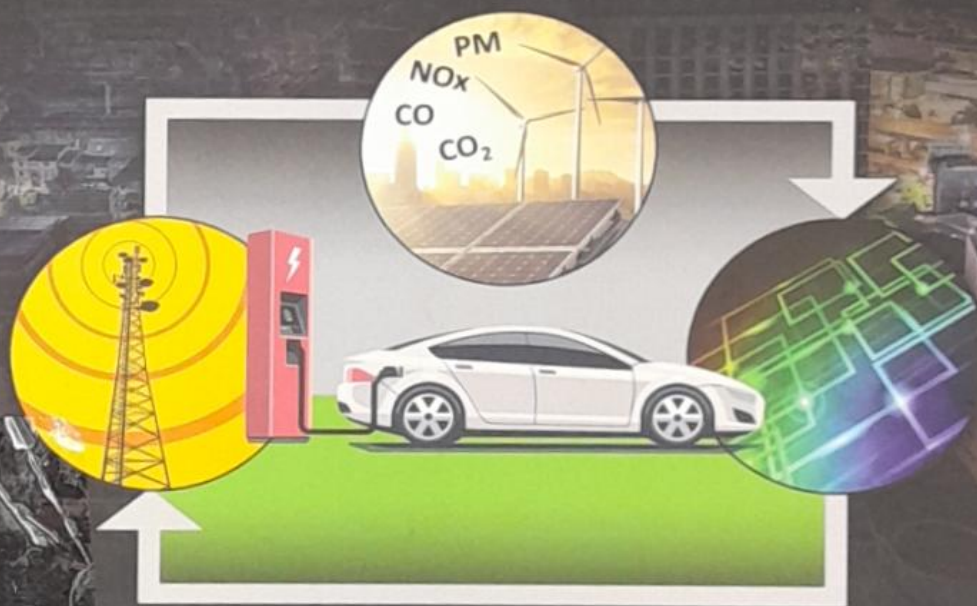


AUTOMATION AND CONTROL ENGINEERING SERIES

# Electric and Plug-in Hybrid Vehicle Networks

OPTIMIZATION AND CONTROL



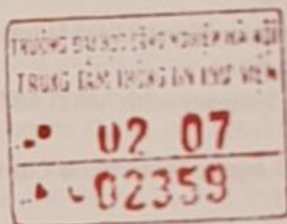
**Emanuele Crisostomi • Robert Shorten**  
**Sonja Stüdl • Fabian Wirth**



CRC Press  
Taylor & Francis Group

# Electric and Plug-in Hybrid Vehicle Networks

OPTIMIZATION AND CONTROL



AUTOMATION AND CONTROL ENGINEERING SERIES

# Electric and Plug-in Hybrid Vehicle Networks

---

OPTIMIZATION AND CONTROL

---

Emanuele Crisostomi • Robert Shorten  
Sonja Stüdl • Fabian Wirth



CRC Press

Taylor & Francis Group

Boca Raton London New York

---

CRC Press is an imprint of the  
Taylor & Francis Group, an Informa business

MATLAB<sup>®</sup> is a trademark of The MathWorks, Inc. and is used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB<sup>®</sup> software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB<sup>®</sup> software.

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

First issued in paperback 2020

© 2018 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

ISBN-13: 978-1-4987-4499-7 (hbk)  
ISBN-13: 978-0-367-73559-3 (pbk)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

---

#### Library of Congress Cataloging-in-Publication Data

---

Names: Crisostomi, Emanuele, 1980- author.  
Title: Electric and plug-in hybrid vehicle networks : optimization and control / Emanuele Crisostomi, Robert Shorten, Fabian Wirth, Sonja Stuedli.  
Description: Boca Raton : CRC Press, Taylor & Francis Group, [2018] | Includes bibliographical references and index.  
Identifiers: LCCN 2017032134 | ISBN 9781498744997 (hardback : alk. paper) | ISBN 9781315151861 (ebook)  
Subjects: LCSH: Hybrid electric vehicles--Design and construction. | Electric vehicles--Batteries. | Structural optimization.  
Classification: LCC TL221.15 .C75 2018 | DDC 629.22/93--dc23  
LC record available at <https://lccn.loc.gov/2017032134>

---

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>

and the CRC Press Web site at  
<http://www.crcpress.com>



---

# Contents

---

Preface	xiii
Acronyms	xv
<b>1 Introduction to Electric Vehicles</b>	<b>1</b>
1.1 Introduction	1
1.2 Benefits and Challenges	1
1.3 Contribution of the Book	5
<b>2 Disruption in the Automotive Industry</b>	<b>7</b>
2.1 Introduction	7
2.2 Causes for Change	7
<b>I Energy Management for Electric Vehicles (EVs)</b>	<b>11</b>
<b>3 Introduction to Energy Management Issues</b>	<b>13</b>
3.1 Introduction	13
3.2 Energy Consumption in Road Networks	13
3.3 Distribution of Charging Facilities	14
3.4 Interaction with the Power Grid	15
<b>4 Traffic Modeling for EVs</b>	<b>17</b>
4.1 Introduction	17
4.2 Traffic Model	17
4.2.1 Basic Notions of Markov Chains and Graph Theory	17
4.2.2 Basic Markovian Model of Traffic Dynamics	19
4.2.3 Benefits of Using Markov Chain to Model Mobility Dynamics	20
4.2.4 Energy Consumption in a Markov Chain Traffic Model of EVs	21
4.2.5 Dealing with Negative Entries	24
4.3 Sample Applications	26
4.3.1 Traffic Load Control	26

4.3.1.1	Theoretical Approach . . . . .	27
4.3.1.2	Decentralized Traffic Load Control . . . . .	28
4.4	Concluding Remarks . . . . .	29
<b>5</b>	<b>Routing Algorithms for EVs</b>	<b>33</b>
5.1	Introduction . . . . .	33
5.2	Examples of Selfish Routing for EVs . . . . .	35
5.3	Collaborative Routing . . . . .	40
5.3.1	A Motivating Example . . . . .	40
5.3.2	Collaborative Routing under Feedback . . . . .	41
5.4	Concluding Remarks . . . . .	44
<b>6</b>	<b>Balancing Charging Loads</b>	<b>45</b>
6.1	Introduction . . . . .	45
6.2	Stochastic Balancing for Charging . . . . .	46
6.3	Basic Algorithm . . . . .	47
6.3.1	Charging Stations . . . . .	47
6.3.2	Electric Vehicles . . . . .	47
6.3.3	Protocol Implementation . . . . .	48
6.4	Analysis . . . . .	49
6.4.1	Quality of Service Analysis: Balancing Behavior . . . . .	49
6.4.2	Quality of Service Analysis: Waiting Times . . . . .	50
6.5	Simulations . . . . .	52
6.6	Concluding Remarks . . . . .	54
<b>7</b>	<b>Charging EVs</b>	<b>57</b>
7.1	Introduction . . . . .	57
7.2	EV Charging Schemes . . . . .	60
7.2.1	Control Architectures . . . . .	60
7.2.2	Communication Requirements . . . . .	62
7.2.3	Degree of Control Actuation . . . . .	62
7.2.4	Supported Services . . . . .	63
7.2.5	Control Methods . . . . .	63
7.2.6	Measurement and Forecasting Requirements . . . . .	64
7.2.7	Operational Time Scales . . . . .	65
7.2.8	Charging Policies . . . . .	65
7.3	Specific Charging Algorithms for Plug-In EVs . . . . .	65
7.3.1	Management Strategies . . . . .	66
7.3.2	Binary Automaton Algorithm . . . . .	67
7.3.3	AIMD Type Algorithm . . . . .	69
7.4	Test Scenarios . . . . .	70
7.4.1	Domestic Charging . . . . .	70

7.4.2	Workplace Scenario . . . . .	70
7.5	Simulations . . . . .	71
7.5.1	Binary Algorithm . . . . .	72
7.5.2	AIMD in a Domestic Scenario . . . . .	72
7.5.3	AIMD in a Workplace Scenario . . . . .	77
7.5.4	Binary and AIMD Algorithm Scenario . . . . .	77
7.6	Concluding Remarks . . . . .	78
<b>8</b>	<b>Vehicle to Grid</b>	<b>81</b>
8.1	Introduction . . . . .	81
8.2	V2G and G2V Management of EVs . . . . .	82
8.2.1	Assumptions and Constraints . . . . .	82
8.2.2	Management of Active/Reactive Power Exchange . . . . .	83
8.2.3	V2G Power Flows . . . . .	83
8.3	Unintended Consequences of V2G Operations . . . . .	86
8.3.1	Utility Functions . . . . .	86
8.3.2	Optimization Problem . . . . .	88
8.3.3	Example . . . . .	89
8.3.4	Alternative Cost Functions . . . . .	90
8.4	Concluding Remarks . . . . .	90
<b>II</b>	<b>The Sharing Economy and EVs</b>	<b>91</b>
<b>9</b>	<b>Sharing Economy and Electric Vehicles</b>	<b>93</b>
9.1	Introduction and Setting . . . . .	93
9.2	Contributions . . . . .	94
<b>10</b>	<b>On-Demand Access and Shared Vehicles</b>	<b>97</b>
10.1	Introduction . . . . .	97
10.2	On Types of Range Anxiety . . . . .	98
10.3	Problem Statement . . . . .	99
10.3.1	Data Analysis and Plausibility of Assumptions . . . . .	100
10.3.2	Comments on NTS Dataset . . . . .	103
10.4	Mathematical Models . . . . .	104
10.4.1	Model 1: Binomial Distribution . . . . .	105
10.4.2	Model 2: A Queueing Model . . . . .	106
10.4.3	Two Opportunities for Control Theory . . . . .	107
10.5	Financial Calculations . . . . .	109
10.5.1	Range Anxiety Model (VW Golf vs. Nissan Leaf) . . . . .	111
10.5.2	Range Anxiety Model with a Range of Vehicle Sizes . . . . .	112
10.5.3	Financial Assumptions and Key Conclusions . . . . .	113
10.5.4	Long-Term Simulation . . . . .	114
10.6	Reduction of Fleet Emissions . . . . .	116

10.6.1 Case Study . . . . .	116
10.7 Concluding Remarks . . . . .	118
<b>11 Sharing Electric Charge Points and Parking Spaces</b>	<b>119</b>
11.1 Introduction . . . . .	119
11.2 Setting: Parking Spaces . . . . .	120
11.3 Dimensioning and Statistics . . . . .	122
11.3.1 The Dimensioning Formulae . . . . .	123
11.3.2 Parking Data and Example . . . . .	124
11.4 Efficient Allocation of Premium Spaces . . . . .	129
11.4.1 Algorithm . . . . .	129
11.4.2 Example . . . . .	132
11.5 Turning Private Charge Points into Public Ones . . . . .	132
11.6 Concluding Remarks . . . . .	135
<b>III EVs and Smart Cities</b>	<b>139</b>
<b>12 Context-Awareness of EVs in Cities</b>	<b>141</b>
12.1 Introduction . . . . .	141
<b>13 Using PHEVs to Regulate Aggregate Emissions (twinLIN)</b>	<b>143</b>
13.1 Background . . . . .	145
13.2 Cooperative Pollution Control . . . . .	147
13.2.1 The Networked Car . . . . .	148
13.2.2 Pollution Modeling and Simulation . . . . .	149
13.2.3 Mathematical Formulation . . . . .	151
13.2.4 Integral Control . . . . .	152
13.3 Simulations . . . . .	153
13.3.1 Simulation Set-up . . . . .	153
13.3.2 Disturbance Rejection . . . . .	153
13.3.3 Extensions . . . . .	155
13.4 Concluding Remarks . . . . .	156
<b>14 Smart Procurement of Naturally Generated Energy (SPONGE)</b>	<b>159</b>
14.1 Mathematical Formulation . . . . .	161
14.2 Practical Implementation . . . . .	163
14.2.1 SPONGE Simulation Results . . . . .	165
14.3 Specific Use Case: SPONGE for Plug-in Buses . . . . .	168
14.3.1 Sponge Bus Problem Formulation . . . . .	169
14.3.2 Construction of the Utility Functions . . . . .	171
14.3.2.1 Electrical Energy Consumption . . . . .	171



14.3.2.2	Saving of $CO_2$ . . . . .	171
14.3.2.3	Utility Functions $f_i$ . . . . .	172
14.4	Optimization Problem . . . . .	173
14.5	Simulation Results . . . . .	175
14.6	Concluding Remarks . . . . .	176
<b>15</b>	<b>An Energy-Efficient Speed Advisory System for EVs</b>	<b>179</b>
15.1	Introduction . . . . .	179
15.2	Power Consumption in EVs . . . . .	180
15.3	Algorithm . . . . .	182
15.4	Simulation . . . . .	185
15.4.1	Consensus and Optimality . . . . .	185
15.5	Concluding Remarks . . . . .	186
<b>IV</b>	<b>Platform Analytics and Tools</b>	<b>191</b>
<b>16</b>	<b>E-Mobility Tools and Analytics</b>	<b>193</b>
16.1	Introduction . . . . .	193
<b>17</b>	<b>A Large-Scale SUMO-Based Emulation Platform</b>	<b>195</b>
17.1	Introduction . . . . .	195
17.2	Prior work . . . . .	196
17.3	Description of the Platform . . . . .	198
17.4	Sample Application . . . . .	201
17.5	Concluding Remarks . . . . .	201
<b>18</b>	<b>Scale-Free Distributed Optimization Tools for Smart City Applications</b>	<b>205</b>
18.1	Introduction . . . . .	205
18.2	The AIMD Algorithm . . . . .	205
18.3	Optimal Resource Allocation . . . . .	207
18.4	Scale-Free Advantages of AIMD . . . . .	209
18.5	Passivity . . . . .	210
18.6	Concluding Remarks . . . . .	212
<b>Postface</b>		<b>213</b>
<b>References</b>		<b>215</b>
<b>Index</b>		<b>235</b>

---

## *Preface*

---

This book describes work carried out by the authors and their co-authors during the period 2011-2017. From its beginnings at the Hamilton Institute in Ireland, the work eventually embraced a rich network of researchers in several disciplines from across the globe, involving collaborators from North America, Europe, Australia and Asia, and researchers from both academia and industry.

The period 2011-2017 will probably be considered to be a very disruptive period in the evolution of the automobile. Cars have basically been in the same form, with the same functionality, since the invention of the diesel engine. Now, suddenly, disruption and innovation are coming from every direction, causing a rethink of the ways that cars are designed and used in cities. It is our great fortune to have been active in the automotive area during this period, and to have been able to work on some of the research challenges that have arisen.

As we have mentioned, this book describes work carried out not only by the authors, but also by a host of other collaborators, to all of whom we owe a huge debt of gratitude.

First and foremost, we would like to thank our Ph.D. and Masters students who worked directly on this topic. In particular, we would like to mention and acknowledge the contributions of Arieh Schlote, and Florian Hausler who were (along with Sonja) our first students working on this topic, as well as the more recent contributions of Mingming Liu, Yingqi Gu, and Eoin Thompson. All of the aforementioned contributed greatly to our EV work, and many of our joint results are reported in this book.

Thanks is also due to our colleagues, Wynita Griggs and Rodrigo Ordóñez-Hurtado, for their substantial contributions.

We are also greatly indebted to our close collaborators: Chris King (Northeastern University); Martin Corless (Purdue University); Jia Yuan Yu (Concordia University); Joe Naoum-Sawaya (Ivey Business School); Giovanni Russo, Jakub Mareček (both IBM Research); Kay Massow, Ilja Radusch, Thomas Hecker (all from Fraunhofer Fokus); Steve Kirkland (University of Manitoba); Rick Middleton (the University of Newcastle, Australia); Astrid Bergmann and Jörg Raisch (both Technical University of Berlin);

Julio Braslavsky (CSIRO Energy); Mahsa Faizrahnemoon (Simon Fraser University); and Brian Purcell (Nissan Ireland). Finally we thank Julian Danner for his tireless work in helping prepare the figures in this book.

Robert Shorten also thanks ESB swimming club for facilitating work on this manuscript during the long winter training sessions of 2016-17.

We are also very grateful to our funding agencies; in particular Science Foundation Ireland.

Finally, we thank CRC Press -Taylor & Francis for giving us the opportunity to write this book. In particular, we would like to thank Nora Konopka for supporting this project, Kyra Lindholm for coordinating the manuscript preparation, Karen Simon for handling the final production, Shashi Kumar for his LaTeX assistance, and John Gandour for designing the book cover.

### References and footnotes

Throughout this book we shall use references for archival sources, and footnotes, among other things, for non-archival material such as websites. Some figures and partial content are reprinted with permission from published papers. Where appropriate, chapters containing such content are indicated using footnotes: ©IEEE. Reprinted, with permission, from source.

MATLAB® is a registered trademark of The MathWorks, Inc. For product information please contact:

The MathWorks, Inc.  
3 Apple Hill Drive  
Natick, MA, 01760-2098 USA  
Tel: 508-647-7000  
Fax: 508-647-7001  
E-mail: info@mathworks.com  
Web: www.mathworks.com