

# **Contents**

Acknowledgments xvii

Preface xiii

Participants at the UNEP Workshop xix Chapter 1 Emission Standards and Regulations 1 International Standards 2 U.S. Standards 2 U.N. Economic Commission for Europe (ECE) and European Union (EU) Standards 6 Country and Other Standards 9 Argentina 11 Australia 11 Brazil 12 Canada 13 Chile 14 China 15 Colombia 15 Eastern European Countries and the Russian Federation 15 Hong Kong 16 India 17 Japan 18 Republic of Korea 18 Malaysia 19 Mexico 19 Saudi Arabia 19 Singapore 19 Taiwan (China) 20 Thailand 20 Compliance with Standards 21 Certification or Type Approval 21 Assembly Line Testing 22 In-Use Surveillance and Recall 22 Warranty 23 On-Board Diagnostic Systems 23

## Chapter 2 Quantifying Vehicle Emissions 25

References 24

Alternatives to Emission Standards 23

Emissions Measurement and Testing Procedures 25

Exhaust Emissions Testing for Light-Duty Vehicles 25

Exhaust Emissions Testing for Motorcycles and Mopeds 29

Exhaust Emissions Testing for Heavy-Duty Vehicle Engines 29

Crankcase Emissions 32

Evaporative Emissions 32

Refueling Emissions 33

On-Road Exhaust Emissions 33

Vehicle Emission Factors 33

Gasoline-Fueled Vehicles 37

Diesel-Fueled Vehicles 39

Motorcycles 43

References 46

Appendix 2.1 Selected Exhaust Emission and Fuel Consumption Factors for Gasoline-Fueled Vehicles 49 Appendix 2.2 Selected Exhaust Emission and Fuel Consumption Factors for Diesel-Fueled Vehicles 57

## Chapter 3 Vehicle Technology for Controlling Emissions 63

Automotive Engine Types 64

Spark-Ignition (Otto) Engines 64

Diesel Engines 64

Rotary (Wankel) Engines 65

Gas-Turbine (Brayton) Engines 65

Steam (Rankine Engines) 65

Stirling Engines 65

Electric and Hybrid Vehicles 65

Control Technology for Gasoline-Fueled Vehicles (Spark-Ignition Engines) 65

Air-Fuel Ratio 66

Electronic Control Systems 66

Catalytic Converters 67

Crankcase Emissions and Control 67

Evaporative Emissions and Control 67

Fuel Dispensing/Distribution Emissions and Control 69

Control Technology for Diesel-Fueled Vehicles (Compression-Ignition Engines) 69

Engine Design 70

Exhaust Aftertreatment 71

Emission Control Options and Costs 73

Gasoline-Fueled Passenger Cars and Light-Duty Trucks 73

Heavy-Duty Gasoline-Fueled Vehicles 76

Motorcycles 76

Diesel-Fueled Vehicles 76

References 79

Appendix 3.1 Emission Control Technology for Spark-Ignition (Otto) Engines 81 Appendix 3.2 Emission Control Technology for Compression-Ignition (Diesel) Engines 101

Appendix 3.3 The Potential for Improved Fuel Economy 119

## Chapter 4 Controlling Emissions from In-Use Vehicles 127

Inspection and Maintenance Programs 127

Vehicle Types Covered 129

Inspection Procedures for Vehicles with Spark-Ignition Engines 130

Exhaust Emissions 131

Evaporative Emissions 133

Motorcycle White Smoke Emissions 133

Inspection Procedures for Vehicles with Diesel Engines 133

Institutional Setting for Inspection and Maintenance 135

Centralized I/M 136

Decentralized I/M 137

Comparison of Centralized and Decentralized I/M Programs 138

Inspection Frequency 140

Vehicle Registration 140

Roadside Inspection Programs 140

Emission Standards for Inspection and Maintenance Programs 141

Costs and Benefits of Inspection and Maintenance Programs 144

Emission Improvements and Fuel Economy 149

Impact on Tampering and Misfueling 151

Cost-Effectiveness 153

International Experience with Inspection and Maintenance Programs 154

Remote Sensing of Vehicle Emissions 159

Evaluation of Remote-Sensing Data 162

On-Board Diagnostic Systems 164

Vehicle Replacement and Retrofit Programs 164

Scrappage and Relocation Programs 165

Vehicle Replacement 165

Retrofit Programs 166

Intelligent Vehicle-Highway Systems 167

References 168

Appendix 4.1 Remote Sensing of Vehicle Emissions: Operating Principles, Capabilities, and Limitations 171

### Chapter 5 Fuel Options for Controlling Emissions 175

#### Gasoline 176

Lead and Octane Number 176

Fuel Volatility 179

Olefins 180

Aromatic Hydrocarbons 180

Distillation Properties 181

Oxygenates 182

Sulfur 183

Fuel Additives to Control Deposits 184

Reformulated Gasoline 184

#### Diesel 186

Sulfur Content 187

Cetane Number 188

Aromatic Hydrocarbons 188

Other Fuel Properties 189

Fuel Additives 190

Effect of Diesel Fuel Properties on Emissions: Summary of EPEFE Results 191

#### Alternative Fuels 193

Natural Gas 195

Liquefied Petroleum Gas (LPG) 200

Methanol 202

Ethanol 204

Biodiesel 206

Hydrogen 210

Electric and Hybrid-Electric Vehicles 211

Factors Influencing the Large-Scale Use of Alternative Fuels 213

Cost 213

End-Use Considerations 215

Life-Cycle Emissions 216

Conclusions 218

References 219

Appendix 5.1 International Use of Lead in Gasoline 223

Appendix 5.2 Electric and Hybrid-Electric Vehicles 227

Appendix 5.3 Alternative Fuel Options for Urban Buses in Santiago, Chile: A Case Study 237

#### Abbreviations and Conversion Factors 241

#### Country Index 245

## Boxes

Box 2.1 Box 2.2	Factors Influencing Motor Vehicle Emissions 34 Development of Vehicle Emissions Testing Capability in Thailand 36
Box 3.1	Trap-Oxidizer Development in Greece 72
Box A3.1.1	Compression Ratio, Octane, and Fuel Efficiency 90
Box 4.1 Box 4.2 Box 4.3 Box 4.4	Effectiveness of California's Decentralized "Smog Check" Program 128 Experience with British Columbia's AirCare I/M Program 129 On-Road Smoke Enforcement in Singapore 142 Replacing Trabants and Wartburgs with Cleaner Automobiles in Hungary 167
Box 5.1 Box 5.2 Box 5.3 Box 5.4 Box 5.5 Box 5.6 Box 5.7 Box 5.8	Gasoline Blending Components 176 Low-Lead Gasoline as a Transitional Measure 178 Use of Oxygenates in Motor Gasolines 182 CNG in Argentina: An Alternative Fuel for Buenos Aires Metropolitan Region 196 Brazil's 1990 Alcohol Crisis: the Search for Solutions 207 Electric Vehicle Program for Kathmandu, Nepal 214 Ethanol in Brazil 216 Compressed Natural Gas in New Zealand 217
Figures	
Figure 2.1 Figure 2.2 Figure 2.3 Figure 2.4 Figure 2.5 Figure 2.6 Figure 2.7 Figure 2.8 Figure 2.9 Figure 2.10 Figure 2.11 Figure 2.12 Figure 2.13 Figure 2.14	Exhaust Emissions Test Procedure for Light-Duty Vehicles 26 Typical Physical Layout of an Emissions Testing Laboratory 27 U.S. Emissions Test Driving Cycle for Light-Duty Vehicles (FTP-75) 27 Proposed U.S. Environmental Protection Agency US06 Emissions Test Cycle 28 European Emissions Test Driving Cycle (ECE-15) 30 European Emissions Test Driving Cycle (EUDC) 30 European Emissions Test Driving Cycle for Mopeds 31 Relationship between Vehicle Speed and Emissions for Uncontrolled Vehicles 35 Effect of Average Speed on Emissions and Fuel Consumption for European Passenger Cars without Catalyst (INRETS Driving Cycles; Fully Warmed-Up In-use Test Vehicles) 39 Cumulative Distribution of Emissions from Passenger Cars in Santiago, Chile 40 Effect of Average Speed on Emissions and Fuel Consumption for Heavy-Duty Swiss Vehicles 42 Effect of Constant Average Speed and Road Gradient on Exhaust Emissions and Fuel Consumption for a 40-ton Semi-Trailer Truck 43 Cumulative Distribution of Emissions from Diesel Buses in Santiago, Chile 44 Smoke Opacity Emissions from Motorcycles in Bangkok, Thailand 46
Figure 3.1 Figure 3.2 Figure 3.3 Figure 3.4 Figure 3.5	Effect of Air-Fuel Ratio on Spark-Ignition Engine Emissions 66 Types of Catalytic Converters 68 Effect of Air-Fuel Ratio on Three-Way Catalyst Efficiency 69 Hydrocarbon Vapor Emissions from Gasoline Distribution 70 Nitrogen Oxide and Particulate Emissions from Diesel-Fueled Engines 71
Figure A3.1. Figure A3.1. Figure A3.1. Figure A3.1. Figure A3.1.	Piston and Cylinder Arrangement of a Typical Four-Stroke Engine 84 Exhaust Scavenging in a Two-Stroke Gasoline Engine 85 Mechanical Layout of a Typical Four-Stroke Engine 86

Figure A3.1.6 Combustion Rate and Crank Angle for Conventional and Fast-Burn Combustion Chambers 89

Figure A3.2.1	Diesel Combustion Stages 102
Figure A3.2.2	Hydrocarbon and Nitrogen Oxide Emissions for Different Types of Diesel Engines 103
Figure A3.2.3	Relationship between Air-Fuel Ratio and Emissions for a Diesel Engine 106
Figure A3.2.4	Estimated PM-NO <sub>x</sub> Trade-Off over Transient Test Cycle for Heavy-Duty Diesel Engines 109
Figure A3.2.5	Diesel Engine Combustion Chamber Types 110  Pure Planta Volume for Concentration Companies a horacon Vertical and Haringatal Fatherests 116
Figure A3.2.6	Bus Plume Volume for Concentration Comparison between Vertical and Horizontal Exhausts 116
Figure A3.2.7	Truck Plume Volume for Concentration Comparison between Vertical and Horizontal Exhausts 116
Figure A3.3.1	Aerodynamic Shape Improvements for an Articulated Heavy-Duty Truck 120
Figure A3.3.2	Technical Approaches to Reducing Fuel Economy of Light-Duty Vehicles 121
E 6.1	Effect of Maintenance on Emissions and Evel Economy of Dusco in Centions Chile 120
Figure 4.1 Figure 4.2	Effect of Maintenance on Emissions and Fuel Economy of Buses in Santiago, Chile 130 Schematic Illustration of the IM240 Test Equipment 132
Figure 4.3	Bosch Number Compared with Measured Particulate Emissions for Buses in Santiago, Chile 134
Figure 4.4	Schematic Illustration of a Typical Combined Safety and Emissions Inspection Station: Layout and
	Equipment 137
Figure 4.5	Schematic Illustration of an Automated Inspection Process 138
Figure 4.6	Cumulative Distribution of CO Emissions from Passenger Cars in Bangkok 143
Figure 4.7	Cumulative Distribution of Smoke Opacity for Buses in Bangkok 143
Figure 4.8	Illustration of a Remote Sensing System for CO and HC Emissions 160
Figure 4.9	Distribution of CO Concentrations Determined by Remote Sensing of Vehicle Exhaust in Chicago in 1990 (15,586 Records) 161
Figure 4.10	Distribution of CO Concentrations Determined by Remote Sensing of Vehicle Exhaust
71	in Mexico City 161
Figure 4.11	Distribution of HC Concentrations Determined by Remote Sensing of Vehicle Exhaust
	in Mexico City 161
Figure 5.1	Range of Petroleum Products Obtained from Distillation of Crude Oil 186
Figure 5.2	A Comparison of the Weight of On-Board Fuel and Storage Systems for CNG and Gasoline 199
Figure A5.2.1	Vehicle Cruise Propulsive Power Required as a Function of Speed and Road Gradient 228
Tables	
Table 1.1	Progression of U.S. Exhaust Emission Standards for Light-Duty Gasoline-Fueled Vehicles 3
Table 1.2	U.S. Exhaust Emission Standards for Passenger Cars and Light-Duty Vehicles Weighing Less than 3,75
14010 1.2	Pounds Test Weight 4
Table 1.3	U.S. Federal and California Motorcycle Exhaust Emission Standards 5
Table 1.4	U.S. Federal and California Exhaust Emission Standards for Medium-Duty Vehicles 6
Table 1.5	U.S. Federal and California Exhaust Emission Standards for Heavy-Duty and Medium-Duty Engines
Table 1.6	European Emission Standards for Passenger Cars with up to 6 Seats 9
Table 1.7	European Union 1994 Exhaust Emission Standards for Light-Duty Commercial Vehicles (Ministerial
Table 1.0	Directive 93/59/EEC) 10  ECF and Other Francisco Exhaust Emission Standards for Matagorales and Manada 10
Table 1.8	ECE and Other European Exhaust Emission Standards for Motorcycles and Mopeds 10  Smoke Limits Specified in ECE Regulation 24 03 and EU Disastive 72/2/06/EEC 11
Table 1.9 Table 1.10	Smoke Limits Specified in ECE Regulation 24.03 and EU Directive 72/306/EEC 11 European Exhaust Emission Standards for Heavy-Duty Vehicles for Type Approval 11
Table 1.10	Exhaust Emission Standards (Decree 875/94), Argentina 12
Table 1.11	Exhaust Emission Standards (Decree 873794), Algentina 12  Exhaust Emission Standards for Motor Vehicles, Australia 13
Table 1.13	Exhaust Emission Standards for Light-Duty Vehicles (FTP-75 Test Cycle), Brazil 13
Table 1.14	Exhaust Emission Standards for Heavy-Duty Vehicles (ECE R49 Test Cycle), Brazil 14
Table 1.15	Exhaust Emission Standards for Light- and Heavy-Duty Vehicles, Canada 14
Table 1.16	Exhaust Emission Limits for Gasoline-Powered Heavy-Duty Vehicles (1983), China 15
Table 1.17	Proposed Exhaust Emission Limits for Gasoline-Powered Heavy-Duty Vehicles, China 16
Table 1.18	List of Revised or New Emission Standards and Testing Procedures, China (Effective 1994) 16

Table 1.19	Emission Limits for Gasoline-Fueled Vehicles for Idle and Low Speed Conditions, Colombia 16
Table 1.20	Exhaust Emission Standards for Gasoline- and Diesel-Fueled Vehicles, Colombia 17
Table 1.21	Summary of Vehicle Emission Regulations in Eastern Europe 17
Table 1.22	Exhaust Emission Standards for Gasoline-Fueled Vehicles, India 18
Table 1.23	Motorcycle Emission Standards, Republic of Korea 18
Table 1.24	Emission Standards for Light-Duty Vehicles, Mexico 19
Table 1.25	Exhaust Emission Standards for Light-Duty Trucks and Medium-Duty Vehicles by Gross Vehicle Weight, Mexico 20
Table 1.26	Exhaust Emission Standards for Motorcycles, Taiwan (China) 21
Table 1.27	Exhaust Emission Standards, Thailand 21
Table 2.1	Estimated Emission Factors for U.S. Gasoline-Fueled Passenger Cars with Different Emission Control Technologies 37
Table 2.2	Estimated Emission Factors for U.S. Gasoline-Fueled Medium-Duty Trucks with Different Emission Control Technologies 38
Table 2.3	Estimated Emission and Fuel Consumption Factors for U.S. Diesel-Fueled Passenger Cars and Light- Duty Trucks 41
Table 2.4	Estimated Emission and Fuel Consumption Factors for U.S. Heavy-Duty Diesel-Fueled Trucks and Buses 41
Table 2.5	Emission and Fuel Consumption Factors for Uncontrolled U.S.Two- and Four-Stroke Motorcycles 45
Table 2.6	Emission Factors for Uncontrolled European Motorcycles and Mopeds 45
Table 2.7	Emission and Fuel Consumption Factors for Uncontrolled Thai Motorcycles 45
Table A2.1.1	Exhaust Emissions, European Vehicles, 1970-90 Average 49
Table A2.1.2	Exhaust Emissions, European Vehicles, 1995 Representative Fleet 49
Table A2.1.3	Estimated Emissions and Fuel Consumption, European Vehicles, Urban Driving 50
Table A2.1.4	Estimated Emissions and Fuel Consumption, European Vehicles, Rural Driving 51
Table A2.1.5	Estimated Emissions and Fuel Consumption, European Vehicles, Highway Driving 52
Table A2.1.6	Automobile Exhaust Emissions, Chile 53
Table A2.1.7	Automobile Exhaust Emissions as a Function of Test Procedure and Ambient Temperature, Finland 53
Table A2.1.8	Automobile Exhaust Emissions as a Function of Driving Conditions, France 53
Table A2.1.9	Automobile Exhaust Emissions and Fuel Consumption as a Function of Driving Conditions and Emission Controls, Germany 53
Table A2.1.10	Exhaust Emissions, Light-Duty Vehicles and Mopeds, Greece 54
Table A2.1.11	Hot-Start Exhaust Emissions, Light-Duty Vehicles, Greece 54
Table A2.1.12	Exhaust Emissions, Light-Duty Vehicles and 2-3 Wheelers, India 54
Table A2.2.1	Exhaust Emissions, European Cars 57
Table A2.2.2	Estimated Emissions and Fuel Consumption, European Cars and Light-Duty Vehicles 57
Table A2.2.3	Estimated Emissions, European Medium- to Heavy-Duty Vehicles 58
Table A2.2.4	Exhaust Emissions, European Heavy-Duty Vehicles 58
Table A2.2.5	Exhaust Emissions and Fuel Consumption, Utility and Heavy-Duty Trucks, France 58
Table A2.2.6	Exhaust Emissions, Santiago Buses, Chile 59
Table A2.2.7	Exhaust Emissions, London Buses, United Kingdom 59
Table A2.2.8	Exhaust Emissions, Utility and Heavy-Duty Vehicles, Netherlands 59
Table A2.2.9	Automobile Exhaust Emissions as a Function of Driving Conditions, France 59
Table A2.2.10	Automobile Exhaust Emissions and Fuel Consumption as a Function of Testing Procedures, Germany 60
Table A2.2.11	Exhaust Emissions, Cars, Buses, and Trucks, Greece 60
Table A2.2.12	Exhaust Emissions, Light-Duty Vehicles and Trucks, India 60

Table 3.1 Table 3.2 Table 3.3	Automaker Estimates of Emission Control Technology Costs for Gasoline-Fueled Vehicles 74  Exhaust Emission Control Levels for Light-Duty Gasoline-Fueled Vehicles 75  Recommended Emission Control Levels for Motorcycles in Thailand 76  Ledward Estimates of Emission Control Technology Costs for Discal Evaled Vehicles 77
Table 3.4	Industry Estimates of Emission Control Technology Costs for Diesel-Fueled Vehicles 77
Table 3.5	Emission Control Levels for Heavy-Duty Diesel Vehicles 78
Table 3.6	Emission Control Levels for Light-Duty Diesel Vehicles 78
Table A3.1.1	Effect of Altitude on Air Density and Power Output from Naturally Aspirated Gasoline Engines in Temperate Regions 87
Table A3.1.2	Cold-Start and Hot-Start Emissions with Different Emission Control Technologies 91
Table A3.1.3	Engine Performance and Exhaust Emissions for a Modified Marine Two-Stroke Engine 93
Table A3.1.4	Exhaust Emissions and Fuel Economy for a Fuel-Injected Scooter 94
Table A3.1.5	Moped Exhaust Emissions 97
Table A3.3.1	Energy Efficiency of Trucks in Selected Countries 122
Table A3.3.2	International Gasoline and Diesel Prices 124
Table A3.3.3	Gasoline Consumption by Two- and Three-Wheelers 125
Table 4.1	Characteristics of Existing I/M Programs for Heavy-Duty Diesel Vehicles in the United States, 1994 136
Table 4.2	Estimated Costs of Centralized and Decentralized I/M Programs in Arizona, 1990 139
Table 4.3	Schedule of Compulsory Motor Vehicle Inspection in Singapore by Vehicle Age 141
Table 4.4	Inspection and Maintenance Standards Recommended for Thailand 145
Table 4.5	Distribution of Carbon Monoxide and Hydrocarbon Emissions from 17,000 Short Tests on Gasoline Cars in Finland 145
Table 4.6	In-Service Vehicle Emission Standards in the European Union, 1994 146
Table 4.7	In-Service Vehicle Emission Standards in Argentina, New Zealand, and East Asia, 1994 147
Table 4.8	In-Service Vehicle Emission Standards in Poland, 1995 148
Table 4.9	In-Service Vehicle Emission Standards for Inspection and Maintenance Programs in Selected U.S. Jurisdictions, 1994 148
Table 4.10	U.S. IM240 Emission Standards 149
Table 4.11	Alternative Options for a Heavy-Duty Vehicle I/M Program for Lower Fraser Valley, British Columbia, Canada 150
Table 4.12	Estimated Emission Factors for U.S. Gasoline-Fueled Automobiles with Different Emission Control Technologies and Inspection and Maintenance Programs 151
Table 4.13	Estimated Emission Factors for U.S. Heavy-Duty Vehicles with Different Emission Control Technologies and Inspection and Maintenance Programs 152
Table 4.14	U.S. EPA's I/M Performance Standards and Estimated Emissions Reductions from Enhanced I/M
1able 4.14	Programs 153
Table 4.15	Effect of Engine Tune-Up on Emissions for European Vehicles 153
Table 4.16	Tampering and Misfueling Rates in the United States 154
Table 4.17	In-Use Emission Limits for Light-Duty Vehicles in Mexico 158
Table 4.18	Remote Sensing CO and HC Emissions Measurements for Selected Cities 163
1able 4.10	Remote sensing co and the Emissions measurements for selected cities 105
Table 5.1	Incremental Costs of Controlling Gasoline Parameters 185
Table 5.2	Influence of Crude Oil Type on Diesel Fuel Characteristics 187
Table 5.3	Influence of Diesel Fuel Properties on Exhaust Emissions 190
Table 5.4	Properties of Diesel Test Fuels Used in EPEFE Study 192
Table 5.5	Change in Light-Duty Diesel Vehicle Emissions with Variations in Diesel Fuel Properties 192
Table 5.6	Change in Heavy-Duty Diesel Vehicle Emissions with Variations in Diesel Fuel Properties 193
Table 5.7	Toxic Emissions from Gasoline and Alternative Fuels in Light-Duty Vehicles with Spark-Ignition Engines 194

**Table A5.3.1** 

Table A5.3.2

Emissions of Buses with Alternative Fuels, Santiago, Chile 238

Economics of Alternative Fuel Options for Urban Buses in Santiago, Chile 238