Bosch Professional Automotive Information

BOSCH
Invented for life

Konrad Reif *Ed.*

Brakes, Brake Control and Driver Assistance Systems

Function, Regulation and Components

Springer Vieweg

Bosch Professional Automotive Information

Bosch Professional Automotive Information is a definitive reference for automotive engineers. The series is compiled by one of the world´s largest automotive equipment suppliers. All topics are covered in a concise but descriptive way backed up by diagrams, graphs, photographs and tables enabling the reader to better comprehend the subject.

There is now greater detail on electronics and their application in the motor vehicle, including electrical energy management (EEM) and discusses the topic of intersystem networking within vehicle. The series will benefit automotive engineers and design engineers, automotive technicians in training and mechanics and technicians in garages.

Konrad Reif
Editor

Brakes, Brake Control and Driver Assistance Systems

Function, Regulation and Components

Springer

Editor
Prof. Dr.-Ing. Konrad Reif
Duale Hochschule Baden-Württemberg
Friedrichshafen, Germany
reif@dhbw-ravensburg.de

ISBN 978-3-658-03977-6 ISBN 978-3-658-03978-3 (eBook)
DOI 10.1007/978-3-658-03978-3

Library of Congress Control Number: 2014945109

Springer Vieweg

Printed on acid-free paper

Springer is part of Springer Science+Business Media
www.springer.com

Foreword

Braking systems have been continuously developed and improved throughout the last years. Major milestones were the introduction of antilock braking system (ABS) and electronic stability program. This reference book provides a detailed description of braking components and how they interact in electronic braking systems.

Complex technology of modern motor vehicles and increasing functions need a reliable source of information to understand the components or systems. The rapid and secure access to these informations in the field of Automotive Electrics and Electronics provides the book in the series “Bosch Professional Automotive Information” which contains necessary fundamentals, data and explanations clearly, systematically, currently and application-oriented. The series is intended for automotive professionals in practice and study which need to understand issues in their area of work. It provides simultaneously the theoretical tools for understanding as well as the applications.

Contents

Authors

Motor-vehicle safety
Dipl.-Ing. Wulf Post.

Basic principles of vehicle dynamics
Dipl.-Ing. Friedrich Kost.

Car braking systems
Dipl.-Ing. Wulf Post.

Car braking-system components
Dipl.-Ing. Wulf Post.

Wheel brakes
Dipl.-Ing. Wulf Post.

Antilock braking system (ABS)
Dipl.-Ing. Heinz-Jürgen Koch-Dücker,
Dipl.-Ing. (FH) Ulrich Papert.

Traction control system (TCS)
Dr.-Ing. Frank Niewels,
Dipl.-Ing. Jürgen Schuh.

Electronic stability program (ESP)
Dipl.-Ing. Thomas Ehret.

Automatic brake functions
Dipl.-Ing. (FH) Jochen Wagner.

Hydraulic modulator
Dr.-Ing. Frank Heinen,
Peter Eberspächer.

Sensors for brake control
Dr.-Ing. Erich Zabler.

Sensotronic brake control (SBC)
Dipl.-Ing. Bernhard Kant.

Active steering
Dipl.-Ing. (FH) Wolfgang Rieger,
ZF Lenksysteme, Schwäbisch Gmünd, Germany.

Occupant protection systems
Dipl.-Ing. Bernhard Mattes.

Driving assistance systems
Prof. Dr.-Ing. Peter Knoll.

Adaptive cruise control (ACC)
Prof. Dr. rer. nat. Hermann Winner,
Dr.-Ing. Klaus Winter,
Dipl.-Ing. (FH) Bernhard Lucas,
Dipl.-Ing. (FH) Hermann Mayer,
Dr.-Ing. Albrecht Irion,
Dipl.-Phys. Hans-Peter Schneider,
Dr.-Ing. Jens Lüder.

Parking systems
Prof. Dr.-Ing. Peter Knoll.

Instrumentation
Dr.-Ing. Bernhard Herzog.

Orientation methods
Dipl.-Ing. Gerald Spreitz,
S. Rehlich,
M. Neumann,
Dipl.-Ing. Marcus Risse,
Dipl.-Ing. Wolfgang Baierl.

Navigation systems
Dipl.-Ing. Ernst-Peter Neukirchner,
Dipl.-Kaufm. Ralf Kriesinger,
Dr.-Ing. Jürgen Wazeck.

Workshop technology
Dipl.-Wirtsch.-Ing. Stephan Sohnle,
Dipl.-Ing. Rainer Rehage,
Rainer Heinzmann.

and the editorial team in cooperation with the responsible in-house specialist departments.

Unless otherwise stated, the authors are all employees of Robert Bosch GmbH.

Basics

Motor-vehicle safety

In addition to the components of the drivetrain (engine, transmission), which provide the vehicle with its means of forward motion, the vehicle systems that limit movement and retard the vehicle also have an important role to play. Without them, safe use of the vehicle in road traffic would not be possible. Furthermore, systems that protect vehicle occupants in the event of an accident are also becoming increasingly important.

Safety systems

There are a many factors that affect vehicle safety in road traffic situations:

- the condition of the vehicle (e.g. level of equipment, condition of tires, component wear),
- the weather, road surface and traffic conditions (e.g. side winds, type of road surface and density of traffic), and
- the capabilities of the driver, i.e. his/her driving skills and physical and mental condition.

In the past, it was essentially only the braking system (apart, of course, from the vehicle lights) consisting of brake pedal, brake lines and wheel brakes that contributed to vehicle safety. Over the course of time though, more and more systems that actively intervene in braking-system operation have been added. Because of their active intervention, these safety systems are also referred to as *active safety systems.*

The motor-vehicle safety systems that are found on the most up-to-date vehicles substantially improve their safety.

The brakes are an essential component of a motor vehicle. They are indispensable for safe use of the vehicle in road traffic. At the slow speeds and with the small amount of traffic that were encountered in the early years of motoring, the demands placed on the braking system were far less exacting than they are today. Over the course of time, braking systems have become more and more highly developed. In the final analysis, the high speeds that cars can be driven at today are only possible because there are reliable braking systems which are capable of slowing down the vehicle and bringing it safely to a halt even in hazardous situations. Consequently, the braking system is a key part of a vehicle's safety systems.

As in all other areas of automotive engineering, electronics have also become established in the safety systems. The demands now placed on safety systems can only be met with the aid of electronic equipment.

1 Safety when driving on roads (concepts and influencing variables)

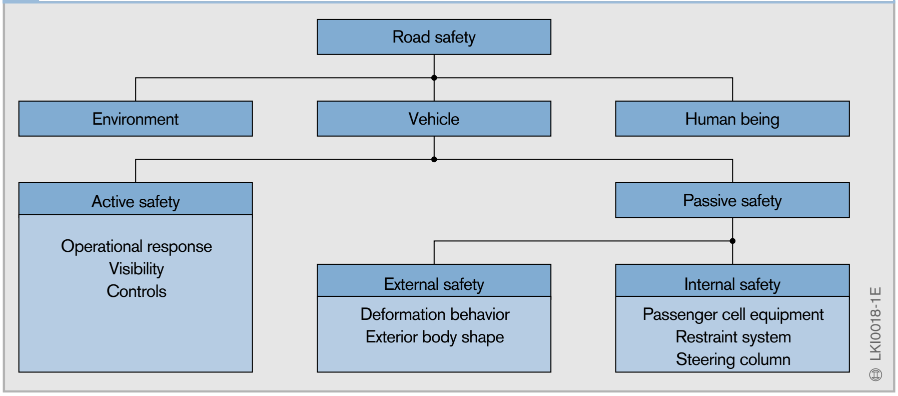


Table 1

K. Reif (Ed.), *Brakes, Brake Control and Driver Assistance Systems,* Bosch Professional Automotive Information, DOI 10.1007/978-3-658-03978-3_1, © Springer Fachmedien Wiesbaden 2014

1 Motor-vehicle safety systems

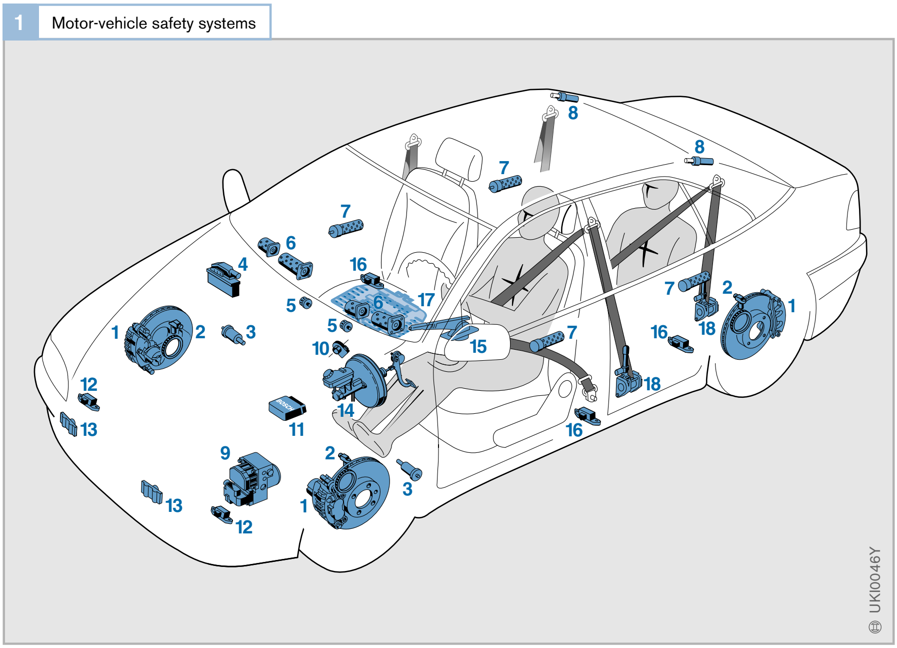


Fig. 1

1	Wheel brake with brake disk
2	Wheel-speed sensor
3	Gas inflator for foot airbag
4	ESP control unit (with ABS and TCS function)
5	Gas inflator for knee airbag
6	Gas inflators for driver and passenger airbags (2-stage)
7	Gas inflator for side airbag
8	Gas inflator for head airbag
9	ESP hydraulic modulator
10	Steering-angle sensor
11	Airbag control unit
12	Upfront sensor
13	Precrash sensor
14	Brake booster with master cylinder and brake pedal
15	Parking brake lever
16	Acceleration sensor
17	Sensor mat for seat-occupant detection
18	Seat belt with seat-belt tightener

Active safety systems

These systems help to prevent accidents and thus make a preventative contribution to road safety. Examples of active vehicle safety systems include

- ABS (**A**ntilock **B**raking **S**ystem),
- TCS (**T**raction **C**ontrol **S**ystem), and
- ESP (**E**lectronic **S**tability **P**rogram).

These safety systems stabilize the vehicle's handling response in critical situations and thus maintain its steerability.

Apart from their contribution to vehicle safety, systems such as **A**daptive **C**ruise **C**ontrol (ACC) essentially offer added convenience by maintaining the distance from the vehicle in front by automatically throttling back the engine or applying the brakes.

Passive safety systems

These systems are designed to protect vehicle occupants from serious injury in the event of an accident. They reduce the risk of injury and thus the severity of the consequences of an accident.

Examples of passive safety systems are the seat-belts required by law, and airbags – which can now be fitted in various positions inside the vehicle such as in front of or at the side of the occupants.

Fig. 1 illustrates the safety systems and components that are found on modern-day vehicles equipped with the most advanced technology.

Basics of vehicle operation

Driver behavior

The first step in adapting vehicle response to reflect the driver and his/her capabilities is to analyze driver behavior as a whole. Driver behavior is broken down into two basic categories:

- vehicle guidance, and
- response to vehicle instability.

The essential feature of the "vehicle guidance" aspect is the driver's aptitude in anticipating subsequent developments; this translates into the ability to analyze current driving conditions and the associated interrelationships in order to accurately gauge such factors as:

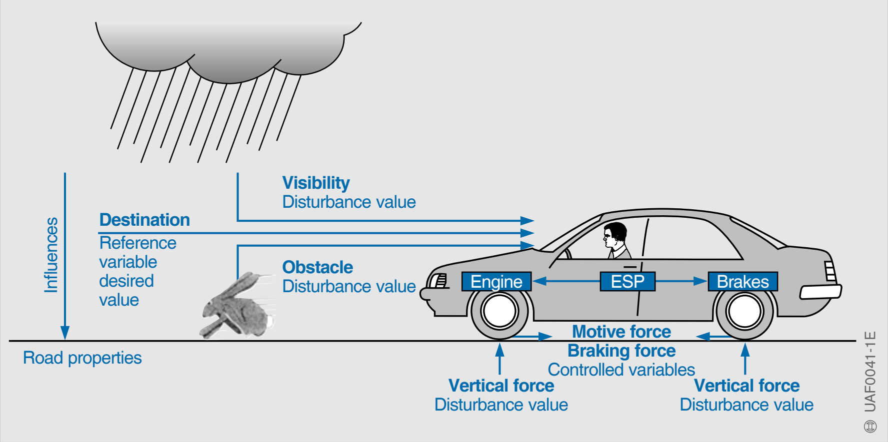
- the amount of initial steering input required to maintain consistently optimal cornering lines when cornering,
- the points at which braking must be initiated in order to stop within available distances, and
- when acceleration should be started in order to overtake slower vehicles without risk.

Steering angle, braking and throttle application are vital elements within the guidance process. The precision with which these functions are discharged depends upon the driver's level of experience.

While stabilizing the vehicle (response to vehicle instability), the driver determines that the actual path being taken deviates from the intended course (the road's path) and that the originally estimated control inputs (steering angle, accelerator pedal pressure) must be revised to avoid traction loss or prevent the vehicle leaving the road. The amount of stabilization (correction) response necessary after initiation of any given maneuver is inversely proportional to the driver's ability to estimate initial guidance inputs; more driver ability leads to greater vehicle stability. Progressively higher levels of correspondence between the initial control input (steering angle) and the actual cornering line produce progressively lower correction requirements; the vehicle reacts to these minimal corrections with "linear" response (driver input is transferred to the road surface proportionally, with no substantial deviations).

Experienced drivers can accurately anticipate both how the vehicle will react to their control inputs and how this reactive motion will combine with predictable external factors and forces (when approaching curves and road works etc.). Novices not only need more time to complete this adaptive process, their results will also harbor a greater potential for error. The conclusion is that inexperi-

1 Overall system of "Driver – Vehicle – Environment"



enced drivers concentrate most of their attention on the stabilization aspect of driving.

When an unforeseen development arises for driver and vehicle (such as an unexpectedly sharp curve in combination with restricted vision, etc.), the former may react incorrectly, and the latter can respond by going into a skid. Under these circumstances, the vehicle responds non-linearly and transgresses beyond its physical stability limits, so that the driver can no longer anticipate the line it will ultimately take. In such cases, it is impossible for either the novice or the experienced driver to retain control over his/her vehicle.

Accident causes and prevention

Human error is behind the vast majority of all road accidents resulting in injury. Accident statistics reveal that driving at an inappropriate speed is the primary cause for most accidents. Other accident sources are

- incorrect use of the road,
- failure to maintain the safety margin to the preceding vehicle,
- errors concerning right-of-way and traffic priority,
- errors occurring when making turns, and
- driving under the influence of alcohol.

Technical deficiencies (lighting, tires, brakes, etc.) and defects related to the vehicle in general are cited with relative rarity as accident sources. Accident causes beyond the control of the driver more frequently stem from other factors (such as weather).

These facts demonstrate the urgency of continuing efforts to enhance and extend the scope of automotive safety technology (with special emphasis on the associated electronic systems). Improvements are needed to

- provide the driver with optimal support in critical situations,
- prevent accidents in the first place, and
- reduce the severity of accidents when they do occur.

The designer's response to critical driving conditions must thus be to foster "predictable" vehicle behavior during operation at physical limits and in extreme situations. A range of parameters (wheel speed, lateral acceleration, yaw velocity, etc.) can be monitored for processing in one or several electronic control units (ECUs). This capability forms the basis of a concept for virtually immediate implementation of suitable response strategies to enhance driver control of critical processes.

The following situations and hazards provide examples of potential "limit conditions":

- changes in prevailing road and/or weather conditions,
- "conflicts of interest" with other road users,
- animals and/or obstructions on the road, and
- a sudden defect (tire blow-out, etc.) on the vehicle.

Critical traffic situations

The one salient factor that distinguishes critical traffic situations is abrupt change, such as the sudden appearance of an unexpected obstacle or a rapid change in road-surface conditions. The problem is frequently compounded by operator error. Owing to lack of experience, a driver who is travelling too fast or is not concentrating on the road will not be able to react with the judicious and rational response that the circumstances demand.

Because drivers only rarely experience this kind of critical situation, they usually fail to recognize how close evasive action or a braking maneuver has brought them to the vehicle's physical limits. They do not grasp how much of the potential adhesion between tires and road surface has already been "used up" and fail to perceive that the vehicle may be at its maneuverability limit or about to skid off the road. The driver is not prepared for this and reacts either incorrectly or too precipitously. The ultimate results are accidents and scenaria that pose threats to other road users.

These factors are joined by still other potential accident sources including outdated technology and deficiencies in infrastructure (badly designed roads, outdated traffic-guidance concepts).

Terms such as "improvements in vehicle response" and "support for the driver in critical situations" are only meaningful if they refer to mechanisms that produce genuine long-term reductions in both the number and severity of accidents. Lowering or removing the risk from these critical situations entails executing difficult driving maneuvers including

- rapid steering inputs including countersteering,
- lane changes during emergency braking,
- maintaining precise tracking while negotiating curves at high speeds and in the face of changes in the road surface.

These kinds of maneuvers almost always provoke a critical response from the vehicle, i.e., lack of tire traction prevents the vehicle reacting in the way that the driver would normally expect; it deviates from the desired course.

Due to lack of experience in these borderline situations, the driver is frequently unable to regain active control of the vehicle, and often panics or overreacts. Evasive action serves as an example. After applying excessive steering input in the moment of initial panic, this driver then countersteers with even greater zeal in an attempt to compensate for his initial error. Extended sequences of steering and countersteering with progressively greater input angles then lead to a loss of control over the vehicle, which responds by breaking into a skid.

Driving behavior

A vehicle's on-the-road handling and braking response are defined by a variety of influences. These can be roughly divided into three general categories:

- vehicle characteristics,
- the driver's behavior patterns, ability and reflexes, and
- peripheral circumstances/or influences from the surroundings or from outside.

A vehicle's handling, braking and overall dynamic response are influenced by its structure and design.

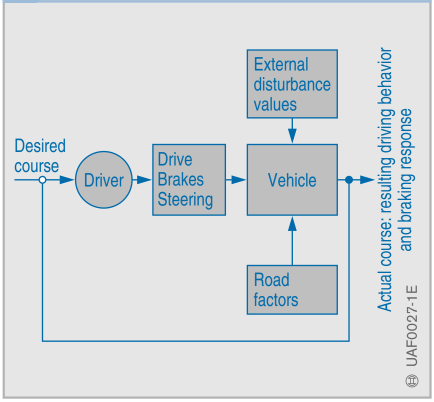
Handling and braking responses define the vehicle's reactions to driver inputs (at steering wheel, accelerator pedal, brakes, etc.) as do external interference factors (road-surface condition, wind, etc.).

Good handling is characterized by the ability to precisely follow a given course and thus comply in full with driver demand.
The driver's responsibilities include:

- adapting driving style to reflect traffic and road conditions,
- compliance with applicable traffic laws and regulations,
- following the optimal course as defined by the road's geometry as closely as possible, and
- guiding the vehicle with foresight and circumspection.

The driver pursues these objectives by continuously adapting the vehicle's position and motion to converge with a subjective conception of an ideal status. The driver relies upon personal experience to anticipate developments and adapt to instantaneous traffic conditions.

2 Overall system of "driver – vehicle – environment" as a closed control loop



Evaluating driver behavior

Subjective assessments made by experienced drivers remain the prime element in evaluations of vehicle response. Because assessments based on subjective perceptions are only relative and not absolute, they cannot serve as the basis for defining objective “truths”. As a result, subjective experience with one vehicle can be applied to other vehicles only on a comparative, relative basis.

Test drivers assess vehicle response using selected maneuvers conceived to reflect “normal” traffic situations. The overall system (including the driver) is judged as a closed loop. While the element “driver” cannot be precisely defined, this process provides a replacement by inputting objective, specifically defined interference factors into the system. The resulting vehicular reaction is then analyzed and evaluated. The following maneuvers are either defined in existing ISO standards or currently going through the standardization process. These dry-surface exercises serve as recognized procedures for assessing vehicular stability:

- steady-state skid-pad circulation,
- transition response,
- braking while cornering,
- sensitivity to crosswinds,
- Straight-running properties (tracking stability), and
- load change on the skid pad.

In this process, prime factors such as road geometry and assignments taken over by the driver assume vital significance. Each test driver attempts to gather impressions and experience in the course of various prescribed vehicle maneuvers; the subsequent analysis process may well include comparisons of the impressions registered by different drivers. These often hazardous driving maneuvers (e.g. the standard VDA evasive-action test, also known as the “elk test”) are executed by a series of drivers to generate data describing the dynamic response and general handling characteristics of the test vehicle. The criteria include:

- stability,
- steering response and brake performance, and
- handling at the limit. The tests are intended to describe these factors as a basis for implementing subsequent improvements.

The advantages of this procedure are:

- it allows assessment of the overall, synergistic system (“driver – vehicle – environment”) and
- supports realistic simulation of numerous situations encountered under everyday traffic conditions.

The disadvantages of this procedure are:

- the results extend through a broad scatter range, as drivers, wind, road conditions and initial status vary from one maneuver to the next,
- subjective impressions and experience are colored by the latitude for individual interpretation, and
- the success or failure of an entire test series can ultimately be contingent upon the abilities of a single driver.

Table 1 (next page) lists the essential vehicle maneuvers for evaluating vehicle response within a closed control loop.

Owing to the subjective nature of human behavior, there are still no definitions of dynamic response in a closed control loop that are both comprehensive and objectively grounded (closed-loop operation, meaning with driver, Fig. 2).

Despite this, the objective driving tests are complimented by various test procedures capable of informing experienced drivers about a vehicle’s handling stability (example: slalom course).

Table 1

1 Evaluating driver behavior

Vehicle response	**Driving maneuver** (Driver demand and current conditions)	**Driver makes continuous corrections**	**Steering wheel firmly positioned**	**Steering wheel released**	**Steering angle input**
Linear response	Straight-running stability – stay in lane	●	●	●	
	Steering response/turning	●			
	Sudden steering – releasing the steering			●	
	Load-change reaction	●	●	●	
	Aquaplaning	●	●	●	
	Straight-line braking	●	●	●	
	Crosswind sensitivity	●	●	●	
	High-speed aerodynamic lift		●		
	Tire defect	●	●	●	
Transition input/ transmission response	Sudden steering-angle change				●
	Single steering and countersteering inputs				●
	Multiple steering and countersteering inputs				●
	Single steering impulse				●
	“Random” steering-angle input	●			●
	Driving into a corner	●			
	Driving out of a corner	●			
	Self-centering			●	
	Single lane change	●			
	Double lane change	●			
Cornering	Steady-state skid-pad circulation		●		
	Dynamic cornering	●	●		
	Load-change reaction when cornering	●	●		
	Steering release			●	
	Braking during cornering	●	●		
	Aquaplaning in curve	●	●		
Alternating directional response	Slalom course around marker cones	●			
	Handling test (test course with sharp corners)	●			
	Steering input/acceleration			●	
Overall characteristics	Tilt resistance	●			●
	Reaction and evasive action tests	●			

Driving maneuvers

Steady-state skid-pad circulation

Steady-state cornering around the skid pad is employed to determine maximum lateral acceleration. This procedure also provides information on the transitions that dynamic handling undergoes as cornering forces climb to their maximum. This information can be used to define the vehicle's intrinsic handling (self-steering) properties (oversteer, understeer, neutral cornering response).

3 Evasive maneuver ("Elk Test")

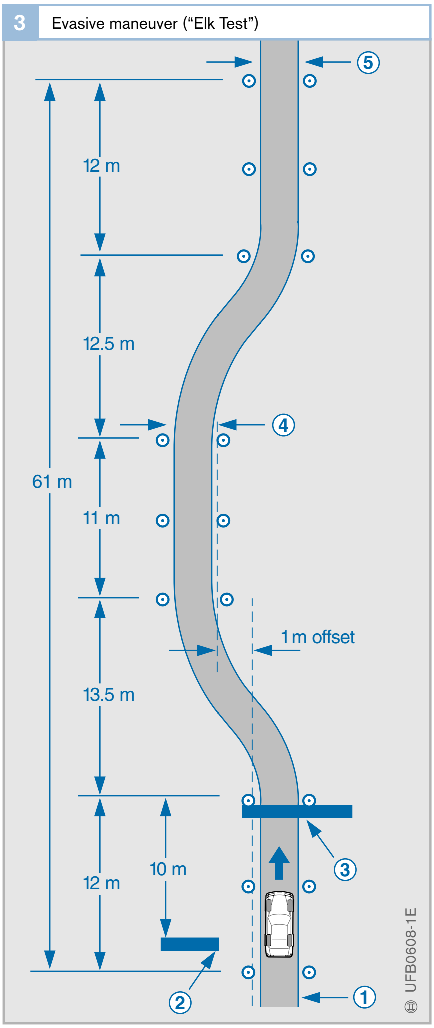


Fig. 3
Test start:
Phase 1:
Top gear (manual transmission)
Position D at 2,000 rpm (automatic transmission)

Phase 2:
Accelerator released

Phase 3:
Speed measurement with photoelectric light barrier

Phase 4:
Steering to the right

Phase 5:
End of test

Transition response

Transition response joins steady-state self-steering properties (during skid-pad circulation) as a primary assessment parameter. This category embraces such maneuvers as suddenly taking rapid evasive action when driving straight ahead.

The "elk test" simulates an extreme scenario featuring sudden evasive action to avoid an obstacle. A vehicle traveling over a 50 meter stretch of road must safely drive around an obstacle 10 meters in length projecting outward onto the track by a distance of 4 meters (Fig. 3).

Braking during cornering – load-change reactions

One of the most critical situations encountered in every-day driving – and thus one of the most vital considerations for vehicle design – is braking during cornering.

From the standpoint of the physical forces involved, whether the driver simply releases the accelerator or actually depresses the brake pedal is irrelevant; the physical effects will not differ dramatically. The resulting load shift from rear to front increasing the rear slip angle while reducing that at the front, and since neither the given cornering radius nor the vehicle speed modifies the lateral force requirement, the vehicle tends to adopt an oversteering attitude.

With rear-wheel drive, tire slip exerts less influence on the vehicle's intrinsic handling response than with front-wheel drive; this means that RWD vehicles are more stable under these conditions.

Vehicle reaction during this maneuver must represent the optimal compromise between steering response, stability and braking efficiency.

Parameters

The primary parameters applied in the assessment of dynamic handling response are:

- steering-wheel angle,
- lateral acceleration,
- longitudinal acceleration or longitudinal deceleration,
- yaw velocity,
- side-slip angle and roll angle.

Additional data allow more precise definition of specific handling patterns as a basis for evaluating other test results:

- longitudinal and lateral velocity,
- steering angles of front/rear wheels,
- slip angle at all wheels,
- steering-wheel force.

Reaction time

Within the overall system “driver-vehicle-environment”, the driver’s physical condition and state of mind, and thus his/her reaction times, join the parameters described above as decisive factors. This lag period is the time that elapses between perception of an obstacle and initial application of pressure to the brake pedal. The decision to act and the foot movement count as intermediate stages in this process. This period is not consistent; depending upon personal factors and external circumstances it is at least 0.3 seconds.

Special examinations are required to quantify individual reaction patterns (as conducted by medical/psychological institutes).

Motion

Vehicle motion may be consistent in nature (constant speed) or it may be inconsistent (during acceleration from a standing or rolling start, or deceleration and braking with the accompanying change in velocity).

The engine generates the kinetic energy required to propel the vehicle. Forces stemming either from external sources or acting through the engine and drivetrain must always be applied to the vehicle as a basic condition for changes in the magnitude and direction of its motion.

Handling and braking response in commercial vehicles

Objective evaluation of handling and braking response in heavy commercial vehicles is based on various driving maneuvers including steady-state skid-pad cornering, abrupt steering-angle change (vehicle reaction to “tugging” the steering wheel through a specified angle) and braking during cornering.

The dynamic lateral response of tractor and trailer combinations generally differs substantially from that of single vehicles. Particular emphasis is placed on tractor and trailer loading, while other important factors include design configuration and the geometry of the linkage elements within the combination.

The worst-case scenario features an empty truck pulling a loaded central-axle trailer. Operating a combination in this state

4 Actions: reaction, brake and stop

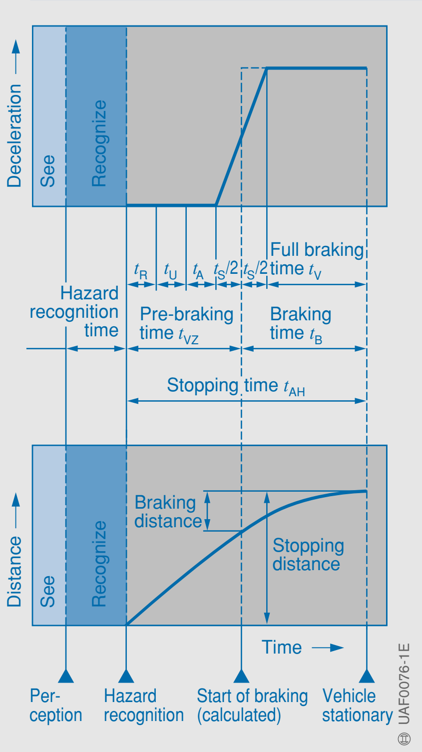


Fig. 4

t_R	Reaction time
t_U	Conversion time
t_A	Response time
t_S	Pressure buildup

requires a high degree of skill and circumspection on the part of the driver.

Jack-knifing is also a danger when tractor-trailer combinations are braked in extreme situations. This process is characterized by a loss of lateral traction at the tractor's rear axle and is triggered when "overbraking" on slippery road surfaces, or by extreme yaw rates on µ-split surfaces (with different friction coefficients at the center and on the shoulder of the lane). Jack-knifing can be avoided with the aid of antilock braking systems (ABS).

2 Personal reaction-time factors

➜	Psychophysical reaction		←	➜ Muscular reaction		➜
Perceived object	Perception	Comprehension	Decision	Mobilization	Motion	Object of action
(e.g. traffic sign)	Visual acuity	Perception and registration	Processing	Movement apparatus	Personal implementation speed	(e.g. brake pedal)

Table 2

3 Reaction time as a function of personal and external factors

Short reaction time ←	➜ **Long reaction time**
Personal factors, driver	
Trained reflex action	Ratiocinative reaction
Good condition, optimal performance potential	Poor condition, e.g. fatigue
High level of driving skill	Low level of driving skill
Youth	Advanced age
Anticipatory attitude	Inattention, distraction
Good physical and mental health	Physical or mental impediment
	Panic, alcohol
External Factors	
Simple, unambiguous, predicable and familiar traffic configuration	Complex, unclear, incalculable and unfamiliar traffic conditions
Conspicuous obstacle	Inconspicuous obstacle
Obstacle in line of sight	Obstacle on visual periphery
Logical and effective arrangement of the controls in the vehicle	Illogical and ineffective control arrangement in vehicle

Table 3

Basic principles of vehicle dynamics

A body can only be made to move or change course by the action of forces. Many forces act upon a vehicle when it is being driven. An important role is played by the tires as any change of speed or direction involves forces acting on the tires.

Tires

Task

The tire is the connecting link between the vehicle and the road. It is at that point that the safe handling of a vehicle is ultimately decided. The tire transmits motive, braking and lateral forces within a physical environment whose parameters define the limits of the dynamic loads to which the vehicle is subjected. The decisive criteria for the assessment of tire quality are:

- Straight-running ability
- Stable cornering properties
- Ability to grip on a variety of road surfaces
- Ability to grip in a variety of weather conditions
- Steering characteristics
- Ride comfort (vibration absorption and damping, quietness)
- Durability and
- Economy

Design

There are a number of different tire designs that are distinguished according to the nature and sophistication of the technology employed. The design of a conventional tire is determined by the characteristics required of it in normal conditions and emergency situations.

Legal requirements and regulations specify which tires must be used in which conditions, the maximum speeds at which different types of tire may be used, and the criteria by which tires are classified.

Radial tires

In a radial tire, the type which has now become the standard for cars, the cords of the tire-casing plies run radially, following the shortest route from bead to bead (Fig. 1).
A reinforcing belt runs around the perimeter of the relatively thin, flexible casing.

1 Structure of a radial car tire

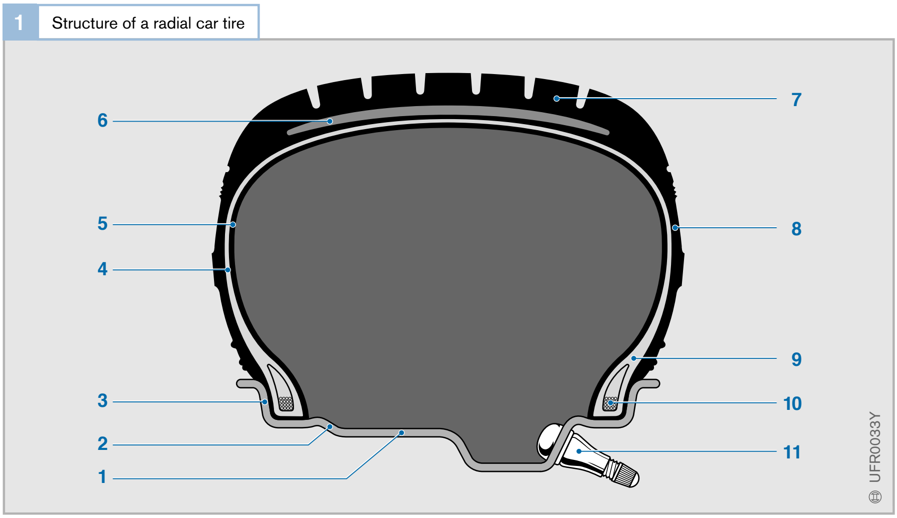


Fig. 1

1	Rim bead seat
2	Hump
3	Rim flange
4	Casing
5	Air-tight rubber layer
6	Belt
7	Tread
8	Sidewall
9	Bead
10	Bead core
11	Valve

K. Reif (Ed.), *Brakes, Brake Control and Driver Assistance Systems,* Bosch Professional Automotive Information, DOI 10.1007/978-3-658-03978-3_2, © Springer Fachmedien Wiesbaden 2014

Cross-ply tires

The cross-ply tire takes its name from the fact that the cords of alternate plies of the tire casing run at right angles to one another so that they cross each other. This type of tire is now only of significance for motorcycles, bicycles, and industrial and agricultural vehicles. On commercial vehicles it is increasingly being supplanted by the radial tire.

Regulations

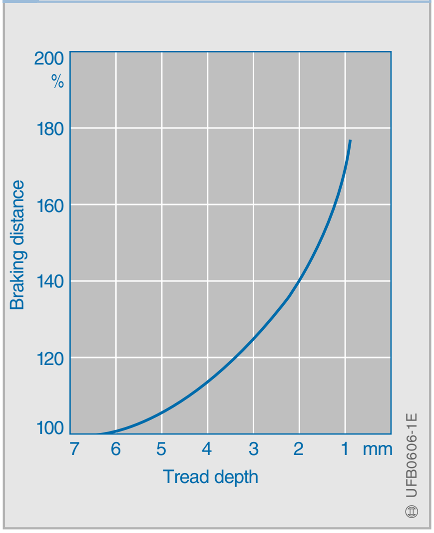
In Europe, the Council Directives, and in the USA the *FMVSS (Federal Motor Vehicle Safety Standard)* require that motor vehicles and trailers are fitted with pneumatic tires with a tread pattern consisting of grooves with a depth of at least 1.6 mm around the entire circumference of the tire and across the full width of the tread.

Cars and motor vehicles with a permissible laden weight of less than 2.8 tonnes and designed for a maximum speed of more than 40 km/h, and trailers towed by them, must be fitted either with cross-ply tires all round or with radial tires all round; in the case of vehicle-and-trailer combinations the requirement applies individually to each unit of the combination. It does not apply to trailers towed by vehicles at speeds of up to 25 km/h.

Application

To ensure correct use of tires, it is important the correct tire is selected according to the recommendations of the vehicle or tire manufacturer. Fitting the same type of tire to all wheels of a vehicle ensures the best handling results. The specific instructions of the tire manufacturer or a tire specialist regarding tire care, maintenance, storage and fitting should be followed in order to obtain maximum durability and safety.

2 Increase in braking distance on wet road surface as a function of tread depth at 100 km/h



When the tires are in use, i.e. when they are fitted to the wheel, care should be taken to ensure that

- the wheels are balanced so as to guarantee optimum evenness of running,
- all wheels are fitted with the same type of tire and the tires are the correct size for the vehicle,
- the vehicle is not driven at speeds in excess of the maximum allowed for the tires fitted, and
- the tires have sufficient depth of tread.

The less tread there is on a tire, the thinner is the layer of material protecting the belt and the casing underneath it. And particularly on cars and fast commercial vehicles, insufficient tread depth on wet road surfaces has a decisive effect on safe handling characteristics due to the reduction in grip. Braking distance increases disproportionately as tread depth reduces (Fig. 2). An especially critical handling scenario is aquaplaning in which all adhesion between tires and road surface is lost and the vehicle is no longer steerable.

Tire slip

Tire slip, or simply “slip”, is said to occur when there is a difference between the theoretical and the actual distance traveled by a vehicle.

This can be illustrated by the following example in which we will assume that the circumference of a car tire is 2 meters. If the wheel rotates ten times, the distance traveled should be 20 meters. If tire slip occurs, however, the distance actually traveled by the braked vehicle is greater.

3 Effect of braking on a rolling wheel

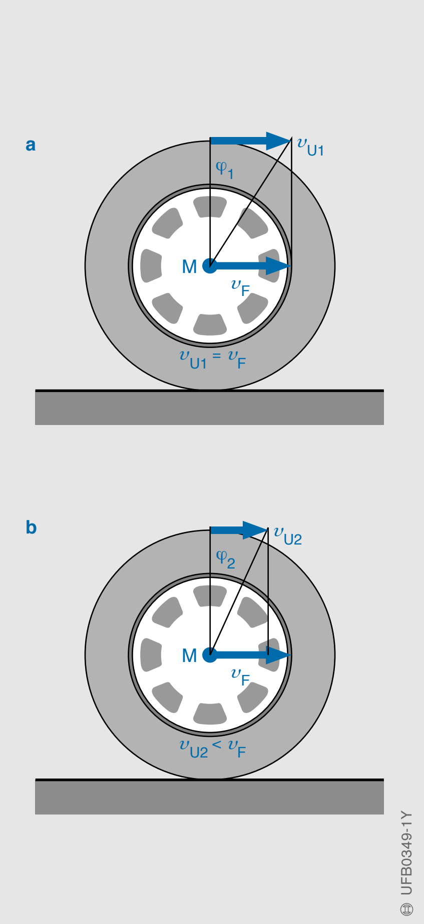


Fig. 3
a Rolling wheel (unbraked)
b Braked wheel
v_F Vehicle speed at wheel center, M
v_U Circumferential speed

On a braked wheel, the angle of rotation, φ, per unit of time is smaller (slip)

Causes of tire slip

When a wheel rotates under the effect of power transmission or braking, complex physical processes take place in the contact area between tire and road which place the rubber parts under stress and cause them to partially slide, even if the wheel does not fully lock. In other words, the elasticity of the tire causes it to deform and “flex” to a greater or lesser extent depending on the weather conditions and the nature of the road surface. As the tire is made largely of rubber, only a proportion of the “deformation energy” is recovered as the tread moves out of the contact area. The tire heats up in the process and energy loss occurs.

Illustration of slip

The slip component of wheel rotation is referred to by λ, where

$$\lambda = (v_F - v_U)/v_F$$

The quantity v_F is the vehicle road speed, v_U is the circumferential velocity of the wheel (Fig. 3). The formula states that brake slip occurs as soon as the wheel is rotating more slowly than the vehicle road speed would normally demand. Only under that condition can braking forces or acceleration forces be transmitted.

Since the tire slip is generated as a result of the vehicle’s longitudinal movement, it is also referred to as “longitudinal slip”. The slip generated during braking is usually termed “brake slip”.

If a tire is subjected to other factors in addition to slip (e.g. greater weight acting on the wheels, extreme wheel positions), its force transmission and handling characteristics will be adversely affected.

Forces acting on a vehicle

Theory of inertia

Inertia is the property possessed by all bodies, by virtue of which they will naturally maintain the status in which they find themselves, i.e. either at rest or in motion. In order to bring about a change to that status, a force has to be applied to the body. For example, if a car's brakes are applied when it is cornering on black ice, the car will carry on in a straight line without altering course and without noticeably slowing down. That is because on black ice, only very small tire forces can be applied to the wheels.

Turning forces

Rotating bodies are influenced by turning forces. The rotation of the wheels, for example, is slowed down due to the braking torque and accelerated due to the drive torque.

Turning forces act on the entire vehicle. If the wheels on one side of the vehicle are on a slippery surface (e.g. black ice) while the wheels on the other side are on a road surface with normal grip (e.g. asphalt), the vehicle will slew around its vertical axis when the brakes are applied (μ-split braking). This rotation is caused by the yaw moment, which arises due to the different forces applied to the sides of the vehicle.

Distribution of forces

In addition to the vehicle's weight (resulting from gravitational force), various different types of force act upon it regardless of its state of motion (Fig. 1). Some of these are

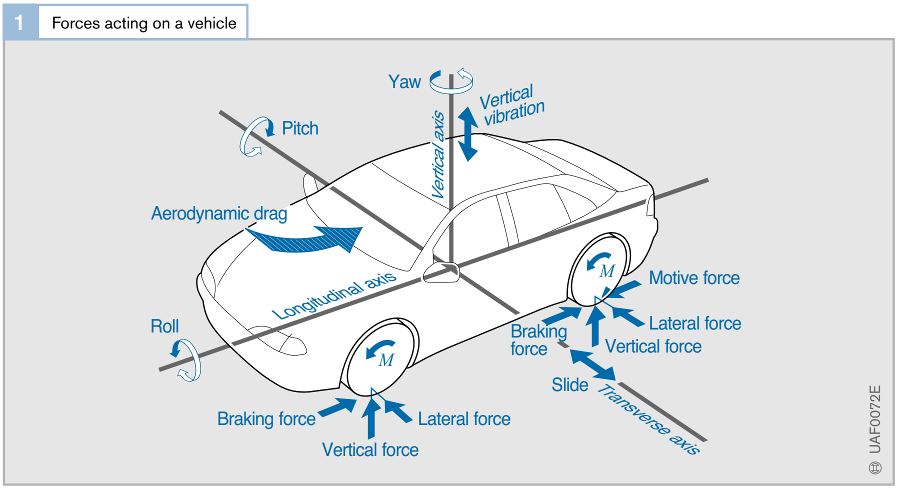
- forces which act along the longitudinal axis of the vehicle (e.g. motive force, aerodynamic drag or rolling friction); others are
- forces which act laterally on the vehicle (e.g. steering force, centrifugal force when cornering or crosswinds). The tire forces which act laterally on the vehicle are also referred to as lateral forces.

The longitudinal and the lateral forces are transmitted either "downwards" or "sideways" to the tires and ultimately to the road. The forces are transferred through

- the chassis (e.g. wind),
- the steering (steering force),
- the engine and transmission (motive force), or
- the braking system (braking force).

Opposing forces act "upwards" from the road onto the tires and thence to the vehicle because every force produces an opposing force.

1 Forces acting on a vehicle



Basically, in order for the vehicle to move, the motive force of the engine (engine torque) must overcome all forces that resist motion (all longitudinal and lateral forces) such as are generated by road gradient or camber.

In order to assess the dynamic handling characteristics or handling stability of a vehicle, the forces acting between the tires and the road, i.e. the forces transmitted in the contact areas between tire and road surface (also referred to as “tire contact area” or “footprint”), must be known.

With more practice and experience, a driver generally learns to react more effectively to those forces. They are evident to the driver when accelerating or slowing down as well as in cross winds or on slippery road surfaces. If the forces are particularly strong, i.e. if they produce exaggerated changes in the motion of the vehicle, they can also be dangerous (skidding) or at least are detectable by squealing tires (e.g. when accelerating aggressively) and increased component wear.

2 Components of tire force and pressure distribution over the footprint of a radial tire

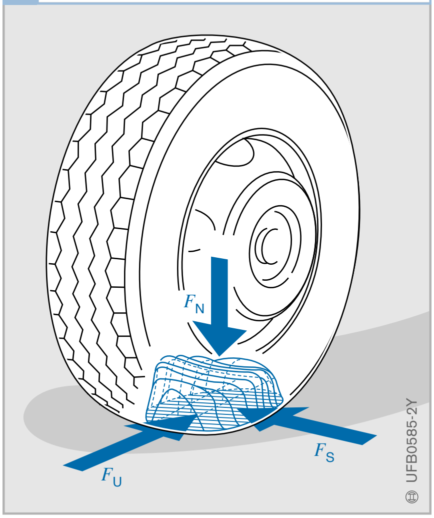


Fig. 2

F_N Vertical tire force, or normal force
F_U Circumferential force (positive: motive force; negative: braking force)
F_S Lateral force

Tire forces

A motor vehicle can only be made to move or change its direction in a specific way by forces acting through the tires. Those forces are made up of the following components (Fig. 2):

Circumferential force

The circumferential force F_U is produced by power transmission or braking. It acts on the road surface as a linear force in line with the longitudinal axis of the vehicle and enables the driver to increase the speed of the vehicle using the accelerator or slow it down with the brakes.

Vertical tire force (normal force)

The vertical force acting downwards between the tire and road surface is called the vertical tire force or normal force F_N. It acts on the tires at all times regardless of the state of motion of the vehicle, including, therefore, when the vehicle is stationary.

The vertical force is determined by the proportion of the combined weight of vehicle and payload that is acting on the individual wheel concerned. It also depends on the degree of upward or downward gradient of the road that the vehicle is standing on. The highest levels of vertical force occur on a level road.

Other forces acting on the vehicle (e.g. heavier payload) can increase or decrease the vertical force. When cornering, the force is reduced on the inner wheels and increased on the outer wheels.

The vertical tire force deforms the part of the tire in contact with the road. As the tire sidewalls are affected by that deformation, the vertical force cannot be evenly distributed. A trapezoidal pressure-distribution pattern is produced (Fig. 2). The tire sidewalls absorb the forces and the tire deforms according to the load applied to it.

Lateral force

Lateral forces act upon the wheels when steering or when there is a crosswind, for example. They cause the vehicle to change direction.

Braking torque

When the brakes are applied, the brake shoes press against the brake drums (in the case of drum brakes) or the brake pads press against the disks (in the case of disk brakes). This generates frictional forces, the level of which can be controlled by the driver by the pressure applied to the brake pedal.

The product of the frictional forces and the distance at which they act from the axis of rotation of the wheel is the braking torque M_B.

That torque is effective at the circumference of the tire under braking (Fig. 1).

Yaw moment

The yaw moment around the vehicle's vertical axis is caused by different longitudinal forces acting on the left and right-hand sides of the vehicle or different lateral forces acting at the front and rear axles. Yaw moments are required to turn the vehicle when cornering. Undesired yaw moments, such as can occur when braking on μ-split (see above) or if the vehicle pulls to one side when braking, can be reduced using suitable design measures. The kingpin offset is the distance between the point of contact between the tire and the road and the point at which the wheel's steering axis intersects the road surface (Fig. 3). It is negative if the point at which the steering axis intersects the road surface is on the outside of the point of contact between tire and road. Braking forces combine with positive and negative kingpin offset to create a lever effect that produces a turning force at the steering which can lead to a certain steering angle at the wheel. If the kingpin offset is negative, this steering angle counters the undesired yaw moment.

3 Kingpin offset

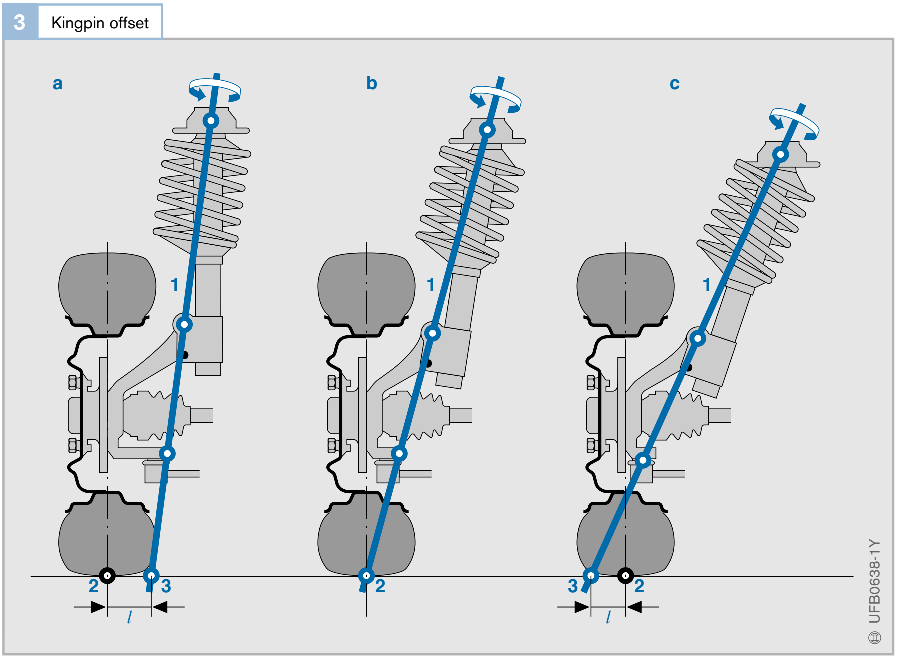


Fig. 3

a	Positive kingpin offset: $M_{Ges} = M_T + M_B$
b	Zero kingpin offset: no yaw moment
c	Negative kingpin offset: $M_{Ges} = M_T - M_B$
1	Steering axis
2	Wheel contact point
3	Intersection point
l	Kingpin offset
M_{Ges}	Total turning force (yaw moment)
M_T	Moment of inertia
M_B	Braking torque

Friction force

Coefficient of friction

When braking torque is applied to a wheel, a braking force F_B is generated between the tire and the road surface that is proportional to the braking torque under stationary conditions (no wheel acceleration). The braking force transmitted to the road (frictional force F_R) is proportional to the vertical tire force F_N:

$$F_R = \mu_{HF} \cdot F_N$$

The factor μ_{HF} is the coefficient of friction. It defines the frictional properties of the various possible material pairings between tire and road surface and the environmental conditions to which they are exposed.

The coefficient of friction is thus a measure of the braking force that can be transmitted. It is dependent on

- the nature of the road surface,
- the condition of the tires,
- the vehicle's road speed, and
- the weather conditions.

The coefficient of friction ultimately determines the degree to which the braking torque is actually effective. For motor-vehicle tires, the coefficient of friction is at its highest on a clean and dry road surface; it is at its lowest on ice. Fluids (e.g. water) or dirt between the tire and the road surface reduce the coefficient of friction. The figures quoted in Table 1 apply to concrete and tarmacadam road surfaces in good condition.

On wet road surfaces in particular, the coefficient of friction is heavily dependent on vehicle road speed. At high speeds on less than ideal road surfaces, the wheels may lock up under braking because the coefficient of friction is not high enough to provide sufficient adhesion for the tires to grip the road surface. Once a wheel locks up, it can no longer transmit side forces and the vehicle is thus no longer steerable. Fig. 5 illustrates the frequency distribution of the coefficient of friction at a locked wheel at various road speeds on wet roads.

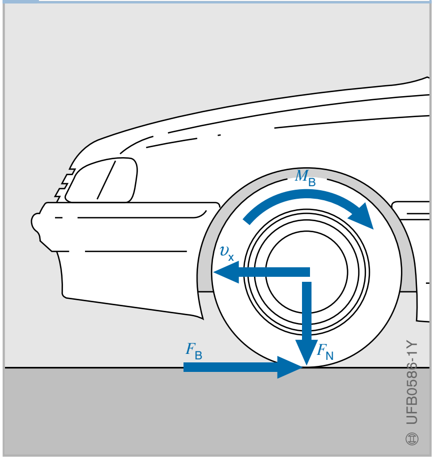
The friction or adhesion between the tire and the road surface determines the wheel's ability to transmit force. The ABS (**A**ntilock **B**raking **S**ystem) and TCS (**T**raction **C**ontrol **S**ystem) safety systems utilize the available adhesion to its maximum potential.

Fig. 4

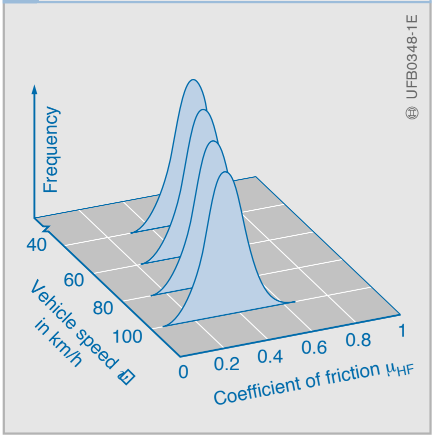
v_x	Linear velocity of wheel
F_N	Vertical tire force (normal force)
F_B	Braking force
M_B	Braking torque

Fig. 5
Source:
Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren, Stuttgart, Germany (research institute for automotive engineering and automotive engines)

4 Linear wheel velocity, v_x, with braking force, F_B, and braking torque, M_B



5 Frequency distribution of the coefficient of friction at a locked wheel at various road speeds on wet roads



Aquaplaning

The amount of friction approaches zero if rainwater forms a film on the road surface on which the vehicle then “floats”. Contact between the tires and the road surface is then lost and the effect known as aquaplaning occurs. Aquaplaning is caused by a “wedge” of water being forced under the entire contact area of the tire with the road surface, thereby lifting it off the ground. Aquaplaning is dependent on:

- the depth of water on the road,
- the speed of the vehicle,
- the tire tread pattern, tire width and level of wear, and
- the force pressing the tire against the road surface.

Wide tires are particularly susceptible to aquaplaning. When a vehicle is aquaplaning, it cannot be steered or braked. Neither steering movements nor braking forces can be transmitted to the road.

Kinetic friction

When describing processes involving friction, a distinction is made between static friction and kinetic friction. With solid bodies, the static friction is greater than kinetic friction. Accordingly, for a rolling rubber tire there are circumstances in which the coefficient of friction is greater than when the wheel locks. Nevertheless, the tire can also slide while it is rolling, and on motor vehicles this is referred to as slip.

Effect of brake slip on coefficient of friction

When a vehicle is pulling away or accelerating – just as when braking or decelerating – the transmission of forces from tire to road depends on the degree of adhesion between the two. The friction of a tire basically has a constant relationship to the level of adhesion under braking or acceleration.

Fig. 6 shows the progression of the coefficient of friction μ_{HF} under braking. Starting from a zero degree of brake slip, is rises steeply to its maximum at between 10% and 40% brake slip, depending on the nature of the road surface and the tires, and then drops away again. The rising slope of the

6 Coefficient of friction, μ_{HF}, and lateral-force coefficient, μ_S, relative to brake slip

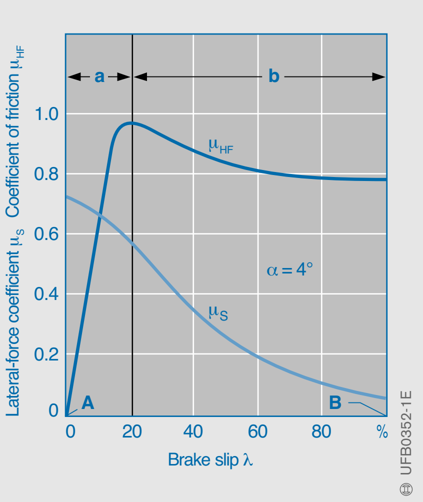


Fig. 6

a	Stable zone
b	Unstable zone
α	Slip angle
A	Rolling wheel
B	Locked wheel

1 Coefficients of friction, μ_{HF}, for tires in various conditions of wear, on various road conditions and at various speeds

Vehicle road speed km/h	Tire condition	Dry road μ_{HF}	Wet road (depth of water 0.2 mm) μ_{HF}	Heavy rain (depth of water 1 mm) μ_{HF}	Puddles (depth of water 2 mm) μ_{HF}	Icy (black ice) μ_{HF}
50	new	0.85	0.65	0.55	0.5	0.1 and below
	worn out	1	0.5	0.4	0.25	
90	new	0.8	0.6	0.3	0.05	
	worn out	0.95	0.2	0.1	0.0	
130	new	0.75	0.55	0.2	0	
	worn out	0.9	0.2	0.1	0	

Table 1

curve represents the "stable zone" (partial-braking zone), while the falling slope is the "unstable zone".

Most braking operations involve minimal levels of slip and take place within the stable zone so that an increase in the degree of slip simultaneously produces an increase in the usable adhesion. In the unstable zone, an increase in the amount of slip generally produces a reduction in the level of adhesion. When braking in such situations, the wheel can lock up within a fraction of a second, and under acceleration the excess power-transmission torque rapidly increases the wheel's speed of rotation causing it to spin.

When a vehicle is traveling in a straight line, ABS and TCS prevent it entering the unstable zone when braking or accelerating.

Sideways forces

If a lateral force acts on a rolling wheel, the center of the wheel moves sideways. The ratio between the lateral velocity and the velocity along the longitudinal axis is referred to as "lateral slip". The angle between the resulting velocity, v_α, and the forward velocity, v_x, is called the "lateral slip angle α" (Fig. 7). The side-slip angle, γ, is the angle between the vehicle's direction of travel and its longitudinal axis. The side-slip angle encountered at high rates of lateral acceleration is regarded as an index of controllability, in other words the vehicle's response to driver input.

Under steady-state conditions (when the wheel is not being accelerated), the lateral force F_S acting on the center of the wheel is in equilibrium with the lateral force applied to the wheel by the road surface. The relationship between the lateral force acting through the center of the wheel and the wheel contact force F_N is called the "lateral-force coefficient μ_S".

7 Lateral slip angle, α, and the effect of lateral force, F_S, (overhead view)

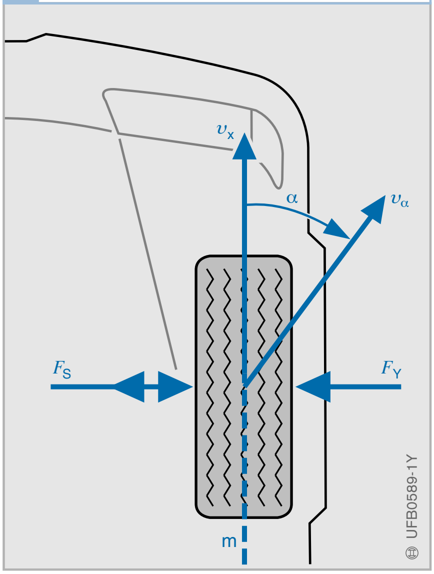


Fig. 7

v_α	Velocity in lateral slip direction
v_x	Velocity along longitudinal axis
F_S, F_y	Lateral force
α	Slip angle

8 Position of tire contact area relative to wheel in a right-hand bend showing lateral force, F_S, (front view)

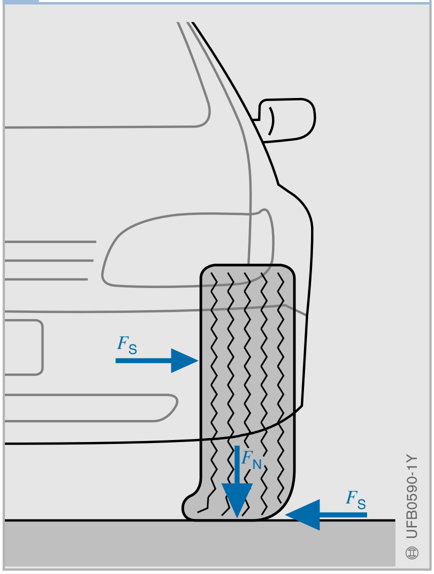


Fig. 8

F_N	Vertical tire force (normal force)
F_S	Lateral force