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.
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.

  - A motor rated at 24 horsepower is required for the electric vehicle power train.
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

ELECTROMATIC TRANSMISSION

MOTOR

DRIVE CHAIN

DIFFERENTIAL

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 lightweight 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
- Rear Axle
- Differential
- 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 (Date)</th>
<th>Type/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>Gal Electricovil II (1967)</td>
<td>3 passenger 3400 lbs.</td>
<td>Silver-zinc 520 V., 40 Ah</td>
<td>Delco, 4 pole, 3 phase AC induction, 110 lbs, 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>80 mph max</td>
<td>0-60/17 sec</td>
<td>60 - 70 mi range</td>
<td>(167)</td>
</tr>
<tr>
<td>GM XEP Opel (1974)</td>
<td>4 passenger 3000 lbs.</td>
<td>Zinc-air and Lead-acid</td>
<td>Two DC series in parallel, rear mount, 126 lbs, 26 HP each Blower cooled.</td>
<td>Two synchronized SCR</td>
<td>Dual input gearbox</td>
<td>Standard</td>
<td>60 mph max</td>
<td>0-10/19 sec</td>
<td>7, 80 mi. range</td>
<td>(62)</td>
</tr>
<tr>
<td>Ford Crown Estate Wagon</td>
<td>5 passenger 3206 lbs.</td>
<td>Nickel-cadmium 110 V., 900 lbs</td>
<td>GE DC series, 150 lbs, 40 HP, 190 V, 36 ft., 126 lbs, 8000 rpm Fan cooled (60 watt).</td>
<td>SCR and bypass converter</td>
<td>Front wheel drive, standard manual, 3.9:1 in second</td>
<td>3.9:1</td>
<td>Radial</td>
<td>27 mph max</td>
<td>(3rd gear), 40 mi at 25 mph</td>
<td>-</td>
</tr>
<tr>
<td>Boeing LRV</td>
<td>Full</td>
<td>Pennograph</td>
<td>2 in series, DC separately excited, 310 HP Blower cooled.</td>
<td>SCR armature chopper</td>
<td>Fixed gear reduction.</td>
<td>3.9:1</td>
<td>Dynamic (re-</td>
<td>(155)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVA Metro</td>
<td>Renault R-12 4 passenger 3150 lbs.</td>
<td>Lead-acid 96 V., 1946 lbs.</td>
<td>GE DC series, 13.6 HP, 4500 HP Fan cooled.</td>
<td>SCR, no bypass, 310 amp limit.</td>
<td>Turbine convertor and 3 speed Renault automatic.</td>
<td>2.74:1</td>
<td>155-13</td>
<td>32 psi</td>
<td>50 mph max, 26 mi at 25 mph</td>
<td>(152), (161)</td>
</tr>
<tr>
<td>EVA Convertor (1977)</td>
<td>4 passenger 4 passenger 3150 lbs.</td>
<td>Lead-acid 96 V., 1946 lbs.</td>
<td>GE DC series, 13.6 HP, 4500 HP Fan cooled.</td>
<td>SCR, no bypass, 310 amp limit.</td>
<td>Turbine convertor and 3 speed Renault automatic.</td>
<td>2.74:1</td>
<td>155-13</td>
<td>32 psi</td>
<td>50 mph max, 26 mi at 25 mph</td>
<td>(152), (161)</td>
</tr>
<tr>
<td>Rainier Midovan (1973)</td>
<td>Van 5800 lbs.</td>
<td>Lead-acid 112 V, 330 Ah</td>
<td>GE DC series, 54 V., 42 HP, 6000 rpm</td>
<td>GE SCR chopper, field weakening bypass converter, current limit</td>
<td>2 speed, hydraulic rear axle</td>
<td>1 96, 1.0 T</td>
<td>6.70 x 15</td>
<td>Hydraulic</td>
<td>60 mph max, 60 mi. at 25 mph</td>
<td>(168)</td>
</tr>
</tbody>
</table>

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**Original Page Quality:** Poor
# Domestic Electric Vehicles

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type/ Curd Weight</th>
<th>Batteries</th>
<th>Motor</th>
<th>Controller/ Transmission</th>
<th>Differential</th>
<th>Tires</th>
<th>Brakes</th>
<th>Performance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watermark Civic-V6</td>
<td>2 passenger, 200 lbs.</td>
<td>Lead-acid, 4V</td>
<td>Pratellite, DC series 12 H</td>
<td>Contact, 2 speed</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>40 mpg max,</td>
<td>(160)</td>
</tr>
<tr>
<td>Jet Industries</td>
<td>Subaru Van 2500 lbs</td>
<td>Lead-acid, EV-106 94 V, 943 lbs.</td>
<td>Reliance, DC series 10 HP, 3500 rpm, 184 lbs, 24V</td>
<td>Reliance, SCR, standard manual 120 lbs, 3 speed, clutch, 5/10</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>40 MPG, 40 mi at 30 mph</td>
<td>(163)</td>
</tr>
<tr>
<td>Dane Electric Van</td>
<td>Van 8003 lbs.</td>
<td>Lead-acid 92 AH/5 hr</td>
<td>Reliance, DC series 100 V, 3500 rpm, 210 lbs</td>
<td>Reliance, SCR, 200 lbs, 150 lbs</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>40 MPG, 40 mi at 30 mph</td>
<td>(164)</td>
</tr>
<tr>
<td>All General</td>
<td>D-1850 (1975)</td>
<td>Lead-acid 54 V, 1210 lbs.</td>
<td>DC Compound, 283 lbs</td>
<td>Reliance, SCR, standard manual 120 lbs, 3 speed, clutch, 5/8</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>45 MPG, 40 mi at 30 mph, 200 mi at 35 mph</td>
<td>(165)</td>
</tr>
<tr>
<td>Otis R-500</td>
<td>Van 2500 lbs.</td>
<td>Lead-acid, 96 V, EV-106, 1400 lbs.</td>
<td>Otis, DC series 30 HP, 4000 rpm, 184 lbs, 24V, 220V</td>
<td>Otis, DC series 30 HP, 4000 rpm, 184 lbs, 24V</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>45 MPG, 40 mi at 30 mph, 200 mi at 35 mph</td>
<td>(17), (166)</td>
</tr>
<tr>
<td>Sabring Van-Guard</td>
<td>2 passenger, 1200 lbs</td>
<td>Lead-acid, 42 V</td>
<td>GE, DC series 30 HP, 4000 rpm, 285 lbs, 24V</td>
<td>GE, DC series 30 HP, 4000 rpm, 285 lbs, 24V</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>45 MPG, 40 mi at 30 mph, 200 mi at 35 mph</td>
<td>(17), (166)</td>
</tr>
<tr>
<td>CM DeVoe</td>
<td>(1971)</td>
<td>Lead-acid and nickel cadmium</td>
<td>Reliance, DC series 50 HP, 2100 rpm, 184 lbs, 24V, 220V</td>
<td>Reliance, DC series 50 HP, 2100 rpm, 184 lbs, 24V</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>45 MPG, 40 mi at 30 mph, 200 mi at 35 mph</td>
<td>(17), (166)</td>
</tr>
<tr>
<td>Ltliner Alpha</td>
<td>(1975)</td>
<td>Lead-acid 72 AH, 180 V, 1353 lbs.</td>
<td>3-phase AC induction, 36 HP, 184 lbs</td>
<td>3-phase AC induction, 36 HP, 184 lbs</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>45 MPG, 40 mi at 30 mph, 200 mi at 35 mph</td>
<td>(17), (166)</td>
</tr>
<tr>
<td>EPP</td>
<td>Mars II 4 passenger, Renault R-10 4100 lbs</td>
<td>Lead-acid 120 V 1840 lbs</td>
<td>DC Series, 1550 rpm, 184 lbs, 24V</td>
<td>DC Series, 1550 rpm, 184 lbs, 24V</td>
<td>Standard</td>
<td>Bridgestone</td>
<td>Hydraulic</td>
<td>45 MPG, 40 mi at 30 mph, 200 mi at 35 mph</td>
<td>(17), (166)</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/ gehört 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>Taiwan</td>
<td>4 passenger</td>
<td>Lead-acid 216 V</td>
<td>Yongyuan, DC series, rear mount</td>
<td>SCR</td>
<td>Fixed reduction 1:1</td>
<td>Standard</td>
<td></td>
<td></td>
<td>66 mph max., 8 - 27/12 sec., 200 m.p.h. at 20 mph</td>
<td>(90)</td>
</tr>
<tr>
<td>Toyia Taxi</td>
<td>4551 lbs.</td>
<td>Lead-acid 216 V</td>
<td>Lucas SCR chopper</td>
<td></td>
<td></td>
<td>5:1:3:1</td>
<td></td>
<td></td>
<td>60 mph max., 200 m.p.h. at 20 mph</td>
<td>(55)</td>
</tr>
<tr>
<td>Datsun Kogyo Lightweight Car</td>
<td>2 passenger</td>
<td>Lead-acid, 98 V, 120 Ah/5 hr.</td>
<td>Two rear wheel, DC series, 7.5 HP each, 45 V.</td>
<td>SCR</td>
<td>Automatic</td>
<td></td>
<td></td>
<td></td>
<td>Regenerative and hydraulic.</td>
<td>(90), (153)</td>
</tr>
<tr>
<td>Toyota Compact Car</td>
<td>5 passenger</td>
<td>Lead-acid, 191 V, 155 Ah/5 hr.</td>
<td>DC separately excited 13 HP, 20 kw/1, rated 54 hp, (40 awe) max. Blower cooled</td>
<td>SCR</td>
<td>Automatic</td>
<td>Rear transverse, automatic field weakening</td>
<td>Field weakening, 7-speed hydraulic from electric pump</td>
<td>58 mph max., 0-20/2 5 sec., 160 m.p.h. at 25 mph</td>
<td>(67), (98), (153)</td>
<td></td>
</tr>
<tr>
<td>Toyota Small Truck</td>
<td>2 passenger + 2 children</td>
<td>Lead-acid, 96 V, 115 Ah/5 hr.</td>
<td>DC separately excited 13 HP, 20 kw/1, rated, 18 HP max.</td>
<td>SCR</td>
<td>Fixed gear reduction</td>
<td></td>
<td></td>
<td></td>
<td>Regenerative and hydraulic.</td>
<td>(67), (153)</td>
</tr>
<tr>
<td>Enfield 8000</td>
<td>2 passenger + 2 children</td>
<td>Lead-acid, 2100 lbs.</td>
<td>DC series, 48 V, Manwiley, 8 HP, 275 lbs, Blower cooled</td>
<td>6 step converter, field weakening, Optiional</td>
<td>3:3:1</td>
<td>Radial, 35 psi</td>
<td>0-10/17 sec., 40 mph max</td>
<td></td>
<td>(102)</td>
<td></td>
</tr>
<tr>
<td>Bedford Van ERC</td>
<td>6000 lbs</td>
<td>110 V</td>
<td>DC series, 53 HP.</td>
<td>5 step converter (optional)</td>
<td>Torque converter, Variable Kinetic Drive, 4:1 at stall, 90% cruise efficiency</td>
<td>0-30/14 sec, 47 mph max, 33 m.p.h. over cycle</td>
<td></td>
<td>(47)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The table above lists various foreign electrical vehicles along with their specifications and performance metrics. Each row details a specific vehicle model, its type, curb weight, batteries, motor specifications, controller type, transmission, differential, tires, brakes, and performance reference with the corresponding page numbers.
<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 Connecta England (1968)</td>
<td>2 passenger 3 children</td>
<td>1200 lbs.</td>
<td>Lead-acid 48V, 120 Ah/5 hr, 384 lbs.</td>
<td>Thyristor pulse controller, Secan Mk VI, bypass contactor.</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>Radial</td>
<td>100 mph max, 80 mph, at 15 mph</td>
<td>(23)</td>
</tr>
<tr>
<td>VW Electric Transporter</td>
<td>Van 5000 lbs approx.</td>
<td>12 V, 110 Ah, 6 hr</td>
<td>DC separately excited, Bosch and Siemens, 31 HP (10 peak), 6000 rpm max, Separate fan</td>
<td>Electronic, pulse width and frequency modulation.</td>
<td>Fixed gear, VW Standard transaxle</td>
<td>Standard</td>
<td>Regenerative and hydraulic.</td>
<td>-</td>
<td>(3), (5)</td>
<td></td>
</tr>
<tr>
<td>Citroën LE 166</td>
<td>Van 6100 lbs approx.</td>
<td>Lead-acid 110 V, 110 Ah, 3 hr, 1210 lbs.</td>
<td>DC Separately excited, 42 HP (10 peak), 6000 rpm max.</td>
<td>Electronic, 2 position variable pulse width and frequency</td>
<td>Fixed gear reduction</td>
<td>Standard</td>
<td>Regenerative and hydraulic.</td>
<td>57 mph max.</td>
<td>(3), (5)</td>
<td></td>
</tr>
<tr>
<td>Elcar Model 4000 (1973)</td>
<td>4 passenger 1500 lbs.</td>
<td>Lead-acid 48 V, 260 Ah</td>
<td>DC series, OR, 3.5 HP, 300 rpm, 0.577 kW</td>
<td>SCR chopper with converters and resistor.</td>
<td>Fixed reduction</td>
<td>Steel Radial SIN-155H10</td>
<td>Hydraulics</td>
<td>45 mi at 35 mph, 10 mi at 40 mph</td>
<td>153, 159</td>
<td></td>
</tr>
<tr>
<td>SRF Combi-Truck Israel</td>
<td>2 passenger van 3800 kg.</td>
<td>Varta, MD T6A-03 144 V.</td>
<td>DC separately excited, 25 HP, continuous at 6500 rpm, GE.</td>
<td>No armature control, field weakening, fixed reduction</td>
<td>Front wheel drive, continuously variable transmission, drywheel</td>
<td>Steel Radial SIN-155H10</td>
<td>Hydraulics</td>
<td>42 mph max.</td>
<td>(153)</td>
<td></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 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>Copper Development Association Van II (1970)</td>
<td>2 passenger 5100 lbs</td>
<td>Lead-acid, 100 V</td>
<td>DC series, 80 HP</td>
<td>SCR, 100 amp and bypass contactor</td>
<td>Front wheel drive</td>
<td>4 55 1</td>
<td>Firestone radial</td>
<td>60 mph max, 0-20/11.2 sec</td>
<td>(1)</td>
</tr>
<tr>
<td>Copper Development Association Van III (1970)</td>
<td>2 passenger 2302 lbs</td>
<td>Lead-acid, 100 V</td>
<td>DC separately excited, 60 HP max.</td>
<td>SCR, 400 amp</td>
<td>Front wheel drive, standard through belt and spiral bevel gear</td>
<td>Dana EG-20</td>
<td>Good year low rolling resistance. 6.55 x 9. 30 psi.</td>
<td>100 ml, 10 mph, 45 ml at 60 mph</td>
<td>(35)</td>
</tr>
<tr>
<td>ESB/McKee Sundercer - T (1972)</td>
<td>2 Passenger 2500 lbs</td>
<td>Lead-acid 72 V, 710 lbs</td>
<td>Dual link, DC series, 8/17 HP</td>
<td>SCR chopper, 600 amp</td>
<td>Rear transaxle and motor McKee 2-speed 6 02, 3 14 1, manual</td>
<td>Good year, Run Flat.</td>
<td>Disc/drum hydraulic</td>
<td>65 mph max, 100 ml at 55 mph</td>
<td>(40)</td>
</tr>
<tr>
<td>American EXAR-1</td>
<td>4 Passenger 2800 lbs</td>
<td>Lead-acid</td>
<td>DC</td>
<td>Solid state</td>
<td>Fixed</td>
<td>31.81</td>
<td>Good year, Run Flat.</td>
<td>Disc Brake.</td>
<td>55 mph max, 60 ml at 45 mph</td>
</tr>
<tr>
<td>Anderson Utility Van Third Generation</td>
<td>2500 lbs</td>
<td>Lead-acid 72 V</td>
<td>DC series, 20 HP, SCR</td>
<td>2-speed automatic, planetary gear, mechanical shift on speed and torque, FWD</td>
<td>Radial, 165 x 15,</td>
<td>65 mph max, 100 ml at 55 mph</td>
<td>Disc/drum hydraulic</td>
<td>30 mph max, 9-20/16 sec</td>
<td>(40)</td>
</tr>
<tr>
<td>TSL - T/3 Van (1974)</td>
<td>Van 3000 lbs</td>
<td>Lead-acid 74 V, 500 lbs</td>
<td>DC series 30 HP (25 HP, peak)</td>
<td>SCR, 600 amp</td>
<td>Fixed</td>
<td>7 80.1</td>
<td>Radial, 165 x 15,</td>
<td>Disc/drum</td>
<td>40 mph max, 9-20/16 sec</td>
</tr>
<tr>
<td>Lunar Rover (1971)</td>
<td>500 lbs</td>
<td>Lead-acid 74 V, 500 lbs</td>
<td>Four DC series, brush type, or four permanent magnet brushless</td>
<td>Electronic plus four power contacts for reversing</td>
<td>22 in diameter wire mesh, 4 wheel regenerative brakes</td>
<td>15 mph</td>
<td>76 ml range</td>
<td>15 mph</td>
<td>(3)</td>
</tr>
</tbody>
</table>
(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.
## FREQUENCY OF ELECTRIC VEHICLE DESIGN APPROACH

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

*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 Application Areas:</td>
<td>Constant speed</td>
<td>Variable speed</td>
<td>Variable speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torque control</td>
<td>Speed control</td>
</tr>
</tbody>
</table>

**Advantages:**
- Low cost motor which is rugged and is brushless.
- Is low in weight and 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, and high reliability.

**Disadvantages:**
- Low speed operation is difficult to achieve.
- Complex controller is required. This leads to low reliability, high costs, and 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 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
<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 and &quot;V&quot; belt types</td>
</tr>
<tr>
<td>Germany</td>
<td></td>
</tr>
<tr>
<td>Industrial Tectonics, Inc.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Ann Arbor, Michigan</td>
<td></td>
</tr>
<tr>
<td>McKee Engineering Corp.</td>
<td>Modified STD automotive automatic</td>
</tr>
<tr>
<td>Palatine, Illinois</td>
<td>transmissions</td>
</tr>
<tr>
<td>Marathon - USA Inc.</td>
<td>CVT-hydrostatic type</td>
</tr>
<tr>
<td>Stamford, Connecticut</td>
<td></td>
</tr>
<tr>
<td>Morse Chain Div.</td>
<td>Fixed ratio chain &amp; belt types</td>
</tr>
<tr>
<td>Ithaca, New York</td>
<td></td>
</tr>
<tr>
<td>Neuweg GmbH</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Wuert, West Germany</td>
<td></td>
</tr>
<tr>
<td>SRF</td>
<td>CVT - hydrostatic</td>
</tr>
<tr>
<td>Jerusalem, Israel</td>
<td></td>
</tr>
<tr>
<td>Sunimoto Machinery Co. Ltd.</td>
<td>CVT - various traction element types</td>
</tr>
<tr>
<td>Carlstadt, New Jersey</td>
<td></td>
</tr>
<tr>
<td>Walter Chery</td>
<td>CVT</td>
</tr>
<tr>
<td>Meadville, Pennsylvania</td>
<td></td>
</tr>
<tr>
<td>Warner Gear Div.</td>
<td>Fixed ratio gear reducers</td>
</tr>
<tr>
<td>Muncie, Indiana</td>
<td></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 Beeckle</td>
<td>Multi-ratio 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>Exceleramic</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Austin, Texas</td>
<td></td>
</tr>
<tr>
<td>Fafnir Bearing Co.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>New Britain, Connecticut</td>
<td></td>
</tr>
<tr>
<td>Floyd Drives Co.</td>
<td>CVT - traction type</td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td></td>
</tr>
<tr>
<td>Fluid Drive Engineering Co.</td>
<td>Fluid torque converter &amp; variable speed</td>
</tr>
<tr>
<td>Wilmette, Illinois</td>
<td>&quot;V&quot; belt</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 reducers</td>
</tr>
<tr>
<td>Springfield, New York</td>
<td></td>
</tr>
<tr>
<td>SEW - Eurodrive</td>
<td>CVT - traction and self types, fixed ratio gear reducers</td>
</tr>
<tr>
<td>Bruchsal, West Germany</td>
<td></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>Rydreo</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 CHANGE</th>
<th>OUTPUT SPEED, 1750 RPM INPUT</th>
<th>WEIGHT, LB, WITHOUT JOINT, 10 HP</th>
<th>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></td>
<td>Graham-Shimpo SC</td>
<td>1/8 5</td>
<td>4:1</td>
<td>112-150</td>
<td>--</td>
<td>--</td>
<td>82</td>
</tr>
<tr>
<td>Dual with planetary</td>
<td>Graham-Shimpo</td>
<td>1/8-5</td>
<td>10:1</td>
<td>300-0-350</td>
<td>--</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td>Single cone</td>
<td>Graham-Shimpo NT</td>
<td>1/10-2</td>
<td>10:1</td>
<td>5-500</td>
<td>--</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td>Variator Ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With planetary</td>
<td>Eaton</td>
<td>1/2-16</td>
<td>9:1</td>
<td>600-5400</td>
<td>500</td>
<td>--</td>
<td>75-93</td>
</tr>
<tr>
<td>With new-Allspeed</td>
<td>Winshmidt-</td>
<td>1/4-15</td>
<td>0:1</td>
<td>600-5200</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>93-94</td>
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<tr>
<td></td>
<td>Parker-Union</td>
<td>1/4-20</td>
<td>0:1</td>
<td>300-2500</td>
<td>150</td>
<td>--</td>
<td>77-52</td>
</tr>
<tr>
<td>Free Ball</td>
<td>Floyd</td>
<td>1/3-1 1/2</td>
<td>1:0:1</td>
<td>to 5 1750</td>
<td>--</td>
<td>--</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>TPK-Contraves</td>
<td>1-25</td>
<td>40:1</td>
<td>80-3500</td>
<td>100</td>
<td>--</td>
<td>85-90</td>
</tr>
<tr>
<td>Disc planetary</td>
<td>ITI Divco-Lenco</td>
<td>1/3-15</td>
<td>6:1</td>
<td>300-1200</td>
<td>230</td>
<td>--</td>
<td>75-84</td>
</tr>
<tr>
<td>Beier</td>
<td>Sunstone</td>
<td>1/4-220</td>
<td>4:1</td>
<td>360-1400</td>
<td>400</td>
<td>4290</td>
<td>80-67</td>
</tr>
<tr>
<td>Toroidal</td>
<td>David Brown-Salt</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 In H</td>
<td>FMC PIV</td>
<td>7.5-75</td>
<td>6:1</td>
<td>715-4200</td>
<td>310</td>
<td>1230</td>
<td>85-90</td>
</tr>
</tbody>
</table>

HANS HEYNAU TRANSMISSION
(BELT TYPE)

Source: Hans Heynau GmbH, Germany
FAFNIR TRANSMISSION

DRIVEN ROLLS

LOAD SPRINGS

RATIO ADJUSTER

DRIVE RACES

TRACTION-DRIVE

REGENERATIVE GEARS

INPUT

OUTPUT

Source: Fafnir
ELECTROMATIC DRIVE TRANSMISSION

DRIVE SHAFT
HOUSING
FIXED FACE

STUBBED SHAFT
SPRING RETAINER
PATTERN SLEEVE
OPTICAL SENSOR
CABLE SOCKET

DRIVEN ASSEMBLY

MOVEABLE FACE
RETURN SPRING
LEAD SCREW
BALL NUT FLANGE
FAN DISC HUB
POLE PIECES
MAGNETIZING COIL
END PLATE

EXIT AIR
AIR COOLING PORT
COOLING FAN

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
BRÁKE SUPPLIERS

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

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

- A78-13 BIAS PLY (NO. 623)
- 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)

INITIAL INFLATION PRESSURE

30 psi
50 mph (COLD)
T & RA LOAD @ 24 psi
24 psi (COLD)
32 psi (HOT)

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

ROLLING RESISTANCE, lb

TIRE LOAD, lb
EQUILIBRIUM TIRE ROLLING RESISTANCE

ROLLING RESISTANCE COEFFICIENT

SPEED (MPH)

0 20 40 60 80 100

0.008 0.012 0.016 0.020 0.024

New
Worn
Radial
Bias
Radial
Bias

ORIGINAL PAGE IS OF POOR QUALITY
RELATIVE ROLLING RESISTANCE AS A FUNCTION OF DISTANCE TRAVELED DURING WARMUP
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></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></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
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
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
### Vehicle Weight (lbs.)

<table>
<thead>
<tr>
<th>Range</th>
<th>Efficiency</th>
<th>Rolling Resistance (lb./lb.)</th>
<th>Regenerative Braking</th>
</tr>
</thead>
<tbody>
<tr>
<td>3500 - 4000</td>
<td>0.92</td>
<td>0.014</td>
<td>No</td>
</tr>
<tr>
<td>3600</td>
<td>0.85 - 0.98</td>
<td>0.014</td>
<td>No</td>
</tr>
<tr>
<td>3600</td>
<td>0.92</td>
<td>0.008 - 0.014</td>
<td>No</td>
</tr>
<tr>
<td>3600</td>
<td>0.92</td>
<td>0.01</td>
<td>Yes</td>
</tr>
<tr>
<td>3600</td>
<td>0.92</td>
<td>0.01</td>
<td>No</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 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>
</tbody>
</table>
| Size                      | Chopper: 14" x 10" x 7"
                      | Logic: 3" x 11" x 6"
                      | Coil: 6" x 4" x 5"
                      | Capacitors: 10" x 5" x 6" |
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 equivalent</td>
<td>4 x 20</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: 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.

ORIGINAL PAGE IS OF POOR QUALITY.
CASE 5
3 SPEED AUTOMATIC TRANSMISSION CHAIN COUPLED TO THE DIFFERENTIAL WITHOUT TORQUE CONVERTER

MOTOR

TRANSMISSION

TO WHEEL

TO WHEEL

TRANSMISSION EFFICIENCY

TRANSMISSION EFFICIENCY

DIFFERENTIAL EFFICIENCY

RANGE

SAE J227a/D

55 MPH

30 MPH, 10% GRADE

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.

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

SAE 28-42 MILES

42 MILES

4.0 MILES
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 J276a/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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WEIGHT PENALTY</strong></td>
<td>+50 LBS</td>
</tr>
<tr>
<td><strong>TRANSMISSION RATIO</strong></td>
<td></td>
</tr>
<tr>
<td>0-2.5 MPH</td>
<td>1.0:1</td>
</tr>
<tr>
<td>2.5-5 MPH</td>
<td>1.25:1</td>
</tr>
<tr>
<td>5-10 MPH</td>
<td>1.5:1</td>
</tr>
<tr>
<td>10+ MPH</td>
<td>1.75:1</td>
</tr>
<tr>
<td><strong>TRANSMISSION EFFICIENCY</strong></td>
<td></td>
</tr>
<tr>
<td>0-2.5 MPH</td>
<td>0.20</td>
</tr>
<tr>
<td>2.5-5 MPH</td>
<td>0.65</td>
</tr>
<tr>
<td>5-10 MPH</td>
<td>0.91</td>
</tr>
<tr>
<td>10+ MPH</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>DIFFERENTIAL RATIO</strong></td>
<td></td>
</tr>
<tr>
<td><strong>DIFFERENTIAL EFFICIENCY</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.92</td>
</tr>
</tbody>
</table>

**RANGE**

<table>
<thead>
<tr>
<th>Speed</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 MPH</td>
<td>36-36 MILES</td>
</tr>
<tr>
<td>2.5-5 MPH</td>
<td>48 MILES</td>
</tr>
<tr>
<td>5-10 MPH</td>
<td>4.4 MILES</td>
</tr>
</tbody>
</table>

**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.

---

![Diagram](image)
HYPOTHETICAL INFINITELY VARIABLE SPEED TRANSMISSION, ROLLING ELEMENT TYPE

PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHT PENALTY</td>
<td>200 LBS</td>
</tr>
<tr>
<td>TRANSMISSION RATIO</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>1.0:1 (ABOVE 30 MPH)</td>
</tr>
<tr>
<td>TRANSMISSION EFFICIENCY</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 (20-30 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

<table>
<thead>
<tr>
<th>RANGE</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE J287a/D</td>
<td>29-35 MILES</td>
</tr>
<tr>
<td>55 MPH</td>
<td>45 MILES</td>
</tr>
<tr>
<td>30 MPH, 10% GRADE</td>
<td>5.2 MILES</td>
</tr>
</tbody>
</table>

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: -100 LBS
- TRANSMISSION RATIO:
  - 4.8:1 (0-10 MPH)
  - 3.0:1 (10-20 MPH)
  - 1.0:1 (20-30 MPH)
  - 0.8:1 (30-40 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: +100 LBS
- TRANSMISSION RATIO: 4.0.1 (0-20 MPH)
  1.0.1 (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.
<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.
## 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>Moderate</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.
Source: Booz-Allen & Hamilton Inc.
CASE 11 - FULL CONTROL

Bypass Contactor

Armature Chopper

Field Chopper

Battery

Field

Reverse Contractor

Arm

CVT

Differential
CASE 12 PERFORMANCE

(a)

Motor - Separately excited
Control - Field only
Transmission - CVT

Transmission Control

Field Control

Source: Booz, Allen & Hamilton Inc.
CASE 13 PERFORMANCE

Battery Current, Amps

Motor Control - Separately excited
Armature only
Transmission - CVT

Transmission Control

Armature Chopping

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

Field

Reverse Contactor

Battery

Arm.

Differential
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><strong>Motor Type</strong></td>
<td>Series</td>
<td>Shunt</td>
<td>Shunt</td>
<td>Shunt</td>
<td>Shunt</td>
</tr>
<tr>
<td><strong>Armature Control</strong></td>
<td>Chop</td>
<td>Chop</td>
<td>Fixed</td>
<td>Chop</td>
<td>Chop</td>
</tr>
<tr>
<td><strong>Separate Field Control</strong></td>
<td>---</td>
<td>Chop</td>
<td>Chop</td>
<td>Fixed</td>
<td>Chop</td>
</tr>
<tr>
<td><strong>Transmission Type</strong></td>
<td>EM/CVT</td>
<td>EM/CVT</td>
<td>EM/CVT</td>
<td>EM/CVT</td>
<td>---</td>
</tr>
<tr>
<td><strong>Differential</strong></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><strong>Range Over SAE J227a/D, 3,600 lb. vehicle (miles)</strong></td>
<td>4000</td>
<td>3491</td>
<td>3491</td>
<td>2094</td>
<td>5870</td>
</tr>
<tr>
<td><strong>Motor Speed at 55 mph (RPM)</strong></td>
<td>30</td>
<td>34</td>
<td>33.5</td>
<td>34.5</td>
<td>36.1</td>
</tr>
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</table>

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

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>CASE STUDIED</th>
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<tbody>
<tr>
<td></td>
<td>9</td>
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<tr>
<td>Motor Type</td>
<td>Series</td>
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<tr>
<td>Armature Control</td>
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<td>Separate Field Control</td>
<td>---</td>
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<tr>
<td>Transmission</td>
<td>EM/CVT</td>
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<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></td>
</tr>
<tr>
<td>Actual Weight (miles)</td>
<td>31.2</td>
</tr>
<tr>
<td>Relative Weight (lbs.)</td>
<td>0</td>
</tr>
<tr>
<td>Reliability</td>
<td>Moderate</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
</tr>
<tr>
<td>Development Risk</td>
<td>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

1.03:1 RATIO
4:1 RD.
33 T.

1 1/4" DIA TRACTION MOTOR

DIFFERENTIAL INPUT 4:1:1 RATIO

DIFFERENTIAL - 1:1 RATIO

2ND GEAR
103:1 RATIO
4125 RD.
33 T.

GEAR
49 RD.
32 T.

3RD GEAR
ELECTROMAGNETIC

40 RD.
13 T.

CLUTCHES - DRY

DUAL DISC CLUTCH
(ELECTROMAGNETIC)

1ST RATIO
6.8 RD.
52 T.

UNIVERSAL COUPLING

2" MIL. INSIDE TUBE SURFACE

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

BATTERIES
ACCELERATOR
CONTROL
FRAME
BATTERIES
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.
TOOTH TYPE ELECTROMAGNETIC
3 SPEED TRANSMISSION

1st Gear

2nd Gear

3rd Gear

1 1/4" Dia. Traction Motor

Differential - 1:1 Ratio

Universal Coupling

Remain Inner Tire Surface
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.