

UNIVERSITY OF TECHNOLOGY SYDNEY

Faculty of Engineering and Information Technology

**A Comprehensive Study on Energy
Management Strategy Design of an Extended-
Range Electric Vehicle**

A thesis submitted for the degree of

Doctor of Philosophy

Boyi XIAO

June 2022

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Boyi Xiao declare that this thesis, is submitted in fulfilment of the requirements for the award of a Doctor of Philosophy degree, in the School of Mechanical and Mechatronic Engineering/Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

Production Note:

Signature: Signature removed prior to publication.

Date: 05-June-2022

Acknowledgments

I would like to take this opportunity to thank the following people and organizations for their assistance and support during my candidature.

I would express my deep gratitude to my supervisors Professor Nong Zhang, A.Prof. Dongbin Wei, A.Prof. JC Ji and Dr Paul Walker for their tremendously valuable suggestions, thoughtful guidance, and continuous support throughout past years. Their valuable knowledge and research attitude reshaped me and made it possible for me to continue my research career.

I would also like to thank my colleagues and friends: Jiageng Ruan, Weiwei Yang, Shilei Zhou, Tim Patten, Wenwei Mo, Yang Tian, Shengxiong Sun, Hanfei Wu, Enoch Zhao, Anna Lidfors Lindqvist and all other friends at the Faculty of Engineering and Information Technology, for their support and assistance.

Financial support for my study is provided by the University of Technology Sydney (UTS) and the Guangzhou Elite Project (GEP).

Finally, my deepest thanks go to my family. It is their love, understanding and support that accompany me so far.

Boyi Xiao

Sydney, 2022

Publications

International journals

- [1] B. Xiao, J. Ruan, W. Yang, P.D. Walker, N. Zhang, A review of pivotal energy management strategies for extended range electric vehicles, Renewable and Sustainable Energy Reviews, vol. 149, 2021, 111194.
- [2] B. Xiao, P. D. Walker, S. Zhou, W. Yang, N. Zhang, A Power Consumption and Total Cost of Ownership Analysis of Extended Range System for a Logistics Van, IEEE Transactions on Transportation Electrification. Vol. 8, pp. 72-81, 2022.
- [3] B. Xiao, P. D. Walker, W. Yang, N. Zhang, Energy management strategy via maximum entropy reinforcement learning for an extended range logistics vehicle, Energy, 2022, 124105.
- [4] S. Zhou, P. D. Walker, B. Xiao, N. Zhang, Modelling and Vibration Analysis of a Parallel Hydraulic Hybrid Vehicle, IEEE Transactions on Vehicular Technology, vol. 69, no. 10, pp. 10710-10723, Oct. 2020.

International conferences

- [1] B. Xiao, P. D. Walker, N. Zhang, Performance Analysis of A Electric Vehicles Energy Flow and Regenerative Braking Strategy, Intern. Conf. on Adv. Veh. Powert. (ICAVP), 2019.
- [2] B. Xiao, P. D. Walker, N. Zhang, Energy Management and Economic Analysis of an Extended Range Electric Vehicle using Scotch Yoke Boxer Engine, Intern. Conf. on Adv. Veh. Powert. (ICAVP), 2021.

Contents

Acknowledgments.....	3
Publications.....	4
List of figures.....	9
List of tables.....	12
Abbreviations.....	13
Chapter 1 Introduction.....	1
1.1 Background and significance.....	1
1.2 Research objectives and innovations.....	3
1.3 Presentation of this thesis.....	4
1.4 Statement of COVID-19 impact on the research.....	5
Chapter 2 Literature review.....	6
2.1 Introduction.....	6
2.2 System Design of Extended Range Electric Vehicle.....	6
2.3 Basic operation pattern of EREV.....	9
2.3.1 Auxiliary power unit.....	10
2.4 Hybrid energy storage system constitution.....	11
2.4.1 Battery.....	12
2.4.2 Supercapacitor (SC).....	13
2.5 Energy management classification.....	15
2.6 APU Charging control strategy.....	19
2.6.1 Power following strategy.....	19
2.6.2 Optimal range strategy.....	22

2.6.3 Comparison of the two strategies	24
2.7 Dynamic power management for HESS	25
2.7.1 Sizing design	28
2.7.2 Power distribution control of HESS.....	31
2.7.3 Existed problems and future trends.....	34
2.8 A case analysis of a specific EREV	35
2.8.1 Validation and on-road testing.....	36
2.8.2 Energy management studies applied on Chevrolet Volt.....	38
2.9 Economic, Fuel Cost and performance trade-off.....	39
2.9.1 Parts prices comparison	39
2.9.2 Comparison of vehicle total cost of ownership.....	40
2.10 Chapter summary	42
Chapter 3 Vehicle modelling design.....	43
3.1 Introduction.....	43
3.2 Vehicle parameter	43
3.3 Driving cycle.....	45
3.4 Vehicle dynamics	47
3.5 Auxiliary power unit	47
3.6 Traction motor.....	48
3.7 Battery equivalent model	50
3.8 Chapter summary	52
Chapter 4 Investigation of energy potential and TCO for an ERLV	53
4.1 Introduction.....	53
4.2 Optimization logic implementation.....	56

4.3 Global optimization algorithm	56
4.4 Battery degradation prediction	59
4.5 Simulation results.....	62
4.5.1 Consumption comparison.....	63
4.5.2 The total cost of ownership analysis	67
4.6 Chapter summary	70
Chapter 5 Multi-target energy management strategy of the ERLV	72
5.1 Introduction.....	72
5.2 The EMS Design and requirement.....	74
5.2.1 Vehicle modelling for RL training.....	77
5.3 Multi-target optimization and environment	82
5.4 Reinforcement learning algorithm	85
5.4.1 DDPG algorithm	87
5.4.2 SAC algorithm	90
5.5 Pre-training process.....	95
5.5.1 Agent implementation.....	97
5.6 Result analysis.....	98
5.7 Chapter summary	104
Chapter 6 A case study of an ERLV with a scotch yoke boxer engine	106
6.1 Introduction.....	106
6.2 Vehicle platform and modelling	108
6.2.1 Engine operating point selection.....	109
6.2.2 APU charging strategy design.....	110
6.3 Performance and energy potential comparison	111

6.4 Chapter summary	116
Chapter 7 Conclusions and future works	117
7.1 Thesis conclusions	117
7.2 Future research	119

List of figures

<i>Figure 1.1 Estimation of the emission distribution to 2070 [4].</i>	2
<i>Figure 2.1 Powerflow overview of an engine-based EREV [24].</i>	7
<i>Figure 2.2 A CD-CS mode switching sample of an EREV.</i>	9
<i>Figure 2.3 Downsize engine equipped with a Scotch yoke (a) Engine outer shell; (b) Scotch yoke mechanism.</i>	11
<i>Figure 2.4 Samples of an ESS and a HESS: (a) ESS, (b) HESS [24].</i>	12
<i>Figure 2.5 Appearance of an SC pack [62].</i>	14
<i>Figure 2.6 Classification of energy management strategies.</i>	16
<i>Figure 2.7 Logic diagram of a power following strategy example [24].</i>	20
<i>Figure 2.8 Basic logic diagram of an optimal range strategy [24].</i>	22
<i>Figure 2.9 Wide-adopted topology structures of HESS.</i>	26
<i>Figure 2.10 Flowchart of Possible HESS design options identification [24].</i>	29
<i>Figure 2.11 The concept model of the Chevrolet Volt [168].</i>	35
<i>Figure 2.12 Average travel distance and Wh/km in different seasons.</i>	38
<i>Figure 2.13 The average market price growth of Li-ion battery cells [179].</i>	40
<i>Figure 3.1 ERLV architecture.</i>	44
<i>Figure 3.2 Speed profiles of (a) CLTC-C and (b) WLTC (class 3b)</i>	46
<i>Figure 3.3 The engine efficiency map.</i>	48
<i>Figure 3.4 Traction motor and its controller [200].</i>	49
<i>Figure 3.5 Efficiency map of the drive motor.</i>	50
<i>Figure 3.6 Simplified battery ECM diagram.</i>	51
<i>Figure 3.7 The electrical characteristics of a single battery cell.</i>	51
<i>Figure 4.1 Double-loop DP flow diagram for the ERLV model.</i>	58
<i>Figure 4.2 Outer layer of the DP process (possible SOC nodes search).</i>	59
<i>Figure 4.3 The battery capacity loss accumulation of (a) BELV and (b) ERLV in WLTC-3B</i>	61
<i>Figure 4.4 Power demands on (a) CLTC and (b)WLTC</i>	63

<i>Figure 4.5 Engine operation points of CLTC (top) and WLTC.....</i>	<i>64</i>
<i>Figure 4.6 Results of engine and battery power from DP optimization</i>	<i>65</i>
<i>Figure 4.7 Variation of the battery SOC and fuel consumption.....</i>	<i>66</i>
<i>Figure 4.8 TCO growth comparisons with the highest (a) and lowest (b) diesel prices.....</i>	<i>69</i>
<i>Figure 5.1 A Markov decision process diagram.....</i>	<i>75</i>
<i>Figure 5.2 Closed-loop control in RL environment.....</i>	<i>75</i>
<i>Figure 5.3 The Simulink framework of the RL-based ERLV model.....</i>	<i>76</i>
<i>Figure 5.4 The framework of the vehicle model.....</i>	<i>77</i>
<i>Figure 5.5 Driver model.....</i>	<i>78</i>
<i>Figure 5.6 Traction motor model.....</i>	<i>79</i>
<i>Figure 5.7 Vehicle body dynamics.....</i>	<i>79</i>
<i>Figure 5.8 Battery model design.....</i>	<i>80</i>
<i>Figure 5.9 APU model.....</i>	<i>81</i>
<i>Figure 5.10 The capacity fading factor with different SOC and C-rates.....</i>	<i>84</i>
<i>Figure 5.11 The reward calculation.....</i>	<i>84</i>
<i>Figure 5.12 Structure of the Actor-Critic algorithm.....</i>	<i>86</i>
<i>Figure 5.13 System diagram of the DDPG-based EMS.....</i>	<i>88</i>
<i>Figure 5.14 System diagram of the SAC-based EMS.....</i>	<i>91</i>
<i>Figure 5.15 Architecture of the neural networks.....</i>	<i>94</i>
<i>Figure 5.16 The reward convergence performance of SAC and DDPG.....</i>	<i>96</i>
<i>Figure 5.17 The engine operation samples of the premature/trained SAC agent.....</i>	<i>97</i>
<i>Figure 5.18 The power output of the engine and battery with the SAC agent.....</i>	<i>98</i>
<i>Figure 5.19 The battery SOC trajectories.....</i>	<i>100</i>
<i>Figure 5.20 The transient battery C-rate comparisons.....</i>	<i>101</i>
<i>Figure 5.21 Engine operation points using different algorithms.....</i>	<i>103</i>
<i>Figure 6.1 Piston motion comparison of (a) conventional; (b) Scotch Yoke.....</i>	<i>107</i>
<i>Figure 6.2 Scotch Yoke engine prototypes of (a) S415; and (b) S208.....</i>	<i>108</i>
<i>Figure 6.3 The partial BSFC map of the engine.....</i>	<i>110</i>

<i>Figure 6.4 Operating logic of the CD-CS strategy.....</i>	<i>111</i>
<i>Figure 6.5 Transient power variation of the vehicle (a) WLTC; (b) CLTC</i>	<i>112</i>
<i>Figure 6.6 SOC variation pattern (S208 engine) using the (a) CD-CS strategy; (b) sustaining strategy.</i>	<i>113</i>
<i>Figure 6.7 SOC variation pattern (S415 engine) using the (a) CD-CS strategy; (b) sustaining strategy.</i>	<i>114</i>
<i>Figure 6.8 Specification comparison of the engine prototypes.</i>	<i>115</i>

List of tables

<i>Table 2.1 Alternative vehicle configurations and comparison.</i>	7
<i>Table 2.2 Classification of energy management control strategies.</i>	16
<i>Table 2.3 Introduction of the two APU charging classifications.</i>	25
<i>Table 2.4 General price and performance comparison of energy sources.</i>	39
<i>Table 2.5 TCO comparison of market competitors (US \$).</i>	40
<i>Table 3.1 Parameters of the extended range logistics van.</i>	44
<i>Table 3.2 Patterns of the representative driving cycles</i>	46
<i>Table 3.3 Configuration of the PMSM motor.</i>	49
<i>Table 4.1 Diesel consumption and driving range comparison.</i>	67
<i>Table 4.2 Predicted data of TCO and energy consumption(US \$).</i>	69
<i>Table 5.1 DDPG Algorithm.</i>	90
<i>Table 5.2 Hyperparameters of the DDPG agent.</i>	90
<i>Table 5.3 SAC Algorithm.</i>	94
<i>Table 5.4 Hyperparameters of the SAC agent.</i>	95
<i>Table 5.5 Results of the fuel consumption and SOC variation.</i>	104
<i>Table 5.6 Fuel consumption and energy cost comparison when reaching 200 km.</i>	104
<i>Table 6.1 Specifications of the engine prototypes.</i>	108
<i>Table 6.2 S208 energy consumption of the CS-CD&Sustaining strategy under different driving cycles.</i>	114
<i>Table 6.3 S415 energy consumption of the CS-CD&Sustaining strategy.</i>	114

Abbreviations

BEV - Battery Electric Vehicle

EREV - Extended Range Electric Vehicle

ERLV - Extended Range Logistics Vehicle

FCV - Fuel Cell Vehicles

HEV - Hybrid Electric Vehicle

PHEV - Plug-in Hybrids Electric Vehicles

APU - Auxiliary Power Unit

ICE - Internal Combustion Engine

ISG - Integrated Starter Generator

Li-Ion - Lithium-Ion

NiMH - Nickel-metal Hydride

SC - Supercapacitor

SOC - State of Charge

SOH - State of Health

NEDC - New European Driving Cycle

CLTC - China Light-duty Vehicle Test Cycle

WLTC - Worldwide Harmonized Light Vehicles Test Cycle

PMP - Pontryagin's Minimum Principle

MPC - Model Predictive Control

MDP - Markov Decision Process

DP - Dynamic Programming

DL - Deep Learning

DRL - Deep Reinforcement Learning

RL - Reinforcement Learning

DQN - Deep Q Network

DDPG - Deep Deterministic Policy Gradient

A3C - Asynchronous Advantage Actor Critic

TD3 - Twin Delayed DDPG

SAC - Soft Actor-Critic

BMS - Battery Management Strategy

EMS - Energy Management Strategy

CD - Charge-depleting

CS - Charge-sustaining

ESS - Energy Storage System

HESS - Hybrid Energy Storage System

HIL - Hardware in the Loop

TCO - Total Cost of Ownership

Abstract

The extensive usage of conventional internal combustion engine vehicles (ICEVs) is responsible for a large amount of greenhouse gas emissions. However, the battery electric vehicle can not substitute for the traditional vehicle due to its limited energy storage ability. To moderate this issue, the extended range electric vehicle (EREV) provides a solution by providing a satisfactory driving range and lower production cost than battery electric vehicle (BEV). An EREV is characterized by having an auxiliary power unit (APU) to provide electric power to the traction motor and the energy storage system, and its battery pack can meet a majority of pure-electric driving needs. To distinguish from the other vehicle structures, the potential of the EREV platform should be further studied/presented on a full scale, and novel control strategies can be designed to improve the power performance of the vehicle. In this thesis, a research on the development process of an extended range logistics vehicle is conducted in the automobile theory and vehicle control points of view. The research priority of the study consists of three parts: the background review and the vehicle structure design, the consumption and cost analysis and the innovation on its control strategy.

First of all, a comprehensive background investigation and literature review are conducted and discussed. The investigation systematically introduces the current developments of EREV in terms of the powertrain structure, energy management and vehicle performance, while the two key focus areas of the auxiliary power are the unit (APU) charging control and hybrid energy storage system (HESS) power management. A case analysis on a typical EREV is presented along with a general

manufacturing cost analysis for different types of vehicles, showing the EREV as one of the cheapest options for long term usage.

Secondly, an extended range mathematical platform for a logistics van is proposed. Suitable configurations for the sizing of the APU, ESS and the traction motor are selected for a standardized mid-size van. This study presents a thorough energy consumption and Total cost of ownership (TCO) analysis for an Extended range logistics van (ERLV). Both EREV and BEV mathematical models are constructed and compared, and their dynamic long-term battery degradation comparison is conducted. Dynamic programming (DP) algorithm is adopted in the energy management strategy optimization, and the global result reveals the optimal energy consumption of the EREV. Comparative results demonstrate that the ERLV has a relatively long drive distance, slower battery aging trend and cheaper TCO (6.6%) when compared to the BELV.

Thirdly, a novel auxiliary power unit (APU) charging strategy with multi-object optimization is proposed on the ERLV platform to achieve high fuel conversion efficiency while maintaining battery charging health. The state-of-the-art algorithm, Soft Actor-Critic (SAC) is applied to perform a better exploration of the possible APU behaviour, and its performance is further verified by the results of the Deep Deterministic Policy Gradient (DDPG) algorithm and DP. Three targets are selected as the RL rewards for optimization: the engine fuel rate, SOC charging trajectory, and the battery charging rate (C-rate). The comparative results show that the SAC had a 36% faster convergence speed than DDPG while providing a smoother and more stable action space. The fuel consumption with SAC also outplays DDPG by around 3%, which achieves almost 90% of the global optimization result. The

successful deployment of the SAC algorithm as an EMS indicates its standout ability in dealing with wide-range actions and states with high randomness, revealing the practical potential compared with the existing RL strategies.