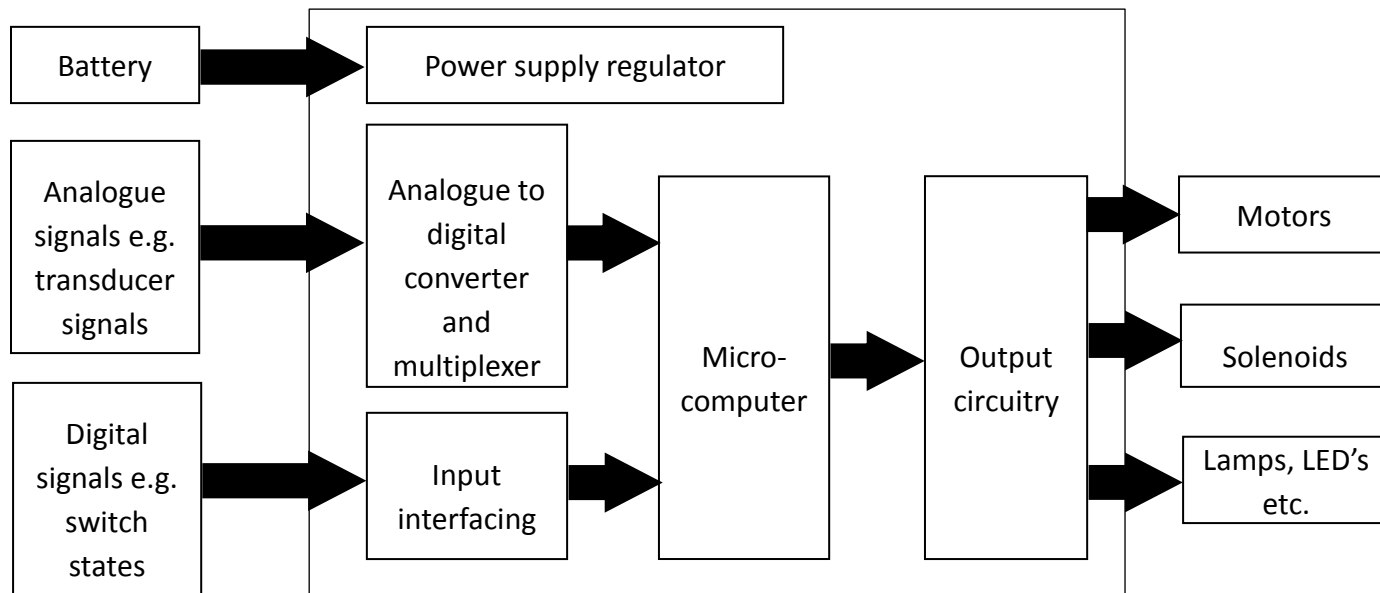


Control Systems in Automobiles

Examples of Automotive Closed-loop Control Systems

Control System	Indirectly controlled variable	Directly controlled variable	Manipulated variable	Sensor	Actuator
Fuel injection system	Air-fuel ratio	Exhaust oxygen content	Quality of injection fuel	Zirconia or Titania based electro-chemical	Fuel injector
Knock control	Knock	Knock sensor output	Ignition timing	Piezo-electric accelerometer	Ignition coil switch. Transistor
Anti-lock braking system	Wheelslip limit	Wheelspeed	Brake time pressure	Magnetic reluctance	ABS solenoid valve

ECU (based on Micro Computers)



Engine Management Sensors

Measured variable	Direct/indirect measurement	Sensor technology/ reference	Sensor mounting location
Intake manifold absolute pressure	Indirect measurement of engine load or mass air-flow intake	Wheatstone bridge arrangement of thick film resistors bonded onto a thin alumina diaphragm	Within intake manifold
Mass airflow	Direct and indirect measurement of fuel injector basic pulse width	Various forms including 'flap' type, 'hot-wire', Karman vortex and thick-film diaphragm	Within air intake
Temperature	Direct measurement at various locations	Thermistor or thermocouple depending on temperature range	Intake air, outside air, catalytic converter, engine coolant, hydraulic oil
Engine speed and crankshft reference position	Direct measurement	Magnetic reluctance or Hall effect device	Flywheel on end of engine crankshaft

Engine Management Sensors (contd)

Measured variable	Direct/indirect measurement	Sensor technology/ reference	Sensor mounting location
Battery voltage	Direct measurement	Resistive attenuator	
Throttle position	Direct measurement	Potentiometer	Accelerator pedal
Knock (engine cylinder pressure oscillations during ignition)	Direct measurement	Piezoelectric accelerometer type.	Cylinder block or head
Oxygen concentration in exhaust gas (Lambda sensor)	Direct measurement	Zirconia or Titania based exhaust gas oxygen sensors	Exhaust manifold (normal operation above 300 ⁰ C)

Chassis Control Sensors

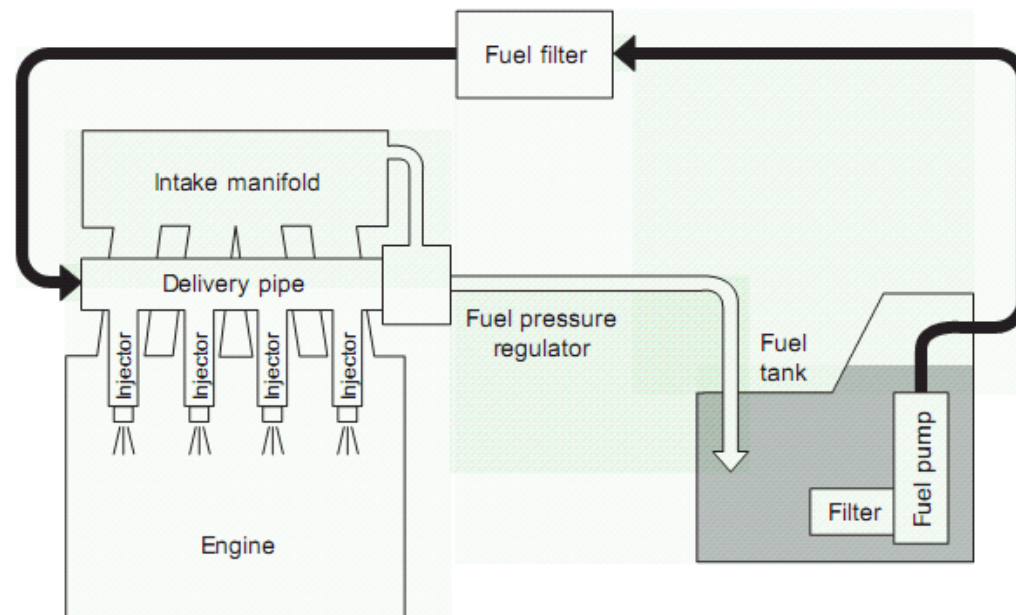
Measured variable and application	Direct/indirect measurement	Sensor technology/ reference	Sensor mounting location
Wheelspeed and engine speed, (ABS, TCS and electronic damping)	Direct measurement	Magnetic reluctance or Hall effect device	Brake assembly and crankshaft flywheel respectively
Steering wheel angle, (Electronic damping)	Direct measurement	Potentiometer or optical encoder	Steering shaft
Throttle position	Indirect measurement of vehicle accel.	Potentiometer	Accelerator pedal
Chassis and wheel acceleration, (electronic damping)	Direct	Piezo-electric accelerometer	Engine compartment and wheel assembly
Brake system pressure (electronic damping)	Indirect measurement of vehicle deceleration	Flexing plate sensor with strain gauges mounted on plate	Brake master cylinder
Steering shaft torque (Electric power assisted steering)	Direct measurement	Optical device relying on steering shaft distortion under driver's twisting action	Steering shaft

Safety and Onboard navigation

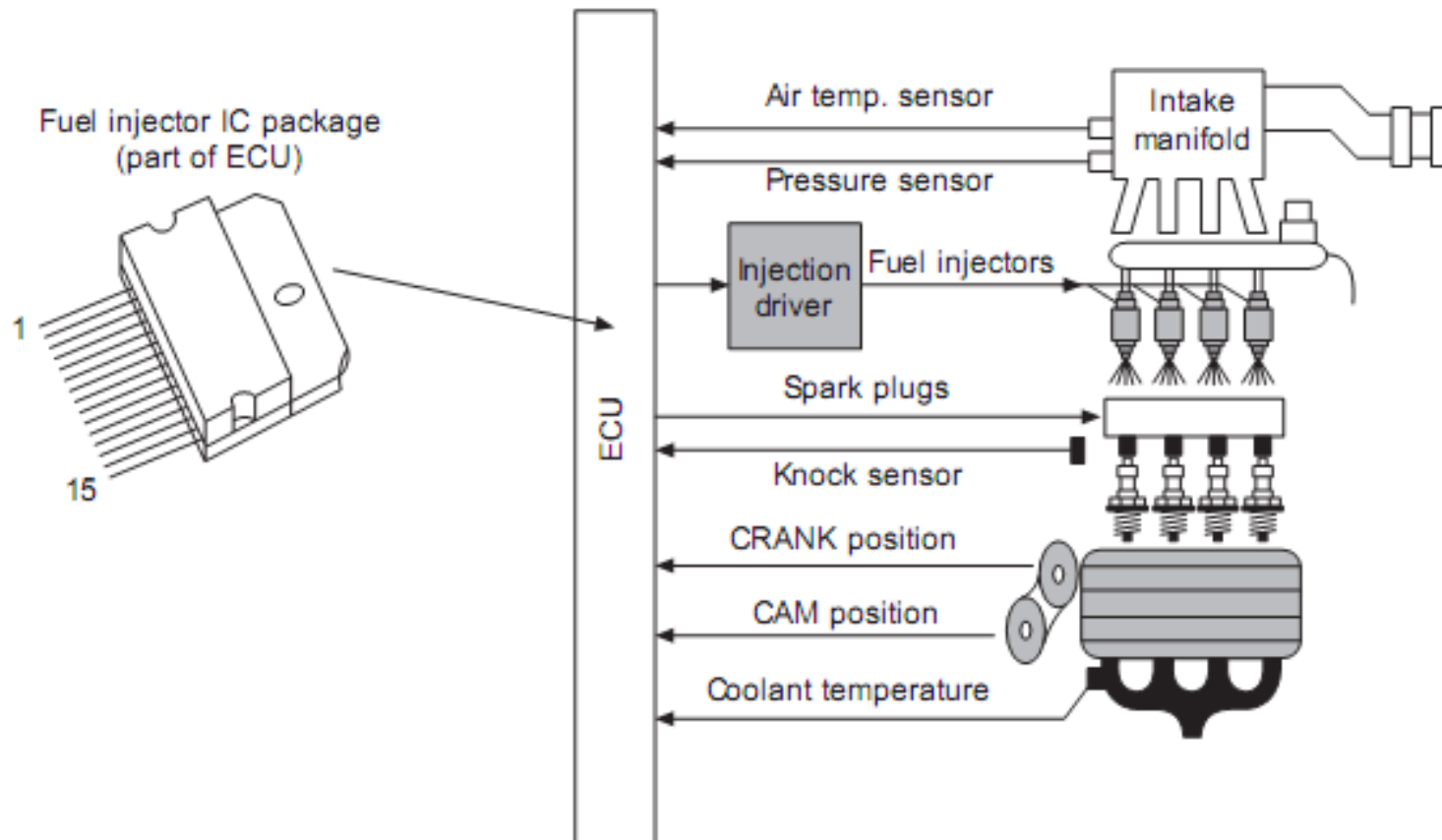
Measured variable	Direct/indirect measurement	Sensor technology/ reference	Sensor mounting location
Vehicle deceleration (air-bag systems)	Direct measurement	'G' sensor (Piezo-electric accelerometer)	Single-point electronic sensing, location in dashboard or steering wheel
Wheelspeed and engine speed (Vehicle nav. Systems)	Direct measurement	Magnetic reluctance or Hall effect device	Brake assembly.

Electronic fuel injection (EFI)

- allows precise and fast control of fuel injected
- by control of the 'on-time' period of the solenoid operated injectors (spray nozzle) and plunger.
- delivery pipe fuel pressure is maintained constant by a fuel pressure regulator
- opening and closing times of between 0.5 and 1 ms.
- engine operating speed of 6000 rpm (10 ms revolution time)
- injector on-time can be controlled between 1 and 10 ms.



Power driver application



- multi-point or sequential fuel injection, with one fuel injector near the intake valve (or valves) of each cylinder.
- At a device level, a fuel injector IC package
- provides the high solenoid drive current required
- Incorporates both over-voltage and short-circuit protection,
- fault reporting diagnostic routines also included

Two types of EFI System ----- Speed-density EFI

- inlet manifold absolute pressure (MAP) sensor has an important role
- **fuel injection opening period** or pulse width is related directly to the mass of air flowing into the engine as fuel-air ratio must be maintained constant in steady-state operation
- and the mass of air-flow is related to the manifold absolute pressure by the equation

$$m_a = \frac{V_d n_v P_i}{RT_i}$$

- where V_d is the displacement of the cylinder,
- n_v is the volumetric efficiency or the fraction of V_d actually filled on each stroke, [= f(speed)]
- p_i is manifold absolute pressure,
- R is a constant and
- T_i is the intake air temperature.

Mass air-flow EFI

- direct measurement of the quantity of air drawn into the engine (using an air-flow sensor (AFS)).
 - simple flap-type,
 - hot-wire and
 - Karman vortex devices,
- Direct measurement is better than feed-forward control in speed density EFI
- (factors like variation in volumetric efficiency, engine displacement due to speed and internal deposits need to be taken care of).

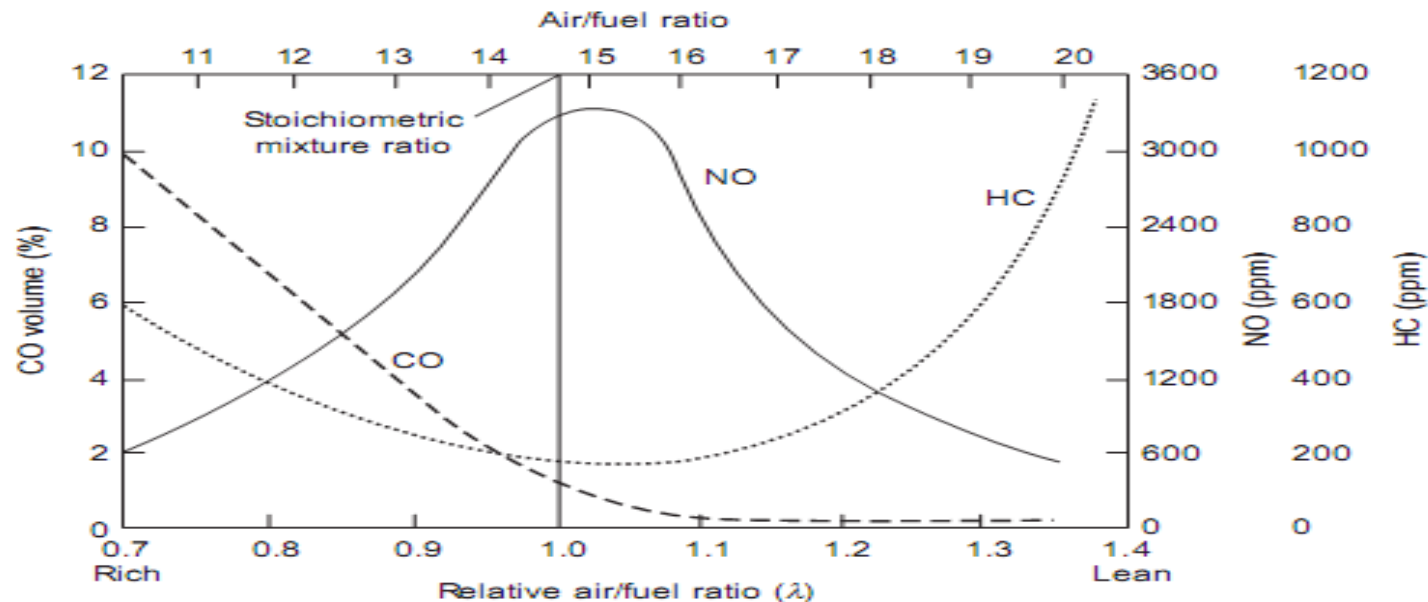
Both of these forms of EFI may be improved

- exhaust gas oxygen sensor for closed-loop control of the air–fuel ratio.
- if engine is to be controlled precisely air–fuel ratio must be controlled to within 1%.
- only possible with closed-loop control,

- ***Closed-loop control of air–fuel ratio***
- The objective of low exhaust-gas emission levels
 - maintain the air–fuel ratio at 14.7:1
[stoichiometrically / chemically perfect]
 - three-way catalytic converters to control emission

- In a closed loop system
- the fuel injection period computed by air intake measurement is modified
 - Based on measured exhaust gas oxygen (EGO) content.
 - injection period modification factor between 0.8 and 1.2.
- EGO tells whether $\lambda < 1$ or $\lambda > 1$
- Closed loop system has a limit cycle frequency between 0.5 to 2 Hz

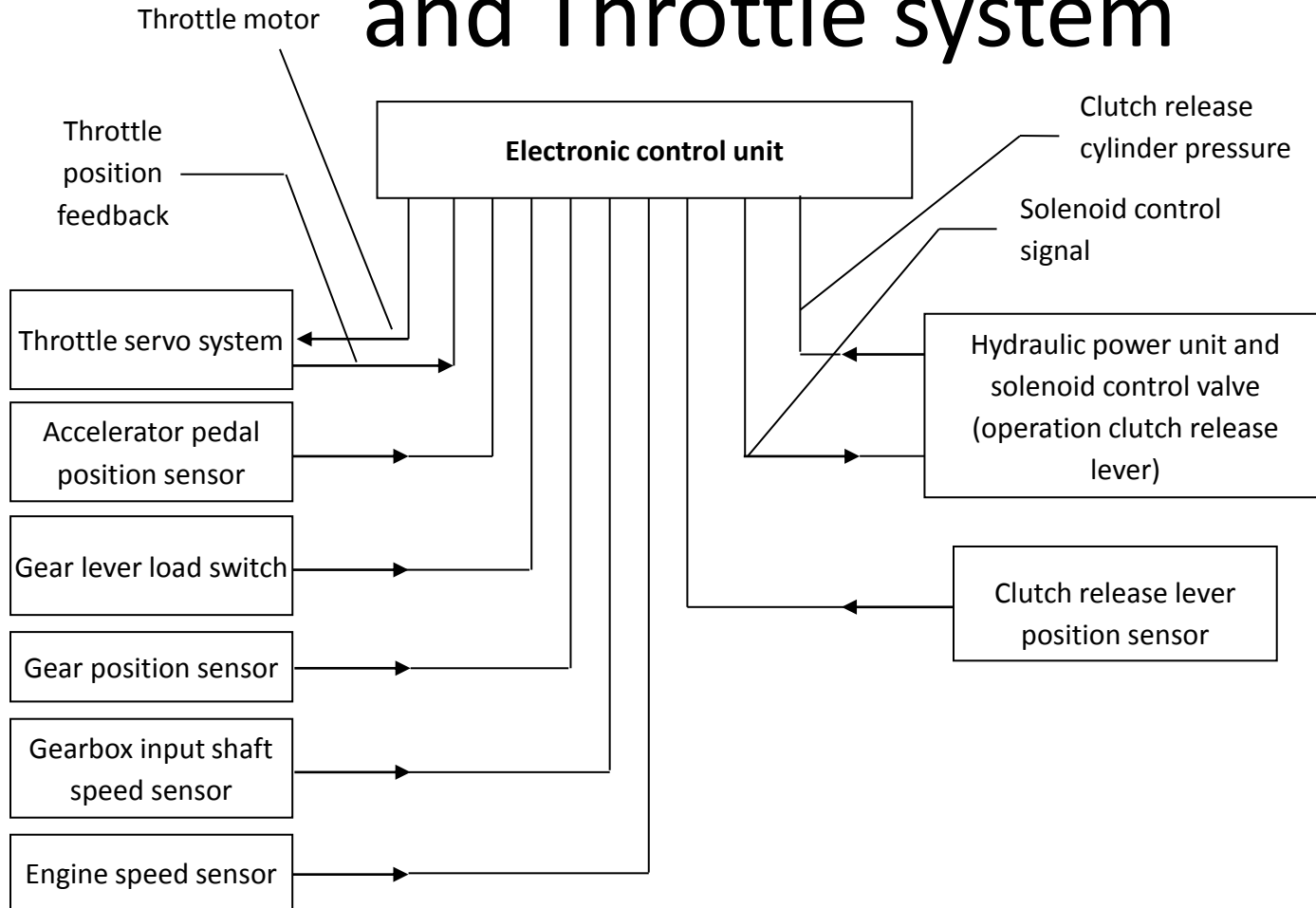
Pollutant emission as a function of relative air–fuel ratio, λ (Chowanietz, 1995)



Electronic clutch control

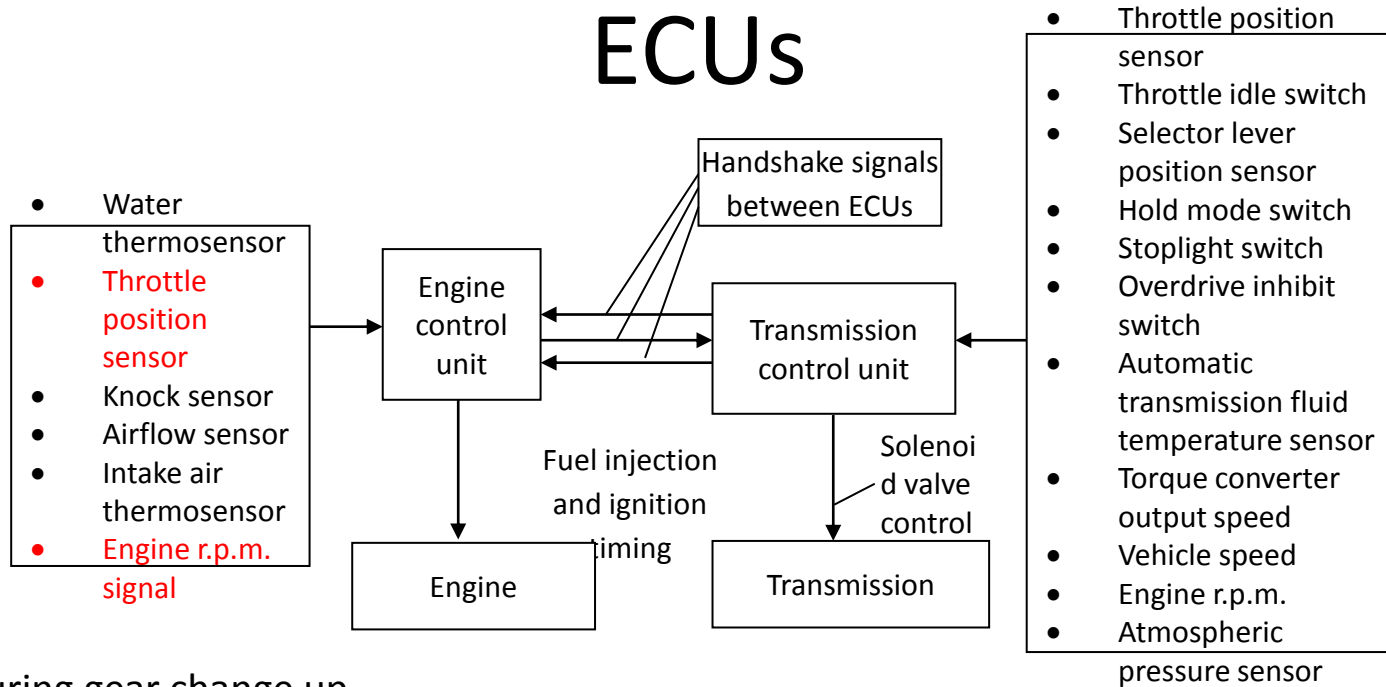
- To relieve pressing of clutch during gear change
- Throttle cable of accelerator pedal replaced by closed loop control system
 - Accelerator pedal position sensor and servomotor
 - Connected to an ECU for the gear change process

Block Diagram of an Automatic Clutch and Throttle system



- Control of clutch engagement and disengagement
- Improved safety
 - Prevention of engine starting when in gear
 - Inappropriate gear change

Integration of Transmission and Engine



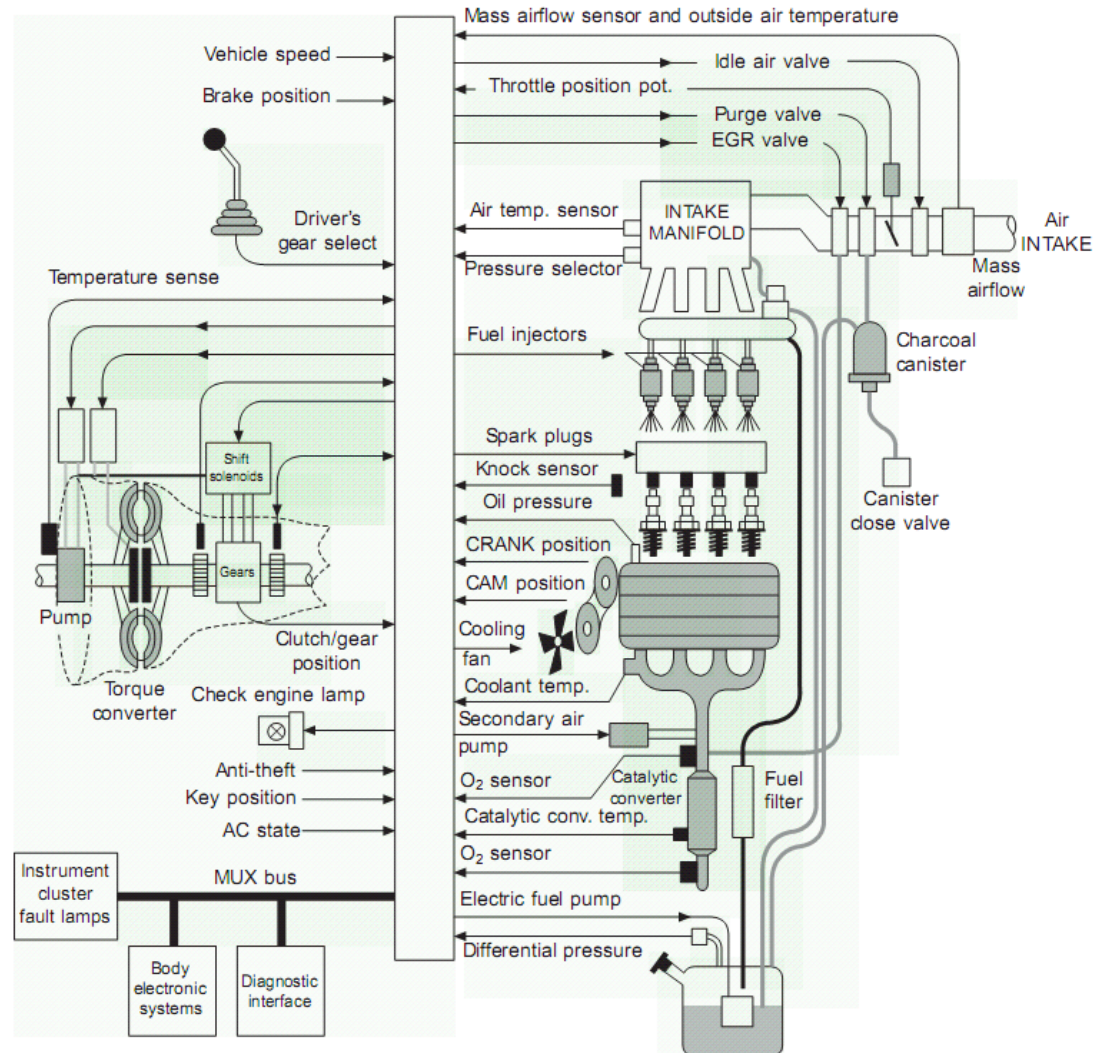
- During gear change up
 - transmission ECU signals the engine management ECU
 - cut off fuel injection and
 - Signals TECU to allow gear change
- During gear change down
 - TECU energizes signals E-ECU
 - Changes ignition timing a few degrees to reduce engine torque,
 - Signals TECU to allow gear change
- In the end both systems return to independent operation.

Integration of engine management and transmission control systems

- the multi-way switch reports position of the selector lever
 - If the lever is not in either Park or Neutral when starting, operation of the starter motor is inhibited
 - a warning buzzer sounded
- The hold switch (push-button switch on the selector lever)
 - instructs the ECU to hold the transmission in a current gear ratio
 - useful in descending a hill.
- The stoplight switch
 - When the brakes are applied and transmission is in a lockup condition,
 - the lockup clutch is then disengaged.
- The overdrive inhibit signal (O/D) (from a separate cruise control unit)
 - prevents the transmission from changing into overdrive (fourth gear) if
 - cruise control is activated and
 - vehicle speed is more than a certain amount below the set cruising speed.
- The Automatic Transmission Fluid (ATF) thermosensor
 - modify the line pressure at temperature extremes
 - To account for changes in fluid viscosity.
- Atmospheric pressure
 - If above 1500 m (engine develops less power at high altitudes)
 - the automatic gear change points are modified to suit the change in performance.

Powertrain Control System

- Also includes
 - Exhaust gas recirculation system (circulating exhaust into intake to reduce max combustion temp, and hence NO_x)
 - Controlled by powertrain ECU
 - Engine temp, load, speed
 - Evaporative Emission Control System (to circulate fuel vapour into intake and prevent leakage into atmosphere)

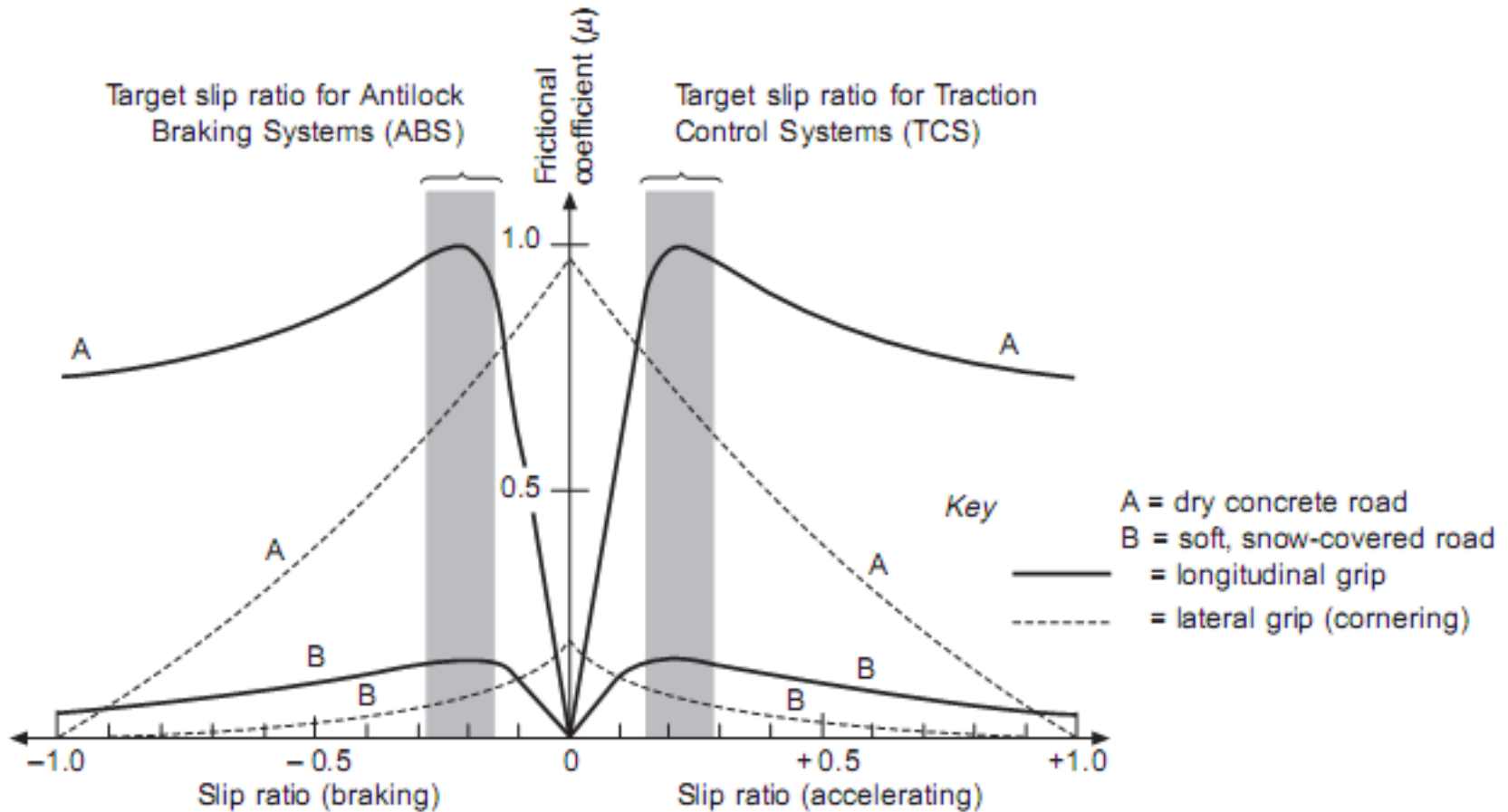


Chassis Control Systems

- Anti Lock Braking system
- Electronic Damping Control system
- Power Assisted Steering System
- Traction Control Systems

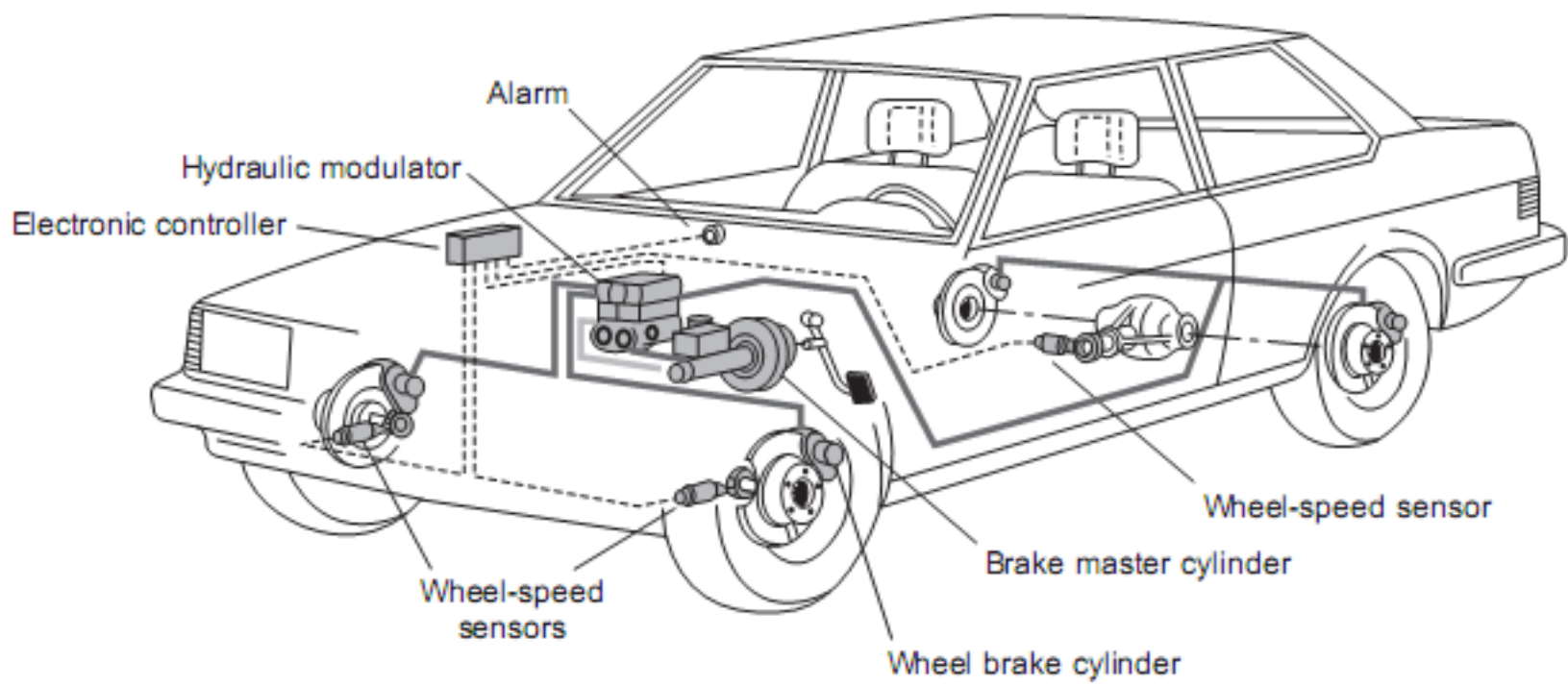
Anti-lock braking systems (ABS)

- The vehicle skids, the wheels lock and driving stability is lost so the vehicle cannot be steered;
- If a trailer or caravan is being towed it may jack-knife;
- The braking distance increases due to skidding;
- The tyres may burst due to excessive friction and forces being concentrated at the points where the locked wheels are in contact with the road surface;



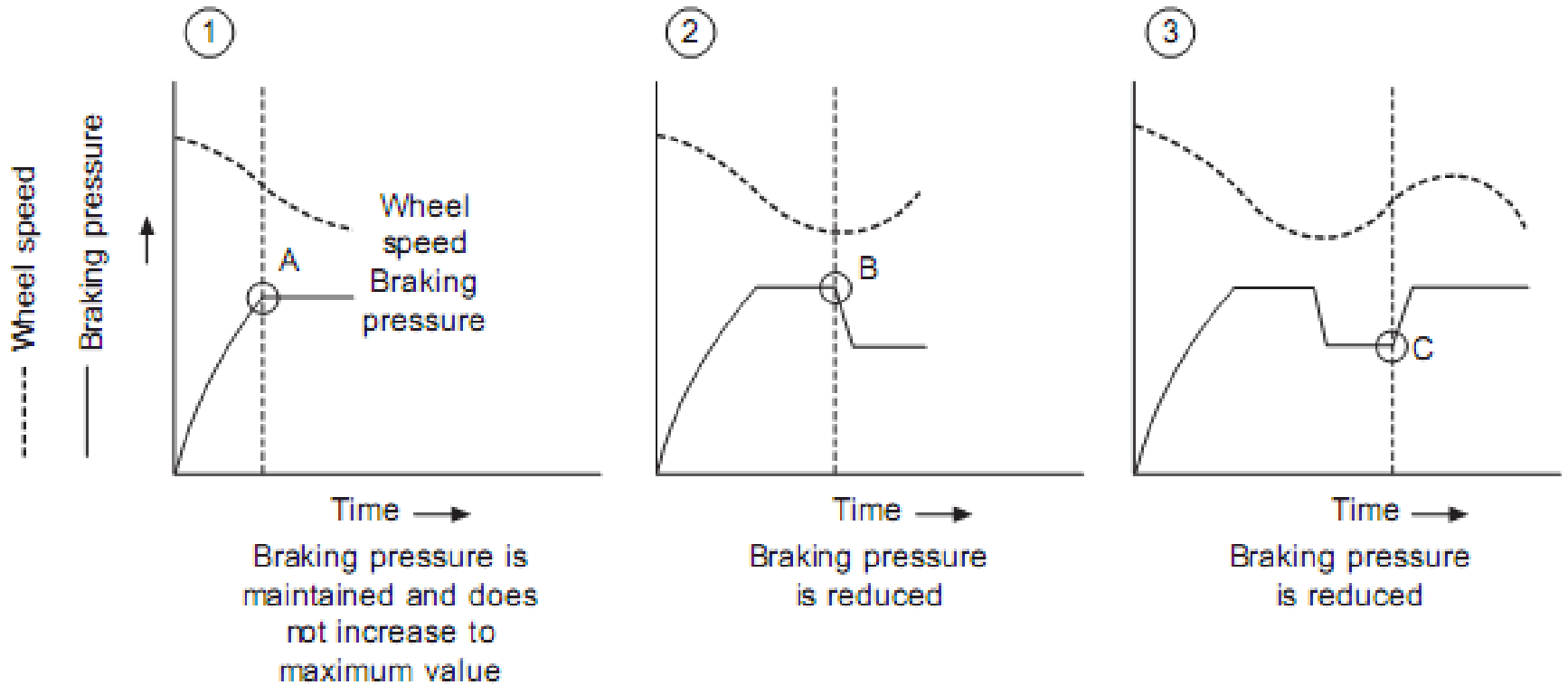
Variation of the coefficient of friction (μ) with slip ratio

- Induction type wheel-speed sensors on the wheel assembly or differential
- couple magnetically to a toothed wheel known as an impulse ring.



Antiskid braking system (ABS)

- All electronic signals come to the electronic controller (ECU)
- The ECU controls the hydraulic modulator
 - To control the Brake line pressure in Brake master cylinder



Wheel-speed and braking pressure during ABS-controlled braking

- If wheel decelerates beyond a certain level, curtail brake pressure (1)
- If wheel decelerates further, reduce brake pressure further (2)
- If wheel accelerates, increase brake pressure (3)

Traction control systems

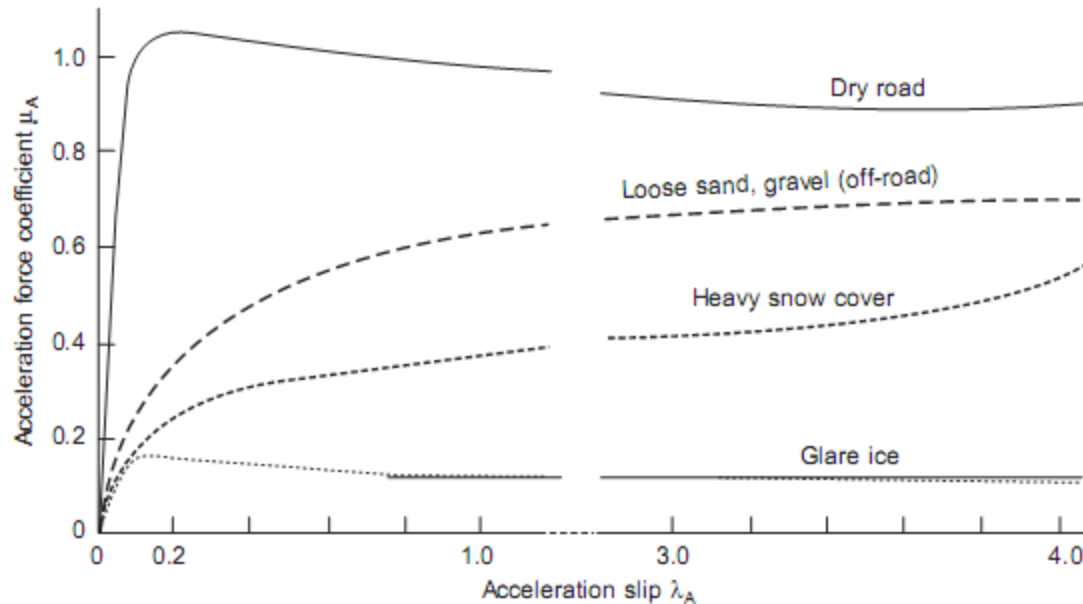
- prevent drive wheels from wheelspinning during starting or
 - accelerating on a wet or icy surface.
- avoid reduction of either steering response in front-wheel-drive (FWD) / vehicle stability on rear-wheel-drive (RWD) vehicles.

TCS operates

- to maximize adhesion to the road surface during acceleration
- Same sensors as in ABS
- The actuation uses fuel, ignition and driven wheel braking action

Traction Control Systems (TCS)

- to achieve reduction in driven wheel torque during wheelspin.
- maintain the acceleration slip of the driven wheels equal to the mean rotational velocity of the non-driven wheels + a specified speed difference known as the slip threshold.
- driven wheels are kept at a faster speed than the non-driven wheels
- the vehicle accelerates at a constant rate proportional to the difference in the two speeds. (if difference is not in limits (slip threshold), traction needs to be controlled)
- Control depends on road surface conditions or adhesion coefficient.
- on dry road surfaces, maximum acceleration at slip rates of 10 to 30%.
- On glare ice, maximum traction between 2 and 5 percent
- so TCS systems designed for a slip rate range between 2 and 20%.



Adhesion force coefficient μ_A as a function of acceleration λ_A (Jurgen, 1995)

- on loose sand or gravel and in deep snow the coefficient of adhesion increases continually with the slip rate
- TCS systems incorporate slip-threshold switches to allow the driver to select a higher slip threshold or switch off the TCS
- The control objectives of TCS are modified by vehicle speed and curve recognition.
- Both of these variables can be derived from the speeds of the non-driven wheels.
- coefficient of adhesion or friction decided on the basis of acceleration rate and engine torque
- The slip threshold is raised in response to higher friction coefficients to allow higher acceleration rates

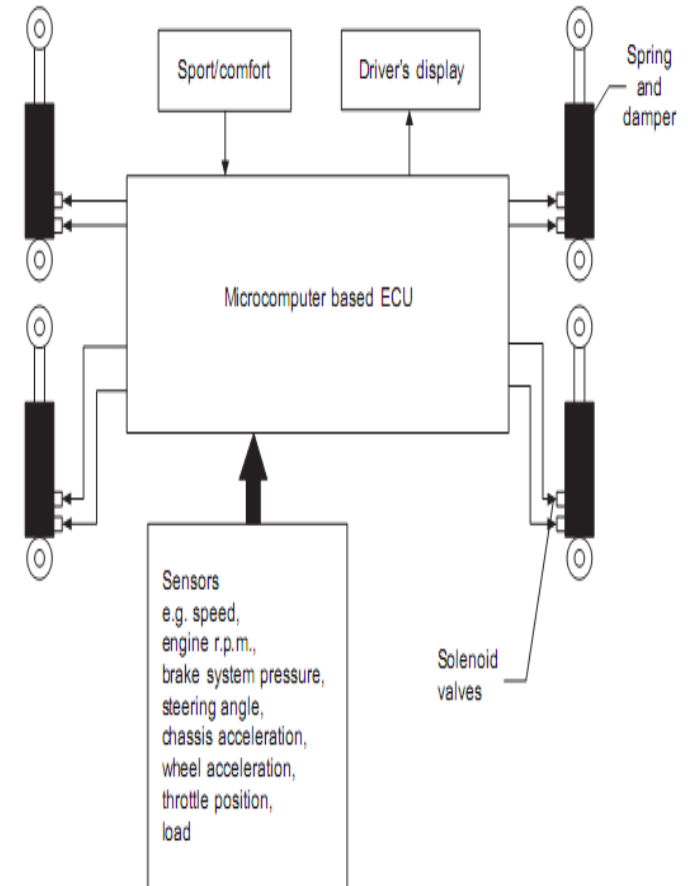
- Curve recognition or cornering detection also affects the control strategy for TCS.
- This strategy employs the difference in wheel speeds of the non-driven wheel speeds as a basis for reductions in the slip setpoint to enhance stability in curves.
- High vehicle speeds and low acceleration requirements on low coefficient of adhesion surfaces imply
 - a control strategy of progressively lower slip threshold setpoints as the vehicle speed increases,
 - gives maximum lateral adhesion on the surface.

Electronic damping control

- The primary function of a shock absorber
 - control vehicle movement against roll during turning and pitch during acceleration or braking.
 - Requires hard suspension
- secondary role
 - To prevent vehicle vibration caused by a poor road surface.
 - Requires a soft suspension
- Electronic damping control (EDC) used to attain these twin objectives
- altering the characteristics of spring and oil-filled damper arrangement
 - difficult and expensive
- Simple option - Suspensions with at least three settings; 'soft', 'medium' and 'firm'
- OR electronically controlled suspension systems using air, nitrogen gas and hydraulic oil as a suspension agent.

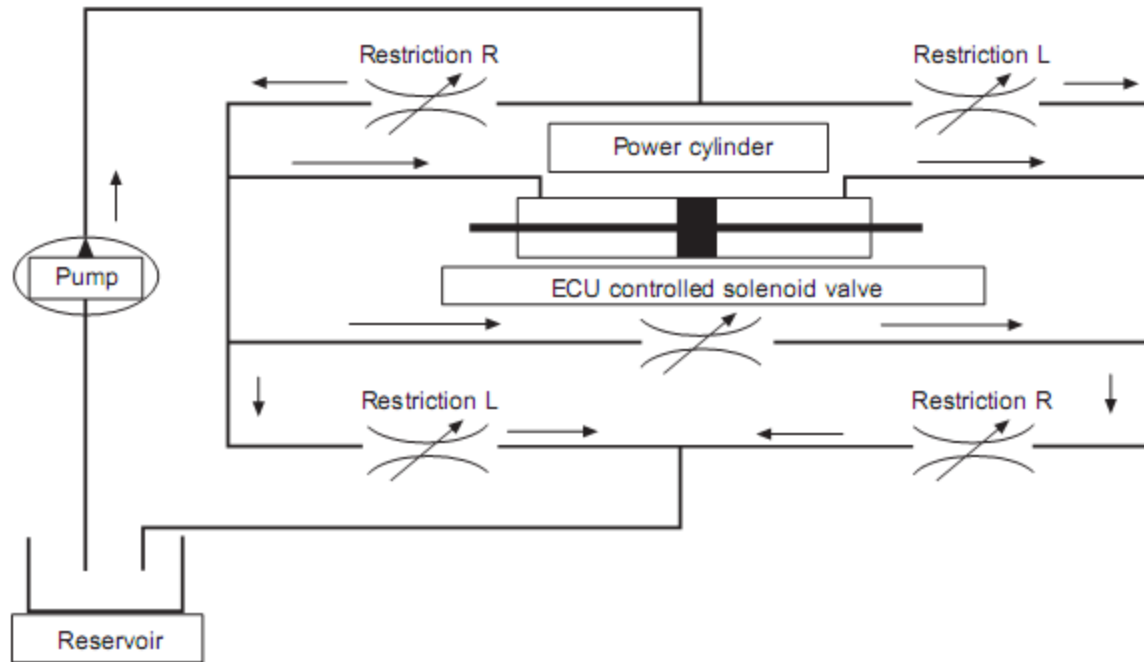
- sensors used
 - vehicle speed,
 - engine r.p.m.,
 - brake system pressure,
 - steering angle,
 - chassis and wheel acceleration,
 - throttle position,
 - vehicle load and
 - even road surface condition
- Road condition - implied by processing signals from front and rear height sensors rather than direct measurement.
 - if the height sensor signals a small high frequency but a large low frequency amplitude
 - a heaving or undulating road surface
 - Does not require a softening of damper.
 - A large high frequency component would suggest
 - a rough road surface and
 - Softening of damper action.
 - Conflicts with damper requirement to prevent rolling during cornering.
 - If the vehicle corners on a rough surface this must be resolved by the ECU.

- Longitudinal acceleration
 - measured directly using an acceleration sensor, or
 - inferred from brake system pressure and throttle opening angle.
 - Used to control pitching during acceleration / braking
- lateral forces
 - inferred by the rate at which the steering wheel is being turned and the vehicle speed.
 - used by the ECU to prevent rolling.
- the actuators are dampers fitted with two ON-OFF fluid control solenoids used to select one of four different damper settings (normal, soft, super-soft and firm).
- Driver can choose sport or smooth ride mode
 - In sport mode soft or super-soft damper settings excluded
 - Result in a harder but more stable ride.



Electronically controlled damping system

Electronically controlled power-assisted steering (PAS)



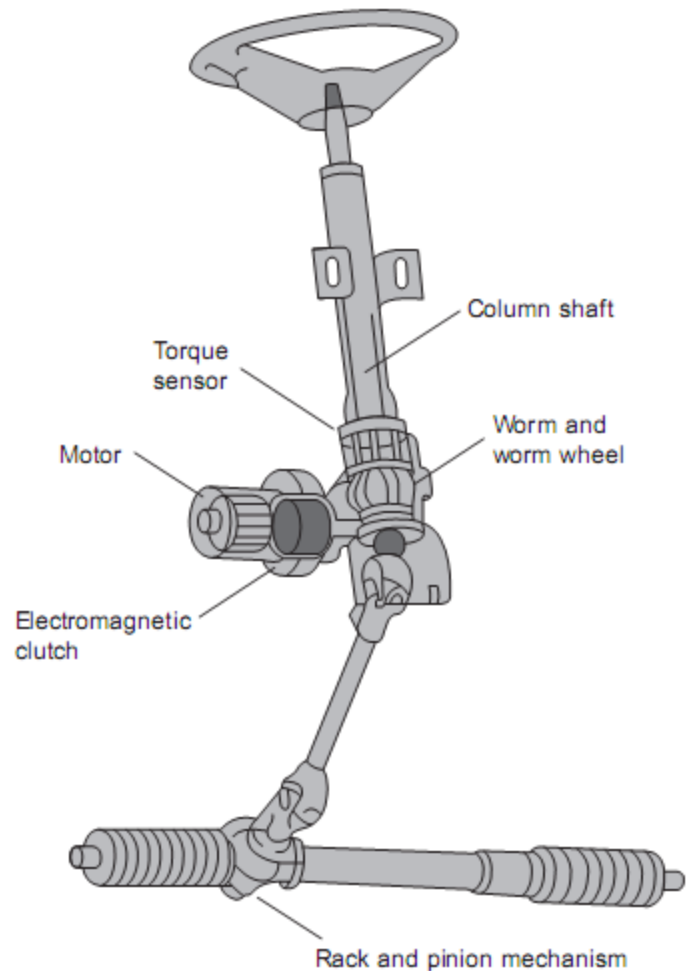
Hydraulic bridge circuit for electronically-controlled power steering showing flow paths

Electronically controlled hydraulic PAS

- the ports of a solenoid valve are connected across the rack and pinion steering hydraulic power cylinder.
- with increasing vehicle speed the valve opening is extended
 - reducing the hydraulic pressure in the power cylinder
 - increasing the steering effort.
- bridge-like restrictions for control of the power cylinder are formed by the paths through the pump to port connections of a rotary valve
- The valve is connected directly to the steering wheel and
 - a small movement of this controls the high pressure hydraulic fluid to reach the power cylinder/solenoid valve.

Electric PAS

- input to the rack and pinion steering system is from a motor/reduction gearbox
- motor torque is applied directly to either the pinion gear shaft or to the rack shaft.
- The steering effort range is greater than with hydraulic systems,
- installations are cheaper and reliable.
- Power is only consumed when steering wheel moves, (unlike hydraulic system)
- a torque sensor on the column shaft
- The electric motor coupled to the worm wheel mechanism through a reduction gearbox.
- The load torque T_L on the steering column is the load presented by the worm mechanism and the rack and pinion assembly to which it is attached.



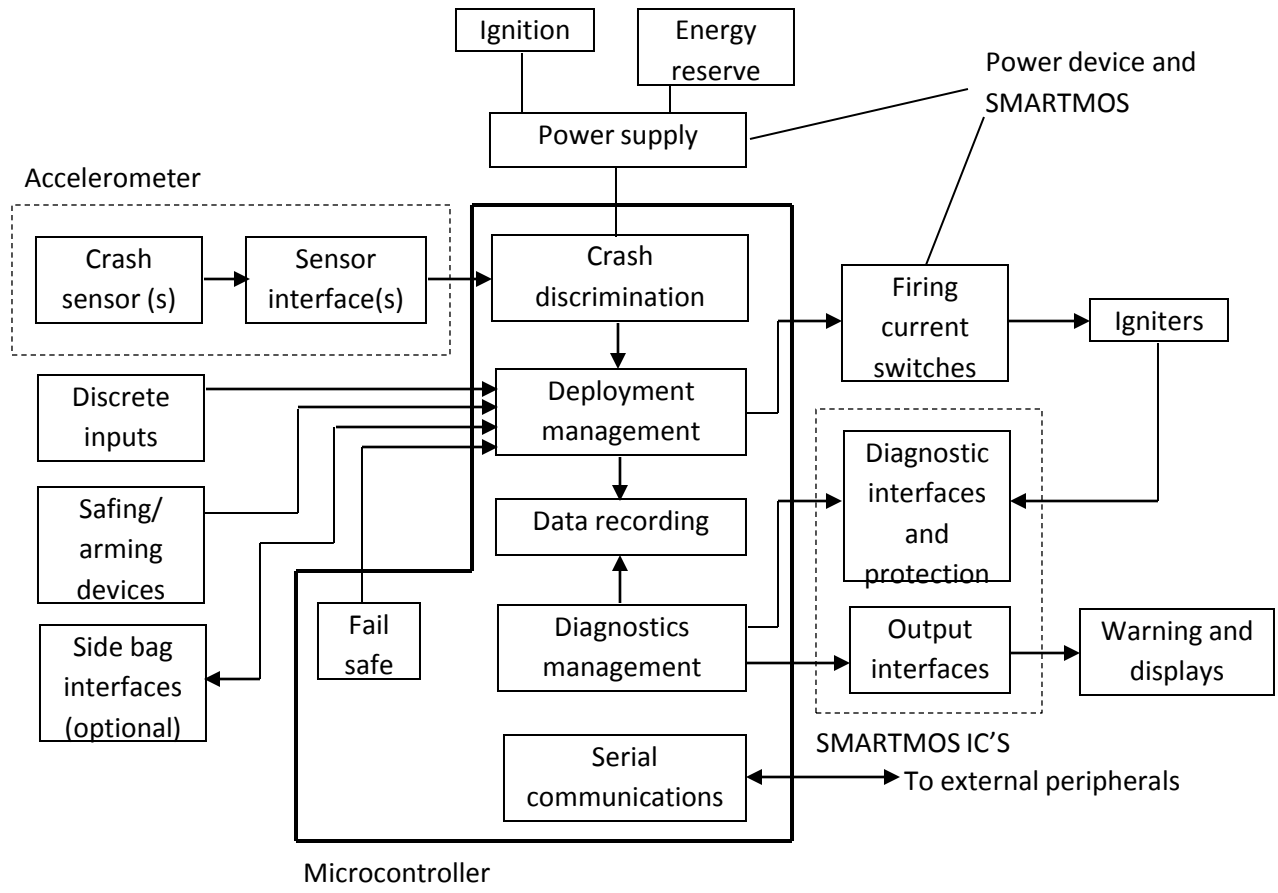
- The amount of motor torque is proportional to the motor current I_M .
- in a simple armature controlled d.c. motor the average current is given

$$I_M = \frac{V_M - k \times N}{R}$$

- where R is the armature resistance,
- N is the speed of the motor and V_M the motor voltage,
- the set point motor voltage depends on how much control effort is required from the d.c. motor.
- When a driver turning a steering wheel at a constant rate, say in cornering.
 - The d.c. motor, must turn at a speed proportional to this rate.
 - Controlling term --- motor voltage = $k \times N$
- at high vehicle speeds the assistance given to the driver must decrease in proportion to speed
 - i.e., Decrease motor current or voltage as vehicle speed increases.
 - Motor voltage component = $k_T \times T_m$ (T_m is output from Torque sensor)
 - Inverse function of vehicle speed
- Add both components to get appropriate control

Air-bag and seat belt pre-tensioner systems

- systems consist of
 - crash detection sensors (typically piezoelectric) with a signal conditioning amplifier
 - a microcontroller distinguishing between crashes and normal vehicle dynamics,
 - igniter triggering for the pyrotechnic inflator
 - used for air-bag deployment and seat belt tightening.
- The allowable forward passenger travel with an air-bag system is 12.5 cm
 - with seat belt tensioning systems it is about 1 cm.
- Approximately 30 ms are required to inflate air-bags and
- time required to tension a seat belt with a retractor = ~10 ms.
- triggering must be done by the time forward displacement is reached minus the activation time of the respective restraining device.
- Often multiple sensors and sensor mounting positions
- When airbag is triggered
 - ECU turns on the firing current switches,
 - allows current through the igniter,
 - initiates a gas generation reaction inside the inflation module.
 - Capacitance based power maintained even if battery is disconnected



Air-bag electronics block diagram