

Contents

1 Introduction and Fundamentals	1
1.1 History, Definition, Function, and Significance	2
1.1.1 History	2
1.1.2 Definition and Scope	7
1.1.3 Purpose and Significance	8
1.2 Chassis Design	9
1.2.1 Vehicle Classification	9
1.2.2 Powertrain Configurations	10
1.2.3 Chassis Composition	13
1.2.4 Trends in Chassis Composition	13
1.3 Chassis Layout	15
1.3.1 Chassis Requirements	16
1.3.2 Layout of Suspension Kinematics	18
1.3.3 Suspension Kinematics	18
1.3.3.1 Suspension Parameters Relative to Vehicle	18
1.3.3.2 Roll and Pitch Center	20
1.3.3.3 Wheel Travel	20
1.3.3.4 Wheel Travel Parameters	21
1.3.3.5 Steering Kinematic Parameters	24
1.3.3.6 Kinematic Parameters of Current Vehicles	28
1.3.3.7 Wheel Travel Curves	28
1.3.3.8 Wheel Kinematic Calculation Software	31
1.3.4 Elastokinematics and Component Compliances in Suspension Design	31
1.3.5 Target Parameter Values	32
1.3.6 Suspension Composition	33
2 Driving Dynamics	35
2.1 Driving Resistances and Energy Requirements	35
2.1.1 Driving Resistances	35
2.1.1.1 Rolling Resistance	35
2.1.1.2 Effect of Road Surface on Rolling Resistance $F_{R,Tr}$	40
2.1.1.3 Aerodynamic Drag F_A	43
2.1.1.4 Climbing Resistance F_C	44
2.1.1.5 Inertial Resistance F_I	45
2.1.1.6 Total Driving Resistance	46
2.1.2 Crosswind Response Behavior	46
2.1.3 Performance and Energy Requirements	49
2.1.4 Fuel Consumption	50
2.2 Tire Traction and Force Transfer to the Roadway	52
2.2.1 The Physics of Tire Traction and Force Transfer	54
2.2.1.1 Acceleration and Braking	57
2.2.1.2 Cornering	58
2.2.2 Detailed Tire Forces	63
2.3 Longitudinal Dynamics	65
2.3.1 Acceleration and Braking	65
2.3.1.1 Anti-Dive	65
2.3.1.2 Anti-Lift (Anti-Squat)	66
2.3.1.3 Load Changes During Straightline Driving	67
2.4 Vertical Dynamics	67
2.4.1 Springs	67
2.4.1.1 Spring Ratio	68
2.4.1.2 Natural (Eigen) Frequencies	68
2.4.2 Vibration Dampers	69

2.4.3	Excitations from the Roadway	70
2.4.3.1	Harmonic Excitations	70
2.4.3.2	Periodic Irregularities	71
2.4.3.3	Stochastic (Random) Irregularities	71
2.4.3.4	Spectral Density of Road Surface Irregularities	72
2.4.3.5	Measured Road Surface Irregularities	73
2.4.4	Tires as Spring/Damper Elements	73
2.4.5	Suspension Models	74
2.4.5.1	Single-Mass System	74
2.4.5.2	Dual-Mass System	75
2.4.5.3	Expansion of the Model to Include Seat Suspension Effects	75
2.4.5.4	Single-Track Suspension Model	76
2.4.5.5	Two-Track Suspension Model	77
2.4.6	Parameter Variation	79
2.4.7	The Roadway/Vehicle Connection	81
2.4.7.1	Spectral Density of Vehicle Body Accelerations	82
2.4.7.2	Spectral Density of Dynamic Wheel Loads	84
2.4.8	Human Oscillation Evaluation	84
2.4.9	Conclusions from the Fundamentals of Vertical Dynamics	86
2.5	Lateral Dynamics	86
2.5.1	Handling Requirements	86
2.5.2	Steering Kinematics	87
2.5.2.1	Static Steering Layout	87
2.5.2.2	Dynamic Steering Layout	88
2.5.3	Vehicle Modeling	89
2.5.3.1	Simple Single-Track (Bicycle) Model	89
2.5.3.2	Simple Vehicle Dynamics	90
2.5.3.3	Understeer and Oversteer	93
2.5.3.4	Expanded Single-Track Model with Rear-Wheel Steering	94
2.5.3.5	Nonlinear Single-Track Model	95
2.5.3.6	Analysis of Transient Behavior Using the Simple Single-Track Model	97
2.5.3.7	The Vehicle as Part of a Closed-Loop System	99
2.5.3.8	Dynamic Behavior of the Vehicle as part of a Closed-Loop System	100
2.5.3.9	Slip Angle Compensation Using Rear-Wheel Steering	103
2.5.3.10	Investigation of Frequency Response for Varied Vehicle Configurations	105
2.5.3.11	Dual-Track Model	106
2.5.3.12	Parameter Variations	109
2.6	General Vehicle Dynamics	113
2.6.1	Interactions between Vertical, Longitudinal, and Lateral Dynamics	113
2.7	Chassis Control Systems	118
2.7.1	Definition of Terms	118
2.7.2	Limitations of the Passive Vehicle – Basic Goal Conflicts	118
2.7.3	The Driver-Vehicle Control Loop	119
2.7.4	Division of Chassis Control Systems into Domains	120
2.7.4.1	Longitudinal Dynamics	120
2.7.4.2	Lateral Dynamics	121
2.7.4.3	Vertical Dynamics	121
2.7.5	Requirements for Chassis Control Systems	121
2.8	Handling Characteristics	122
2.8.1	Handling Evaluation	122
2.8.2	Driving Maneuvers	124
2.8.3	Parameter Range of Maneuvers	124
2.8.4	Tuning Procedures	127
2.8.4.1	Tuning Procedures for Steady-State Steering Behavior	127
2.8.5	Subjective Handling Evaluation	127
2.8.5.1	Evaluation Methods and Representation	130
2.8.5.2	Acceleration (Driveoff) Behavior	130

2.8.5.3	Braking Behavior	130
2.8.5.4	Steering Behavior	132
2.8.5.5	Cornering Behavior	134
2.8.5.6	Straightline Driving Behavior	134
2.8.5.7	Ride Comfort	136
2.8.6	Objective Handling Evaluations	137
2.8.6.1	Measurement Parameters	137
2.8.6.2	Acceleration (Driveoff) Behavior	137
2.8.6.3	Braking Behavior	138
2.8.6.4	Steering Behavior	139
2.8.6.5	Cornering Behavior	141
2.8.6.6	Straightline Driving Behavior	143
2.8.6.7	Ride Comfort	145
2.9	Active and Passive Safety	145
3	Chassis Components	149
3.1	Chassis Structuring	149
3.1.1	Classification by Function	149
3.1.2	Modular Chassis Structure	150
3.1.3	Chassis Components	150
3.2	Drivetrain	151
3.2.1	Configurations	151
3.2.2	Axle Drives	151
3.2.2.1	Differentials	151
3.2.2.2	Locking Differentials	151
3.2.2.3	Active Differentials	153
3.2.2.4	Torque Vectoring	153
3.2.3	Four-wheel-drive (All-wheel-drive)	154
3.2.4	Control Strategies	155
3.2.5	Half-shafts	156
3.3	Wheel Brakes and Braking Systems	157
3.3.1	Fundamentals and Requirements	157
3.3.2	Types of Braking Systems	158
3.3.2.1	General Requirements	159
3.3.3	Legal Regulations	160
3.3.4	Brake System Design	160
3.3.4.1	Brake Force Distribution	160
3.3.4.2	Dimensioning	162
3.3.5	Braking Torque and Dynamics	162
3.3.5.1	Braking Torque	162
3.3.5.2	Braking Dynamics	163
3.3.6	Brake System Components	164
3.3.6.1	Brake Calipers	164
3.3.6.2	Brake Discs	168
3.3.6.3	Brake Linings	169
3.3.6.4	Drum Brakes	169
3.3.6.5	Brake Fluid	172
3.3.6.6	Brake Force Booster	172
3.3.6.7	Tandem Master Cylinder	173
3.3.6.8	Human Machine Interface (HMI)	173
3.3.7	Electronic Braking Control Systems	177
3.3.7.1	Brake Assistant (MBA, EBA, HBA)	177
3.3.7.2	Wheel Speed Sensors	180
3.3.7.3	Electronic Braking System Functions	181
3.3.7.4	Electrohydraulic Brake (EHB)	187
3.3.7.5	Electromechanical Brake (EMB)	188
3.3.7.6	Networked Chassis	190

3.4	Steering Systems	191
3.4.1	Requirements and Designs	191
3.4.2	Hydraulic Rack and Pinion Steering	194
3.4.2.1	Technology and Function	194
3.4.2.2	Design and Components	197
3.4.3	Steering Tie Rods	200
3.4.4	Steering Driveline and Steering Column	203
3.4.4.1	Components and Function Modules	203
3.4.4.2	Design and Testing	205
3.4.4.3	Crash Requirements and Energy Absorption Mechanisms	206
3.4.4.4	Future Prospects and Modularization	209
3.4.5	Electromechanical Steering Systems	209
3.4.5.1	Design Concepts	209
3.4.5.2	Configuration and Advantages	212
3.4.6	Active Steering and Superposition Steering	215
3.4.6.1	Functional Principles and Configuration	215
3.4.6.2	Functions – Present and Future	217
3.4.7	Rack and Pinion Power Steering with Torque and Angle Actuators	219
3.4.8	Rear-wheel and Four-wheel Steering Systems	220
3.4.9	Steer-by-wire and Single-wheel Steering Systems	222
3.4.9.1	System Configuration and Components	223
3.4.9.2	Technology, Advantages, Opportunities	225
3.5	Springs and Stabilizers	226
3.5.1	The Purpose of the Spring System	226
3.5.2	Design and Calculation of Steel Springs	226
3.5.2.1	Leaf Springs	227
3.5.2.2	Torsion Bar Springs	230
3.5.2.3	Stabilizers	231
3.5.2.4	Coil Springs	239
3.5.3	Spring Materials	247
3.5.4	Steel Spring Manufacture	249
3.5.4.1	Hot Forming	249
3.5.4.2	Heat Treating Hot Formed Springs	251
3.5.4.3	Cold Forming	251
3.5.4.4	Shot Peening	252
3.5.4.5	Plastification	253
3.5.4.6	Corrosion Protection	253
3.5.4.7	Final Inspection and Marking	254
3.5.5	Roll-Control Using Stabilizers	254
3.5.5.1	Passive Stabilizers	254
3.5.5.2	Switchable Off-Road Stabilizers	255
3.5.5.3	Switchable On-Road Stabilizers	255
3.5.5.4	Semi-Active Stabilizers	255
3.5.5.5	Active Stabilizers	257
3.5.6	Springs for use with Automatic Leveling Systems	257
3.5.6.1	Purpose and Configurations	257
3.5.6.2	Leveling Using a Gas Spring	258
3.5.7	Hydropneumatic Springs	261
3.5.7.1	Self-Pumping Hydropneumatic Spring/Damper Elements	261
3.5.8	Air Springs	264
3.6	Damping	266
3.6.1	The Purpose of Damping	266
3.6.2	Telescopic Shock Absorber Designs	270
3.6.2.1	Twin-Tube Shock Absorbers	270
3.6.2.2	Monotube Shock Absorbers	271
3.6.2.3	Comparison of Damper Types	271
3.6.2.4	Special Designs	272

3.6.3	Coilover Shock Absorber and Strut	272
3.6.4	Shock Absorber Calculations	274
3.6.5	Additional Damper Futures	275
3.6.5.1	Rebound and Compression Bump Stops	275
3.6.5.2	Stroke-Dependent Damping	277
3.6.5.3	Amplitude-Selective Damping	279
3.6.6	Damper End Mounts	280
3.6.7	Semi-Active Damping and Spring Functions	281
3.6.8	Alternative Damping Concepts	285
3.6.8.1	Magneto-Rheological (MRF) Dampers	285
3.6.8.2	Conjoined Damping	286
3.6.8.3	Load-Dependent Damping (PDC)	286
3.7	Wheel Control	287
3.7.1	Purpose, Requirements, and System Structure	287
3.7.2	Suspension Links: Purpose, Requirements, and System Structure	288
3.7.2.1	Control Arms (Control Links)	289
3.7.2.2	Support Links	290
3.7.2.3	Auxiliary Links	290
3.7.2.4	Suspension Link Requirements	291
3.7.2.5	Suspension Link Materials	291
3.7.2.6	Suspension Link Manufacturing Processes	292
3.7.2.7	Manufacturing Methods for Aluminum Suspension Links	298
3.7.2.8	Configuration and Optimization of Suspension Links	300
3.7.2.9	Integration of the Joints into the Link	300
3.7.3	Ball Joints	301
3.7.3.1	Purpose and Requirements	302
3.7.3.2	Types of Ball Joints	302
3.7.3.3	Ball Joint Components	303
3.7.3.4	Bearing System (Ball Race, Grease)	306
3.7.3.5	Sealing System (Sealing Boot, Retaining Ring)	309
3.7.3.6	Suspension Ball Joints	312
3.7.3.7	Preloaded Ball Joints	313
3.7.3.8	Cross Axis Ball Joints	314
3.7.4	Rubber Bushings	316
3.7.4.1	Purpose, Requirements, and Function	316
3.7.4.2	Types of Rubber Bushings	318
3.7.5	Pivot Joints	320
3.7.6	Rotational Sliding Joints (Trunnion Joints)	321
3.7.7	Chassis Subframes	322
3.7.7.1	Purpose and Requirements	322
3.7.7.2	Types and Designs	322
3.8	Wheel Carriers and Bearings	325
3.8.1	Types of Wheel Carriers	325
3.8.2	Wheel Carriers Materials and Manufacturing Methods	327
3.8.3	Types of Wheel Bearings	328
3.8.3.1	Bearing Seals	331
3.8.3.2	Lubrication	331
3.8.3.3	ABS Sensors	332
3.8.4	Wheel Bearing Manufacturing	334
3.8.4.1	Rings and Flanges	334
3.8.4.2	Cages and Rolling Elements	335
3.8.4.3	Assembly	335
3.8.5	Requirements, Design, and Testing	335
3.8.5.1	Bearing Rotational Fatigue Strength	337
3.8.5.2	Component Strength and Tilt Stiffness	339
3.8.5.3	Verification by Testing	341
3.8.6	Future Prospects	342

3.9	Tires and Wheels	346
3.9.1	Tire Requirements	346
3.9.1.1	Properties and Performance	346
3.9.1.2	Legal Requirements	348
3.9.2	Types, Construction, and Materials	349
3.9.2.1	Tire Types	349
3.9.2.2	Tire Construction	350
3.9.2.3	Tire Materials	350
3.9.2.4	The Viscoelastic Properties of Rubber	351
3.9.3	Transmission of Forces between the Tire and the Road Surface	352
3.9.3.1	Supporting Force	352
3.9.3.2	Adhesion Behavior and Lateral Force Buildup	353
3.9.3.3	Tangential Forces: Driving and Braking	354
3.9.3.4	Sideslip, Lateral Forces, and Aligning Moments	354
3.9.3.5	Sideslip Stiffness	355
3.9.3.6	Tire Behavior under Slip	357
3.9.3.7	Tire Uniformity	358
3.9.4	Tire Simulation Models	358
3.9.4.1	Tire Models for Lateral Dynamics	358
3.9.4.2	Tire Models Using Finite Elements (FEM)	360
3.9.4.3	Tire Models for Vertical Dynamics	360
3.9.4.4	Tire Vibration Modes	361
3.9.4.5	Cavity Natural Frequencies	361
3.9.4.6	Full Tire Models	362
3.9.5	Modern Tire Technologies	364
3.9.5.1	Tire Sensors	364
3.9.5.2	Run-Flat Tires	366
3.9.5.3	Tires and Control Systems	367
3.9.5.4	High Performance (HP) and Ultra High Performance (UHP) Tires	368
3.9.6	Vehicle Testing and Measurement	369
3.9.6.1	Subjective Test Procedures	369
3.9.6.2	Objective Test Procedures for Longitudinal Adhesion	370
3.9.6.3	Objective Test Procedures for Lateral Adhesion	371
3.9.6.4	Acoustics	372
3.9.7	Laboratory Testing and Measurement Methods	372
3.9.7.1	Basic Tire Test Rig Designs	372
3.9.7.2	Strength Tests	373
3.9.7.3	Measuring Tire Characteristics Using a Test Rig	373
3.9.7.4	Measuring Tire Characteristics Using a Vehicle-Mounted Test Rig	373
3.9.7.5	Measuring Tire Rolling Resistance	374
3.9.7.6	Measuring Uniformity and Geometry	374
3.9.7.7	Roadway Measurements and Modeling	376
3.9.7.8	Power Loss Analysis	376
3.9.7.9	Tire Temperature Measurement	377
3.9.8	The Future of Tire Technology	378
3.9.8.1	Material Developments	378
3.9.8.2	Energy Saving Tires	378
4	Axles and Suspensions	383
4.1	Rigid Axles	385
4.1.1	The De Dion Driven Rigid Axle	387
4.1.2	Rigid Axles with Longitudinal Leaf Springs	387
4.1.3	Rigid Axles with Longitudinal and Lateral Links	388
4.1.4	Rigid Parabolic Axle with a Central Joint and Lateral Control Links	389

4.2	Semi-Rigid Axles	389
4.2.1	Twist Beam Axles	390
4.2.1.1	Torsion-Type Twist Beam Axles	391
4.2.1.2	Standard Twist Beam Axles	391
4.2.1.3	Couple-Type Twist Beam Axles	392
4.2.2	The Dynamic Twist Beam Axle	392
4.3	Independent Suspension	393
4.3.1	Independent Suspension Kinematics	393
4.3.2	The Advantages of Independent Suspension	395
4.3.3	Single-Link Independent Suspension Systems	395
4.3.3.1	Trailing Link Independent Suspension	396
4.3.3.2	Semi-Trailing Link Independent Suspension	397
4.3.3.3	Screw-Link Independent Suspension	398
4.3.4	Two-Link Independent Suspension	398
4.3.4.1	Lateral-Longitudinal Swing Axles	398
4.3.4.2	Trapezoidal Link with One Lateral Link (Audi 100 Quattro)	399
4.3.4.3	Trapezoidal Link with One Flexible Lateral Link (Porsche Weissach Axle)	399
4.3.5	Three-Link Independent Suspension	399
4.3.5.1	Central Link Independent Suspension	399
4.3.5.2	Double Wishbone Independent Suspension	400
4.3.6	Four-Link Independent Suspension	402
4.3.6.1	Rear Axle Multi-Link Independent Suspension	402
4.3.6.2	Multi-Link Suspension with Two Lower Two-Point Links	403
4.3.6.3	Trapezoidal (Integral) Link Suspension	403
4.3.6.4	Two Longitudinal and Two Lateral Links	404
4.3.6.5	One Longitudinal and Three Lateral Links	404
4.3.6.6	One Diagonal and Three Lateral Links	405
4.3.7	Five-Link Independent Suspension	406
4.3.7.1	Five-Link Front Suspension (SLA with two Decomposed 3-Point Links)	406
4.3.7.2	Five-Link Rear Suspension	406
4.3.8	Strut-Type Suspension System	407
4.4	Front Axle Suspension	410
4.4.1	Front Axle Suspension System Requirements	410
4.4.2	Front Axle Components	412
4.4.3	Front Axle Suspension Types	412
4.4.3.1	McPherson with Upper Strut Brace	412
4.4.3.2	McPherson with Optimized Lower Control Arm	412
4.4.3.3	McPherson with Decomposed Lower Control Arm	412
4.4.3.4	McPherson with Two-Piece Wheel Carrier	413
4.4.3.5	Double Wishbone with Decomposed Control Arms	413
4.5	Rear Axle Suspension	414
4.5.1	Rear Axle Suspension Requirements	414
4.5.2	Rear Axle Components	414
4.5.3	Rear Axle Suspension Types	414
4.5.3.1	Non-Driven Rear Axles	414
4.5.3.2	Driven Rear Axles	414
4.5.4	ULSAS Rear Axle Benchmark	415
4.6	Design Catalog for Axle Type Selection	416
4.7	The Chassis as a Complete System	416
4.7.1	Front/Rear Axle Interaction	416
4.8	Future Suspension Systems	418
4.8.1	Axles of the Past 20 Years	418
4.8.2	Relative Popularity of Various Current Axle Designs	418
4.8.3	Future Axle Designs (Trends)	418

5 Ride Comfort and NVH	421
5.1 Fundamentals: NVH and the Human Body	421
5.1.1 Concepts and Definitions	421
5.1.2 Sources of Vibrations, Oscillations, and Noise	422
5.1.3 Limits of Human Perception	423
5.1.4 Human Comfort and Well-Being	424
5.1.5 Mitigation of Oscillation and Noise	425
5.2 Bonded Rubber Components	426
5.2.1 Bonded Rubber Component Functions	426
5.2.1.1 Transferring Forces	426
5.2.1.2 Enabling Defined Movements	426
5.2.1.3 Noise Isolation	427
5.2.1.4 Vibration Damping	428
5.2.2 The Specific Definition of Elastomeric Components	429
5.2.2.1 Force-Displacement Curves	429
5.2.2.2 Damping	429
5.2.2.3 Setting	430
5.3 Engine and Transmission Mounts	431
5.4 Chassis and Suspension Mounts and Bushings	435
5.4.1 Rubber Bushings	435
5.4.2 Sliding Bushings	436
5.4.3 Hydraulically-Damped Bushings (Hydro Bushings)	437
5.4.4 Chassis Subframe Mounts	440
5.4.5 Upper Strut Bearings and Damper Mounts	441
5.4.6 Twist Beam Axle Mounts	443
5.5 Future Component Designs	444
5.5.1 Sensors	445
5.5.2 Switchable Chassis Mounts	445
5.6 Computation Methods	446
5.7 Acoustic Evaluation of Bonded Rubber Components	447
6 Chassis Development	449
6.1 The Development Process	449
6.2 Project Management (PM)	455
6.3 The Planning and Definition Phase	455
6.3.1 Target Cascading	456
6.4 The Concept Phase	457
6.5 Computer-Aided Engineering	457
6.5.1 Multi-Body Simulation (MBS)	458
6.5.1.1 MBS Chassis and Suspension Models in ADAMS/Car	458
6.5.1.2 CAD Chassis Models and Multi-Body Systems	458
6.5.1.3 Multi-Body Simulation with Rigid and Flexible MBS	459
6.5.1.4 Multi-Body Simulation Using Whole Vehicle, Chassis, and Axle Models	460
6.5.1.5 Effects of Manufacturing Tolerances on Kinematic Parameters	461
6.5.2 Finite Element Method (FEM)	462
6.5.2.1 Classification of Analyses	462
6.5.2.2 Strength Analyses	463
6.5.2.3 Stiffness Analyses	463
6.5.2.4 Natural Frequency Analyses	463
6.5.2.5 Service Life and Durability Analyses	464
6.5.2.6 Crash Simulations	464
6.5.2.7 Topology and Shape Optimization	464
6.5.2.8 Simulations of Manufacturing Processes	466
6.5.3 Whole-Vehicle Simulations	466
6.5.3.1 Vehicle Handling and Dynamic Simulations	466
6.5.3.2 Kinematics and Elastokinematics	466
6.5.3.3 Standard Load Cases	467

6.5.3.4	MBS Model Verification	468
6.5.3.5	NVH	468
6.5.3.6	Loads Management (Load Cascading from Systems to Components)	470
6.5.3.7	Whole-Vehicle Durability Simulations	474
6.5.3.8	Whole-Vehicle Handling Fingerprint	474
6.5.3.9	Specification of Elastokinematics using Control-System Methods	475
6.5.4	3D Modeling Software (CAD)	476
6.5.5	Integrated Simulation Environment	477
6.5.5.1	Kinematic Analysis Using ABE Software	477
6.5.5.2	The Virtuel Product Development Environment (VPE)	480
6.6	Series Development and Validation	482
6.6.1	Design	482
6.6.1.1	Component Design	483
6.6.1.2	Package Volume	484
6.6.1.3	Failure Mode and Effects Analysis (FMEA)	485
6.6.1.4	Tolerance Investigations	485
6.6.2	Validation	485
6.6.2.1	Prototypes	485
6.6.2.2	Validation Using Test Rigs	485
6.6.2.3	Roadway Simulation Test Rig	488
6.6.3	Whole-Vehicle Validation	489
6.6.4	Optimization and Fine-Tuning	490
6.7	Development Activities During Series Production	490
6.8	Summary and Future Prospects	491
7	Chassis Control Systems	493
7.1	Chassis Electronics	493
7.2	Electronic Chassis Control Systems	493
7.2.1	Domains	493
7.2.2	Longitudinal Dynamic Control Systems – Wheel Slip Regulation	494
7.2.2.1	Braking Control	494
7.2.2.2	Electronically-Controlled Center Differentials	494
7.2.2.3	Torque-on-Demand Transfer Cases	494
7.2.2.4	Electronically-Controlled Axle Differentials	495
7.2.2.5	Axle Drive for Lateral Torque Distribution	496
7.2.3	Lateral Dynamic Control Systems	497
7.2.3.1	Electric Power Steering Systems (EPS)	497
7.2.3.2	Superimposed Steering	498
7.2.3.3	Active Rear-Wheel Steering	498
7.2.3.4	Active Rear-Axle Kinematics	499
7.2.4	Vertical Dynamic Control Systems	499
7.2.4.1	Variable Dampers	499
7.2.4.2	Active Stabilizers	501
7.2.4.3	Active Leveling Systems	501
7.2.5	Safety Requirements	502
7.2.6	Bus Systems	503
7.2.6.1	CAN	503
7.2.6.2	FlexRay	503
7.3	System Networking	503
7.3.1	Vehicle Dynamic Control (VDC)	503
7.3.2	Torque Vectoring	505
7.3.3	Vertical Dynamic Management	506
7.4	Functional Integration	506
7.4.1	System Architecture	506
7.4.2	Standard Interfaces	507
7.4.3	Smart Actuators	508
7.5	Chassis Control System Simulating	508

7.5.1	Simulation Models	509
7.5.2	Hardware-in-the-Loop- Simulation	510
7.6	Mechatronic Chassis Systems	511
7.6.1	Longitudinal Dynamics	511
7.6.1.1	Powertrain Systems	512
7.6.1.2	Braking Systems	514
7.6.2	Lateral Dynamics	516
7.6.2.1	Front-Wheel Steering Systems	516
7.6.2.2	Rear-Wheel Steering Systems	517
7.6.2.3	Roll Stabilization Systems	520
7.6.2.4	Active Kinematics	523
7.6.3	Vertical Dynamics	526
7.6.3.1	System Requirements	526
7.6.3.2	Classification of Vertical Dynamic Systems	526
7.6.3.3	Damping Systems	527
7.6.3.4	Active Leveling Systems	531
7.6.3.5	Current Active Spring Systems	532
7.6.3.6	Fully Active Integrated Suspension Systems	535
7.6.3.7	Pivots (Bushings, Joints, Mounts)	537
7.7	X-by-wire	539
7.7.1	Steer-by-wire	539
7.7.2	Brake-by-wire	540
7.7.2.1	Elektrohydraulic Baking (EHB) Systems	541
7.7.2.2	Elektromechanical Braking (EMB) Systems	541
7.7.2.3	ContiTeves Elektromechanical Brake	542
7.7.2.4	Radial (Full-Contact) Disc Brakes	542
7.7.2.5	Wedge Brake	544
7.7.3	Leveling-by-wire	545
7.8	Driver Assistance Systems	545
7.8.1	Braking Assistance Systems	545
7.8.1.1	Safety-Relevant Braking Assistance	546
7.8.1.2	Comfort-Oriented Braking Assistance	547
7.8.1.3	Braking Assistance System Requirements	547
7.8.2	Distance Assistance Systems	548
7.8.3	Steering Assistance Systems	549
7.8.3.1	Steering Assistance Using Adaptive Assistance Torque	549
7.8.3.2	Steering Assistance Using Additional Steering Torque	549
7.8.3.3	Steering Assistance Using a Supplemental Steer Angle	550
7.8.3.4	Summary	551
7.8.4	Parking Assistance Systems	551
7.8.4.1	Introduction	551
7.8.4.2	Parking Space Recognition	551
7.8.4.3	Parallel Parking	553
7.8.4.4	Steering Actuators	554
8	The Future of Chassis Technology	557
8.1	Chassis System Concepts – Focus on Customer Value	557
8.1.1	Choosing Handling Behavior	557
8.1.2	Diversification of Vehicle Concepts – Stabilization of Chassis Concepts	559
8.1.2.1	Front Suspension as of 2004	559
8.1.2.2	Rear Suspension as of 2004	560
8.1.3	The Future of Chassis Subsystems and Components	560
8.1.3.1	The Future of Axle Drive Units	560
8.1.3.2	The Future of Braking Systems	561
8.1.3.3	The Future of Steering Systems	561
8.1.3.4	The Future of Suspension Spring Systems	561
8.1.3.5	The Future of Dampers	561

8.1.3.6	The Future of Wheel Control Components	561
8.1.3.7	The Future of Wheel Bearings	561
8.1.3.8	The Future of Tires and Wheels	561
8.2	Electronic Chassis Systems	561
8.2.1	Electronic Assistance Systems and Networking	561
8.2.2	Networking, Chassis Control Systems	562
8.2.2.1	Peaceful Coexistence	562
8.2.2.2	Integral Control	563
8.2.2.3	Networked Control	563
8.2.2.4	Performance / Efficiency	564
8.2.2.5	System Safety	564
8.2.2.6	The Development Process	564
8.2.2.7	Data Transmission Requirements	565
8.2.2.8	Summary	565
8.3	The Future of X-by-wire-Systems	565
8.4	Intelligent and Predictive Future Chassis Systems	566
8.4.1	Sensors	567
8.4.2	Actuators	567
8.4.3	Predictive Driving	568
8.5	Hybrid Vehicles	570
8.6	The Rolling/Driving Chassis	571
8.7	The Vision of Autonomous Vehicle Control	572
8.8	Future Scenarios for Vehicle and Chassis Technology	573
8.9	Outlook	576
Index		579