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**Cooperative Research and Development
Agreement Between The California Air
Resources Board and Lockheed-Martin
Idaho Technologies Company**

FINAL REPORT

G. H. Cole

LOCKHEED MARTIN

The Lockheed Martin logo, which consists of a stylized, multi-pointed star or arrow shape pointing upwards and to the right.

**Cooperative Research and Development Agreement
Between
The California Air Resources Board
And
Lockheed-Martin Idaho Technologies Company**

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April 1998

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

**Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy (EE)
Under DOE Idaho Operations Office
Contract DE-AC07-94ID13223**

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**Cooperative Research and Development Agreement
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And
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Final Report**

INTRODUCTION

This report summarizes the activities under a Cooperative Research and Development Agreement (CRADA) between Lockheed-Martin Idaho Technologies Company (LMITCO) and the California Air Resources Board (CARB). The activities were performed at the Idaho National Engineering and Environmental Laboratory (INEEL) between June 1995 and December 1997.

Work under this agreement was concentrated in two task areas as defined in the California Air Resources Board's contract number 94-908 having an approval date of June 9, 1995: Task 1 - EV and HEV Vehicle Testing and Assessment and Task 4 - Advanced Battery Testing.

ADVANCED VEHICLE TESTING

Under the Advanced Vehicle Testing task, chassis dynamometer and road tests were performed on three electric vehicles: an U. S. Electricar Geo Prism sedan, a Ford Ecostar, and a TDM pickup. Additionally, coast-down tests were performed on a Hyundai sedan. All data recorded during the testing of these vehicles is archived at the INEEL and is available upon request.

U. S. Electricar Geo Prism Tests

A full range of chassis dynamometer performance tests were performed on a 1994 U. S. Electricar Geo Prism electric vehicle conversion borrowed from the Los Angeles Department of Water and Power. The results of these tests indicated a driving range of between 71 km and 95 km, depending upon the type of driving, which is judged to be inadequate for widespread customer acceptance. Computer simulations were conducted and validated using the dynamometer test data. Investigations using the computer model indicated vehicle range could be improved significantly by using advanced battery technologies having higher specific energy than the sealed lead-acid batteries furnished with the vehicle.

The net DC energy consumption, as a function of the vehicle test weight measured over the UDDS driving cycle, did not indicate any improvement over vehicles previously tested representing earlier (1994) technologies.

The vehicle proved highly reliable during the test program, with no breakdowns occurring. The improved charge algorithm supplied by U. S. Electricar to shorten the time necessary to charge the traction battery from approximately 18 hours to 8 hours worked well. Data recorded during the charge half-cycle showed that the battery recharge was very consistent.

A summary of the results of the tests performed on the U. S. Electricar Geo Prism conversion vehicle is contained in the Appendix to this report. A more detailed description and the complete results of this test program were published in the report "Dynamometer Testing of the U. S. Electricar Geo Prism Conversion Electric Vehicle", INEL-96-0090, April 1996.

Ford Ecostar Tests

A Ford Ecostar electric vehicle powered by a sodium-sulfur battery was tested on the chassis dynamometer over two standard driving regimes. The test vehicle was delivered to the INEL on February 19, 1995 under the DOE sponsored Modular Electric Vehicle Program (MEVP). Tests sponsored by the DOE were concluded in June 1995. Subsequently, additional testing was requested by the California Air Resources Board (CARB) to obtain test data that could not be gathered under the DOE-sponsored testing because of funding constraints. Specifically, CARB was interested in obtaining the actual road coast-down parameters and traction battery charge data for this vehicle. A series of on-road vehicle coast-down and dynamometer tests were performed. The dynamometer tests used the Federal Urban Dynamometer Driving Schedule (UDDS), and Highway Fuel Economy Test driving schedules. Time based traction battery charge data was recorded after the dynamometer driving schedule tests. The equipment and methods required to obtain the charge data was difficult to design and required very elaborate instrumentation techniques.

Vehicle coast-down tests were performed on a smooth level roadway located on the INEEL property. Differences between the calculated speed-dependent road load measured by Ford and derived from these tests were observed. INEL calculated the Ecostar road load as a result of the coast-down tests as being approximately 7% higher than that previously determined from Ford's coast-down data.

Energy consumption over the two different dynamometer driving schedules were measured using the force-speed relationships derived from the coast-down tests performed by INEEL. The energy consumption measured on the Urban Dynamometer Driving Schedule (UDS) and the Highway Fuel Economy Test (HWFET) driving schedule were 204 and 188 Wh/km, respectively. The distance driven on these two driving regimes was 120 and 199 km, respectively. An anomaly in the vehicle caused the system to shut off during a rest period near the end of the tests. Therefore, these distances do not represent the full driving range of the vehicle.

A summary of the results of the tests performed on the Ford Ecostar vehicle is contained in the Appendix to this report. This summary includes the results of the DOE sponsored tests. A more detailed description and the complete results of this test program were published in the report "Additional Dynamometer Tests of the Ford Ecostar Electric Vehicle #41", DOE/ID-10543, June 1996.

TDM Pickup Truck Tests

A Ford Ranger pickup truck converted to electric power by TDM, Inc. was chassis dynamometer tested in the INEEL HEV Laboratory. Driving distance on a single battery charge ranged from a low of 45.7 km on the Air Resources Board's "All Electric" Driving Schedule and a high of 76.6 km on the Urban Dynamometer Driving Schedule. Net DC energy consumption on the standard driving schedules ranged from 274 to 335 Wh/km. AC Energy Consumption for this vehicle was disappointing due to the inefficient battery charger. The vehicle required 616 Wh of energy for each kilometer traveled to recharge the battery pack. Vehicle acceleration was also judged to be slower than most internal combustion engine vehicles of this type. An acceleration time of 28.4 seconds was measured for maximum effort acceleration to 96 km/h with the traction battery state-of-charge near 50%. Calculations from the test data indicated that the maximum gradeability the vehicle at 96 km/h and 50% battery SOC is 2.3%.

A summary of the results of the tests performed on the TDM pickup truck is contained in the Appendix to this report. A more detailed description and the complete results of this test program were published in the report "Dynamometer Tests of the Ford/TDM Ranger Electric Pickup Truck", INEL/EXT-97-00692, June 1997.

Hyundai Accent Coast-down Tests

Tests to determine the road load forces as a function of vehicle speed were performed on an experimental electric vehicle built by Hyundai America Technical Center, Inc. for purposes of performing dynamometer tests on this vehicle. The method was that which is routinely used at the INEEL for calibrating our dynamometer and specified by the Society of Automotive Engineers Recommended Practice SAE J1263. . Eight coast-down pairs were analyzed for

statistical validity, which resulted in 5 valid pairs for determining the road load. The resultant road load force as a function of vehicle speed corrected to standard conditions was calculated from test data as:

$$F = 41.69 + .02508 v^2$$

where F the road force in lbs. and v is the vehicle speed in mph.

The maximum effort acceleration of the vehicle was also measured. These measurements and the calculated coast-down times to be used for dynamometer calibration were provided via a letter report in October 1996.

ADVANCED BATTERY TESTING

Under the Advanced Battery Testing task, performance and characterization tests were performed on two advanced electric vehicle batteries: a sodium nickel chloride battery manufactured by AEG and a nickel metal chloride battery manufactured by Ovonic Battery Company. A state-of-the-art lead acid battery was purchased and conditioned for use by Southern California Edison Company in their electric vehicle test fleet. Investigations into the requirements of energy storage devices for hybrid vehicle propulsion applications were conducted and a test method for these types of batteries was formulated. This effort was performed with the cooperation of the U. S. Department of Energy/USABC Partnership for New Generation of Vehicle (DOE/USABC PNGV) Program Energy Storage Team. All data recorded during the testing of these batteries is archived at the INEEL and is available upon request.

AEG Z5 Sodium-Nickel-Chloride Battery Tests

A total of 42 charge/discharge cycles was performed on an AEG Z5 battery. The discharge cycles consisted of constant current and constant power discharges, United States Advanced Battery Consortium Dynamic Stress Test (DST), and peak power tests. These data were verified and transmitted via a letter report in November 1995. Constant current discharge tests verified the manufacturer's rated capacity. The peak power of the battery was determined to be 126 W/kg at 0% depth-of-discharge and 65.1 W/kg at 80% depth-of-discharge. The battery exhibited consistent performance over the forty-two charge/discharge cycles. The life test portion of the planned test program was not performed per mutual agreement. At the conclusion of our tests, the battery was shipped to Southern California Edison Company for further evaluation.

Ovonic Battery Company Nickel Metal Hydride Battery Tests

A 190-volt nickel metal hydride battery pack manufactured by Ovonic Battery Company was performance tested. This battery pack represented Ovonic's designated Generation I+A state of this battery technology development. The battery was tested utilizing the test procedures developed by the United States Advanced Battery Consortium. Throughout the twenty-nine cycles of the test program, all modules appeared balanced and the capacity proved adequate to successfully perform each test. Results of the tests confirmed the manufacturer's ratings for ampere-hour capacity and peak power capability (100 Ah and 150 W/kg at 80% depth-of-discharge). Complete results of this test program were reported via a letter report in December 1997. At the conclusion of our tests, the battery was shipped to Southern California Edison Company for further evaluation.

Optima Sealed Lead-Acid Battery Pack Conditioning

An "advanced" sealed lead-acid battery pack consisting of 28 Optima "Yellow Top" modules was obtained and conditioned in the INEEL Energy Storage Technologies Laboratory for eventual field evaluation by Southern California Edison Company. Initially, a wide range of module imbalance detracted from the full potential capacity of the twenty-eight-module battery pack. We worked closely with the battery manufacturer to complete the conditioning of these modules via modified charge algorithms using the laboratory battery testers. After several cycles

on different groups of modules, full rated capacity was obtained and thus the battery pack was qualified for vehicle use. The 28 fully conditioned modules were shipped AC Propulsion in San Dimas, CA for further evaluation in an electric vehicle. The results our activity was transmitted via letter report in December 1997.

Other Advanced Battery Testing Activities

A new test procedure was developed, in cooperation with DOE/USABC PNGV Program Energy Storage Team, for testing high-power energy storage devices in a power assist-type hybrid vehicle. This procedure is designed to exercise a high power battery at power levels in excess of those used for conventional EV batteries (i.e. 150 to 1000 W/kg) while maintaining it continuously in an intermediate state of charge. This procedure was tested using two lead-acid battery packs: one comprised of Hawker Genesis modules and one comprised of Electrosorce modules. Results of the trial tests suggest that selecting the state-of-charge operating region for hybrid energy storage devices is critical because of the relatively narrow voltage swing which will be allowable between maximum regeneration and minimum discharge conditions.

A number of small Sony lithium ion batteries were also acquired, and a test matrix was developed for these batteries to investigate several aspects of high power performance and test methods for advanced technologies. Because Sony has not disclosed their approach to charging these batteries, a preliminary charging investigation was conducted using a Sony charger to identify their preferred approach to proper charging. This activity was performed because prior testing of these batteries yielded somewhat inconsistent results, including unexpectedly rapid performance deterioration, and the charge half-cycle was one of the primary suspected causes for this behavior.

PROJECT MANAGEMENT

During the period of performance, two project review meetings were held at the Air Resources Board offices in El Monte, CA in August 1995 and August 1996. Additional project management activities included tracking and reporting of costs, and preparation and transmittal of bimonthly progress reports.

The following reports of the efforts under this CRADA were published. Copies are available upon request.

- *"Dynamometer Testing of the U. S. Electricar Geo Prism Conversion Electric Vehicle"*, INEL-96-0090, April 1996
- *"Additional Dynamometer Tests of the Ford Ecostar Electric Vehicle #41"*, DOE/ID-10543, June 1996
- *"Dynamometer Tests of the Ford/TDM Ranger Electric Pickup Truck"*, INEL/EXT-97-00692, June 1997.

■

APPENDIX A

Test Result Summary Sheets

TEST RESULTS SUMMARY SHEET

INEEL Hybrid/Electric Vehicle Laboratory

VEHICLE DESCRIPTION	TEST RESULTS																																																											
VEHICLE TYPE Manufacturer: U. S. Electricar Model: 1994 Geo Prism (conversion) VIN: 1Y1SK5363RZ082892 Seating Capacity: 4 Drive configuration: Front motor, front wheel drive	40A (C/3 rate) CONSTANT CURRENT RANGE (Average of two tests) <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td>Range (km)</td> <td style="text-align: center;">150</td> </tr> <tr> <td>Net Veh. DC E. C. (Wh/km)</td> <td style="text-align: center;">105</td> </tr> <tr> <td>Average Speed (km/h)</td> <td style="text-align: center;">43</td> </tr> <tr> <td>AC E. C. (Wh/km)</td> <td style="text-align: center;">166</td> </tr> </table>	Range (km)	150	Net Veh. DC E. C. (Wh/km)	105	Average Speed (km/h)	43	AC E. C. (Wh/km)	166																																																			
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DIMENSIONS Wheelbase: 2459 mm Track F/R: 1461/1440 mm Length: 1461 mm Width: 1692 mm Height: 1402 mm Ground Clearance: 165 mm Cargo Volume: N/A	DRIVING CYCLES (Average of two range tests) <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th></th> <th style="text-align: center;">LA92</th> <th style="text-align: center;">UDDS</th> <th style="text-align: center;">HFEDS</th> </tr> <tr> <td>Range (km)</td> <td style="text-align: center;">71</td> <td style="text-align: center;">82</td> <td style="text-align: center;">95</td> </tr> <tr> <td>Net DC E. C. (Wh/km)</td> <td style="text-align: center;">199</td> <td style="text-align: center;">167</td> <td style="text-align: center;">154</td> </tr> <tr> <td>Gross DC E. C. (Wh/km)</td> <td style="text-align: center;">232</td> <td style="text-align: center;">195</td> <td style="text-align: center;">161</td> </tr> <tr> <td>AC E. C. (Wh/km)</td> <td style="text-align: center;">331</td> <td style="text-align: center;">274</td> <td style="text-align: center;">249</td> </tr> </table>		LA92	UDDS	HFEDS	Range (km)	71	82	95	Net DC E. C. (Wh/km)	199	167	154	Gross DC E. C. (Wh/km)	232	195	161	AC E. C. (Wh/km)	331	274	249																																							
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AC E. C. (Wh/km)	331	274	249																																																									
WEIGHTS Curb Weight: 1578 kg Inertia Test Weight: 1714 kg GVWR: 1822 kg	ENERGY ECONOMY @ SPEED (Wh/km) (Average of two tests) <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th rowspan="2">Speed</th> <th colspan="5">Nominal State-of-Charge</th> </tr> <tr> <th style="text-align: center;">100%</th> <th style="text-align: center;">80%</th> <th style="text-align: center;">60%</th> <th style="text-align: center;">40%</th> <th style="text-align: center;">20%</th> </tr> <tr> <td>40 km/h</td> <td style="text-align: center;">142</td> <td style="text-align: center;">108</td> <td style="text-align: center;">107</td> <td style="text-align: center;">103</td> <td style="text-align: center;">102</td> </tr> <tr> <td>48 km/h</td> <td style="text-align: center;">136</td> <td style="text-align: center;">118</td> <td style="text-align: center;">109</td> <td style="text-align: center;">106</td> <td style="text-align: center;">107</td> </tr> <tr> <td>56 km/h</td> <td style="text-align: center;">137</td> <td style="text-align: center;">120</td> <td style="text-align: center;">118</td> <td style="text-align: center;">113</td> <td style="text-align: center;">113</td> </tr> <tr> <td>64 km/h</td> <td style="text-align: center;">140</td> <td style="text-align: center;">129</td> <td style="text-align: center;">125</td> <td style="text-align: center;">122</td> <td style="text-align: center;">122</td> </tr> <tr> <td>72 km/h</td> <td style="text-align: center;">146</td> <td style="text-align: center;">143</td> <td style="text-align: center;">134</td> <td style="text-align: center;">130</td> <td style="text-align: center;">136</td> </tr> <tr> <td>80 km/h</td> <td style="text-align: center;">155</td> <td style="text-align: center;">149</td> <td style="text-align: center;">147</td> <td style="text-align: center;">147</td> <td style="text-align: center;">145</td> </tr> <tr> <td>88 km/h</td> <td style="text-align: center;">165</td> <td style="text-align: center;">160</td> <td style="text-align: center;">155</td> <td style="text-align: center;">154</td> <td style="text-align: center;">155</td> </tr> <tr> <td>96 km/h</td> <td style="text-align: center;">180</td> <td style="text-align: center;">175</td> <td style="text-align: center;">171</td> <td style="text-align: center;">173</td> <td style="text-align: center;">164</td> </tr> </table>	Speed	Nominal State-of-Charge					100%	80%	60%	40%	20%	40 km/h	142	108	107	103	102	48 km/h	136	118	109	106	107	56 km/h	137	120	118	113	113	64 km/h	140	129	125	122	122	72 km/h	146	143	134	130	136	80 km/h	155	149	147	147	145	88 km/h	165	160	155	154	155	96 km/h	180	175	171	173	164
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88 km/h	165	160	155	154	155																																																							
96 km/h	180	175	171	173	164																																																							
WHEELS & TIRES Tire Mfg. & Type: Firestone Tire Size: P175/65R14 Tire Pressure (F/R): 35/35 psi																																																												
DRIVE SYSTEM Type: 3 Phase vector AC Motor: Hughes Power Control Systems Controller Mfg. Hughes Power Control Systems Transmission: Single speed																																																												
BATTERY Mfg.: Hawker Model: Genesis G12V26AH10C Type: Sealed Lead-acid Rated Capacity: 45 Ah @ C/3 Number of Modules: 50 Nominal Voltage: 300 V Weight: approx 500 kg (modules only)																																																												
CHARGER Input Voltage: 110/220 Input Power: NA																																																												
MISCELLANEOUS Power Steering, Power Brakes (front disk) Parameters Derived from Coastdown Aerodynamic drag coefficient: 0.45 Frontal Area (.8 x W x H): 1.90 sq. m. Drag Area Product: 0.85 sq. m. Tire rolling resistance: 0.0105	State-of-Charge Meter Evaluation Acceleration

TEST RESULTS SUMMARY SHEET

INEEL Hybrid/Electric Vehicle Laboratory

VEHICLE DESCRIPTION	TEST RESULTS																																																																		
VEHICLE TYPE Manufacturer: Ford Motor Company Model: Ecostar VIN: IFTCV10E7P3S11041 Seating Capacity: 2 Drive configuration: Front motor, front wheel drive	40A (C/3 rate) CONSTANT CURRENT RANGE <table><tr><td>Range (km)</td><td>243</td></tr><tr><td>Net DC E. C. (Wh/km)</td><td>153</td></tr><tr><td>Average Speed (km/h)</td><td>78</td></tr><tr><td>AC E. C. (Wh/km)</td><td>NA</td></tr></table>	Range (km)	243	Net DC E. C. (Wh/km)	153	Average Speed (km/h)	78	AC E. C. (Wh/km)	NA																																																										
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DRIVE SYSTEM Type: Liquid cooled, AC Motor: 75 HP, 3 phase AC Controller Mfg. Ford/GE Transmission: Single speed Gear Ratio: 12.18																																																																			
BATTERY Mfg.: ABB Type: Sodium-sulfur Rated Capacity: 120 Ah Number of Modules: n/a Nominal Voltage: 330V Weight: ~350 kg																																																																			
CHARGER Input Voltage: 240/120 AC Input Power: 30A@240V, 15A@120V																																																																			
MISCELLANEOUS Solar assisted ventilation, regenerative braking AC/heater, cellular phone, power brakes Parameters Derived from Coastdown Aerodynamic drag coefficient: 0.421 Frontal Area (.8 x W x H): 2.17 sq. m. Drag Area Product: .913 sq. m. Tire rolling resistance: 0.0065	Remaining Range Indicator Evaluation State-of-Charge Meter Evaluation

TEST RESULTS SUMMARY SHEET

INEEL Electric Vehicle Test Laboratory

04/14/98

VEHICLE DESCRIPTION	TEST RESULTS																																																															
VEHICLE TYPE Manufacturer: TDM Inc. Model: Ford Ranger (conversion) VIN: 1FFDR1007TTA301 Seating Capacity: 3 Drive configuration: Front motor, rear wheel drive	ACCELERATION (sec.) <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th rowspan="2">Speed</th> <th colspan="3">State-of-charge</th> </tr> <tr> <th>97%</th> <th>55%</th> <th>34%</th> </tr> </thead> <tbody> <tr><td>0-24 km/h</td><td>2.1</td><td>2.1</td><td>3.7</td></tr> <tr><td>0-32 km/h</td><td>2.8</td><td>2.9</td><td>5.1</td></tr> <tr><td>0-40 km/h</td><td>3.5</td><td>3.8</td><td>7.0</td></tr> <tr><td>0-48 km/h</td><td>4.5</td><td>5.1</td><td>9.5</td></tr> <tr><td>0-56 km/h</td><td>5.8</td><td>6.7</td><td>12.7</td></tr> <tr><td>0-64 km/h</td><td>7.6</td><td>8.8</td><td>17.1</td></tr> <tr><td>0-72 km/h</td><td>9.9</td><td>11.5</td><td>23.0</td></tr> <tr><td>0-80 km/h</td><td>13.0</td><td>14.9</td><td>31.6</td></tr> <tr><td>0-88 km/h</td><td>17.6</td><td>19.9</td><td>47.0</td></tr> <tr><td>0-96 km/h</td><td>24.6</td><td>28.2</td><td>-</td></tr> </tbody> </table>	Speed	State-of-charge			97%	55%	34%	0-24 km/h	2.1	2.1	3.7	0-32 km/h	2.8	2.9	5.1	0-40 km/h	3.5	3.8	7.0	0-48 km/h	4.5	5.1	9.5	0-56 km/h	5.8	6.7	12.7	0-64 km/h	7.6	8.8	17.1	0-72 km/h	9.9	11.5	23.0	0-80 km/h	13.0	14.9	31.6	0-88 km/h	17.6	19.9	47.0	0-96 km/h	24.6	28.2	-																
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DIMENSIONS Wheelbase: 2921 mm Track F/R: 1676/1727 mm Length: 5003 mm Width: 1702 mm Height: 1626 mm Ground Clearance: n/a Cargo Volume: n/a	DRIVING CYCLE RESULTS <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th></th> <th>LA92</th> <th>A-E</th> <th>FUD</th> <th>HWFET</th> </tr> </thead> <tbody> <tr><td>Range (km)</td><td>54.0</td><td>46.8</td><td>65.1</td><td>64.5</td></tr> <tr><td>Net DC E. C. (kWh)</td><td>335</td><td>284</td><td>284</td><td>274</td></tr> <tr><td>Gross DC E. C. (Wh/km)</td><td>367</td><td>297</td><td>310</td><td>281</td></tr> <tr><td>AC E. C. (Wh/km)</td><td>n/a</td><td>n/a</td><td>616</td><td>n/a</td></tr> </tbody> </table> <p>A-E = All Electric Driving Schedule</p>		LA92	A-E	FUD	HWFET	Range (km)	54.0	46.8	65.1	64.5	Net DC E. C. (kWh)	335	284	284	274	Gross DC E. C. (Wh/km)	367	297	310	281	AC E. C. (Wh/km)	n/a	n/a	616	n/a																																						
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CHARGER Input Voltage: 208/220 Input Power: Max. 18 amperes																																																																
MISCELLANEOUS Air conditioning, power steering, power brakes, front disk brakes, tilt steering wheel Traction battery pack located in and under cargo bed. Parameters Derived from Coastdown Road Load Force (N) = $324.1 + 0.06965 v^2$																																																																