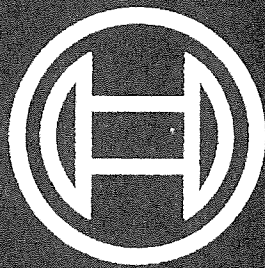


# **AUTOMOTIVE HANDBOOK**



**BOSCH**

**4<sup>th</sup>**  
EDITION

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## Forev

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## Drivetrain

### Quantities and units

Quantity	Unit
$a$ Acceleration	m/s <sup>2</sup>
$c_w$ Aerodynamic drag	—
$e$ Rotational inertia coefficient	—
$f$ Coefficient of rolling resistance	—
$g$ Gravitational acceleration	m/s <sup>2</sup>
$i$ Conversion ratio	—
$m$ Vehicle mass	kg
$n$ Rotational speed	1/min
$r$ Dynamic tire radius	m
$v$ Vehicle velocity	m/s
$A$ Frontal area	m <sup>2</sup>
$J$ Mass moment of inertia	kg · m <sup>2</sup>
$M$ Torque	N · m
$P$ Power	kW
$\alpha$ Ascent angle	°
$\phi$ Overdrive factor	—
$\eta$ Efficiency	—
$\lambda$ Power number	—
$\mu$ Conversion	—
$\rho$ Density	kg/m <sup>3</sup>
$\omega$ Angular velocity	rad/s
$\nu$ Rotational speed ratio	—

Subscripts:	m engine
rms root mean square	o pertaining to max. power
tot total	A drivetrain
hydr hydraulic	G transmission
max maximum	P pump
min minimum	R wheel
h final drive	T turbine

### Function

The function of the automotive drivetrain is to provide the thrust and tractive forces required to overcome running resistance

and induce motion. Energy in chemical (fuels) or electrical (batteries, solar cells) form is converted into mechanical energy within the power unit, with spark-ignition and diesel internal-combustion engines representing the powerplants of choice. Every power unit operates within a specific revolution range as defined by two extremities: the idle speed and the maximum rpm. Torque and power are not delivered at uniform rates throughout the operating range; the respective maxima are available only within specific bands. The drivetrain's conversion ratios adapt the available torque to the momentary requirement for tractive force.

### Drivetrain configurations

The layout of the automotive drivetrain varies according to the position of the engine and the drive axle:

Drive layout	Engine position	Driven axle
Standard	front	rear
Front-wheel drive	front, longitudinal or transverse	front
All-wheel drive	front (rear or center in isolated applications)	front and rear permanent or driver-selected (between single and two-axle drive), gradual transition also possible
Rear drive	rear	rear

### Equilibrium relation between drive forces and tractive resistance

The equation defining the equilibrium between drive forces and resistance factors is applied to determine various quantities, such as acceleration, top speed, climbing ability, etc.

Available power = Tractive resistance at drive wheels (power requirement)

$$M_m \cdot \frac{i_{\text{tot}}}{r} \cdot \eta_{\text{tot}} = m \cdot g \cdot f \cdot \cos \alpha + m \cdot g \cdot \sin \alpha + e \cdot m \cdot \alpha + c_w \cdot A \cdot \frac{\rho}{2} \cdot v^2$$

Drive force at tire contact patches	Rolling resistance	Ascent resistance	Acceleration resistance	Aerodynamic resistance

With rational inertia coeffic.  $e = 1 + \frac{J}{m \cdot r^2}$  and mass moment of inertia  $J = J_R + i_h^2 J_A + i_h^2 i_G^2 J_m$

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### Drivetrain elements

The drivetrain components must satisfy the basic requirements associated with vehicle operation in all ranges, from the stationary state and through all desired operating points up to top speed. This entails satisfying the following requirements:

- achieving the transition from a stationary to a mobile state,
- converting torque and rotational speed,
- supplying forward and reverse motion,
- compensating for wheel-speed variations in curves,
- ensuring that the power unit remains within a range on the operating curve commensurate with minimum fuel consumption and exhaust emissions.

Stationary idle, transition to motion and interruption of the power flow are all made possible by the clutch. The clutch slips to compensate for the difference in the rotational speeds of engine and drivetrain when the vehicle is being set in motion. When a change in operating conditions makes it necessary to change gears, the clutch disengages the engine from the drivetrain for the duration of the procedure. In automatic transmissions hydrodynamic clutches or torque converters assume responsibility for the drive-engagement process.

The transmission (gearbox) modifies the engine's torque and rpm to adapt them to the vehicle's momentary tractive requirements, maintaining the power  $P = M \cdot \omega$  at a relatively constant level.

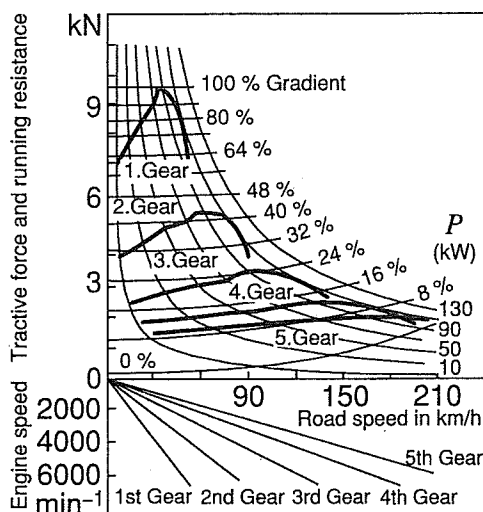
The overall conversion ratio is generally a composite of the ratios provided by a transmission (gearbox), with several available ratios (less commonly with infinitely-variable arrangements), and a constant-ratio final-drive unit. Positive-transfer gear transmissions are more common than non-positive units due to their superior performance-to-weight ratio.

Gear transmissions generally fall into one of two categories: the manually-shifted spur-gear transmission with main and countershaft (layshaft, idler shaft), and the planetary-gear unit featuring power-demand shifting (in automatic transmissions). The transmission also allows the selection of different rotational directions for forward and reverse operation.

The differential allows laterally opposed axles and wheels to rotate at varying rates during cornering while providing uniform distribution of the driving forces. Limited-slip final drives respond to slippage at one of the wheels by limiting the differential effect, shifting additional power to the wheel at which traction is available.

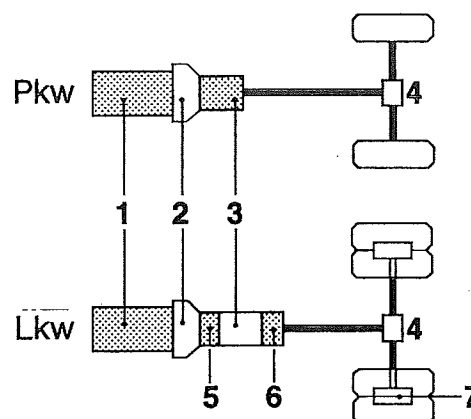
In the control system, final-control elements (actuators) and switches supervise

**Tractive force/speed diagram**



**Multiple-ratio transmission in drivetrain**

1 Engine, 2 Clutch, 3 Manual transmission, 4 Final-drive unit, 5 Front splitter unit, or, alternatively, 6 Rear range group, 7 Planetary-gear set.



execution of the required ratio conversions. The control-elements are actuated either directly, by the driver, or automatically, as sensor signals are processed in an electronic or hydraulic control unit in accordance with a specific program.

Torsion dampers, mass compliance systems and hydraulic transmission elements are all available to attenuate high-frequency vibrations. These protect the power unit from excessive loads and enhance comfort by reducing vibration.

## Clutches and couplings

### Friction clutch

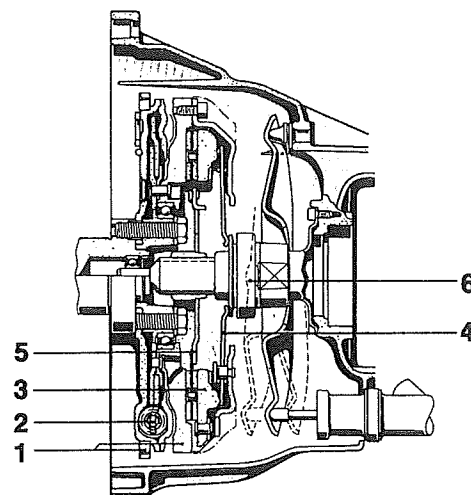
The friction clutch consists of a pressure plate, a clutch disk — featuring bonded or riveted friction surfaces — and the second friction surface represented by the engine-mounted flywheel. The flywheel and pressure plate provide the thermal absorption required for friction operation of the clutch; flywheel and pressure plate are connected directly to the engine, while the clutch disk is mounted on the transmission's input shaft.

A spring arrangement, frequently in the form of a central spring plate, applies the force which joins the flywheel, pressure plate and clutch disk for common rotation;

in this state, the clutch is engaged for positive torque transfer. To disengage the clutch (e.g., for shifting), a mechanically or hydraulically actuated throwout bearing applies force to the center of the pressure plate, thereby releasing the pressure at the periphery. The clutch is controlled either with a clutch pedal or

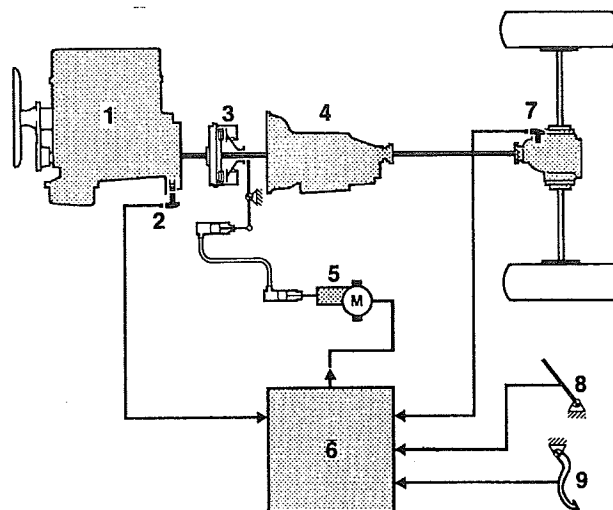
### Clutch with dual-mass flywheel

1 Dual-mass flywheel, 2 Flexible element, 3 Pressure plate, 4 Diaphragm spring, 5 Clutch disk, 6 Throwout bearing.



### Automatic clutch, limited to clutch actuation

- 1 Engine
- 2 Engine rpm sensor
- 3 Clutch
- 4 Transmission
- 5 Servomotor
- 6 Control unit
- 7 Speed sensor
- 8 Accelerator pedal
- 9 Clutch pedal





with an electrohydraulic or electromechanical final-control element. A single or multi-stage torsion damper, with or without a predamper, may be integrated in the clutch plate to absorb vibration.

A two-section (dual-mass) flywheel featuring a flexible intermediate element can be installed forward of the clutch for maximum insulation against vibrations. Because the intrinsic resonant frequency of this spring-mass system is below the excitation (ignition) frequency of the engine at idle, it lies outside the normal rpm range. It thus insulates the engine from the other drive-train components ("low-pass filter").

When used together with an electronic control unit, the automatic clutch can provide either gradual engagement for starting off, or it can be applied in conjunction with a servo-operated shifting mechanism to form a fully-automatic transmission unit. Among such a device's other potential functions are traction control under acceleration and interruption of power transfer during braking.

### Hydrodynamic couplings and converters

Hydrodynamic couplings and torque converters employ the force represented by a moving fluid to transmit engine torque. Because these devices compensate for differences in the rotating speeds of engine and drivetrain, they are ideal for effecting the transition from stationary to mobile operation. The torque converter also multiplies torque. First, an impeller converts the mechanical energy emanating from the power unit into fluid energy (hydraulic fluid – ATF – is the preferred medium); a second transformation, back into mechanical energy, occurs at the blades within the turbine.

The impeller's input torque  $M_P$  and input power  $P_P$  are calculated as follows:

$$M_P = \lambda \cdot \rho \cdot D^5 \cdot \omega_P^2$$

$$P_P = \lambda \cdot \rho \cdot D^5 \cdot \omega_P^3$$

$\lambda$  Performance index

$\rho$  Density of medium  
( $\approx 870 \text{ kg/m}^3$  for hydraulic fluid)

$D$  Circuit diameter in m

$\omega_P$  Angular velocity of impeller in rad/s

The dependence of input torque  $M_P$  and input power  $P_P$  on  $D^5$  on the other, is characteristic for all hydropneumatic drive systems.

The ratio of turbine torque  $M_T$  to impeller force  $M_P$  determines the torque-conversion factor  $\mu = M_T/M_P$ .

The  $v$  factor is defined as the ratio of turbine speed to impeller speed; it exercises a determining influence on both the performance index  $\lambda$  and the conversion factor  $\mu$ . The relevant equation:  $v = \omega_T/\omega_P$ .

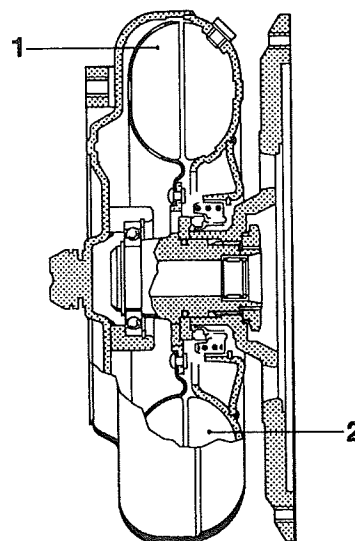
The slip factor  $s = 1 - v$  and the force conversion together determine the hydraulic efficiency:

$$\eta_{\text{hydr}} = \mu (1 - s) = \mu \cdot v.$$

Among the benefits offered by hydrodynamic couplings and torque converters are the following attributes: infinitely-variable, stepless variations in torque and rpm, vibration insulation, absorption of torque peaks and virtually wear-free power transfer. These devices offer economical operation when used together with mechanical variable-ratio transmissions; operation with non-positive engagement (slip) is limited in the interests of efficiency. It is also possible to divert torque flow from the hydrodynamic element to a friction clutch to achieve further reductions in undesirable slip, with commensurate improvements in the efficiency factor.

### Hydrodynamic coupling

1 Turbine, 2 Impeller.



### Hydrodynamic couplings

In its standard configuration, the hydrodynamic (or Föttinger) coupling is composed of an impeller and a turbine with (normally) radial vanes. The impeller is often expanded to include a housing enclosing the turbine. The absence of a stator means that there is no flow diversion between turbine and impeller; thus the torque at the turbine is equal to that at the impeller  $M_T = -M_P$ . This means that  $\mu = 1$  (force ratio) and  $\eta_{\text{hydr}} = \nu$ . The factor  $\nu$  is determined by vane geometry, although the coupling's volumetric efficiency may also exercise some influence. The normal automotive operating range is around  $\nu \approx 0.95$  with up to  $\nu \approx 0.98$  possible in highway applications.

### Hydrodynamic torque converters

The hydrodynamic torque converter – also known as the Föttinger speed transformer or converter – consists of an impeller, a turbine and a stator. The converter is capable of operation in two distinct ranges, providing torque multiplication in the first stage, and functioning as a simple hydrodynamic coupling with no torque gain in the second. Operation is similar to that of the basic hydrodynamic coupling; the vehicle's power unit drives the impel-

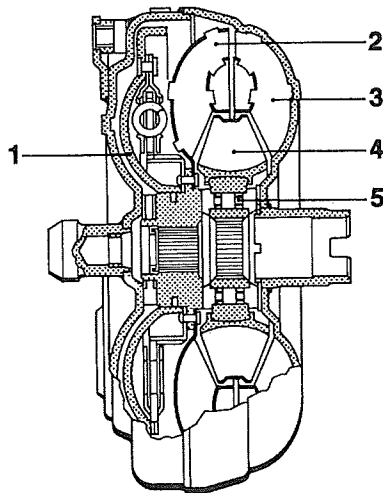
ler to produce fluid energy in the hydraulic medium, while the turbine connected to the transmission input shaft transforms this hydraulic energy back into mechanical force. A stator located between impeller and turbine diverts the hydraulic medium back to the input side of the impeller.

This raises the torque beyond the initial engine output as exerted at the impeller. The degree of torque multiplication  $\mu = M_T/M_P$  increases as a function of the difference in the respective rotating speeds (expressed as slip) of impeller and turbine. Maximum torque multiplication is achieved at  $\nu = 0$ , i.e., with the turbine at stall speed. Further increases in turbine speed are accompanied by a virtually linear drop in multiplication until a torque ratio of 1:1 is reached at the coupling point. Above this point the stator, which is housing-mounted with a one-way clutch, freewheels in the flow.

A Föttinger torque converter featuring a centripetal turbine – the Trilok converter – has become the standard for automotive applications. The geometrical configuration of this unit's blades is selected to provide torque multiplication in the range of 1.9...2.5 at stall speed ( $\nu = 0$ ). The curve defining the hydraulic efficiency factor  $\eta_{\text{hydr}} = \nu \cdot \mu$  in the conversion range is

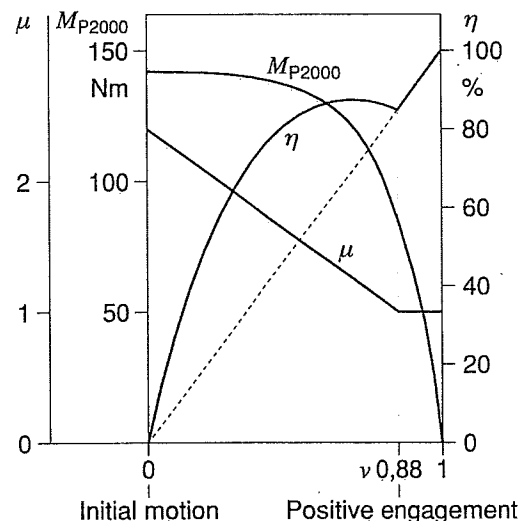
#### Hydrodynamic converter with lockup clutch

1 Lockup clutch, 2 Turbine, 3 Impeller, 4 Stator, 5 One-way clutch.



#### Trilok converter

(typical passenger-car performance curve).



roughly parabolic. Above the coupling point, at which the slip rates lie in a range of 10...15% the efficiency level is equal to the rpm ratio  $\nu$  reaching levels around 97% at high rpm. Fluid couplings form the initial input element of automatic transmissions (where they operate together with planetary-gear sets, clutches, brake bands and one-way clutches). They are also used in converter-clutch units for semiautomatic transmissions.

### Converter lockup clutch

The converter lockup clutch provides a friction coupling between impeller and turbine to avoid the efficiency losses associated with slip under those conditions in which torque multiplication and damping are not required. The converter lockup clutch consists of a plunger with friction surface; this is connected to the turbine hub via a torsion damper. As far as basic principles are concerned, both the layout and the operation of the torsion damper correspond to those of the dry friction clutch. The transmission's valve body regulates the direction in which the fluid flows through the converter to regulate coupling engagement.

## Transmission (gearbox)

The required total conversion range  $I$  is approximately:

$$I \approx \frac{\tan \alpha_m \cdot v_0}{(P/G)_{\text{eff}} \cdot \varphi}$$

$\tan \alpha_m$  is maximum hill-climbing ability,  $v_0$  is the power-specific top speed,  $(P/G)_{\text{eff}}$  is the effective specific output,  $\varphi$  is the over-drive factor, with

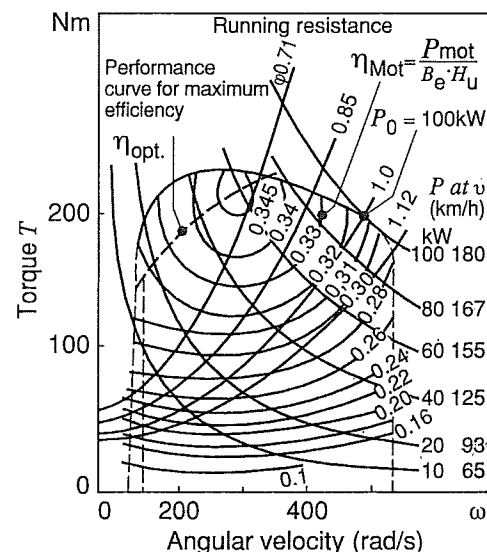
$$\varphi = \frac{(i/r)_{\min}}{\omega_0 / v_0}$$

$r$  dynamic tire radius,  $(i/r)_{\min}$  minimum conversion,  $\omega_0$  is the engine's rated angular velocity.

Calculations of effective specific output should always be based on the power  $P$  which is actually available for tractive application (net power minus driven ancillaries, power losses, altitude loss). Special conditions, such as automobile trailer towing, must be factored into the weight  $G$ .  $\varphi = 1$  when the curve for cumulative running resistance in top gear directly intersects the point of maximum output. For passenger cars, the required conversion range  $I$  is 3...4 at  $\varphi = 1$ ; for a truck with a minimum specific output of 4.5 kW/t the figure is 8...10. Because the  $\varphi$  factor

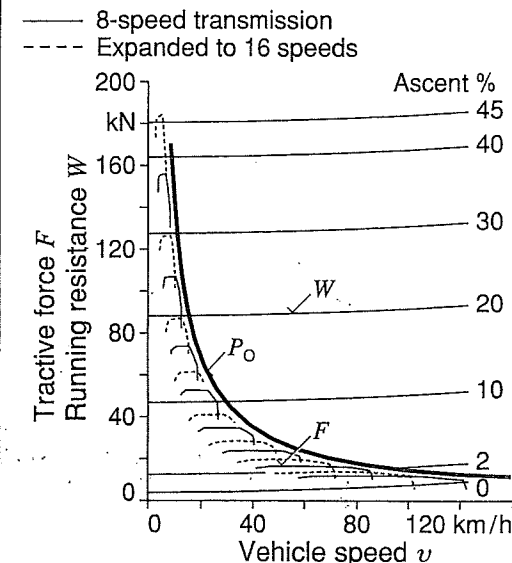
### Engine performance curve with curves for running resistance

(Example). Car engine with  $P_0 = 100$  kW at  $\omega_0 = 500$  rad/s and  $T_{\max} = 230$  N·m bei  $\omega = 250$  rad/s.



### Operating diagram for truck with multiple gear ratios

Specific output 8.5 kW/t.  $P_0$  Nominal output



transmission with several ratios  $i_G$  and a final drive unit with conversion  $i_h$  the relationship between the rpm of the power unit  $n_d$  and that of the wheels  $n_R$  (with tire radius  $r$ ) is defined as:

$$n_R = n_m / (i_G \cdot i_h)$$

Vehicle speed is then:

$$v = \frac{2 \cdot \pi \cdot n_m \cdot r}{i_G \cdot i_h}$$

In most automotive applications the final-drive unit consists of a ring-and-pinion unit with hypoid-bevel gears (longitudinal engine) or a spur-gear set (transverse engine). The tooth ratio determines the conversion factor, which generally lies within a range of between 2.2:1 and 5.0:1 for production vehicles.

On commercial vehicles, it will seldom be possible to achieve the required conversion range with a single ring-and-pinion set; more complicated arrangements are usually employed:

- single-ratio axles (for up to  $i_h = 7$ ),
- dual-shaft axle with front or top-mounted pinion drive,
- two-speed axle (overall conversion  $i_h = 9$ ),
- pinion drive (spur-gear assembly in hub unit),

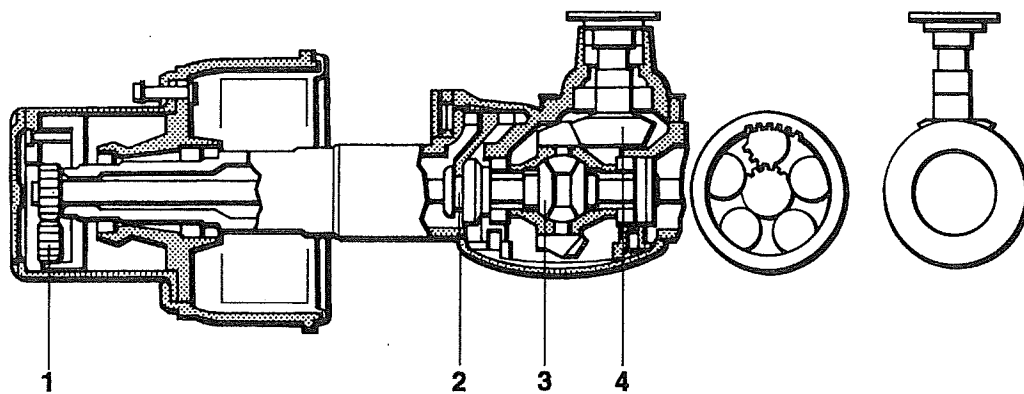
– hub-mounted planetary-gear set (variable-ratio in special applications). Large-diameter sun gears reduce ground clearance beneath the differential. The use of supplementary pinion-gear sets and outside planetary-gear axles to divide final conversion into two stages makes it possible to reduce the dimensions of both differential unit and axle shafts, allowing adequate ground clearance to be maintained even in high-power configurations.

### Planetary-gear sets

Major areas of application for planetary-gear sets include final-drive units, front and rear range divider (splitter) units, and automatic transmissions. The basic planetary-gear set consists of the sun gear, internal ring gear and the planet gears with carrier. Each element can act as input or output gear, or may be held stationary. The coaxial layout of the three elements makes this type of unit ideal for use with friction clutches and brake bands, which are employed for selective engagement and retention of individual elements. The engagement pattern can be changed – and a different conversion ratio selected – without interrupting torque flow; this capability is of particular significance in automatic transmissions.

#### Hub planetary-gear axle for trucks

1 Planetary-gear set, 2 Differential lock, 3 Differential, 4 Final drive.





Because the forces are distributed among several gears in simultaneous, parallel engagement, dimensions remain compact. The gear unit exhibits no free bearing forces, is suitable for high torques, and can be used for torque division and/or addition. Efficiency is high.

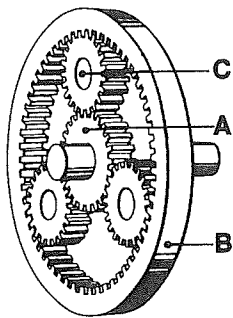
## Differential

The differential unit compensates for discrepancies in the respective rotation rates of the drive wheels: between inside and outside wheels during cornering, and between different drive axles on AWD vehicles.

### Planetary-gear set with various conversion ratios

A Sun gear, B Internal ring gear, C Planet gears with carrier.

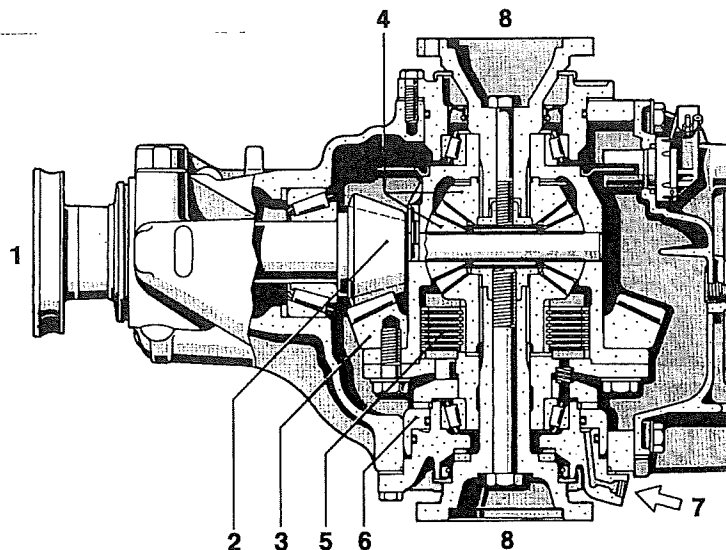
Basic equation for planetary-gear sets:  $n_A + (Z_B / Z_A) \cdot n_B - [1 + Z_B / Z_A] \cdot n_C = 0$



Input	Output	Locked	Ratio	Remarks
A	C	B	$i = 1 + Z_B / Z_A$	$2.5 \leq i \leq 5$
B	C	A	$i = 1 + Z_A / Z_B$	$1.25 \leq i \leq 5$
C	A	B	$i = \frac{1}{1 + Z_B / Z_A}$	$0.2 \leq i \leq 0.4$ Upward conversion
C	B	A	$i = \frac{1}{1 + Z_A / Z_B}$	$0.6 \leq i \leq 0.8$ Upward conversion
A	B	C	$i = -Z_B / Z_A$	Stationary transmission with direction reversal $-0.4 \leq i \leq -1.5$
B	A	C	$i = -Z_A / Z_B$	Stationary transmission with direction reversal $-0.25 \leq i \leq -0.67$

### Final-drive unit with electronic-hydraulic limited-slip differential

1 Input side, 2 Drive pinion, 3 Ring gear, 4 Differential gears, 5 Plate set, 6 Hydraulic plunger, 7 Hydraulic connection, 8 Output side.



With rare exceptions for special applications, the differential is a bevel-gear drive unit. When the output bevel gears on the left and right sides (most common arrangement) are of equal dimensions, the differential gears act as a balance arm to equalize the distribution of torque to the left and right wheels. When lateral variations in the road surface (split) produce different coefficients of friction at the respective wheels, this balance effect limits the effective drive torque to a level defined as twice the tractive force available at the wheel (tire) with the lower coefficient of friction. This wheel then responds to the application of excessive torque by spinning.

The limited-slip differential combats this undesirable tendency by employing friction plates, friction cones, self-locking gears, or multiplate units in high-viscosity fluid media to limit the differential effect. The locking factor defines the effectiveness of the limited-slip differential:

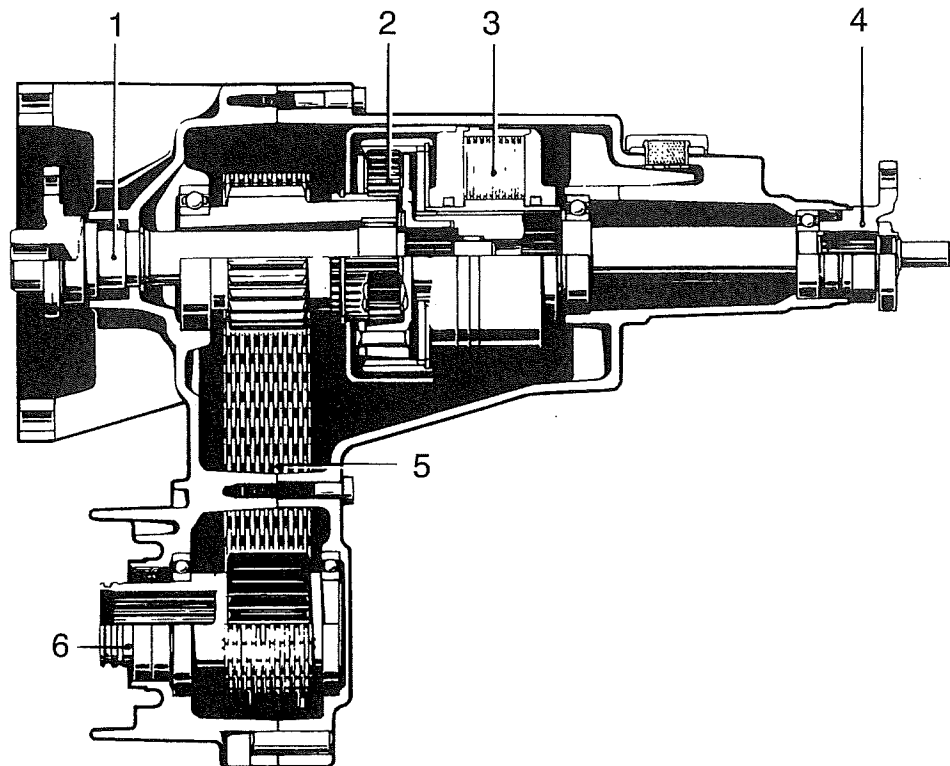
$$S = \frac{|M_{\text{left wheel}} - M_{\text{right wheel}}|}{M_{\text{left wheel}} + M_{\text{right wheel}}} \cdot 100\%$$

Typical locking factors for passenger vehicles lie between 25 and 40%. The locking effect increases in response to variations in input torque (normal multiplate limited-slip unit), to differences in torque (self-locking gear sets) or rotating speed (viscous limited slip).

Limited-slip differentials can also employ electronic control to adapt to a widely variegated range of operating conditions: A high locking factor for starting off can be succeeded by a lower factor as speed increases or as the traction limit is reached. Driver-activated positive-action differential locks are available for use under special conditions (e.g., off-road).

**Transfer case for AWD with viscous coupling**

1 Input shaft, 2 Planetary-gear set, 3 Viscous coupling  
4 To rear axle, 5 Chain drive, 6 To front axle



## All-wheel drive, transfer case

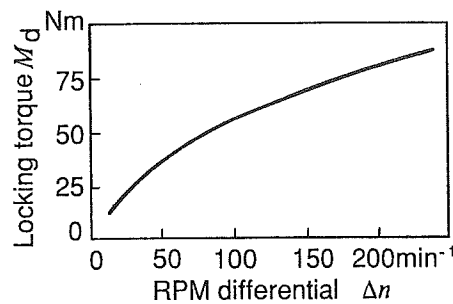
All-wheel drive must meet especially stringent requirements for traction while simultaneously reducing the effects which this traction exerts on active vehicle response. Various types of systems are employed:

Permanent all-wheel drive, with 50% /50% distribution using a bevel-gear differential or asymmetrical distribution via planetary-gear unit. The theoretical torque distribution is modified by the effect of automatic or controlled limited-slip differentials.

– Driver-selected all-wheel drive (solid couplings at front/rear, viscous coupling or transfer case), with driver-actuated differential locks in transfer case and final drive. Transfer cases for off-road vehicles incorporate an additional driver-controlled conversion range for steep gradients, low speeds and high torque transfer. The viscous coupling ( an encapsulated multiplate unit with a high-viscosity sili-

cone fluid) represents yet another means of activating the all-wheel drive. Once the traction limit at the permanently-engaged axle is exceeded, the unit responds to variations in slip by transferring torque to the secondary drive axle in accordance with the viscous-drive response curve. A unidirectional coupling interrupts the power flow to the secondary axle in the trailing-throttle mode, making the system suitable for use with ABS.

**Locking-torque curve for viscous-coupling transfer case**



### 4wd layout

1 Engine, 2 Transmission, 3 Transfer case, 4 Driveshaft to rear differential, 5 Differential, 6 Driveshaft to front differential.

