
CONTENTS

LIST OF FIGURES	VII
LIST OF TABLES	XI
NOMENCLATURE	XIII
1 INTRODUCTION	1
1.1 Motivation	1
1.2 State of the art - technologies	2
1.3 State of the art - emissions	7
1.4 State of the art - control	13
2 SIMULATION METHODOLOGY	17
2.1 Virtual calibration: model of the ECU and driver actuation	17
2.1.1 Engine Control Unit	17
2.1.2 Driver actuation	22
2.2 Physical system: combustion engine and vehicle powertrain	22
2.2.1 Combustion engine model	23
2.2.2 Vehicle powertrain model	25
2.3 Simulation environment	26
2.4 Formation of in-cylinder and tailpipe emissions	27
2.4.1 In-cylinder NO _x emissions	27
2.4.2 In-cylinder CO emissions	28
2.4.3 In-cylinder HC emissions	29
2.4.4 Tailpipe emissions	33
3 MODELING	35
3.1 ECU model	35
3.2 Driver actuation	43
3.3 Engine model	44
3.3.1 Modeling	44
3.3.2 Model calibration	53
3.4 Vehicle model	54
3.5 Coupled model	58
3.6 In-cylinder emissions	60
3.6.1 NO _x -and CO-model	61
3.6.2 Unburned hydrocarbon model	64
3.7 Tailpipe emissions	76
3.7.1 Numerical simulation	76
3.7.2 Simulation of the light-off behavior of three-way catalysts	81
3.7.3 Influence of aging	83
3.7.4 Influence of precious metal loading	86
4 TRANSIENT SIMULATION	89
4.1 Measurements	89
4.2 Validation process	90
4.3 Proof of concept	93
4.3.1 ECU model	93

4.3.2	Engine model	96
4.3.3	Vehicle model	102
4.3.4	Coupled overall model	102
4.3.5	Emission models	108
4.3.6	Summary	114
5	APPLICATION EXAMPLES	116
5.1	Worldwide harmonized Light-Duty Test Procedure (WLTP)	116
5.2	Sensitivity of air-fuel ratio	122
5.3	Applications of crank angle based analyses	127
5.4	Transient simulation of tailpipe emissions	129
6	SUMMARY	136
	BIBLIOGRAPHY	139
A	APPENDIX	152
A.1	Further results of transient simulation	152
A.1.1	Transient validation of the engine stand-alone model	152
A.1.2	Transient validation of the driver control model in the coupled simulation	154
A.1.3	Transient validation of the engine model in the coupled simulation . .	155
A.2	Modeling approaches for three-way catalysts	156
A.3	Chemical Reaction Mechanism for Tailpipe Emissions	157
A.4	Process scheme of the oxygen storage module	159