

CONCEPTUAL DESIGN AND MODELING OF  
A FUEL CELL SCOOTER FOR URBAN ASIA

by

Bruce Lin

Princeton University  
School of Engineering and Applied Sciences  
Department of Mechanical and Aerospace Engineering

Submitted in partial fulfillment of the requirements for the degree  
of Master of Science in Engineering from Princeton University, 1999

Prepared by:

---

(Author's signature)

Approved by:

---

Professor Robert H. Socolow  
Thesis Advisor

---

Professor Enoch Durbin  
Thesis Reader

November, 1999

© Copyright by Bruce Lin, 1999. All rights reserved

## *abstract*

---

Air pollution is of serious concern in many Asian countries, especially in densely-populated cities with many highly-polluting two-stroke engine vehicles. The present value of health effects have been estimated at hundreds of dollars or more, over each vehicle's lifetime, for a reasonably wealthy country like Taiwan. Four-stroke engines and electric battery-powered scooters are often proposed as alternatives, but a fuel cell scooter would be superior to both by offering both zero tailpipe emissions and combustion-scooter class range (200 km).

Unlike 50 kW automobile-sized fuel cell stacks, the vehicular 5 kW fuel cell needed here has not received much attention. This niche is examined here with a conceptual design and consideration of the issues of water, heat, and gas management. The application is extremely sensitive to size, weight, and cost, so a proton exchange membrane fuel cell using hydrogen stored in a metal hydride is best. Hydrides also act as sinks for waste heat due to the endothermic hydrogen desorption process. Pressurized operation is found to be ineffective due to high parasitic power demands and low efficiencies at the low powers involved.

A computer simulation is developed to examine overall vehicle design. Vehicle characteristics (weight, drag, rolling resistance), fuel cell polarization curves, and a Taiwanese urban driving cycle are specified as inputs. Transient power requirements reach 5.9 kW due to the rapid accelerations, suggesting a large fuel cell. However, average power is only 600 W: a hybrid vehicle with a small fuel cell and peaking batteries could also handle the load. Results show that hybrid vehicles do not significantly improve mileage, but are certain to precede pure fuel cell scooters while fuel cells are still more expensive than peaking batteries.

System size is approximately the same as current electric scooters, at 43 L and 61 kg for the fuel cell, hydrogen storage, and electric motor / controller. Manufacturing costs of fuel cell scooters are expected to decrease to under \$1,300 in the long term, with per-km fuel costs half of those for gasoline scooters. Hybrid zinc-air scooters offer similar performance at slightly lower vehicle price, but the fuel infrastructure costs may be prohibitive.

## *acknowledgments*

---

With periods of hard acceleration, rapid decelerations, and occasional stalls in the course of writing this thesis, sometimes I felt that I was on the Taipei Motorcycle Driving Cycle myself. Thanks to everyone who had a part in this effort.

Thanks to my advisors Robert Socolow, Bob Williams, and Joan Ogden, and my thesis reader Enoch Durbin.

Thanks to the many people from various research groups, companies, and academic institutions who helped with guidance, hard data, and advice.

Thanks also to my family and friends and colleagues who supported me in the past twelve months, and for many, much longer than that.

Support for this research came from the Center for Energy and Environmental Studies, the Mechanical and Aerospace Engineering Department (including a Daniel and Florence Guggenheim Fellowship and a Sayre Prize), the United States Department of Energy, and the Energy Foundation.

This thesis carries 3055-T in the records of the Department of Mechanical and Aerospace Engineering.

# *table of contents*

---

Abstract .....	i
Table of contents .....	iv
List of tables .....	xi
List of figures .....	xiv
<b>1 Introduction</b> .....	<b>1</b>
1.1 Transportation Background .....	6
1.1.1 Why Taiwan? .....	6
1.1.2 Taiwan vehicle fleet .....	8
1.1.3 Taiwan Energy .....	11
1.2 Air pollution .....	12
1.2.1 The internal combustion engine .....	12
1.2.1.1 The four-stroke spark-ignition cycle .....	13
1.2.1.2 The two-stroke spark-ignition cycle .....	17
1.2.1.3 Advantages and disadvantages .....	20
1.2.2 Pollutants .....	21
1.2.3 Vehicle emissions standards and the reality .....	23
1.2.4 Air pollution sources in Taiwan .....	27
1.2.5 Cleaner combustion technology .....	31
1.2.5.1 Exhaust gas recirculation .....	31
1.2.5.2 Superchargers .....	31
1.2.5.3 Fuel injection .....	32
1.2.5.4 Catalysis of exhaust gases .....	33
1.2.5.5 Replacement by four-stroke engines .....	34

1.2.5.6 Relative costs and benefits of various technologies .....	34
1.2.6 Assessing the damage .....	35
1.2.6.1 Reduction estimate .....	36
1.2.6.2 Externality damage estimate .....	38
1.2.7 Government Policy Approaches .....	40
1.2.7.1 Taiwan policy history: tighter emissions standards .....	40
1.2.7.2 Later years: inspection and maintenance .....	41
1.2.7.3 Future direction: zero-emission vehicles .....	42
1.2.7.4 Research interest in fuel cell scooters .....	44
1.2.8 Conclusion .....	45
References for Chapter 1 .....	46
<b>2 Electric Vehicles .....</b>	<b>51</b>
2.1 Drive Systems .....	53
2.1.1 Electric drive systems: introduction .....	54
2.1.2 Electric motor theory .....	55
2.1.2.1 DC motors .....	56
2.1.2.2 AC motors .....	57
2.1.2.3 Hub motors .....	58
2.1.3 Converters and controllers .....	59
2.1.4 Choice .....	60
2.2 Chemical batteries .....	63
2.2.1 Theory .....	64
2.2.2 Technology .....	65

2.2.2.1 Existing scooter battery systems	65
2.2.2.2 Technology predictions	66
2.2.2.3 Lead-acid batteries	68
2.2.2.4 NiMH and NiCd batteries	69
2.2.2.5 Lithium variants	70
2.2.2.6 Zinc-air “regenerative” batteries	70
2.2.2.7 Summary	73
2.2.3 Peaking power and batteries for hybrids	74
2.2.3.1 Peaking battery modeling	76
2.2.3.2 Charge and discharge	78
2.2.3.3 Hybrid battery conclusion	79
References for Chapter 2	80
<b>3 The hydrogen fuel cell power system</b>	<b>83</b>
3.1 Fuel Cell Science	85
3.1.1 Fundamentals	85
3.1.1.1 Thermodynamics	86
3.1.1.2 Kinetics	91
3.1.1.3 A note on efficiency	94
3.1.2 Types of fuel cells	95
3.1.2.1 Phosphoric Acid Fuel Cell: well-developed, low density	96
3.1.2.2 Proton Exchange Membrane Fuel Cell: for mobile applications, the best	97
3.1.2.3 Alkaline Fuel Cell: poisoned by carbon dioxide	101
3.1.2.4 Solid Oxide and Molten Carbonate Fuel Cells: higher temperature	102

3.1.2.5 Direct Methanol Fuel Cells: long-term promise	102
3.1.3 Stack characteristics	104
3.1.3.1 Fuel cell stack specifications	105
3.1.3.2 Published results for automobile fuel cell stacks	105
3.1.3.3 Detailed construction	106
3.1.3.4 Detailed construction results	110
3.1.4 Gas flow management	111
3.1.4.1 Blowers	112
3.1.4.2 Compressors	113
3.1.5 Water management	114
3.1.6 Heat	116
3.1.6.1 Active cooling	118
3.1.6.2 Passive cooling	118
3.1.6.3 Boiling refrigerant	119
3.2 Fuel for the fuel cell	120
3.2.1 Reformed fuels	120
3.2.1.1 Hydrocarbon reforming	120
3.2.1.2 Methanol reforming example	125
3.2.1.3 Ammonia	126
3.2.1.4 Chemical hydride energy storage	128
3.2.2 Direct hydrogen storage	131
3.2.2.1 Safety	131
3.2.3 Metal hydride energy storage	133
3.2.3.1 Thermodynamics	134

3.2.3.2 Kinetics .....	137
3.2.3.3 Classification .....	138
3.2.3.4 Metal hydride performance .....	139
3.2.4 Compressed gas storage .....	142
3.2.4.1 Cylinder performance .....	143
3.2.4.2 Cylinder safety .....	145
3.2.5 Liquid hydrogen storage .....	146
3.2.6 Selection .....	147
References for Chapter 3 .....	149
<b>4 Modeling and design .....</b>	<b>154</b>
4.1 Performance requirements .....	156
4.2 Vehicle modeling .....	160
4.2.1 Physical model .....	160
4.2.2 Modeling parameter selection .....	164
4.2.3 Relative importance of various factors .....	165
4.2.4 Validation .....	168
4.3 Driving Cycle .....	170
4.3.1 TMDC .....	172
4.3.2 Modification of TMDC .....	176
4.3.3 Torque vs. rpm requirements .....	180
4.3.4 Modeling results .....	183
4.3.4.1 Battery powered scooter .....	184
4.4 Fuel Cell System Design and Integration .....	186

4.4.1 Design tradeoffs	186
4.4.1.1 Maximum power and the polarization curve	187
4.4.1.2 Power density	188
4.4.1.3 Number of cells	189
4.4.1.4 Flow rate parameters	190
4.4.2 Gas subsystem	191
4.4.3 Water subsystem	192
4.4.4 Cooling subsystem	192
4.4.4.1 Cooling from storage system	194
4.4.4.2 Active cooling	196
4.4.4.3 Heat generation under the TMDC	198
4.4.4.4 Selection	202
4.5.4 Overall parasitics	203
4.5 Integrated Model	206
4.5.1 System performance	206
4.5.2 Size and weight of power system	208
4.5.3 Evaluation	211
4.6 Pressurized fuel cell option	213
4.7 Hybrid option designs	215
4.7.1 Types of hybrids	216
4.7.2 Fuel cell sizing	218
4.7.3 Peaking battery and operation policy	221
4.7.4 Simulation results	222
4.7.5 Hybrid power system designs	228

4.7.5.1 Design for 3.2 kW fuel cell .....	229
4.7.5.2 Design for 1.1 kW fuel cell .....	231
4.7.5.3 Hybrid zinc-air scooters .....	232
4.7.6 Hybrid results .....	234
4.7.7 Near-term possibilities .....	237
References for Chapter 4 .....	239
<b>5 Implementation and Conclusions .....</b>	<b>242</b>
5.1 Scooter cost .....	243
5.1.1 Base cost by subtraction .....	244
5.1.2 Cost of hydrogen storage system .....	245
5.1.3 Fuel cell system cost based on parts predictions .....	246
5.1.3.1 The short term .....	249
5.2 Wells-to-wheels efficiency .....	250
5.3 Fuel cost and infrastructure .....	251
5.3.1 Zinc-air battery “fuel” costs .....	253
5.3.2 Hydrogen costs and infrastructure .....	255
5.3.3 Combustion scooter gasoline costs .....	257
5.3.4 Fuel cost summary .....	257
5.4 Final conclusions .....	259
5.4.1 Background .....	260
5.4.2 Modeling results .....	261
5.4.3 Design .....	262
5.4.4 Costs and infrastructure .....	263

5.4.5 Parting words	265
References for Chapter 5	267
<b>Appendices</b>	268
A. Electric scooters	268
B. Detailed stack cost/size analysis	269
C. Radiator performance curves	284
D. Conversion factors	286
E. Acronyms and abbreviations	286
F. MATLAB simulation	288
G. A prototype scooter	300

## *list of tables*

---

### *Chapter 1*

1.1	Motorcycle populations in selected countries, 1993	6
1.2	VMT data for Taipei, 1987	11
1.3	A comparison of vehicle emissions standards	24
1.4	Data on motorcycle emissions: four-strokes and catalysts	26
1.5	Simulated emissions from more realistic driving cycle	26
1.6	PSI subindex pollutants in Taiwan	29
1.7	Cleanup technology, effects and prices	35
1.8	ITRI prediction of effects of scooter replacement on pollution	37
1.9	Estimate of externality damages from air pollutants	38
1.10	Electric Motorcycle Development Action Plan	43

## *Chapter 2*

2.1	Comparison of power systems	54
2.2	Motor specifications: UQM brushless and NGM hub motors	61
2.3	ZES-2000 electric scooter performance	66
2.4	Battery goals for various time frames	67
2.5	Peaking power battery characteristics	76

## *Chapter 3*

3.1	Stack size, weight, cost summary	110
3.2	Fuel gravimetric and volumetric energy densities, lower heating value basis	121
3.3	Steam reforming versus partial oxidation	122
3.4	Hydrogen output from reformed hydrocarbon fuels	124
3.5	Reformer performance	126
3.6	Chemical hydride comparison	129
3.7	Theoretical performance of various metal hydrides	138
3.8	Metal hydride systems comparison	141
3.9	Compressed gas options	145
3.10	Storage technology comparison	148

## *Chapter 4*

4.1	Performance of various vehicles of about 5 kW power	157
4.2	Fuel cell scooter performance requirements	159
4.3	Typical modeling parameters	164
4.4	Validation of physical model	168
4.5	Driving cycle comparison	174
4.6	Effects of “jitter”	175

4.7	Results of different algorithms applied to TMDC; comparison to FTP	178
4.8	Taiwan battery-powered scooter	185
4.9	Various battery-powered designs for Taiwan scooter	185
4.10	Fuel cell design parameters at maximum power	190
4.11	Flow rate parameters at maximum power	191
4.12	Stack temperature model parameters	200
4.13	System performance under TMDC and at cruising speed	208
4.14	Subcomponent summary	208
4.15	Size of various storage designs	209
4.16	Hybrid 1.1 kW scooter inadequacies	219
4.17	Hybrid fuel cell stack designs	221
4.18	Peaking power battery characteristics	221
4.19	Hybrid performance at 30 km/h	223
4.20	Hybrid performance under TMDC	223
4.21	Hybrid system design	229
4.22	Component breakdown for 3.2 kW scooter	230
4.23	Component breakdown for 1.1 kW scooter	232
4.24	Hybrid battery configuration for Taiwan scooter model	233
4.25	Hybrid power system summary	235
4.26	Performance metrics	236
4.27	Near term 1 kW fuel cell hybrid designs	238

## *Chapter 5*

5.1	Internal combustion engine scooter parts	244
5.2	Battery-powered electric scooter parts	245
5.3	Metal hydride storage costs	245
5.4	Long-term scooter cost to manufacture	247

5.5	Summary of cost estimates	248
5.6	Short term bridging to the future	249
5.7	Taiwan vs. USA energy prices, 1997 USD	252
5.8	Fuel costs of Taiwan in \$/GJ LHV	252
5.9	Comparison of assumptions for zinc-air electrowinning costs	253
5.10	Fuel cost summary	258
5.11	Fuel cell scooter performance requirements	261
5.12	System design results	263
5.13	Long-term cost of hybrid fuel cell scooters	264
5.14	Fuel cost summary	264

## *list of figures*

---

### *Chapter 1*

1.1	A scooter	3
1.2	Taiwan vehicle mix 1991-1998	9
1.3	Scooter distribution in Taiwan 1991-1998	9
1.4	Four-stroke cycle	15
1.5	Two-stroke cycle	18
1.6	Carbon monoxide emissions by source	28
1.7	Hydrocarbon emissions by source	28
1.8	PSI in Taiwan, 1994-1996	50

### *Chapter 2*

2.1	Axial-gap pancake motor	59
2.2	Typical torque vs. rpm curve for DC motor	63

2.3	Voltage and internal resistance of Bolder peaking battery	78
-----	---	----

### *Chapter 3*

3.1	Fuel cell schematic	87
3.2	Tafel plot	92
3.3	Effects of pressurization on polarization curves	94
3.4	Nafion chemical structure	98
3.5	Stack diagram	100
3.6	Active cell	109
3.7	Ignition energy of hydrogen	132
3.8	Metal hydride adsorption curve	136

### *Chapter 4*

4.1	Free body diagram of scooter	161
4.2	Cruising power required at various speeds	166
4.3	Power required to climb various slopes at 15 km/h	166
4.4	Power required for various accelerations from 30 km/h	167
4.5	Validation of physical model	169
4.6	mFTP: modified Federal Test Procedure	171
4.7	ECE-40	172
4.8	Taipei Motorcycle Driving Cycle (TMDC)	173
4.9	Smoothed TMDC	180
4.10	Torque vs. rpm during TMDC	182
4.11	Power required in TMDC	183
4.12	Polarization curve	187
4.13	Metal hydride cooling vs. power	195
4.14	Heat generation as a function of time in TMDC	198

4.15	Stack temperature as a function of time in TMDC	201
4.16	Parasitics as a function of power	204
4.17	Parasitics as a percentage of power	205
4.18	Effect of parasitics on efficiency	206
4.19	Weights of subsystems	212
4.20	Volumes of subsystems	212
4.21	Atmospheric power versus 3 atm power	214
4.22	Division of power between fuel cell and battery during TMDC, 3.2 kW stack	225
4.23	State of charge of battery over TMDC, 3.2 kW stack	226
4.24	Division of power between fuel cell and battery during TMDC, 1.1 kW stack	227
4.25	State of charge of battery over TMDC, 1.1 kW stack	228