Bernd Heißing | Metin Ersoy (Eds.)

# Chassis Handbook

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# Chassis Handbook

## Fundamentals, Driving Dynamics, Components, Mechatronics, Perspectives

With 970 figures and 75 tables

ATZ

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# Preface

As vehicle technology progresses into the second decade of the 21st century, chassis technology continues to play an important role in automotive engineering education and practice. In spite of the rapid pace of chassis technology development over the past 20 years, particularly with respect to chassis electronics, no single book has yet addressed the need for a comprehensive work which combines the basics of vehicle design and dynamics with in-depth information about components, systems, mechatronics, and future developments in the field of chassis technology. The goal of this handbook is to satisfy this need in an easy-to-read reference book format.

This chassis technology handbook was published by the Vieweg Verlag publishing house as a completion of their renowned ATZ/MTZ automotive technical book series. In order to satisfy the educational needs of automakers, automotive suppliers, universities, and colleges, this book provides an overview of a wide range of topics with a level of detail suitable for both engineers and students. During the writing of this book, particular emphasis was placed on readability and the use of the most relevant, up-to-date information available. A large number of figures and tables are used to explain a wide variety of topics in a systematic, understandable, and clearly-arranged manner.

The level of detail contained in this book was selected to provide car chassis engineers with a complete overview of their area of work and/or study, to help applications engineers understand the driving dynamics of modern automobiles, and to give students a comprehensive basic knowledge for future work and learning.

The first chapters discuss basic chassis concepts, configurations, and layouts, explain the physical basis of longitudinal, vertical, and lateral dynamics, and describe chassis parameters and parameter values in the context of their effect on driving dynamics and vehicle behavior properties. Subsequent sections describe all chassis subsystems and components in greater detail, including braking systems, steering systems, spring systems, dampers, wheel control components, wheel support components, tires, and wheels. The fourth chapter provides descriptions and comparisons of various axles and suspension systems. Noise, vibration, and harshness (NVH) is the topic of the fifth chapter, which also includes a discussion of rubber-metal components. The sixth chapter deals with modern development methods and the tools used by chassis engineers during the planning and series launch phases to simulate and design chassis components, modules, and systems up to and including validation. The penultimate chapter describes those systems which are used to satisfy modern chassis safety standards and comfort requirements and provide assistance to the driver. These mechatronic and electronic systems include all active, semi-active, adaptive, and X-by-wire chassis systems. The final chapter provides an analysis of future chassis concepts and systems including ideas for the chassis of tomorrow and special considerations relating to hybrid vehicle chassis systems. Predictive and intelligent chassis systems, autonomous driving, and the visions of the driving chassis and the e-corner module are discussed in the final chapter. Three possible future scenarios are also presented in order to help predict what chassis systems could look like in the year 2025.

This book features the combined knowledge and contributions of over 40 well-known European experts from world-class automakers, automotive suppliers, and universities. In addition to those authors credited by name, the authors and editors were also assisted by a large number of additional engineers and experts who contributed to the writing of this book via technical discussions, consultations, presentations, recommendations, corrections, and/or technical proofreading. The authors and editors would like to thank these engineers and experts, who are too numerous to list here. We would be doing a terrible injustice if we were did not also thank the office staff members at our German-university partners (RWTH Aachen and TU Munich), our industry partners (Audi, Continental, Mubea, Schaeffler KG, FAG, TÜV-Süd, and ZF Friedrichshafen AG), and the Vieweg+Teubner Verlag publishing house for their unwavering patience and tireless assistance with organizational tasks. The authors and editors would also like to thank the staff of ZF Lemförder North America for their assistance with proofreading the English text.

In order to make future editions even better, we invite the readers of this book to email us with their ideas, improvements, completions, and suggestions at fahrwerkhandbuch@zf.com.

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# Contents

# Abbreviations

| | |
|---|---|
| AAS | Adaptive Air Suspension |
| ABC | Active Body Control |
| ABS | Anti-Blocking System |
| ACC | Autonomous / Adaptive Cruise Control |
| ACE | Active Cornering Enhancement |
| ADR | Autom. Distanzregelung (*distant control*) |
| ADS | Adaptives Dämpfungssystem (*damping*) |
| AFS | Active Front Steering |
| AFS | Aktive Fahrwerkstabilisierung |
| AGCS | Active Geometry Control Suspension |
| AHK | Aktive Hinterachskinematik (*rear steering*) |
| AICC | Autonomous Intelligent Cruise Control |
| AKC | Active Kinematics Control |
| ALC | Automatic Linear Guidance Control |
| AMR | Antriebsmoment Regelung (*traction control*) |
| ANB | Automatische Notbremsung (*emerg. Braking*) |
| AOS | Adaptive Off-Road Stabilizer |
| APB | Aktive Parkbremse – Active Parking Brake |
| APS | Automatic Parking System |
| APQP | Advanced Product Quality Planning |
| ARM | Active Roll Mitigation |
| ARP | Active Rollover Prediction |
| ARS | Active Roll Stability |
| ASC | Automatic Stability Control |
| ASCA | Active Suspension via Control Arm |
| ASCS | Active Suspension Control System |
| ASCx | Automatic Stability Control x (*all wheel*) |
| ASIC | Application Specific Integrated Circuit |
| ASL | Anhänger-Schlingern-Logik (*trailer stability*) |
| ASMS | Autom. Stabilitätsmanagementsystem |
| ASR | Antriebsschlupfregelung (*anti spin regulation*) |
| ASTC | Advanced Stability Control |
| ATC | Active Traction Control |
| ATC | Active Tilt Control |
| ATTC | Active Tire Tilt Control |
| AWD | All Wheel Drive |
| AWS | All Wheel Steering |
| AYC | Active Yaw Control |
| BAB | Bundesautobahn (*German highway*) |
| BAS | Bremsassistenz (*braking assistance system*) |
| BASR | Bremsen-Antriebs-Schlupf-Regelung |
| BBC | Brake Boost Control |
| BbW | Brake by Wire |
| BKV | Bremskraftverstärker (*brake booster*) |
| BMR | Bremsmomentenregelung (*brake moment r.*) |
| BBA | Betriebsbremsanlage (*service brake system*) |
| CAD | Computer Aided Design |
| CAE | Computer Aided Engineering |
| CAM | Computer Aided Manufacturing |
| CAN | Controller Area Network |
| CASE | Computer Aided Software Engineering |
| CATS | Computer Active Technology Suspension |
| CBC | Cornering Brake Control |
| CBS | Combined Brake System |
| CDC | Continuous Damper Control |
| CDL | Collision Danger Level |
| DBC | Dynamic Brake Control |
| DBS | Dynamic Brake Support |
| DD | Dynamic Drive |
| DDE | Digitale Dieselelektronik (*Diesel inj. control*) |
| DDS | Deflation Detection System |
| DIN | Deutsches Institut für Normung (*German institution for standardization*) |
| DME | Digitale Motorelektronik (*dig.engine control*) |
| DMU | Digital Mock Up |
| DOE | Design of Experiment |
| DQL | Doppelquerlenker (*SLA Suspension*) |
| DRC | Dynamic Ride Control |
| DSC | Dynamic Stability Control |
| DSP | Dynamisches Stabilitätsprogramm |
| DSCT | Dynamic Stability and Traction Control |
| DTC | Dynamic Traction Control |
| DXC | Dynamic x(Allrad) Control |
| eABC | Electromechanical Active Body Control |
| EAS | Electronic Active Steering Assistant |
| EBA | Elektronischer Bremsassistent (*Brake ass.*) |
| EBC | Electronic Body Control |
| EBD | Electronic Brake Force Distribution |
| EBM | Elektronisches Bremsen-Management |
| EBS | Electronically Controlled Braking System |
| EBD | Elektronic  Brake force Distrubution |
| ECD | Electronic Controlled Deceleration |
| ECE | Economic Commission for Europe |
| ECM | Electronic Chassis Management |
| ECU | Electronic Control Unit |
| EDC | Electronic Damper Control |
| EDC | Engine Drag Control |
| EDS | Elektronische Differenzialsperre (e*Diff*) |
| E/E | Elektrik/Elektronik |
| EHB | Elektrohydraulische Bremse |
| EHC | Electric Hydraulic Combi Brake |
| EGS | Elektronische Getriebesteuerung (*electronical transmission contro*l) |
| EMB | Elektromechanische Bremse (*eBrake*) |
| EMC | Electro Magnetic Compatibility |
| EMF | Elektromechanische Feststellbremse (*electro mechanical parking brake*) |
| EMP | Elektronische Parkbremse (*e-parking brake*) |
| EPS | Electric Power Steering |
| ESD | Electrostatic Discharge |
| ESC | Elektronic Stability Control |
| ESP | Elektronisches Stabilitätsprogramm |
| ETC | Elektronische Traktionskontrolle (*electronical traction control*) |
| FA | Front axle |
| FAS | Fahrerassistenzsysteme (*driver assistance*) |
| FDR | Fahrdynamikregelung (*chassis control system*) |
| FEA | Finite-Elemente-Analyse (*finite elements*) |

FEM Finite-Elemente-Methode (*finite elements*)
FFT Fast Fourier Transformation
FGR Fahrgeschwindigkeitsregler (*speed control*)
FMEA Fehlermöglichkeits- und Einflussanalyse (*Failure Mode and Effect Analysis*)
FPDS Ford Product Development System
FPM Fahrpedal-Modul (*brake pedal module*)
FSR Fahrstabilitätsregelung (*stability control*)

GCC Global Chassis Control
GMR Giermomentenregelung (*yaw moment control*)
GM General Motors

HA Hinterachse (*rear axle RA*)
HAQ Hinterachs-Quersperre (*rear diff lock*)
HBA Hydraulischer Bremsassistent (*assist*)
HCU Hydraulic Control Unit
HDC Hill Descent Control
HECU Hydraulic Electronic Control Unit
HiL Hardware in the Loop
HMI Human Machine Interface
HPS Hydraulic Power Servo-steering

ICC Intelligent Cruise Control
ICC Integrated Chassis Control
ICCS Integrated Chassis Control System
ICD Intelligent Controlled Damper
ICM Integrated Chassis Management
IDS Interaktives Dynamisches Fahrsystem (*interactive chassis dynamics system*)
ISAD Integrated Starter Alternator Damper
ISG Integrated Starter Generator
ISO International Standards Organization
IWD Intelligent Wheel Dynamics

K&C Kinematics and Compliances

LbW Leveling by Wire
LCC Lane Change Control
LIN Local Interconnected Network
LWS Lenkwinkelsensor (*steer angle sensor*)

MB Mercedes Benz
MBA Mech. Bremsassistent (*mech. brake assist*)
MBS Multi Body System / Simulation
MBU Motorbremsmomentunterstützung
MKS Multikörpersimulationssystem (*MBS*)
MMI Man Machine Interface
MPV Multi Purpose Vehicle
MSR Motor Schleppmomentenregelung (*engine drag regulation*)

NVH Noise Vibration Harshness

OCP Optimized Contact Patch
OEM Original Equipment Manufacturer

PCB Printed Circuit Board
PDC Park Distance Control
PDM Product Data Management
PEP Produktentstehungsprozess (*product development process PDP*)
PM Projektmanagement
PSD Power Spectral Density
PTO Power Take Off

RA Rear Axle
RDK Reifendruckkontrolle (*tire pressure control*)
RLDC Road Load Data Collections
ROP Roll Over Protection
RSP Roll Stability Control

SBC Sensotronic Brake Control
SbW Steer by Wire
SE Simultaneous Engineering
SiL Software in the Loop
SIL Safety Integrity Level
SLA Short Long Arm independent suspension
SLS Self Leveling Suspension
SMR Schleppmomentenregelung (*drag moment control*)
SOP Start of Production
SPICE Software Process Improvement and Capability Determination
SSP Strassensimulationsprüfstand (*road simulation test rig*)
STC Stability Traction Control
SUC Sport Utility Cabriolet
SUV Sport Utility Vehicle
SW Software
SSS Superposition steering system
S&G Stop and Go

TCS Traction Control System
THZ Tandemhauptbremszylinder
TMC Tandem Master Cylinder
TPMS Tire Pressure Monitoring System
TTP Time Triggered Protocol

UCL Under Steer Control Logic
ÜLL Überlagerungslenkung

VA Vorderachse (*front axle FA*)
VDC Vehicle Dynamic Control
VGRS Variable Gear Ration Steering
VPE Virtual Product Environment
VSA Vehicle Stability Assist
VSC Vehicle Stability Control
VTD Variable Torque Distribution
VTG Verteilergetriebe (*power take off*)

xDRIVE Allrad System (*all wheel drive*)

WSS Wheel Speed Sensor

µC/µP Microcomputer / Microprocessor
4Motion Permanent all wheel drive
4WS Four Wheel Steering

# Notations

$A$ acceleration; initial displacement; frontal area
$B$ fuel consumption
$C$ cornering stiffness; damping coefficient
$CG$ center of gravity
$D$ dynamic magnifier; deflection; diameter; damping constant
$DEQ$ differential equation
$E$ Young's modulus; energy
$EG$ self steering (gradient)
$F$ force
$G$ sheer modulus; brake gain
$H$ height of center of gravity; height
$I$ moment of inertia
$K$ understeer gradient; rolling resistance
$L$ wheelbase
$M$ moment; torque
$N$ normal force
$P$ pressure (tire inflation); force; power
$Q$ thermal flux
$R$ radius; radius of turn
$Re$ residual
$S$ spring rate; surface
$T$ track width; torque; temperature
$V$ velocity; vehicle; volume
$W$ weight
$X$ forward direction of travel; anti dive/lift
$Y$ lateral direction of travel
$Z$ vertical direction of travel

$a$ acceleration; distance CG to front axle
$b$ deceleration; distance CG to rear axle
$c$ coefficient of viscous damping
$d$ distance; diameter
$e$ exponential function; offset
$f$ frequency; stress; rolling resistance
$g$ acceleration of the earth gravity
$h$ height; wheel deflection
$i$ gear ratio
$k$ coefficient; stiffness
$l$ length; wheel base
$m$ mass
$n$ factor; ratio
$p$ pressure
$r$ radius; rolling radius of tire
$s$ thickness; stopping distance
$t$ time; thickness; temperature; track; tread
$v$ velocity, slipping speed
$x$ deflection, forward direction of vehicle
$y$ lateral direction of vehicle
$z$ vertical direction of vehicle; number of teeth

$\alpha$ tire slip angle
$\beta$ side slip angle
$\chi$ CG height to wheelbase ratio; ratio of unsprung to sprung mass
$\gamma$ camber angle
$\Delta$ difference; incremental
$\delta$ steer angle; toe angle
$\varepsilon$ roll steer coefficient; inclination of roll axis; supporting angle
$\kappa$ slip
$\eta$ efficiency
$\phi$ roll angle
$\lambda$ lateral inclination of steer axis
$\Phi$ pitch angle
$\rho$ density; air density
$\mu$ coefficient of friction
$\upsilon$ castor angle of steer axis
$\Psi$ yaw angle; heading angle
$\omega$ angular velocity; frequency
$\Omega$ angular speed

**Suffixes**

A air; aerodynamic resistance
AM Ackermann
at aligning torque
amb ambient
atm atmospheric
acc acceleration
B brake
C climbing
c centre of gravity
centrif centrifugal
char characteristic
conserv conservative energy / force
crit critical
D; d damping
dissp dissipative energy / force
dyn dynamic
E earth; environmental
e /eng engine
f front
flex flexing resistance
h hitch point, hand
I inertial resistance
i inner; inside; inboard
kin kinematic
L luft (air, wind)
l longitudinal; left
m middle; mean
n natural; normal
o outer; outside; outboard
opt optimal
p peak
pl plastic (ground)
R roll; rolling resistance
Req required
r rear; right
red reduced
rel relative

| | |
|---|---|
| res | resulting |
| rot | rotational |
| Sl | slope of the roadway |
| s | stiffness; sliding; steer; side (slip); scrub |
| sp | spring; Schwerpunkt (center of gravity) |
| stab | stabilizer bar |
| stat | static |
| T | tire; torque; traction; trailer; transmission |
| t | time; traction |
| th | theoretical |
| trans | translation |
| tot | total |
| u | unsprung mass |
| V | vehicle |
| x | longitudinal |
| W; w | wheel |
| y | lateral |
| z | vertical |

# 1 Introduction and Fundamentals

When specialists discuss motor vehicle technology, topics such as mobility, power, efficiency, vehicle classification, chassis, safety, ride comfort, dynamics, and environmental concerns are all frequently mentioned. Electrical systems and electronics are also topics which are discussed with increasing frequency. Active systems, X-by-wire, driver assistance systems, control systems, hybrid drive, vehicle agility, and infotainment are all areas of current importance.

The chassis plays a key role in determining vehicle safety, ride comfort, dynamics and agility. Electronic control systems such as X-by-wire, driver assistance and active systems are increasingly integrated into the chassis systems of modern cars.

The complete vehicle is traditionally divided into three groups: powertrain, chassis/suspension, and body. The powertrain contains elements which propel the vehicle, the body provides room for people and cargo, and the chassis and suspension allow the vehicle to ride, turn, and stop. Modern vehicles integrate the body and chassis into a structure known as unibody or monocoque. A result of this integration is that not all components necessary for conveyance are included in the chassis. Pick-ups and some sports utility vehicles are still built using a body-on-frame construction which allows a complete rolling chassis independent of the body. (**Figure 1-1**)

In 1906, Karl Blau described the chassis as follows: "The chassis is made up of the wagon's wheels and the suspended steel frame, which carries the motor and all accessories necessary for regular operation." [1] In addition to body and powertrain, the chassis and suspension are main components of the automobile and together are made up of the wheels, wheel carriers, wheel bearings, brakes, wheel suspension, subframes, springs (including stabilizers), dampers, steering gear, steering linkage, steering column and wheel, pedal cluster, motor mounts, driveshafts, differential, and any chassis control systems (**Figure 1-2**). These components represent approximately 20% of the total weight and 15% of the total production costs of a standard, mid-sized vehicle [2] (**Figure 1-3**).

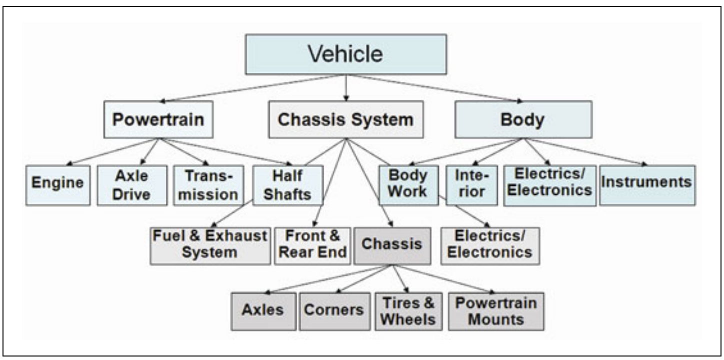


**Fig. 1-1:**
Vehicle components and systems

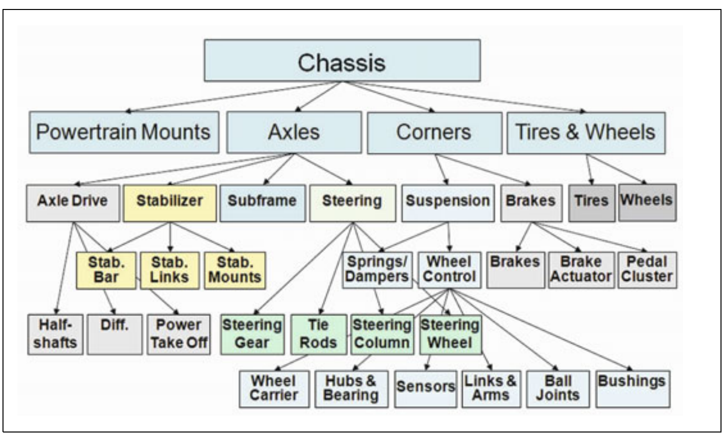


**Fig. 1-2:**
Components of a modern chassis system

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The chassis and suspension act as an interface between the vehicle to the roadway and enable all functions required to control the vehicle: applying the driving torque to the road surface (overcoming rolling resistance, accelerating), braking, the operation of the clutch and accelerator pedals, steering, springing, and damping.

| MANUFACTURER | Volvo | Ford | Ford | Toyota | Average | | |
|---|---|---|---|---|---|---|---|
| MODEL | S80 | Taurus | Mondeo | Camry | kg | % | |
| Body | 301 | 286 | 276 | 299 | 291 | 20 | |
| Doors | 90 | 111 | 97 | 102 | 100 | 7 | |
| Window Glasses | 55 | 56 | 36 | 45 | 48 | 3 | |
| Bumpers | 31 | 31 | 28 | 23 | 28 | 2 | |
| Seats | 78 | 69 | 72 | 59 | 69 | 5 | |
| Dashboard | 48 | 52 | 40 | 49 | 47 | 3 | BODY |
| Subtotal | 604 | 604 | 550 | 577 | 584 | 39.4 | |
| Chassis | 233 | 180 | 191 | 187 | 198 | 13 | |
| Tires & Wheels | 94 | 92 | 87 | 97 | 93 | 6 | CHASSIS |
| Subtotal | 326 | 272 | 279 | 285 | 290 | 19.6 | |
| Engine | 167 | 157 | 156 | 137 | 154 | 10 | |
| Transmission | 101 | 103 | 86 | 89 | 95 | 6 | |
| Driveshafts | 14 | 13 | 16 | 15 | 14 | 1 | |
| Exhaust System | 38 | 30 | 40 | 26 | 34 | 2 | |
| Fuel Tank | 80 | 63 | 56 | 70 | 67 | 5 | POWERTRAIN |
| Subtotal | 400 | 366 | 355 | 336 | 364 | 24,5 | |
| Air Conditioning | 28 | 29 | 26 | 27 | 28 | 2 | |
| Electrics | 57 | 49 | 40 | 46 | 48 | 3 | ACCESORIES |
| Subtotal | 85 | 77 | 66 | 73 | 75 | 5.1 | |
| Other | 196 | 210 | 115 | 157 | 170 | 11 | OTHERS |
| Subtotal | 196 | 210 | 115 | 157 | 170 | 11.4 | |
| TOTAL kg | 1611 | 1530 | 1365 | 1428 | 1483 | 100 | |

**Fig. 1-3:** Distribution of total vehicle weight among the main modules and systems in selected passenger cars (MY 2000)

This book was conceived as an academic handbook for suspension and chassis specialists and students of vehicle technology. Rather than concentrating on theory and fundamentals, this book covers all aspects of the latest suspension and chassis technology and focuses on current issues and innovation. Perspectives on the future of suspension and chassis technology are also presented.

Chapter 1 provides an introduction to the basic concepts of suspension and chassis layout. An extensive description of all aspects of "Driving Dynamics" (Chapter 2) follows.

Chapter 3 ("Suspension and Chassis Elements"), which makes up most of the book, describes all systems, modules, and components: axle drive, braking, steering, springing, damping, wheel control, wheel carriers, wheel bearings, tires and wheels. Chapters 4 and 5 are devoted to "Axles" and "Ride Comfort".

The processes involved in the various phases of product creation are illuminated in Chapter 6 "Suspension and Chassis Development". Planning, development, simulation, validation, and project management are all discussed up to and including the start of production.

All modern chassis modules are affected by electronics, either directly or indirectly. These elements are described in depth in Chapter 7, "Suspension and Chassis Electronics". The book ends with Chapter 8, "The Future of Suspension and Chassis Technology".

## 1.1 History, Definition, Function, and Significance

### 1.1.1 History

The history of vehicle suspension began over 6000 years ago with the invention of the wheel. The wheel is recognized as one of the most significant inventions in the history of mankind. As early as 2700 BC, Sumerian parade wagons featured four disclike wheels with a metallic outer band. These wheels were free to rotate about axles which were mounted rigidly to the wagon (**Figure 1-4**). The metallic outer surface was intended to increase the wheels' longevity. Contact surfaces between wheel and axle were lubricated with animal fat or oil. The first steering systems appeared between 1800 and 800 BC, and consisted of a front axle mounted to the wagon body by means of a single pivot joint at the center of the axle.

**Fig. 1-4:** Sumerian parade wagons (2700 BC)

In order to increase passenger comfort, the Romans separated the wagon body from the axles. The wagon coachwork, which would later become the body, was suspended from the axles by chains or leather straps. This system was intended to mitigate impacts from the road surface, and is recognized today as the first known suspension system. The first suspended wagon with steering and brakes appeared in Europe in the 10th century (**Figure 1-5**) This wagon featured leaf springs, a steerable axle, and a braking system consisting of a brake shoe suspended from a chain. This design separated the wagon into a sprung and an unsprung mass, a fundamental requirement for increasing vehicle speed beyond 30 km/h.

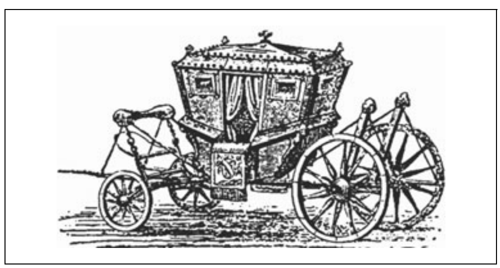

**Fig. 1-5:** Horse-drawn buggy with wheel suspension, springs, brakes, and steering

In the 18th century, a further improvement in ride comfort was achieved with the introduction of self-damping elliptical leaf spring sets. Damping in these leaf spring sets is provided by friction between the individual springs. These leaf spring sets were also capable of locating the axles in the vehicle's longitudinal direction, thus eliminating the need for heavy support beams between the axles.

After the fall of the Roman Empire, improved roadways were largely neglected. As a result, the only way to economically operate the heavy, steam-powered vehicles of the early 19th century was on rails. During the 19th century, several developments combined to lay the groundwork for rapid road transport in England. The first paved street networks, which were made possible by MacAdam, the introduction of the spoked wheel by Walter Hancock in 1830, and the first pneumatic tire from John Boyd Dunlop in 1888 (based on an invention by Robert William Thomson from 1845) all combined to enable smooth and rapid travel on roadways.

Another important invention in the history of vehicle development was knuckle-pin (kingpin) steering, patented in 1816 by Georg Lankensperger, a Munich coachbuilder. Rather than steering the entire axle, kingpin steering allows each steered wheel to pivot about a separate axis. By connecting both wheels with a tie rod, each wheel can steer at a different angle, which allows the rotational axes of the wheels to intersect one another. This principle is known as the "Ackermann Principle" [4,5] (named after Lankensperger's London licensee, Rudolph Ackermann) and is still an important consideration in the design of steering systems today (**Figure 1-41**).

In the 18th century, the first steam vehicles appeared on the road (1769 Nicolas Joseph Cugnot, 1784 James Watt, 1802 Richard Trevithick). Although some of these vehicles featured advanced suspension systems, this first type of self-propelled transport was not the model for today's automobiles. The gaseous-fuel engine was invented in 1860 by Etienne Lenoir and was subsequently developed into the four-cycle engine in 1876 by August Otto, Gottlieb Daimler, and Wilhelm Maybach. The introduction of petroleum as a fuel in 1883 allowed Daimler to create the fast-running gasoline engine, which made it possible for Karl Benz to patent the first self-propelled vehicle with an internal combustion engine on January 29th, 1886. This groundbreaking vehicle (**Figure 1-6**) formed the basis for today's automobiles.

The automotive pioneers carried over suspensions and most other components from horse-drawn carriage designs. A typical carriage chassis consisted of spoked wheels with a flat-base rim and bead tire, tiller steering, elliptical leaf springs, block (scrub) brakes, rigid axles, and dampers made from leather straps. The appearance of the automobile changed rapidly, however, and became more oriented toward high-speed operation. The configuration known today as the "standard layout" resembles the powertrain and chassis layout that developed during this time. An example of this, the 1910 Mercedes F 188, can be seen in **Figure 1-7**.

**Fig. 1-6:** The first automobile (Karl Benz, 1886)

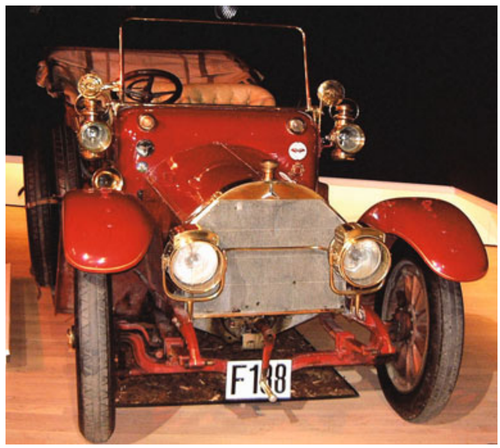

**Fig. 1-7:** Early automobile (1910 Mercedes), no longer based on horse-drawn carriage design

The history of suspension development is closely linked with the separation of functions which were previously performed by a single module. Some examples of this are [7]:

- Separation of the body from the chassis
- Separation of sprung and unsprung mass
- Separation of springing and damping functions
- Separation of the wheel from the tire
- Separation of the wheel and the axle (independent suspension)
- Separation of the control arms (multi-link suspensions)
- Separation of the connection between suspension and chassis by a subframe.

The most important inventions during the first century of chassis development include radial tires, coil and air springs, hydraulic shock absorbers, ball joints, rubber bushings and mounts, rack-and-pinion power steering, hydraulic four-wheel brakes, disc brakes, separation of wheel control and springing functions, independent suspensions, multi-link suspensions, all-wheel drive, and electronic systems (ABS, ASR, EBV, ESP, ACC, etc.).

**Powertrain Configurations**: The horse-drawn carriages which formed the basis for early automobiles had no driven axles; they were always pulled. The first automobiles featured a rear engine mounted directly above a driven rear axle. Due to the steering function of the front wheels, a driven front axle was too complex for these early vehicles. The drawback of such a rear-engine, rear-drive configuration is that the rear wheels bear a much greater load than the front wheels. Weight distribution on axles was improved by shifting the engine to the front of the vehicle and driving the rear wheels with a driveshaft. The first vehicles to feature this layout (known today as the "standard layout") were introduced by Renault and Daimler in 1898, by Horch in 1900 and by Ford in the USA as the T Model in 1908 (**Figure 1-8**). The development of constant velocity (CV) joints in 1931 enabled mass production of front wheel drive vehicles. The DKW F1 and Citroen Traction are examples of front-wheel-drive vehicles from this time period. The introduction of front-wheel-drive brought several important advantages, especially for small vehicles. These advantages include low weight, increased cabin space, and most importantly, low cost.

**Fig. 1-8:** The first series-production Ford T Model "Tin Lizzy" with rear wheel drive (standard layout) from 1908

**Brakes**: The first automobiles featured simple block (scrub) brakes which used leather brake pads to apply friction directly to the wheel's surface. These early braking systems were soon replaced by the more effective drum brake, which applies a force to the inner or outer surface of a drum attached to the wheel. A significant problem with early cable-operated braking systems was that the braking force was not evenly distributed to all wheels. This problem was solved in 1920 when the Californian Malcolm Lockheed patented a hydraulic braking system with a slave cylinder at each wheel. The first production vehicle with a hydraulic braking system was the 1920 Chrysler 70. In order to prevent a complete loss of braking in the event of hydraulic failure, dual-circuit braking systems became standard in the 1930s. For heavier vehicles, a power braking system was developed which used a partial vacuum to enable greater hydraulic pressures. Disc brakes were successfully used by Jaguar in motorsport starting in 1952. Disc brake technology for passenger vehicles was first presented to the public by Dunlop at the 1957 Frankfurt auto show, and quickly became the standard for front wheel braking systems. The first disc brake systems featured a stationary caliper with pistons acting on either side of the brake disc. A main drawback of these early systems was their large size. Package size was later reduced with the introduction of the floating caliper, whereby pistons are only required on the inner side of the brake disc. The floating-frame caliper was replaced by the stiffer fully-floating caliper starting in 1978 [8].

A revolutionary advancement in braking technology came in 1965 with the introduction of the first electronically-regulated braking system in the Jensen C-V8 FF. This technology, known as ABS (anti-lock braking system), restricts wheel lock-up during braking. The first modern ABS system using freely programmable electronics and wheel speed sensors was proposed by Fritz Oswald [7], developed at Bosch, and entered series production as an option on some 1978 Mercedes-Benz vehicles. An electronic system to regulate tire slip under power was introduced in 1987 as ASR (anti-slip regulation). A further system known as ESC (electronic stability control) was introduced in 1995. ESP combines electronic braking and engine regulation to stabilize vehicle behavior in extreme situations. Two further electronic braking regulation systems, EBD (electronic brake force distribution) and BAS (braking assistance system), were introduced in 1995 and 1996, respectively.

**Steering**: The steering wheel dates back to the Englishman Walter Hancock's steam-powered car, which appeared at the beginning of the 19th century. After the introduction of kingpin steering, the first vehicle with rack-and-pinion steering was Amedee Bollee's 1878 steam-powered car "La Mancelle". The gear ratio between the pinion and rack allowed a reduction of the force required to steer the wheels. This also meant, however, that the steering wheel must be turned further to achieve the same steering angle at the wheels. The American L. Megy integrated the function of the toe link into the steering rack as early as 1902, thus inventing the most commonly used steering layout today. Due to the low efficiency of the rack-and-pinion system, it was largely neglected in favor of the worm-and-roller of Henry Marles (1913) or the worm-and-peg of Bishop (also known as the 1923 Ross steering system). The high friction of the worm-and-roller was greatly reduced in the 1930s by Saginaw Steering Division's worm and recirculating-ball nut steering gear. Recirculating-ball steering was standard until the 1960s, and was used by Mercedes until as recently as the 1990s.

Power steering was introduced in the USA in 1951, first at Chrysler, and then at General Motors. The introduction of power steering, combined with improved materials, better machining processes, and greatly reduced manufacturing costs, resulted in rack-and-pinion completely replacing recirculating-ball steering in passenger vehicles.

Although a vehicle with rear-wheel steering is more maneuverable than a vehicle with front-wheel steering, steering has remained chiefly the domain of the front wheels, due to the simple fact that a vehicle with rear-wheel steering would be too difficult for any driver to control at high speeds. The advantages of rear-wheel steering were first explored a century ago, and were combined with front-wheel steering to create all-wheel or four-wheel steering systems. Four-wheel steering was offered in the 1990s by several Japanese manufacturers, but production was stopped just a few years later. Despite this rough start, four-wheel steering has made a comeback in recent years.

The history of steering systems also includes such innovations as the adjustable steering column (invented in the USA) and the collapsible steering column invented by Bela Bereny at Daimler Benz. The invention of the collapsible steering column for crash safety helped coin the term "passive safety" as it pertains to vehicle development.

**Springs**: Torsion beams and coil springs proved to be the successors to the above-mentioned elliptical leaf springs. The development of coil springs with a customized, progressive spring rate can be traced back to Jean Alber Gregorie. The Lloyd Arabella featured progressive-rate coil springs as early as 1959. In 1978, Opel introduced a smaller version, the space-saving miniblock spring. Spring materials and surface treatments have improved dramatically in recent years. This has led to smaller springs which are capable of handling larger loads.

Torsion bar springs are tunable and compact, but this solution is seldom used due to its high cost. In spite of their lack of use as primary springs, torsion bars are widely used as stabilizers to increase roll stiffness by increasing the load difference between the outer and inner wheels during cornering. Stabilizer bars are especially common in independent front suspensions.

Pneumatic springs were used in horse-drawn carriage suspensions since 1845. Hydropneumatic springs were used in George Stephenson's locomotives as early as 1816. Westinghouse, an American, developed pneumatic springs for use in passenger cars around 1920. Citroen offered hydropneumatic suspension as a special option ("Traction Avant") on the last version of the 15 CV, and as standard equipment on the legendary DS in 1955.

Air springs have been used since the 1930s, and are used today mainly in luxury cars to improve ride comfort. Air springs boast greatly reduced rubber wall thickness and minimal hysteresis, which enables them to be effective even at very small amplitudes.

**Damping**: True velocity-dependent damping elements were absent from the first 50 years of automobile development. The dampers during this time period functioned mainly using dry friction, with leather or asbestos as a friction element. The static friction in a damper of this type is much greater than the dynamic friction, which eliminates the possibility of a damper with an increased damping rate at higher relative velocities. This makes the damping of small-amplitude vibrations nearly impossible. Even more advanced friction dampers, such as the popular 1920 Gabriel Snubber with its leather damping element, could not satisfactorily dampen wheel vibrations. Houdaille suggested as early as 1906 that a hydraulic fluid be used as a damping element, whereby a pumping mechanism would transport the fluid back and forth between two chambers [9]. This type of hydraulic rotational damper was common from 1915 until the first translational, double-walled telescoping hydraulic shock absorbers were mass-produced by the American company Monroe in 1934. These unpressurized, twin-tube, telescoping shock absorbers were introduced in Europe in the 1950s. The two main problems with this type of damper are the limited range of installation angles and the risk of water contamination in the oil. These problems were solved by Christian Bourcier de Carbon's invention of the monotube gas pressure shock absorber, which uses a volume of compressible gas to compensate for volume differences during the compression and expansion of the shock absorber. Hans Bilstein bought the rights from De Carbon and developed the first high-quality single-tube damper with Mercedes in 1953.

Adjustable dampers were introduced in the early 1980s by Kayaba and Tokico in Japan. These dampers automatically increase their damping rates at high speeds. The first European damper of this kind was developed by Boge for Mercedes. This concept was further developed into a multi-stage damper, which was controlled by a stepper motor mounted directly to the shaft of the shock absorber. CDC (continuously variable dampers) which use a proportionally adjustable valve, have been available for the past 15 years.

**Wheel Control**: The age of modern wheel control and suspension began with the switch from rigid axles to independent suspension and the switch from leaf springs to coil, torsion bar, or air springs. Prior to this, the first parallel-displacement wheel control systems were already in use. The "Motorwagen Wartburg" from 1898 used a wheel-displacement system along the kingpin, whereas the 1923 Lancia Lambda used a vertically telescoping front wheel control system. The maintenance-free ball joint, introduced in 1952, replaced the kingpin hub system, thus simplifying suspension design.

The dual swingarm suspension of the Volkswagen Beetle and the double-wishbone design of the 1933 Mercedes Typ 380 were the first independent suspension systems. One of the most common designs today is the McPherson front suspension, which was first described in a patent by Fiat in 1926 and used by Ford in the 1948 Consul and Anglia models. Another standard design today is the multi-link suspension, first described in a 1958 patent by Fritz Oswald [7].

The first unibody design was patented and produced by Opel in 1934. This revolutionary design effectively replaced the term "axle" with "suspension". Audi introduced the twist beam rear axle in 1975 to reduce costs and save space in vehicles with non-driven rear axles. This suspension is still the standard today for small, front-wheel-drive cars. Multi-link rear suspensions with one trailing arm are widely used, and offer better characteristics than the twist beam design for driven rear axles. A multi-link rear suspension, however, is typically larger, heavier, and more expensive than a trailing arm solution.

The kinematics of a suspension system can be manipulated by carefully choosing the positions and orientations of the control arms and joints. An example of this is the negative scrub radius patented by Fritz Oswald and first used in the 1972 Audi 80. A negative scrub radius improves braking and roadholding during cornering and on μ-split road surfaces.

Ball joints with three degrees of rotational freedom were unknown in the early years of automobile design; steering was accomplished using a simple swivel pin with two pivot bearings. In 1922, the German engineer Fritz Faudi was granted a patent for his invention entitled "ball joint, specifically intended for the steering of vehicles". This design consisted of a steel ball stud housed between two steel cups. The invention of the ball joint enabled the kingpin to be replaced by a wheel carrier. A further development came in 1952 with Ehrenreich's introduction of a maintenance-free ball joint with a plastic race.

Rubber bushings were first introduced in the USA as motor mounts in the 1930s under the name "Floating Power". They later found use as joints between the chassis and control arms. The initial function of rubber bushings was to isolate the body from the noise, vibration, and harshness (NVH) of the roadway. Over time, rubber bushings have become an integral suspension component, and can be tuned to achieve improved suspension dynamics. This integration is reflected in the use of the term "elastokinematics" by automotive engineers since 1955.

**Wheel Bearings**: A rolling wheel is connected to its hub carrier by means of a bearing. Sliding bearings were used in early vehicles, in spite of their large friction losses and inaccuracies due to high wear rates. After the invention of the rolling bearing with its low friction losses, low wear rates, and high precision, sliding bearings were completely replaced as wheel bearings. Regular ball bearings were initially used, but were soon replaced by angular-contact ball bearings.

**Tires**: The pneumatic tire was invented by the Scotsman Dunlop in 1888. Dunlop's invention originally found use exclusively as a form of bicycle suspension. Early automobiles used a solid rubber tire, which allowed only speeds of up to 30 km/h. The first pneumatic tires for automotive use were clincher tires on flat-base rims, based on an invention by the American William Bartlett. Bartlett's patent was also the basis for the first removable tire, which was developed by Michelin. These early tires were made from natural rubber, and featured textile strands in a crisscross pattern on their interior surface. The service life of these early tires was very short, and removal of the tire from the wheel for repair was a difficult, time-consuming process. To make wheel replacement easier, the removable Stepney wheel was introduced, followed by the Rudge-Whitworth wheel. Tire longevity increased by a factor of ten with Goodyear's introduction of a rubber-soot compound in 1910. But the first use of carbon as additive to increase the longevity was by Pirelli in 1907.

The ride comfort of these early tires left much to be desired, with their high air pressure and hard rubber construction, combined with increasing speeds on bumpy roads. The first low-pressure tire, or so-called "balloon tire", was introduced by Michelin on 1923 Citroen models. This tire was mounted on a drop-base rim and had a low positive pressure of just 2.5 bar. Its diagonal cord (or "bias-ply") structure, an invention by Palmer from 1908, prevented the tire from overheating during use. Extension-resistant cord restricted the relative movement of the rubber layers during deformation, which increased tire life by a factor of ten and improved lateral stability. The early cords were made from cotton and replaced by more durable Rayon in the 1930s.

The air in these early tires was contained in an inner tube. The inner tube was not entirely necessary, however, since the interface between the tire's beaded edge and the wheel's flange was typically airtight. The first tubeless tires were introduced in America by

Dunlop in 1938 and by Goodrich in 1948. Inner tubes were used until 1960 and then gradually phased out.
The next and perhaps most important advancement in tire technology was the invention of the radial tire, which was patented by Michelin in 1946 and featured on the 1949 Citroen 2CV. The radial tire featured textile cloth around the bead core lateral to the direction of travel, which decreases deformation due to inner pressure and increases lateral stability. A circumferential steel belt was added to strengthen the sidewall, which made the diagonal cord structure obsolete. The elimination of the diagonal cord structure reduced friction, which led to a decrease in tire wear. The additional support provided by the steel belt allowed an increase in maximum speed. Radial construction also allowed tires to be made with a flat cross-section instead of a balloon-like round profile. This increased the size of the contact patch, which provided higher lateral grip. A further advancement in tire technology came with the addition of tread patterns. In 1932 the German Robert Sommer invented the laterally-oriented fine tread pattern (or "sipe"), which increased traction on snow, ice, and wet surfaces. Rolling resistance, which is responsible for nearly one-third of fuel consumption, was later reduced by adding silica instead of carbon powder to the rubber compounds used in tires.
Efforts to develop a safety (or "run-flat") tire, which would not deflate in the event of a puncture, were underway as early as the 1920s. This technology has found its way into high-end vehicles in recent years.

**Wheels**: The first automobiles featured spoked wagon wheels with wire or wooden spokes. The spokes on these early wheels came together at the hub in a conical shape. Early steel-spoked wheels featured steel wires in a crisscross pattern. Race cars and sports cars used these wire wheels for weight reduction and brake ventilation. Increasing wheel loads led to the introduction of spoked wheels with a cast or forged construction. Flexible wheels with a solid outer edge were in use before the introduction of the air-filled tire, but proved to be too expensive and complex. The ubiquitous stamped-steel wheel with inwardly-angled flanges was first available as a flat-base rim with a beaded-edge tire, and later as a drop-base rim with a balloon tire. The modern, removable drop-base rim with bolt centering and a low-pressure tire with a valve was in use by the end of the 1920s.

**Chassis Development**: During the first 50 years of automobile development, chassis systems were the domain of tinkers and inventors. Designs were intuitive, and solutions often improvised.
The focus of early automotive engineers was the development of a lightweight and efficient powertrain. Although Karl Benz emphasized chassis development early on, general chassis development lagged behind that of the powertrain until the 1930s. As powertrain technology improved, the maximum speeds of early automobiles increased rapidly. This resulted in increasing demands on reliability, comfort, and safety, especially concerning cornering and braking. In order to meet these demands, the focus of vehicle development shifted to suspension. In the 1950s, the chassis development departments of most vehicle manufacturers consisted of only about 50 engineers and draftsmen. This resulted in long lead times for new chassis developments and components. An example of this is the Mercedes S-class W108/109, which took an entire decade, from 1956 until 1965, to develop and bring into series production [7]. For a vehicle manufacturer to remain competitive today, this entire process can only take about 3 years, despite the fact that the number of models and derivatives has increased tenfold. The introduction of CAD in 1970 allowed vehicle manufacturers to move away from the traditional drawing board to the much more effective computer workstation. This shift has enabled engineers not only to simulate complex wheel movements on-screen, but also to quickly conduct package size and interference investigations. Optimization and the management of product changes have also been greatly simplified with the introduction of computer tools.
The introduction of ever more advanced computer simulation and CAE programs over the past 20 years, combined with the increasing general knowledge of vehicle dynamic behavior, has led to significant improvements in vehicle safety and comfort.
The focus of today's chassis technology is the integration and networking of basic mechanical functions with sensors, electrical equipment, and electronics. Refined hydraulic control of steering, damping, and braking, combined with electronic control systems, will pave the way for the "intelligent" suspension of tomorrow. A central role is played by the "global chassis management" concept, whereby individual control systems are integrated with one another to form a central control loop.

## 1.1.2 Definition and Scope

Suspension and chassis technology is defined as the sum of all vehicle systems that are responsible not only for the generation of forces between the tires and the road surface, but also for the transfer of these forces to the road in order to enable driving, steering, and braking. These systems include the tires, wheels, bearings, hub carriers, brakes, suspension, springs, dampers, steering, stabilizers, subframes, differentials, half-shafts, pedals, steering column, steering wheel, all control systems which support the chassis and suspension, and all driver assistance systems [10].

Chapter 3 of this book deals with all of the above-mentioned components, with the exception of the steering wheel. As a result of increased functionality, the steering wheel has developed into a highly complex part which includes components of numerous other systems such as supplementary restraints, media interfaces, and assistance systems. For this reason, a complete and appropriate description of the steering wheel is beyond the scope of this book

### 1.1.3 Purpose and Significance

The suspension creates a connection between the vehicle (including occupants and cargo) and the roadway. With the exception of aerodynamic and inertial forces, all external forces and moments are applied to the vehicle through the contact patch between the road surface and the tire. The most important criterion for driving is an uninterrupted contact between the road surface and tire. If this contact is broken, steering, acceleration, deceleration, and the transfer of lateral forces become impossible.

In the absence of external forces, the satisfaction of this requirement would be trivial if the road surface were always straight, dry, adherent, and free of obstacles and bumps. If all of these criteria were satisfied and the vehicle was only to move in a straight line, the suspension and chassis would only be responsible for acceleration, deceleration, and keeping the vehicle on a straight path. Even this simple task would become difficult as the vehicle's velocity increased. A vehicle can theoretically reach 400 km/h without lifting off the road surface (Bugatti Veyron with 736 kW [11]). The suspension's task is so difficult because the road surface is not always straight, dry, adherent, and free of obstacles and bumps. The task of the suspension is made more difficult as vehicle speed increases, since the energy which must be controlled increases exponentially with vehicle velocity (vehicle mass multiplied by the square of vehicle velocity).

The driver can influence the vehicle's movements in the longitudinal and lateral directions. In the vertical direction, the vehicle follows the road surface without any active intervention by the driver. In order to maximize comfort and safety, the transfer of vertical bumps and impulses from the road to the vehicle must be minimized [10].

As illustrated above, the chassis has many tasks. They can be summarized as follows [12]:

- Move, roll, and stop the vehicle.
- Keep the vehicle on course while driving.
- Support and spring the vehicle mass while dampening vibrations.
- Isolate the vehicle from the vibration and noise of the roadway.
- Compensate for external interference factors.
- Transfer the powertrain torque to the roadway.
- Hold, control, steer, and brake the wheels.
- Allow the driver to control the vehicle safely and comfortably.

Collectively, the chassis is responsible for dynamic vehicle behavior as well as driving comfort and safety. As a result, the chassis, along with the engine and transmission, is one of the most important and technically sophisticated vehicle systems.

The above description explains the significance and versatility of chassis technology. The chassis not only includes the individual functional groups, it is also responsible for their control and the regulation of their effects on one another.

With the exception of the steering wheel, tires, and wheels, the chassis is invisible to the driver and thus does not represent a direct incentive for vehicle purchase. Only while driving the vehicle, and more importantly during critical driving situations, does the driver notice the significant role played by the chassis [10]:

- A vehicle with an optimally tuned chassis is easier to drive, since the driver's inputs are quickly, predictably, and precisely followed. This gives the driver a feeling of security and safety. The feeling of "driving enjoyment" is an important criterion for many car buyers.
- The driving dynamics of a vehicle play a large role in determining how well the driver can control or avoid critical driving situations.
- Driving comfort is not only perceived as pleasant by the driver, but also has a proven effect on his or her physical and psychological capabilities.

According to accident statistics, 36% of all accidents with fatalities are caused by the vehicle leaving the roadway. This can be the result of excessive speed, driver negligence, or poor road surface conditions. A better, safer chassis greatly increases the chances of a vehicle staying on the roadway.

The chassis also plays a basic role in the total cost, weight, aerodynamics, and use of space in a vehicle. Lightweight design plays a more important role in the chassis than in any other area, since the entire unsprung mass of the vehicle is included in the suspension. The unsprung mass of a vehicle consists of the wheels, tires, wheel carriers, wheel bearings, brakes, and parts of the springs, dampers, and control arms. The driving characteristics of a vehicle can be greatly improved by reducing the unsprung mass. A smaller unsprung mass reduces the effect of wheel vibrations on the vehicle's body and on dynamic wheel load fluctuations. This allows the wheels to stay in more continuous contact with the roadway, thereby reducing the number of external factors that can negatively influence safety and driving comfort.

## 1.2 Chassis Design

Before the design of chassis systems can be discussed, it is important to explain the concepts of vehicle classes and powertrain configurations, since these play an important role in the determination and discussion of the chassis

### 1.2.1 Vehicle Classification

A vehicle's class is determined by its purpose and external dimensions. 25 years ago, vehicles could be organized into a relatively small number of categories: compact sedans, mid-sized sedans, and premium sedans. In addition to these, variants such as station wagons, fastbacks, coupes, convertibles, and sports cars could be defined.

Today's vehicles are harder to categorize, as new variants and so-called "crossovers" are introduced every year (**Figure 1-9**). Classification tables with varying levels of detail can be found. The classification table used throughout most of this book can be seen in **Table 1-1**.

In order to avoid creating an entirely new chassis for every variant, automakers use so-called "module" or "platform" strategies. Every OEM has a limited number of chassis and powertrain configurations which can be modified for the track width, wheelbase, and wheel loads of individual models. The price of the series-production vehicle is used as a guideline for the design of module and platform configurations.

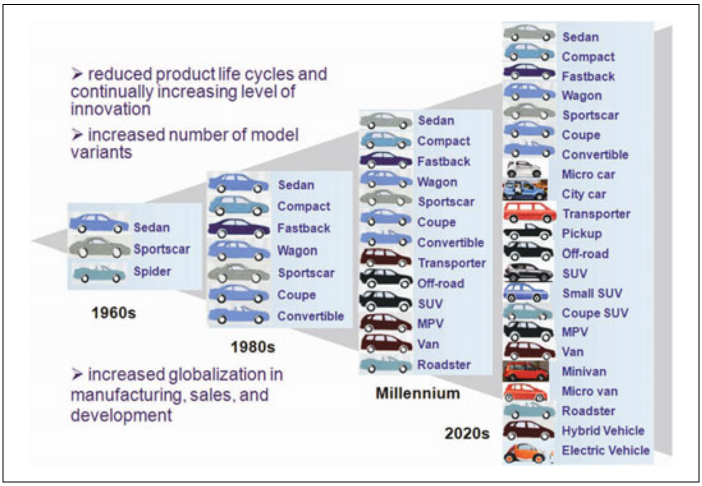


**Fig. 1-9:** The increase in vehicle model variants over time

**Table 1-1:** Vehicle type classes

| Segment | | Current European vehicle examples |
|---|---|---|
| 1 | SUPERMINI | Citroen C1, Daimler Smart, Fiat Panda, Renault Twingo, Seat Aroso, Toyota Aygo, VW Lupo |
| 2 | SUBCOMPACT | Audi A2, Fiat Uno, Ford Fiesta, Opel Corsa, Renault Clio, Peugeot 207, Toyota Yaris, VW Polo |
| 3 | COMPACT | BMW 1-Series, Ford Focus, MB A-,B-Class, Opel Astra, Renault Megane, Toyota Auris,VW Golf |
| 4 | MIDSIZE | Alfa 156, Audi A4, BMW 3, Ford Mondeo, MB C-Class, Citroen C5, Opel Vectra, VW Passat |
| 5 | UPPER MIDSIZE | Alfa 167, Audi A6, BMW 5-Series, Opel Signum, MB E-Class, Renault Vel Satis, Volvo S80 |
| 6 | LUXURY | Audi A8, BMW 7-Series, MB S-Class, Maybach, Rolls Royce, VW Phaeton, Bentley |
| 7 | SPORTSCAR | Audi TT, BMW Z8, 6-Series, MB SL, SLK, Porsche 911, Boxster, Opel Tigra, VW Eos |
| A | VAN | MB V-Class, Opel Combo, VW Multivan |
| B | MINIVAN | Citroen Berlingo, Fiat Doblo, Opel Combo, Renault Kangoo, Toyota Hijet, VW Caddy |
| D | TRANSPORTER | MB Sprinter, Fiat Ducato, Ford Transit, Opel Vivaro, Toyota Hiace, Peugeot Boxer, VW T5 |
| F | SUV | Audi Q7,Q5, BMW X3, X5, MB M, GKL Class, Toyota RAV, Land Rover, VW Touareg, Tiguan |
| G | PICKUP | Ford F-series, Ranger, Toyota Hilux, Dodge Ram, Dakota |
| M | MPV | Fiat Ulysse, Ford Galaxy, Peugeot 807, Renault Espace, VW Sharan |