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MOTRONIC – Torque Guided Engine Management Systems to Meet Future Challenges in Emissions and Fuel Consumption Reduction

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1 Abstract

Due to the social and legal requirements on the engine and the entire vehicle the functional scope of modern Engine Management Systems (EMS) has dramatically grown. As driving forces of this ongoing process the reduction of fuel consumption and emissions have to be considered - in the past as well as in the future. But also increasing comfort and diagnosis demands lead to a further increasing complexity of today's and future EMS. In order to securely control this complexity a well structured functional architecture in combination with physically based functions forms the necessary basis.

With the launch of the MOTRONIC ME7 Bosch introduced a torque based functional architecture to meet these requirements. This includes not only the mentioned optimization of engine performance and compliance with legal standards on emission, fuel consumption and diagnosis. As additional key factor the re-usability of components and control strategies allows the adaptation to strongly differing demands in various markets, but also e.g. to alternative engine concepts, such as Gasoline Direct Injection or Variable Valve Lift systems. Eventually even the integration of the engine control as a subsystem into the functional architecture of a vehicle control concept is possible.

Based on a brief description of the torque based architecture – as the system's "backbone" – this paper describes the MOTRONIC M7, an Engine Management System to meet the demands of the Indian market. Coming from the M7 system this discourse also includes suitable solutions for essential future tasks regarding exhaust emission standards and fuel consumption reduction in the USA, Europe and Japan, based on Port Fuel Injection or Gasoline Direct Injection. It also gives a short overview concerning alternative

approaches for the control of the powertrain or entire vehicle based on the Bosch CARTRONIC, an ordering concept which integrates the engine control into a vehicle control system.

2 Introduction

Electronic engine management systems have emerged as indispensable tools for meeting legal requirements, such as emissions and fuel consumption, as well as improving driveability of spark ignition engines (start, warm-up behavior, transient response etc.).

The output torque of a S.I. engine is primarily influenced by the amount of fuel injected. However, in case of a common S.I. engine the output torque is controlled by the throttle (at a given A/F-ratio the cylinder charge with fresh air represents the engine load which means, that the engine load can be varied by variation of the mass airflow). In addition the engine torque is influenced by the ignition timing and of course also by additional engine features such as EGR, cam control, variable manifold geometry or boost pressure control for turbocharged engines.

3 A Torque Guided System Structure

3.1 Motivation for introducing the system architecture

The task of an engine management system for a S.I. engine exceeds by far just injection and ignition control. Regarding additional functionality two categories can be distinguished:

1. Engine control functions such as start control, idle speed control, limitation of the maximum engine speed, catalyst heat-up by the engine (by means of increased exhaust temperature due to artificially deteriorated engine efficiency), boost pressure control for turbocharged engines, as well as the protection of peripheral components (exhaust manifold, catalyst,.) from overheating, etc.

2. The interaction with superimposed drive train and vehicle dynamic func tions such as driving comfort func tions for damping load changes or surging, cruise control, limitation of

the maximum vehicle speed, the optimization of gear shifting in case of transmission control, vehicle dynamics control (i.e. prevention of undesired yaw acceleration to the vertical axis of the vehicle), traction control, etc.

3.2 Previous situation

In previous engine management systems the described (sub-)systems directly influenced the torque-relevant control variable of the engine control system **(figure 1):**

- the cylinder charge by directly influencing the throttle angle
- the amount of injected fuel by directly influencing the calculated injection time and/or the request of fuel cut-off
- the engine efficiency by direct adjustment of ignition timing
- the desired boost pressure controlling the boost pressure actuator (waste-gate) in turbo-charged engines.

By directly influencing the basic and additional torque influencing parameters the complexity of the complete system drastically increases. Since many of these interactions occur simultaneously, it's difficult to predict the effects on the overall system. If torque-relevant control values are directly requested from one of the systems or subsystems shown in fig.1, the various interactions influence each other. This requires a complex and iterative data calibration of the EMS-subsystems or even the entire systems regarding the various ECU's installed in a vehicle.

These uncoordinated interactions of different internal and external (sub-) systems incorporate significant disadvantages:

Since above mentioned interactions frequently occur simultaneously, a prioritization is required. However, since they take place in the various functions and (sub-)systems, the effects on the complete system cannot be clearly overseen. This especially applies if parameters in single stand-alone systems are modified, or if a new feature such as variable valve train or Gasoline Direct Injection requires the modification of additional (sub-)systems.

If torque-influencing control values are directly given by means of above mentioned functions or (sub-)systems, it adversely affects the data calibration of the various ECU's installed in the vehicle. This is caused by the interaction of the various operations due to the respective shift of the operating point, as well as the necessity to adapt engine-specific parameters (throttle angle or variation of the ignition timing) in non engine-specific systems such as traction control or vehicle dynamics control. There are also strong interdependencies of the parameters to be calibrated within the (sub-)systems. The selection of the ignition angle during catalyst heating, for instance, influences the respective cylinder charge and, therefore, the pilot control of the idle speed control system.

3.3 Torque guided system architecture

With the introduction of the worldwide first torque guided engine management system in fall 1997, the MOTRONIC ME 7, the engine torque has been introduced as a central intermediate value to solve this situation ***/lit 1, lit 2/***. Based on this physical value, all demands can be coordinated before the optimal conversion to the respective engine control values takes place (criteria such as emissions, fuel economy and protection of components are considered). This means, that interfaces within single functions as well as between (sub-) systems are defined as torque or efficiency, enabling a transparent and simplified system architecture **(figure 2)**:

In an initial step, all torque demands are coordinated in a central module and reduced to a resulting torque demand, considering the actual required engine efficiency. Besides driver's demand, the torque demands of both the (sub-) systems of the engine control system and superimposed vehicle control functions are considered.

As a second step, the resulting torque demand is converted into the available torque-influencing control values, which are the throttle angle (in case of a drive-by-wire system with an Electronic Throttle Control ETC), the injection time, the „pattern“ of the injection deactivation (for torque reduction, the fuel is not injected into all cylinders), the ignition timing, as well as waste-gate control for turbo-charged engines. In addition to this, emissions and fuel consumption are minimized as well.

This torque guided system architecture offers significant advantages:

- **Improved accuracy when converting the demanded torque**

Based on a torque model the most important torque-influencing values are considered, such as cylinder charge, engine speed, ignition timing, mixture and torque losses. When executing the torque requests the current values of these torque influencing parameters is taken into account. So the demanded torque can be generated more precisely.

- **Simplified application of all control modules installed in the vehicle**

The basic mapping of 'engine-specific' parameters is exclusively carried out in the engine control system. Therefore, in case of engine modifications, only the engine management system is affected.

This means there is no direct adjustment of the ignition angle required (which would lead to different torque reductions, depending on the chosen base ignition angle), if, for instance, utilizing an electronic transmission control system improving of driveability while gear shifting is requested. The transmission control rather directly demands for the reduction of the torque which is then processed by the engine control system.

- **Simplified application within subsystems**

Since, with previous systems, e.g. the 'engine catalyst heating' function directly influenced the ignition timing and airflow or throttle angle, the pilot control of the idle speed control system (with the appropriate airflow or throttle angle) had to be determined and then adapted during recalibration, after a modification of the ignition timing. With the new process torque demands are directly calibrated, which simultaneously affect both control paths.

- **Simple modifications or additions to the complete system**

The prioritization of additional subsystems can be handled by the coordination block (e.g., limitation of the engine performance for specific markets). It is also possible to extend the conversion block in **figure 2** by additional output signals (such as variable valve lift), as well as to consider additional operating conditions for coordination of the various control signals (e.g., torque control during the transition between homogeneous and stratified operation by Gasoline Direct Injection).

3.4 Adaptation to systems w/o Electronic Throttle Control (ETC)

To use the advantages of a torque guided system structure also in an engine management system w/o an ETC the introduced system architecture has also been adapted to a system with an Idle Speed Actuator (ISA). Besides targeting the mentioned advantages this common system structure allows to generate an EMS family with common features. So similar functions and analog calibration strategies can be found in a simple basic system as well as in a top level system, e.g. a control of a powertrain including a Gasoline Direct Injection engine and a Continuously Variable Transmission.

A system with an ISA is characterized as follows:

- The cylinder charge with fresh air is mainly controlled directly by the driver, the EMS can only control this charge within a small operation range defined by the maximum air mass flow through the ISA.
- The EMS has no direct information on the current value of the engine output torque requested by the driver.

Adapting a torque based architecture to an EMS with an Idle Speed Actuator means, that the EMS can only modify the output torque generated on driver's request within the operating range of the ISA. It therefore

- determines an internal torque value which increases or decreases the driver's torque request considering all other torque demands (e.g. from the idle speed controller).
- It therefore calculates the current torque value requested by the driver out of the current engine output torque taking into account present friction losses, and, of course, the current output value of the above mentioned torque controller. When computing the engine output torque (representing the system's "backbone") a torque model is used. Considering, that all torque influencing parameters are well known in the system (either as measured values or calculated based upon additional models) for modeling the engine output torque, exactly the same algorithms as in the drive-by-wire system can be used (for detailed description of these algorithms see ***/lit1/*** or **/lit 2/**).

This results in an EMS structure **(figure 3)** which is very similar to the structure described in chapter 1.3. As an additional input variable the central torque demand coordinator receives the current value of the drivers request, generated in a block with the current engine speed and cylinder charge with fresh air as main input variables. Based on this "driver's torque request" and considering the other torque demands (from EMS internal subsystems or external systems) the needed torque variation can be calculated and is then transmitted to the torque conversion block. Using the mentioned torque model this block calculates the control parameters ISA duty cycle, injection time, cylinder individual fuel cut-off and ignition angle.

That means that in the entire EMS family the same or very similar models and control functions are used; this results in the same or very similar calibration strategies within the EMS family. Similar functionality and same calibration methods are used in a simple basic system as well as in a complex high-end system and are prerequisites for the use of an EMS family in a wide range of applications.

4 Family of Engine Management Systems

4.1 The M-Motronic

System Overview

Figure 4 shows a Motronic system overview with the main sensors and actuators - here shown as the generation 7 (M7-) system. The M7 represents our newest base system. It is ready to meet the future requirements on engine control and diagnostics for smaller engines and EU IV or ULEV I applications. It does not include ETC, the idle speed is controlled through an ISA.

Based on the set of sensors and actuators and the performance of the 16-bit electronic control unit, the M-System integrates all functions to control a modern S.I.-engine. Due to the system's modularity very different system configurations can be realized. For example, systems with different sensors for cylinder charge determination (air mass or speed density), engines with or without EGR, and engines with variable intake geometry are possible. The main system features are as follows:

- The engine torque management which controls all torque influencing actuators besides the driver.
- An A/F ratio control with a central A/F manager, including the A/F pilot control, the closed loop control to be realized with an oxygen sensor upstream the catalyst and a trim control, based on an oxygen sensor downstream the catalyst.
- Sequential, cylinder-individual fuel injection.

- Ignition timing, including control of dwell angle and ignition angle.
- Cylinder-individual knock control.
- Idle speed control with an Idle Speed Actuator.
- Emission control functions for optimized emissions during cranking, start and afterstart which enable the realization of different catalyst warm-up strategies, using a lean or a rich mixture including exhaust gas recirculation (EGR) and secondary air injection (SAI) control, if necessary .
- Canister purge control based on canister charge.
- Diagnostic and monitoring functions: The system integrates the complete OBD II and EOBD functionality to meet diagnostic requirements in the U.S. and in Europe.
- A monitoring systems supervises the idle speed controller under all operating conditions and reacts with an appropriate limp-home functionality in case of a failure.
- To communicate with external systems, such as a transmission control system or a vehicle dynamic control system, torque demands can be received via a torque interface, realized through the CAN bus system. Therefore the EMS is able to process external torque demands within the torque manager.
- Resonance flap actuation.
- The system contains the necessary interfaces to application tools, end of line programming tools, service and SCAN-tools.
- Immobilizer interface.
- Additional customer defined functions as required.

4.2 The ME-Motronic

System Overview

Figure 5 shows an ME system overview with it's main sensors and actuators. In addition to the components of the M-Motronic, the ME-Motronic system comprises of the ETC related elements, which include the accelerator pedal module to interpret the driver's request, the throttle actuator for cylinder charge control, which also makes the Idle Speed Actuator obsolete, and the cruise control lever. So this system offers all opportunities of a drive-by-wire-system.

ADVANTAGES OF AN ETC-SYSTEM

Decoupling the driver's request from the throttle actuation leads to distinctive system improvements ***/lit 3/:***

- **Improved driveability,** caused by a programmable accelerator pedal characteristic and additional functionality to manage strong engine load variations (e.g. heavy tip-in, sudden deceleration).

- **Integrated cruise control**
- **Compensation of torque losses**, e.g. during catalyst heating: A rapid catalyst heating by means of engine related measures requires a strong ignition retard in combination with an increased air mass flow in post start and early warm-up operation. Without a drive-by-wire system this leads to a deviation in the engine's response when the driver expects a certain engine output torque at a given accelerator pedal position. Decoupling the throttle position from the pedal position allows to compensate for this deviation **(figure 6)** and ***/lit 3/***. Thus the system with ETC can adapt to the same "pedal feeling" for the driver.
- Last but not least: ETC is a distinctive prerequisite for an integrated powertrain management /lit3/ or a Gasoline Direct Injection (see next chapter) or a vehicle dynamic control system.

4.3 The MED-Motronic

In a system with Gasoline Direct Injection (GDI) the fuel is no longer injected into the intake manifold but directly into the combustion chamber **(figure 7)**. This enables the generation of an inhomogeneous mixture and thus a realization of a very lean mixture (up to $\lambda=4$). Generating an inhomogeneous but ignitable mixture requires a more or less stoichiometric mixture in the area of the spark plug. To realize this an excellent fuel spray with small droplet size and an appropriate spray geometry is requested. That means spray geometry and mixture transport (realized by means of mixture motion inside the combustion chamber and piston geometry) are the key elements for a robust combustion. A sufficient droplet size requires an increased fuel pressure (up to 12 MPa) and therefore a fuel supply system which differs from the conventional Port Fuel Injection system.

System Overview

Based on the ME-Motronic with an integrated Electronic Throttle control **figure 8** shows the next step within the BOSCH EMS family. The MED-Motronic integrates a high-pressure fuel system **(figure 9)** consisting of

- a high-pressure fuel pump (in addition to the low pressure pump),
- the high pressure fuel rail,
- the high pressure injectors,

- the pressure control system (pressure sensor + pressure control actuator), and
- the ECU with the integrated power stage for the injectors

To control the exhaust aftertreatment system for lean mixture the system (figure 8) utilizes

- a wide band oxygen sensor upstream the pre-catalyst (→ determination of λ for closed loop control and system monitoring)
- an exhaust temperature sensor (→ needed for NOx-emission controlling and diagnosis of pre-catalyst)
- and a conventional oxygen sensor downstream the NOx trap and main catalyst-(→ control of NOx-trap and pilot control).

Advantages of a GDI System

The major advantage of a GDI system is it's potential for fuel consumption reduction. Worldwide, there are ongoing debates concerning the reduction of CO_2 emissions - in Europe currently focusing on a target value of 140 g CO_2/km for the total vehicle fleet in the year 2008. That means a reduction by 25% based on the fleet emission of 1995.

Regarding the purely engine related fuel economy measures all currently discussed concepts aim to reduce or to even eliminate the fundamental disadvantage of throttle losses of the S. I. engine at part-load. This applies to the Gasoline Direct Injection ***/lit 4/ and /lit 5/***, the variable valve train ***/lit 6/***, and to the so-called down-sizing concepts ***/lit 7/*** as well. Also combinations of these concepts are in discussion.

As most promising single measure the Gasoline Direct Injection represents a particular chance. In consequence, Bosch is developing the components and the control strategies for a direct injection system, utilizing the torque based architecture described in the previous chapters. Thus, the customer enjoys the advantage of approved structures and functions as well as the benefits of a complete out-of-one-hand system.

Many publications on the fuel economy potential of Gasoline Direct Injection were presented in the last years. The results at Bosch demonstrate, that based on stratified charge at part-load, the fuel consumption can be reduced by 15 % in the New European driving cycle. ***/lit5/***

Stratified charge means operating the engine with excess-air. By optimizing the air flow in the combustion chamber in combination with the directly injected fuel an ignitable mixture is generated and brought directly in the area of the spark plug. The first vehicle equipped with a Bosch GDI system will go into production during the next year.

System Structure

Referring to **figure 3** and the ME-Motronic the fresh air charge is defined as main variable to affect the output torque of a S. I. engine with port injection. In consequence the throttle angle is the main correcting-variable since we have a fixed coupling between fresh air charge and related fuel quantity (stoichiometric system).

For the direct injected engine, however, the fuel quantity (correcting-variable: injection time) represents the main path affecting the torque. Thanks to the torque guided structure this can easily be realized **(figure 10).** It is sufficient to merely adapt the torque conversion to the direct injected engine. Besides the obviously modified priorities of the possible correcting-paths the related torque model has to be adapted to the direct injected engine as well. The modified torque model considers additional parameters, such as the position of an intake swirl flap or the injection timing.

5 MOTRONIC as a Subsystem

As already discussed the BOSCH MOTRONIC family has a modular structure and entails in addition the following prerequisites facilitating individual extensions:

- Torque based functional structure
- Central coordination of torque and A/F-demands
- Physically based functions
- Encapsulation of components and controller hardware

The engine control functions are based on a natural physical description. Physical values – especially at the interfaces of the individual functional modules – enable the adaptation of the whole system to the different strategies of emission and fuel consumption reduction.

The encapsulation of components and microcontrollers is quite important since it allows an easy adaptation of the program to different components and the reusability of the complete control function related software for different microcontrollers. Thus the individual component and the related software driver inseparably grow close. Whenever a component is substituted by another one the accompanying software driver will be replaced as well. In consequence, the interface towards the system belongs to the software driver.

In order to further improve fuel consumption, comfort and safety, EMS like the MOTRONIC will increasingly be networked with other systems for coordinated powertrain or vehicle propulsion control. The resulting system network communicating through a car-wide web will even further stress the question how to manage functions and programs and how to keep them accurate.

Adaptive Cruise Control is an example for such system networks. Based on the evaluation of additional radar sensors this system accelerates or brakes the vehicle in order to maintain a safety distance to the preceding car. The network functions are featured by utilizing complete subsystems like the MOTRONIC as actuators and information providers, thus indirectly leading to a multiple use of sensors and actuators.

In order to safely control this growing complexity of technology in the future a functional architecture forms the necessary basis. Functional architecture means fundamental conventions, how the system is divided into subsystems, how these subsystems interact and which axioms these modular structures are subjected to. Only if such functional architecture is agreed upon, individual functions can be re-used on a modular basis and alternative solutions exchanged for identical job steps.

Stepping from the MOTRONIC as a pure engine management system to a car wide web the following needs occur:

- Regarding the integration into a future vehicle control system an ordering concept to systematically build-up the vehicle control network is required. Under the name of CARTRONIC this ordering concept has been developed and presented on different conferences by Bosch */lit 8/ and /lit9/*.. **(figure 11).**
- The EMS itself has to separate all functions which are defined to be part of other blocks in this ordering concept (e.g. the interpretation of driver's request being part of the block "vehicle and brakes"). In addition, one single common interface

between the engine control and the superimposed powertrain management has to be found. A common interface valid for S.I. engine as well as for diesel or hybrid engines has to be developed **(figure 12).**

A first step towards such a concept is the coordinated powertrain control **(figure 13),** including engine, clutch or torque converter and transmission. The characteristic of the powertrain control can be adapted to the driver, the driving situation and the running conditions in order to achieve the best possible vehicle operation, regarding fuel consumption, driving safety and comfort as well as exhaust emission. The architecture of the coordinated powertrain control is then designed for modular implementation of the control functions. Hence it is suitable for different configurations, comprising powertrain concepts with S. I. or Diesel engine, continuous (CVT) and multistage transmission (automatic or automated shift). Likewise, the related application data are physically based in order to support a fast and flexible adaptation of the different configurations.

In this context vehicle subsystems like the MOTRONIC must not only be oriented towards the related unit (engine), in the same way they must be able to be integrated into a superior vehicle control system. The CARTRONIC constitutes a possible concept for those systems, in consequence the related MOTRONIC interface has been designed accordingly.

6 Conclusion

A family of BOSCH Engine Management or MOTRONIC systems is presented **(figure 14).** The Bosch M7- and ME7-MOTRONIC with their unique and advanced torque guided functional architecture offer an appropriate answer to meet today's and upcoming challenges on emission and fuel consumption reduction. Modular structure, the use of very similar physically based functions over the total range of the family and last but not least a common calibration concept offer a quick response to an ongoing change in legal and market requirements, especially considering also the needs of a compact EMS for smaller engines.

The decisive technical advantages of a torque guided system are: improved comprehensibility of the total complexity, combined with decoupling of the data to be calibrated, extension for new system configurations (e.g. Gasoline Direct Injection), as well as a high degree of interchangeability and reusable software (e.g. as base for software sharing).

In the same way the BOSCH EMS family allows to reliably manage and control the growing complexity of engine control also in the future. At BOSCH, similar structures will be also used for Diesel control systems (which are naturally torque guided). The CARTRONIC®-conform design of a drive train control system can be introduced to a high degree independently of the engine concept. Therefore, this concept offers a solid base for the installation of additional intelligent control systems in future vehicles.

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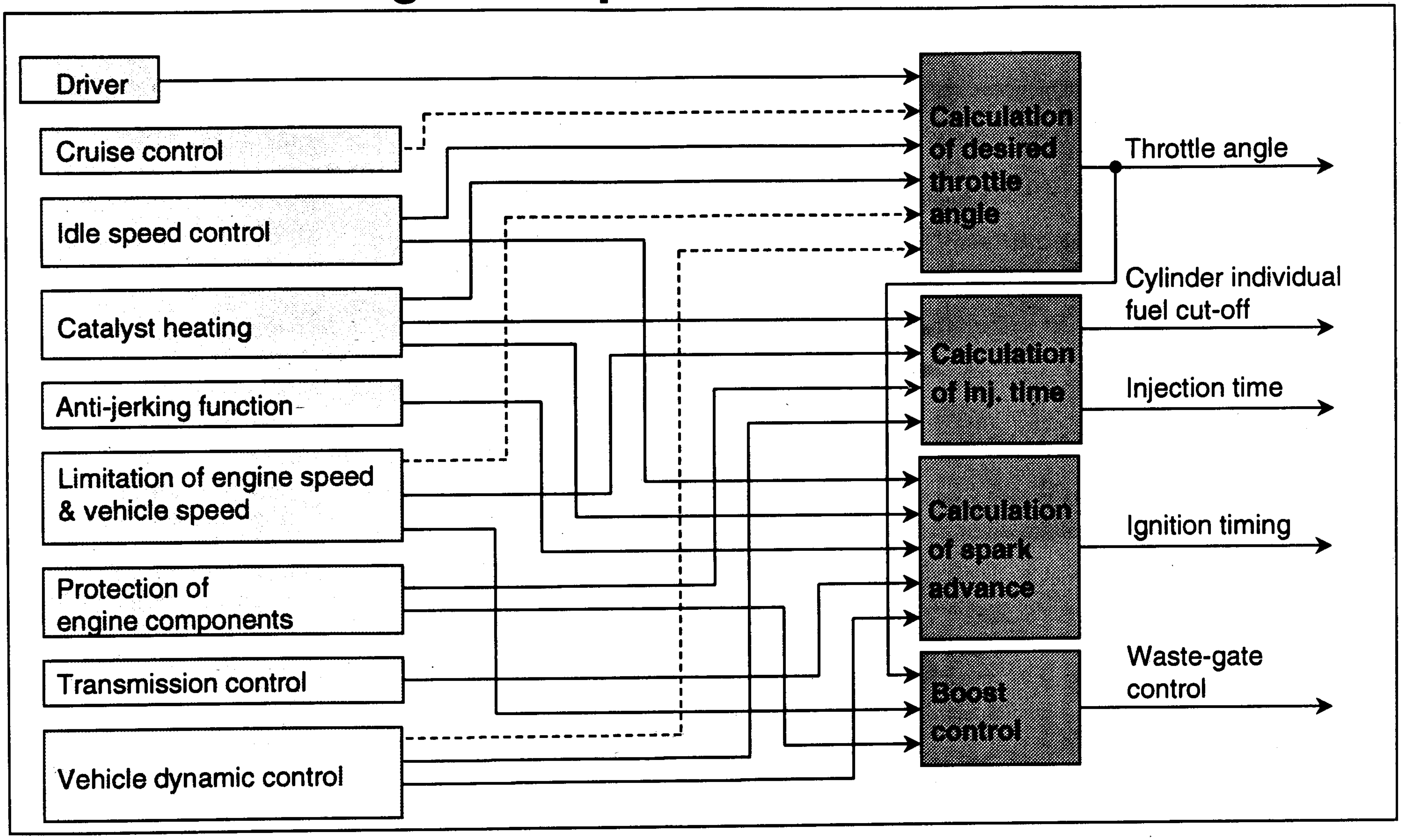
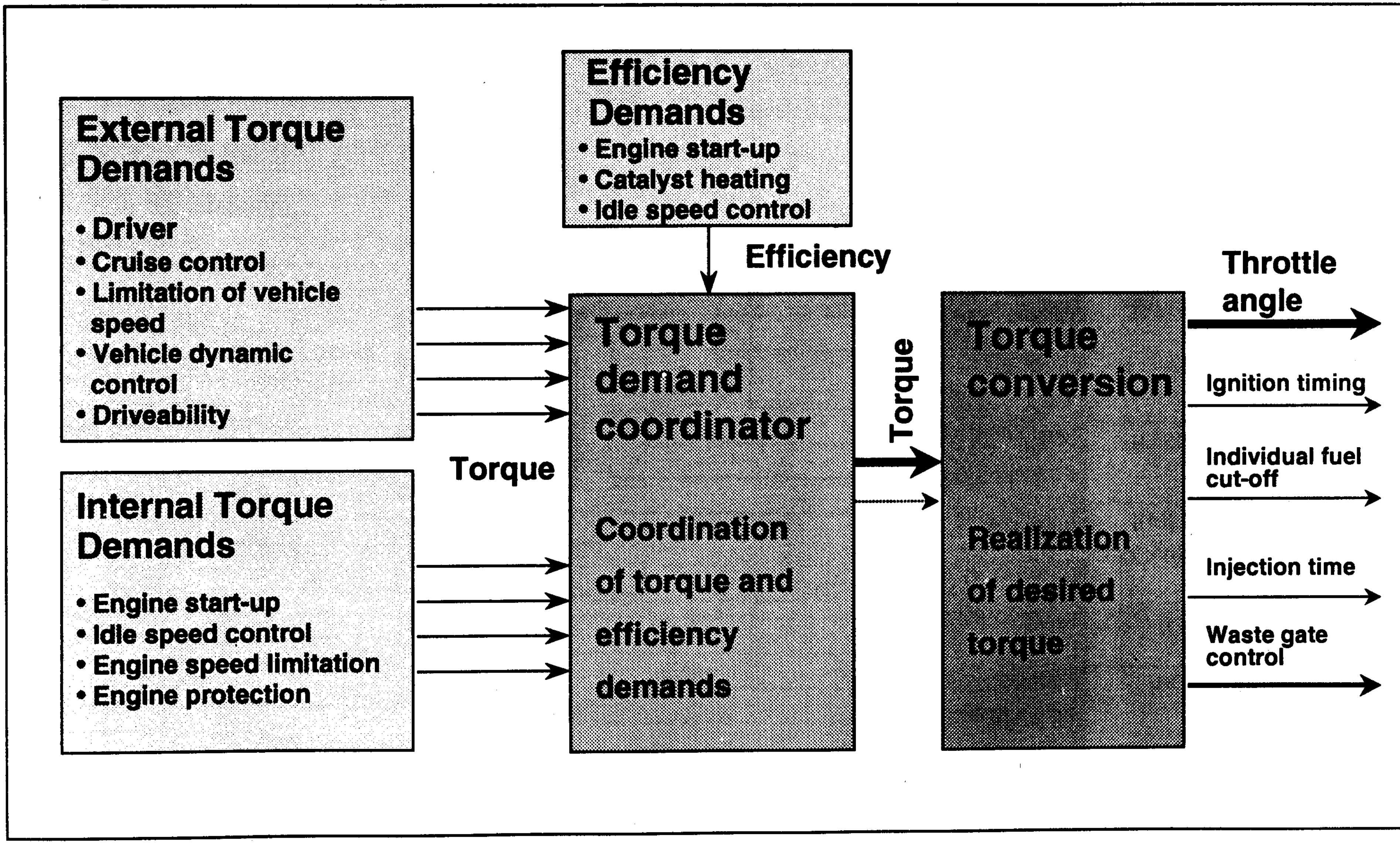
MOTRONIC - Torque Guided Engine Management Systems
Influences on Engine Torque - Previous Situation



BOSCH

SAE India 2000 - Figure 1

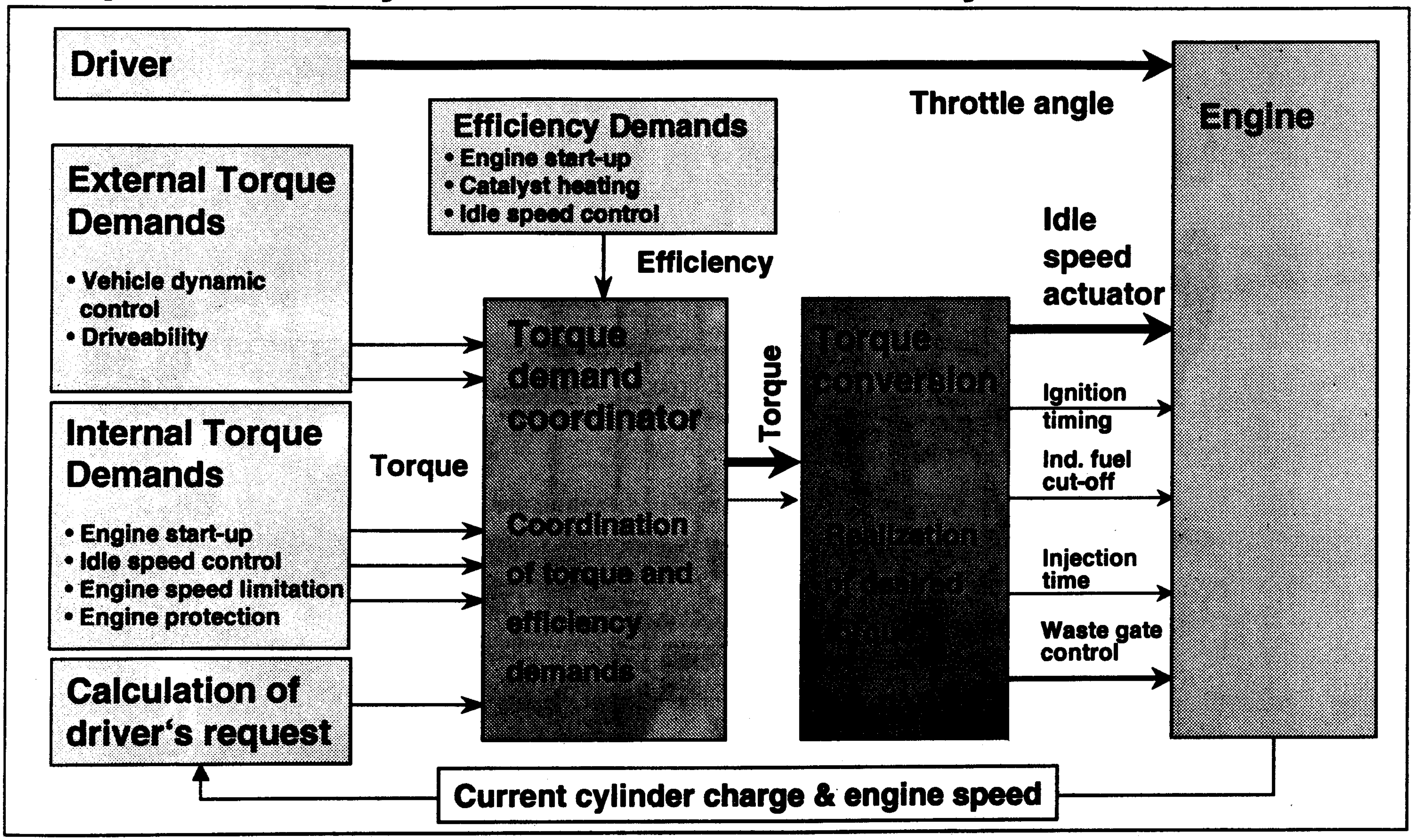
MOTRONIC - Torque Guided Engine Management Systems
Torque Based System Structure for PFI Systems with ETC



BOSCH

SAE India 2000 - Figure 2

MOTRONIC - Torque Guided Engine Management Systems
Torque Based System Structure for PFI Systems w/o ETC



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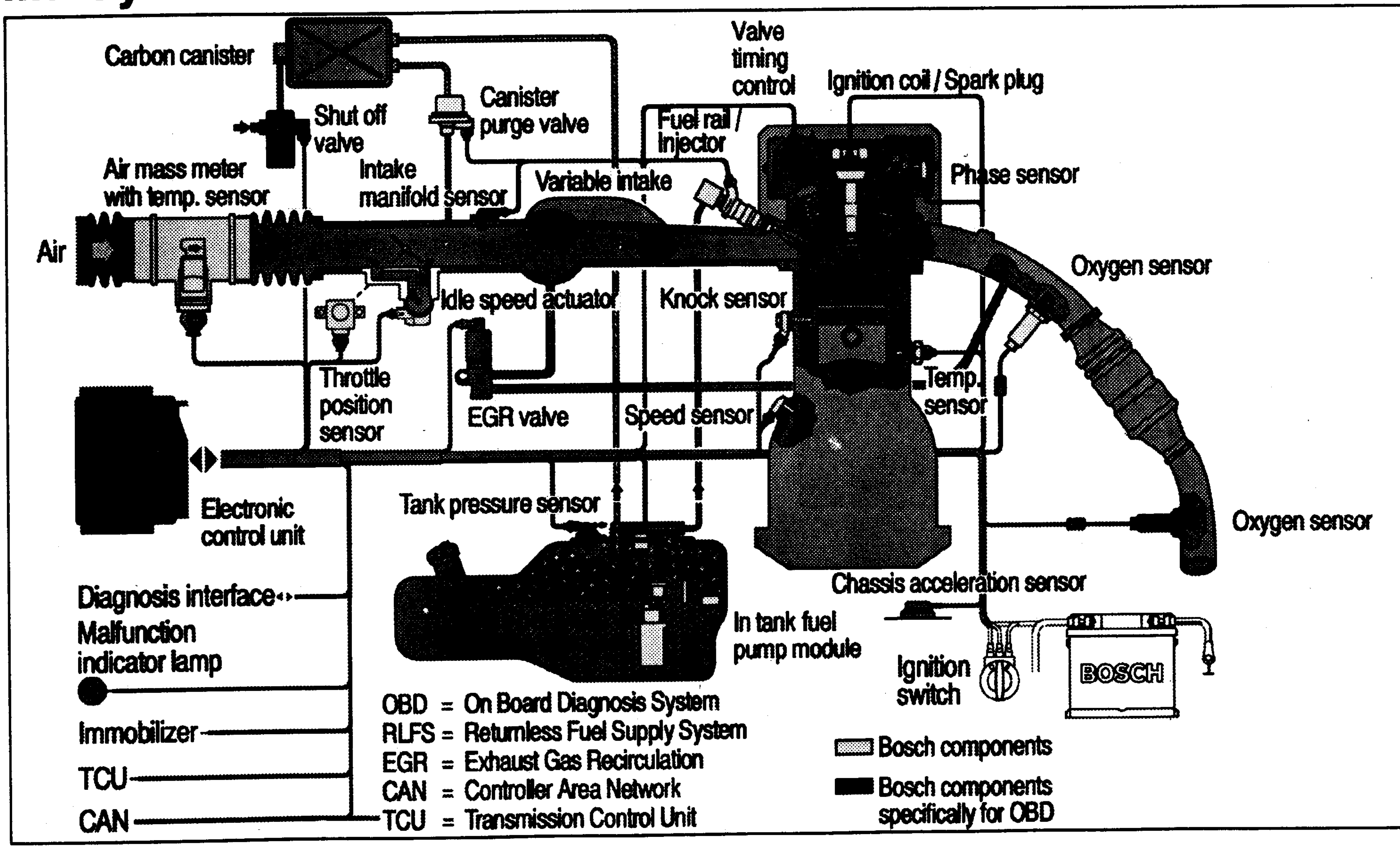
SAE India 2000 - Figure 3

MOTRONIC - Torque Guided Engine Management Systems
M7 System Overview with OBD and RLFS



SAE India 2000 - Figure 4

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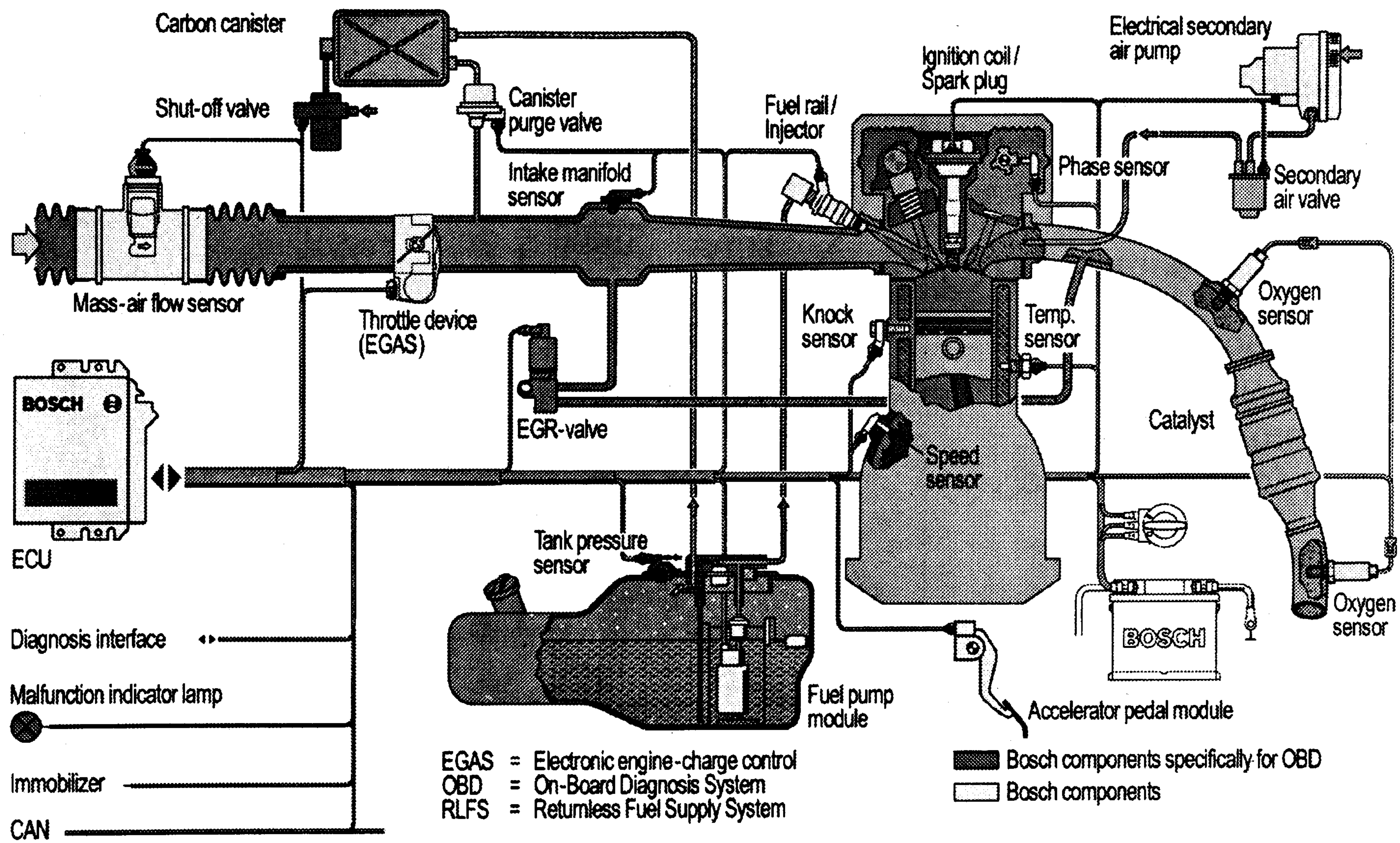
MOTRONIC - Torque Guided Engine Management Systems

Motronic ME7 with ETC, OBD and RLFS



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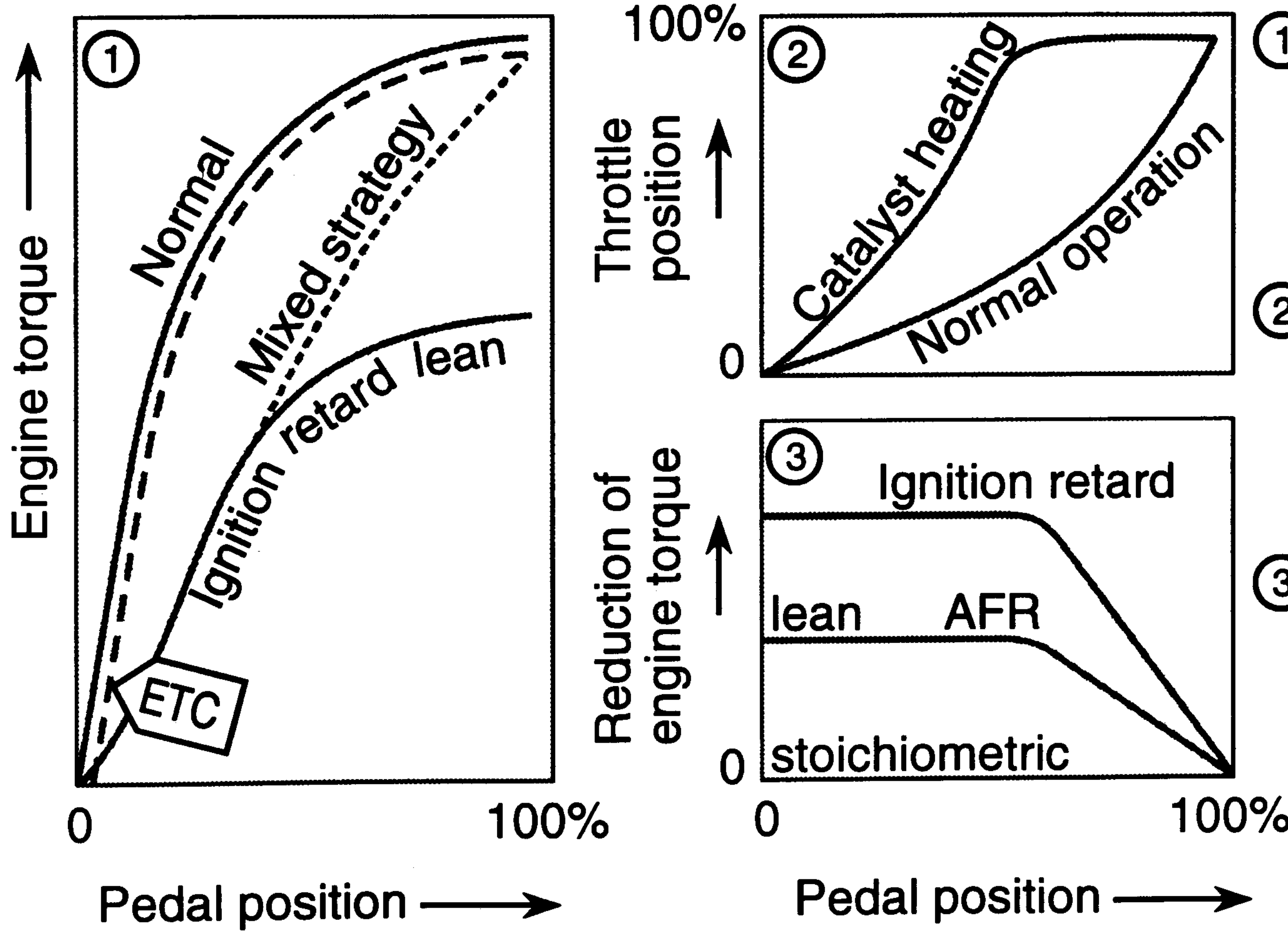
SAE India 2000 - Figure 5

MOTRONIC - Torque Guided Engine Management Systems
Compensation of Torque Losses with an ETC System



(1) Ignition retard
+ lean mixture
} reduced torque at given pedal position

(2) Compensation by ETC:
- increased throttle opening at given pedal position

(3) High torque operation:
- reduction of ignition retard
- AFR towards stoichiometric according to pedal position

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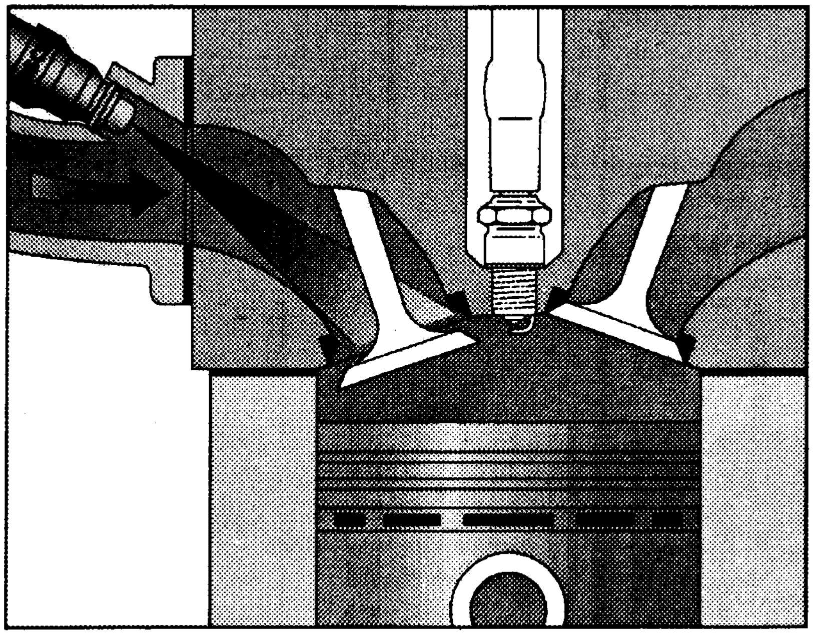
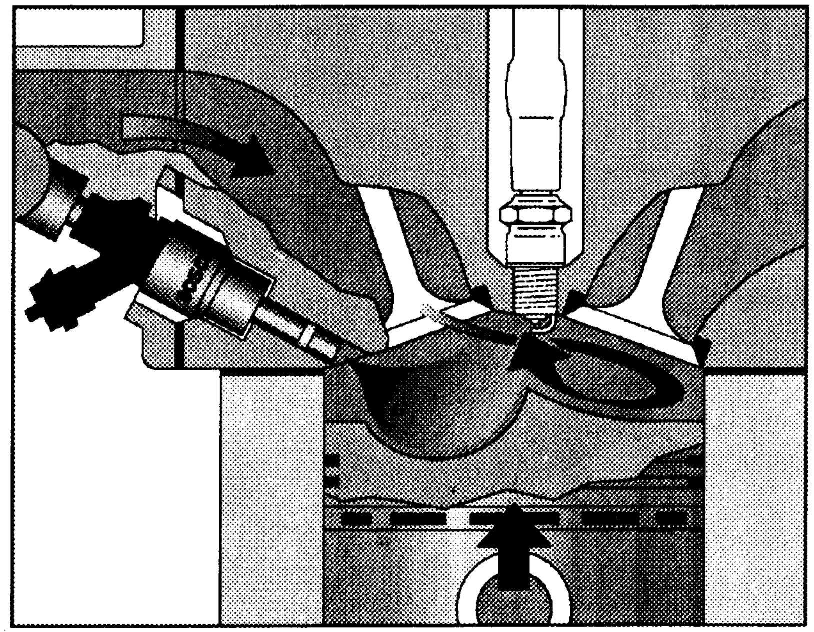
MOTRONIC - Torque Guided Engine Management Systems
Fuel Injection Concepts for S.I. Engines

Port Fuel Injection



Mixture transport over the intake stroke

Gasoline Direct Injection



Mixture transport by charge motion and piston geometry

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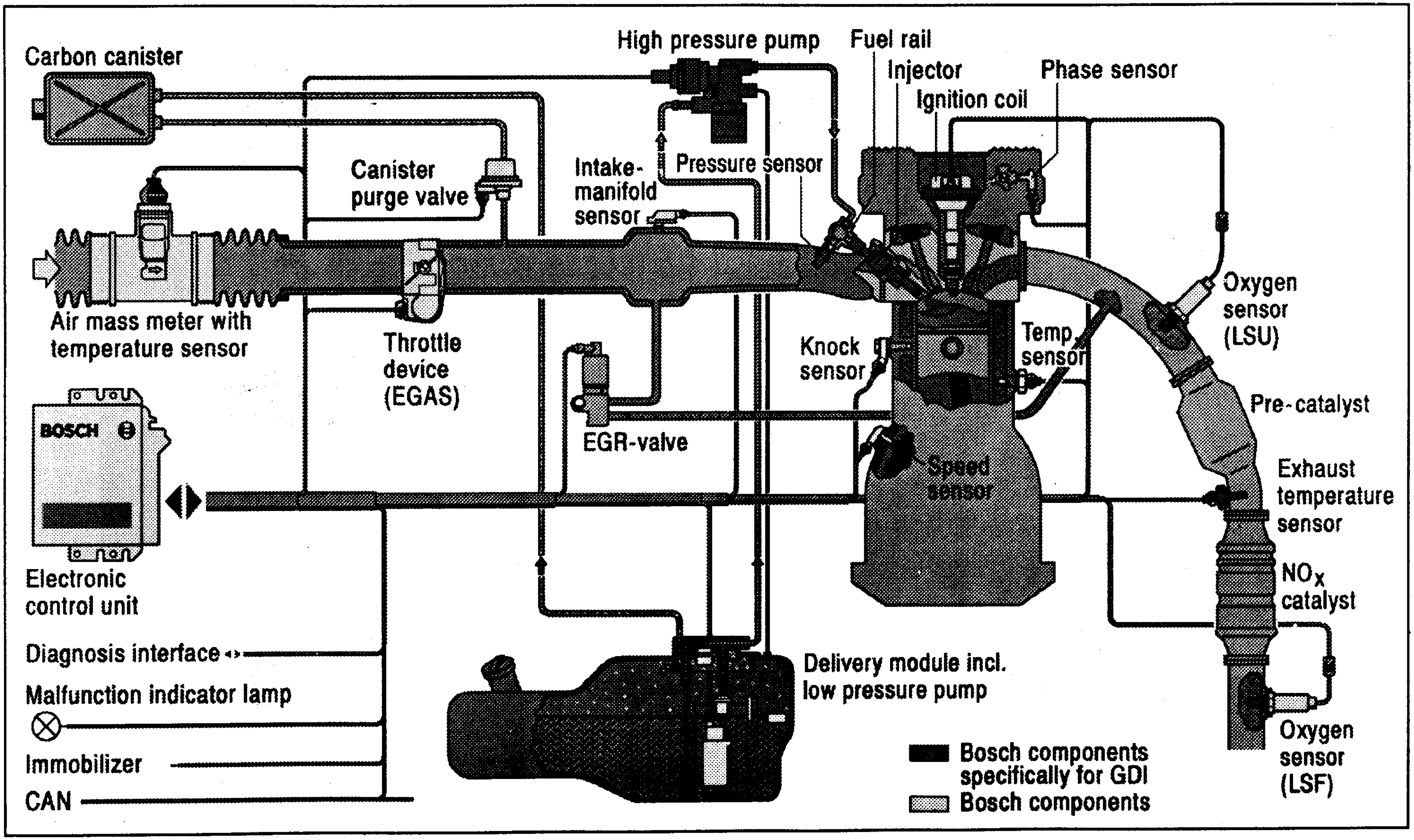
SAE India 2000 - Figure 7

MOTRONIC - Torque Guided Engine Management Systems
Motronic MED7 for Gasoline Direct Injection



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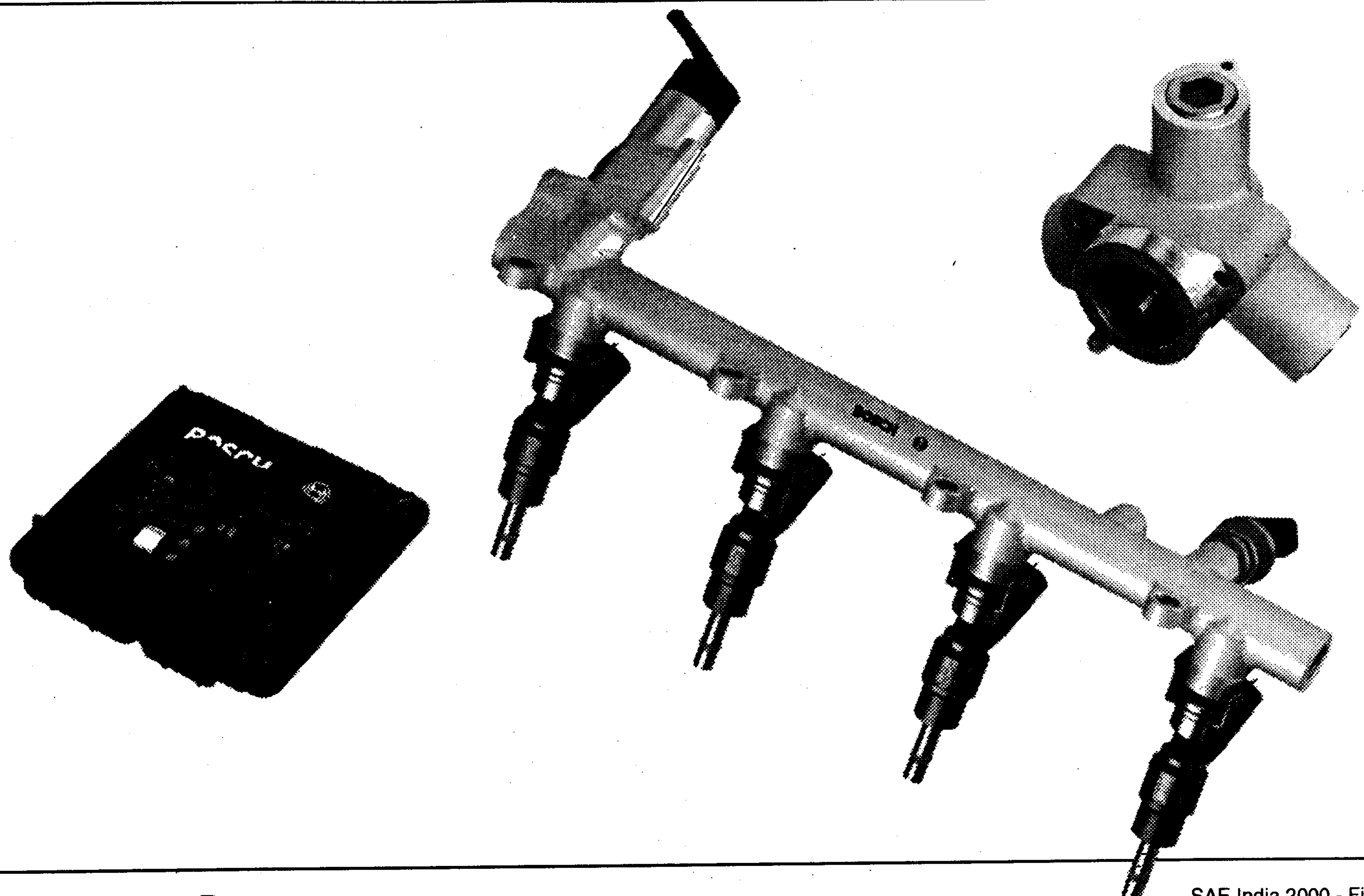
SAE India 2000 - Figure 8

MOTRONIC - Torque Guided Engine Management Systems
MED7 - High Pressure Components and ECU



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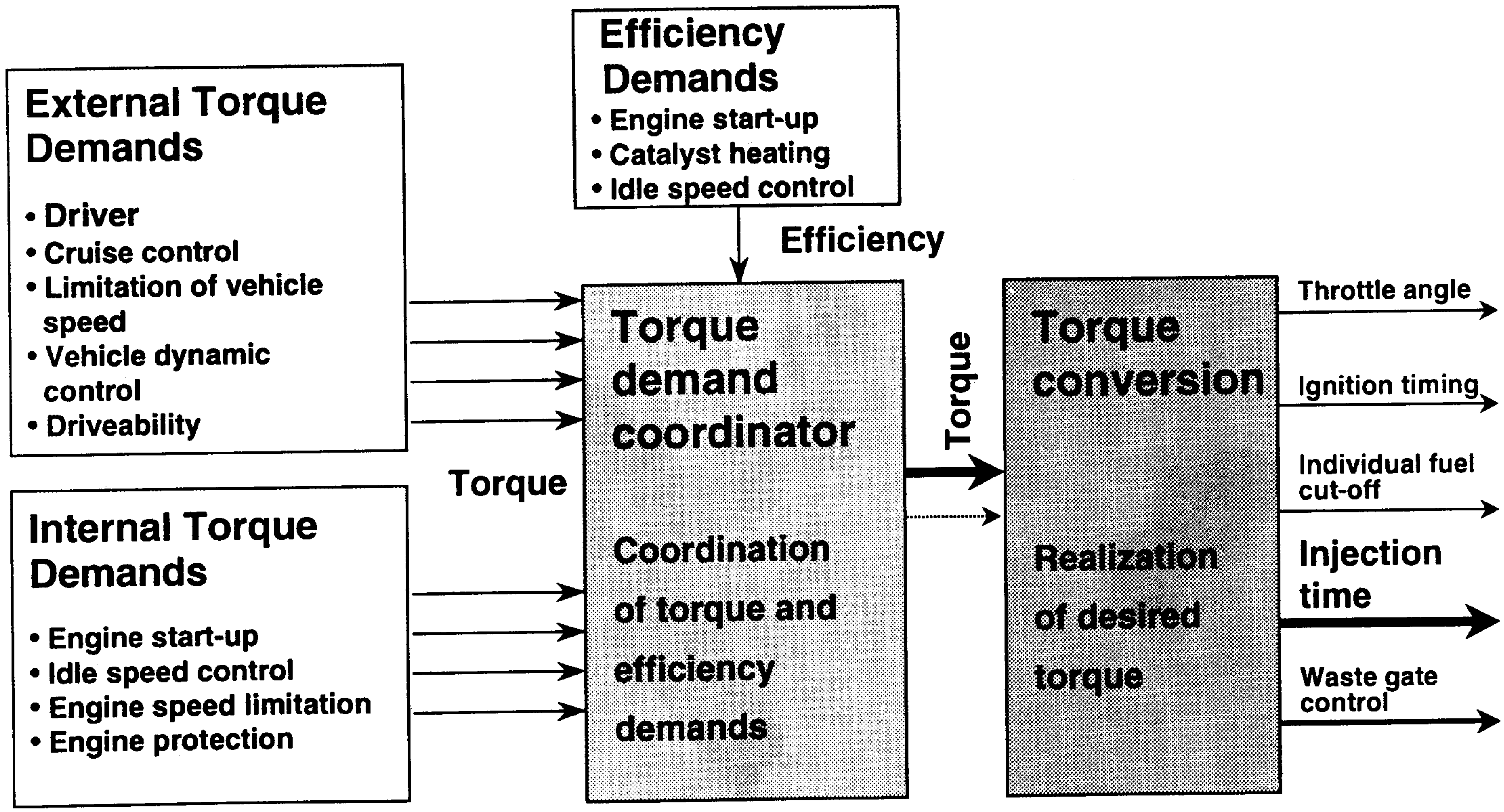
SAE India 2000 - Figure 9

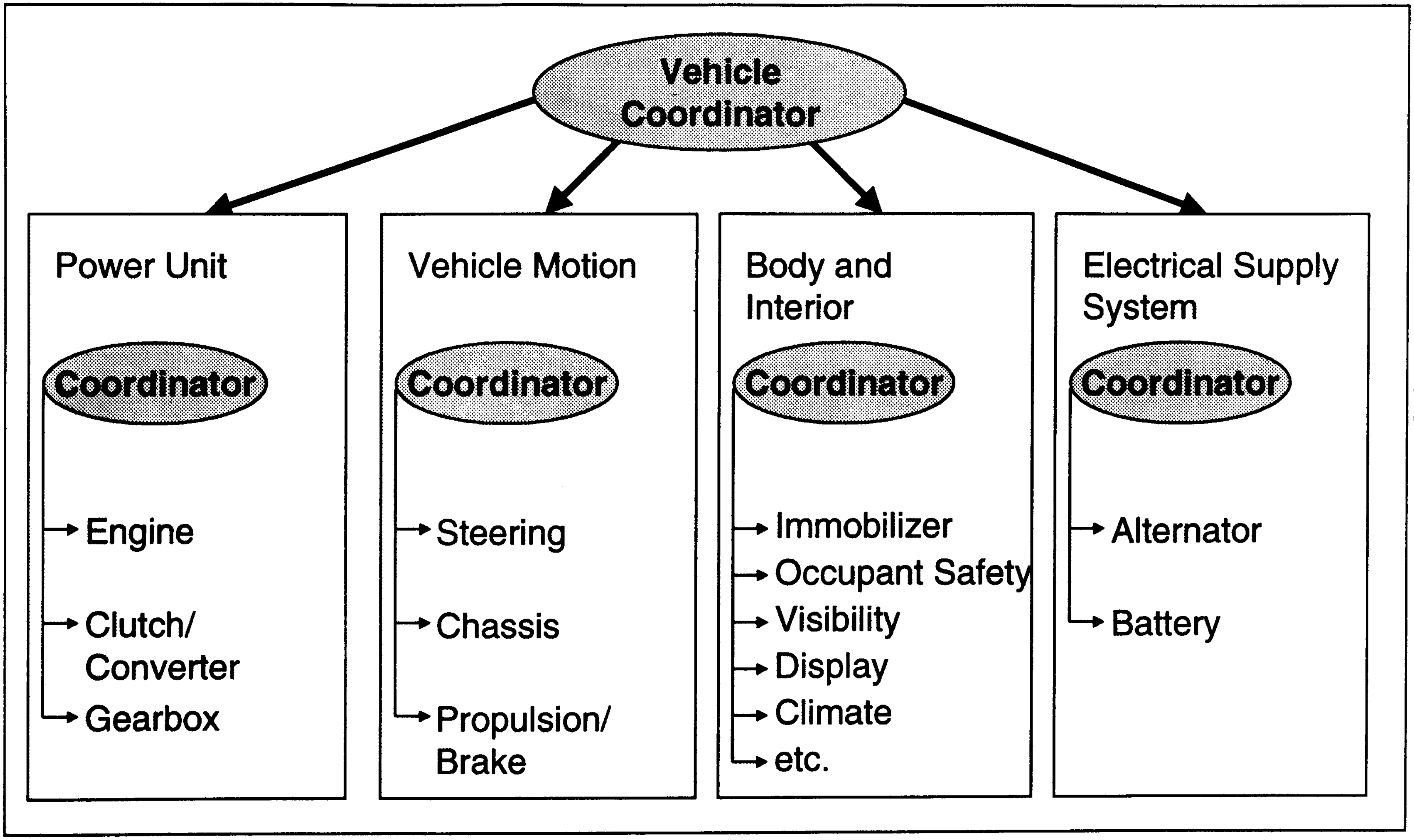
MOTRONIC - Torque Guided Engine Management Systems
Torque Based System Structure for GDI Systems



BOSCH

SAE India 2000 - Figure 10

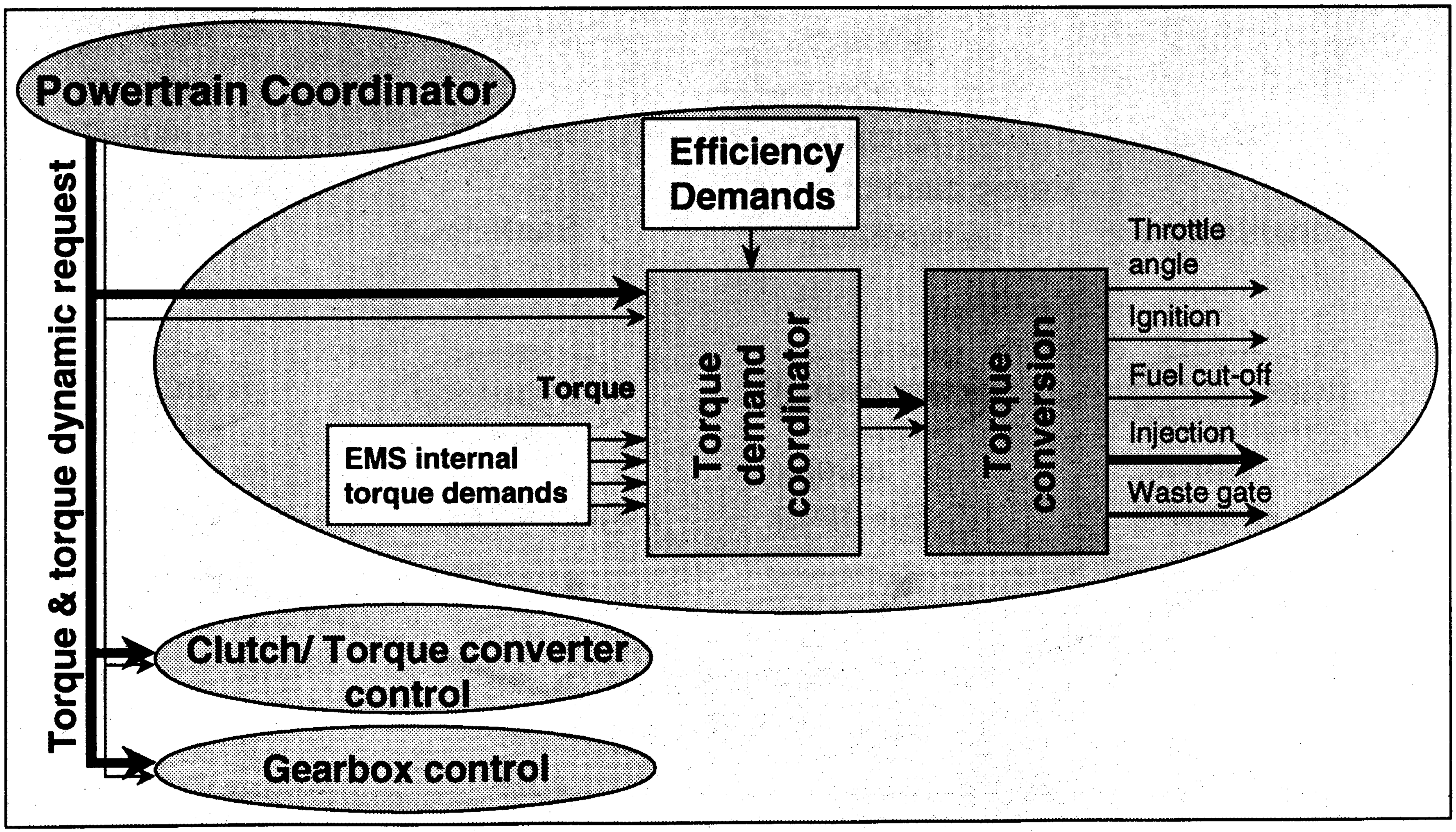
MOTRONIC - Torque Guided Engine Management Systems
CARTRONIC - Car Wide Web (Vehicle Level)



BOSCH

SAE India 2000 - Figure 11

MOTRONIC - Torque Guided Engine Management Systems
Motronic as Subsystem in Car Wide Web

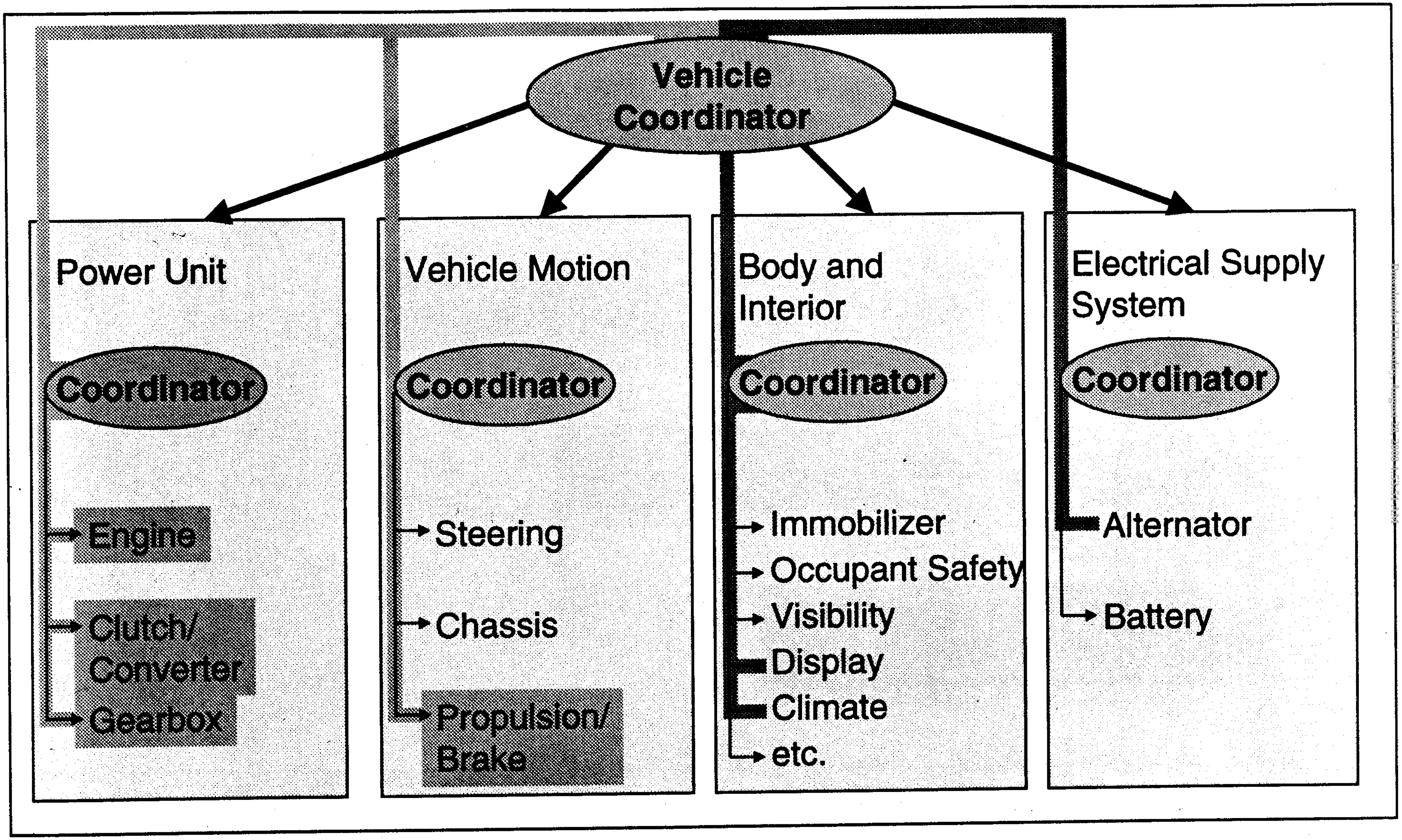


BOSCH

SAE India 2000 - Figure 12

CARTRONIC - Car Wide Web
Powertrain Level

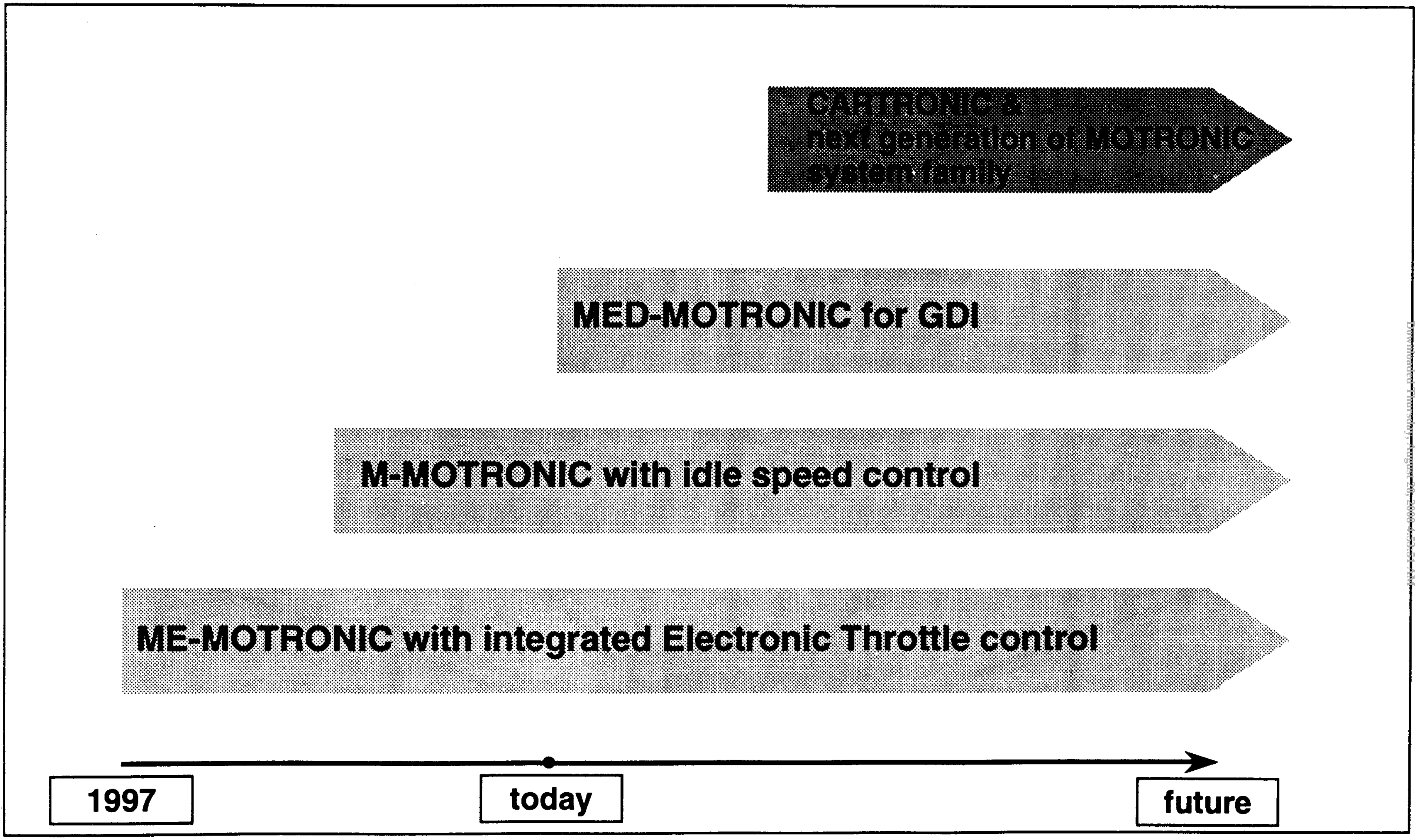
Powertrain Management



BOSCH

SAE India 2000 - Figure 13

MOTRONIC - Torque Guided Engine Management Systems System Family



BOSCH

SAE India 2000 - Figure 14