

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Potential of Series Hybrid Drive Systems to Reduce Fuel Use and Emissions in Domestic Vehicles

A thesis presented in partial fulfillment of the requirements for the degree of

Master of Technology
in
Energy Management

at Massey University, Palmerston North,
New Zealand.

Richard Yates

2005

SUMMARY

Hybrid vehicles use both an internal combustion engine and an electric motor to provide propulsion resulting in reduced fuel consumption and emissions when compared to the conventional approach. In this study computer modelling was employed to assess the potential of series hybrid drive systems to reduce fuel use and emissions in domestic vehicle transport. Selected reference vehicles equipped with conventional drive systems were compared with those same vehicles equipped with a selected range of series hybrid drive system options to assess their potential for fuel use and emissions reduction during two standard drive cycles simulating urban and aggressive driving patterns respectively. The modelling emphasis was placed on efficient drive systems, component downsizing, efficient combustion cycles and control strategies. The computer simulations indicated the potential for significant reductions in fuel use and emissions by domestic vehicles equipped with series hybrid drive systems when compared to domestic vehicles equipped with conventional drive systems. Series hybrid drive systems equipped with a Diesel cycle engine as the internal combustion component of the on-board power source showed the greatest overall reductions. Computer simulations also accounted for the input from the main electrical grid network (for on-board battery recharging) and its effect on fuel use and emissions and found potential for even further reductions particularly in regions where the source of grid electricity has a low environmental impact.

ACKNOWLEDGEMENTS

I would like to thank Professor Ralph Sims and the Massey University Institute of Technology and Engineering for allowing me to undertake this thesis. Ralph has also been an immense help during the thesis process.

CONTENTS

SUMMARY	II
ACKNOWLEDGEMENTS	III
LIST OF FIGURES	VII
LIST OF TABLES	VIII
1.0 INTRODUCTION	1
1.1 APPROACH AND METHODOLOGY OF THE THESIS	2
1.1.1 Thesis outline	3
1.2 THE AUTOCENTRICITY OF MODERN SOCIETY	4
1.3 ENVIRONMENTAL IMPACTS	8
1.3.1 Carbon dioxide	8
1.4 HEALTH CONCERNS FROM EMISSIONS	9
1.4.1 Carbon monoxide	9
1.4.2 Unburned hydrocarbons	9
1.4.3 Nitrous oxides	10
1.5 OIL DEPENDENCE	10
1.6 GLOBAL PEAK IN OIL EXTRACTION	13
1.7 METHODS OF REDUCING FUEL USE AND EMISSIONS IN CONVENTIONAL VEHICLES	16
1.7.1 Weight reduction	16
1.7.2 Aerodynamic design	17
1.7.3 Reduced rolling resistance	17
1.7.4 Alternative fuels	18
1.7.5 Improved engine efficiency	20
1.7.6 Reduced accessory loads	20
1.7.7 Reduced idling loss	20
1.7.8 Reduced braking and deceleration loss	20
1.7.9 Reduced heat loss	21
1.7.10 Mass transport	21
1.7.11 Efficient alternative vehicle technologies	21
2.0 CURRENT DOMESTIC TRANSPORT TECHNOLOGIES	24
2.1 INTERNAL COMBUSTION ENGINE TECHNOLOGIES	24
2.2 PART LOAD EFFICIENCY	26
2.3 CURRENT ALTERNATIVES TO CONVENTIONAL DOMESTIC TRANSPORT TECHNOLOGIES	27
2.3.1 Electric vehicles	27
2.3.2 Electric drive	28
2.3.3 Batteries	30
2.3.4 Ultra-capacitors	32
2.3.5 Flywheels	33
2.3.6 Fuel cells	34
3.0 HYBRID VEHICLES	37
3.1 PARALLEL HYBRIDS	39
3.2 SERIES HYBRID DRIVE SYSTEM	39
3.3 DUAL MODE HYBRID DRIVE SYSTEM	40
4.0 SERIES HYBRID DRIVE SYSTEMS	42
4.1 COMPARISONS OF ENERGY FLOW PATHS	45
4.2 DOWN SIZING	46
4.3 ADAPTABILITY TO OTHER TECHNOLOGIES	48
4.4 OPERATIONAL, DESIGN, AND MARKETING ISSUES	49
4.5 MODELLING	51
5.0 REFERENCE VEHICLE MODEL	53
5.1 METHODOLOGY OVERVIEW	53
5.2 GENERAL VEHICLE PARAMETERS	54
5.3 DRIVE CYCLE MODEL	55
5.3.1 Initial speed and final speed	57
5.3.2 Average speed	57
5.3.3 Acceleration	57

5.4 TRANSMISSION MODEL.....	58
5.4.1 Transmission methodology and efficiency.....	58
5.4.2 Final drive efficiency.....	61
5.5 ROAD-LOAD MODEL.....	61
5.5.1 Air resistance.....	61
5.5.2 Rolling resistance.....	62
5.5.3 Inertial resistance.....	63
5.5.4 Road load energy requirement.....	63
5.5.5 Road-load calculation.....	65
5.6 ENGINE MODEL.....	65
5.6.1 Torque and power.....	65
5.6.2 Brake mean effective pressure.....	66
5.6.3 Engine friction.....	66
5.7 FUEL USE MODEL.....	68
5.7.1 Methodology.....	68
5.7.2 Fuels.....	68
5.7.3 Fuel consumption calculation.....	69
5.8 EMISSIONS.....	71
5.8.1 Equivalence ratio.....	71
5.8.2 Combustion stoichiometry.....	71
5.8.3 Otto cycle emissions.....	73
5.8.4 Diesel cycle emissions.....	74
5.8.5 Emissions species considered.....	74
5.8.6 Emissions calculation.....	75
5.9 SYSTEM EFFICIENCY.....	77
5.10 MODEL VALIDATION.....	78
6.0 SERIES HYBRID DRIVE SYSTEM MODEL.....	81
6.1 METHODOLOGY OVERVIEW.....	81
6.2 STORAGE (BATTERY) MODEL.....	82
6.2.1 Battery type.....	83
6.2.2 Battery specific power density.....	83
6.2.3 Battery weight.....	84
6.2.4 Battery specific energy density.....	84
6.2.5 Battery capacity.....	84
6.2.6 State of charge.....	85
6.2.7 Charge and discharge efficiency.....	85
6.2.8 Methodology.....	86
6.3 ELECTRIC MOTOR MODEL.....	87
6.3.1 Motor power.....	87
6.3.2 Motor specific power and weight.....	88
6.3.3 Motor efficiency.....	88
6.3.4 Final drive.....	88
6.4 ENERGY REGENERATION MODEL.....	89
6.4.1 Regeneration energy status.....	89
6.4.2 Regenerative braking output.....	89
6.5 ON-BOARD POWER SOURCE (OPS) MODEL.....	90
6.5.1 Generator efficiency.....	91
6.5.2 Generator output.....	91
6.5.3 Generator weight.....	91
6.5.4 OPS status.....	92
6.5.5 OPS output.....	92
6.5.6 Internal combustion engine.....	93
6.5.7 Engine weight.....	94
6.5.8 Engine friction.....	95
6.6 POWER CONTROLLER/INVERTER MODEL.....	95
6.6.1 Control strategy.....	96
6.6.2 Inverter/controller efficiency.....	98
6.6.3 Inverter/controller power density and weight.....	98
6.7 VEHICLE WEIGHT MODEL.....	98
6.7.1 Shell weight.....	98
6.7.2 Mounting weight.....	99
6.7.3 Total weight.....	99

6.8 USE OF GRID RECHARGING.....	99
6.9 DRIVE CYCLE MODEL.....	100
6.10 ROAD LOAD MODEL.....	101
6.11 FUEL USE MODEL.....	102
6.12 EMISSIONS MODEL.....	104
6.13 SYSTEM EFFICIENCY.....	105
7.0 RESULTS AND DISCUSSION.....	108
7.1 FUEL USE.....	108
7.2 EMISSIONS.....	113
7.3 CARBON DIOXIDE EMISSIONS.....	113
7.4 CARBON MONOXIDE EMISSIONS.....	115
7.5 NITROGEN OXIDE EMISSIONS.....	118
7.6 HYBRID DRIVE SYSTEM OPTION COMPARISONS.....	122
7.7 SYSTEM EFFICIENCY.....	124
8.0 CONCLUSIONS AND FUTURE WORK.....	127
8.1 FUTURE WORK.....	130
8.2 EPILOGUE.....	131
APPENDIX A.....	133
REFERENCES.....	135

LIST OF FIGURES

Figure 1-1. Fuel efficiency trends of domestic transport over two decades for various countries (IEA, 2001b).	6
Figure 1-2. Fuel use per unit weight and average vehicle weight for various countries (IEA, 2001b).	6
Figure 1-3. Transport sector proportion of total OECD oil demand (IEA, 2000c).	12
Figure 1-4. Incremental oil demand by sector between actual demand in 1997 and assumed demand in 2020 (IEA, 2000a).	12
Figure 1-5. Bell curve of actual and predicted annual fuel use since 1900 (World watch institute, 2002).	14
Figure 2-1. Efficiency vs. rotational engine speed and cylinder pressure for a 135hp and a 16hp ICE. Source: CAE (1996).	26
Figure 3-1. Parallel hybrid drive system (York Tech, 2000).	39
Figure 3-2. Series hybrid drive system (York Tech, 2000).	40
Figure 3-3. Dual mode hybrid drive system (York Tech, 2000).	41
Figure 4-1. Comparison of energy flows in conventional, pure electric and series hybrid drive systems.	46
Figure 5-1. Speed versus time plots of NYCC and US06 drive cycles over 4 km and 12.8 km respectively (Dieselnet, 2005).	56
Figure 5-2. Relationship between CO ₂ , CO, NO _x and equivalence ratio for a Diesel cycle ICE.	76
Figure 7-1. Fuel use versus drive system option.	109
Figure 7-2. Carbon dioxide emissions versus drive system option.	114
Figure 7-3. Carbon monoxide emissions versus drive system option.	116
Figure 7-4. Nitrogen oxide emissions versus drive system option.	119
Figure 7-5. System efficiency versus drive system option.	125
Figure A-1. Chemwork6 output screen: Otto cycle combustion (expansion phase) of iso-octane for an equivalence ratio of 1 (fixed).	133
Figure A-2. Chemwork6 output screen: Diesel cycle combustion (expansion phase) of cetane for an equivalence ratio of 0.5 (variable).	134

LIST OF TABLES

Table 2-1. Energy storage comparisons	32
Table 5-1. Vehicle Parameters for 4 selected reference vehicles.....	54
Table 5-2. Vehicle gear shift points and gear ratios.....	59
Table 5-3. Coefficients for the various vehicle torque output curves.....	61
Table 5-4. Fuel Properties.....	69
Table 5-5. Input data used for chemwork6.	75
Table 5-6. Pollutant gases in proportion to equivalence ratio used during Otto cycle combustion of iso-octane.....	77
Table 5-7. Pollutant gases in proportion to equivalence ratios used during diesel combustion of cetane.....	77
Table 5-8. Coefficients for the pollutant species.	77
Table 6-1. Engine parameters for the series hybrid drive system options.	93
Table 6-2. Friction relationships for the various engines used in the series hybrid drive system.....	95