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)

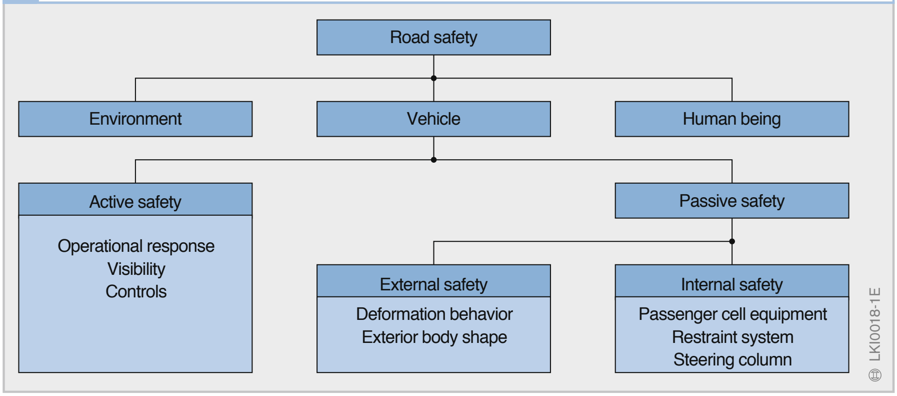


Table 1

K. Reif (Ed.), *Fundamentals of Automotive and Engine Technology*,
DOI 10.1007/978-3-658-03972-1_9, © Springer Fachmedien Wiesbaden 2014

1 Motor-vehicle safety systems

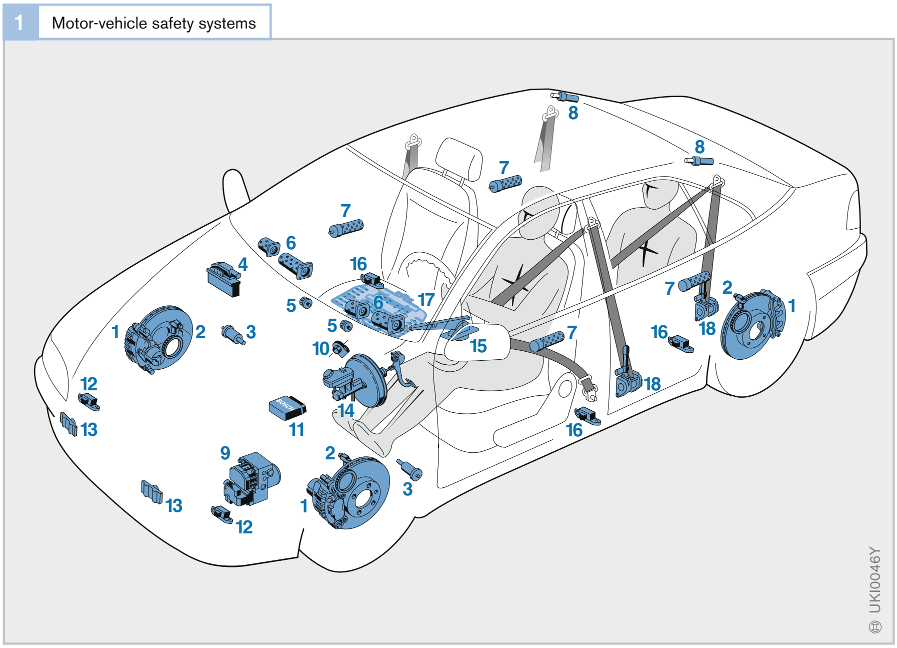


Fig. 1

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 Adaptive Cruise Control (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:

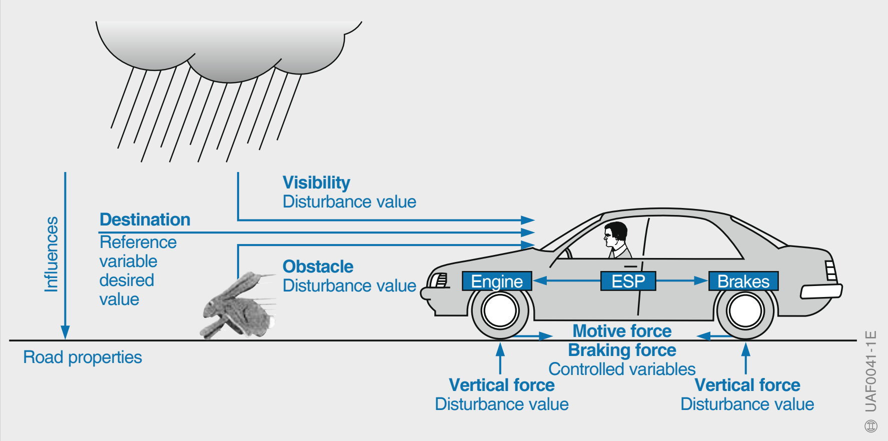
- the amount of initial steering input required to maintain consistently optimal cornering lines when cornering,
- the points at which braking must be initiated in order to stop within available distances, and
- when acceleration should be started in order to overtake slower vehicles without risk.

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.

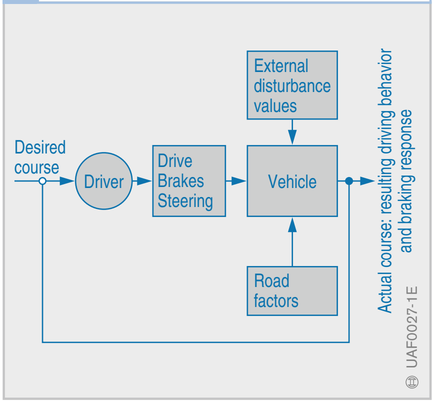
Handling and braking responses define the vehicle's reactions to driver inputs (at steering wheel, accelerator pedal, brakes, etc.) as do external interference factors (road-surface condition, wind, etc.).

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")

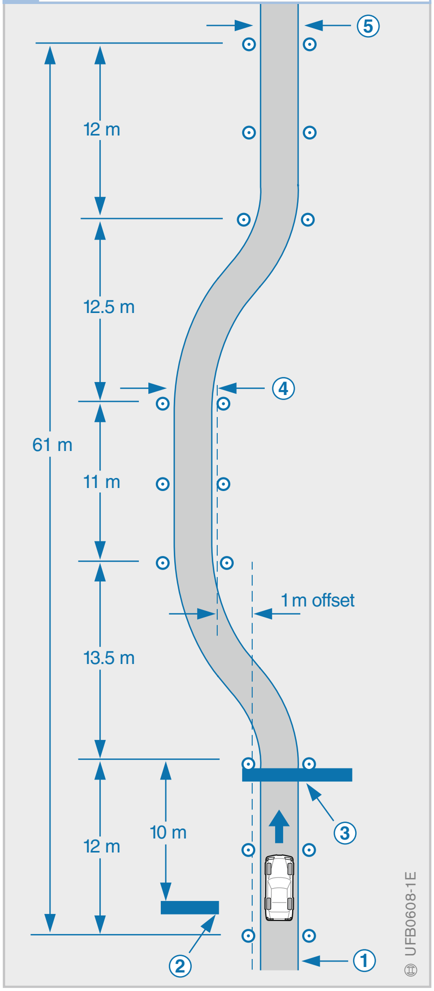


Fig. 3
Test start:
Phase 1:
Top gear (manual transmission)
Position D at 2,000 rpm (automatic transmission)

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

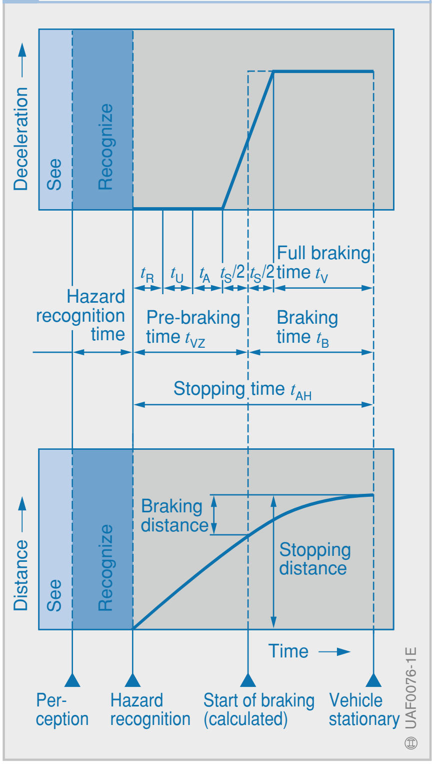


Fig. 4

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 (e.g. traffic sign)	Perception	Comprehension	Decision	Mobilization	Motion	Object of action (e.g. brake pedal)
	Visual acuity	Perception and registration	Processing	Movement apparatus	Personal implementation speed	

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