinder bank shut off, and by optimizing the shift pattern of an automatic transmission. ETC compensates the driveability impact of these measures.

The development of integrated ECUs for the whole engine management including ETC and a new actuator designs resulted in a sharp decline of ETC system costs. With this very cost effective system are available for satisfying the above mentioned demands.

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