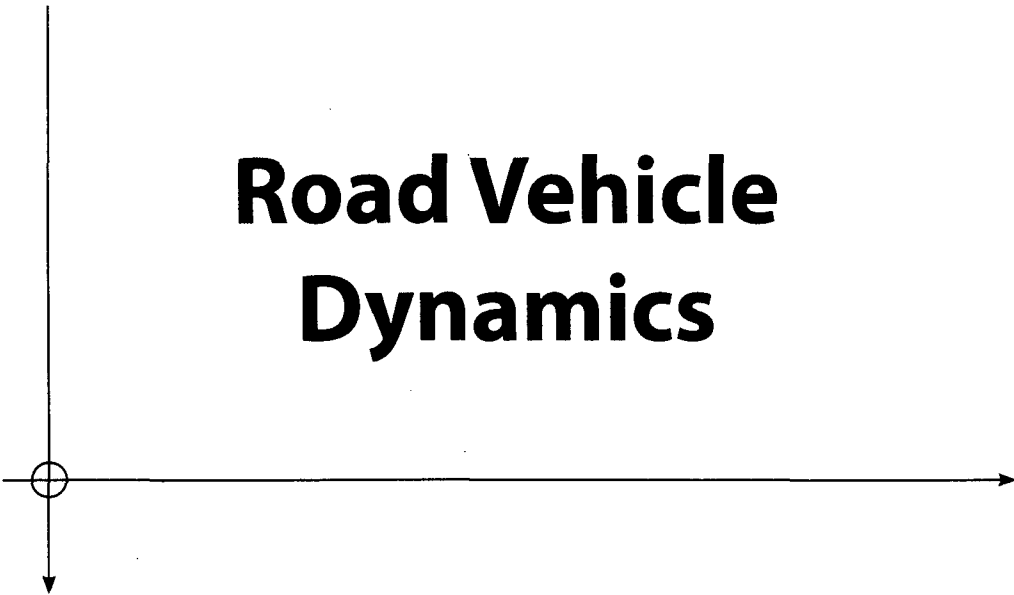


Road Vehicle Dynamics



Contents

Foreword.....	xvii
Preface.....	xix
Chapter 1 Introduction.....	1
1.1 General.....	1
1.2 Vehicle System Classification.....	2
1.3 Dynamic System.....	3
1.4 Classification of Dynamic System Models.....	4
1.5 Constraints, Generalized Coordinates, and Degrees of Freedom.....	4
1.6 Discrete and Continuous Systems.....	10
1.7 Vibration Analysis.....	10
1.8 Elements of Vibrating Systems.....	15
1.8.1 Spring Elements.....	15
1.8.2 Potential Energy of Linear Springs.....	18
1.8.3 Equivalent Springs.....	18
1.8.3.1 Springs in Parallel.....	19
1.8.3.2 Springs in Series.....	20
1.8.4 Mass or Inertia Elements.....	25
1.8.5 Damping Elements.....	25
1.8.5.1 Viscous Damping.....	25
1.8.5.2 Coulomb Damping.....	27
1.8.5.3 Structural or Hysteretic Damping.....	29
1.8.5.4 Combination of Damping Elements.....	30
1.9 Review of Dynamics.....	32
1.9.1 Newton's Laws of Motion.....	32
1.9.2 Kinematics of Rigid Bodies.....	33
1.9.3 Linear Momentum.....	37
1.9.4 Principle of Conservation of Linear Momentum.....	37
1.9.5 Angular Momentum.....	38
1.9.6 Equations of Motion for a Rigid Body.....	39
1.9.7 Angular Momentum of a Rigid Body.....	39
1.9.8 Principle of Work and Energy.....	40
1.9.9 Conservation of Energy.....	41
1.9.10 Principle of Impulse and Momentum.....	42
1.9.11 Mechanical Systems.....	45
1.9.12 Translational Systems.....	46
1.9.13 Rotational Systems.....	47
1.9.14 Translation and Rotational Systems.....	48
1.9.15 Angular Momentum and Moments of Inertia.....	48
1.9.16 Geared Systems.....	52
1.10 Lagrange's Equation.....	59
1.10.1 Degrees of Freedom.....	59
1.10.2 Generalized Coordinates.....	60
1.10.3 Constraints.....	61
1.10.4 Principle of Virtual Work.....	63

	1.10.5	D'Alembert's Principle
	1.10.6	Generalized Force
	1.10.7	Lagrange's Equations of Motion
	1.10.8	Holonomic Systems
	1.10.9	Nonholonomic Systems
	1.10.10	Rayleigh's Dissipation Function
1.11		Summary.....
1.12		References
Chapter 2		Analysis of Dynamic Systems.....
2.1		Introduction
2.2		Classification of Vibrations
2.3		Classification of Deterministic Data.....
	2.3.1	Sinusoidal Periodic Data
	2.3.2	Complex Periodic Data
	2.3.3	Almost Periodic Data
	2.3.4	Transient Nonperiodic Data
2.4		Linear Dynamic Systems.....
	2.4.1	Linear Single-Degree-of-Freedom System
	2.4.2	Free Vibration of a Single-Degree-of-Freedom System
	2.4.3	Forced Vibration of a Single-Degree-of-Freedom System
	2.4.4	Linear Multiple-Degrees-of-Freedom System
	2.4.5	Eigenvalues and Eigenvectors: Undamped System
	2.4.6	Eigenvalues and Eigenvectors: Damped System
	2.4.7	Forced Vibration Solution of a Multiple-Degrees-of-Freedom System
2.5		Nonlinear Dynamic Systems
	2.5.1	Exact Methods for Nonlinear Systems.....
	2.5.2	Approximate Methods for Nonlinear Systems.....
		2.5.2.1 Iterative Method.....
		2.5.2.2 Ritz Averaging Method.....
		2.5.2.3 Perturbation Method
		2.5.2.4 Variation of Parameter Method.....
	2.5.3	Graphical Method.....
		2.5.3.1 Phase Plane Representation
		2.5.3.2 Phase Velocity.....
		2.5.3.3 Pell's Method
	2.5.4	Multiple-Degrees-of-Freedom Systems
2.6		Random Vibrations
	2.6.1	Probability Density Function
	2.6.2	Autocorrelation Function
2.7		Gaussian Random Process.....
	2.7.1	Fourier Analysis
		2.7.1.1 Fourier Series.....
		2.7.1.2 Fourier Integral
	2.7.2	Response of a Single-Degree-of-Freedom Vibrating System
		2.7.2.1 Impulse Response Method.....
		2.7.2.2 Frequency Response Method.....
	2.7.3	Power Spectral Density Function.....
	2.7.4	Joint Probability Density Function.....
	2.7.5	Cross-Correlation Function

2.7.6	Application of Power Spectral Densities to Vehicle Dynamics.....	166
2.7.7	Response of a Single-Degree-of-Freedom System to Random Inputs	168
2.7.8	Response of Multiple-Degrees-of-Freedom Systems to Random Inputs	170
2.8	Summary.....	174
2.9	References	174
Chapter 3	Tire Dynamics	177
3.1	Introduction	177
3.2	Vertical Dynamics of Tires	180
3.2.1	Vertical Stiffness and Damping Characteristics of Tires.....	180
3.2.2	Vertical Vibration Mechanics Models of Tires.....	181
3.2.2.1	Point Contact Model of Tires.....	181
3.2.2.2	Fixed Contact Patch Model of Tires	182
3.2.2.3	Time-Varying Contact Patch Model of Tires	183
3.2.3	Enveloping Characteristics of Tires	185
3.3	Tire Longitudinal Dynamics.....	186
3.3.1	Tire Rolling Resistance	187
3.3.2	Rolling Resistance of the Tire with Toe-In	188
3.3.3	Rolling Resistance of the Turning Wheel	189
3.3.4	Longitudinal Adhesion Coefficient	191
3.3.5	Theoretical Model of Tire Longitudinal Force Under Driving and Braking.....	194
3.4	Tire Lateral Dynamics	196
3.4.1	Tire Cornering Characteristics	196
3.4.2	Mathematical Model of the Tire Cornering Characteristic	198
3.4.2.1	Simplified Mathematical Model of the Tire Cornering Characteristic	199
3.4.2.2	Cornering Characteristic with Lateral Bending Deformation of the Tire Case.....	204
3.4.3	Rolling Properties of Tires	208
3.4.3.1	Cambered Tire Models.....	209
3.4.3.2	Cambered Tire Model with Roll Elastic Deformation of the Tire Carcass.....	211
3.5	Tire Mechanics Model Considering Longitudinal Slip and Cornering Characteristics	211
3.5.1	C.G. Gim Theoretical Model.....	212
3.5.2	K.H. Guo Tire Model	214
3.5.2.1	Steady-State Simplified Theoretical Tire Model.....	214
3.5.2.2	Nonsteady-State Semi-Empirical Tire Mechanics Model.....	219
3.5.3	H.B. Pacejka Magic Formula Model.....	224
3.6	References	228
Chapter 4	Ride Dynamics	231
4.1	Introduction	231
4.2	Vibration Environment in Road Vehicles	233
4.2.1	Vibration Sources from the Road.....	233
4.2.1.1	Power Spectral Density in Spatial Frequency.....	233

	4.2.1.2	Power Spectral Density in Temporal Frequency ..	
4.2.2		Vehicle Internal Vibration Sources.....	
	4.2.2.1	Vibration Sources from the Powerplant	
	4.2.2.1.1	Coordinates and Powerplant Modes..	
	4.2.2.1.2	Vibration Sources from Engine Firing Pulsation.....	
	4.2.2.1.3	Vibration Sources from Powerplant Inertia Forces and Moments.....	
	4.2.2.1.4	Powerplant Isolation Design	
	4.2.2.2	Vibration Sources from the Driveline	
	4.2.2.2.1	Driveline Imbalance	
	4.2.2.2.2	Gear Transmission Error	
	4.2.2.2.3	Second Order Excitation	
	4.2.2.2.4	Driveshaft Modes and Driveline Modes.....	
	4.2.2.3	Vibration Sources from the Exhaust System	
4.3		Vehicle Ride Models.....	
4.3.1		Quarter Car Model	
	4.3.1.1	Modeling for the Quarter Car Model.....	
	4.3.1.2	Modal Analysis for the Quarter Car Model	
	4.3.1.3	Dynamic Analysis for the Quarter Car Model	
	4.3.1.3.1	Transmissibility Between the Body Response and Road Excitation.....	
	4.3.1.3.2	Transmissibility Between the Body Response and Vehicle Excitation	
	4.3.1.3.3	Dynamic Response at Random Input.	
	4.3.2	Bounce-Pitch Model.....	
	4.3.3	Other Modeling	
4.4		Seat Evaluation and Modeling.....	
	4.4.1	Introduction	
	4.4.2	SEAT Value	
	4.4.3	Seat Velocity.....	
	4.4.4	Linear Seat Modeling and Transmissibility	
	4.4.5	Nonlinear Seat Modeling and Transmissibility.....	
4.5		Discomfort Evaluation and Human Body Model.....	
	4.5.1	Discomfort and Subjective Evaluation.....	
	4.5.2	Objective Evaluation of Ride Discomfort.....	
	4.5.2.1	Weighted Root-Mean-Square Method	
	4.5.2.2	Objective Evaluation by the Vibration Dose Value	
	4.5.3	Linear Human Body Modeling	
	4.5.4	Objective Evaluation by Nonlinear Seat-Human Body Modeling	
4.6		Active and Semi-Active Control	
	4.6.1	Introduction	
	4.6.2	Basic Control Concepts.....	
	4.6.3	Active Control.....	
	4.6.4	Semi-Active Control	
4.7		Summary.....	
4.8		References	

Chapter 5	Vehicle Rollover Analysis	311
5.1	Introduction	311
5.1.1	Rollover Scenario	311
5.1.2	Importance of Rollover	314
5.1.3	Research on Rollover	314
5.1.4	Scope of This Chapter	315
5.2	Rigid Vehicle Rollover Model	316
5.2.1	Rigid Vehicle Model	316
5.2.2	Steady-State Rollover on a Flat Road	317
5.2.3	Tilt Table Ratio	318
5.2.4	Side Pull Ratio	320
5.3	Suspended Vehicle Rollover Model	321
5.3.1	Steady-State Rollover Model for a Suspended Vehicle	321
5.3.2	Contribution from the Tire Deflection	323
5.3.3	Contribution from the Suspension Deflection	324
5.3.4	Parameters Influencing the Suspended Rollover Model	326
5.4	Dynamic Rollover Model	333
5.4.1	Rigid Dynamic Model	333
5.4.2	Dynamic Rollover Model for a Dependent Suspension Vehicle	334
5.4.3	Dynamic Rollover Model for an Independent Suspension Vehicle	336
5.4.4	Rollover Simulation Tools	336
5.5	Dynamic Rollover Threshold	338
5.5.1	Dynamic Stability Index	338
5.5.2	Rollover Prevention Energy Reserve	339
5.5.3	Rollover Prevention Metric	340
5.5.4	Critical Sliding Velocity	340
5.6	Occupant in Rollover	341
5.6.1	Overview of the Occupant and Rollover	341
5.6.2	Testing of an Occupant Model	342
5.6.3	Simulation of Occupant Rollover	343
5.7	Safety and Rollover Control	345
5.7.1	Overview of Rollover Safety	345
5.7.2	Sensing of Rollover	349
5.7.3	Rollover Safety Control	350
5.8	Summary	352
5.9	References	353
Chapter 6	Handling Dynamics	357
6.1	Introduction	357
6.1.1	Tire Cornering Forces	358
6.1.2	Forces and Torques in the Tire Contact Area	360
6.2	The Simplest Handling Models—Two-Degrees-of-Freedom Yaw Plane Model	361
6.3	Steady-State Handling Characteristics	365
6.3.1	Yaw Velocity Gain and Understeer Gradient	365
6.3.1.1	Neutral Steer	367
6.3.1.2	Understeer	367
6.3.1.3	Oversteer	368
6.3.2	Difference Between Slip Angles of the Front and Rear Wheels	368

	6.3.3	Ratio of Radius of Turn.....	.....
6.4		Dynamic Characteristics of Handling .....	.....
	6.4.1	Handling Damping and Natural Frequency .....	.....
	6.4.2	Step Steer Input Response.....	.....
	6.4.3	Ramp Steer Input Response .....	.....
	6.4.4	Impulse Input Excitation Response.....	.....
	6.4.5	Frequency Response of Yaw Velocity .....	.....
	6.4.6	Stability Analysis .....	.....
	6.4.7	Curvature Response .....	.....
6.5		Chassis System Effects on Handling Characteristics .....	.....
	6.5.1	Lateral Force Transfer Effects on Cornering.....	.....
	6.5.2	Steering System.....	.....
	6.5.3	Camber Change Effect .....	.....
	6.5.4	Roll Steer Effect.....	.....
	6.5.5	Lateral Force Compliance Steer.....	.....
	6.5.6	Aligning Torque Effects .....	.....
	6.5.7	Effect of Tractive Forces on Cornering.....	.....
6.6		Handling Safety—Overturning Limit Handling Characteristics.....	.....
6.7		Nonlinear Models of Handling Dynamics.....	.....
	6.7.1	Multiple-Degrees-of-Freedom System Models.....	.....
	6.7.2	An Eight-Degrees-of-Freedom System Model .....	.....
6.8		Testing of Handling Characteristics .....	.....
	6.8.1	Constant Radius Turn.....	.....
	6.8.2	Constant Speed Test .....	.....
	6.8.3	Constant Steer Angle Test .....	.....
		6.8.3.1 Dynamic Testing .....	.....
		6.8.3.2 Simulations and Testing Validation.....	.....
6.9		Summary.....	.....
6.10		References .....	.....
Chapter 7 Braking.....			
7.1		Introduction .....	.....
	7.1.1	Types of Automotive Brakes .....	.....
	7.1.2	Braking Distance and Deceleration.....	.....
7.2		Brake Torque Distribution.....	.....
	7.2.1	Drum Brakes .....	.....
		7.2.1.1 Mechanical Advantage.....	.....
		7.2.1.2 Torque Calculations .....	.....
	7.2.2	Disk Brakes .....	.....
	7.2.3	Consideration of Temperature .....	.....
7.3		Load Transfer During Braking .....	.....
	7.3.1	Simple Braking on a Horizontal Road .....	.....
	7.3.2	Effect of Aerodynamic and Other Forces.....	.....
		7.3.2.1 Rolling Resistance .....	.....
		7.3.2.2 Aerodynamic Drag.....	.....
		7.3.2.3 Powertrain Resistance.....	.....
		7.3.2.4 Load Transfer on a Horizontal Plane .....	.....
	7.3.3	Effect of Grade.....	.....
7.4		Optimal Braking Performance.....	.....
	7.4.1	Braking of a Single Axle .....	.....
		7.4.1.1 Braking of the Front Axle .....	.....

7.4.1.2	Braking of the Rear Axle	441
7.4.1.3	Safety Considerations	443
7.4.2	Braking at Both Axles	444
7.4.2.1	Front Lock-Up	445
7.4.2.2	Rear Lock-Up	446
7.4.3	Achieving Optimal Braking Performance.....	450
7.5	Considerations of Vehicle Safety.....	459
7.5.1	Skid (Slip) Condition and Braking.....	460
7.5.2	Anti-Lock Braking System	462
7.6	Pitch Plane Models	464
7.7	Recent Advances in Automotive Braking.....	464
7.8	Summary.....	466
7.9	References	468
Chapter 8	Acceleration.....	471
8.1	Introduction	471
8.2	Load Transfer During Acceleration.....	473
8.2.1	Simple Acceleration on a Horizontal Road.....	473
8.2.2	Effect of Aerodynamic and Other Forces.....	475
8.2.3	Effect of Grade	477
8.3	Traction-Limited Acceleration	480
8.3.1	Drivetrain Configurations.....	480
8.3.2	Front-Wheel Drive	483
8.3.3	Rear-Wheel Drive	484
8.3.4	All-Wheel-Drive and Four-by-Four Systems.....	486
8.3.4.1	Front Skid	486
8.3.4.2	Rear Skid.....	487
8.3.5	Optimal Tractive Effort	490
8.4	Power-Limited Acceleration.....	499
8.4.1	The Engine	501
8.4.2	Internal Combustion Engines	504
8.4.3	The Transmission	508
8.4.3.1	Manual Transmissions	509
8.4.3.2	Automatic Transmissions.....	514
8.4.3.3	Continuously Variable Transmissions.....	519
8.4.4	Vehicle Acceleration.....	521
8.5	Safety Features	526
8.5.1	Limited Slip Axle	526
8.5.2	Traction Control	527
8.6	Summary.....	528
8.7	References	529
Chapter 9	Total Vehicle Dynamics.....	531
9.1	Introduction	531
9.1.1	Subjective and Objective Evaluations.....	531
9.1.2	Target Setting	532
9.1.3	Vehicle Dynamics Tests and Evaluations.....	533
9.1.3.1	Ride.....	533
9.1.3.2	Steering.....	534
9.1.3.3	Handling.....	535

	9.1.3.4	Braking.....	.....
	9.1.3.5	Performance.....	.....
9.2		Steering and Braking.....	.....
	9.2.1	Simple Braking and Steering on a Horizontal Road.....	.....
	9.2.2	Optimal Braking Performance Under Steering.....	.....
		9.2.2.1 Front Lock-Up.....	.....
		9.2.2.2 Rear Lock-Up.....	.....
9.3		Steering and Acceleration.....	.....
	9.3.1	Simple Acceleration and Steering on a Horizontal Road.....	.....
	9.3.2	Optimal Acceleration Performance Under Steering.....	.....
		9.3.2.1 Front Skid.....	.....
		9.3.2.2 Rear Skid.....	.....
9.4		Vehicle Critical Speed.....	.....
9.5		Vehicle Stability.....	.....
9.6		Summary.....	.....
9.7		References.....	.....
Chapter 10		Accident Reconstruction.....	.....
	10.1	Introduction and Objectives.....	.....
	10.2	Basic Equations of Motion.....	.....
	10.3	Drag Factor and Coefficient of Friction.....	.....
	10.4	Work, Energy, and the Law of Conservation of Energy.....	.....
	10.5	Driver Perception and Response.....	.....
	10.6	Engineering Models and Animations.....	.....
		10.6.1 Function of Accident Scene Models.....	.....
		10.6.2 Model Application.....	.....
		10.6.3 Reconstruction Animations.....	.....
	10.7	Lane Change Maneuver Model.....	.....
	10.8	Speed Estimates for Fall, Flip, or Vault.....	.....
		10.8.1 Fall.....	.....
		10.8.2 Flip.....	.....
		10.8.3 Vault.....	.....
	10.9	Speed Estimates from Yaw Marks.....	.....
	10.10	Impact Analysis.....	.....
		10.10.1 Straight Central Impact.....	.....
		10.10.2 Noncentral Collisions.....	.....
		10.10.3 Crush Energy and ΔV.....	.....
	10.11	Vehicle-Pedestrian Collisions.....	.....
		10.11.1 Pedestrian Trajectories.....	.....
		10.11.2 Mathematical and Hybrid Models.....	.....
	10.12	Accident Reconstruction Software.....	.....
		10.12.1 Software Acronyms: REC-TEC with DRIVE ³ and MSMAC ^{RT}.....	.....
		10.12.2 VCRware.....	.....
		10.12.3 CRASHEX.....	.....
		10.12.4 ARSoftware.....	.....
		10.12.5 Engineering Dynamics Corporation.....	.....
		10.12.6 Macinnis Engineering Associates (MEA) and MEA Forensic Engineers & Scientists.....	.....
		10.12.7 Maine Computer Group.....	.....
		10.12.8 McHenry Software, Inc.....	.....
		10.12.9 Software Acronym: VDANL.....	.....

10.12.10	Expert AutoStats [®] —Vehicle Dimension-Weight-Performance	
	Data	622
10.12.11	Other Accident Reconstruction Software Sites	622
10.13	Low-Speed Sideswipe Collisions	623
	10.13.1 Funk-Cormier-Bain Model.....	624
	10.13.2 Modeling Procedure	625
10.14	Summary.....	629
10.15	References	629
Appendix A	Vector Algebra	635
A.1	Real and Complex Vectors	635
A.2	Laws of Vector Operation.....	636
A.3	Linear Dependence.....	636
A.4	Three-Dimensional Vectors	637
A.5	Properties of the Scalar Product of Vectors	638
A.6	Direction Angles.....	638
A.7	Vector Product	638
A.8	Derivative of a Vector.....	639
A.9	References	640
Appendix B	Matrix Analysis	643
B.1	Introduction	643
B.2	Definitions of Matrices	643
B.3	Matrix Operations.....	648
B.4	Matrix Inversion	651
B.5	Determinants.....	652
B.6	More on Matrix Inversion	657
B.7	System of Algebraic Equations	660
B.8	Eigenvalues and Eigenvectors.....	664
B.9	Quadratic Forms	668
B.10	Positive Definite Matrix	668
B.11	Negative Definite Matrix.....	670
B.12	Indefinite Matrix.....	671
B.13	Norm of a Vector	671
B.14	Partitioning of Matrices.....	672
B.15	Augmented Matrix.....	673
B.16	Matrix Calculus	674
B.17	Summary.....	675
B.18	References	675
B.19	Glossary of Terms.....	676
Appendix C	Laplace Transforms	679
C.1	Laplace Transformation.....	679
C.2	Existence of Laplace Transform.....	680
C.3	Inverse Laplace Transform	681
C.4	Properties of the Laplace Transform	681
	C.4.1 Multiplication by a Constant.....	681
	C.4.2 Sum and Difference.....	682
C.5	Special Functions.....	682
	C.5.1 Exponential Function	682
	C.5.2 Step Function	682

C.5.3	Ramp Function
C.5.4	Pulse Function
C.5.5	Impulse Function
C.5.6	Dirac Delta Function
C.5.7	Sinusoidal Function
C.6	Multiplication of $f(t)$ by e^{-at}
C.7	Differentiation
C.8	Integration
C.9	Final Value Theorem
C.10	Initial Value Theorem
C.11	Shift in Time
C.12	Complex Shifting
C.13	Real Convolution (Complex Multiplication)
C.14	Inverse Laplace Transformation
C.14.1	Partial Fraction Expansions
C.14.2	Case I—Partial Fraction Expansion When $Q(s)$ Has Distinct Roots
C.14.3	Case II—Partial Fraction Expansion When $Q(s)$ Has Complex Conjugate Roots
C.14.4	Case III—Partial Fraction Expansion When $Q(s)$ Has Repeated Roots
C.15	Solution of Differential Equations
C.16	Summary
C.17	References
Appendix D	Glossary of Terms
Appendix E	Direct Numerical Integration Methods
E.1	Introduction
E.2	Single-Degree-of-Freedom System
E.2.1	Finite Difference Method
E.2.2	Central Difference Method
E.2.3	Runge-Kutta Method
E.3	Multiple-Degrees-of-Freedom System
E.4	Explicit Schemes
E.4.1	Central Difference Method
E.4.2	Fourth-Order Runge-Kutta Method
E.5	Implicit Schemes
E.5.1	Houbolt Method
E.5.2	Wilson- θ Method
E.5.3	Newmark- β Method
E.6	Case Studies
E.6.1	Linear Dynamic System
E.6.2	Nonlinear Dynamic System
E.7	Summary
E.8	References
Appendix F	Units and Conversion
F.1	The S.I. System of Units
F.2	S.I. Unit Prefixes

F.3	S.I. Conversion	785
F.4	References	788
Appendix G	Accident Reconstruction Formulae	789
G.1	Center of Mass.....	789
G.2	Slide-to-a-Stop Speed.....	792
G.3	Yaw, Sideslip, and Critical Curve Speed.....	794
G.4	Combined Speeds	795
G.5	360-Degree Momentum Speed Analysis	797
G.6	Tip and Rollover Speed	799
G.7	Weight Shift and Speed	800
G.8	Kinetic Energy and Speed	801
G.9	Fall, Slip, and Vault Speeds.....	802
Bibliography	.....	805
List of Symbols	.....	811
Index	.....	833
About the Authors	.....	849