Manfred Harrer · Peter Pfeffer *Editors*

Steering Handbook

Springer

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Preface

In recent years, steering system technologies have undergone rapid development. This was caused by increased regulatory requirements in the areas of environment and safety, through the increased comfort requirements of the customer and not least by the continuing cost pressure. New ways has been taken up for steering components such as steering wheel, steering column, and steering gear. The most substantial change has been the progressive substitution of conventional hydraulic steering systems with electrical steering systems. With this change in technology a variety of new steering functions have been made possible. It is therefore not surprising that the steering system development as such occupies an ever-increasing role in modern chassis development. Due to the lack of a standard English book on the subject of steering systems/steering behavior, which describes the current state of the art, we decided with Springer Verlag to publish the German Steering Handbook also in English. We have taken into account the different interests and requirements of automotive manufacturers, suppliers, and universities in such a standard work by the involvement of proven experts from these areas.

In the first part of this book, the kinematic and vehicle dynamics of steering is explained and discussed, and also the influence of the suspension characteristics for the steering operation is investigated. A chapter is devoted to the interaction between driver and vehicle to analyze the aspects of steering feel. The central chapters of this book are devoted to individual steering modules, their design, and component tests. Described in detail are the components steering wheel, steering column with intermediate steering shaft, and the steering rack in mechanical, hydraulic, and electro-mechanical design. Special steering system technologies such as the superimposed steering system and four-wheel steering are also discussed in detail. Much attention was paid to illustrate the current state of the steering system technology and its interaction with the entire vehicle comprehensibly. Also important secondary aspects such as acoustic performance, energy requirements, and functional safety are treated in detail. Furthermore, the possibilities regarding driver assistance functions enabled by modern steering systems are shown. The profound expertise of nearly 40 experts from industry and academia was utilized for the creation of the steering handbook. We would like to thank all the authors for their expertise and perseverance. Also we thank Springer for publishing. Only through the dedication of all those involved, this textbook has been possible.

The readers of this book were asked by us to give feedback for improvements. Please send your suggestions to the following email address: peter.pfeffer@hm.edu. We will accommodate your suggestions in the next editions.

Stuttgart, Feldafing
January 2014

Manfred Harrer
Peter Pfeffer

Contents

Abbreviations and Symbols

Abbreviations

4WAS	4 Wheel Active Steer (Nissan)
ABS	Anti-Lock Brake System
AC	Alternating Current
AD	Analog-Digital Converter
AFS	Active Front Steering
AHK	Aktive rear axle kinematic
AMR	Anisotropen Magnetoresistiv
APA	Paraxial drive unit
ASIC	Application-Specific Integrated Circuit
ASIL	Automotive Safety Integrity Level
ASM	Asynchronous Motor
ASM	Assembly
ATF	Automatic Transmission Fluid
BCM	Body-Control-Modul
BLDC	Brushless Direct Current Motor
BRIC	Brasil, Russia, India, China
CAE	Computer Aided Engineering
CAN	Controller Area Network
C-EPS	Steering Column Assisted EPS
CFD	Computational Fluid Dynamics
CFK	Fiber-Reinforced Plastic Material
CGR	Constant Gear Ratio
CPU	Central Processor Unit
CR	Chloroprene Rubber
CR-EPS	Rack Concentric EPS
CS	Circular-Spline
CSM	Chlorosulphonated-Polyethylene-Rubber
CV	Concept Verification
DBC	Direkt Bonded Copper

DBV	Pressure Limitation Valve
DC	Direct Current
DCM	Direct Current Motor
DMS	Strain gauge
DP-EPS	Dual Pinion EPS
DV	Design Verification
EC	Electronically Commutated Motor
ECE	Economic Commission for Europe
ECU	Electronic Control Unit
EHPS	Electro Hydraulic Power Steering
EMC	Electro Magnetic Compatibility
EPS	Electric Power Steering
EPSapa	EPS with Paraxial Drive
EPSc	Column EPS
EPSdp	Dual Pinion EPS
EPSp	Pinion EPS
EPSrc	Rack Concentric EPS
ESD	Electrostatic Discharge
ESP	Elektronisches Stability Program
ESV	Experimental-Safety-Vehicle
EU	European Union
EV	Electric Vehicle
EVLS	Elektric adjustable steering column
EWG	European Economic Community (Europäische Wirtschaftsgemeinschaft)
FA	Front Axle
FAD	Front Axle Damper
FB	Flex-Bearing
FCV	Fuel Cell Vehicle
FEA/FEM	Finite-Element-Analysis/Method
FMVSS	Federal Motor Vehicle Safety Standard
FS	Flex-Spline
FS (FDR)	Vehicle Stability (Vehicle Dynamics Control)
FS (VS)	Vehicle Stability (Feedforward)
GAAI	German Association of the Automotive Industry
GFK	Glass fiber reinforced plastic
GIS	German Institute for Standardization
GND	Ground
HA	Rear Axle
HAD	Rear Axle Damper
HEV	Hybrid Electric Vehicle
HICAS	High Capacity Actively Controlled Suspension
HNBR	Hydrierter Acrylnitrilbutadien-Kautschuk
HPS	Hydraulic Power Steering
IAS	Integral Aktiv Steering

IC	Electrical Circuit
IEC	International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistor
IMS	Insulated Metal Substrate
ISO	International Standards Organization
KGT	Recirculating ball
KTL	Cathodic dip painting
LCV	Light Commercial Vehicle
LDM	Free steering torque
LDS	Steering nibble (steering torsional vibrations)
LDW	Lane Departure Prevention
LED	Light Emitting Diode
LIN	Local Interconnected Network
LKS	Lane Keeping Support
MAC	Manual Adjustable column
MFS	Magnetic Field Sensor
MFS	Multi-Function Switch
ML	Engine Mount
MOST	Media Oriented Systems Transport
MPA	Motor-Pump-Unit
MR	Magnetoresistiv
MS	Manual Steering
NBR	Nitrile Butadiene Rubber
NEDC	New European Driving Cycle
Nfz CV	Commercial Vehicle
NHTSA	National Highway Safety Traffic Administration
NVH	Noise Vibration Harshness
OA-EPS	Offset Axis-EPS
OEM	Original Equipment Manufacturer
OOP	Out Of Position
OSEK/VDX	Offene Systeme und deren Schnittstellen für die Elektronik in Kraftfahrzeugen/Vehicle Distributed eXecutive
PA	Polyamide
PC	Passenger Car
PCB	Printed Circuit Board
PDC	Park Distance Control
PEEK	Polyetherketone
P-EPS	Pinion EPS
P-EPS	Paraxial EPS
PMSM	Permanent Magnet Synchronous Motor
POM	Polyoxymethylene
ppm	parts per million
PTFE	Polytetrafluoroethylene
PUR	Polyurethane
PV	Product Validation

PVD	Physical Vapour Deposition
PWM	Pulse Width Modulation
QM	Quality Management
RAM	Random Access Memory
ROM	Read Only Memory
ROW	Rest of the World
RTLG	Road Traffic Licensing regulations
SA	Steering Arm
SAE	Society of Automotive Engineers
SAW	Surface Acoustic Wave
SCU	Steering Control Unit
SH	Sensor Host
SIL	Safety Integrity Level
SISO	Single Input Single Output
SMD	Surface Mounted Device
SR	Switched Reluctance
SUV	Sport Utility Vehicle
TCR	Turning Circle Reduction
TFC	Thick Film Copper
THC	Through Hole Component
UV	Ultra Violette
VCC	Common-Collector Voltage
VGR, VGS	Variable Gear Ratio
WG	Wave Generator
ZFLS	ZF Lenksysteme GmbH (now Robert Bosch Automotive Steering GmbH)

Formula Index

α	Tire side slip angle (rad)
α	Working angle of joint steering countershaft (rad)
β	Slip angle (rad)
β	Angle between joint planes (rad)
β T/β U	Transmission angle
β x	Separation ratio
β z	Helix angle (rad)
γ	Shearing angle (rad)
γ	Offset angle steering countershaft (rad)
γ	Installation angle bevel axle (rad)
δ *	Steering arm rotation angle (rad)
δ, δ	Steering angle, velocity (rad, rad/s)
δ A	Ackermann angle (rad)
δ D	Dynamic reference steering angle (rad)
δ G	Rotation angle of steering arm lever (rad)

δ h	Rear steering angle (rad)
δ H	Steering wheel angle (rad)
δ H *	Bevel rotation axle (rad)
δ LS	Steering column angle (rad)
δ M	Superposing angle (rad)
δ o, max	Maximum steering angle of front outer wheel (rad)
δ v	Front steering angle (rad)
Δδ	Required difference steering angle (rad)
Δδ A	Track difference angle, difference steering angle according to Ackermann (rad)
Δδ F	Difference steering angle (rad)
Δδ H	Steering wheel angle (rad)
Δδ H,e	Steering system compiance at steering wheel (rad)
Δδ H,Re	Steering wheel rest angle (rad)
ε	Wheel camber angle (rad)
ε V,ϕ,F	Roll induced steering factor (rad)
ε α	Gearing transverse contact ratio
ε β	Gearing overlap ratio
ε γ	Gearing overall overlap
Δε V,ϕ,F	Camber part due to rolling (rad)
ζ	Attenuation ratio
η	Efficiency
η	Frequency rate
k	Is Curvature (1/m)
λ	Direction of steering arm (rad)
ρ	Path curve radius (m)
σ	Spread (rad)
τ	Castor angle (rad)
ϕ	Rotation angle (rad)
χ	Roll angle (1/m)
ψ, ψ	Yaw angle, yaw angle velocity (rad), (rad/s)
ω	Angle velocity (rad/s)
ω E	Cutt-off frequency (rad/s)
ω n	Steering system natural frequency (1/s)

Symbol Description

a	Air
dyn	Dynamic
o (curve)	Outside
i (curve)	Inside
F	Front
R	Rear

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Chapter 1
Introduction and History

Peter Pfeffer and Hartmut Ulrich

The main advantage of automobiles over the railway is that the driver determines the trajectory of the vehicle. In other words, motor vehicles can be steered and are not tied to any defined track. The steering assembly is part of the chassis. With the exception of aerodynamic forces, all the forces acting between the vehicle body and the road are transmitted via the chassis. The tasks of the chassis are typically divided into vertical, longitudinal and lateral dynamics. The lateral momentum is largely a function of the steering system in conjunction with the suspension and the tires.

The components of the steering system are the steering wheel, steering column, steering gear and tie rod (steering linkage) (Fig. 1.1). The driver gives his steering commands through the steering wheel. These are transferred via the steering column to the steering gear. Nowadays, the steering gear is usually implemented as a rack-and-pinion drive. It translates the rotary motion into a linear motion. The linear motion is transmitted to the wheel carrier via the tie rod with its ball joints. As the wheel carrier is not directly linked to the steering axle, the wheel is forced to perform a rotary motion around the steering axle. The lateral forces caused by the inclination of the wheel cause the desired yawing moment of the vehicle and thus the movement around the curve. To reduce the forces the driver has to apply when turning, the steering gear usually provides a support for the force of the driver. Steering systems with such a support are called power- or servo-assisted steering systems. The steering system has to allow for predictable and comfortable

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Fig. 1.1 Components of a steering assembly (*Porsche 997*)

driving without suppressing useful feedback to the driver. At the same time disruptive interferences coming from the road surface and the wheels should be kept away from the driver.

This steering handbook is aimed at experts working on the design and construction of vehicle chassis professionally, as well as students and lecturers at universities. It covers the scientific fundamentals of steering systems in motor vehicles. In addition, it documents the present state of the art and identifies current trends. Here, we make use of the expertise of many renowned experts from industry and academia.

The first few chapters deal with the history, the basic principles, and the different types of steering systems as well as the requirements they have to meet. We shall focus on steering kinematics, the requirements of driving dynamics, occurring vibrations, the steering experience of the driver, and the basic functional design (Chaps. 1–8). Chapters 9–15 deal with the different components of the steering system, from the steering wheel to the tie rod. We shall discuss the different types of steering gears such as hydraulic power steering (HPS) or electric power steering (EPS). Special types of steering systems such as the superimposed steering system (Chap. 16), four-wheel steering (Chap. 17) and steer by wire steering (Chap. 18) provide a significant number of additional functions. Chapters 19 and 20 deal with electronic stability control, driver assistance in steering systems and test systems for steering systems and offer an outlook on future trends.

1.1 Definition and Delimitation

The purpose of the steering system is to provide the driver with the possibility of lateral vehicle guidance, i.e. to influence the lateral dynamics of the vehicle. It is a system that connects the driver with the steered wheels of the vehicle. In most cases, turning the steering wheel causes a rotational movement of the steered wheels around the steering axles. This pitching of the (steered) wheels creates lateral forces which turn the vehicle around the vertical axis while driving. This manual covers the dynamics of this steering process in connection with the vehicle and the necessary components. These are the steering wheel, the steering column, the steering gear, the tie rods, the steering assistance and the components necessary for their control and power supply. As for the components of the axle we refer to the specialist literature (cf. Heißing and Ersoy 2007 or Reimpell and Betzler 2005). In addition we shall discuss special designs such as superimposed steering, rear-wheel steering, steer by wire, and active suspension, as well as driver assistance systems, which are closely related to the steering system. This book is limited to the steering systems of passenger cars (also referred to as vehicles in this book). The steering systems of racing cars, commercial vehicles, motorcycles, airplanes and trains will not be discussed in detail.

1.2 Task and Significance of the Steering System

Road vehicles are controlled by the driver almost entirely via the steering system. For traffic safety, it is crucial that the vehicle precisely follows the course set by the driver on the basis of the course of the road and the traffic situation and largely retains it (Braess and Seiffert 2007, p 580). The driver must always have the reassuring feeling that the vehicle responds predictably and reliably to his steering input. To ensure a high quality directional stability, it is crucial that the steering input is promptly translated by the steering system and the vehicle in the expected way, so that the driver can recognise changes of the course and, in turn react to them.

Developers of steering systems therefore have to consider numerous demands and tasks to achieve a customer-friendly design:

- Sufficiently low steering wheel torques and a narrow steering wheel angle required for parking
- Ease of movement, sensitivity, accuracy, a high degree of directional stability, sufficient immediacy and spontaneous responsiveness
- Pronounced road contact, responsiveness of tire-road adhesion
- Automatic return to the central position, good centering, stabilising behaviour in any driving situation
- Compensation of disturbance variables stemming from road surface irregularities, drive, braking, and irregularities of the tires

- Adequate absorption to suppress self-induced vibrations of the vehicle
- Compliance with the crash safety requirements and passenger safety regulations
- Low energy consumption
- Sufficiently low noise level
- Vibrational stability (no self-induced vibrations)
- Low wear and low maintenance over the entire vehicle life cycle.

1.2.1 Basic Types

The steering of two- or multi-axle road vehicles is generally affected by changing the angle between the vehicle's longitudinal axis and the centre planes of some, or all, of the vehicle wheels (Matschinsky 2007). The oldest type is the turntable steering, a design in which a rigid axle is turned around its centre (Fig. 1.2a). This turntable steering is commonly used in coaches and trailers. The same effect can be achieved by turning the front section of the vehicle towards the rear. This type of steering system is called articulated steering (Fig. 1.2b) and is primarily employed in machines and special purpose vehicles. A disadvantage for the turntable and articulated steerings may arise when disturbing forces occur, stemming from their reduced footprint and their long lever arm. This so-called kingpin offset at hub equals half the track width.

Modern road vehicles are almost exclusively steered at the front wheels with a so-called Ackermann steering. In the case of rigid axles this is designed with a continuous tie rod (Fig. 1.2c), in the case of independent suspension a split design of the tie rod is used, as shown in Fig. 1.2d in diagram form (cf. Chap. 4).

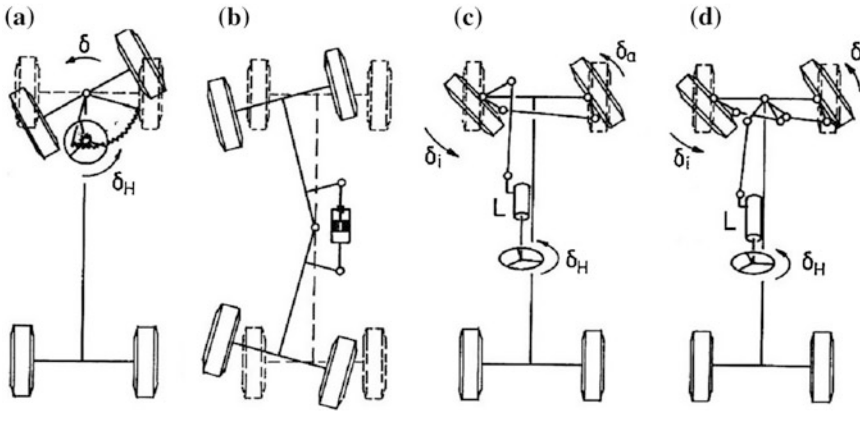

Fig. 1.2 Basic types of vehicle steering systems (Matschinsky 2007)

1.2.2 Designs

The two standard designs of mechanical steering systems, as shown in Fig. 1.3, are recirculating ball steering and rack-and-pinion steering. Because of its reduced steering force recirculating ball steering is used mainly in the commercial vehicle sector and to some extent in SUVs, while rack-and-pinion steering is the most common approach in the passenger car segment. With the increase in car weight, purely mechanical steering has been gradually replaced by hydraulically assisted steering systems. Rack-and-pinion hydraulic power steering (HPS) has prevailed over recirculating ball hydraulic power steering, as it has proved to be a cheaper option.

The supporting power of HPS is provided by a volume flow, which is usually generated by a vane pump. This pump is driven by the internal combustion engine. A pump operating independently of the internal combustion engine is used for electro hydraulic power steering (EHPS). The flow rate can be controlled in some HPS systems and in all EHPS systems. This leads to very smooth and easy steering when parking. With increasing travel speed this flow rate is lowered to achieve a higher steering wheel torque to increase the stability of the vehicle. In addition to the hydraulically assisted steering systems, electrically assisted steering systems (electric power steering—EPS) are becoming more common. In these systems, the supporting power is generated by an electric motor, which is powered by the electrical system on board. Depending on the location of the electric motor in the steering system, the EPS can be subdivided into different designs (cf. Chap. 15).

In the superimposed steering system a synthetically generated steering angle is added to or subtracted from the steering angle given by the driver. Here, an ordinary hydraulic or electric steering system is amplified by a steering angle actuator.

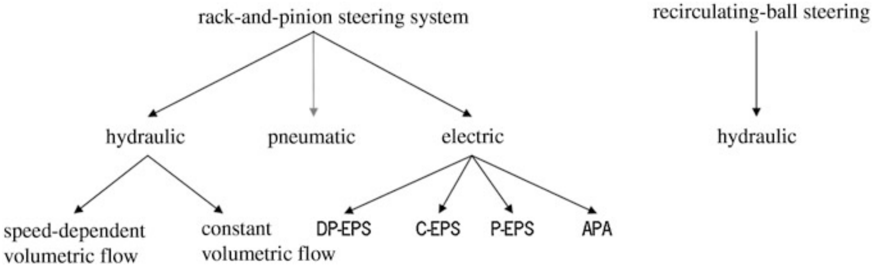

Fig. 1.3 Breakdown of the standard designs of mechanical steering systems

1.3 History of Lateral Dynamics

In the early days of mankind single-axle carts were often drawn by animals or humans. Behind a long drawbar the cart followed. It was only when the driver himself was sitting on the cart that he could feel the forces acting on the steering axle. These are caused by different rolling resistance and irregularities on the road surface. For that reason the first and often very heavy steam vehicles were designed as tricycles with only one steered wheel (Fiala 2006). The single steered front wheel causes much smaller interference torques that need to be compensated by the driver. This explains why the first steering systems were partially self-locking.

The early motor vehicles in their present form were shaped by Gottlieb Daimler and Carl Benz. While Gottlieb Daimler devoted himself to the motorisation of existing vehicles such as carriages or velocipedes, Carl focused his attention on the problem of steering right from the beginning. In his Patent-Motorwagen of 1886 (Fig. 1.9) he eliminated the disturbances by means of fork steering with a zero offset radius, i.e. axial force fluctuations generated by irregularities of the road surface could not impact the actuating force. In contrast, axle pivot steering with its offset radius of half a track width is impeded very strongly. For this reason, this steering technique is nowadays only used for trailers, carriages, and special purpose vehicles. The steering systems of modern motor vehicles are derived from the axle pivot steering of Carl Benz's Patent of 1893 (cf. Sect. 1.3).

The influence of the steering system on vehicle behaviour was recognized quite early. In the annual issues of the periodical "Der Motorwagen" VII–X (from 1904 onwards) various theories of the sideway skid were published (Zomotor 1991). The engineers were particularly concerned with the question of how many and which of the wheels of the vehicle should be driven or steered. In 1907, in a lecture to the Berlin Automotive Engineering Society, Dr. Fritz Huth aptly summed up the following guiding principles:

1. "Any means to increase the friction on the ground is advantageous not only for the drive, but also improves steering and reduces skidding.
2. It is advisable to steer *all four wheels of the car*.
3. It is always advisable and sometimes even necessary to drive each of the four wheels.
4. In cars with a two-wheel drive, the superiority of a front-wheel drive compared to a the rear-wheel drive is so marginal, that the additional complications resulting from combining steering and locomotion are not worth the effort.
5. The centre of gravity of the vehicle should be as close as possible to the middle of the car.
6. It is desirable that the relationship between friction and load is further investigated for different tires and road conditions."

Thus the potential of four-wheel steering to improve driving behaviour was recognised even in the early phase of the automobile. Interestingly, in the same

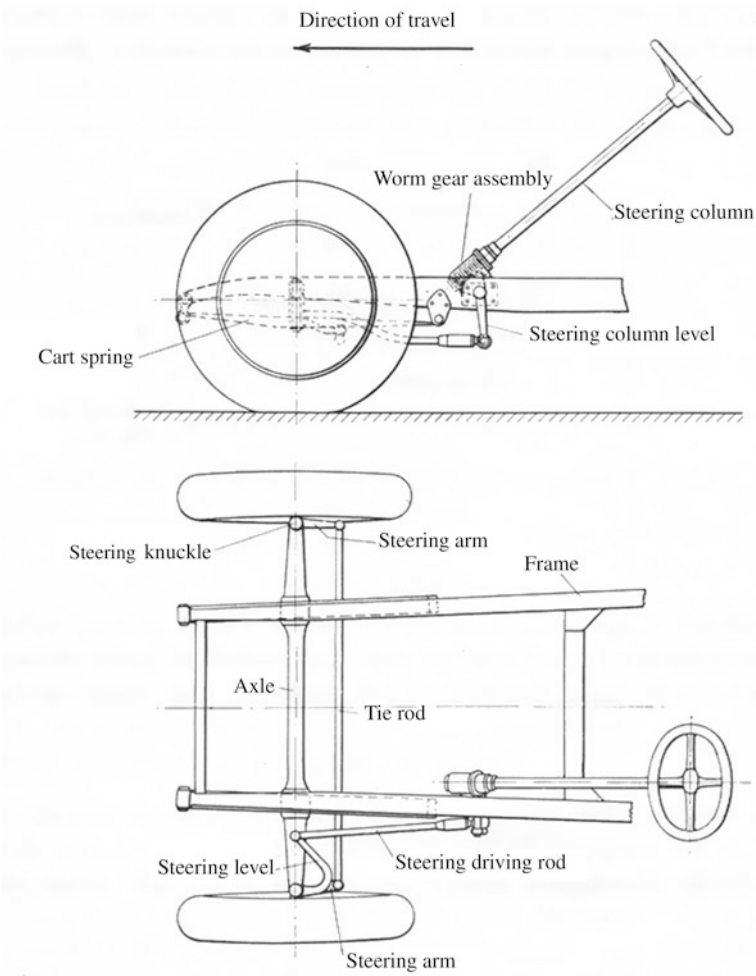

Fig. 1.4 Schematic view of the standard steering system from 1930 (from Becker et al. 1931)

year a study was published by Lanchester of the "Institution of Automobile Engineers" (IAE), in which for the first time the term 'oversteering' was mentioned in connection with the phenomenon of sideways skidding (Fig. 1.4).

A further important step towards understanding the fast turning was the realisation that a tire needs a slip angle to transfer the lateral forces. This insight is attributed to Georges Broulhiet. In 1925 he published a report to the French Institution of Civil Engineers entitled 'The Suspension and the Automobile Steering Mechanism'. These studies were certainly furthered by the first introduction of low-pressure tires by the Michelin Company for Citroën. But these tires produced the new safety-affecting phenomenon of shimmy to the steered wheels. Shortly afterwards Becker et al. (1931) published an in-depth analysis with proposals to solve the 'shimmy in automobile steering systems' which became the most common steering design of the time (Fig. 1.11). In the context of these studies the first tire measurements were performed on a roller drum test rig. At around the same time, Sensaud de Lavaud worked on the mathematical theory of the relation between shimmy and rolling motion in Paris. He showed that the wheels must be uncoupled at the axles to prevent the vehicle from rolling. It was he who patented the swing axle in 1928. This design for driven rear axles dominated our streets until the sixties of the last century. Well-known examples of this design were the VW Beetle or the Tatra 87. De Lavaud was also the creator of the principle of the descending roll axle, i.e. the roll center is very low at the front of the vehicle, while it is located at the level of the suspension at the rear axle. One disadvantage was the resulting self-steering behaviour characterized by oversteering, which was, however, considered to be desirable at the time. In the Mercedes Benz Type 380 of 1933 a combination of decoupled front wheels and a descending roll axle was implemented. For the first time front wheels were linked to elastically mounted wishbones and mounted on unguided coil springs. This compliance enabled the wheel to move to the back when encountering obstacles, thus marking the beginning of elastokinematics.

Vehicle dynamics and self-steering behaviour were first systematically studied in the nineteen-thirties. The term *understeering*, which had been introduced by Lanchester, was complemented with the terms *oversteering* and *neutral behaviour*. These terms were first published by Maurice Olley in 1938 (Fig. 1.5), although he had already investigated vehicle dynamics at General Motors for many years before. As early as 1931 he had studied the importance of roll steer and the influence of tire pressure on vehicle stability. Later he established the definition of under- and oversteering, depending on the slip angles occurring at the front and rear axles. If these slip angles were greater at the front axle than at the rear axle, this was described as understeering, while the opposite was defined as oversteering. When these angles were similar at both axles, the vehicle behaviour was described as neutral. Nowadays, this definition is no longer used and has been replaced by a definition based on the occurring steering wheel angle gradient in relation to the lateral acceleration (see Chap. 5).

The above terms over- and under-steering are related to the stationary circular movement of a vehicle. At the same time the first transient driving tests were conducted (Stonex 1941). Stonex introduced the so-called checkerboard test, a drivability test similar to the step steering input.

By the end of the nineteen-thirties the theoretical treatment of stationary driving conditions had already been established. Our understanding of the transient vehicle behaviour was significantly enhanced by Riekert and Schunck (1940) in their ground-breaking study on the driving mechanics of rubber-tired motor vehicles. For the first time, they analytically solved the motion equations of a simplified vehicle model, which today is referred to as the single-track model. The two degrees of freedom used for the equation were the yaw and the sideslip angle, and even the aerodynamics were taken into account. Interestingly, their analysis concluded that all the vehicles of that time were unstable, even at low speeds.

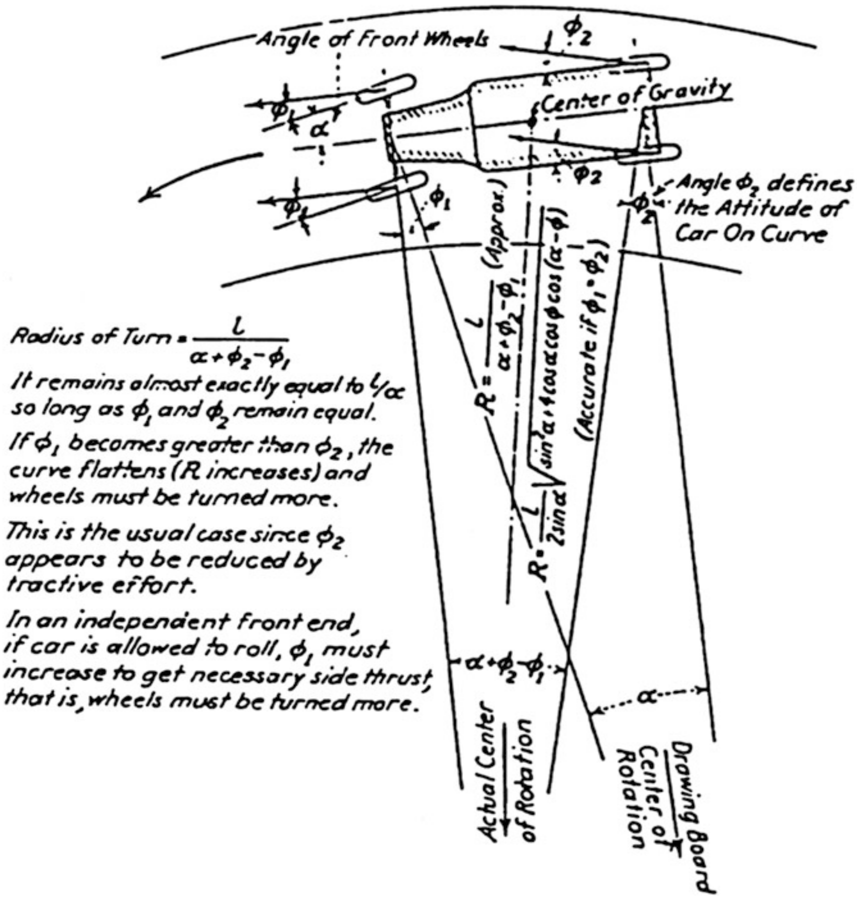

Fig. 1.5 First studies on vehicle dynamics by Olley (1934) (from Dixon 1996)

But these instabilities occurred only at high lateral acceleration and were produced by the saturation of the lateral traction of the tires. This paradox was only solved with the introduction of steering elasticity into the theoretical examination of vehicle behaviour by Fiala (1960). The reduction of lateral tire stiffness by the steering elasticity had already been recognised by Fujii (1956). Based on the findings of Riekert and Schunck, many other practical and theoretical studies followed in the nineteen-forties. The first basic theory of the pneumatic tire was formulated by Von Schlippe and Dietrich (1942). This theory describes the relationship between cornering stiffness, lateral tire stiffness, and the chronological sequence of the lateral forces subject to the slip angle.

Inspired by aircraft stability analysis, Milliken, Whitcombe, and Segel published a series of fundamental studies on vehicle behaviour at the IMechE in 1956 (Segel 1956). They extended Riekert's and Schunck's vehicle model to include the additional degree of freedom of rolling and conducted thorough stability tests. Böhm (1961), Schmid (1964), and Mitschke (1968) pointed out that driving stability is not the same as directional stability. From then the studies on the steering feel of vehicles began. At the time the vehicles differed a lot in the steering characteristics and the required steering wheel torque. The driver, as a 'controller', was also taken into account. Segel (1964) presented the first reference values for optimally perceived steering wheel torque gradients as well as damping and friction in the steering system. Reference should be made here to the very comprehensive summary of the historical development of vehicle dynamics by Milliken and Whitcomb (1956) with an extensive bibliography. Other historical contributions can be found in Dixon (1996) or in Zomotor (1991). The theoretical foundations of vehicle dynamics were first summarised by Mitschke in his "Dynamik der Kraftfahrzeuge" (Dynamics of Motor Vehicles) first published in 1972. The current fourth edition remains the most comprehensive work on this subject.

In 1966 Ralph Nader (1996) published his "Unsafe at any Speed". In this book he highlighted how critically unsafe the cars marketed at the time were. Among other things, he denounced the extreme oversteering driving behaviour of the Chevrolet Corvair, which led to many fatal accidents. Because of the strong political pressure afterward, the automotive industry started to improve the safety of their products and push the research into vehicle dynamics. Another consequence of the criticism was the launching of the Experimental Safety Vehicle (ESV) program by the NHTSA (National Highway Traffic Safety Administration), a sub-agency of the U.S. Department of Transportation. Its aim was to identify objective parameters for a safe vehicle. These efforts resulted in a series of standardized drivability tests and test methods, though they did not succeed in finding any comprehensive limits for the safety of the vehicle or the design of the steering system.

Due to unsatisfactory driving behaviour of the vehicles, better axle suspensions und safer vehicle designs were developed. Cars with swing axles disappeared from the market and were replaced by inherently understeering vehicles. This was realized by equipping front-heavy vehicles with a front-wheel drive. The most well-known example of this design is the Volkswagen Golf which was launched in 1974. Regarding the axle suspensions, the trend was towards independent suspensions, as they allowed an easier resolution of the conflicting goals. To improve steering and braking behaviour a negative offset radius and the Weissach axle were introduced in the nineteen-seventies. Increased attention was paid to the kinematic effects such as the roll steer and elastokinematics.

Other milestones included the introduction of the anti-lock braking system (ABS) in the nineteen-seventies and the large-scale production of four-wheel steering systems in the nineteen-eighties (see Chap. 17). With the introduction of a yaw-moment control (electronic stability program—ESP) an even greater improvement of the stability of the vehicle was obtained compared to four-wheel steering, so that the latter system was forced out of the market again. But in recent years, four-wheel steering is once more in the ascendant. The superimposed steering system (Chap. 16) has been reserved to the optional equipment of premium vehicles up to now. The same applies to systems which influence the yawing moment via drive torques, the so-called torque vectoring. In recent years, the introduction of driver assistance systems has come to the fore. Many of those systems are based on the steering or use the steering as an actuator (Chap. 19). Here we shall only mention steering torque overlay systems and the parking assistant. Chapter 20 presents an outlook on future systems.

1.4 The History of Vehicle Steering Systems

With the development from towed vehicles to powered vehicles, from a chassis with rigid axles to a single-wheel chassis and the constant increase of vehicle speeds and traffic requirements, demands on the steering equipment of vehicles have become more and more complex.

For motorised vehicles, the hitherto proven turntable steering for carriages was replaced by the Ackermann steering. To reduce the steering forces various types of mechanical steering gears were developed over the decades, until finally in the nineteen-fifties hydraulic power steering systems were introduced for commercially available cars. These were complemented by electric power steering systems in the nineteen-nineties. Advances in mechatronics finally enabled the serial production of active steering systems.

1.4.1 Turntable Steering

Transom and turntable steering were invented in the Celtic and Roman era. In the Roman chariot (Fig. 1.6) the front axle could swing around the linchpin through which it was connected to the drawbar and its shafts. The front of the chariot was supported by the transom under the perch and thus maintained in a horizontal position.

Turntable steering allowed wide steering angles and hence a good steerability of the vehicle. There was however the danger of tilting the chariot, when the axle was turned strongly in curves. For towed vehicles, the turntable steering proved to be satisfactory. The steering was affected only slightly by bumps in the track, since the tensile forces acting in the steering direction counteracted the resistances of the track surface.

Because of the limitations of available materials and the slow speeds which could be attained by horse-drawn vehicles, the steering systems made only slow progress in the following centuries. The basic principle of turntable steering was retained, although the transom and the linchpin were gradually replaced by ball rows and ball joints.

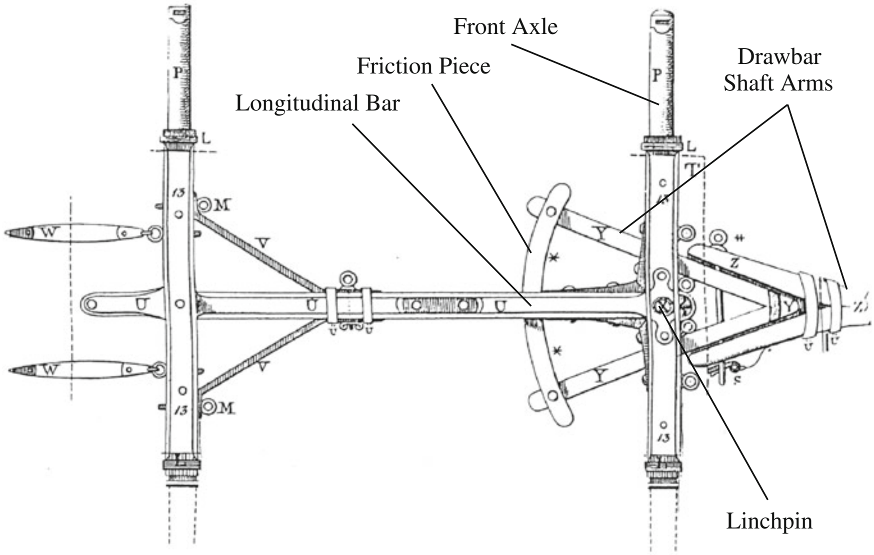

Fig. 1.6 Roman chariot with turntable steering, Eckermann (1984)

1.4.2 The Ackermann Steering

Increasing passenger transport and higher demands on the comfort and speed of the vehicles promoted the evolution of the coach chassis, until, in 1816, the carriage builder Georg Lankensperger received the royal privilege from the Bavarian Court of producing a type of axle pivot steering which made use of steering arms and tie rods.

The characteristic feature of this steering architecture is that the wheels of an axle are mounted on steering knuckles, which are pivotable about almost vertical steering axles. In a curve the inside wheel has to be turned to a narrower angle than the outside wheel. In addition, the extensions of the axles of the left and right front wheels have to intersect at a point which is on the extension of the rear axle (Fig. 1.7).

In 1818 Georg Lankensperger had his invention patented by his friend Rudolf Ackermann under the number 3212 in England, which is the reason for its designation as Ackermann steering.

1.4.3 The Steering of the First Motor Vehicles

The matter of steering gained additional relevance with the development of lightweight, high-speed petrol engines and the first motor vehicles by Gottlieb Daimler and Karl Benz.

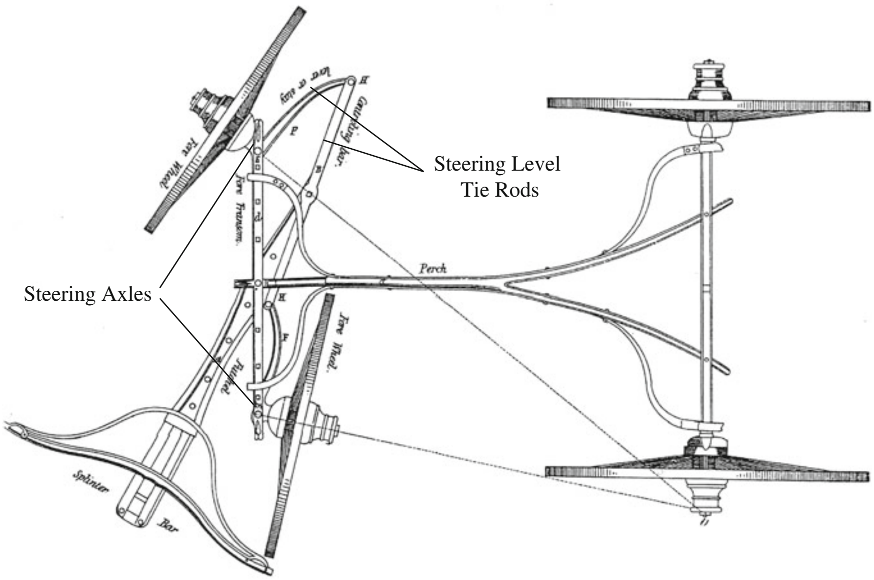

Fig. 1.7 Lankensperger's axle pivot steering with a continuous tie rod, Eckermann (1998)

Daimler's first automobile in 1886 emerged from a carriage (Fig. 1.8), the rear wheels of which were driven via a belt drive. The steering system was a turntable steering, which was operated by the driver via a steering tiller. The tiller was used to rotate the steering column, which—via a pinion and a turntable—turned the front axle around a central stud. In spite of the low travel speed of the carriage car—about 10 km/h—the steering system was suitable to only a limited extent. Due to the large lever arm between the wheel and the swiveling axis, obstacles which were passed by one of the wheels produced steering forces which were difficult to master by the driver at the tiller.

Benz solved this problem when he developed his Patent-Motorwagen in 1886 (Fig. 1.9) by using only one front wheel which, like a bicycle, was steered by fork steering.

The rotation of the steering column, which was effected by turning the tiller, produced, via the pinion and the rack, a displacement of the steering rod. This in turn rotated, via the steering arm as the lever arm, the steering fork with the front wheel.

A disadvantage of the vehicle was its low tipping stability, which led Wilhelm Maybach in 1889 to develop his "Stahlradwagen" (Fig. 1.10), a chassis which was entirely independent of the principles of carriage construction. Like Benz, he was inspired by the principles of bicycle construction.

Maybach transferred the movement of the steering tiller via a V-shaped pitman arm and two tie rods to the front wheel forks. As Maybach had no knowledge of

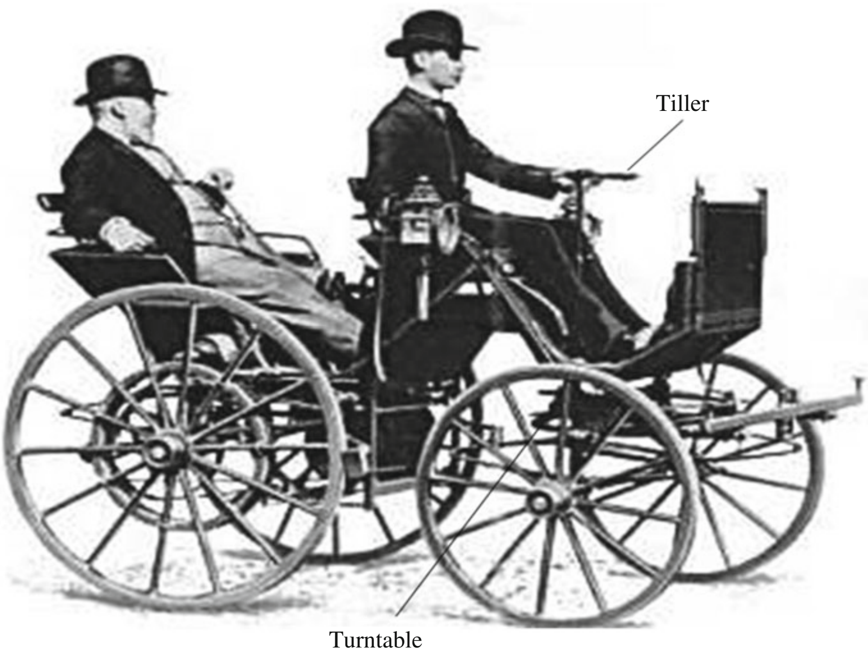

Fig. 1.8 Daimler motor carriage with turntable steering, Walz (1983)

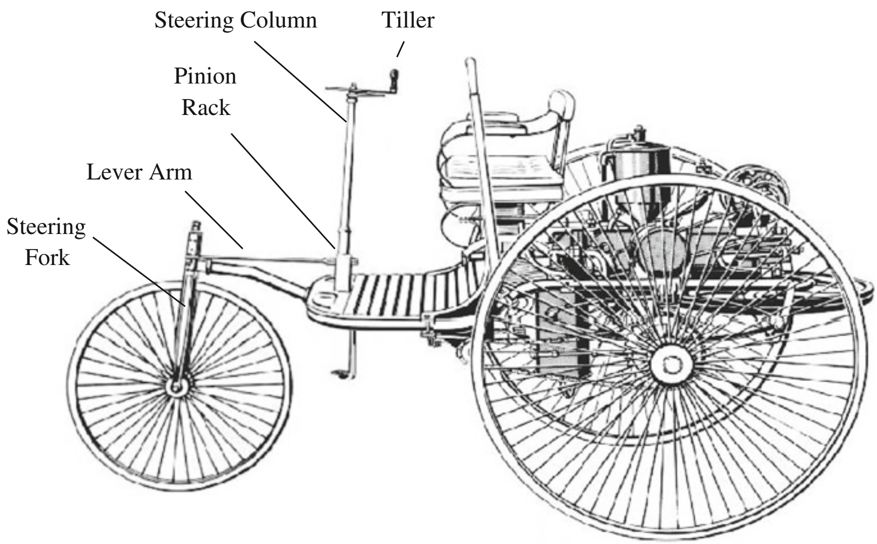

Fig. 1.9 Benz Patent-Motorwagen with fork steering