Engine Emissions Measurement Handbook

Other SAE books of interest:

Onboard Diagnostics and Measurement in the Automotive Industry, Shipbuilding and Aircraft Construction

By Michael Palocz-Andresen
(Product Code: R-410)

Diesel Emissions and Their Control

By Magdi K. Khair, W. Addy Majewski
(Product Code: R-303)

Technologies for Near-Zero-Emission Gasoline-Powered Vehicles

By Fuquan Zhao
(Product Code: R-359)

For more information or to order a book, contact SAE International at

400 Commonwealth Drive,
Warrendale, PA 15096-0001, USA;

phone 877-606-7323 (U.S. and Canada only)
or +1-724-776-4970 (outside U.S. and Canada);
fax +1-724-776-0790;

email CustomerService@sae.org;
website <http://books.sae.org>.

Engine Emissions Measurement Handbook

HORIBA Automotive Test Systems

Edited by

Masayuki Adachi and Hiroshi Nakamura

Warrendale, Pennsylvania, USA

400 Commonwealth Drive
Warrendale, PA 15096-0001 USA

E-mail: CustomerService@sae.org
Phone: 877-606-7323 (inside USA and Canada)
+1-724-776-4970 (outside USA)
Fax: +1-724-776-0790

Copyright © 2014 SAE International. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system, distributed, or transmitted, in any form or by any means without the prior written permission of SAE International. For permission and licensing requests, contact SAE Permissions, 400 Commonwealth Drive, Warrendale, PA 15096-0001 USA; email: copyright@sae.org; phone: 724-772-4028; fax: 724-772-9765.

ISBN 978-0-7680-8012-4
SAE Order Number JPF-HOR-002

Library of Congress Cataloging-in-Publication Data

Engine emissions measurement handbook / edited by Masayuki Adachi and Hiroshi Nakamura.

pages cm

Includes bibliographical references.

ISBN 978-0-7680-8012-4

1. Automobiles—Pollution control devices—Testing—Handbooks, manuals, etc. 2. Automobiles—Motors—Exhaust gas—Measurement—Handbooks, manuals, etc. I. Adachi, Masayuki (Engineer), editor. II. Nakamura, Hiroshi (Engineer), editor.

TL214.P6E57 2014

629.25'28—dc23

2013021859

Information contained in this work has been obtained by SAE International from sources believed to be reliable. However, neither SAE International nor its authors guarantee the accuracy or completeness of any information published herein and neither SAE International nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that SAE International and its authors are supplying information, but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

To purchase bulk quantities, please contact:

SAE Customer Service

Email: CustomerService@sae.org
Phone: 877-606-7323 (inside USA and Canada)
+1-724-776-4970 (outside USA)
Fax: +1-724-776-0790

Visit the SAE International Bookstore at

<http://books.sae.org>

Contents

Foreword	xi
Acknowledgments	xiii
Introduction	xv
Chapter 1 Engine Emissions	1
1.1 Characteristics of Engine Exhaust Gas	1
1.1.1 Major Components of Engine Exhaust Gas	1
1.1.2 Units Used for Exhaust Gas Components.	1
1.1.3 Concentration Variations of Exhaust Gas Components	2
1.1.4 Exhaust Gas as Fluid (Physical Characteristics)	2
1.1.4.1 Density	3
1.1.4.2 Viscosity (Coefficient of Viscosity)	3
1.1.4.3 Specific Heat	4
1.1.4.4 Temperature.	4
1.2 Major Air Pollutants in Engine Exhaust.	5
1.2.1 Inorganic Compounds	5
1.2.2 Organic Compounds	6
1.2.2.1 Hydrocarbons	6
1.2.2.2 Alcohols and Carbonyls.	6
1.2.3 Engine Exhaust Particulates	7
1.3 Greenhouse Gases in Exhaust Emissions.	7
References.	7
Appendix A.1 Calculations of Engine Exhaust Gas Composition	9
A.1.1 Combustion Reaction Formula	9
A.1.2 Calculations of Gas Component Concentration	11
A.1.3 Excess Air Ratio and Gas Component Concentration	12
Chapter 2 Gaseous Emissions Measurement	13
2.1 Overview.	13
2.1.1 Direct Sampling Method	13
2.1.1.1 Gas Sampling with the Direct Sampling Method.	14
2.1.1.2 Equations of Mass Emission	14
2.1.2 Dilution Sampling Method	15
2.2 Constant Volume Sampler	15
2.2.1 Overview of the Constant Volume Sampler.	15
2.2.2 System Structure.	16
2.2.2.1 Mixing Tee	16

- 2.2.2.2 Flow Controller 18
 - 2.2.2.3 Gas Sampling Bags 20
 - 2.2.3 Calculation of Mass Emission 21
 - 2.2.4 System Setup and System Check 22
 - 2.2.4.1 Setting the Dilution Flow Rate 22
 - 2.2.4.2 Calibration of the Dilution Flow Rate 24
 - 2.2.4.3 Total System Verification 26
 - 2.3 Measurement of Ultra-Low-Emission Vehicles by the CVS Method 27
 - 2.3.1 Compensation of Background (Dilution Air) 29
 - 2.3.1.1 Active Carbon Filter 29
 - 2.3.1.2 Dilution Air Refiner 29
 - 2.3.1.3 Proportional Ambient Sampling Method 30
 - 2.3.2 Optimization of Dilution Ratio 31
 - 2.3.2.1 Variable-Flow CVS 31
 - 2.3.2.2 Heated CVS 31
 - 2.3.2.3 Dehumidification of the Dilution Air 32
 - 2.3.3 Preventing HC Hang-Up 32
 - 2.3.3.1 Selection of Materials 32
 - 2.3.3.2 Separate Sample Lines for Low-Concentration Measurement 32
 - 2.3.3.3 Extensive Purging 32
 - 2.3.3.4 Blank Tests 33
 - 2.4 Bag Mini Diluter 34
 - 2.4.1 System Configuration and Features 34
 - 2.4.2 Mass Emission Calculation 36
 - 2.5 Exhaust Flow Rate Measurement 36
 - 2.5.1 Summary of Exhaust Flow Measurement 36
 - 2.5.2 Direct Measurement Method 36
 - 2.5.2.1 Ultrasonic Flow Meter 36
 - 2.5.2.2 Pitot Tube Flow Meter 39
 - 2.5.3 Indirect Measurement Method 40
 - 2.5.3.1 Intake Air Flow and Fuel Flow 40
 - 2.5.3.2 Intake Air Flow and Air-to-Fuel Ratio 41
 - 2.5.3.3 Tracer Method 41
 - References 43

Chapter 3 Measurement of Particle Emissions and Black Smoke 45

- 3.1 PM Mass Filter Weighing (Balance) Method 47
 - 3.1.1 PM Sampling from a Tunnel 47
 - 3.1.1.1 Full-Flow Dilution Tunnel 47
 - 3.1.1.2 Micro Dilution Tunnel 48
 - 3.1.2 Filter Weighing 51

3.1.3	Separate Analysis of Soluble Organic Fraction	53
3.2	Other Methods for Exhaust Particle Mass Measurement	53
3.2.1	Filter Combustion Method for Measuring Low-Mass PM	53
3.2.2	Continuous Measurement of PM Mass Concentration	55
3.3	Particle Number Measurement	56
3.3.1	Continuous Measurement of Solid Particle Number	56
3.3.2	Particle Size Distribution Measurement	57
3.4	Measurement of Black Smoke	60
3.4.1	Opacity Meter	60
3.4.2	Light Reflection	61
	References	61
Chapter 4	Evaporative Emissions Measurement	63
4.1	Outline of Evaporative Emission Regulation	63
4.2	Evaporation Test of Parked Vehicles	64
4.2.1	Outline of the Test	64
4.2.1.1	Variable Pressure Absorption System	66
4.2.1.2	Calibration and HC Retention Test	66
4.2.2	Analyzer for Evaporative Emission Measurement	67
4.2.2.1	Analyzer	67
4.2.2.2	Calculation of Evaporation Rate	67
4.3	Running Loss Evaporation Test	67
4.3.1	Evaluation of the Entire Vehicle	68
4.3.1.1	SHED Configuration	68
4.3.1.2	Fuel Temperature Profile	69
4.3.2	Evaluation of Evaporative Emission by the Point-Source Method	70
4.4	Evaporative Test After Vehicle Driving	71
	References	71
Chapter 5	Principles of Exhaust Gas Analyzers	73
5.1	Analytical Principles for Regulated Emission Components of Interest	73
5.2	Non-Dispersive Infrared Detection	74
5.2.1	Principle	75
5.2.2	Infrared Detector	76
5.2.2.1	Pyroelectric-Type Infrared Detector	77
5.2.2.2	Pneumatic Cell-Type Detector	78
5.2.2.3	Detector Using Lead Selenide	79
5.2.3	Application to Exhaust Gas Analyzers	80
5.2.3.1	Interference Compensation by AS Method	80
5.2.3.2	Adjustment of Water Concentration in Calibration Gas	81
5.3	Flame Ionization Detection	82
5.3.1	Principle of Flame Ionization Detection	82

5.3.2	Application to Exhaust Gas Analyzer	83
5.3.2.1	Separate Measurement of Methane	83
5.3.2.2	Compensation of Oxygen Interference	84
5.4	Chemiluminescence Detection	85
5.4.1	Principle of Chemiluminescence Detection	86
5.4.2	Application to the Exhaust Gas Analyzer	87
5.4.2.1	Atmospheric Pressure-Type and Vacuum Pressure-Type NO _x Analyzers	87
5.4.2.2	Options of Sample Dehumidification	88
5.5	Paramagnetic Detection	89
5.6	Zirconia Solid Electrolyte Method	91
5.6.1	Zirconia-Type Air-to-Fuel Ratio Sensor	91
5.6.2	Zirconia-Type Nitrogen Oxide Sensor	92
5.7	Fourier Transform Infrared Spectroscopy	93
5.7.1	Principle of Fourier Transform Infrared Gas Analyzer	93
5.7.2	Analyzer Configuration and Target Gas Components	94
5.8	Mid-Infrared Laser Spectroscopy	96
5.9	Gas Chromatography	97
5.9.1	Principle of Gas Chromatography	97
5.9.2	System Components and Conditions	98
5.9.2.1	Column	98
5.9.2.2	Oven Temperature	99
5.9.2.3	Detector	99
5.9.2.4	Sample Injector	99
	References	100
Chapter 6	Testing Equipment for Vehicle Emissions	101
6.1	General Configuration	101
6.2	Equipment for Simulating Actual Driving Conditions	103
6.3	Equipment for Gas Component Analysis	103
6.3.1	Constant Volume Sampling System	103
6.3.2	Exhaust Gas Analyzer	104
6.4	Particle Measurement Equipment	105
6.5	Driving Aid Equipment/Automatic Driving Equipment	105
6.5.1	Driver's Aid System	105
6.5.2	Robot Driver	105
6.6	Automation System	107
6.6.1	Laboratory Automation System	107
6.6.2	Full-Automatic Unmanned Testing System	108
Chapter 7	Practical Measurement of Engine Emissions	111
7.1	Emission Measurements for Powertrain Development	111
7.1.1	Air-to-Fuel Ratio and Excess Air Ratio	111

7.1.1.1	Calculating from Exhaust Gas Concentrations.	111
7.1.1.2	Real-Time Measurement Using Zirconia Sensor	114
7.1.2	Exhaust Gas Recirculation Ratio	115
7.1.2.1	Calculation from CO ₂ Concentrations	115
7.1.2.2	Transient Measurement of EGR Ratio	116
7.1.3	Fuel Consumption	117
7.1.3.1	Vehicles Using Combustion Engine for Power Source	117
7.1.3.2	Hybrid Vehicles	118
7.1.4	Engine Oil Consumption	120
7.1.4.1	S-trace Method	121
7.1.4.2	Calculation of Oil Consumption	122
7.1.5	Catalytic Converter Evaluation	124
7.1.5.1	Three-Way Catalytic Converter Evaluation	124
7.1.5.2	Evaluation of Aftertreatment System for Nitrogen Compounds	125
7.1.5.3	Evaluation of Diesel Particulate Filter	128
7.1.5.4	Evaluation of Aftertreatment Catalyst Using Model Gas	128
7.1.6	Measurement of Oxygenated Hydrocarbons	129
7.1.6.1	Quantitative Estimation of Alcohols	129
7.1.6.2	Quantitative Estimation of Carbonyl Compounds ...	131
7.1.6.3	Measurement of Non-Methane Organic Gases	133
7.1.7	Measurement of Greenhouse Gases	136
7.1.8	Modal Mass Analysis	137
7.1.9	Onboard Emission Measurements	140
7.2	Emission Test for Type Approval	146
7.2.1	Scope of Regulation and Test Procedures	146
7.2.2	Common Test Procedure	147
7.2.2.1	Test Cycles	148
7.2.2.2	Off-Cycle Emission Tests	149
7.3	Emission Test for Production Vehicles	151
7.3.1	Random Sampling Inspection on Production Line	151
7.3.2	In-Use Vehicle Measurement	151
	References	152

Chapter 8 Emission Regulations Around the World and Worldwide Harmonization of Technical Regulations 157

8.1	Emission Regulations Around the World	157
8.1.1	Japanese Emission Standards	157
8.1.1.1	History and Regulatory Process	157
8.1.1.2	Recent Trend	159
8.1.2	United States Emission Standards	160
8.1.2.1	History and Regulatory Process	160

- 8.1.2.2 Recent Trend 161
 - 8.1.3 European Union Emission Standards 163
 - 8.1.3.1 History and Regulatory Process 163
 - 8.1.3.2 Recent Trend 164
 - 8.1.4 Other Nations and Regions..... 164
- 8.2 Worldwide Harmonization of Technical Regulations and Mutual Recognition of Approval..... 165
 - 8.2.1 1958 Agreement and ECE Regulation 166
 - 8.2.2 1998 Agreement and gtr..... 166
- References..... 167
- Index..... 169**

Foreword

The HORIBA Group marked its 60th anniversary in 2013, growing together with the advancement of a variety of industries in the world.

During these years, engine emission measurement technologies have made remarkable progress, which has corresponded to the growth of the automotive industry, and have become HORIBA's largest business segment. This history reflects an expansion on the concept of simple gas analyzers to more sophisticated, integrated laboratory automation systems, ranging in purpose from sample handling to test automation. The development needs of low-emission, high-efficiency engines; alternative fuels; and catalyst systems have provided HORIBA with great opportunities to develop new technologies. We deeply appreciate the valuable input and constructive relationship that has been developed between our company, the industry, and our valued customers.

Recent advancements in computers and information technology have somewhat overshadowed the intrinsic analytical technologies and their historical background. This handbook summarizes the necessary knowledge of analytical methods and advanced applications for the latest engine emission measurements.

I hope this handbook will help with powertrain R&D activities, and further contribute to the growth of the automotive industry.

May 2013
Atsushi Horiba
Chairman, President & CEO

Acknowledgments

This book is the result of extensive teamwork at HORIBA. The following contributors should be recognized, as their expertise was critical in the creation of the *Engine Emissions Measurement Handbook*. Their effort and technical input were invaluable to the success of this project.

Masayuki Adachi, Masanobu Akita, Tetsuji Asami, Ichiro Asano, Hirokazu Fukushima, Kenji Hara, Masahiro Higuchi, Aoi Ikushima, Kaori Inoue, Yuki Itoga, Yoshinori Kato, Hiroshi Kawamura, Nobutaka Kihara, Kenji Kondo, Yoshinori Kondo, Satoshi Koyama, Tatsuki Kumagai, Takeshi Kusaka, Hiroshi Nakamura, Shigeo Nakamura, Shigeru Nakatani, Satoko Nishikawa, Masashi Nishimura, Shinji Noguchi, Masaru Miyai, Shinichi Murakami, Yoichi Okada, Yoshinori Otsuki, Masashi Sakaguchi, Tetsuo Sasaki, Katsushi Taguchi, Yasushi Takahashi, Kei Tanaka, Masatsune Tokuhira, Osamu Yamada, Masahiro Yamaoka, and Tomoshi Yoshimura (HORIBA, Ltd.).

Mike Akard, Sally Every, Neal Harvey, Tim Nevius, Scott Porter, and Rick Rooney (HORIBA Instruments Incorporated).

Introduction

The origin of the internal combustion engine dates back to 1860 when Jean-Joseph Etienne Lenoir developed a gas engine. This was followed by Nikolaus Otto's invention in 1876 of the Otto cycle engine, which is the fundamental concept of current engines. The development of Rudolph Diesel's engine in 1893 helped accelerate the industrial revolution as the primary power source during the late 19th and early 20th centuries.

Progress in the development of the internal combustion engine has become the driving force for the development of the automobile, fulfilling the human appetite for mobility. Mass production since the early 20th century has made automobiles an affordable purchase for many in the consumer market. In the late 20th century, the automotive market expanded worldwide.

Consumption of fossil fuels, namely coal and petroleum, has rapidly expanded worldwide with the economic development and infrastructure advancements in many countries. Most of these countries have experienced health hazards related to automotive emission, such as photochemical smog, which was first identified in Los Angeles in the 1950s. The scientific community has repeatedly issued an alarm that continued consumption of huge amounts of fossil fuels will result in global warming with serious implications on the environment.

Under such circumstances, technology to improve energy efficiency and reduce emissions has become the top priority to minimize environmental impact by automobiles. The auto industry has responded to this requirement by developing advanced engines and vehicles with high efficiency and low emissions such as super clean diesel engines, hybrid electric powertrains, fuel cell vehicles, and vehicles with alternative fuels from biomass. In fact, the concentrations of some pollutants in exhaust gas from recent advanced vehicles, called Super-Ultra-Low-Emission Vehicles, can be lower than those in ambient air.

In the process of establishing new energy-efficient emission-reduction technologies during the past half a century, analytical instruments for emission measurement have provided essential research and development support, and become fundamental tools. Requirements for future analytical instruments are anticipated to be even more sophisticated and diversified with the continued progress of automotive technologies.

The year 2013 is the 60th anniversary of the foundation of the HORIBA group, and the 50th year since the launch of the first HORIBA emissions measurement system. This handbook provides a wide range of topics: from the fundamental principles of analytical technologies, to the most recent measurement applications for advanced emission reduction systems. I hope this handbook will provide useful technical support for the engineers engaged in the development of new emission technologies, a field of study in which reliable, adequate analytical instruments are indispensable.

In closing, I would like to express my great appreciation to SAE International, Mr. Toshiji Yamazaki, Mr. Neal Harvey, and all the authors who contributed their knowledge toward the publication of this handbook.

May 2013
Kozo Ishida
Executive Vice President
HORIBA, Ltd.