Fahrzeugtechnik

Maximilian Tschochner

Comparative Assessment of Vehicle Powertrain Concepts in the Early Development Phase

SHAKER
VERLAG

Lehrstuhl für Fahrzeugtechnik

Comparative Assessment of Vehicle Powertrain Concepts
in the Early Development Phase

Dipl.-Ing. Univ. Maximilian Karl Tschochner

Vollständiger Abdruck der von der
Fakultät für Maschinenwesen
der Technischen Universität München zur Erlangung des akademischen Grades eines Doktor-Ingenieurs (Dr.-Ing)
genehmigte Dissertation

Vorsitzender Prof. Dr.-Ing. Georg Wachtmeister

Prüfende/-r der Dissertation

1. Prof. Dr.-Ing. Markus Lienkamp

2. Assistant Prof. Dr. Erik Wilhelm

Die Dissertation wurde am 22.05.2018 bei der Technischen Universität München eingereicht und durch die
Fakultät für Maschinenwesen am 14.08.2018 angenommen

Berichte aus der Fahrzeugtechnik

Maximilian Tschochner

Comparative Assessment of Vehicle Powertrain Concepts in the Early Development Phase

Shaker Verlag
Aachen 2019

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: München, Techn. Univ., Diss., 2018

Printed in Germany.

ISBN 978-3-8440-6461-2
ISSN 0945-0742

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

Acknowlegements

This work was mainly created during the TUM CREATE "Center for Electromobility" project in Singapore, which is a joint research collaboration between TU München (TUM) and Singapore's Nanyang Technological University (NTU). The project is financially supported by the National Research Foundation (NRF) Singapore under its Campus for Research Excellence And Technological Enterprise (CREATE) program. I would like to acknowledge with great gratitude the trust and freedom granted to me during my affiliation.

There are many people who contributed to and essentially enabled my work in various ways. First of all I would like to thank my supervisor Professor Markus Lienkamp for his trust to originally employ me. His continuous support and optimism, even when I was in doubt, was the stable and much needed base.

My co-supervisor Assistant Professor Erik Wilhelm provided an essential contribution in reserving his scarce time for discussion and guidance, despite pressing things on his side. Beyond his continuous and always quick support, I value his broad knowledge, sharp assessment ability, and his inspiring academic and technological idealism.

Much more than he is probably aware of, I owe Dr Daniel Gleyzes. He introduced me to the "scientific" way of vehicle engineering and gave me invaluable personal feedback, which set me on the right track. His early topic and literature recommendations are the nucleus of this thesis. Furthermore, I copied his being a "tool and hotkey wizard", which is fun and saves me often little and cumulatively lots of time.

The colleagues from TUM CREATE and the TUM Chair of Automotive Technology were the best. I would like to mention (all in alphabetic order) the people from the early pioneer team in Singapore: Sebastian Bender, Pablo Hidalgo, Robert Kochhan, Stephan Schickram and Andreas Schwab. Further Christian Angerer, David Ciechanowicz, Rahul Gujarathi, Raymond Khoo, Patrick Osswald, Sebastian Osswald, Dominik Pelzer, Benjamin Reuter, Felix Römer and Reinhard Sellmair. They provided support through inspiring discussions with consistent personal dedication. I hope the bonds will prevail beyond work and last a lifetime.

Working with good students is a gift in itself. They provided me with an unbiased view, an incentive to reconsider and trained my ability to explain. Although not all of their theses were related to this work, I would like to mention Niklas Frank, Wen Gao, Nils Hoppe, Alexander Koch, Patrick Kraft, Srikkanth Ramachandran, Andreas Sauer, Jeanette Seewald and Adam Waclaw.

This work was undeniably a challenge. Eventually, the scientific insights gained and the vehicle powertrain system improvements with its potential environment impact gave me great personal satisfaction. Motivation in difficult times and the opportunity to grow in a multitude of ways was especially provided by the outstanding people I was lucky to meet along the way.

May 2018
Maximilian Tschochner

Abstract

In recent years vehicle powertrains show a growing trend towards diversification. This helps to mitigate inevitable conflicts between objectives, but vastly expands and complicates the concept solution space. The fair optimization and assessment across a number of distinct powertrain structures poses a considerable challenge for vehicle concept teams in the early development phase. Previous work fails to derive a realistic and holistic approach to tackle this challenge, which is still viable under tight time constraints. The solution presented in this thesis is based on novel combination of state-of-the-art concepts. Flexible powertrain definition is achieved with graph theory and parametric component models. Important secondary mass decompounding effects are considered. A vectorized quasi-static backward simulation approach and derived meta-models guarantee high computational performance. Fair dynamic assessment is realized consistently with global optimal control. Component sizing uses closed-loop optimization. The implementation of the methodology is applied for five technical vehicle criteria and to 10 powertrain structures as an example. For each structure two criteria are simultaneously optimized and depicted as a Pareto front. Concurrent visualization of the respective components' characteristics provides transparent insight on the relation between objective and decision space. Families of Pareto fronts allow comparative graphical decision making. The methodology presented here contributes to advanced vehicle systems engineering and its application in a practical development context.

Contents

1 Introduction 1
1.1 Motivation 1
1.2 Outline of Thesis 2
2 State of the Art 5
2.1 Vehicle Development Process 5
2.2 Powertrain Classification and Component Choices 7
2.3 Longitudinal Dynamics Simulation Approaches 9
2.4 Optimization Aspects of Powertrains 13
2.5 Efficient Optimization with Meta-Modeling 25
2.6 Critical Assessment of the State of the Art 27
3 Methodological Overview and Simulation Design 31
3.1 System Boundary and Objectives 31
3.2 Requirements for an Early Phase Powertrain Concept Tool 32
3.3 Simulation Approach and Idealizations 33
3.4 Simulation Model Architecture 35
3.5 Heuristic Powertrain Pre-Sizing and Choice 38
4 Powertrain Component Modeling 41
4.1 General Remarks 41
4.2 Vehicle Glider 43
4.3 Thermal Engine 51
4.4 Fuel Tank 54
4.5 Electric Motor 55
4.6 Battery Pack 57
4.7 Transmission 58
4.8 Clutch 60
4.9 Engine-Generator Unit 61
4.10 Fuel Cell 63
4.11 Components for Simulation 64
5 Powertrain Structures and Optimal Dynamic Control 65
5.1 Overview and General Remarks 65
5.2 Powertrain Structures and Minimum Consumption Determination 66
5.3 Minimum Acceleration Time Determination 75
5.4 Top Speed Determination 77
6 Selective Consumption Model Validation 79
6.1 Types of Data Sources and Suitability 79
6.2 Dynamometer Database Data Extraction and Preparation 80
6.3 Simulation Validation 84
7 Multi-Objective Powertrain Sizing Optimization with Meta-Models 89
7.1 Challenges Regarding Computation Time 89
7.2 Derivation of Meta-Models and Design of Experiments 90
7.3 Validation of Meta-Models 92
7.4 Genetic Multi-Objective Optimization and Pareto Fronts 93

8 Case Studies and Results 97
8.1 Assumptions for Case Studies 97
8.2 1D Parameter Variation in Decision Space 97
8.3 Pareto Optimal Configurations 101
8.4 Comparative Pareto Optimal Assessment 107
9 Summary and Outlook 111
9.1 Summary 111
9.2 Outlook 113

List of Figures 115

List of Tables 123

List of Abbreviations 125

List of Symbols 127

Bibliography 133

Relevant Publications and Supervised Theses 147

Appendix 149
A Overview Schematic Blocks and Symbols 149
B Simulation Parameters 150
C Relevant Design of Experiments Fundamentals 158
D Meta-Models Correlation Values and Plots 160
E Driving Cycles 163
F Vehicle Parameters 167
G Comparative Pareto Front Further Results 168
H Thermal Engine Typical Data 170
I Investigation of Willan's Line Approach 171
J Plausibility of Rotational Mass Factor 173
K Static Driving Cycle Characterization 174
L Power/ Energy Requirements at Wheels 175