

Contents

Preface	xxiii
Part I: Diesel Engine Basics	<u>1</u>
CHAPTER 1	
The Diesel Engine	<u>3</u>
1.1. Introduction	<u>3</u>
1.2. What Is a Diesel Engine?	<u>4</u>
1.3. Types of Diesel ICEs	<u>5</u>
1.3.1. IDI Engines	<u>5</u>
1.3.2. DI Engines	<u>6</u>
1.4. Early History of the Diesel Engine	<u>7</u>
1.4.1. Akroyd-Stuart's Engine	<u>8</u>
1.4.2. Fuel Injection Challenges	<u>9</u>
1.4.3. High-Speed Engines for Commercial Vehicles	<u>10</u>
1.4.4. High-Speed Passenger Car Engines	<u>12</u>
1.5. Efficiency and Greenhouse Gas Emissions	<u>14</u>
1.5.1. Efficiency of Spark-Ignited Engines	<u>15</u>
1.6. Comparison to Otto Cycle Engines	<u>16</u>
1.6.1. Criteria Emissions	<u>16</u>
1.6.2. Durability	<u>17</u>
1.6.3. Reliability	<u>17</u>
1.6.4. Fuel Characteristics	<u>18</u>
1.6.5. Compression Ratio	<u>18</u>
1.6.6. Friction Losses	<u>18</u>
1.6.7. Pumping Losses	<u>18</u>
1.6.8. Noise	<u>19</u>
1.6.9. Specific Output	<u>19</u>
1.6.10. Cost	<u>20</u>
1.6.11. Exhaust Temperature	<u>20</u>

1.7. ICEs and Future Mobility	<u>20</u>
1.7.1. Drivers of Change	<u>20</u>
1.7.2. Energy Supply	<u>21</u>
1.7.3. Resource Demands	<u>22</u>
1.7.4. GHG Emissions	<u>24</u>
1.7.5. Energy Efficiency	<u>25</u>
1.7.6. Additional Challenges	<u>26</u>
Additional Resources	<u>26</u>
References	<u>26</u>
<hr/>	
CHAPTER 2	
Engine Fundamentals	<u>29</u>
2.1. Introduction	<u>29</u>
2.2. Heat Engines	<u>29</u>
2.2.1. Definition and Classification	<u>29</u>
2.2.2. Internal Combustion Engines	<u>30</u>
2.2.3. External Combustion Engines	<u>31</u>
2.3. Reciprocating ICE Classification	<u>32</u>
2.3.1. Four-Stroke and Two-Stroke Cycles	<u>32</u>
2.3.1.1. Four-Stroke Cycle Engines	<u>32</u>
2.3.1.2. Two-Stroke Cycle Engines	<u>34</u>
2.3.2. Other Classifications of Engines	<u>36</u>
2.4. Reciprocating ICE Fundamentals	<u>39</u>
2.4.1. Basic Parameters	<u>39</u>
2.4.2. First and Second Laws of Thermodynamics	<u>41</u>
2.4.3. Engine Efficiency Terms	<u>43</u>
2.4.4. Engine Mass Balance	<u>44</u>
2.5. Engine Performance Parameters	<u>45</u>
2.5.1. Introduction	<u>45</u>
2.5.2. Power Output	<u>45</u>
2.5.3. Indicated Power	<u>47</u>
2.5.4. Indicated Mean Effective Pressure	<u>48</u>
2.5.5. Brake Mean Effective Pressure	<u>48</u>
2.5.6. Specific Fuel Consumption	<u>49</u>
2.5.7. Engine-Specific Weight and Volume	<u>49</u>
Additional Resources	<u>50</u>
References	<u>50</u>

CHAPTER 3

Engine Intake Charge Management	<u>51</u>
3.1. Introduction	<u>51</u>
3.2. Volumetric Efficiency	<u>53</u>
3.3. Charge Pressure Management	<u>54</u>
3.3.1. Effect on Performance	<u>54</u>
3.3.2. Turbochargers	<u>56</u>
3.3.2.1. Compressor	<u>57</u>
3.3.2.2. Turbine	<u>60</u>
3.3.2.3. Turbocharging Challenges	<u>62</u>
3.3.2.4. Types of Turbochargers	<u>63</u>
3.3.3. Superchargers	<u>66</u>
3.3.4. Multiple Compressors	<u>67</u>
3.3.5. Assisted Turbocharging	<u>70</u>
3.3.6. Dynamic Charging	<u>73</u>
3.4. Charge Temperature Management	<u>74</u>
3.4.1. Charge Air Cooling	<u>75</u>
3.4.2. Charge Air Heating	<u>77</u>
3.5. Charge Composition Management	<u>80</u>
3.6. Control of Flow into and out of the Combustion Chamber	<u>83</u>
3.7. Crankcase Ventilation	<u>89</u>
Additional Resources	<u>90</u>
References	<u>90</u>

CHAPTER 4

Diesel Fuel Injection	<u>94</u>
4.1. Introduction	<u>94</u>
4.1.1. Purposes of the Fuel Injection System	<u>94</u>
4.1.2. Definition of Terms	<u>95</u>
4.2. Diesel Fuel Injection System Architectures	<u>97</u>
4.3. Fuel Metering	<u>100</u>
4.4. Merits of the CR Fuel Injection System	<u>101</u>
4.5. CR Fuel Injection System Components	<u>103</u>
4.5.1. Piping System and Rail	<u>103</u>
4.5.2. HP Pump	<u>103</u>
4.5.3. Fuel Injection Nozzles	<u>106</u>

4.5.3.1. Spring-Biased Nozzle	106
4.5.3.2. Servo Control	107
4.5.3.3. Direct Needle Actuation	109
4.5.4. Injectors	110
4.6. Functions of CR Injection Systems	112
4.7. Control of CRS	115
4.7.1. Electronic Control Layout	115
4.7.2. ECU Control Functions	116
4.7.2.1. Pressure Control	116
4.7.2.2. Injection Control	117
4.7.2.3. Drift Compensation	118
4.7.2.4. Control of Multiple Injections	118
4.8. Fuel Injection for Clean Diesel Engines	119
4.8.1. Injection Timing	119
4.8.1.1. NO _x Emissions Control	119
4.8.1.2. Thermal Management	120
4.8.2. Injection Pressure	121
4.8.3. Multiple Injections	123
4.8.3.1. Pilot Injections	123
4.8.3.2. Post Injections	124
4.8.3.3. After Injections	126
4.8.4. Rate Shaping	127
Additional Resources	128
References	129
CHAPTER 5	
Combustion in Diesel Engines	135
5.1. Introduction	135
5.2. Combustion Stoichiometry	137
5.2.1. Fuel Composition	137
5.2.2. Stoichiometric Ratio in Combustion	138
5.3. Heat Release Rates in DI Engines	138
5.4. Three Phases of Diesel Combustion	139
5.4.1. Overview	139
5.4.2. Ignition Delay	140
5.4.3. Premixed Combustion	142
5.4.4. Rate-Controlled Combustion	143
5.4.4.1. Late Combustion	144

5.5. Conceptual Diesel Combustion Model	<u>144</u>
5.5.1. Evolution of Diesel Combustion Model	<u>144</u>
5.5.2. Conceptual Model of Conventional Diesel Combustion	<u>145</u>
5.5.3. Mixing Controlled (Diffusion) Flame	<u>148</u>
5.6. Flame Lift-Off	<u>149</u>
5.7. ϕ-T Maps	<u>150</u>
5.8. Combustion-Generated Noise	<u>152</u>
Additional Resources	<u>153</u>
References	<u>153</u>

CHAPTER 6

Emission Formation in Diesel Engines	<u>155</u>
6.1. Introduction	<u>155</u>
6.2. Nitrogen Oxides	<u>156</u>
6.2.1. Mechanism of NO_x Formation	<u>156</u>
6.2.1.1. Thermal NO	<u>157</u>
6.2.1.2. Nitrous Oxide Pathway	<u>157</u>
6.2.1.3. NO ₂ Formation	<u>159</u>
6.2.1.4. Nitric Acid	<u>161</u>
6.2.1.5. Other Potential Mechanisms	<u>162</u>
6.2.2. Effects of Engine Variables on NO_x Emissions	<u>162</u>
6.2.2.1. Engine Speed	<u>162</u>
6.2.2.2. Fuel-Air Ratio	<u>163</u>
6.2.2.3. Combustion Phasing	<u>163</u>
6.2.2.4. Fuel Properties	<u>165</u>
6.2.2.5. Soot	<u>165</u>
6.2.2.6. Swirl	<u>166</u>
6.2.2.7. Intake Charge Dilution	<u>166</u>
6.3. Particulate Matter	<u>166</u>
6.3.1. Sources of PM Emission	<u>166</u>
6.3.2. Carbonaceous Particulate Release and Oxidation	<u>167</u>
6.3.3. Other Sources of Particulate Matter	<u>168</u>
6.3.4. Smoke in Diesel Engines	<u>169</u>
6.4. Unburned HCs	<u>170</u>
6.4.1. Sources of HCs	<u>170</u>
6.4.2. Effects of Engine Variables on HC Emissions	<u>171</u>
6.4.2.1. F/A Ratio	<u>171</u>
6.4.2.2. Engine Load	<u>172</u>
6.4.2.3. After Injections and Secondary Injections	<u>172</u>

6.4.2.4. Cold Start and Misfires	173
6.4.2.5. Turbocharging	173
6.4.2.6. Nozzle Opening Pressure	173
6.4.2.7. Injection Timing	174
6.4.2.8. Intake Swirl	175
6.4.2.9. Fuel System Design	175
6.5. Carbon Monoxide	175
Additional Resources	176
References	176
Part: II Diesel Emissions	179
<hr/>	
CHAPTER 7	
Characterization of Emissions	181
7.1. What Are Diesel Emissions?	181
7.1.1. Overview	181
7.1.2. Regulated Emissions	183
7.1.2.1. Pollutant Emissions	183
7.1.2.2. Greenhouse Gases	185
7.1.3. Unregulated Emissions	185
7.2. Gaseous Emissions	187
7.2.1. Nitrogen Oxides—NO _x	187
7.2.2. Hydrocarbons—HC	189
7.2.3. Carbon Monoxide—CO	190
7.2.4. Sulfur Dioxide—SO ₂	190
7.2.5. Nitrous Oxide—N ₂ O	192
7.2.6. Hydrogen—H ₂	192
7.3. Diesel Particulate Matter	193
7.3.1. What Are Diesel Particulates?	193
7.3.2. Composition of Exhaust Particulates	197
7.3.3. Solid Fraction	200
7.3.3.1. Carbon	200
7.3.3.2. Ash	203
7.3.4. Organic Fraction	204
7.3.4.1. Composition	204
7.3.4.2. Polynuclear Aromatic Hydrocarbons	206
7.3.4.3. Dioxins	208
7.3.5. Sulfate Particulates	209

7.4. Diesel Particle Size and Size Distribution	<u>211</u>
7.4.1. Introduction	<u>211</u>
7.4.2. Impact of Engine Technology	<u>213</u>
7.4.3. Impact of Particulate Sampling	<u>215</u>
7.4.4. Nanoparticles Composition	<u>217</u>
Additional Resources	<u>219</u>
References	<u>219</u>

CHAPTER 8

Health and Environmental Effects 223

8.1. Introduction	<u>223</u>
8.2. Emission Inventories	<u>225</u>
8.2.1. Overview	<u>225</u>
8.2.2. Emissions of Criteria Air Pollutants	<u>226</u>
8.2.2.1. Emission Trends	<u>226</u>
8.2.2.2. Contributions from Combustion Engines	<u>227</u>
8.2.3. GHG Emissions	<u>231</u>
8.3. Exposure to Diesel Emissions	<u>232</u>
8.3.1. Introduction	<u>232</u>
8.3.2. Exposure Estimation	<u>233</u>
8.3.3. Particulate Matter	<u>234</u>
8.3.3.1. Ambient Exposure	<u>234</u>
8.3.3.2. Occupational Exposure	<u>235</u>
8.3.4. Polynuclear Aromatic Hydrocarbons	<u>236</u>
8.3.5. Hydrocarbons and Aldehydes	<u>237</u>
8.4. Health Effects of Diesel Emissions	<u>238</u>
8.4.1. Introduction	<u>238</u>
8.4.2. Particulate Emissions	<u>240</u>
8.4.2.1. Particle Properties and Toxicity	<u>240</u>
8.4.2.2. Non-cancer Health Effects	<u>244</u>
8.4.2.3. Carcinogenicity of Diesel Exhaust	<u>246</u>
8.4.3. Hydrocarbons—HC	<u>249</u>
8.4.4. Carbon Monoxide—CO	<u>249</u>
8.4.4.1. Acute Poisoning	<u>249</u>
8.4.4.2. Air Pollution Effects	<u>251</u>
8.4.5. Nitrogen Oxides—NO _x	<u>252</u>
8.4.5.1. Nitric Oxide	<u>252</u>
8.4.5.2. Nitrogen Dioxide	<u>252</u>
8.4.6. Sulfur Dioxide—SO ₂	<u>253</u>

8.5. Environmental Effects of Emissions	<u>253</u>
8.5.1. Pollutants and Air Quality	<u>253</u>
8.5.2. Ozone and Photochemical Smog	<u>256</u>
8.5.2.1. Atmospheric Ozone	<u>256</u>
8.5.2.2. Ground-Level Ozone and Smog	<u>257</u>
8.5.2.3. Secondary Organic Aerosols	<u>257</u>
8.5.2.4. Weekend Ozone Effect	<u>259</u>
8.5.3. Global Warming	<u>261</u>
8.5.3.1. Introduction	<u>261</u>
8.5.3.2. Climate-Forcing Agents	<u>262</u>
8.5.3.3. Radiative Forcing Estimates	<u>265</u>
8.5.3.4. Role of Black Carbon	<u>265</u>
8.5.4. Acid Rain	<u>267</u>
8.5.5. Reduced Atmospheric Visibility	<u>267</u>
Additional Resources	<u>268</u>
References	<u>268</u>

CHAPTER 9

Measurement of Emissions	<u>275</u>
9.1. Introduction	<u>275</u>
9.2. Emission Test Cycles	<u>277</u>
9.3. Exhaust Gas Sampling and Conditioning	<u>281</u>
9.3.1. Overview	<u>281</u>
9.3.2. Dilution Systems	<u>282</u>
9.3.2.1. Classification	<u>282</u>
9.3.2.2. Constant Volume Sampling	<u>282</u>
9.3.2.3. Partial Flow Dilution System	<u>284</u>
9.3.2.4. Constant Dilution Ratio Systems	<u>285</u>
9.3.3. Sample Conditioning	<u>286</u>
9.3.3.1. Measurements of Gas Species	<u>286</u>
9.3.3.2. Solid Particle Measurement	<u>286</u>
9.3.4. Sampling Issues	<u>289</u>
9.4. Gas Phase Measurements	<u>291</u>
9.4.1. Techniques of Gas Analysis	<u>291</u>
9.4.1.1. Overview	<u>291</u>
9.4.1.2. Nondispersive Infra-Red	<u>292</u>
9.4.1.3. Nondispersive Ultraviolet	<u>293</u>
9.4.1.4. Flame Ionization Detector	<u>293</u>
9.4.1.5. Chemiluminescence Analyzer	<u>294</u>
9.4.1.6. Fourier Transform Infra-Red	<u>294</u>

9.4.1.7. Laser Diode Spectrometer	<u>295</u>
9.4.1.8. Magnetic Methods	<u>295</u>
9.4.2. Analysis of Engine Exhaust Gases	<u>296</u>
9.4.2.1. Carbon Monoxide and Carbon Dioxide	<u>296</u>
9.4.2.2. Hydrocarbons	<u>296</u>
9.4.2.3. Nitrogen Oxides	<u>297</u>
9.4.2.4. Ammonia	<u>297</u>
9.5. Particulate Measurements	<u>298</u>
9.5.1. Introduction	<u>298</u>
9.5.1.1. Measurement of “Wet” and “Dry” Particles	<u>298</u>
9.5.1.2. Particle Measurement Parameters	<u>300</u>
9.5.1.3. Types of Measuring Techniques	<u>301</u>
9.5.2. Collecting Methods	<u>302</u>
9.5.2.1. Sample Collection	<u>302</u>
9.5.2.2. Gravimetric Analysis	<u>303</u>
9.5.2.3. Particulate Composition	<u>305</u>
9.5.2.4. Thermal Mass Analysis	<u>306</u>
9.5.2.5. Analysis of Other PM Properties	<u>307</u>
9.5.3. In-Situ Methods	<u>308</u>
9.5.3.1. Particle Number Concentration	<u>308</u>
9.5.3.2. Particle Size and Size Distributions	<u>309</u>
9.5.3.3. DC Sensors for Surface Area and Other Parameters	<u>318</u>
9.5.3.4. Particle Mass and Black Carbon	<u>319</u>
9.5.3.5. Particle Composition	<u>322</u>
9.5.3.6. Field Measurement of Particle Aerosols	<u>323</u>
9.5.4. Smoke Opacity	<u>324</u>
9.5.4.1. Introduction	<u>324</u>
9.5.4.2. Definitions	<u>325</u>
9.5.4.3. Opacity Meters	<u>325</u>
9.5.4.4. Smoke Number Meters	<u>326</u>
9.5.4.5. Opacity and PM Mass Fraction	<u>327</u>
9.6. Real-World Emission Testing	<u>328</u>
9.6.1. PEMS Testing	<u>328</u>
9.6.2. Remote Emission Sensing	<u>329</u>
9.7. Measurement of Ambient Diesel Aerosol	<u>331</u>
9.7.1. Aerosol Sampling and Analysis	<u>331</u>
9.7.2. Measurement in Ambient Air	<u>332</u>
9.7.3. Measurement in Occupational Health Settings	<u>334</u>
9.7.4. Measurement in Mines	<u>335</u>
Additional Resources	<u>337</u>
References	<u>337</u>

CHAPTER 10

Emission Regulations	<u>349</u>
10.1. Historical Background	<u>349</u>
10.2. Types of Emission Regulations	<u>352</u>
10.3. Emission Test Cycles	<u>354</u>
10.3.1. Overview	<u>354</u>
10.3.2. US Heavy-Duty FTP Transient Cycle	<u>354</u>
10.3.3. US FTP-75 Cycle	<u>356</u>
10.3.4. European Stationary Cycle	<u>356</u>
10.3.5. European Transient Cycle	<u>358</u>
10.3.6. World Harmonized Stationary Cycle (WHSC)	<u>359</u>
10.3.7. World Harmonized Transient Cycle (WHTC)	<u>360</u>
10.3.8. ECE 15 + EUDC/NEDC	<u>361</u>
10.3.9. Worldwide Harmonized Light Vehicles Test Cycles	<u>363</u>
10.3.10. ISO 8178	<u>364</u>
10.3.11. Nonroad Transient Cycle (NRTC)	<u>364</u>
10.4. Selected Diesel Emission Standards	<u>366</u>
10.4.1. Overview	<u>366</u>
10.4.2. United States	<u>368</u>
10.4.2.1. Heavy-Duty Onroad Engines	<u>368</u>
10.4.2.2. Mobile Nonroad Diesel Engines	<u>372</u>
10.4.3. European Union	<u>373</u>
10.4.3.1. Heavy-Duty Onroad Engines	<u>373</u>
10.4.3.2. Mobile Nonroad Engines	<u>374</u>
10.5. Selected Ambient Air and Occupational Health Regulations	<u>375</u>
Additional Resources	<u>377</u>
References	<u>377</u>
Part III Diesel Fuels	<u>379</u>

CHAPTER 11

Petroleum Diesel Fuel	<u>381</u>
11.1. Crude Oil Refining	<u>381</u>
11.2. Components of Diesel Fuel	<u>383</u>
11.3. Diesel Fuel Properties	<u>386</u>
11.3.1. Overview	<u>386</u>

11.3.2. Ignition Quality	<u>387</u>
11.3.3. Density and Heating Value	<u>389</u>
11.3.4. Volatility—Distillation Temperature	<u>390</u>
11.3.5. Viscosity	<u>391</u>
11.3.6. Low-Temperature Operability Properties	<u>392</u>
11.3.7. Flash Point	<u>394</u>
11.3.8. Engine and Components Wear Properties	<u>395</u>
11.3.8.1. Lubricity	<u>395</u>
11.3.8.2. Cleanliness	<u>397</u>
11.3.8.3. Acidity	<u>397</u>
11.3.9. Fuel Stability	<u>397</u>
11.3.9.1. Storage Stability	<u>397</u>
11.3.9.2. Thermal Stability	<u>398</u>
11.3.10. Sulfur	<u>398</u>
11.4. Ultra-Low Sulfur Diesel (ULSD)	<u>399</u>
11.4.1. Sulfur Effects on Diesel Engines	<u>399</u>
11.4.2. Reduction of Sulfur in Diesel Fuels	<u>399</u>
11.4.3. Ultra-Low Sulfur Diesel Issues	<u>401</u>
11.4.3.1. Transition to ULSD Fuel	<u>401</u>
11.4.3.2. Fuel Economy	<u>402</u>
11.4.3.3. Seal Compatibility	<u>402</u>
11.4.3.4. Deposits	<u>402</u>
11.4.3.5. Corrosion in Storage Systems	<u>402</u>
11.4.3.6. Static Dissipation	<u>403</u>
11.5. Diesel Fuel Additives	<u>403</u>
11.6. Typical Specifications	<u>405</u>
11.7. Fuel Properties and Emissions	<u>407</u>
11.7.1. Introduction	<u>407</u>
11.7.2. Heavy-Duty Diesel Engines	<u>408</u>
11.7.2.1. Overview	<u>408</u>
11.7.2.2. Sulfur	<u>409</u>
11.7.2.3. Cetane Number	<u>410</u>
11.7.2.4. Aromatics	<u>410</u>
11.7.2.5. Density	<u>411</u>
11.7.2.6. Volatility	<u>411</u>
11.7.2.7. Oxygenates	<u>412</u>
11.7.3. Light-Duty Diesel Engines	<u>412</u>
11.7.4. Engines with Emission Aftertreatment	<u>413</u>
Additional Resources	<u>414</u>
References	<u>414</u>

CHAPTER 12

Alternative Diesel Fuels	<u>417</u>
12.1. Alternative Fuel Options	<u>417</u>
12.2. Energy Efficiency and Emissions	<u>420</u>
12.2.1. Life Cycle Analysis	<u>420</u>
12.2.2. Well-to-Tank	<u>420</u>
12.2.3. Tank-to-Wheel	<u>421</u>
12.2.4. Well-to-Wheel	<u>422</u>
12.3. Alcohol Fuels	<u>423</u>
12.3.1. Ethanol	<u>423</u>
12.3.2. Butanol	<u>425</u>
12.3.3. Methanol	<u>425</u>
12.4. Biodiesel	<u>425</u>
12.4.1. What Is Biodiesel	<u>425</u>
12.4.2. Life Cycle Effects: Energy Efficiency and GHG Emissions	<u>427</u>
12.4.3. Commercial Status	<u>429</u>
12.4.4. Manufacturing Process	<u>431</u>
12.4.5. Properties and Specifications	<u>433</u>
12.4.5.1. Standard Specifications	<u>433</u>
12.4.5.2. Properties: Comparison with Petrodiesel	<u>434</u>
12.4.5.3. Fuel Quality Concerns	<u>436</u>
12.4.6. Engine Emissions	<u>436</u>
12.4.7. Compatibility of Biodiesel with Petroleum Diesel Engines	<u>441</u>
12.4.7.1. Material Compatibility	<u>441</u>
12.4.7.2. Engine Oil Dilution	<u>441</u>
12.4.7.3. Fuel System Compatibility	<u>443</u>
12.4.7.4. Diesel Aftertreatment Effects	<u>444</u>
12.4.7.5. Manufacturers' Position	<u>446</u>
12.5. Renewable Diesel	<u>446</u>
12.5.1. Introduction	<u>446</u>
12.5.2. Oleochemical Production	<u>448</u>
12.5.3. Commercial Status	<u>449</u>
12.5.4. Fuel Properties and Emissions	<u>450</u>
12.6. Synthetic Fuels	<u>451</u>
12.6.1. Synthesis Gas	<u>451</u>
12.6.2. Fisher-Tropsch Process	<u>452</u>
12.6.2.1. Historical Background	<u>452</u>
12.6.2.2. FT Process Description	<u>453</u>
12.6.2.3. Biomass-to-Liquid Processes	<u>454</u>

12.6.3. FT Fuel Properties	455
12.6.4. Life Cycle Analysis	455
12.6.5. Emissions with Synthetic Fuel	458
12.7. Dimethyl Ether	460
12.7.1. Introduction	460
12.7.2. Properties and Specifications	460
12.7.3. DME Engines	463
12.7.4. DME Fuel and Emissions	463
12.8. Natural Gas/Methane	464
12.8.1. Introduction	464
12.8.2. Natural Gas Properties	464
12.8.3. Utilization of Natural Gas	466
12.8.4. Methane Emissions	468
12.8.4.1. Methane as a Climate Change Gas	468
12.8.4.2. Methane as a Pollutant	471
12.8.4.3. Methane Emissions from NG Engines	471
12.8.5. Pollutant Emissions	475
12.8.5.1. Regulated Emissions	475
12.8.5.2. Unregulated Emissions	477
12.9. Hydrogen	478
12.10. Ammonia	480
Additional Resources	482
References	483

CHAPTER 13

Diesel Engine Lubricants	495
13.1. Introduction	495
13.2. Lubricant Formulation	496
13.2.1. Base Oil	496
13.2.2. Additives	496
13.3. Viscosity	497
13.3.1. Overview	497
13.3.2. SAE Viscosity Grades	498
13.4. Emissions Performance	500
13.5. Fuel Economy	501
13.6. Lubricating Oil Consumption	505
13.6.1. Overview	505

13.6.2. Evolution of Lubricating Oil Consumption Rates	<u>507</u>
13.6.3. Proportion of Consumed Oil that Survives to Contribute to PM	<u>508</u>
Additional Resources	<u>509</u>
References	<u>509</u>
Part IV Engine Efficiency and Emission Control Technologies	<u>511</u>

CHAPTER 14

Efficiency Technologies	<u>513</u>
14.1. Introduction	<u>513</u>
14.2. Engine Efficiency Technologies	<u>514</u>
14.2.1. Distribution of Fuel Energy In the Engine	<u>514</u>
14.2.2. Improving Thermodynamic Efficiency	<u>515</u>
14.2.3. Improving Gas Exchange Efficiency	<u>517</u>
14.2.4. Reducing Mechanical Losses	<u>518</u>
14.2.5. Engine Materials and Coatings	<u>521</u>
14.3. Alternatives to the Conventional Internal Combustion Engine	<u>521</u>
14.3.1. Two-Stroke Engines	<u>521</u>
14.3.2. Opposed Piston Two-Stroke Engines	<u>522</u>
14.3.3. Six-Stroke Engines	<u>523</u>
14.3.4. Split Cycle Engines	<u>524</u>
14.3.5. Gas Turbines	<u>526</u>
14.3.6. Stirling Engine	<u>527</u>
14.3.7. Fuel Cells	<u>527</u>
14.4. Transmissions	<u>529</u>
14.5. Hybridization and Electrification	<u>530</u>
14.6. Vehicle Efficiency Technologies	<u>532</u>
Additional Resources	<u>535</u>
References	<u>535</u>

CHAPTER 15

Engine Emission Control	<u>539</u>
15.1. Introduction	<u>539</u>
15.1.1. Pollutant Emissions	<u>539</u>
15.1.2. GHG Emissions and Fuel Economy	<u>540</u>
15.2. Emission Control Technologies	<u>541</u>
15.3. In-Cylinder Emission Control	<u>543</u>

15.3.1. Diesel NO_x-PM Trade-Off	<u>543</u>
15.3.2. Charge Management	<u>545</u>
15.3.2.1. Charge Pressure	<u>545</u>
15.3.2.2. Charge Temperature	<u>547</u>
15.3.2.3. Charge Composition	<u>548</u>
15.3.2.4. Variable Valve Actuation	<u>549</u>
15.3.3. Fuel Supply	<u>549</u>
15.3.3.1. Injection Timing	<u>549</u>
15.3.3.2. Injection Pressure	<u>550</u>
15.3.3.3. Multiple Injections and Injection Rate Shaping	<u>551</u>
15.3.3.4. Fuel Injector Nozzles	<u>552</u>
15.3.4. Combustion	<u>553</u>
15.3.4.1. Combustion Chamber	<u>553</u>
15.3.4.2. Compression Ratio	<u>556</u>
15.3.4.3. Low-Temperature Combustion	<u>559</u>
15.4. Crankcase Emissions	<u>560</u>
15.5. Emission Aftertreatment	<u>561</u>
15.5.1. CO and HC Aftertreatment	<u>561</u>
15.5.2. PM Aftertreatment	<u>562</u>
15.5.2.1. Diesel Oxidation Catalyst	<u>562</u>
15.5.2.2. Particle Oxidation Catalyst	<u>562</u>
15.5.2.3. Particulate Filters	<u>562</u>
15.5.2.4. Other PM Aftertreatment Technologies	<u>562</u>
15.5.3. NO_x Aftertreatment	<u>563</u>
15.5.3.1. Selective Catalytic Reduction	<u>563</u>
15.5.3.2. NO _x Adsorbers	<u>563</u>
15.5.3.3. Lean NO _x Catalyst	<u>564</u>
15.5.3.4. Other NO _x Aftertreatment Technologies	<u>564</u>
15.5.4. SO_x Aftertreatment	<u>564</u>
15.6. Control and System Integration	<u>565</u>
15.6.1. Electronic Engine Control	<u>565</u>
15.6.2. Engine-Aftertreatment Integration	<u>565</u>
15.6.3. On-Board Diagnostics	<u>566</u>
15.7. Fuels and Lubricants	<u>566</u>
15.7.1. Fuel and Lubricant Quality	<u>566</u>
15.7.2. Oil Control	<u>567</u>
15.7.3. Alternative Fuels	<u>567</u>
15.8. Costs	<u>568</u>
15.9. Emission Control from In-Use Engines	<u>569</u>
Additional Resources	<u>570</u>
References	<u>570</u>

CHAPTER 16

Exhaust Gas Recirculation	<u>575</u>
16.1. Introduction	<u>575</u>
16.2. EGR for NO_x Reduction	<u>577</u>
16.2.1. Light-Duty Engines	<u>578</u>
16.2.2. Heavy-Duty Engines	<u>578</u>
16.2.3. Nonroad Engines	<u>579</u>
16.2.4. Marine Engines	<u>579</u>
16.3. Principle of Operation	<u>579</u>
16.3.1. EGR Rate	<u>579</u>
16.3.2. Effect on Air-Fuel Ratio	<u>580</u>
16.3.3. How EGR Reduces NO _x	<u>580</u>
16.3.4. Combustion Impacts	<u>584</u>
16.3.5. EGR Cooling	<u>586</u>
16.4. EGR System Configurations	<u>587</u>
16.4.1. High-Pressure Loop EGR	<u>587</u>
16.4.2. Low-Pressure Loop EGR	<u>590</u>
16.4.3. Hybrid EGR Systems	<u>591</u>
16.4.4. Internal EGR	<u>592</u>
16.4.5. Dedicated EGR	<u>593</u>
16.5. Effect of EGR on Emissions and Engine Performance	<u>594</u>
16.5.1. NO _x Reduction	<u>594</u>
16.5.2. NO ₂ Emissions	<u>597</u>
16.5.3. Particulate Emissions	<u>597</u>
16.5.4. Particle Number Emissions	<u>600</u>
16.5.5. Fuel Consumption	<u>601</u>
16.6. EGR Systems	<u>601</u>
16.6.1. Heavy-Duty Engines	<u>602</u>
16.6.2. Light-Duty Engines	<u>604</u>
16.6.3. Design Considerations	<u>604</u>
16.7. EGR Control	<u>606</u>
16.7.1. Sensors	<u>607</u>
16.7.2. Control Inputs and Outputs	<u>608</u>
16.7.3. Controller Structure	<u>610</u>
16.7.3.1. Open-Loop Control	<u>610</u>
16.7.3.2. Closed-Loop Control	<u>610</u>
Additional Resources	<u>613</u>
References	<u>613</u>

CHAPTER 17

Waste Heat Recovery	<u>617</u>
17.1. Introduction	<u>617</u>
17.2. Heat Exchangers	<u>621</u>
17.2.1. Integrated Exhaust Manifold	<u>621</u>
17.2.2. Exhaust Heat Exchanger	<u>622</u>
17.2.3. Thermal Storage	<u>623</u>
17.2.4. Optimization of Waste Heat Utilization	<u>623</u>
17.3. Bottoming Cycles	<u>624</u>
17.3.1. Rankine Cycles	<u>624</u>
17.3.2. Brayton Cycles	<u>626</u>
17.4. Turbocompounding	<u>627</u>
17.5. Thermoelectrics	<u>630</u>
17.6. Thermochemical Recuperation	<u>633</u>
17.7. Thermoacoustic Converters	<u>634</u>
Additional Resources	<u>637</u>
References	<u>637</u>

CHAPTER 18

Controls for Modern Diesel Engines	<u>641</u>
18.1. Introduction	<u>641</u>
18.2. Sensors	<u>642</u>
18.2.1. Physical Sensors	<u>642</u>
18.2.2. Virtual Sensors	<u>643</u>
18.3. Basic Operating Principles of the Control System	<u>644</u>
18.3.1. Open-Loop Control Systems	<u>644</u>
18.3.2. Closed-Loop Control Systems	<u>645</u>
18.4. Diesel Engine Control	<u>647</u>
18.4.1. Fuel Quantity	<u>647</u>
18.4.2. Fuel Injection Timing and Pressure	<u>647</u>
18.4.3. Boost Pressure	<u>648</u>
18.4.4. EGR Control	<u>648</u>
18.5. Model-Based Control Systems	<u>648</u>
18.5.1. System Elements	<u>649</u>
18.5.2. Some Principles of Modeling	<u>650</u>
18.5.3. Discrete and Continuous Models	<u>650</u>
18.5.4. Data Conversion and Diagnostics Models	<u>652</u>

18.6. Data Communication Networks	<u>653</u>
18.7. Challenges in Engine Control Systems	<u>654</u>
18.8. Neural Networks	<u>655</u>
Additional Resources	<u>658</u>
References	<u>658</u>
Part V Exhaust Gas Aftertreatment	<u>659</u>

CHAPTER 19

Emission Control Catalysts	<u>661</u>
19.1. Catalytic Conversion of Pollutants	<u>661</u>
19.1.1. Background	<u>661</u>
19.1.2. Catalytic Reactors	<u>663</u>
19.1.3. Conversion of Pollutants: Basic Terms	<u>665</u>
19.1.3.1. Conversion Efficiency	<u>665</u>
19.1.3.2. Light-Off Temperature	<u>665</u>
19.1.3.3. Catalyst Window	<u>665</u>
19.1.3.4. Space Velocity	<u>666</u>
19.1.3.5. Noble Metal Loading	<u>666</u>
19.2. Catalyst Fundamentals	<u>667</u>
19.2.1. Chemical Reaction Kinetics	<u>667</u>
19.2.2. Definitions and Basic Terms	<u>668</u>
19.2.2.1. Catalyst Definition	<u>668</u>
19.2.2.2. Activity and Selectivity	<u>669</u>
19.2.2.3. Classification of Catalyst Systems	<u>669</u>
19.2.2.4. Heterogeneous Catalyst	<u>670</u>
19.2.3. Conversion Rate in Heterogeneous Catalyst	<u>671</u>
19.2.4. Catalyst Deactivation	<u>675</u>
19.2.4.1. Catalyst Durability Requirements	<u>675</u>
19.2.4.2. Modes of Catalyst Deactivation	<u>676</u>
19.2.4.3. Thermal Deactivation	<u>677</u>
19.2.4.4. Poisoning	<u>677</u>
19.2.4.5. Deactivation Modes and Conversion	<u>678</u>
19.2.4.6. Restoring Catalyst Activity	<u>679</u>
19.2.4.7. Determination of Catalyst Durability	<u>680</u>
19.3. Cellular Monolith Substrates	<u>681</u>
19.3.1. Catalyst Substrates	<u>681</u>
19.3.2. Cellular Properties of Monoliths	<u>682</u>

19.3.3. Substrate Configuration and Performance	684
19.3.4. Catalyst Pressure Drop	686
19.4. Ceramic Catalyst Substrates	688
19.4.1. Introduction	688
19.4.2. Material Characterization Parameters	689
19.4.2.1. Overview	689
19.4.2.2. Thermal Expansion and Thermal Strain	689
19.4.2.3. Elastic Modulus and Thermal Stress	690
19.4.2.4. Strength	690
19.4.2.5. Fatigue	692
19.4.2.6. Thermal Shock Parameter	692
19.4.3. Cordierite	693
19.4.4. Commercial Substrates	693
19.5. Metallic Catalyst Substrates	696
19.5.1. Introduction	696
19.5.2. Substrate Materials	696
19.5.3. Substrate Designs	698
19.5.3.1. Overview	698
19.5.3.2. Uncoated Foil Designs	699
19.5.3.3. Catalyst-Coated Foil Designs	701
19.5.4. Specialized Designs	703
19.5.4.1. Turbulent Flow Catalysts	703
19.5.4.2. Particle Oxidation Catalysts (POC)	704
19.5.4.3. Electrically Heated Catalysts (EHC)	704
19.6. Catalytic Coating and Materials	705
19.6.1. Introduction	705
19.6.2. Catalyst Coating	707
19.6.2.1. Washcoat Technology	707
19.6.2.2. Segregated Washcoats	709
19.6.2.3. Zone Coating	710
19.6.2.4. Single Atom Catalysts	711
19.6.3. Catalytic Materials	712
19.6.3.1. Aluminum Oxide	712
19.6.3.2. Silicon Oxide	713
19.6.3.3. Cerium Dioxide	713
19.6.3.4. Zirconium Oxide	714
19.6.3.5. Titanium Dioxide	714
19.6.3.6. Zeolites	714
19.7. Catalytic Converters	715
19.7.1. Introduction	715
19.7.2. Packaging Materials	716
19.7.2.1. Overview	716

19.7.2.2. Ceramic Mats	717
19.7.2.3. Wire Mesh	719
19.7.2.4. End Seals	719
19.7.2.5. Steel	719
19.7.3. Mounting System Design	720
19.7.4. Canning Methods	722
19.7.4.1. Overview	722
19.7.4.2. Clamshell	724
19.7.4.3. Tourniquet	725
19.7.4.4. Shoebox	727
19.7.4.5. Stuffing	727
19.7.4.6. Swaging	727
19.7.5. Header Design	728
19.7.6. Converter Testing	729
19.7.7. Integrated Aftertreatment Systems	730
19.7.7.1. Catalytic Mufflers	730
19.7.7.2. Single-Module Aftertreatment Systems	731
References	732

CHAPTER 20

Diesel Catalysts	737
20.1. Catalyst Technologies	737
20.1.1. Overview	737
20.1.2. Oxidation Catalysts	738
20.1.3. NO _x Reduction Catalysts	739
20.1.3.1. Reduction of NO _x in Lean Exhaust	739
20.1.3.2. Decomposition of Nitric Oxide	739
20.1.3.3. HC-SCR Catalyst	739
20.1.3.4. NO _x Adsorber Catalysts	740
20.1.3.5. Ammonia-SCR Catalysts	741
20.1.3.6. Comparison of Catalyst Technologies	741
20.2. Diesel Oxidation Catalyst	742
20.2.1. Catalytic Reactions	742
20.2.2. Catalyst Types and Functionality	743
20.2.3. Emission Performance	745
20.2.3.1. CO and HC Performance	745
20.2.3.2. Nitrogen Oxides Performance	747
20.2.3.3. Particulate Matter Performance	750
20.2.3.4. Sulfate Formation and DOC Selectivity	755
20.2.3.5. Effect on Unregulated Emissions	758

20.2.4. DOC Applications	760
20.2.4.1. Catalysts for PM Control	760
20.2.4.2. NO ₂ Generation and Heat-Up Catalysts	764
20.2.5. DOC Deactivation	766
20.2.5.1. Modes of Deactivation	766
20.2.5.2. Thermal Deactivation	767
20.2.5.3. Catalyst Poisoning	768
20.2.5.4. PGM Oxidation	770
20.3. Particle Oxidation Catalysts	770
20.3.1. Introduction	770
20.3.2. POC Construction	771
20.3.3. Operation and Emissions	772
20.4. Selective Catalytic Reduction	774
20.4.1. Historical Background	774
20.4.2. Reductants and Catalytic Reactions	775
20.4.2.1. Ammonia	775
20.4.2.2. Urea	778
20.4.3. SCR Catalysts	782
20.4.3.1. Overview	782
20.4.3.2. Pt Catalysts	784
20.4.3.3. Vanadia/Titania Catalysts	784
20.4.3.4. Zeolite Catalysts	785
20.4.3.5. Other Catalysts	789
20.4.4. Impact of Exhaust Gas Species on SCR Catalysis	789
20.4.4.1. Nitrogen Dioxide	789
20.4.4.2. Hydrocarbons	791
20.4.4.3. Sulfur Compounds	791
20.4.5. Auxiliary Catalysts	794
20.4.5.1. Ammonia Slip Catalyst	794
20.4.5.2. Urea Hydrolysis Catalyst	795
20.4.6. SCR Systems for Diesel Engines	796
20.4.6.1. System Schematic	796
20.4.6.2. Urea Dosing and Injection Systems	797
20.4.6.3. Urea Consumption and Replenishment	802
20.4.6.4. Emission Performance	803
20.4.6.5. DPF Integration	808
20.4.6.6. Low-Temperature Operation	811
20.5. NOx Adsorbers	813
20.5.1. Terms and Definitions	813
20.5.2. Principle of Operation	814
20.5.3. Chemical Reactions	816
20.5.4. Catalyst Systems	818

20.5.4.1. NO _x Storage Components	818
20.5.4.2. Washcoat	820
20.5.4.3. Noble Metals	820
20.5.5. NO_x Conversion Efficiency	821
20.5.6. Regeneration	822
20.5.6.1. Overview	822
20.5.6.2. Reductant Evolution	823
20.5.6.3. Product Selectivity	824
20.5.7. Sulfur Effects	826
20.5.7.1. Inhibition by Sulfur	826
20.5.7.2. Desulfation	827
20.5.8. Passive NO_x Adsorbers	828
20.5.8.1. Overview	828
20.5.8.2. Catalyst Systems	828
20.5.8.3. Performance	830
20.5.9. NO_x Adsorber Applications	831
20.5.9.1. Configurations	831
20.5.9.2. Example Applications	832
20.6. HC-SCR (Lean NO_x) Catalyst	837
20.6.1. Introduction	837
20.6.2. Chemical Reactions	838
20.6.3. Passive and Active LNC Systems	838
20.6.4. HC-SCR Catalysts	839
20.6.5. Diesel Engine Experience	840
Additional Resources	842
References	842

CHAPTER 21

Diesel Particulate Filters	857
21.1. Introduction	857
21.1.1. Definitions	857
21.1.2. Collection and Regeneration	858
21.1.3. Commercial Status	858
21.2. Principle of Operation	860
21.2.1. Filter Configuration	860
21.2.2. Filtration Efficiency	861
21.2.3. Filtration Mechanisms	861

21.3. Diesel Filter Materials	<u>863</u>
21.3.1. Material Requirements	<u>863</u>
21.3.2. Wall-Flow Monoliths	<u>864</u>
21.3.2.1. Introduction	<u>864</u>
21.3.2.2. Monolith Characterization Parameters	<u>865</u>
21.3.2.3. Materials	<u>873</u>
21.3.2.4. Pressure Drop	<u>880</u>
21.3.3. Other Ceramic Filters	<u>883</u>
21.3.3.1. Wound and Knitted Ceramic Fibers	<u>883</u>
21.3.3.2. Fiber Papers and Fabrics	<u>884</u>
21.3.3.3. Ceramic Foams	<u>884</u>
21.3.4. Metal Filters	<u>884</u>
21.3.4.1. Sintered Metal	<u>884</u>
21.3.4.2. Metal Fiber Filters	<u>886</u>
21.3.4.3. Other Metal Filters	<u>887</u>
21.3.5. Pleated Paper Filters	<u>887</u>
21.4. Regeneration	<u>887</u>
21.4.1. Oxidation of Diesel Soot	<u>887</u>
21.4.1.1. Introduction	<u>887</u>
21.4.1.2. Oxidation by Oxygen	<u>888</u>
21.4.1.3. Oxidation by Nitrogen Dioxide	<u>889</u>
21.4.1.4. Catalyst-Assisted Soot Oxidation	<u>891</u>
21.4.1.5. Soot Ignition Temperature	<u>892</u>
21.4.2. Regeneration as Equilibrium Process	<u>892</u>
21.4.2.1. Soot Mass Balance	<u>892</u>
21.4.2.2. Determination of Balance Temperature	<u>894</u>
21.4.3. Passive Regeneration	<u>896</u>
21.4.4. Active Regeneration	<u>899</u>
21.4.4.1. Overview	<u>899</u>
21.4.4.2. DPF Regeneration Process Using Heat-Up Catalyst	<u>901</u>
21.4.5. Emissions During Regeneration	<u>905</u>
21.4.5.1. Emission Sources	<u>905</u>
21.4.5.2. Example Study with Euro 6d-TEMP Vehicles	<u>907</u>
21.5. Emission Performance	<u>909</u>
21.5.1. Particle Mass	<u>909</u>
21.5.2. Particle Numbers	<u>911</u>
21.5.3. Production Vehicles with DPFs	<u>913</u>
Additional Resources	<u>917</u>
References	<u>917</u>

CHAPTER 22

Diesel Filter Systems	<u>925</u>
22.1. Classification of Systems	<u>925</u>
22.2. Design Considerations	<u>928</u>
22.2.1. Design Targets	<u>928</u>
22.2.2. Regeneration and Durability	<u>929</u>
22.2.3. Fuel Economy Penalty	<u>931</u>
22.3. Passive Filter Systems	<u>932</u>
22.4. Active Filter Systems	<u>933</u>
22.4.1. Overview	<u>933</u>
22.4.2. Regeneration Strategy	<u>934</u>
22.4.2.1. Soot Load Determination	<u>934</u>
22.4.2.2. Start of Regeneration	<u>936</u>
22.4.2.3. Maximum Soot Load	<u>937</u>
22.4.2.4. Regeneration Frequency	<u>937</u>
22.4.2.5. Temperature and Duration of Regeneration	<u>939</u>
22.4.2.6. System Monitoring	<u>939</u>
22.4.2.7. Operator-Assisted Regeneration	<u>940</u>
22.5. Durability and Maintenance	<u>940</u>
22.6. Catalytic Filters	<u>941</u>
22.6.1. Configurations	<u>941</u>
22.6.2. Catalyst Systems	<u>943</u>
22.6.2.1. Catalytic Oxidation of Soot	<u>943</u>
22.6.2.2. DOC Catalysts	<u>946</u>
22.6.2.3. DPF Catalysts	<u>946</u>
22.6.3. Emission Performance	<u>949</u>
22.6.3.1. Particle Filtration Efficiency	<u>949</u>
22.6.3.2. Gaseous Emissions Performance	<u>951</u>
22.6.4. DPF System Design	<u>952</u>
22.6.4.1. Filter Design	<u>952</u>
22.6.4.2. Active vs Passive Regeneration	<u>954</u>
22.6.4.3. DOC/DPF Integration	<u>955</u>
22.7. Filters Using Fuel-Borne Catalysts	<u>955</u>
22.7.1. Introduction	<u>955</u>
22.7.2. Considerations for Using Fuel-Borne Catalyst Systems	<u>957</u>
22.7.2.1. Fuel-Borne Catalyst Formulation	<u>957</u>
22.7.2.2. Potential Issues with FBC Filters	<u>958</u>
22.7.2.3. Fuel Quality	<u>960</u>
22.7.2.4. Gaseous Emissions	<u>960</u>

22.7.3. Metals Used for Fuel-Borne Catalysts	961
22.7.3.1. Catalytic Reactions	961
22.7.3.2. Cerium	961
22.7.3.3. Iron	962
22.7.3.4. Fe/Sr	962
22.7.3.5. Platinum	963
22.7.3.6. Copper	963
22.7.4. Fuel-Borne Catalyst Dosing	963
22.7.5. Commercial FBC/DPF Systems	964
22.8. Filters with Fuel Burners	966
22.8.1. Introduction	966
22.8.1.1. Definitions and Classifications	966
22.8.1.2. Commercial Status	968
22.8.2. Fuel Burner System	969
22.8.2.1. System Schematic	969
22.8.2.2. Burner Design	970
22.8.2.3. Filter Operation and Regeneration	972
22.8.3. Combined Burner-Catalyst Systems	973
22.9. Electrically Regenerated Filters	974
22.9.1. Electric Regeneration	974
22.9.1.1. Methods of Energy Deposition	974
22.9.1.2. Classification of Systems	975
22.9.1.3. Design Considerations	976
22.9.2. Example Filer Systems	976
22.9.2.1. Off-Board Regenerated Filer (ETB)	976
22.9.2.2. Rypos Active Filter System	977
22.9.2.3. SMF-AR Filter System	978
Additional Resources	980
References	980

CHAPTER 23

Exhaust Gas Thermal Management [987](#)

23.1. Introduction	987
23.2. Engine Based Measures	989
23.2.1. Overview	989
23.2.2. Increased Exhaust Losses	991
23.2.3. Decreased AFR	992
23.2.4. Cylinder Deactivation	995
23.2.4.1. Introduction	995

23.2.4.2. Hardware	995
23.2.4.3. Benefits	996
23.2.4.4. Challenges	1001
23.2.4.5. Effect on Catalyst Light-Off	1003
23.2.5. Increased Engine Fuel Consumption	1003
23.2.6. Heat Redistribution	1005
23.2.7. Combinations	1005
23.3. Exhaust System-Based Measures	1007
23.3.1. Overview	1007
23.3.2. Heat-Up Catalyst Systems	1009
23.3.2.1. Introduction	1009
23.3.2.2. System Schematic	1009
23.3.2.3. Controller	1010
23.3.2.4. Heat-Up Catalyst	1011
23.3.2.5. Fuel Delivery System	1012
23.4. Passive Measures	1013
Additional Resources	1014
References	1014
Part VI Engine Systems	1019
CHAPTER 24	
Heavy-Duty Diesel Engine Technology Evolution	1021
24.1. Introduction	1021
24.2. Engine Technologies for Meeting Early Emission Standards	1022
24.3. Engines with Exhaust Aftertreatment	1024
24.4. Fuels and Engine Fluids	1027
24.5. Thermal Efficiency and Fuel Economy	1027
Additional Resources	1028
References	1029
CHAPTER 25	
Heavy-Duty Diesel Engine Technology—US 1990–2004	1031
25.1. Introduction	1031
25.2. NO_x Control Measures	1032
25.3. Fuel Consumption Control Measures	1033

25.4. PM Control Measures	<u>1035</u>
25.4.1. Carbon	<u>1035</u>
25.4.2. Lubricating Oil Organic Fraction	<u>1037</u>
25.4.3. Sulfate	<u>1037</u>
25.5. White Smoke	<u>1037</u>
25.5.1. White Smoke Formation	<u>1037</u>
25.5.2. White Smoke Control	<u>1038</u>
25.5.2.1. Increased Engine Load at Idle	<u>1038</u>
25.5.2.2. Increased Idle Speed	<u>1039</u>
25.5.2.3. Fuel Shut-Off during Initial Crank	<u>1039</u>
25.5.2.4. Intake Air Heating	<u>1039</u>
25.5.2.5. ATA Cooler Bypass	<u>1039</u>
25.6. Engine Design	<u>1040</u>
25.6.1. Four-Stroke Engines	<u>1040</u>
25.6.2. Two-Stroke Engines	<u>1041</u>
25.6.3. Consent Decrees	<u>1041</u>
25.7. Heavy-Duty Engines with EGR	<u>1042</u>
25.7.1. US EPA 2004 Engines	<u>1043</u>
25.7.2. Diesel Oxidation Catalysts	<u>1044</u>
25.7.3. Euro IV Engines	<u>1045</u>
Additional Resources	<u>1046</u>
References	<u>1046</u>

CHAPTER 26

Heavy-Duty Diesel Engines with Aftertreatment 1047

26.1. Introduction	<u>1047</u>
26.2. North American Engines	<u>1048</u>
26.2.1. Manufacturers' Strategies	<u>1048</u>
26.2.1.1. Summary	<u>1048</u>
26.2.1.2. Cummins	<u>1048</u>
26.2.1.3. Navistar	<u>1053</u>
26.2.1.4. Caterpillar	<u>1055</u>
26.2.1.5. Volvo	<u>1056</u>
26.2.1.6. Hino	<u>1058</u>
26.2.2. Chassis Certification of Heavy Pickup Trucks and Vans	<u>1058</u>
26.2.3. On-Board Diagnostics (OBD)	<u>1059</u>
26.2.4. Aftertreatment Systems	<u>1060</u>
26.2.4.1. Model Year 2007–2009	<u>1060</u>
26.2.4.2. Model Year 2010 and Later	<u>1061</u>
26.2.4.3. Model Year 2024 and Later	<u>1065</u>

26.3. European Engines	<u>1066</u>
26.3.1. Emission Strategies	<u>1066</u>
26.3.1.1. Euro V	<u>1066</u>
26.3.1.2. Euro VI	<u>1067</u>
26.3.2. Aftertreatment	<u>1068</u>
26.3.3. Real-World NOx Emissions	<u>1072</u>
26.3.3.1. Euro IV/V	<u>1072</u>
26.3.3.2. Euro VI	<u>1073</u>
Additional Resources	<u>1074</u>
References	<u>1074</u>
Additional Resources	<u>1077</u>
Index	<u>1079</u>
About the Authors	<u>1097</u>