PRELIMINARY POWER TRAIN DESIGN FOR A STATE-OF-THE-ART ELECTRIC VEHICLE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER

CONTRACT NAS3-20595

PART OF THE UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
DIVISION OF TRANSPORTATION ENERGY CONSERVATION ELECTRIC AND HYBRID VEHICLE SYSTEMS PROGRAM
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EXECUTIVE SUMMARY
I. INTRODUCTION

- The preliminary design of a state-of-the-art electric vehicle power train is part of a national effort to reap the potential benefit of useful urban electric passenger vehicles.

- The objectives of the program focused on state-of-the-art electric vehicles and components.

- The methodology for the power train study combined literature search, engineering judgment and computer aided analysis.
II. ASSESSMENT OF THE STATE-OF-THE-ART IN ELECTRIC VEHICLE TECHNOLOGY

- The most common approach taken in the design of an electric vehicle power train has been to convert a conventional internal combustion engine vehicle chassis to electric drive.

  - Many hobbyists have built electric vehicles in this country.
  
  - Electric vehicle technology is more advanced in foreign countries.
  
  - By designing from the "ground up", improved performance has been obtained in several experimental research vehicles.
DC MOTORS AND CONTROLLERS REPRESENT A MATURE TECHNOLOGY WHICH IS WELL SUITED TO THE ON-THE-ROAD, ELECTRIC VEHICLE APPLICATION.

THE MECHANICAL PORTION OF AN ELECTRIC VEHICLE POWER TRAIN SERVES TO MATCH THE OUTPUT OF THE MOTOR TO THE LOAD REQUIRED AT THE VEHICLE WHEELS.

- Mechanical Transmissions Generally Sacrifice Efficiency For the Flexibility of Automatic Ratio Change.

- The Radial Tire Represents the State-of-the-Art Tire For an Electric Vehicle.
COMPONENTS WHICH REPRESENT THE CURRENT STATE-OF-THE-ART INCLUDE THE SERIES DC MOTOR, CHOPPER CONTROLLER AND RADIAL TIRES.

- The Rear Mounted Motor/Transaxle Or The Front Wheel Drive Are Preferred Power Train Architectures.

- The Selection of an Optimum Power Train Requires a Systems Analysis of the Hardware Operating Over the Drive Cycle.
III. STATE-OF-THE-ART POWER TRAIN DESIGN

- The calculation of range proceeds by accounting for the energy consumed by the components and then drawn from the batteries as the vehicle operates over a driving cycle.

- Analyses served to establish the maximum potential range, the sensitivity of range to the component parameters and to size the components.

- An ideal, 3,600 Pound Vehicle Can Achieve a Range of 50 Miles Over the SAE J227a/D Driving Cycle and 75 Miles at a Constant 55 MPH.

- Lighter Weight Vehicles, Lower Tire Rolling Resistance and the Use of Regenerative Braking Are Most Effective in Extending Range.

THE STATE-OF-THE-ART POWER TRAIN CONSISTS OF A DC SERIES WOUND MOTOR, SCR CONTROLLER, V-BELT TRANSMISSION, LOW-LOSS DIFFERENTIAL AND RADIAL TIRES.

DRIVE TRAIN UTILIZING THE "V" BELT TRANSMISSION

TIRES

DRIVE CHAIN

DIFFERENTIAL

ELECTROMATIC TRANSMISSION

MOTOR

UNIVERSAL DRIVE SHAFTS
IV. IMPROVED POWER TRAINS

- BY APPLYING NEAR-TERM ADVANCES IN TECHNOLOGY, AN IMPROVED POWER TRAIN DESIGN WILL INCREASE VEHICLE RANGE.

- THE USE OF A SEPARATELY EXCITED DC MOTOR, AS COMPARED TO A SERIES MACHINE, CAN IMPROVE THE RANGE OF AN ELECTRIC VEHICLE.

- Analysis Predicts That the Range of an Electric Vehicle With a Separately Excited Motor is 20% Greater Than the Comparable Series Motor Design.

- SEVERAL OTHER IMPROVEMENTS WILL LEAD TO FEATURES WHICH WILL ENHANCE THE SUCCESS OF THE ELECTRIC VEHICLE.
V. SUMMARY AND RECOMMENDATIONS

- **STATE-OF-THE-ART ELECTRIC VEHICLES ARE PRIMARILY CONVERSIONS WITH A HANDFUL OF ORIGINAL DESIGNS.**

- **THE MAJOR ELEMENTS OF THE PRELIMINARY POWER TRAIN DESIGN DEVELOPED IN THIS STUDY ARE A DC SERIES MOTOR, SCR CONTROLLER AND V-BELT CVT.**

- **IMPROVEMENTS STUDIED IN DETAIL INCLUDE THE USE OF SEPARATELY EXCITED MOTORS AND AN ELECTROMAGNETIC TRANSMISSION.**

- **FUTURE WORK SHOULD EMPHASIZE NEAR TERM TECHNICAL ADVANCES TO BRING A PRACTICAL ELECTRIC VEHICLE CLOSER TO REALITY.**

- Better Batteries, Expanded Use of Light Weight Materials and Low Rolling Resistance Tire Designs Are the Areas With the Major Potential for Improved Range.

- Further Development of High Speed DC Motors and Electronic Control Packages Will Enhance the Potential for "All Electric" Drives.

- The Electromatic CVT and the Electromagnetically Shifted Transmission Should Be Applied To Vehicle Power Trains To Demonstrate Their Reliability in the Field.
DETAILED PRESENTATION
DETAILED PRESENTATION

I. INTRODUCTION

II. ASSESSMENT OF THE STATE-OF-THE-ART IN ELECTRIC VEHICLE TECHNOLOGY

III. STATE-OF-THE-ART POWER TRAIN DESIGN

IV. IMPROVED POWER TRAIN

V. SUMMARY AND RECOMMENDATIONS
1. INTRODUCTION
1. INTRODUCTION

1. The preliminary design of a state-of-the-art electric vehicle power train is part of a national effort to reap the potential benefit of useful urban electric passenger vehicles.

(1) Over one half of the nation's air pollution is associated with gasoline powered automobiles.

(2) An electric vehicle moves the energy conversion back to the central power plant, thereby controlling pollution and reducing the consumption of petroleum.

(3) Studies have shown that a useful electric vehicle with a range of 80 - 100 miles would meet the requirements for a second car.

2. The objectives of the program focused on state-of-the-art electric vehicles and components.

(1) Identify and evaluate the state-of-the-art of electric vehicles and electric vehicle power train components.

(2) Develop a power train design using state-of-the-art components.

(3) Identify and evaluate the benefit of potential, near-term improvements to the state-of-the-art electric vehicle power train.
3. THE METHODOLOGY FOR THE POWER TRAIN STUDY COMBINED LITERATURE SEARCH, ENGINEERING JUDGMENT AND COMPUTER AIDED ANALYSIS.

(1) Information Was Obtained by Literature Search, In Person and Telephone Interviews and Mailings To Manufacturers of Vehicles and Components.

(2) Conceptual Approaches To Electric Vehicle Design Were Identified and Studied.

(3) Analyses of Parameter Sensitivity, Idealized Performance and Range Over a Driving Cycle Guided the State-Of-The-Art Design.

(4) Engineering Design Study and Computer Aided Analyses Were Used To Evaluate Potential Improvements in Power Train Performance.
BASIC POWER TRAIN

DRIVER INPUT

CONTROL LOGIC

BATTERY

CONTROLLER

MOTOR

DIFFERENTIAL

REAR AXLE

DRIVE LINE
II. ASSESSMENT OF THE STATE-OF-THE-ART IN ELECTRIC VEHICLE TECHNOLOGY
1. THE MOST COMMON APPROACH TAKEN IN THE DESIGN OF AN ELECTRIC VEHICLE POWER TRAIN HAS BEEN TO CONVERT A CONVENTIONAL INTERNAL COMBUSTION ENGINE VEHICLE CHASSIS TO ELECTRIC DRIVE.

(1) Many Hobbyists Have Built Electric Vehicles In This Country.

(2) The Conversion Approach Has Been Employed In Several Professional Electric Vehicle Designs.
## Domestic Electric Vehicles

<table>
<thead>
<tr>
<th>Vehicle (Year)</th>
<th>Tyre/ Curb Weight</th>
<th>Battaries</th>
<th>Motor</th>
<th>Controller</th>
<th>Transmission</th>
<th>Differential</th>
<th>TireS</th>
<th>Brakes</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galileo Energy II (1967)</td>
<td>Curved</td>
<td>4 passenger</td>
<td>3000 lbs.</td>
<td>Silver-zinc 520 V., 60 Ah</td>
<td>Dc, 4 poles, 3-phase AC induction, 110 lbs., 110 HP at 12,000 RPM, oil cooled.</td>
<td>Three Phase SCR, Oil Cooled.</td>
<td>Standard</td>
<td></td>
<td>80 mph max 0-60/17 sec 40 - 70 mi range</td>
</tr>
<tr>
<td>Gal XP Opal (1971)</td>
<td>Curved</td>
<td>4 passenger</td>
<td>3000 lbs.</td>
<td>Zinc-air and Lead-acid</td>
<td>Two DC series in parallel, rear mount, 125 lbs., 28 HP each, Blower cooled.</td>
<td>Two synchronized SCR</td>
<td>Standard</td>
<td>3.91</td>
<td></td>
</tr>
<tr>
<td>Ford Custom Estate Wagon</td>
<td>Curved</td>
<td>5 passenger</td>
<td>3086 lbs.</td>
<td>Nickel-cadmium</td>
<td>GE DC series, 110 V., 40 HP, 120 lbs., 26 ft. lbs., 8000 rpm, Fan cooled (60 watt)</td>
<td>SCR and bypass contactor</td>
<td>Front wheel drive; standard manual, 2.12:1 in second</td>
<td>3.91</td>
<td>Radial</td>
</tr>
<tr>
<td>Boeing LEV</td>
<td>Bent</td>
<td>5 passenger</td>
<td>2086 lbs.</td>
<td>Platinum</td>
<td>2 in series, DC separately excited, 315 HP, Blower cooled.</td>
<td>SCR armature chopper</td>
<td>Fixed gear reduction</td>
<td>3.91</td>
<td>Dynamic (re-regenerative optional) and hydraulic disc.</td>
</tr>
<tr>
<td>EVA Metro</td>
<td>Bent</td>
<td>4 passenger</td>
<td>3150 lbs.</td>
<td>Lead-acid, EV-116 36 V., 1046 lbs.</td>
<td>DC series</td>
<td>SCR, no bypass, 310 amp limit, 6500 RPM, Fan cooled</td>
<td>Turbine converter and 3-speed Renault automatic.</td>
<td>2.36</td>
<td>Radial</td>
</tr>
<tr>
<td>Selectric Holman (1973)</td>
<td>Bent</td>
<td>Van</td>
<td>5800 lbs.</td>
<td>Lead-acid</td>
<td>GE DC series</td>
<td>GE SCR chopper, field weakening, bypass contactor, current limit</td>
<td>3 speed, hils and flat, 96.1.0:1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# DOMESTIC ELECTRIC VEHICLES

<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>TYPE/CURB WEIGHT</th>
<th>BATTERIES</th>
<th>MOTOR</th>
<th>CONTROLLER</th>
<th>TRANSMISSION</th>
<th>DIFFERENTIAL</th>
<th>TIRES</th>
<th>SHAKES</th>
<th>PERFORMANCE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watermark City Car (1984)</td>
<td>3 passenger</td>
<td>Lead-acid</td>
<td>4V</td>
<td>Praxiteles, DC series, 12 HP</td>
<td>3 speed trays</td>
<td>Standard</td>
<td>Bridgestone JK55, bias ply 40 psi</td>
<td>Regenerative available</td>
<td>45 mph max</td>
<td>160</td>
</tr>
<tr>
<td>Jet Industries Electric Van</td>
<td>2500 lbs.</td>
<td>Lead-acid, EV-106 94 Volts...</td>
<td>Stator, DC series, 10 HP, 3500 rpm, 164 lbs</td>
<td>Baldor SCR</td>
<td>Standard</td>
<td>Standard</td>
<td>Bridgestone JK55, bias ply 40 psi</td>
<td>Hydraulic</td>
<td>45 mph max</td>
<td>113</td>
</tr>
<tr>
<td>Dane Electric Van</td>
<td>Van</td>
<td>Lead-acid, 36 V</td>
<td>Reliance, DC shunt, 110 V, 53 HP at 4230 rpm, 810 lbs</td>
<td>Reliance, SCR dropper, 300 lbs</td>
<td>3 speed, clutch standard manual</td>
<td>3/4, 1.75, 1.0</td>
<td>Dura 7.17</td>
<td>50 mph max</td>
<td>200 mi at 25 mph</td>
<td>114</td>
</tr>
<tr>
<td>All General Electruck DJ-75 (1975)</td>
<td>Van</td>
<td>Lead-acid compound</td>
<td>Ola, DC series, 30 HP, 4000 rpm, blower cooled.</td>
<td>GE pulse type, SCR, 96 V, blower cooled</td>
<td>No transmission, conventional shaft with universals</td>
<td>Standard</td>
<td>Uniroyal Retread 180, 4 ply nylon, 6 with 2, 50 psi</td>
<td>Regenerative and hydraulic</td>
<td>45 mi at 30 mph</td>
<td>115, 116</td>
</tr>
<tr>
<td>Onza R-500</td>
<td>Van</td>
<td>Lead-acid, 66 V, EV-106, 1400 lbs.</td>
<td>Ola, DC series, 30 HP, 4000 rpm, blower cooled.</td>
<td>GE pulse type, SCR, 96 V, blower cooled</td>
<td>No transmission, conventional shaft with universals</td>
<td>Standard</td>
<td>Uniroyal Retread 180, 4 ply nylon, 6 with 2, 50 psi</td>
<td>Regenerative and hydraulic</td>
<td>45 mi at 30 mph</td>
<td>115, 116</td>
</tr>
<tr>
<td>Sebring/Viscount Citicolor (1974)</td>
<td>2 passenger</td>
<td>Lead-acid, 42 V</td>
<td>GE, DC series rear mounted, 6 HP, 4100 rpm</td>
<td>Contactor and starting resistor</td>
<td>No transmission</td>
<td>Standard</td>
<td>Goodyear, 2 ply nylon, 6 with 2, 50 psi</td>
<td>Regenerative and hydraulic</td>
<td>35 mph max</td>
<td>163, 164</td>
</tr>
<tr>
<td>GM Delta (1971)</td>
<td></td>
<td>Lead acid and nickel cadmium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liner Alpha (1973)</td>
<td>Dodge Van</td>
<td>Lead-acid (36) 220 Ah, 148 V, 1453 lbs.</td>
<td>3-phase AC induction, 16 HP</td>
<td>Direct 1:1</td>
<td>Standard</td>
<td>regeneration available</td>
<td>GM Radial</td>
<td>Regenerative and hydraulic</td>
<td>180 mi at 20 mph</td>
<td>133</td>
</tr>
<tr>
<td>EFF Mars II (1969)</td>
<td>4 passenger</td>
<td>Lead acid</td>
<td>120 V</td>
<td>1800 lbs</td>
<td>DC series</td>
<td>Contactor</td>
<td>Goodyear radial</td>
<td>Regenerative and hydraulic</td>
<td>123 mi at 30 mph</td>
<td>45</td>
</tr>
</tbody>
</table>
(3) Electric Vehicle Technology Is More Advanced In Foreign Countries.
## FOREIGN ELECTRICAL VEHICLES

<table>
<thead>
<tr>
<th>VEHICLE (Date)</th>
<th>TYPE/ CURB WEIGHT</th>
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<th>BRAKES</th>
<th>PERFORMANCE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tcheh H. Taiwan  1966</td>
<td>4 passenger</td>
<td>2654 lbs</td>
<td>Lead-acid, DC series, 192 V.</td>
<td>11.02 lbs</td>
<td>Yongnur, DC series, rear mount, 176 lbs., 46 HP, 6000 rpm, Blower cooled</td>
<td>SCR chopper</td>
<td>Fixed reduction</td>
<td>Standard differential</td>
<td>1:1</td>
<td>56 mph max., 6 - 22/12 sec., 200 ml at 20 mph</td>
</tr>
<tr>
<td>Lucas Taxi (1976)</td>
<td>451 lbs.</td>
<td>Lead-acid</td>
<td>210 V</td>
<td>DC series, front mount transverse, CAV, 58 HP</td>
<td>Lucas SCR chopper</td>
<td>Double reduction, Morse Hy Vo chain, transverse to differential</td>
<td>5 L3 1</td>
<td>60 mph max.</td>
<td>200 ml at 20 mph</td>
<td>(55)</td>
</tr>
<tr>
<td>Daihatsu Kogyo Lightweight car (1972)</td>
<td>4 passenger</td>
<td>2010 lbs</td>
<td>Lead-acid, DC series, 9 V., 120 Ah/5 hr.</td>
<td>45 V</td>
<td>Two rear wheel, DC series, 7 5 HP each, 45 V.</td>
<td>SCR chopper</td>
<td>Rear mounted, automatic, 2-speed</td>
<td>65 mph max., 0-10/3 sec., 175 ml at 25 mph</td>
<td>(100), (105)</td>
<td></td>
</tr>
<tr>
<td>Toyota Compact car (1973)</td>
<td>5 passenger</td>
<td>3046 lbs</td>
<td>Lead-acid, DC series, 192 V</td>
<td>159.5 Ah/5 hr</td>
<td>DC separately excited 18 HP, 22.5 kw, 2400 rpm, 54 hp, 40 kw max. Blower cooled</td>
<td>SCR chopper, automatic field weakening</td>
<td>Gear transverse mount, automatic, hydraulic, no fluid coupling, 3-speed hydraulic from electric pump</td>
<td>Specal</td>
<td>65 mph max., 0-20/2 5 sec., 160 ml at 25 mph</td>
<td>(67), (99), (113)</td>
</tr>
<tr>
<td>Toyota Small Truck</td>
<td>2 passenger + 2 passenger</td>
<td>260 lbs</td>
<td>Lead-acid, DC series, 96 V.</td>
<td>135 Ah/5 hr., 713 lbs.</td>
<td>DC separately excited 13 HP, rated, 18 HP max.</td>
<td>SCR</td>
<td>Fixed gear reduction</td>
<td>Regenerative and hydraulic, 36 mph max., 26 ml over urban cycle</td>
<td>(67), (103)</td>
<td></td>
</tr>
<tr>
<td>Enfield 8000 (1974)</td>
<td>2 passenger + 2 Children</td>
<td>2100 lbs.</td>
<td>DC series, 48 V., Mawdsley, 8 HP, 115 lbs.</td>
<td>713 lbs.</td>
<td>6 step converter, field weakening</td>
<td>Opti-ena</td>
<td>3 L5 1</td>
<td>Radial, 35 psi</td>
<td>0-10/12 sec., 40 mph max</td>
<td>(110)</td>
</tr>
<tr>
<td>Bedford Van ERC England</td>
<td>Van</td>
<td>6000 lbs</td>
<td>DC series, 53 HP.</td>
<td>713 lbs.</td>
<td>5 step converter (optional)</td>
<td>Torque converter, Variable Kinetic Drive, 0.5 at stall, 90% cruise efficiency</td>
<td>0-30/14 sec</td>
<td>47 mph max, 33 ml over cycle</td>
<td>(67)</td>
<td></td>
</tr>
</tbody>
</table>
## FOREIGN ELECTRICAL VEHICLES

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<th>BRAKES</th>
<th>PERFORMANCE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Comuta England (1964)</td>
<td>2 passenger + 3 children</td>
<td>1200 lbs</td>
<td>Lead-acid (9)</td>
<td>12 V 120 Ah 5 hr 364 lbs</td>
<td>Thyristor pulse controller, Secom 11 V, bypass control</td>
<td>Rear transverse mount fixed gear reduction</td>
<td>Overall ratio 4.0:1, helical pinion</td>
<td>4.4 x 10</td>
<td>Hydraulic drums all wheels</td>
<td>90 mph max 60 mph at 15 mph 0-20/12 sec</td>
</tr>
<tr>
<td>VW Electric Transporter</td>
<td>Van 5000 lbs approx</td>
<td>Lead-acid 120 V 150 Ah 5 hr 1996 lbs</td>
<td>DC separately excited, Bosch and Siemens, 21 HP (16 peaks), 6700 rpm max, Separate fan</td>
<td>Electronic, pulse width and frequency modulation</td>
<td>Fixed gear, VW Standard transmission</td>
<td></td>
<td></td>
<td>Radial</td>
<td>Regenerative and hydraulic</td>
<td></td>
</tr>
<tr>
<td>Daimler Benz LE 300</td>
<td>Van 6000 lbs approx</td>
<td>Lead-acid 120 V 100 Ah 5 hr 1238 lbs</td>
<td>DC Separately excited, 42 HP (10 peaks), 6000 rpm max, Separate fan</td>
<td>Electronic, 2 position variable pulse width and frequency</td>
<td>Fixed gear reduction</td>
<td>Standard</td>
<td></td>
<td></td>
<td>Regenerative and hydraulic</td>
<td>97 mph max</td>
</tr>
<tr>
<td>Elcar Model 4010 (1953)</td>
<td>6 passenger</td>
<td>1500 lbs</td>
<td>Lead-acid 40 V, 250 Ah</td>
<td>DC series, 3.5 HP, worm mount</td>
<td>SCR chopper with contactors and resistor</td>
<td>Fixed reduction</td>
<td>Steel Radial</td>
<td>Hydraulic</td>
<td></td>
<td>(158)</td>
</tr>
<tr>
<td>SRF Combi-Truck Israel</td>
<td>2 passenger van 1800 kg</td>
<td>144 V</td>
<td>DC separately excited, 25 HP, continuous at 4500 rpm, GE</td>
<td>Armature control, field weakening</td>
<td>Front wheel drive, continuously variable transmission, hydrodynamic</td>
<td></td>
<td></td>
<td></td>
<td>42 mph max</td>
<td>(119)</td>
</tr>
</tbody>
</table>
(4) By Designing From The "Ground Up", Improved Performance Has Been Obtained In Several Experimental Research Vehicles.
## NONCONVERSION ELECTRIC VEHICLES

<table>
<thead>
<tr>
<th>VEHICLE (Data)</th>
<th>TYPE/ CURB WEIGHT</th>
<th>BATTERIES</th>
<th>MOTOR</th>
<th>CONTROLLER</th>
<th>TRANSMISSION</th>
<th>DIFFERENTIAL</th>
<th>TIMES</th>
<th>BRAKES</th>
<th>PERFORMANCE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM 512 (1969)</td>
<td>2 passenger</td>
<td>Lead-acid, 10 V, 120 lbs.</td>
<td>DC series, 56 lbs, 8.5 HP, 4400 rpm, Blower cooled</td>
<td>SCR 100 amp and bypass contactor</td>
<td>Chrysler 3-speed automatic, 15.14. 23.33, 6.32; 1 overall ratio: No torque converter</td>
<td>5 6:1 overall ratio</td>
<td>5 6:1 overall ratio</td>
<td>Front wheel drive, Morse Hy-Ven chain to differential</td>
<td>45 mph max, 0-10/12 sec, 100 mi at 24 mph</td>
<td>(91)</td>
</tr>
<tr>
<td>Copper Development Association Van III (1970)</td>
<td>Van 510 lbs</td>
<td>Lead-acid, 10 V</td>
<td>QE, DC series 6 inches, 12 HP, 6750 rpm, 120 lbs.</td>
<td>SCR</td>
<td>Chrysler 3-speed automatic, 15.14, 23.33, 6.32; 1 overall ratio: No torque converter</td>
<td>5 6:1 overall ratio</td>
<td>Front wheel drive, Morse Hy-Ven chain to differential</td>
<td>Firestone radial</td>
<td>Hydraulic</td>
<td>(35)</td>
</tr>
<tr>
<td>Copper Development Association Town Car (1970)</td>
<td>2 passenger 2300 lbs</td>
<td>Lead-acid, 10 V</td>
<td>DC separate excite, 40 HP, max.</td>
<td>SCR chopper, 400 amp</td>
<td>Rear transaxle and motor McKee 2-speed 600, 3.14:1, manual</td>
<td>Dana EG-20</td>
<td>Good/year low rolling resistance 6.55 x 9.30 psi</td>
<td>Disc/drum hydraulic</td>
<td>100 ml at 10 mph, 45 ml at 40 mph</td>
<td>(96)</td>
</tr>
<tr>
<td>ESB/McKee Sundancer - 2 (1972)</td>
<td>3 Passenger 1600 lbs</td>
<td>Lead-acid, 72 V, 710 lbs.</td>
<td>Torq link, DC series, 8/17 HP.</td>
<td>SCR</td>
<td>Rear transaxle and motor McKee 2-speed 600, 3.14:1, manual</td>
<td>Dana EG-20</td>
<td>Good/year low rolling resistance 6.55 x 9.30 psi</td>
<td>Disc/drum hydraulic</td>
<td>100 ml at 10 mph, 45 ml at 40 mph</td>
<td>(96)</td>
</tr>
<tr>
<td>Amercan EKAR-1</td>
<td>4 Passenger 2050 lbs</td>
<td>Lead-acid</td>
<td>DC</td>
<td>Solid state</td>
<td>Fixed</td>
<td>11.81:1</td>
<td>Goodyear, Run Flat.</td>
<td>Disc Brakes.</td>
<td>65 mph max, 100 ml at 55 mph</td>
<td>(147)</td>
</tr>
<tr>
<td>Anderson Third Generation</td>
<td>Utility Van 2540 lbs</td>
<td>Lead-acid</td>
<td>DC series, 20 HP, SCR</td>
<td>2-speed automatic, planetary gear, mechanical shift on speed and torque, FWD</td>
<td>Dana EG-20</td>
<td>Good/year low rolling resistance 6.55 x 9.30 psi</td>
<td>Disc/drum hydraulic</td>
<td>55 mph max, 60 ml at 45 mph</td>
<td>(40), (41)</td>
<td></td>
</tr>
<tr>
<td>TSL - T/3 Van (1974)</td>
<td>Van 1600 lbs</td>
<td>Lead-acid, 14 V, 700 lbs.</td>
<td>DC series, 30 HP, SCR, 600 amp</td>
<td>Fixed</td>
<td>8:10:1</td>
<td>Goodyear, Run Flat.</td>
<td>Disc/drum hydraulic</td>
<td>40 mph max, 0-20/16 sec, 30 ml on cycle</td>
<td>(147)</td>
<td></td>
</tr>
<tr>
<td>Lunar Rover (1971)</td>
<td>Van 500 lbs</td>
<td>Lead-acid, 14 V, 700 lbs.</td>
<td>Four DC series, brush type, or four permanent magnet brushless</td>
<td>SCR, 600 amp</td>
<td>Electronic plus four power contacts for reversing</td>
<td>32 in diameter wire mesh, 4 wheel regenerative brakes</td>
<td>Goodyear, Run Flat.</td>
<td>Disc/drum hydraulic</td>
<td>15 mph, 75 mi range</td>
<td>(73)</td>
</tr>
</tbody>
</table>

(6) The Concept of "Load Levelling" Has Been Given A Good Deal Of Attention In The Electric Vehicle Literature.

(7) Discharge Characteristics Of Lead-Acid Batteries In Electric Vehicle Applications Are Not Well Understood.

(8) Several Trends In The Approach To Electric Vehicle Power Train Design Are Evident.
## FREQUENCY OF ELECTRIC VEHICLE DESIGN APPROACH

| NUMBER* |  
|---------|---
| Total number of vehicles reviewed | 37  
| Motor Types |  
| DC Series | 23  
| DC Separately Excited | 7  
| AC | 2  
| Blower Cooling of Motor | 13  
| Controller Types |  
| Battery Switching (Contactor) | 6  
| Solid State (SCR) | 27  
| Transmission Types |  
| Fixed Gear Reduction | 20  
| Manual Gear Change | 4  
| Automatic Gear Change | 6  
| CVT | 3  
| Power Train Configuration |  
| Rear Motor and Drive | 8  
| Front Motor and Drive | 3  
| Conventional | 11  

*Complete data not available for all vehicles.

**Source:** Booz, Allen & Hamilton Inc.
2. DC MOTORS AND CONTROLLERS REPRESENT A MATURE TECHNOLOGY WHICH IS WELL SUITED TO THE ON-THE-ROAD, ELECTRIC VEHICLE APPLICATION.

(1) AC Motors Are Extensively Used In Constant Speed Applications.

(2) AC Motor Controls Require Complex and Sophisticated Circuitry.

(3) DC Motors Have Been Extensively Used In Variable Speed Applications.

(4) DC Motor Controls Have Covered A Spectrum Ranging From Battery Switching To Variable Duty-Cycle Choppers.

(5) An Integrated Traction Control System For An Electric Automobile Is Desirable.
MOTORS AND CONTROLLERS
## MOTOR/CONTROLLER SUMMARY

<table>
<thead>
<tr>
<th>Motor Type:</th>
<th>AC Induction</th>
<th>DC Series Wound</th>
<th>DC Shunt Wound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Constant speed</td>
<td>Variable speed</td>
<td>Variable speed</td>
</tr>
<tr>
<td>Application Areas:</td>
<td></td>
<td>Torque control</td>
<td>Speed control</td>
</tr>
</tbody>
</table>

### Advantages:

- Low cost motor which is rugged is brushless is low in weight requires little maintenance.
- Control circuitry is isolated from power electronics.
- Compact frame size.
- High starting torque and high torque at low speed.
- Ease of speed control.
- Inherent feedback characteristic of the series field.
- Excellent torque regulation.
- Chopper control offers smooth operation.
- Efficiency.
- High reliability.

### Disadvantages:

- Low speed operation is difficult to achieve.
- Complex controller is required. This leads to low reliability.
- High costs.
- Low efficiency due to power conversions.
- Limited speed range of seven or eight to one.
- Regenerative braking more difficult to accomplish.
- Loss of load results in dangerous overspeed condition.
- Difficult to control under varying load conditions.
- High hysteresis content in the weakened field range.
- Field loss results in dangerous overspeed condition.

Source: Booz, Allen & Hamilton Inc.
PRINCIPAL SUPPLIERS OF DC MOTORS

- BALDOR
- GENERAL ELECTRIC
- GOULD
- LAWNEL
- PRESTOLITE
- RELIANCE

PRINCIPAL SUPPLIERS OF DC MOTOR CHOPPER CONTROLLERS

- CABLEFORM
- GENERAL ELECTRIC
- RELIANCE
- SEVCON
3. THE MECHANICAL PROTON OF AN ELECTRIC VEHICLE POWER TRAIN SERVES TO MATCH THE OUTPUT OF THE MOTOR TO THE LOAD REQUIRED AT THE VEHICLE WHEELS.

(1) Mechanical Transmissions Generally Sacrifice Efficiency For the Flexibility of Automatic Ratio Change.

(2) Differentials and Axles Are Tailored To Each Application.


(4) The Radial Tire Represents the State-of-the-Art Tire For an Electric Vehicle.

(5) Bearing Power Loss Can Be a Relatively Insignificant Part of the Total Power.
- TRANSMISSIONS
- DIFFERENTIALS/AXLES
- BRAKES
- TIRES
- BEARINGS
<table>
<thead>
<tr>
<th>Company</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gates Rubber Co.</td>
<td>Belts for variable speed belt drives</td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td></td>
</tr>
<tr>
<td>Graham Transmissions, Inc.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Menomonee Falls, Wisconsin</td>
<td></td>
</tr>
<tr>
<td>Hans Heynau GmbH</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Germany</td>
<td></td>
</tr>
<tr>
<td>Industrial Tectonics, Inc.</td>
<td>CVT - traction and &quot;V&quot; belt types</td>
</tr>
<tr>
<td>Ann Arbor, Michigan</td>
<td></td>
</tr>
<tr>
<td>McKee Engineering Corp.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Palatine, Illinois</td>
<td></td>
</tr>
<tr>
<td>Marathon - USA Inc.</td>
<td>Modified STD automotive automatic</td>
</tr>
<tr>
<td>Stamford, Connecticut</td>
<td>transmissions</td>
</tr>
<tr>
<td>Morse Chain Div.</td>
<td>CVT-hydrostatic type</td>
</tr>
<tr>
<td>Ithaca, New York</td>
<td></td>
</tr>
<tr>
<td>Neuweg GmbH</td>
<td>Fixed ratio chain &amp; belt types</td>
</tr>
<tr>
<td>Wuerl, West Germany</td>
<td></td>
</tr>
<tr>
<td>SRF</td>
<td>CVT-traction type</td>
</tr>
<tr>
<td>Jerusalem, Israel</td>
<td></td>
</tr>
<tr>
<td>Sunilomo Machinery Co. Ltd.</td>
<td>CVT-hydrostatic</td>
</tr>
<tr>
<td>Carlstadt, New Jersey</td>
<td></td>
</tr>
<tr>
<td>Walter Chery</td>
<td>CVT-variables traction element types</td>
</tr>
<tr>
<td>Meadville, Pennsylvania</td>
<td></td>
</tr>
<tr>
<td>Warner Gear Div.</td>
<td>CVT</td>
</tr>
<tr>
<td>Muncie, Indiana</td>
<td>Fixed ratio gear reducers</td>
</tr>
<tr>
<td>Electromatic Incorporated</td>
<td>CVT - variable slip fluid drive</td>
</tr>
<tr>
<td>Cleveland, Ohio</td>
<td></td>
</tr>
<tr>
<td>Electromatic Drive Corp.</td>
<td>CVT - variable ratio &quot;V&quot; belt</td>
</tr>
<tr>
<td>Orange, California</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Company</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>American-Standard</td>
<td>CVT - fluid drive</td>
</tr>
<tr>
<td>Dearborn, Michigan</td>
<td></td>
</tr>
<tr>
<td>Arter and Co.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Mannedorf, Switzerland</td>
<td></td>
</tr>
<tr>
<td>Emil Beeklege</td>
<td>Multiration planetary - automatic shift</td>
</tr>
<tr>
<td>Willowick, Ohio</td>
<td></td>
</tr>
<tr>
<td>Chrysler Corp.</td>
<td>Standard automotive manual &amp; automatic</td>
</tr>
<tr>
<td>East Syracuse, New York, N.Y.</td>
<td>transmissions</td>
</tr>
<tr>
<td>Chrysler Marine</td>
<td>Standard automotive manual &amp; automatic</td>
</tr>
<tr>
<td>Marysville, Michigan</td>
<td>transmissions</td>
</tr>
<tr>
<td>Dana Corporation</td>
<td>Manual shift, hydrostatic and fixed ratio</td>
</tr>
<tr>
<td>Auburn, Indiana</td>
<td>gear type</td>
</tr>
<tr>
<td>Eaton Corp.</td>
<td>Fixed ratio gear reducers</td>
</tr>
<tr>
<td>Marshall, Michigan</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Excelermatic</td>
<td></td>
</tr>
<tr>
<td>Austin, Texas</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Fafnir Bearing Co.</td>
<td></td>
</tr>
<tr>
<td>New Britain, Connecticut</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Floyd Drives Co.</td>
<td></td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Fluid Drive Engineering Co.</td>
<td>Fluid torque converter &amp; variable speed &quot;V&quot; belt</td>
</tr>
<tr>
<td>Wilmette, Illinois</td>
<td></td>
</tr>
<tr>
<td>Ford Motor Co.</td>
<td>Standard automotive manual &amp; automatic</td>
</tr>
<tr>
<td>Livonia, Michigan</td>
<td>transmissions</td>
</tr>
</tbody>
</table>

Source: Booz, Allen & Hamilton Inc.
## MANUFACTURERS OF CANDIDATE TRANSMISSIONS

<table>
<thead>
<tr>
<th>Company</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holton Axle &amp; Transmission</td>
<td>Fixed ratio transmissions</td>
</tr>
<tr>
<td>Juneau, Wisconsin</td>
<td></td>
</tr>
<tr>
<td>Fairfield Manufacturing Co., Inc.</td>
<td>Fixed ratio gear reducers</td>
</tr>
<tr>
<td>Lafayette, Indiana</td>
<td></td>
</tr>
<tr>
<td>Winsmith</td>
<td>CVT - traction type and fixed ratio gear</td>
</tr>
<tr>
<td>Springfield, New York</td>
<td>reducers</td>
</tr>
<tr>
<td>SEW - Eurodrive</td>
<td>CVT - traction and self types, fixed ratio</td>
</tr>
<tr>
<td>Bruchsal, West Germany</td>
<td>gear reducers</td>
</tr>
<tr>
<td>AVS Ltd.</td>
<td>High efficiency Hobbs torque converter</td>
</tr>
<tr>
<td>England</td>
<td></td>
</tr>
<tr>
<td>Sta Rite</td>
<td>CVT-hydrostatic type</td>
</tr>
<tr>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Rydpreco</td>
<td>CVT-hydrostatic type</td>
</tr>
<tr>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ernodrive Inc.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Troy, Ohio</td>
<td></td>
</tr>
<tr>
<td>Lewellen Mfg. Co.</td>
<td>CVT - pulley type</td>
</tr>
<tr>
<td>Columbus, Ohio</td>
<td></td>
</tr>
<tr>
<td>Reliance Electric Co.</td>
<td>CVT - pulley type</td>
</tr>
<tr>
<td>Cleveland, Ohio</td>
<td></td>
</tr>
<tr>
<td>Lovejoy Inc.</td>
<td>CVT - &quot;V&quot; belt type</td>
</tr>
<tr>
<td>Downers Grove, Illinois</td>
<td></td>
</tr>
</tbody>
</table>

Source: Booz, Allen & Hamilton Inc.
### INPUT/OUTPUT CHARACTERISTICS
### OF TRACTION DRIVES

<table>
<thead>
<tr>
<th>TYPE</th>
<th>SUPPLIER</th>
<th>RATING, HP</th>
<th>RATIO</th>
<th>OUTPUT SPEED RPM</th>
<th>WEIGHT, LB, WITHOUT VOLT</th>
<th>EFFICIENCY %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rung-Cone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With planetary</td>
<td>Graham</td>
<td>1/15-5</td>
<td>3:1</td>
<td>6-500</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Graham-Shimpo SCM</td>
<td>1/8-5</td>
<td>6:1</td>
<td>112-650</td>
<td>--</td>
<td>82</td>
</tr>
<tr>
<td><strong>Dual with planetary</strong></td>
<td>Graham-Shimpo OM</td>
<td>1/8-5</td>
<td>10:1</td>
<td>300-0-500</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td><strong>Single Cone</strong></td>
<td>Graham-Shimpo SCT</td>
<td>1/16-2</td>
<td>10:1</td>
<td>5-500</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td><strong>Variator Roll</strong></td>
<td>Eaton</td>
<td>1/2-16</td>
<td>9:1</td>
<td>600-5400</td>
<td>500</td>
<td>75-63</td>
</tr>
<tr>
<td></td>
<td>Wornum-Allspeed</td>
<td>1/4-15</td>
<td>9:1</td>
<td>600-5200</td>
<td>375</td>
<td>75-60</td>
</tr>
<tr>
<td><strong>Roller</strong></td>
<td>Koppers-Kopp</td>
<td>1-100</td>
<td>12:1</td>
<td>250-3000</td>
<td>285, 1275</td>
<td>91-94</td>
</tr>
<tr>
<td></td>
<td>Parker-Union</td>
<td>1/4-20</td>
<td>1:1</td>
<td>300-2500</td>
<td>480</td>
<td>77-92</td>
</tr>
<tr>
<td><strong>Free Ball</strong></td>
<td>Floyd</td>
<td>1/3-1 1/2</td>
<td>1:0:1</td>
<td>1000-1750</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>TPK-Contraves</strong></td>
<td></td>
<td>1-25</td>
<td>1:1</td>
<td>80-3500</td>
<td>180</td>
<td>95-90</td>
</tr>
<tr>
<td><strong>Disc Planetary</strong></td>
<td>ITI Discotech-Lenz</td>
<td>1/3-15</td>
<td>6:1</td>
<td>200-1200</td>
<td>230</td>
<td>75-84</td>
</tr>
<tr>
<td><strong>Bevel</strong></td>
<td>Sunstone</td>
<td>1/4-220</td>
<td>4:1</td>
<td>360-1440</td>
<td>400, 4200</td>
<td>80-67</td>
</tr>
<tr>
<td><strong>Toroidal</strong></td>
<td>David Brown-Sadler</td>
<td>1/3-3.5</td>
<td>7:1</td>
<td>600-1200</td>
<td>--</td>
<td>80</td>
</tr>
<tr>
<td><strong>Metal HR</strong></td>
<td>FMC PIV</td>
<td>7.5-75</td>
<td>1:1</td>
<td>715-4200</td>
<td>319, 1280 (75HP)</td>
<td>85-90</td>
</tr>
</tbody>
</table>

EXCELERMATIC TRANSMISSION

Source: Excelermatic
HANS HEYNAU TRANSMISSION
(TRANSMISSION TYPE)

Source: Hans Heynau GmbH, Germany
HANS HEYNAU TRANSMISSION
(BELT TYPE)

Source: Hans Heynau GmbH, Germany
FAFNIR TRANSMISSION

Source: Fafnir
ELECTROMATIC DRIVE TRANSMISSION

Source: Electromatic Drive Corp.
TRANSMISSION SELECTION CRITERIA

- SIZE AND WEIGHT
- EFFICIENCY
- POWER CAPACITY
- RANGE OF RATIO CHANGE
- CONTROLLABILITY
- RELIABILITY
PERFORMANCE CHARACTERISTICS

AVS 7.5" DIA HOBBS CONVERTER

ELECTRIC VEHICLE APPLICATIONS

(35° Fixed vane pitch)

Source: Advanced Vehicle Systems, Ltd.
EFFICIENCY OF TYPICAL AUTOMOTIVE TRANSMISSION

Source: Major Automotive Manufacturer
SUPPLIERS OF AXLES AND DIFFERENTIALS

- DANA
- EATON
- FAIRFIELD MANUFACTURING
- HOLTAN AXLE AND TRANSMISSION
- LEAR SIEGLER
BRÄKE SUPPLIERS

- BENDIX
- DELCO MORaine
- GOODYEAR INDUSTRIAL BRAKES
- MERCURY DIVISION OF APRO
- MINNESOTA AUTOMOTIVE
- TOOL-O-MATIC
TIRES
EFFECT OF TORQUE ON ROLLING RESISTANCE OF CROSS-PLY TIRES

Source: Ref. 182
EFFECT OF INFLATION PRESSURE ON
EQUILIBRIUM ROLLING RESISTANCE

INITIAL INFLATION PRESSURE

50 mph T & RA LOAD
@ 24 psi

EQUILIBRIUM INFLATION PRESSURE, psi

EQUILIBRIUM ROLLING RESISTANCE, FR, lb

O A78-13 BIAS PLY (NO. 623)
O A78-13 BIAS BELTED (NO. 624)
△ BR78-13 RADIAL PLY (NO. 631)
◊ G78-14 BIAS PLY (NO. 601)
● G78-14 BIAS BELTED (NO. 612)
□ GR78-14 RADIAL PLY (NO. 618)
EFFECT OF LOAD ON ROLLING RESISTANCE

+ FR78-15 (2P + 2S); CAT = 51.5°C; \( p = 27.3 \) psi
○ HR78-15 (2P + 2S + 2N); CAT = 59.8°C; \( p = 28.4 \) psi
● LR78-15 (2P + 2S); CAT = 55.5°C; \( p = 28.6 \) psi

ROLLING RESISTANCE, lb

TIRE LOAD, lb

Friction and Rolling Resistance
EQUILIBRIUM TIRE ROLLING RESISTANCE

ROLLING RESISTANCE COEFFICIENT

0.008

0.012

0.016

0.020

0.024

SPEED (MPH)

0 20 40 60 80 100

New

Radial

Worn

Bias

Radial

Bias

New
relative rolling resistance as a function of 
distance traveled during warmup

Coefficient of Rolling Resistance

Warmup (Miles)
EFFECT OF TIRE SIZE ON ROLLING RESISTANCE

RATIO OF EQUILIBRIUM ROLLING RESISTANCES FOR DIFFERENT WHEEL DIAMETERS

- 15"/14"
- 14"/13"

RATIO OF EQUILIBRIUM ROLLING RESISTANCES FOR DIFFERENT ASPECT RATIOS

- 78/70
- 78/60
IN GENERAL, TIRES FOR THE ELECTRIC VEHICLE SHOULD BE:

- Of Radial Construction
- With Load Capacity Well In Excess of That Required To Support The Vehicle.
- Inflated To The Maximum Safe Pressure.
## REPRESENTATIVE ROLLING RESISTANCE DATA

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Load</th>
<th>Inflation Pressure</th>
<th>Speed</th>
<th>Rolling Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firestone</td>
<td>ACT P185/65R14</td>
<td>940 lbs.</td>
<td>24 psi</td>
<td>20 mph</td>
<td>13 lbs.</td>
</tr>
<tr>
<td>Firestone</td>
<td>HR7515</td>
<td>80% rated</td>
<td>20</td>
<td>60</td>
<td>15 lbs.</td>
</tr>
<tr>
<td>Firestone</td>
<td>HR7515</td>
<td>80% rated</td>
<td>30</td>
<td>60</td>
<td>12 lbs.</td>
</tr>
<tr>
<td>Firestone</td>
<td>GR7815</td>
<td>700</td>
<td>--</td>
<td>--</td>
<td>6.8 lbs.</td>
</tr>
<tr>
<td>Firestone</td>
<td>GR7815</td>
<td>1000</td>
<td>--</td>
<td>--</td>
<td>10.2 lbs.</td>
</tr>
<tr>
<td>Goodyear</td>
<td>BR7813</td>
<td>980</td>
<td>24</td>
<td>--</td>
<td>9.8 lbs.</td>
</tr>
<tr>
<td>Goodyear</td>
<td>HR7815</td>
<td>1510</td>
<td>24</td>
<td>--</td>
<td>12.1 lbs.</td>
</tr>
</tbody>
</table>
4. COMPONENTS WHICH REPRESENT THE CURRENT STATE-OF-THE-ART INCLUDE THE SERIES DC MOTOR, CHOPPER CONTROLLER AND RADIAL TIRES.

(1) The Series Wound DC Motor and Pulse Type Controller Are Well Suited To Electric Vehicle Power Trains.

(2) Several Mechanical Transmissions Are Suitable For EV's In The Power Range Required.

(3) Low Energy Loss Differentials, Bearings and Tires are Available.

(4) The Rear Mounted Motor/Transaxle Or The Front Wheel Drive Are Preferred Power Train Architectures.

(5) The Selection of an Optimum Power Train Requires a Systems Analysis of the Hardware Operating Over the Drive Cycle.
III. STATE-OF-THE-ART POWER TRAIN DESIGN
VEHICLE CHARACTERISTICS:

- Four Passenger, Urban Type
- Test Weight = 2850 + Power Train
- 16 EV - 106 Batteries
- Effective Frontal Area = 6 ft.$^2$

PERFORMANCE REQUIREMENTS:

- Cruise Speed = 55 MPH
- Gradeability = 10% @ 30 MPH
- Driving Cycle Per SAE J227a, Schedule D
SAE J227a
SCHEDULE D
DRIVING CYCLE

SPEED, Miles Per Hour

TIME, Seconds

Accelerate
Coast
Brake
1. THE CALCULATION OF RANGE PROCEEDS BY ACCOUNTING FOR THE ENERGY CONSUMED BY THE COMPONENTS AND THEN DRAWN FROM THE BATTERIES AS THE VEHICLE OPERATES OVER A DRIVING CYCLE.

   (1) Vehicle Road Load Is the Sum of Aerodynamic Drag and Inertial Forces.

   (2) Losses Due To Tire Rolling Resistance, Mechanical Friction and Windage, As Well As Motor/Controller Losses Require Additional Power.

   (3) Range Is Calculated By Depleting the Energy Stored In the Batteries Until the Vehicle Cannot Operate Over the Driving Cycle.

CALCULATION SEQUENCE

1. Speed and Acceleration
2. Vehicle Model
3. Road Load
4. Tires
5. Shaft Power
6. Differential
7. Transmission
8. Motor
9. Electrical Power
10. Controller
11. Batteries
COMPUTER SIMULATION

1. ELVCC
   - START
   - PREPARE VARIABLES
   - READ DATA
   - INITIALIZE BATTERY
   - PRECOMPUTE POWER REQUIREMENTS

2. POWER CYCLE
   - COMPUTE AND STORE:
     - VELOCITY
     - ACCELERATION
     - RAMP, INC. POWER
   - CYCLE COMPLETE?
     - YES
     - COMPUTE SUMMARY DATA
     - PRINT SUMMARY
     - COMPUTE AVERAGE DATA
     - PRINT AVERAGE DATA
     - PRINT INCOMPLETE DATA

3. POWER REQUIREMENTS
   - SELECT CYCLE
   - COASTING?
     - YES
     - REGENER.
     - NO
   - BRAKING?
     - YES
     - REGENER.
     - NO
   - CALCULATE ROAD LOAD
   - CALCULATE TIME LOSSES
   - COMPUTE EFFiciency DATA
   - PRINT INCOMPLETE DATA
   - CALCULATE POWER AND TORQUE AT DIFFERENTIAL
   - PRINT INCOMPLETE DATA
   - CALCULATE POWER AND TORQUE AT TRANSMISSION

4. TRANSMISSION
   - CALCULATE GEAR RATIO
   - CALCULATE INPUT/OUTPUT ANGULAR SPEEDS
   - TRANSMISSION LOSSES
   - CONSUMPTION OF MITSUBISHI ELECTRIC VEHICLE

5. MOTOR
   - CALCULATE ANOMALOUS CURRENT
   - CALCULATE VOLTAGE
   - CALCULATE MOTOR LOSSES
   - GET POWER FROM CONTROLLER

6. CONTROLLER
   - CALCULATE POWER REQUIRED FROM BATTERY
   - CONTROLLER
   - START
ACCELERATION PROFILE

\[ a = a_0 e^{-a_1 t} \]

- INITIAL ACCELERATION 0.125 G
- FINAL ACCELERATION 0.037 G
2. ANALYSIS SERVED TO ESTABLISH THE MAXIMUM POTENTIAL RANGE, THE SENSITIVITY OF RANGE TO THE COMPONENT PARAMETERS AND TO SIZE THE COMPONENTS.
COMPUTED RANGE OF IDEAL 3600 POUND VEHICLE

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>RANGE (Miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 MPH, CONSTANT SPEED</td>
<td>75</td>
</tr>
<tr>
<td>SAE J227a, SCHEDULE D</td>
<td>51/60*</td>
</tr>
<tr>
<td>30 MPH, 10% GRADE</td>
<td>15</td>
</tr>
</tbody>
</table>

* With Regeneration
**RANGE SENSITIVITY**

A=J 227 CYCLE  
B=55 MPH  
C=30 MPH & 10% GRADE

<table>
<thead>
<tr>
<th>Vehicle Weight (lbs.)</th>
<th>3500 - 4000</th>
<th>3600</th>
<th>3600</th>
<th>3600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Efficiency</td>
<td>0.92</td>
<td>0.85 - 0.98</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Rolling Resistance (lb./lb.)</td>
<td>0.014</td>
<td>0.014</td>
<td>0.008 - 0.014</td>
<td>0.01</td>
</tr>
<tr>
<td>Regenerative Braking</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No-Yes</td>
</tr>
</tbody>
</table>
3. The state-of-the-art power train consists of a DC series wound motor, SCR controller, V-belt transmission, low-loss differential and radial tires.
<table>
<thead>
<tr>
<th><strong>STATE-OF-THE-ART MOTOR</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Manufacturer</strong></td>
</tr>
<tr>
<td><strong>Model</strong></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td><strong>Size</strong></td>
</tr>
<tr>
<td><strong>Power Rating</strong></td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td><strong>Maximum Speed</strong></td>
</tr>
</tbody>
</table>
### MOTOR CONTROLLER SPECIFICATION

<table>
<thead>
<tr>
<th>Type</th>
<th>SCR chopper, logic unit, coil and capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Sevcon</td>
</tr>
<tr>
<td>Model</td>
<td>7650-4</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>80-130 volts</td>
</tr>
<tr>
<td>Rated Current</td>
<td>750 amps max, 400 amps continuous</td>
</tr>
<tr>
<td>Weight</td>
<td>60 lb.</td>
</tr>
<tr>
<td>Size</td>
<td>Chopper: 14&quot; x 10&quot; x 7&quot;</td>
</tr>
<tr>
<td></td>
<td>Logic: 3&quot; x 11&quot; x 6&quot;</td>
</tr>
<tr>
<td></td>
<td>Coil: 6&quot; x 4&quot; x 5&quot;</td>
</tr>
<tr>
<td></td>
<td>Capacitors: 10&quot; x 5&quot; x 6&quot;</td>
</tr>
</tbody>
</table>
CONTACTORS

- Directional Contractor Pair
  - HB Electric
  - Model HB 33BA 123LIB
  - Coil Voltage = 12 volts
  - Weight = 10 lbs.

- Line Contactor
  - HB Electric
  - Model HB 39BD 122LIB
  - Coil Voltage = 12 volts
  - Weight = 5 lbs.
### MECHANICAL COMPONENTS

<table>
<thead>
<tr>
<th>Component</th>
<th>Supplier</th>
<th>Estimated Weight (lbs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tires</td>
<td>Goodyear Custom Polysteel</td>
<td>4 x 20</td>
</tr>
<tr>
<td></td>
<td>Radial HR-78-15, 32 psi, or</td>
<td></td>
</tr>
<tr>
<td></td>
<td>equivalent</td>
<td></td>
</tr>
<tr>
<td>Wheels</td>
<td>Kelsey-Hayes</td>
<td>4 x 20</td>
</tr>
<tr>
<td>Brakes</td>
<td>Delco-Moraine drum type</td>
<td>4 x 20</td>
</tr>
<tr>
<td>Drive Shaft</td>
<td>Dana Spicer Universals and Torque</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Tubes</td>
<td></td>
</tr>
<tr>
<td>Differential</td>
<td>Dana Spicer IS-18, modified</td>
<td>35</td>
</tr>
<tr>
<td>Drive Chain</td>
<td>Morse Hy-Vo</td>
<td>15</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>
SIMULATED POWER TRAIN PERFORMANCE WITH TEN MOTOR/TRANSMISSION COMBINATIONS HAD THE FOLLOWING COMMON FEATURES:

- The motor was the Prestolite EO-26747 DC series motor
- The tires were of 0.32 m radius
- The rolling resistance assumed was 0.098 N/kg.
- The transmission and differential efficiencies were estimated from manufacturer's data.
- A weight penalty (or benefit) was assigned with respect to a baseline of 3600 lbs. (1633 kg)
CASE 1

FIXED RATIO REDUCTION
HYPOID GEARING

PARAMETERS
- WEIGHT PENALTY 0
- TRANSMISSION RATIO 4.2:1
- TRANSMISSION EFFICIENCY 0.92
- DIFFERENTIAL RATIO 1.0
- DIFFERENTIAL EFFICIENCY 1.0

RANGE
- SAE J227a/D 30-36 MILES
- 55 MPH 47 MILES
- 30 MPH, 10% GRADE 4.3 MILES

ADVANTAGES
- SIMPLE, COMMONLY USED CONSTRUCTION
- LIGHTWEIGHT

DISADVANTAGES
- LIMITS VEHICLE RANGE DUE TO POOR MATCHING WITH MOTOR EFFICIENCY CHARACTERISTICS.
- HYPOID GEARING EFFICIENCY IS A SOURCE OF SIGNIFICANT POWER LOSS.
- EFFICIENCY SENSITIVE TO LUBRICANT TEMPERATURE.
CASE 2

FIXED RATIO REDUCTION, HIGH EFFICIENCY CHAIN DRIVE

PARAMETERS
- WEIGHT PENALTY: 0
- TRANSMISSION RATIO: 4.2:1
- TRANSMISSION EFFICIENCY: 0.98
- DIFFERENTIAL RATIO: 1.0
- DIFFERENTIAL EFFICIENCY: 1.0

RANGE
- SAE J227a/D: 31-41 MILES
- 55 MPH: 51 MILES
- 30 MPH, 10% GRADE: 4.6 MILES

ADVANTAGES
- SIMPLE CONSTRUCTION
- HIGH EFFICIENCY FIXED RATIO REDUCTION
- EFFICIENCY RELATIVELY INSENSITIVE TO TEMPERATURE

DISADVANTAGES
- LIMITS RANGE DUE TO POOR MATCHING WITH MOTOR EFFICIENCY CHARACTERISTICS.
CASE 3
DUAL MOTOR DRIVE, FIXED REDUCTION

PARAMETERS
- WEIGHT PENALTY - 100 LBS
- TRANSMISSION RATIO 4.2:1
- TRANSMISSION EFFICIENCY 0.98
- DIFFERENTIAL RATIO 1.0
- DIFFERENTIAL EFFICIENCY 1.0

RANGE
- SAE J227a/D 32-42 MILES
- 55 MPH 51 MILES
- 30 MPH, 10% GRADE 4.8 MILES

ADVANTAGES
- LIGHTWEIGHT DRIVE TRAIN RESULTING IN IMPROVED VEHICLE RANGE COMPARED TO A SINGLE MOTOR.
- HIGH EFFICIENCY CHAIN DRIVE
- DUAL MOTORS PROVIDE DIFFERENTIAL ACTION

DISADVANTAGES
- TWO MOTORS ARE REQUIRED
- TWO SMALL MOTORS MAY BE LESS EFFICIENT THAN ONE LARGE ONE
- FIXED RATIO LIMITS RANGE DUE TO POOR MATCHING WITH MOTOR EFFICIENCY CHARACTERISTICS.
CASE 4

STANDARD 3 SPEED AUTOMATIC TRANSMISSION WITH A TORQUE CONVERTER

PARAMETERS

- WEIGHT PENALTY: +150 LBS
- TRANSMISSION RATIO
  - 3.5:1 (0-20 MPH)
  - 1.7:1 (20-35 MPH)
  - 1.0:1 (ABOVE 35 MPH)
- TRANSMISSION EFFICIENCY
  - 0.70 (0-20 MPH)
  - 0.88 (20-35 MPH)
  - 0.92 (ABOVE 35 MPH)
- DIFFERENTIAL RATIO: 4.2
- DIFFERENTIAL EFFICIENCY: 0.92

RANGE

- SAE J227a/D: 25-39 MILES
- 55 MPH: 0.4 MILES
- 30 MPH, 10% GRADE: 0.9 MILES

ADVANTAGES

- AVAILABLE MULTI-RATIO TRANSMISSION WITH AUTOMATIC SPEED CHANGE.

DISADVANTAGES

- LOW EFFICIENCY COMPARED TO OTHER TRANSMISSION TYPES DUE TO INTERNAL PUMP LOSSES OF 1-3 HP (DEPENDING ON VEHICLE SPEED).
- EFFICIENCY SENSITIVE TO TEMPERATURE CHANGE.
- TORQUE CONVERTER ADDS SIGNIFICANT LOSSES TO THE DRIVE TRAIN DURING BOTH ACCELERATION AND CONSTANT VELOCITY OPERATION.
- LOW PROBABLE VEHICLE RANGE.
CASE 5

3 SPEED AUTOMATIC TRANSMISSION CHAIN
COUPLED TO THE DIFFERENTIAL WITHOUT
TORQUE CONVERTER

![Diagram of motor, transmission, and differential]

PARAMETERS
- WEIGHT PENALTY +100 LBS
- TRANSMISSION RATIO
  - 2.74:1 (0-20 MPH)
  - 1.57:1 (20-35 MPH)
  - 1.0:1 (ABOVE 35 MPH)
- TRANSMISSION EFFICIENCY
  - 0.76 (0-20 MPH)
  - 0.80 (20-35 MPH)
  - 0.82 (ABOVE 35 MPH)
- DIFFERENTIAL RATIO 5.0:1
- DIFFERENTIAL EFFICIENCY 0.98

RANGE
- SAE J227a/D 28-42 MILES
- 55 MPH 42 MILES
- 36 MPH, 10% GRADE 4.0 MILES

ADVANTAGES
- AVAILABLE MULTI-RATIO TRANSMISSION WITH
  AUTOMATIC SPEED CHANGE.

DISADVANTAGES
- LOW EFFICIENCY COMPARED TO OTHER TRANSMISSION
  TYPES DUE TO INTERNAL PUMP LOSSES OF 1-3 HP
  (DEPENDING ON VEHICLE SPEED)
- EFFICIENCY SENSITIVE TO TEMPERATURE CHANGE.
- WHEN COUPLED DIRECTLY TO THE MOTOR, TRANSMISSION
  LIFE IS SHORT DUE TO EXCESS SHOCK LOADING.
STANDARD 2 SPEED AUTOMATIC TRANSMISSION WITHOUT A TORQUE CONVERTER

PARAMETERS

- WEIGHT PENALTY: +75 LBS
- TRANSMISSION RATIO: 2.74:1 (0-20 MPH), 1.0:1 (ABOVE 20 MPH)
- TRANSMISSION EFFICIENCY: 0.50
- DIFFERENTIAL RATIO: 4.2:1
- DIFFERENTIAL EFFICIENCY: 0.82

RANGE

- SAE J276/D: 31-40 MILES
- 55 MPH: 46 MILES
- 30 MPH, 10% GRADE: 4.2 MILES

ADVANTAGES

- AVAILABLE MULTI-RATIO TRANSMISSION WITH AUTOMATIC SPEED CHANGE.

DISADVANTAGES

- LOW EFFICIENCY COMPARED TO OTHER TRANSMISSION TYPES DUE TO INTERNAL PUMP LOSSES OF 1-3 HP (DEPENDING ON VEHICLE SPEED)
- EFFICIENCY SENSITIVE TO TEMPERATURE CHANGE
- IF DIRECTLY COUPLED TO THE MOTOR, TRANSMISSION LIFE IS VERY SHORT DUE TO EXCESSIVE SHOCK LOADING IN FIRST GEAR
CASE 7

TORQUE CONVERTER COUPLED DIRECTLY TO A DIFFERENTIAL

PARAMETERS

- WEIGHT PENALTY: +50 LBS
- TRANSMISSION RATIO:
  14.1 (0-2.5 MPH)
  2.5:1 (2.5-5 MPH)
  1.25:1 (5-10 MPH)
  1:05:1 (ABOVE 10 MPH)
- TRANSMISSION EFFICIENCY:
  0.20 (0-2.5 MPH)
  0.65 (2.5-5 MPH)
  0.91 (5-10 MPH)
  0.95 (ABOVE 10 MPH)
- DIFFERENTIAL RATIO: 4:2:1
- DIFFERENTIAL EFFICIENCY: 0.92

RANGE

- SAE J227a/D: 30-36 MILES
- 55 MPH: 48 MILES
- 30 MPH, 10% GRADE: 4.4 MILES

ADVANTAGES

FORMS A VARIABLE RATIO TRANSMISSION WHICH ALLOWS THE MOTOR TO OPERATE AT HIGHER, MORE EFFICIENT SPEEDS AT LOW VEHICLE SPEEDS

DISADVANTAGES

NO NET GAIN IN PERFORMANCE COMPARED TO A SYSTEM WITHOUT THE TORQUE CONVERTER
CASE 8

HYPOTHETICAL INFINITELY VARIABLE SPEED TRANSMISSION, ROLLING ELEMENT TYPE

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Penalty</td>
<td>+200 lbs</td>
</tr>
<tr>
<td>Transmission Ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.4:1 (0-2.5 MPH)</td>
</tr>
<tr>
<td></td>
<td>16.2:1 (2.5-5.0 MPH)</td>
</tr>
<tr>
<td></td>
<td>8.1:1 (5.0-10 MPH)</td>
</tr>
<tr>
<td></td>
<td>5.76:1 (10-20 MPH)</td>
</tr>
<tr>
<td></td>
<td>1.68:1 (20-30 MPH)</td>
</tr>
<tr>
<td></td>
<td>1.6:1 (ABOVE 30 MPH)</td>
</tr>
<tr>
<td>Transmission Efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.76 (0-2.5 MPH)</td>
</tr>
<tr>
<td></td>
<td>0.86 (2.5-5.0 MPH)</td>
</tr>
<tr>
<td></td>
<td>0.90 (5.0-10 MPH)</td>
</tr>
<tr>
<td></td>
<td>0.91 (10-20 MPH)</td>
</tr>
<tr>
<td></td>
<td>0.92 (20-36 MPH)</td>
</tr>
<tr>
<td></td>
<td>0.93 (ABOVE 30 MPH)</td>
</tr>
<tr>
<td>Differential Ratio</td>
<td>4.2:1</td>
</tr>
<tr>
<td>Differential Efficiency</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Range

- SAE J227a/D: 29-35 miles
- 55 MPH: 45 miles
- 30 MPH, 10% Grade: 5.2 miles

Advantages

- Drive train can be ideally matched with the motor requirements over a wide range of torque and speed.

Disadvantages

- Not available as a state-of-the-art device.
- Probably significantly heavier than alternate multispeed transmissions.
Case 9

Variable Speed V-Belt Transmission

Parameters:
- Weight Penalty: 1100 LBS
- Transmission Ratio:
  - 4.0:1 (0-10 MPH)
  - 3.0:1 (10-20 MPH)
  - 2.0:1 (20-50 MPH)
  - 1.0:1 (above 40 MPH)
- Transmission Efficiency: 0.90
- Differential Ratio: 4.2:1
- Differential Efficiency: 0.99

Range:
- SAE J227a/D: 33-46 Miles
- 55 MPH: 45 Miles
- 30 MPH, 10% Grade: 5.7 Miles

Advantages:
- Variable speed transmission maximizes operation of the drive motor at efficient speed/torque ranges during the driving cycle.
- Claimed efficiencies of 86-94%, relatively constant with speed.
- Electrical actuation compatible with SCR control system.
- Minimizes current demand by providing high wheel torque at low vehicle speeds.
- Efficiency relatively insensitive to ambient temperature.

Disadvantages:
- More complex than a fixed ratio drive.
- No comprehensive documentation on reliability and performance.
CASE 10

2 SPEED TRANSMISSION USING ELECTRICALLY OPERATED CLUTCHES

PARAMETERS

- WEIGHT PENALTY +160 LBS
- TRANSMISSION RATIO 4.0.1 (0-20 MPH)
  1.6.1 (ABOVE 20 MPH)
- TRANSMISSION EFFICIENCY 0.92
- DIFFERENTIAL RATIO 4.5:1
- DIFFERENTIAL EFFICIENCY 0.98

RANGE

- SAE J227a/D 32.5–45 MILES
- 55 MPH 45 MILES
- 30 MPH, 10% GRADE 4.5 MILES

ADVANTAGES

- HIGHLY EFFICIENT TRANSMISSION. ELECTRIC CLUTCHES REQUIRE .07 HP.
- HIGHER PROBABLE VEHICLE RANGE COMPARED TO FIXED RATIO DRIVES.
  LOW GEAR ALLOWS MORE EFFICIENT OPERATION OF THE MOTOR DURING LOW SPEED OPERATION.
  EFFICIENCY RELATIVELY INSENSITIVE TO AMBIENT TEMPERATURE.
- 3 SPEED OPTIONS

DISADVANTAGES

- NOT PROVEN IN CURRENT VEHICLES
- MORE COMPLEX THAN A FIXED RATIO DRIVE.

ALTERNATE: HELICAL GEARING IN PLACE OF CHAINS
<table>
<thead>
<tr>
<th>RANKING OF CALCULATED PERFORMANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RANGE OVER SAE CYCLE (MILES/CASE)</strong></td>
</tr>
<tr>
<td>33-46/9</td>
</tr>
<tr>
<td>32.5-45/10</td>
</tr>
<tr>
<td>32-42/3</td>
</tr>
<tr>
<td>31-41/2</td>
</tr>
</tbody>
</table>
THE SELECTION OF THE ELECTROMATIC DRIVE TRANSMISSION FOR THE STATE-OF-THE-ART POWER TRAIN IS BASED ON:

- High Calculated Range
- Good Efficiency (>90%)
- Low Weight and Compact (40 lbs.)
- Potentially Reliable
- Electrically Controllable
- Emerging in Market Place
- Well Suited to Transaxle Configuration
DRIVE TRAIN UTILIZING THE "V" BELT TRANSMISSION

TIRES

DRIVE CHAIN

DIFFERENTIAL

MOTOR

ELECTROMATIC TRANSMISSION

UNIVERSAL DRIVE SHAFTS
DRIVE TRAIN INSTALLATION IN A TYPICAL VEHICLE CONFIGURATION

BATTERIES

CONTROLLER

ACCELERATOR CONTROL

TRANSMISSION
PREDICTED RANGE OF THE STATE-OF-THE-ART POWER TRAIN (650 lbs.)

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE J227a/D</td>
<td>36-50</td>
</tr>
<tr>
<td>55 MPH</td>
<td>47</td>
</tr>
<tr>
<td>30 MPH, 10% Grade</td>
<td>6.2</td>
</tr>
</tbody>
</table>
IV. IMPROVED POWER TRAINS
1. **BY APPLYING NEAR-TERM TECHNICAL ADVANCES, IMPROVED POWER TRAIN DESIGNS WILL INCREASE VEHICLE RANGE.**

(1) Use a Separately Excited DC Motor

(2) Reduce Vehicle Weight by Using Lightweight Materials in the Power Train Components.

(3) Develop Tires Specifically Designed for the Electric Vehicle Application.

(4) Design an Integral Motor/Transmission Package.

(5) Increase Battery Mass Fraction.

(6) Change Battery Voltage.

(7) Use an AC Motor and Controller.

(8) Incorporate Supplemental Load Leveling Batteries.

(9) Use Batteries With Higher Energy Density.

(10) Use Flywheels for Load Leveling.
## COMPARISON OF POTENTIAL IMPROVEMENT AREAS

<table>
<thead>
<tr>
<th>Evaluation Task Area</th>
<th>State-of-the-Art</th>
<th>Improved Range</th>
<th>Development Risk</th>
<th>Technical Feasibility</th>
<th>Commercialization Potential</th>
<th>Estimated Program Effort</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Separately excited DC motor</td>
<td>Near</td>
<td>Unknown</td>
<td>Moderate</td>
<td>Yes</td>
<td>Yes</td>
<td>Moderate</td>
<td>Improved motor/transmission match. Verify efficiency.</td>
</tr>
<tr>
<td>2. Component weight reduction</td>
<td>Current</td>
<td>Yes</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>3. Electric vehicle tires</td>
<td>Near</td>
<td>Yes</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>4. Integral motor/transmission</td>
<td>Current</td>
<td>None</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
<td>Moderate</td>
<td>Specific to packaging. Possible weight savings.</td>
</tr>
<tr>
<td>7. AC motor system</td>
<td>Near</td>
<td>None</td>
<td>High</td>
<td>?</td>
<td>?</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>9. Improved batteries</td>
<td>Advanced</td>
<td>Yes</td>
<td>High</td>
<td>Yes</td>
<td>Yes</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>10. Flywheels for load-leveling</td>
<td>Advanced</td>
<td>Yes</td>
<td>High</td>
<td>Yes</td>
<td>?</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

Source: Booz-Allen & Hamilton Inc.
2. **THE USE OF A SEPARATELY EXCITED DC MOTOR, AS COMPARED TO A SERIES MACHINE, CAN IMPROVE THE RANGE OF AN ELECTRIC VEHICLE.**

(1) The Power Trains Studied Are Distinguished By Armature Control, Field Control or the Incorporation of the Electromatic CVT.

(2) An Iterative Simulation With Empirically Adjusted Efficiency Models Was Used To Investigate the Performance Of the Separately Excited Motor Systems.

(3) The Computer Analysis Predicted That the Range Over the SAE Cycle With a Separately Excited Motor is 20% Greater Than With a Comparable Series Motor.

(4) The All Electrical Motor Control Scheme Represents the Most Viable Near-Term Design Approach.
SEPARATELY EXCITED DC MOTOR
COMPUTER SIMULATION TRADE-OFF STUDY

- TRIAD iterative model
- Constant current during acceleration
- 3,600 pound vehicle
- Vehicle parameters
  - Effective frontal area = 6 ft$^2$
  - Tire radius = 12.6 inches
  - Rolling resistance = 0.01 lb./lb.
- 96 percent chopper efficiency
- Shunt wound version of Prestolite EO-26747 motor
- Realistic CVT model
- Deceleration limited to 0.1 G.
ELECTROMATIC CVT EFFICIENCY

Source: Booz-Allen & Hamilton Inc.
CASE 9 PERFORMANCE

Motor Control - Separately excited
Armature and field

Transmission - CVT

Transmission Control
Field Control

Armature Chopping

Transmission Upshifting
Transmission Ratio 0.68:1

Source: Booz, Allen & Hamilton Inc.
CASE 11 - FULL CONTROL

Bypass Contactor

Armature Chopper

Field Chopper

Battery

Reverse Contractor

Field

Arm

CVT

Differential
CASE 11 PERFORMANCE

Motor - Series
Control - Armature
Transmission - CVT

Transmission Control

Armature Chopping

Armature Chopping At Cruise

Transmission Ratio
1.95:1
1.27:1

Battery Current, Amps

Motor Speed, R.P.M.

Speed, Miles per Hour

Source: Booz-Allen & Hamilton Inc.
CASE 12 - FIRED ARMATURE

Diagram:
- Battery
- Field Chopper
- Reverse Contactor
- Field
- Arm
- Differential
CASE 12 PERFORMANCE

(a) Transmission

- Control F
- Field Control

Motor
- Separately excited
Control
- Field only
Transmission
- CVT

BATTERY CURRENT, AMPs

TRANSMISSION RATIO

3000
2000
1000

TRANSMISSION RATIO

0.68

TRANSMISSION RATIO

0.68

0.68

Source: Booz, Allen & Hamilton Inc.
CASE 13 - FIXED FIELD

Battery

Armature Chopper

Bypass Contactor

Field

Reverse Contactor

Arm.

CVT

Differential
CASE 13 PERFORMANCE

BATTERY CURRENT, AMPS

Transmission Control

Armature Chopping

Motor - Separately excited
Control - Armature only
Transmission - CVT

MOTOR SPEED, RPM

Transmission Upshifting

SPEED, MILES PER HOUR

Source: Booz, Allen & Hamilton Inc.
CASE 14 - "ALL ELECTRIC" CONTROL

By-pass Contactor

Armature Chopper

Field Chopper

Battery

Reverse Contactor

Differential

Arm.
CASE 14 PERFORMANCE

Motor - Separately excited
Control - Armature and field
Transmission - None

Source: Booz, Allen & Hamilton Inc.
### POWER TRAIN PERFORMANCE
WITH SEPARATELY EXCITED MOTOR

<table>
<thead>
<tr>
<th>CASE STUDIED</th>
<th>9</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Type</td>
<td>Series</td>
<td>Shunt</td>
<td>Shunt</td>
<td>Shunt</td>
<td>Shunt</td>
</tr>
<tr>
<td>Armature Control</td>
<td>Chop</td>
<td>Chop</td>
<td>Fixed</td>
<td>Chop</td>
<td>Chop</td>
</tr>
<tr>
<td>Separate Field Control</td>
<td>---</td>
<td>Chop</td>
<td>Chop</td>
<td>Fixed</td>
<td>Chop</td>
</tr>
<tr>
<td>Transmission Type</td>
<td>EM/CVT</td>
<td>EM/CVT</td>
<td>EM/CVT</td>
<td>EM/CVT</td>
<td>---</td>
</tr>
<tr>
<td>Differential</td>
<td>4.3:1</td>
<td>7:1</td>
<td>7:1</td>
<td>4.2:1</td>
<td>8:1</td>
</tr>
<tr>
<td>Range Over SAE J227a/D, 3,600 lb. vehicle (miles)</td>
<td>4000</td>
<td>3491</td>
<td>3491</td>
<td>2094</td>
<td>5870</td>
</tr>
<tr>
<td>Motor Speed at 55 mph (RPM)</td>
<td>30</td>
<td>34</td>
<td>33.5</td>
<td>34.5</td>
<td>36.1</td>
</tr>
</tbody>
</table>

Source: Booz-Allen & Hamilton Inc.
# Relative Evaluation of Candidate Separately Excited Motor Systems

## Description

<table>
<thead>
<tr>
<th>Motor Type</th>
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</tr>
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<tbody>
<tr>
<td>Armature Control</td>
<td>Series</td>
</tr>
<tr>
<td>Separate Field Control</td>
<td>Chop</td>
</tr>
<tr>
<td>Transmission</td>
<td>EM/CVT</td>
</tr>
<tr>
<td>Differential</td>
<td>4.3:1</td>
</tr>
<tr>
<td>Motor Speed at 55 mph (RPM)</td>
<td>4000</td>
</tr>
<tr>
<td>Range Over SAE J227a/D</td>
<td>31.2</td>
</tr>
<tr>
<td>Actual Weight (miles)</td>
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<tr>
<td>Relative Weight (lbs.)</td>
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<tr>
<td>Reliability</td>
<td>Moderate</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
</tr>
<tr>
<td>Development Risk</td>
<td>High</td>
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</table>

## Case Studied

<table>
<thead>
<tr>
<th>Series</th>
<th>Shunt</th>
<th>Shunt</th>
<th>Shunt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chop</td>
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<td>EM/CVT</td>
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</tr>
<tr>
<td>4000</td>
<td>3491</td>
<td>2094</td>
<td>5870</td>
</tr>
<tr>
<td>31.2</td>
<td>35.3</td>
<td>35.9</td>
<td>38.0</td>
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<tr>
<td>0</td>
<td>+5</td>
<td>0</td>
<td>-35</td>
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<tr>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
3. SEVERAL OTHER IMPROVEMENTS WILL LEAD TO FEATURES WHICH WILL ENHANCE THE SUCCESS OF THE ELECTRIC VEHICLE.

(1) Develop a Brake Blending Control.
(2) Reduce Drive Train Noise.
(3) Assess and Improve Component Reliability.
(4) Assess Safety.
(5) Develop Efficient and Reliable Automatic Transmissions.
ELECTROMAGNETIC TRANSMISSION

1.0311 RATIO
4.125 RD.
33 T.

1/2" DIA TRACTION MOTOR

DIFFERENTIAL INPUT 4.1:1 RATIO

DIFFERENTIAL - 1:1 RATIO

1st GEAR Clutch ELECTROMAGNETIC

2nd GEAR Clutch ELECTROMAGNETIC

3rd RD. 40 RD. 32 T.

4th RD. 65 RD. 52 T.

UNIVERSAL COUPLING

24" MIN INNER TUBE SURFACE

CLUTCHES - DRY ELECTROMAGNETIC
MY MODEL 20 FORMSPRESS
DRY STATIC TORQUE 380 LB. FT. OR EQUIV.

ORIGINAL PAGE IS OF POOR QUALITY
ELECTROMAGNETIC TRANSMISSION
INSTALLED IN A TYPICAL
VEHICLE CONFIGURATION

[Diagram of vehicle showing components such as batteries, accelerator, controller, frame, and motor]
POWER FLOW IN THE
ELECTROMAGNETIC TRANSMISSION

LOW GEAR
POWER FLOW IN THE
ELECTROMAGNETIC TRANSMISSION

HIGH GEAR
CHARACTERISTICS OF THE ELECTROMAGNETIC TRANSMISSION

- Based on off-the-shelf components.
- Weight less than 100 pounds.
- Compact.
- Activation power 0.04 HP.
- Slip friction loss less than 0.1 HP.
- Conservative gear loading.
- Requires synchronized motor control to maximize reliability and smoothness.
- An alternate version using tooth-type clutches would be smaller and lighter.
V. SUMMARY OF RESULTS

1. STATE-OF-THE-ART ELECTRIC VEHICLES ARE PRIMARILY CONVERSIONS WITH A HANDFUL OF ORIGINAL DESIGNS.

   (1) Most Suitable, Off-The-Shelf, Components Are Well Qualified Automotive or Industrial Products.

   (2) Reliability Has Not Been Demonstrated in a Suitable, Efficient Automatic Transmission.

2. THE MAJOR ELEMENTS OF THE PRELIMINARY POWER TRAIN DESIGN DEVELOPED IN THIS STUDY ARE A DC SERIES MOTOR, SCR CONTROLLER AND V-BELT CVT.

   (1) The DC Series Motor With SCR Controller Represents the State-Of-The-Art Prime Mover.

   (2) An Electrically Controlled V-Belt CVT When Used In a State-Of-The-Art Power Train Offers Superior Range When Compared To Other Available Transmissions.

   (3) The State-Of-The-Art Power Train Can Achieve a Range of 36 Miles Over The SAE J227a/D Cycle, 47 Miles at a Constant 55 MPH and 6.2 Miles Up a 10 Percent Grade at 30 MPH.
3. IMPROVEMENTS STUDIED IN DETAIL INCLUDE THE USE OF SEPARATELY EXCITED MOTORS, AN ELECTROMAGNETIC TRANSMISSION AND MORE REALISTIC COMPONENT WEIGHT AND EFFICIENCIES.

(1) The Use of a Separately Excited DC Motor, As Compared To a Series Machine, Can Achieve a Range of Approximately 36 Miles Over the SAE Cycle.

(2) A Two Speed Electromagnetically Shifted Transmission, Composed of Off-the-Shelf Components, May Provide An Efficient and Reliable Electric Vehicle Transmission.

4. FUTURE WORK SHOULD EMPHASIZE NEAR TERM TECHNICAL ADVANCES TO BRING A PRACTICAL ELECTRIC VEHICLE CLOSER TO REALITY.

(1) Better Batteries, Expanded Use of Light Weight Materials and Low Rolling Resistance Tire Designs Are the Areas With the Major Potential for Improved Range.

(2) Further Development of High Speed DC Motors and Electronic Control Packages Will Enhance the Potential for "All Electric" Drives.

(3) The Electromatic CVT and the Electromagnetically Shifted Transmission Should Be Applied To Vehicle Power Trains To Demonstrate Their Reliability in the Field.