## Contents

About the Authors xiii

Preface xv

List of Abbreviations xvii

1 Vehicle Powertrain Concepts 1
   1.1 Powertrain Systems 1
      1.1.1 Systems Approach 1
      1.1.2 History 2
      1.1.3 Conventional Powertrains 3
      1.1.4 Hybrid Powertrains 3
   1.2 Powertrain Components 5
      1.2.1 Engine 5
      1.2.2 Transmission 5
      1.2.3 Vehicle Structure 5
      1.2.4 Systems Operation 6
   1.3 Vehicle Performance 6
   1.4 Driver Behaviour 8
   1.5 The Role of Modelling 9
   1.6 Aim of the Book 10
Further Reading 11
References 11

2 Power Generation Characteristics of Internal Combustion Engines 13
   2.1 Introduction 13
   2.2 Engine Power Generation Principles 13
      2.2.1 Engine Operating Modes 14
      2.2.2 Engine Combustion Review 16
      2.2.3 Engine Thermodynamics Review 18
      2.2.4 Engine Output Characteristics 33
      2.2.5 Cylinder Pressure Variations 34
   2.3 Engine Modelling 39
      2.3.1 Engine Kinematics 40
      2.3.2 Engine Torque 49
      2.3.3 A Simplified Model 58
      2.3.4 The Flywheel 66
2.4  Multi-cylinder Engines  
   2.4.1  Firing Order  
   2.4.2  Engine Torque  
   2.4.3  Quasi-Steady Engine Torque  
2.5  Engine Torque Maps  
   2.5.1  Engine Dynamometers  
   2.5.2  Chassis Dynamometers  
   2.5.3  Engine Torque-Speed Characteristics  
2.6  Magic Torque (MT) Formula for Engine Torque  
   2.6.1  Converting Part Throttle Curves  
   2.6.2  The MT Formula  
   2.6.3  Interpretation  
2.7  Engine Management System  
   2.7.1  Construction  
   2.7.2  Sensors  
   2.7.3  Maps and Look-up Tables  
   2.7.4  Calibration  
2.8  Net Output Power  
   2.8.1  Engine Mechanical Efficiency  
   2.8.2  Accessory Drives  
   2.8.3  Environmental Effects  
2.9  Conclusion  
2.10  Review Questions  
2.11  Problems  
Further Reading  
References  

3  Vehicle Longitudinal Dynamics  
3.1  Introduction  
3.2  Torque Generators  
   3.2.1  Internal Combustion Engines  
   3.2.2  Electric Motors  
3.3  Ttractive Force  
   3.3.1  Tyre Force Generation  
   3.3.2  Mathematical Relations for Ttractive Force  
   3.3.3  Traction Diagrams  
3.4  Resistive Forces  
   3.4.1  Rolling Resistance  
   3.4.2  Vehicle Aerodynamics  
   3.4.3  Slopes  
   3.4.4  Resistance Force Diagrams  
   3.4.5  Coast Down Test  
3.5  Vehicle Constant Power Performance (CPP)  
   3.5.1  Maximum Power Delivery  
   3.5.2  Continuous Gear-Ratio Assumption  
   3.5.3  Governing Equations  
   3.5.4  Closed Form Solution  
   3.5.5  Numerical Solutions  
   3.5.6  Power Requirements
5 Fuel Consumption

5.1 Introduction 341
5.2 Engine Energy Consumption 342
  5.2.1 BSFC Maps 342
  5.2.2 BSFC and Engine Efficiency 344
5.3 Driving Cycles 345
  5.3.1 Typical Driving Cycles 346
  5.3.2 Calculations 348
  5.3.3 Vehicle Tests 350
5.4 Vehicle Fuel Consumption 351
  5.4.1 Map-free Fuel Consumption 352
  5.4.2 Map-based Fuel Consumption 356
  5.4.3 Effect of Rotating Masses 360
5.5 Shifting Effects 360
  5.5.1 Effect of Shifting on EOP 361
  5.5.2 Efficient Operating Points 364
5.6 Software 369
  5.6.1 Solution Methodologies 369
  5.6.2 ADVISOR® 370
5.7 Automated Gearshifts 371
  5.7.1 Engine State 371
  5.7.2 Driver’s Intentions 371
  5.7.3 Combined Shifting 372
  5.7.4 Controller 372
  5.7.5 Multigear Transmission Concept 373
5.8 Other Solutions for Fuel Efficiency 374
  5.8.1 Powertrain Component Improvements 374
  5.8.2 Lightweight Vehicles 375
  5.8.3 Engine 376
  5.8.4 Transmission 377
5.9 Conclusion 378
5.10 Review Questions 379
6 Driveline Dynamics

6.1 Introduction 387

6.2 Modelling Driveline Dynamics 387
   6.2.1 Modelling Methods 388
   6.2.2 Linear Versus Non-linear Models 390
   6.2.3 Software Use 390

6.3 Bond Graph Models of Driveline Components 391
   6.3.1 The Engine 391
   6.3.2 The Clutch 392
   6.3.3 The Transmission 393
   6.3.4 Propeller and Drive Shafts 394
   6.3.5 The Differential 394
   6.3.6 The Wheel 396
   6.3.7 Vehicle 397

6.4 Driveline Models 397
   6.4.1 Full Driveline Model 397
   6.4.2 Straight-Ahead Motion 397
   6.4.3 Rigid Body Model 397
   6.4.4 Driveline with Clutch Compliance 399
   6.4.5 Driveline with Driveshaft Compliance 400
   6.4.6 Driveline with Clutch and Driveshaft Compliances 401

6.5 Analysis 402
   6.5.1 Effect of Clutch Compliance 403
   6.5.2 Effect of Driveshaft Compliance 408
   6.5.3 Effect of Clutch and Driveshaft Compliances 411
   6.5.4 Frequency Responses 415
   6.5.5 Improvements 418

6.6 Conclusion 418

6.7 Review Questions 419

6.8 Problems 419

Further Reading 423

References 424

7 Hybrid Electric Vehicles

7.1 Introduction 425

7.2 Types of Hybrid Electric Vehicles 425
   7.2.1 Basic Classification 426
   7.2.2 Basic Modes of Operation 428
   7.2.3 Other Derivatives 429
   7.2.4 Degree of Hybridization 432

7.3 Power Split Devices 433
   7.3.1 Simple PSD 434
   7.3.2 EM Compound PSD 446

7.4 HEV Component Characteristics 451
   7.4.1 The IC Engine 452
7.4.2 Electric Machines 452
7.4.3 The Battery 457
7.5 HEV Performance Analysis 465
  7.5.1 Series HEV 466
  7.5.2 Parallel HEV 470
7.6 HEV Component Sizing 474
  7.6.1 General Considerations 474
  7.6.2 Sizing for Performance 475
  7.6.3 Optimum Sizing 498
7.7 Power Management 500
  7.7.1 Control Potential 501
  7.7.2 Control 506
7.8 Conclusion 507
7.9 Review Questions 507
7.10 Problems 508
Further Reading 510
 References 510

Appendix: An Introduction to Bond Graph Modelling 511
A.1 Basic Concept 511
A.2 Standard Elements 511
  A.2.1 Sources 512
  A.2.2 Passive Elements 512
  A.2.3 Two Port Elements 514
  A.2.4 Junctions 516
A.3 Constructing Bond Graphs 517
A.4 Equations of Motion 520
  A.4.1 Causality 520
  A.4.2 Assignment Procedure 521
  A.4.3 Bond Graph Numbering 522
  A.4.4 Component Equations 523
  A.4.5 Bond Graph Simplifications 523
  A.4.6 Derivation of Equations of Motion 524

Index 529