

# Contents

Acknowledgement .....	I
Abstract.....	II
Contents.....	IV
List of Figures.....	IX
List of Tables.....	XIV
1. Introduction .....	1
1.1 Background .....	1
1.1.1 Problems of Conventional Vehicles.....	1
1.1.2 Electric Vehicles Development .....	2
1.2 Distributed Drive Electric Vehicles .....	6
1.3 Cut-in Points in this Research .....	11
1.3.1 Stability Based Research.....	11
1.3.2 Energy-Saving Based Research.....	14
1.4 Research Scope and Objectives.....	15
1.5 Thesis Outline .....	16
2. Literature Review.....	19
2.1 Vehicle State and Tire-Road Friction Coefficient Estimation .....	19
2.1.1 Vehicle State Estimation .....	19
2.1.2 Tire-Road Friction Coefficient Estimation.....	22
2.2 Direct Yaw Moment Control .....	25
2.2.1 Fuzzy Logic Based Yaw Moment Control .....	26
2.2.2 PID-Based Direct Yaw Moment Control .....	27
2.2.3 LQR-Based Direct Yaw Moment Control.....	29
2.2.4 Sliding Mode Based Direct Yaw Moment Control .....	31

2.3	Torque Allocation .....	33
2.3.1	Rule-Based Control Allocation .....	34
2.3.2	Objective Function-based Control Allocation.....	35
3.	Distributed Drive Electric Vehicle Model.....	40
	List of Symbols.....	40
3.1	Vehicle Modeling.....	41
3.1.1	Reference Coordinate Systems .....	42
3.1.2	Vehicle Equivalent Mechanical Model .....	44
3.1.3	Model Assumptions .....	44
3.1.4	Vehicle Motion Equations.....	45
3.2	Subsystem Modeling.....	45
3.2.1	Steering System Model.....	45
3.2.2	Wheel Motion Model .....	46
3.2.3	Tire Model .....	48
3.2.4	Electric Motor.....	51
3.2.5	Friction Brake Model.....	52
3.3	Driver Model .....	53
3.3.1	Target Trajectory and Velocity .....	53
3.3.2	Preview-Point Searching Algorithm and Lateral Motion Control.....	54
3.3.3	Longitudinal Motion Control .....	57
3.4	Vehicle and Driver Model Parameters.....	59
3.5	Chapter Summary .....	59
4.	Vehicle State and Tire-Road Friction Coefficient Estimation.....	61
	List of Symbols.....	61
4.1	Vehicle Modeling for State Estimation .....	63
4.1.1	Measurement, Control Input, and State Vectors.....	65
4.1.2	Planar Vehicle Model.....	66

4.1.3	Tire Force Calculation.....	67
4.2	Hierarchical Estimation Algorithm Design.....	68
4.3	Vehicle State Estimation Based on UKF .....	68
4.4	Hybrid Estimator Design for Tire-Road Friction Coefficient .....	73
4.4.1	GRNN-Based Estimator Design .....	73
4.4.2	Bayesian Theorem-based Estimator Design.....	76
4.5	Chapter Summary .....	78
5.	Direct Yaw Moment Controller Design .....	79
	List of Symbols.....	79
5.1	Control Variables .....	82
5.2	Desired Value of Control Variables .....	85
5.3	Feedforward Control .....	91
5.3.1	2-DOF Model Based on Actual Cornering Stiffness.....	93
5.3.2	Linear Cornering Stiffness Estimation .....	94
5.4	Feedback Control .....	97
5.4.1	Conventional Sliding Model Controller .....	98
5.4.2	Adaptive Sliding Model Controller.....	99
5.5	Chapter Summary .....	101
6.	Stability-Based Control Allocation Using KKT Global Optimization Algorithm.....	103
	List of Symbols.....	103
6.1	Objective Function Description for Stability-Based Torque Allocation .....	106
6.2	KKT-Based Global Optimization Algorithm.....	109
6.3	Active-Set Allocation Algorithm.....	113
6.4	Chapter Summary .....	115
7.	Energy-Efficient Torque Allocation for Traction and Regenerative Braking .....	116
	List of Symbols.....	116
7.1	Introduction.....	118

7.2	Energy-Efficient Traction Allocation.....	120
7.3	Energy-Efficient Braking Torque Allocation .....	124
7.3.1	Braking Stability.....	124
7.3.2	Optimization Boundary for Regenerative Braking Force Distribution...127	
7.3.3	Optimal Front-Rear Braking Force Distribution Coefficient $\beta$ .....	128
7.4	Conventional Strategy for Traction and Regenerative Braking Allocation ...131	
7.5	Chapter Summary .....	132
8.	Simulation and Verification on the Proposed Model and Control Strategy.....	134
8.1	Simulation and Verification of Vehicle Simulation System .....	135
8.1.1	Simulation and Verification on 9-DOF Vehicle Dynamics Model.....	135
8.1.2	Simulation and Verification on Driver Model .....	140
8.2	Simulation and Analysis of the State and TRFC Estimation Algorithm .....	143
8.2.1	Acceleration and Brake Maneuver .....	144
8.2.2	Double Lane Change Maneuver .....	147
8.3	Simulation and Analysis of the Direct Yaw Moment Controller.....	152
8.3.1	Simulative Experiment on a Low-g Maneuver.....	152
8.3.2	Simulative Experiment on a High-g Maneuver .....	155
8.4	Simulation and Analysis of the Stability-based Torque Allocation.....	160
8.4.1	Initial Settings of the Simulative Experiments .....	161
8.4.2	Simulation Results and Analysis.....	162
8.5	Simulation and Analysis of the Energy-efficient Toque Allocation.....	166
8.5.1	Energy-Saving Assessment Criteria .....	167
8.5.2	Simulation Results and Analysis.....	167
8.6	Chapter Summary .....	171
9.	Conclusions and Future Work.....	172
9.1	Summary and Conclusions.....	172
9.2	Future Works.....	173

A. References.....	176
B. Appendix.....	190
B.1 PAC2002 MAGIC-FORMULA TIRE MODEL.....	190
Input Variables .....	190
Output Variables.....	190
Basic Tire Parameters .....	190
Tire Model Parameters .....	190
Scaling Factor Coefficients for Pure Slip: .....	191
Scaling Factor Coefficients for Combined Slip:.....	191
Formulas for the Longitudinal Force at Pure Slip .....	192
Formulas for the Lateral Force at Pure Slip.....	192
Formulas for the Aligning Moment at Pure Slip .....	194
Formulas for Longitudinal Force at Combined Slip: .....	195
Formulas for the Lateral Force at Combined Slip: .....	196
Formulas for the Aligning Moment at Combined Slip .....	196
Stretched String Model Transient Tire Behavior .....	197
B.2 Vehicle Motion Equations Derivation .....	199
B.2.1 Vehicle Translational Motion Equations.....	200
B.2.2 Vehicle Rotational Motion Equations.....	203
B.3 Double Lane Change (DLC) Maneuver .....	207