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
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
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.
TYPICAL VEHICLE CONFIGURATION

Source: Booz, Allen & Hamilton Inc.
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

TIRSES

DRIVE CHAIN

DIFFERENTIAL

ELECTROMATIC TRANSMISSION

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.
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/CUMB WEIGHT</th>
<th>BATTERIES</th>
<th>MOTOR</th>
<th>CONTROLLER</th>
<th>TRANSMISSION</th>
<th>DIFFERENTIAL</th>
<th>TIRES</th>
<th>BRAKES</th>
<th>PERFORMANCE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallo Electrico II (1967)</td>
<td>5 passenger</td>
<td>Silver-zinc 320 V. 48 Ah</td>
<td>Delco, 4 poles, 3 phase AC induction, 110 lb. 110 HP at 13,000 RPM, oil cooled.</td>
<td>Three Phase SCR, Oil Cooled.</td>
<td>Fixed gear reduction.</td>
<td>Standard</td>
<td></td>
<td></td>
<td>60 mph max 0-60/17 sec 60 - 70 mi range</td>
<td>(107)</td>
</tr>
<tr>
<td>Gallo XP Opal (1971)</td>
<td>4 passenger</td>
<td>Zinc-air and Lead-acid</td>
<td>Two DC series in parallel, rear motor, 126 lbs. 25 HP each. Blower cooled.</td>
<td>Two synchronized SCR</td>
<td>Dual Input gearbox.</td>
<td>Standard</td>
<td>3.7</td>
<td>Radial</td>
<td>60 mph max 0-30/10 sec. 7, 80 mi. range</td>
<td>(63)</td>
</tr>
<tr>
<td>Ford Corvair Estate Wagon</td>
<td>5 passenger</td>
<td>Nickel-cadmium 110 V., 900 lbs</td>
<td>GE DC series, 40 HP, 26 ft. 800 rpm Fan cooled (60 watts).</td>
<td>SCR and bypass contactor</td>
<td>Front wheel drive, standard manual.</td>
<td>3.9 1</td>
<td></td>
<td>Dynamic (re-</td>
<td>27 mph max (3rd gear), 10 mi at 25 mph</td>
<td>(33)</td>
</tr>
<tr>
<td>Boeing LEV</td>
<td></td>
<td>Penograph</td>
<td>2 in series, DC separately excited, 310 HP Blower cooled.</td>
<td>SCR armature chopper</td>
<td>Fixed gear reduction.</td>
<td></td>
<td></td>
<td>Generative</td>
<td>Dynamic (regenerative optional)</td>
<td>(155)</td>
</tr>
<tr>
<td>EVA Metro</td>
<td></td>
<td></td>
<td>DC series, 13 4 HP, 5000 RPM Fan cooled.</td>
<td>SCR, no bypass, 310 amp limit.</td>
<td>Torque converter and 3 speed Renault automatic.</td>
<td>2.34 1</td>
<td></td>
<td>Radial</td>
<td>50 mph max , 26 mi at 25 mph, 27 mi during urban cycle</td>
<td>(152), (161), (162)</td>
</tr>
<tr>
<td>EVA Convertor (1971)</td>
<td></td>
<td></td>
<td>DC shunt 8 HP</td>
<td>HB contactor</td>
<td>Automatic</td>
<td></td>
<td></td>
<td></td>
<td>155-11-13 32 psi</td>
<td>(163)</td>
</tr>
<tr>
<td>Raisonne Malvern (1973)</td>
<td>4 passenger</td>
<td>Lead-acid 112 V 330 Ah</td>
<td>GE DC series, 42 HP, 6000 rpm</td>
<td>GE SCR chopper, field weakening, bypass contactor, current limit</td>
<td>2 speed, helical gear rear axle 1 96, 1.2 : 1</td>
<td>Hymo differential 3 07 1</td>
<td></td>
<td>Hydraulic</td>
<td>60 mph max , 50 mi. at 25 mph</td>
<td>(168)</td>
</tr>
</tbody>
</table>

Additional notes:
- 5000 RPM
- 2 speed, helical gear rear axle
- Standard manual
- Dynamic (regenerative optional)
<table>
<thead>
<tr>
<th>VEHICLE (Date)</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 Chieftain (1974)</td>
<td>2 passenger 2400 lbs.</td>
<td>Lead-acid, 48 V</td>
<td>Practilite, DC series</td>
<td>Contactor, 1 speed</td>
<td>Infinitely variable belt transmission</td>
<td>Regenerative available</td>
<td>45 mph max</td>
<td>60 mi at 30 mph</td>
<td>(164)</td>
<td></td>
</tr>
<tr>
<td>Jet Industries Electric Van</td>
<td>2500 lbs.</td>
<td>Lead-acid, 8-V, 4000 lbs.</td>
<td>Reliance, DC series, 30 HP, 4000 rpm, cooler, 1200 lbs</td>
<td>Reliance, SCR</td>
<td>3 speed, clutch</td>
<td>Standard</td>
<td>Bridgestone 760/750R16, 6 ply, 60 psi</td>
<td>45 mph max</td>
<td>60 mi at 30 mph</td>
<td>(113)</td>
</tr>
<tr>
<td>Dane Electric Van</td>
<td>Van 8005 lbs.</td>
<td>Lead-acid 56 V, 1250 lbs.</td>
<td>DC compound, 280 lbs.</td>
<td>Reliance, SCR</td>
<td>3 speed, clutch</td>
<td>Standard</td>
<td>Data 7.17</td>
<td>50 mph max, 200 mi at 35 mph</td>
<td>(114)</td>
<td></td>
</tr>
<tr>
<td>All General Electric J1-SE (1975)</td>
<td>Van/jeep 3610 lbs.</td>
<td>Lead-acid, 56 V, 1250 lbs.</td>
<td>DC compound, 280 lbs.</td>
<td>Reliance, SCR</td>
<td>3 speed, clutch</td>
<td>Standard</td>
<td>Data 7.17</td>
<td>50 mph max, 200 mi at 35 mph</td>
<td>(114)</td>
<td></td>
</tr>
<tr>
<td>Ohio R-500</td>
<td>Van 2900 lbs.</td>
<td>Lead-acid, 96 V, EV-106, 1640 lbs.</td>
<td>DC compound, 280 lbs.</td>
<td>Reliance, SCR</td>
<td>3 speed, clutch</td>
<td>Standard</td>
<td>CR 72-15 (Group C)</td>
<td>Regenerative over 15 mph and hydraulic drum</td>
<td>(211), (114)</td>
<td></td>
</tr>
<tr>
<td>Sabinor/Vanguard Citroen (1974)</td>
<td>2 passenger 1300 lbs.</td>
<td>Lead-acid, 42 V</td>
<td>GE, DC series, 6 HP, 4100 rpm.</td>
<td>CE pulse type, SCR, 96 V, cooler, 1200 lbs</td>
<td>No transmission, conventional shaft with universal</td>
<td>Data 7.17</td>
<td>50 mph max, 200 mi at 35 mph</td>
<td>(114)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAM Delta (1971)</td>
<td>Dodge Van 5600 lbs.</td>
<td>Lead-acid and nickel cadmium</td>
<td>3-phase AC induction, 16 HP.</td>
<td>Direct 1.6:1</td>
<td>Standard</td>
<td>Disc/drum hydraulic</td>
<td>35 mph max</td>
<td>60 mi at 25 mph, 20 mi on cycle</td>
<td>(166), (166)</td>
<td></td>
</tr>
<tr>
<td>Linser Alpha (1975)</td>
<td>4 passenger 120 V, 4100 lbs.</td>
<td>Lead-acid 120 V</td>
<td>DC series</td>
<td>Contactor</td>
<td>Regenerative available</td>
<td>180 psi at 20 mph</td>
<td>40 mi at 40 mph</td>
<td>(113)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPP Mars II (1969)</td>
<td>4 passenger 120 V</td>
<td>Lead-acid</td>
<td>DC series</td>
<td>Contactor</td>
<td>Regenerative available</td>
<td>180 psi at 20 mph</td>
<td>40 mi at 40 mph</td>
<td>(113)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(3) Electric Vehicle Technology Is More Advanced In Foreign Countries.
## FOREIGN ELECTRICAL VEHICLES

<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>TYPE/ GLAIVEIGHT</th>
<th>BATTERIES</th>
<th>MOTOR</th>
<th>CONTROLLER</th>
<th>TRANSMISSION</th>
<th>DIFFERENTIAL</th>
<th>TIRES</th>
<th>BRAKES</th>
<th>PERFORMANCE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thev H Taxi Taiwan</td>
<td>4 passenger</td>
<td>Lead-acid series, rear mount, 175 lbs, 46 HP</td>
<td>SCR chopper, 1:6:1</td>
<td>Fixed reduction</td>
<td>Standard</td>
<td>Differential</td>
<td>Standard</td>
<td>Dual drum, automatic, 2-speed</td>
<td>66 mph max.</td>
<td>(50)</td>
</tr>
<tr>
<td></td>
<td>2554 lbs</td>
<td>110 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 - 27/12 sec.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yongyuan, DC series,</td>
<td>Lucas SCR chopper, 65:1:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200 ml at 20 mph</td>
<td></td>
</tr>
<tr>
<td>Lucas Taxi (1976)</td>
<td></td>
<td></td>
<td>Torque converter.</td>
<td>Double reduction, 60 mph max</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55 mph max.</td>
<td>(55)</td>
</tr>
<tr>
<td></td>
<td>48S1 lbs.</td>
<td>216 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200 ml at 20 mph</td>
<td></td>
</tr>
<tr>
<td>Daihatsu Kogyo Lightweight car (1972)</td>
<td>2 passenger</td>
<td>Lead-acid series, front mount, transverse, CAV, 50 HP</td>
<td>Lucas SCR chopper</td>
<td>Double reduction, Morse Hy Vo chain, transverse to differential</td>
<td>55:1:1</td>
<td></td>
<td></td>
<td></td>
<td>Regenerative and hydraulic</td>
<td>(60), (155)</td>
</tr>
<tr>
<td></td>
<td>2010 lbs.</td>
<td>120 Ah/5 hr., 175 lbs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55 mph max.</td>
<td></td>
</tr>
<tr>
<td>Toyota Compact Car (1972)</td>
<td>5 passenger</td>
<td>Lead-acid series, SCR chopper, automatic field weakening</td>
<td>SCR chopper</td>
<td>Rear transverse mount, automatic, 2-speed</td>
<td>5 mph max.</td>
<td></td>
<td></td>
<td></td>
<td>Regenerative and hydraulic</td>
<td>(67), (99), (155)</td>
</tr>
<tr>
<td></td>
<td>50/5 lbs.</td>
<td>192 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 mph max.</td>
<td></td>
</tr>
<tr>
<td>Toyota Small Truck</td>
<td>2 passenger + 2100 lbs.</td>
<td>DC series, separately excited, 12 HP, 60 mph max.</td>
<td>SCR</td>
<td>Fixed gear reduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Regenerative and hydraulic</td>
<td>(67), (99)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 passenger + 2 children</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 mph max.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2100 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10 V max.</td>
<td>(47)</td>
</tr>
<tr>
<td>Bedford Van ERC England</td>
<td>Van</td>
<td>DC series, 53 HP.</td>
<td>DC series, separately excited, 12 HP, 60 mph max.</td>
<td>SCR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35 mph max.</td>
<td>(112)</td>
</tr>
<tr>
<td></td>
<td>6000 lbs</td>
<td>110 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0 - 60/14 sec</td>
<td>(47)</td>
</tr>
</tbody>
</table>

**PERFORMANCE: 35 mph max.**

**REFERENCE: (47)**
### FOREIGN ELECTRICAL VEHICLES

<table>
<thead>
<tr>
<th>VEHICLE (Date)</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>BRAKES</th>
<th>PERFORMANCE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Comuta England (1964)</td>
<td>2 passenger 3 children 1200 lbs.</td>
<td>Lead-acid (4) 12 V 120 Ah 6/9 hr. 384 lbs.</td>
<td>CAV type TM 55, DC series 23, 24 V, 5 HP, Glower cooled.</td>
<td>Thyristor pulse controller, Seccon Mk VI, Bypass controller.</td>
<td>Rear transverse mount, fixed gear reduction</td>
<td>Overall ratio 4.0:1, helical planet</td>
<td>4.4 x 10</td>
<td>Hydraulic drums all wheels</td>
<td>50 mph max, 60 mil at 15 mph 0-20/12 sec</td>
<td>(92)</td>
</tr>
<tr>
<td>VW Electric Transporter</td>
<td>Van 5000 lbs approx.</td>
<td>Lead-acid 144 V, 150 Ah 6 hr. 1496 lbs.</td>
<td>DC separately excited, Bosch and Siemens, 31 HP (10 peak), 6700 rpm max.</td>
<td>Electronic, pulse width and frequency modulation.</td>
<td>Fixed gear, VW Standard transmission</td>
<td>Steel Radial SRN-15X10</td>
<td>Hydraulic.</td>
<td>45 mil at 35 mph 10 mil at 40 mph 0-15/14 sec</td>
<td>(158)</td>
<td>(139)</td>
</tr>
<tr>
<td>Daimler Benz LE 366</td>
<td>Van 6500 lbs approx.</td>
<td>Lead-acid 110 V 100 Ah 6 hr 1238 lbs.</td>
<td>DC Separately excited, 48 HP (10 peak), 6000 rpm max.</td>
<td>Electronic, 2 position variable pulse width and frequency</td>
<td>Fixed gear reduction, Standard</td>
<td>Steel Radial SRN-15X10</td>
<td>Hydraulic.</td>
<td>45 mil at 35 mph 10 mil at 40 mph 0-15/14 sec</td>
<td>(158)</td>
<td>(139)</td>
</tr>
<tr>
<td>Eicar Model 4000 (1973)</td>
<td>4 passenger 1500 lbs.</td>
<td>Lead-acid 90 V, 390 Ah</td>
<td>DC series, OR, 3.5 HP, rotor mount.</td>
<td>SCR chopper with connectors and reactor.</td>
<td>Fixed reduction</td>
<td>Steel Radial</td>
<td>Hydraulic.</td>
<td>45 mil at 35 mph 10 mil at 40 mph 0-15/14 sec</td>
<td>(158)</td>
<td>(139)</td>
</tr>
<tr>
<td>SRF Combi-Truck Israel</td>
<td>Van 3800 kg.</td>
<td>Varia, MD 76A-V3 104 V.</td>
<td>DC separately excited, 25 HP, continuous at 4500 rpm, GE.</td>
<td>No armature control, field weakening</td>
<td>Front wheel drive, continuously variable transmission, flywheel</td>
<td>Steel Radial</td>
<td>Hydraulic.</td>
<td>45 mil at 35 mph 10 mil at 40 mph 0-15/14 sec</td>
<td>(158)</td>
<td>(139)</td>
</tr>
</tbody>
</table>
By Designing From The "Ground Up", Improved Performance Has Been Obtained In Several Experimental Research Vehicles.
### Nonconversion 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>Times</th>
<th>Brakes</th>
<th>Performance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMI 515 (1969)</td>
<td>2 passenger</td>
<td>Lead-acid, 12 V</td>
<td>DC series, 56 lb, 8.5 HP</td>
<td>SCR</td>
<td>Coaxial motor, planetary gear and differential at rear axle.</td>
<td>5.6.1 overall ratio.</td>
<td>45 mph max, 0-10/12 sec, 100 ml at 24 mph.</td>
<td>(93)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper Development Association Van III (1970)</td>
<td>Van 5100 lbs</td>
<td>Lead-acid, 108 V</td>
<td>Q6, DC series 6 interpulse, 11 HP at 8750 rpm, 881 lbs.</td>
<td>SCR, 100 amp and bypass contactor</td>
<td>Chrysler 3-speed automatic, 15, 15, 9.53, 6.52; 1 overall ratio. No torque converter</td>
<td>Front wheel drive, Morse flywheel cable to differential.</td>
<td>Firestone radial</td>
<td>Hydraulic</td>
<td></td>
<td>(35)</td>
</tr>
<tr>
<td>Copper Development Association Town Car (1970)</td>
<td>2 passenger</td>
<td>Lead-acid, 108 V</td>
<td>DC separately excited, 90 HP max.</td>
<td>SCR</td>
<td>Rear transaxle and motor: McKee 2-speed 6.0:1, 3.14:1, manual</td>
<td>Dana EG-20</td>
<td>Goodyear low rolling resistance 6.55 x 9.30 psi.</td>
<td>100 ml at 40 mph, 45 ml at 60 mph.</td>
<td>(96)</td>
<td></td>
</tr>
<tr>
<td>ESB/McKeever Sundernair - 2 (1972)</td>
<td>3 Passenger 1600 lbs</td>
<td>Lead-acid, 72 V, 710 lbs.</td>
<td>Torque link, DC series, 466 amp.</td>
<td>SCR chopper, 466 amp</td>
<td>Rear transaxle and motor: McKee 2-speed 6.0:1, 3.14:1, manual</td>
<td>Dana EG-20</td>
<td>Goodyear low rolling resistance 6.55 x 9.30 psi.</td>
<td>100 ml at 40 mph, 45 ml at 60 mph.</td>
<td>(96)</td>
<td></td>
</tr>
<tr>
<td>Amercian EXAR-I</td>
<td>4 Passenger</td>
<td>Lead-acid</td>
<td>DC</td>
<td>Solid state</td>
<td>Fixed</td>
<td>11.81:1</td>
<td>65 mph max, 100 ml at 55 mph.</td>
<td></td>
<td>(147)</td>
<td></td>
</tr>
<tr>
<td>Anderson Third Generation</td>
<td>Utility Van</td>
<td>Lead-acid, 72 V</td>
<td>DC series, 28 HP, 240 amp, 4000 rpm, 175 lbs, Blower cooled.</td>
<td>SCR</td>
<td>2-speed automatic, planetary gear, mechanical shift on speed and torque, FWD</td>
<td>Radial, 155 x 15,</td>
<td>Disc/Drum hydraulic</td>
<td>55 mph max, 60 ml at 45 mph.</td>
<td>(140), (41)</td>
<td></td>
</tr>
<tr>
<td>TSL - T/3 Van</td>
<td>Van 3600 lbs</td>
<td>Lead-acid, 14 V, 550 lbs.</td>
<td>DC series 30 HP, 22 HP, peak.</td>
<td>SCR, 600 amp</td>
<td>Fixed</td>
<td>7.6:1</td>
<td>60 mph max, 0-20/10 sec, 30 ml on cycle.</td>
<td></td>
<td>(127)</td>
<td></td>
</tr>
<tr>
<td>Lunar Rover</td>
<td>Vans 500 lbs</td>
<td>Lead-acid, 14 V, 550 lbs.</td>
<td>Four DC series, brush type, or four permanent magnet brushless.</td>
<td>Electronic plus four power contacts for reversing</td>
<td>Electronic plus four power contacts for reversing</td>
<td>32 in diameter wire mesh, 4 wheel regenerative brakes</td>
<td>15 mph, 55 ml, range.</td>
<td>(73)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The table includes various models and specifications of nonconversion electric vehicles, focusing on different components such as batteries, motors, controllers, transmissions, differentials, and braking systems, along with performance and reference data.
(5) Generally the overall vehicle body design presents constraints on the power train configuration.

(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.
<table>
<thead>
<tr>
<th><strong>FREQUENCY OF ELECTRIC VEHICLE DESIGN APPROACH</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NUMBER</strong></td>
</tr>
<tr>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>Total number of vehicles reviewed</td>
</tr>
<tr>
<td>Motor Types</td>
</tr>
<tr>
<td>DC Series</td>
</tr>
<tr>
<td>DC Separately Excited</td>
</tr>
<tr>
<td>AC</td>
</tr>
<tr>
<td>Blower Cooling of Motor</td>
</tr>
<tr>
<td>Controller Types</td>
</tr>
<tr>
<td>Battery Switching (Contactor)</td>
</tr>
<tr>
<td>Solid State (SCR)</td>
</tr>
<tr>
<td>Transmission Types</td>
</tr>
<tr>
<td>Fixed Gear Reduction</td>
</tr>
<tr>
<td>Manual Gear Change</td>
</tr>
<tr>
<td>Automatic Gear Change</td>
</tr>
<tr>
<td>CVT</td>
</tr>
<tr>
<td>Power Train Configuration</td>
</tr>
<tr>
<td>Rear Motor and Drive</td>
</tr>
<tr>
<td>Front Motor and Drive</td>
</tr>
<tr>
<td>Conventional</td>
</tr>
<tr>
<td>*Complete data not available for all vehicles.</td>
</tr>
</tbody>
</table>

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

Motor Type:

- AC Induction
- DC Series Wound
- DC Shunt Wound

Primary Application Areas:

- Constant speed
- Variable speed
- Variable speed

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
- Regenerative braking more difficult to accomplish
- Loss of load results in dangerous overspeed condition

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

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 PROOTION 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
## Manufacturers of Candidate Transmissions

<table>
<thead>
<tr>
<th>Company</th>
<th>Type</th>
<th>Company</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gates Rubber Co.</td>
<td>Belts for variable speed belt drives</td>
<td>American-Standard</td>
<td>CVT - fluid drive</td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td></td>
<td>Dearborn, Michigan</td>
<td></td>
</tr>
<tr>
<td>Graham Transmissions, Inc.</td>
<td>CVT - traction type</td>
<td>Arter and Co.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Menomonee Falls, Wisconsin</td>
<td>CVT - traction and &quot;V&quot; belt types</td>
<td>Mannedorf, Switzerland</td>
<td></td>
</tr>
<tr>
<td>Hans Heynau GmbH, Germany</td>
<td>CVT - traction type</td>
<td>Emil Beeklege, Willowick, Ohio</td>
<td>MVSL and automatic</td>
</tr>
<tr>
<td></td>
<td>Modified STD automotive automatic transmissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial Tectonics, Inc.</td>
<td>CVT-hydrostatic type</td>
<td>Chrysler Corp.</td>
<td>MVSL and automatic</td>
</tr>
<tr>
<td>Ann Arbor, Michigan</td>
<td>Fixed ratio chain &amp; belt types</td>
<td>East Syracuse, N.Y.</td>
<td></td>
</tr>
<tr>
<td>McKee Engineering Corp.</td>
<td>CVT - traction type</td>
<td>Chrysler Marine</td>
<td>Fixed ratio gear reducers</td>
</tr>
<tr>
<td>Palatine, Illinois</td>
<td>CVT - traction type</td>
<td>MVSL and automatic transmissions</td>
<td></td>
</tr>
<tr>
<td>Marathon - USA Inc.</td>
<td>CVT-hydrostatic</td>
<td>Dana Corporation</td>
<td>Fluid torque converter &amp; variable speed &quot;V&quot; belt</td>
</tr>
<tr>
<td>Stamford, Connecticut</td>
<td>Fixed ratio chain &amp; belt types</td>
<td>Auburn, Indiana</td>
<td></td>
</tr>
<tr>
<td>Morse Chain Div.</td>
<td>CVT-hydrostatic</td>
<td>Eaton Corp.</td>
<td>Fluid torque converter &amp; variable speed &quot;V&quot; belt</td>
</tr>
<tr>
<td>Ithaca, New York</td>
<td>CVT - traction type</td>
<td>Marshall, Michigan</td>
<td></td>
</tr>
<tr>
<td>Neuweg GmbH, Wuert, West Germany</td>
<td></td>
<td>MVSL and automatic transmissions</td>
<td></td>
</tr>
<tr>
<td>SRF</td>
<td>CVT - traction type</td>
<td>Excelematic</td>
<td>Fixed ratio gear reducers</td>
</tr>
<tr>
<td>Jerusalem, Israel</td>
<td>CVT - traction type</td>
<td>Austin, Texas</td>
<td>Fixed ratio gear reducers</td>
</tr>
<tr>
<td>Sumitomo Machinery Co. Ltd.</td>
<td>CVT-various traction element types</td>
<td>MVSL and automatic transmissions</td>
<td></td>
</tr>
<tr>
<td>Carlstadt, New Jersey</td>
<td>CVT</td>
<td>Fafnir Bearing Co.</td>
<td>Fluid torque converter &amp; variable speed &quot;V&quot; belt</td>
</tr>
<tr>
<td>Walter Chery</td>
<td>Fixed ratio gear reducers</td>
<td>New Britain, Connecticut</td>
<td></td>
</tr>
<tr>
<td>Meadville, Pennsylvania</td>
<td>CVT - variable slip fluid drive</td>
<td>Floyd Drives Co.</td>
<td></td>
</tr>
<tr>
<td>Werner Gear Div.</td>
<td>CVT - variable ratio &quot;V&quot; belt</td>
<td>Denver, Colorado</td>
<td></td>
</tr>
<tr>
<td>Muncie, Indiana</td>
<td></td>
<td>Fluid Drive Engineering Co.</td>
<td></td>
</tr>
<tr>
<td>Electromatic Incorporated</td>
<td></td>
<td>Wilmette, Illinois</td>
<td></td>
</tr>
<tr>
<td>Cleveland, Ohio</td>
<td></td>
<td>Ford Motor Co.</td>
<td></td>
</tr>
<tr>
<td>Electromatic Drive Corp.</td>
<td></td>
<td>Livonia, Michigan</td>
<td></td>
</tr>
<tr>
<td>Orange, California</td>
<td></td>
<td>MVSL and automatic transmissions</td>
<td></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>Rydreco</td>
<td>CVT-hydrostatic type</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>
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</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 1750 RPM</th>
<th>WEIGHT, LB, WITHOUT VATOR 10 HP</th>
<th>WEIGHT, LB, WITHOUT VATOR 100 HP</th>
<th>EFFICIENCY %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring-Cone</td>
<td></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>
<td>65-90</td>
</tr>
<tr>
<td>Graham-Shimpo SCM</td>
<td>1/8 5</td>
<td>6:1</td>
<td>112-450</td>
<td></td>
<td>--</td>
<td>--</td>
<td>82</td>
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<tr>
<td>dual with planetary</td>
<td>Graham-Shimpo OM</td>
<td>1/8-5</td>
<td>10:1</td>
<td>300-0-360</td>
<td>--</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td>single cone</td>
<td>Graham-Shimpo NT</td>
<td>1/16-2</td>
<td>10:1</td>
<td>8-500</td>
<td>--</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td>Varytor ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>roller</td>
<td>Eaton</td>
<td>1/2-16</td>
<td>0.1</td>
<td>600-5400</td>
<td>500</td>
<td>--</td>
<td>75-93</td>
</tr>
<tr>
<td>Winnemuth-Allspeed</td>
<td>1/4-15</td>
<td>0.1</td>
<td>600-5200</td>
<td></td>
<td>375</td>
<td>--</td>
<td>75-90</td>
</tr>
<tr>
<td>roller</td>
<td>Koppers-Kopp</td>
<td>1-100</td>
<td>12:1</td>
<td>250-3000</td>
<td>265</td>
<td>1275</td>
<td>80-94</td>
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<tr>
<td>Parker-Union</td>
<td>1/4-20</td>
<td>0.1</td>
<td>300-2500</td>
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<td>490</td>
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<td>77-92</td>
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<tr>
<td>Free Ball</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floyd</td>
<td></td>
<td>1/3-1/2</td>
<td>0.1</td>
<td>1750</td>
<td>--</td>
<td>--</td>
<td>90</td>
</tr>
<tr>
<td>TFK-Contraves</td>
<td></td>
<td>1-25</td>
<td>40:1</td>
<td>80-3500</td>
<td>180</td>
<td>--</td>
<td>85-90</td>
</tr>
<tr>
<td>Disc planetary</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>ITI Dayco-Lenze</td>
<td></td>
<td>1/3-15</td>
<td>6:1</td>
<td>200-1200</td>
<td>230</td>
<td>--</td>
<td>75-84</td>
</tr>
<tr>
<td>Beser</td>
<td></td>
<td>1/4-220</td>
<td>4:1</td>
<td>300-1440</td>
<td>410</td>
<td>4200</td>
<td>80-87</td>
</tr>
<tr>
<td>Toroidal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>David Brown-Sad</td>
<td></td>
<td>1/3-3.5</td>
<td>7:1</td>
<td>600-1200</td>
<td>--</td>
<td>--</td>
<td>80</td>
</tr>
<tr>
<td>Metal Har</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TMC PIV</td>
<td></td>
<td>7.5-75</td>
<td>6:1</td>
<td>715-4200</td>
<td>319</td>
<td>1230</td>
<td>85-90</td>
</tr>
</tbody>
</table>

EXCELMATIC TRANSMISSION

Source: Excelermatic
HANS HEYNAU TRANSMISSION
(TRANSMISSION TYPE)

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

Source: Hans Heynau GmbH, Germany
Source: Fafnir
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
BRAKE 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

![Graph showing the effect of torque on rolling resistance of cross-ply tires. The graph plots effective rolling resistance coefficient against braking coefficient on the x-axis and driving coefficient on the y-axis. Two curves are shown for 100 km/h and 60 km/h.]

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_{eq}, lb
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
EQUILIBRIUM TIRE ROLLING RESISTANCE

![Graph showing the rolling resistance coefficient of new and worn tires of different types (Bias and Radial) at various speeds.](image)
RELATIVE ROLLING RESISTANCE AS A FUNCTION OF DISTANCE TRAVELED DURING WARMUP

![Graph showing relative rolling resistance as a function of distance traveled during warmup.](image-url)
EFFECT OF TIRE SIZE ON ROLLING RESISTANCE

RATIO OF EQUILIBRIUM ROLLING RESISTANCES FOR DIFFERENT WHEEL DIAMETERS

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

TIRE SIZE: B, D, F, G

TIRE LOAD, lb

RATIO OF EQUILIBRIUM ROLLING RESISTANCES FOR DIFFERENT ASPECT RATIOS

- 78/70
- 78/60

TIRE LOAD, lb
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>50</td>
<td>13.6 lbs.</td>
</tr>
<tr>
<td>Firestone</td>
<td>HR7515</td>
<td>80% rated</td>
<td>30</td>
<td>60</td>
<td>15 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

TIME, Seconds

SPEED, Miles Per Hour

Accelerate

Coast

Brake

0 10 20 30 40 50 60

0 20 40 60

30 50 120

20 40 60
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

- Speed and Acceleration
  - Vehicle Model
    - Tires
      - Road Load
    - Shaft Power
      - Differential
        - Transmission
          - Motor
            - Electrical Power
          - Controller
            - Batteries
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.
<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
### Vehicle Weight (Ibs.)

<table>
<thead>
<tr>
<th>Weight Range</th>
<th>Efficiency</th>
<th>Regenerative Braking</th>
</tr>
</thead>
<tbody>
<tr>
<td>3500-4000</td>
<td>0.92</td>
<td>No</td>
</tr>
<tr>
<td>3600</td>
<td>0.85-0.98</td>
<td>No</td>
</tr>
<tr>
<td>3600</td>
<td>0.92</td>
<td>No</td>
</tr>
<tr>
<td>3600</td>
<td>0.92</td>
<td>No</td>
</tr>
<tr>
<td>3600</td>
<td>0.92</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Transmission Efficiency
- 0.92
- 0.85-0.98
- 0.92
- 0.92
- 0.92

### Rolling Resistance (lb./Ib.)
- 0.014
- 0.014
- 0.008-0.014
- 0.01

### Regenerative Braking
- No
- No
- No
- Yes

### Range (Miles)

<table>
<thead>
<tr>
<th>Speed (MPH)</th>
<th>Grade (%)</th>
<th>Range (Miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=J</td>
<td>B=55</td>
<td></td>
</tr>
<tr>
<td>C=30</td>
<td>MPH</td>
<td></td>
</tr>
<tr>
<td>30 MPH &amp;</td>
<td>10% GRADE</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td></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.
**STATE-OF-THE-ART MOTOR**

<table>
<thead>
<tr>
<th>Type</th>
<th>Series wound DC with interpoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Prestolite</td>
</tr>
<tr>
<td>Model</td>
<td>EO-26747</td>
</tr>
<tr>
<td>Weight</td>
<td>205 lbs.</td>
</tr>
<tr>
<td>Size</td>
<td>11(\frac{1}{4})&quot; OD x 17&quot; L</td>
</tr>
<tr>
<td>Power Rating</td>
<td>24HP continuous (28HP, blower cooled)</td>
</tr>
<tr>
<td>Voltage</td>
<td>100 V Nominal</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>4000 RPM</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 Radial HR-78-15, 32 psi, or</td>
<td>4 x 20</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 Tubes</td>
<td>30</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: 32.02 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: 4.2:1
- DIFFERENTIAL EFFICIENCY: 0.92

RANGE

- SAE J227a/D: 25-39 MILES
- 55 MPH: 64 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

PARAMETERS
- WEIGHT PENALTY: +100 LBS
- TRANSMISSION RATIO:
  2.76:1 (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
- 30 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.

ALTERNATE CONSTRUCTION
CASE 6

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 0.90
- DIFFERENTIAL RATIO 4.2:1
- DIFFERENTIAL EFFICIENCY 0.92

RANGE

- SAE J1274/D 31-40 MILES
- 55 MPH 36 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:
  - 1:1 (0-2.5 MPH)
  - 2.5:1 (2.5-5 MPH)
  - 1.25:1 (5-10 MPH)
  - 0.5:1 (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

PARAMETERS

- WEIGHT PENALTY - 200 LBS
- TRANSMISSION RATIO
  - 32.4:1 (0-2.5 MPH)
  - 16.2:1 (2.5-5.0 MPH)
  - 8:1:1 (5.0-16 MPH)
  - 5.76:1 (10-20 MPH)
  - 1.68:1 (20-30 MPH)
  - 1.0:1 (ABOVE 30 MPH)
- TRANSMISSION EFFICIENCY
  - 0.76 (0-2.5 MPH)
  - 0.86 (2.5-5.0 MPH)
  - 0.9 (5.0-16 MPH)
  - 0.91 (10-20 MPH)
  - 0.92 (20-30 MPH)
  - 0.93 (ABOVE 30 MPH)
- DIFFERENTIAL RATIO - 4.2:1
- DIFFERENTIAL EFFICIENCY - 0.92

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 $\quad 100$ LBS
- TRANSMISSION RATIO
  - 4.8:1 (0-10 MPH)
  - 3.0:1 (10-20 MPH)
  - 2.0:1 (20-36 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] 1.8:1 [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: 9.5 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.
<table>
<thead>
<tr>
<th>RANGE OVER SAE CYCLE (MILES/CASE)</th>
<th>RANGE AT 55 MPH (MILES/CASE)</th>
<th>RANGE AT 30 MPH, 10% GRADE (MILES/CASE)</th>
<th>PEAK CURRENT (AMPERES/CASE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33-46/9</td>
<td>51/2, 3</td>
<td>5.7/9</td>
<td>375/9</td>
</tr>
<tr>
<td>32.5-45/10</td>
<td>49/10</td>
<td>5.2/8</td>
<td>400/5</td>
</tr>
<tr>
<td>32-42/3</td>
<td>48/7</td>
<td>4.9/4</td>
<td>425/4</td>
</tr>
<tr>
<td>31-41/2</td>
<td>47/1</td>
<td>4.8/3</td>
<td>450/10</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 INSTALLATION IN A TYPICAL VEHICLE CONFIGURATION

CONTROLLER

ACCELERATOR CONTROL

BATTERIES

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.
<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

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

[Diagram showing components such as Bypass Contactor, Armature Chopper, Field Chopper, Battery, Arm, CVT, Reverse Contractor, and Differential.]
CASE 11 PERFORMANCE

Motor - Series
Control - Armature
Transmission - CVT

Battery Current, Amps

Transmission Control
Armature Chopping
Armature Chopping At Cruise

Transmission Ratio
1.55.1
1.27.1

Motor Speed, R.P.M.

Transmission Upshifting

Speed, Miles per Hour
CASE 12 - FIRED ARMATURE

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

Motor - Separately excited
Control - Field only
Transmission - CVT

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

Battery

Armature Chopper

Bypass Contactor

Arm.

Field

Reverse Contactor

CVT

Differential
CASE 13 PERFORMANCE

---

**Battery Current, Amps**

- Transmission Control
- Armature Chopping

**Motor Control**
- Separately excited
- Armature only

**Transmission**
- CVT

**Speed, Miles Per Hour**

- Transmission Upshifting

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

By-pass Contactor

Armature Chopper

Field Chopper

Battery

Field

Reverse Contactor

Arm.

Differential
CASE 14 PERFORMANCE

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Case Studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>9  11  13  14</td>
<td></td>
</tr>
<tr>
<td><strong>Motor Type</strong></td>
<td>Series   Shunt</td>
</tr>
<tr>
<td><strong>Armature Control</strong></td>
<td>Chop      Chop</td>
</tr>
<tr>
<td><strong>Separate Field Control</strong></td>
<td>---       Chop</td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>EM/CVT    EM/CVT</td>
</tr>
<tr>
<td><strong>Differential</strong></td>
<td>4.3:1     7:1</td>
</tr>
<tr>
<td><strong>Motor Speed at 55 mph (RPM)</strong></td>
<td>4000      3491</td>
</tr>
<tr>
<td><strong>Range Over SAE J227a/D</strong></td>
<td>31.2      35.3</td>
</tr>
<tr>
<td><strong>Actual Weight (miles)</strong></td>
<td>0         +5</td>
</tr>
<tr>
<td><strong>Relative Weight (lbs.)</strong></td>
<td>Moderate  Moderate</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Moderate  Moderate</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Low       Moderate</td>
</tr>
<tr>
<td><strong>Development Risk</strong></td>
<td>High      High</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 RADIUS

33 T.

4.9 RADIUS

32 T.

6.8 RADIUS

52 T.

DIFFERENTIAL - 1:1 RATIO

DIFHT'ENTIAL INPUT

4:11 RATIO

6.25 RADIUS

13 T.

2ND GEAR

1.03:1 RATIO

4.125 RADIUS

33 T.

1ST GEAR

4.9 RADIUS

32 T.

2ND GEAR

4.9 RADIUS

52 T.

UNIVERSAL COUPLING

3/4 IN. INNER TUBE

OF POOR QUALITY
ELECTROMAGNETIC TRANSMISSION
INSTALLED IN A TYPICAL
VEHICLE CONFIGURATION
POWER FLOW IN THE
ELECTROMAGNETIC TRANSMISSION

LOW GEAR

DIFFERENTIAL - 1:1 RATIO

1ST GEAR
4:1 RATIO
425 RD 57%.

2ND GEAR
1:3:1 RATIO
425 RD 57%.

3RD GEAR

1625 RD 15 T.

9% OH TRACTION MOTOR

GEAR 40 PD 52 E.

CLUTCHES - DRY ELECTROMAGNETIC

524 EMMERICH

DIE STAY TUBE REAR LIP OF CUP

UNIVERSAL COUPLING

SEALS.
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.
TOOTH TYPE ELECTROMAGNETIC
3 SPEED TRANSMISSION

1 1/4" DIA. TRACTION MOTOR

DIFFERENTIAL - 1:1 RATIO -

1ST GEAR

2ND GEAR

3RD GEAR

1ST GEAR CLUTCH

2ND GEAR CLUTCH

3RD GEAR CLUTCH

UNIVERSAL COUPLING
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 38 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.