CONS/1011-14
NASA TM-73769

BASELINE TESTS OF THE KORDESCH HYBRID PASSENGER VEHICLE

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June 1978

Prepared for
U.S. DEPARTMENT OF ENERGY
Division of Transportation Energy Conservation
Under Interagency Agreement EC-77-A-31-1011

NOTICE

The Electric and Hybrid Vehicle Program was conducted under the guidance of the then Energy Research and Development Administration (ERDA), now part of the Department of Energy.

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SUMMARY

The Kordesch hybrid passenger vehicle is propelled by an electric motor that receives its energy from a spark-ignition-engine-driven alternator and an electric battery system. It was developed and is owned by Dr. Karl V. Kordesch, formerly of Lakewood, Ohio, and now living in Graz, Austria. It was tested at the Transportation Research Center of Ohio Test Track, East Liberty, Ohio, between August 17 and September 22, 1977. The tests are part of an Energy Research and Development Administration (ERDA) project to assess the state-of-the-art of electric and hybrid vehicles. The Kordesch hybrid vehicle performance test results are presented in this report.

The Kordesch hybrid is a four-passenger Austin A40 sedan that has been converted to a heat-engine-alternator- and battery-powered hybrid. It is propelled by a conventional, gasoline-fueled, heat-engine-driven alternator and a traction battery pack powering a series-wound, 7.5-kilowatt (10-hp) direct-current electric drive motor. The 12-kilowatt (16-hp) gasoline engine drives the 7-kilowatt alternator, which provides electrical power to the drive motor or to the 96-volt traction battery through a rectifier. The propulsion battery consists of eight 12-volt batteries connected in series. The electric motor is coupled to a four-speed standard Austin transmission, which drives the rear wheels. Power to the motor is controlled by a three-step foot throttle, which actuates relays that control armature current and field excitation. Conventional hydraulic brakes are used. There is no regenerative braking. All tests were run at the gross vehicle weight of 1410 kilograms (3110 lbm).

The vehicle test results show that the range of the hybrid vehicle can be significantly extended if on-board fuel is used to power the heat-engine-driven alternator to produce electric power for the drive motor. But because some energy is supplied by the battery, the range is still limited. The increase in range depends on how much fuel is consumed and on the operating mode of the heat engine. At a constant speed of 40 kilometers per hour (25 mph) the range of the Kordesch vehicle operating with the heat engine turned off is 43 kilometers (27 miles). With the

heat engine producing maximum power the range of the vehicle at the same constant speed can be increased to 173 kilometers (107 miles), but 0.117 liter per kilometer (0.05 gal/mile) of gasoline is consumed in achieving this range. At ranges less than about 64 kilometers (40 miles) the gasoline consumption of the Kordesch vehicle is lower than that of a newer conventional four-passenger vehicle of comparable size and payload. At ranges greater than 64 kilometers (40 miles) the gasoline consumption is higher than that of the conventional vehicle. Similar results were obtained for the higher vehicle test speeds. The range of the Kordesch vehicle varied from 40 to 190 kilometers (25 to 117 miles) for the driving schedule B tests, and from 30 to 70 kilometers (20 to 44 miles) for driving schedule C. The fuel economy is worse than for a comparable conventional vehicle for these driving schedules, except at very short ranges, where significant energy from the battery is used to propel the vehicle.

The Kordesch hybrid accelerates from 0 to 32 kilometers per hour (0 to 20 mph) in 7.5 seconds and from 0 to 48 kilometers per hour (0 to 30 mph) in 14 seconds. At a speed of 32 kilometers per hour (20 mph) the vehicle can negotiate a 9.6-percent grade.

INTRODUCTION

The vehicle tests and the data presented in this report are in support of Public Law 94-413 enacted by Congress on September 17, 1976. The law requires the Energy Research and Development Administration (ERDA) to develop data characterizing the state-of-the-art of electric and hybrid vehicles. The data so developed are to serve as a baseline (1) to compare improvements in electric and hybrid vehicle technologies, (2) to assist in establishing performance standards for electric and hybrid vehicles, and (3) to help guide future research and development activities.

The National Aeronautics and Space Administration (NASA), under the direction of the Electric and Hybrid Vehicle Project Office of the Division of Transportation Energy Conservation of ERDA, has conducted track tests of electric and hybrid vehicles to measure their performance characteristics and vehicle component efficiencies. This report describes the performance test results for a series-hybrid electric vehicle.

The tests were conducted according to the ERDA Electric and Hybrid Vehicle Test and Evaluation Procedure (ERDA-EHV-TEP), described in appendix E of reference 1. This procedure includes the Society of Automotive Engineers (SAE) J227a procedure (ref. 2). Modifications to both procedures were necessary to evaluate the hybrid features of this vehicle. Nineteen electric and hybrid vehicles have been tested under this phase of the program, 14 under the direction of the Lewis Research Center, 4 by MERADCOM, and 1 by the Canadian government.

The assistance and cooperation of Dr. Karl V. Kordesch, the vehicle developer and owner, and of Albert Kordesch, his son, are greatly appreciated. The Energy Research and Development Administration provided funding support and guidance during this project.

U.S. customary units were used in the collection and reduction of data. The units were converted to the International System of Units for presentation in this report. U.S. customary units are presented in parentheses. The parameters, symbols, units, and unit abbreviations used in this report are listed here for the convenience of the reader.

Parameter	Symbol	SI units		U.S. customary units	
		Unit	Abbreviation	Unit	Abbreviation
Acceleration	a	meter per second squared	m/s^2	mile per hour per second	mph/s
Area	---	square meter	m^2	square foot, square inch	ft^2; in^2
Battery capacity	c	ampere-hour	Ah	ampere-hour	Ah
Battery constant	b,n	----------------------	-----	----------------------	------------
Battery current	I	ampere	A	ampere	A
Empirical battery current	I_c	ampere	A	ampere	A
Energy	---	megajoule	MJ	kilowatt-hour	kWh
Energy consumption	E	megajoule per kilometer	MJ/km	kilowatt-hour per mile	kWh/mile
Energy economy	---	megajoule per kilometer	MJ/km	kilowatt-hour per mile	kWh/mile
Force	P	newton	N	pound force	lbf
Gradeability	G	percent	-----	percent	------------
Integrated current	---	ampere-hour	Ah	ampere-hour	Ah
Length	---	meter	m	inch; foot; mile	in.; ft; ---
Mass; weight	W	kilogram	kg	pound mass	lbm
Power	P	kilowatt	kW	horsepower	hp
Pressure	---	kilopascal	kPa	pound per square inch	psi
Range	R	kilometer	km	mile	------------
Recharge fraction	α	----------------------	-----	----------------------	------------
Specific distance	β	kilometer per ampere-hour	km/Ah	mile per ampere-hour	mile/Ah
Specific energy	---	megajoule per kilogram	kW/kg	kilowatt per pound	kW/lbm
Specific power	---	kilowatt per kilogram	kW/kg	kilowatt per pound	kW/lbm
Speed	v	kilometer per hour	km/h	mile per hour	mph
Time	t	second	s	second	s
Volume	---	cubic meter	m^3	cubic inch; cubic foot	in^3; ft^3

OBJECTIVES

The characteristics of interest for the Kordesch hybrid are gasoline economy, electric energy consumption, range at both constant speed and over stop-and-go driving schedules, maximum acceleration, gradeability, road energy consumption, and road power.

TEST VEHICLE DESCRIPTION

The Kordesch hybrid is a converted four-passenger 1961 Austin A40 sedan. It was originally modified by Dr. Karl V. Kordesch to an electric drive powered by a fuel cell and later converted to a heat-engine-alternator - and battery-powered hybrid vehicle. The vehicle is shown in figure 1 and a block diagram of the propulsion system is shown in figure 2. The propulsion system consists of a heat-engine - alternator unit; a rectifier; a DC traction motor; the standard Austin clutch, transmission, and differential; the traction battery; an auxiliary battery; and the electric system control. The propulsion system is a "series" hybrid, where the rectified heat-engine-driven-alternator electrical output charges the battery and/or powers the traction motor. The heat engine can only power the vehicle through the electric motor. The vehicle may be operated in the all-electric mode (heat engine off) or in the hybrid mode (heat engine running).

The heat-engine - alternator, a small industrial unit, is located in the trunk of the vehicle (fig. 3). The unit is manufactured by Tecumseh and marketed by Sears, Roebuck and Company. The heat engine produces 12 kilowatts (16 hp) at 3600 rpm. The alternator produces 7 kilowatts of 60-hertz, 110-volt, single-phase power (at 3600 rpm). The engine is a single-cylinder, air-cooled, four-cycle unit that runs on low-octane gasoline. It is equipped with an electric fuel pump, but it can also be operated by gravity feed. The engine has no emission control devices. A 10-liter (2.6-gal) fuel tank is mounted next to the engine. Choking is automatic and thermostatically controlled. The electrical starter and ignition are powered from the 12-volt accessory battery. The heat engine is started and stopped by means of a manual switch in the trunk of the vehicle. The speed, and consequently the power output, of the heat engine can be selected by the operator with a hand throttle located next to the drivers seat. Once set, the speed remains constant. This speed can be set at discrete values between 2400 and 3600 rpm.

The alternating-current alternator is a rotating-armature alternator driven by the heat engine through a rigid coupling. A series field in the alternator provides DC power for the engine accessories and for charging the 12-volt accessory battery. A separately excited shunt field controls the alternator AC output. The AC power output is connected to a bridge rectifier. The DC output of the rectifier charges the traction battery and/or powers the DC traction motor.

The traction motor is a DC, series-wound motor with two field coils (F1 and F2 in fig. 4). The field coils are connected in series with the motor armature coils. The traction motor torque is varied by controlling its field strength. The control is accomplished through electromechanical relays (K1, K2, K3, and K4) that are activated by means of microswitches through the accelerator foot pedal. These relays switch the two field windings and a resistor in and out of the circuit. With the 12-volt supply on and the accelerator pedal released, all four relays open (fig. 4) and prevent current flow through the armature. Depressing the foot pedal to the first position energizes and closes K1 and K2 and connects the motor, with maximum field strength, to the battery. The 0.5-ohm resistor limits the motor current in this mode. Further depression of the pedal energizes K3, bypassing the 0.5-ohm resistor and increasing the output torque. Fully depressing the foot pedal closes K4, bypassing part of the field and further increasing the output torque. Quantitative motor-control characteristics are not available under any of these conditions.

The heat-engine speed is controlled by a flywheel governor that controls the carburetor throttle valve. The speed can be manually set by a hand throttle next to the drivers seat. The battery charging rate is automatically controlled from the heat engine. When the battery is fully charged, its high voltage allows it to accept only a low charging current. When the battery is discharged, the low battery voltage (near 90 V) allows it to accept a high charging current.

Eight 12-volt traction batteries were supplied with the Kordesch hybrid. Seven of these were Globe-Union EV-27's and one was a Globe-Union EV-27 Die Hard. The batteries were connected in series to produce a propulsion-battery nominal voltage of 96 volts. Characteristics of both battery types are shown in table I. Discharge capacity data for the EV-27's are shown in figures 5 and 6. The performance of the Die Hard battery was similar to that of the EV-27 battery.

The battery charger consists of a variac, a rectifier, a rheostat, and a charge-level controller. The charger requires 115-volt, 60-hertz AC power from an external source. The input voltage is controlled with the variac. The output of the variac is rectified with a 20-ampere rectifier. A rheostat is used for fine control or adjustment of the charging current. Charging current is tapered as the battery is charged. The charge-level controller terminated the charging process automatically when the specified charge level was reached.

Conventional drum brakes are used on both front and rear wheels. No regenerative braking is provided on the vehicle.

INSTRUMENTATION

The Kordesch hybrid was instrumented to measure vehicle speed, distance, total fuel flow, fuel temperature, elapsed time, rectified current and voltage, battery current and voltage, and motor current. Table II lists the parameters that were measured and the method of measurement. The vehicle electrical system is shown in figure 7. Three shunts were provided with the vehicle to measure battery current, motor current, and rectified DC current. These currents are displayed on gages on the vehicle's dashboard (fig. 8). The output of the 150-ampere, 100-millivolt (battery current) shunt is also wired to an ampere-hour meter (fig. 8) underneath the dashboard. This meter shows the state of charge of the traction battery.

Three shunts were added to the electrical system of the vehicle: two for current integrators, and one for a watt-hour meter. The instrumentation wiring is shown in figure 9. Curtis Model SHR-C3 current integrators were used to measure battery current and rectifier current. They are a bipolar digital device capable of measuring current flow in either direction. They were calibrated to read ampere-hours directly when used with a 500-ampere, 100-millivolt shunt.

An electronic watt-hour meter, developed by Deutsche Automobilgesellschaft mbH (DAUG) of Germany, was used in the battery circuit to measure the energy both into and out of the main battery. The meter was powered by the 96-volt vehicle battery. Energy is recorded on two separate counters, one for each direction of current flow. The meter was calibrated to read watt-hours directly when used with a 250-ampere, 60-millivolt shunt. The meter weighed 1.3 kilograms (2.86 lbm), and the measuring error was less than 1 percent.

Fuel consumption (gasoline flow) was measured with a FluiDyne Model 1240 flowmeter package supplied by the Transportation Research Center. Accumulated fuel flow, fuel temperature, and elapsed time for the test run are measured and displayed on three digital readout meters supplied with this package. The accuracy of the flow measurements is 1 percent or better for all flow rates.

Readings of the integrated currents (ampere-hours) and the energy (watt-hours) into and out of the battery were recorded manually before and after each test.

A Nucleus Corporation Model NC-7 precision speedometer (fifth wheel) was used to measure vehicle velocity and distance traveled. Auxiliary equipment used with the fifth wheel included a Model ERP-X1 electronic pulser for distance measurement, a Model NC-PTE pulse totalizer, a Model ESS/E expanded-scale speedometer, and a programmable digital attenuator. The fifth wheel and auxiliaries weighed about 22.7 kilograms (50 lbm).

The fifth-wheel speedometer was calibrated during constant-speed test runs. The driver maintained a given constant speed, while another person, standing adjacent to the vehicle path of travel, verified the vehicle speed with a Kustom Electronics Model HR8 radar gun. The fifth-wheel speed measurements as evaluated by these checks were accurate to within 1.6 kilometers per hour (1 mph). The accuracy of the fifth-wheel distance digital readout was checked against distance markers placed around the track at 0.16-kilometer (0.1-mile) intervals. The distances measured were accurate to 0.5 percent.

Honeywell 195 Electronik, two-channel, strip-chart recorders were used to record motor voltage and current, rectifier voltage and current, and vehicle speed and distance. This model recorder has an accuracy of better than 0.5 percent. During the test program the recorders were calibrated with a Hewlett-Packard Model 6920B meter calibrator, which has a usable range between 0.01 and 1000 volts and has an inherent accuracy of 0.2 percent of the reading.

Two auxiliary batteries connected in parallel were used to power a Tripp Lite 500-watt DC/AC inverter that provided AC power for the current integrators and the strip-chart recorders. DC power for the fifth-wheel instruments and the fuel flowmeter package was also obtained from these 12-volt auxiliary batteries.

While the battery was being charged from an external power source, battery voltage and current were recorded on a strip-chart recorder. The energy delivered to the charger was measured with a General Electric 1-50A, single-phase, residential kilowatt-hour meter. Electrolyte temperatures and specific gravities were measured manually before and after charging.

TEST PROCEDURES

The tests of the Kordesch hybrid described in this report were performed at the Transportation Research Center Test Track, a multilane, 12-kilometer (7.5-mile) track in East Liberty, Ohio. The track is described in appendix B. When the vehicle was delivered to the test track, the pretest checks described in appendix C were conducted. The first test was a formal shakedown to familiarize the driver with the operating characteristics of the vehicle, to check out all instrumentation systems, and to determine the vehicle's maximum speed. All tests were run in accordance with ERDA Electric and Hybrid Vehicle Test and Evaluation Procedure ERDA-EHV-TEP (appendix E of ref. 1) modified for a hybrid as described. The tests were run at a gross vehicle weight of 1410 kilograms (3110 lbm).

Shakedown Tests

Because of the complexity of the hybrid vehicle, including the many control and feedback networks in the electrical system, extensive shakedown testing was required for familiarity with the vehicle operation. During these shakedown tests the instrumentation requirements and testing procedures were developed.

From the shakedown test results it was decided that the all-electric tests would be run until the battery was depleted as for the normal test procedure but that each hybrid test would be run for only one revolution of the test track (12 km, or 7.5 miles). Fuel consumption could be measured directly by this technique, and range could be calculated from the amount the battery was depleted in one lap. This revision to the procedure allowed many hybrid-mode tests to be run each day. This was necessary because of the large number of variables that had to be investigated and the limited time the vehicle was available for testing.

The range and the fuel consumption of the vehicle were found to depend on the alternator power output, which in turn depends on the alternator rotational speed. Therefore, the range tests were conducted at three discrete alternator speeds.

During the shakedown tests, attempts were made to operate at 2600- to 3400-rpm alternator speeds. At the lower speeds, insufficient power was produced to conduct a meaningful test. At the higher speeds the alternator overtemperature or overcurrent cutoff would intermittently shut off alternator power. So the final alternator test speeds selected were 2800, 3000, and 3200 rpm.

Tests at Constant Speed

During the shakedown tests, with the alternator set at maximum output (3200 rpm) and the battery fully charged, the maximum speed of the vehicle was determined. The maximum speed is defined as 95 percent of the minimum speed the vehicle can maintain during one full lap around the test track. At the gross vehicle weight of 1410 kilograms (3110 lbm) the maximum speed of the vehicle was 77 kilometers per hour (48 mph).

The constant-speed range tests were run in the hybrid mode at speeds of 40, 56, and 72 kilometers per hour (25, 35, and 45 mph) at each of the three alternator speeds for one lap (12 km, or 7.5 miles) each. Each test was repeated and some tests were run three times, for a total of 24 constant-speed tests. In the all-electric mode (i.e., with the gasoline engine not operative) the constant-speed tests were run until the vehicle speed fell below 95 percent of the initially programmed steady speed or until the voltage of any one of the eight 12-volt batteries dropped below 9 volts. A voltmeter was provided with a manual switching arrangement that allowed the driver or his assistant in the vehicle to monitor the voltage levels of all the batteries during the test runs.

Tests under Driving Schedules

Stop-and-go driving schedules B and C (shown in fig. 10) were run with the vehicle in the hybrid mode only. The vehicle acceleration was insufficient to meet the schedule D requirements. A complete description of the driving schedules is given in reference 2. A special instrument, called a cycle timer, was developed at NASA Lewis to assist in accurately running these tests. Details of the cycle timer are given in reference 1. The driving schedule tests were run at three alternator speeds, and each was terminated after one lap around the track. Each test was repeated and two tests were run three times, for a total of 14 tests. The range of the vehicle was calculated from the battery data obtained during these tests.

Acceleration and Coast-Down Tests

The maximum acceleration of the Kordesch vehicle was measured with the battery fully charged and with alternator speeds of both 3000 and 3200 rpm. Acceleration was identical for both alternator speeds. With the vehicle near maximum speed after the maximum acceleration tests, coast-down data were recorded by putting the transmission in neutral while simultaneously letting up on the accelerator pedal and coasting to a stop. Both acceleration and coast-down tests were conducted in opposite directions on the outer asphalt-surfaced berm of the track. The results were averaged.

Braking, Tractive Force, and Handling Tests

The braking and tractive force tests called for in the test procedure (appendix E of ref. 1) were not performed because the vehicle was not available for a sufficient time to conduct these tests. The handling tests were not run, at the request of ERDA.

TEST RESULTS

The test data and the analysis of the test data for the range and fuel economy tests, the acceleration and coast-down tests, and the battery energy consumption tests are presented in this section of the report.

Hybrid-Mode Range and Fuel Economy

The Kordesch hybrid was tested at constant speeds and over stop-and-go driving schedules in the hybrid mode to measure fuel economy and to evaluate vehicle range. Each test was run for approximately one lap of the track. A list of the tests conducted and the test data is presented in table III. The percentage of battery discharge at the start of each test shown in the table is an approximation based on a 1-hour discharge rate. It was calculated by subtracting the integrated ampere-hours into the battery from the ampere-hours out of the battery and dividing this number by the ampere-hour capacity of the battery at the 1-hour discharge rate (60 Ah).

The fuel economy data for the early tests are suspect because of erratic operation of the automatic choke. The choke was repaired on August 24, 1977. However, all data points are used in the calculations.

The range of the Kordesch hybrid, in the hybrid mode, was calculated from the manufacturers rated battery capacity and the ampere-hours removed from the battery while the vehicle was driven approximately one lap (12 km) around the track. In the calculations the range of the vehicle was usually limited by battery capacity not by fuel-tank capacity. Increasing the fuel-tank capacity from 10 liters to 20 liters would make the vehicle battery-limited for all tests except driving schedule B at 3200 rpm.

For constant-speed tests, the range of the vehicle was calculated from

$$R = VbI^n \qquad (D3)$$

where

R   range, km (miles)

V   vehicle or test velocity, km/h (mph)

I   average current drain from battery calculated by dividing integrated current in ampere-hours by test time

and b and n are battery constants defined in appendix D.

The range of the vehicle for the driving schedule tests was calculated from

$$R = \beta b I_c^{n+1} \qquad (D4)$$

where

β distance traveled per ampere-hour removed from battery

I_C empirically determined battery current defined in appendix D

The derivations of these equations and the details of their use are provided in appendix D. Calculations of range for the Kordesch hybrid are presented in appendix E.

The fuel economy of the Kordesch hybrid was calculated from the measured fuel flow and the measured range. Fuel flow corrections for fuel temperature, barometric pressure, and air temperatures were negligible and were not included in the calculations.

The results of the range, fuel, and energy economy calculations are summarized in table IV for each test. The test data have been averaged for each operating condition, and all the data from every test run are included in the averages.

All-Electric-Mode Range

When the hybrid-mode tests were completed, constant-speed range tests were conducted with the vehicle in the all-electric mode (i.e., operating on battery power alone with the heat engine turned off). The tests were performed at constant speeds of 40, 56, and 72 kilometers per hour (25, 35, and 45 mph). One test each was conducted at 40 and 72 kilometers per hour, and two tests were conducted at 56 kilometers per hour.

Several of the 12-volt batteries in the traction battery had deteriorated in capacity before the all-electric range test was run. As replacement batteries were not available, the tests were conducted with a depreciated battery and the potential range achievable with a full-capacity battery was calculated. Range tests were terminated when the voltage of any of the eight batteries dropped to below 9 volts, as continued operation at or below 9 volts would cause rapid deterioration and permanent damage to that battery.

The integrated battery discharge current was measured during these short tests. From these data, the manufacturer's rated battery capacity, and equation (D3), the expected vehicle range achievable with good batteries was predicted. The results of these calculations and the measured ranges are shown in table V. The estimated accuracy of these predictions is ± 10 percent.

Maximum Acceleration

The maximum acceleration of the vehicle was determined with the battery fully charged. Vehicle speed as a function of time is shown in figure 11 and table VI. The average acceleration $\bar{a}_n$ was calculated for the time period t_{n-1} to t_n, where the vehicle speed increased from V_{n-1} to V_n, from the equation

$$\bar{a}_n = \frac{V_n - V_{n-1}}{t_n - t_{n-1}}$$

and the average speed of the vehicle $\bar{V}$ from the equation

$$\bar{V} = \frac{V_n + V_{n-1}}{2}$$

Maximum acceleration as a function of vehicle speed is shown in figure 12 and table VII.

Gradeability

The maximum grade, in percent, that a vehicle can climb at an average vehicle speed $\bar{V}$ was determined from maximum acceleration tests by using the equations

$$G = 100 \tan (\sin^{-1} 0.1026\ \bar{a}_n) \qquad \text{for V in km/h}$$

in SI units

or

$$G = 100 \tan (\sin^{-1} 0.0455\ \bar{a}_n) \qquad \text{for } \bar{V} \text{ in mph}$$

in U.S. customary units

where $\bar{a}_n$ is average acceleration in meters per second squared (mph/sec). The maximum grade the Kordesch hybrid can negotiate as a function of speed in shown in figure 13 and table VIII.

Road Energy Consumption

Road energy is a measure of the energy consumed in overcoming the vehicle's aerodynamic and rolling resistance plus the energy consumed in the differential drive shaft and that portion of the transmission that is rotating when in neutral. It was obtained during coast-down tests, when the differential was being driven by the wheels, and thus may be different than the energy consumed when the differential is being driven by the motor.

The average deceleration of the Kordesch hybrid as determined from a total of four coast-down tests, two in each direction, is shown in figure 14. From a vehicle speed of 72 kilometers per hour (45 mph), it took nearly 2 minutes for the vehicle to come to a complete stop.

Road energy consumption E_n was calculated from the following equations:

$$E_n = 2.78 \times 10^{-4} W \frac{V_{n-1} - V_n}{t_n - t_{n-1}}, \text{ MJ/km}$$

or

$$E_n = 9.07 \times 10^{-5} W \frac{V_{n-1} - V_n}{t_n - t_{n-1}}, \text{ kWh/mile}$$

where

W vehicle mass, kg (lbm)

V vehicle speed, km/h (mph)

t time, s

The results of the road energy calculations are shown in figure 15 and table IX.

Road Power Requirements

The road power is analogous to the road energy. It is a measure of vehicle aerodynamic and rolling resistance plus the power losses from the differential, the drive shaft, and a portion of the transmission. The road power P_n required to propel a vehicle at various speeds is also determined from the coast-down tests. The following equations are used:

$$P_n = 3.86x10^{-5}W \frac{V_{n-1}^2 - V_n^2}{t_n - t_{n-1}}, \text{ kW}$$

or

$$P_n = 6.08x10^{-5}W \frac{V_{n-1}^2 - V_n^2}{t_n - t_{n-1}}, \text{ hp}$$

The results of road power calculations are shown in figure 16 and table X.

Electric Energy Consumption

The vehicle's indicated electric energy consumption is defined as the electric energy required to recharge the battery after a test, divided by the vehicle range achieved during the test, where the energy is the input to the battery charger.

Many different hybrid vehicle tests were run each day. Because the battery was only partially recharged between tests either from the vehicle's heat-engine-driven alternator or from external electric power, electric energy consumption could not be measured directly. Energy consumption was calculated from the measured ampere-hours removed from the battery for each test condition and the measured characteristics of the battery charger.

The energy that must be put into the battery charger to restore the indicated battery capacity is plotted in figure 17 from 14 test points. The calculations of energy consumption for each constant-speed and driving-schedule test are shown in table XI for the hybrid tests and in table XII for the all-electric tests . The calculated range used in table XI is the average of several tests at the designated conditions. The capacity removed was obtained by using the average current drawn per test in conjunction with figure 5 to obtain a discharge time. Capacity restored is capacity removed plus 10 percent. The ampere-hours required to recharge the battery were based on a 10-percent overcharge. The required energy input to the charger was then obtained from figure 17. Dividing the charger input by the calculated range gives the electrical energy consumption per unit of distance traveled.

VEHICLE RELIABILITY AND SERVICEABILITY

No major problems were encountered that prevented completion of the test program. However, numerous difficulties arose that created delays. Some batteries deteriorated during the program: Two of them were changed when recharge became impossible. Others required excessive overcharge to achieve full charge. On one occasion, the 12-volt accessory battery was discharged overnight when the light switch was inadvertently left on. The automatic choke tended to flutter between fully open and partially closed. This affected the fuel flow rate and resulted in erratic fuel consumption. The choke assembly was modified to hold it fully open during the test runs. During one test the starter solenoid would not disengage and the test run had to be aborted when the starter began to smoke. The alternator would cut out, even at low speeds, if high currents were drawn or if the alternator overcharged; as a result, a number of test runs were aborted.

The original Austin A40 design was a comfortable, easily handled vehicle. The Kordesch hybrid modification somewhat compromised these characteristics. The higher tire pressures necessitated by the increased vehicle weight resulted in a slightly harsher ride and more difficult steering. The weight increase also resulted in sagging springs. The front-end alignment was out of specification and could not be adjusted for these tests. Consequently, the right-front-tire wear was excessive, and the road power and energy required by the vehicle were increased. Because the light switch was beneath the steering column, it was vulnerable to inadvertent actuation. The sensitivity of the alternator output to battery charge level and throttled current demand made engine speed setting adjustments necessary to maintain reasonably constant rectifier output. Engine vibration loosened fittings in the engine compartment, a condition that required daily maintenance. Engine heat dissipation was marginal. Engine noise was so high that it was hard to hear both normal conversation and the beeper on the cycle timer.

COMPONENT CHARACTERISTICS

Component test data obtained from the battery, the battery charger, and the heat-engine - alternator system of the Kordesch hybrid vehicle are presented in this section of the report.

Battery Charger

The energy efficiency of the charger was calculated from measurements of the energy input to the charger and the energy input to the battery during recharge. Energy input to the charger was measured with a residential kilowatt-hour meter. Energy input to the battery was measured by the battery energy meter (DAUG meter). The results of these measurements are shown in table XIII.

Battery

Before the track tests were started, the vehicle battery was tested as specified in appendix E of reference 1 to measure its capacity.

Separate tests were run on the seven EV-27 batteries connected to form an 84-volt series string and on the single 12-volt Die Hard battery. A constant-current load bank was used to discharge the batteries. The initial capacity test was unsatisfactory because one EV-27 could not be charged to the specified specific gravity. This defective battery was replaced and the capacity test was repeated. The results of this capacity check on both batteries are shown in figure 18. The capacity removed from the EV-27 batteries was 60.3 ampere-hours, which is 92 percent of the manufacturer's specified average capacity. The single Die Hard battery delivered 56.9 ampere-hours at 37.5 amperes. Since the delivered capacities were within the 80-percent criterion, both batteries passed the capacity test.

Heat-Engine - Alternator System

The heat-engine alternator on the Kordesch hybrid vehicle is a commercial, standby, power-generating system rated at 7-kilowatt, 110-volt output at 3600 rpm. It was not developed for automotive applications, where low fuel consumption is important. Heat-engine perfomance data were not available.

In the NASA tests of the Kordesch hybrid, gasoline consumption and rectifier electrical output were measured. The rectifier power output was calculated from the ampere-hour measurements, the test duration, and an average voltage obtained from the rectified output strip charts for a number of test runs at the three alternator speeds. The voltages used were assumed to be constant at 95, 97, and 100 volts for 2800-, 3000-, and 3200-rpm alternator speeds, respectively. These data were used to analyze the performance of the heat-engine - alternator system. The results are shown in figures 19 to 21.

Heat-engine fuel consumption as a function of rectified power output is shown in figure 19, specific fuel consumption is presented in figure 20, and overall heat-engine - alternator - rectifier efficiency is shown in figure 21. The thermal efficiencies were calculated by assuming the 34-megajoule-per-liter (122,000-Btu/gal) lower heating value for gasoline at a specific gravity of 0.737 at 16° C (60° F). The maximum thermal efficiency calculated for this unit was slightly over 10 percent.

Motor and Rectifier

Strip-chart recorders were used to continuously monitor electric motor voltages and currents. Motor current and voltage are shown in figure 22 for a 40-kilometer-per-hour (25-mph) constant-speed vehicle test for a range of approximately 6.4 kilometers (4.5 miles). The motor voltage, as shown by the upper trace in figure 22, remained essentially constant except for the small voltage spikes. These spikes result from the larger spikes in the motor current, as shown by the lower trace. The motor current remained fairly constant at about 50 amperes, except for the current spikes that occurred when the driver adjusted the accelerator pedal to maintain a constant vehicle speed.

Much larger motor-current spikes occurred during the 72-kilometer-per-hour (45-mph) test runs as shown in figure 23. These spikes occurred because the motor was alternately operating in and out of the field bypass mode. Changes in current of more than 100 amperes were measured. The motor-voltage trace is mostly obscured by the current trace, but it also experienced spikes in voltage from current switching. The average voltage level was approximately 97 volts.

The associated rectifier voltage and current traces for the 40-kilometer-per-hour (25-mph) test are shown in figure 24. The voltage level, as expected, is identical to the level of motor voltage and shows the same spikes from current switching. The trace of rectifier current is somewhat erratic, but the average remains essentially constant at 37 amperes.

The variations in rectifier voltage and current during a driving schedule C vehicle test are shown in figure 25. Even though the rectifier output voltage is approximately constant, the voltage varies inversely with the rectifier current and sometimes drops below 80 volts. The current level is highest during the acceleration phase, decreases during the cruise phase, and drops to near zero for the coast, brake, and idle period. The near zero currents occurred because the battery was nearly fully charged and the alternator speed was low, at 2800 rpm.

Figure 26 shows another schedule C test where the battery was 40 percent discharged and the alternator speed was higher (3000 rpm). The overall current level is much higher and decreases to only 15 amperes for the idle period of the cycle. Thus the battery was being charged for most of the cycle.

The component voltages and currents depend on the state of charge of the battery. Data taken for two tests at the same operating conditions, a 40-kilometer-per-hour vehicle speed and a 2800-rpm alternator setting but at a different battery state of charge are presented in table XIV. In one test, with the battery discharged to 20 percent of its capacity, the alternator-rectifier current output varied from 10 to 32 amperes. In the other test, with the battery discharged to 90 percent of its capacity, the current varied from 1 to 4 amperes. Fuel consumption was higher for the higher current output.

DISCUSSION OF RESULTS

The range of the Kordesch hybrid vehicle when operated as a battery-powered electric vehicle is limited. By adding a heat-engine - alternator unit that produces electric power from on-board fuel (gasoline), the range can be extended significantly. The heat-engine alternator in the Kordesch hybrid vehicle is in series with the electric drive motor, so it supplies electric power to the motor or battery and does not increase the torque to the drive wheels, which would increase acceleration and gradeability.

The calculated range of the Kordesch vehicle as an all-electric varies from 37 to 43 kilometers (23 to 27 miles) at constant speeds, depending on the speed.

The vehicle range at constant speed can be increased as shown in figure 27 by using electric energy from the heat-engine alternator. Plotted is the vehicle range at constant speed versus the quantity of gasoline consumed while traveling that distance. The range at 40 kilometers per hour (25 mph) can be increased from 48 to 160 kilometers (30 to 100 miles); lesser improvements were seen at higher speeds.

The increase in range depends not only on how much gasoline is consumed, but also on how efficiently it is converted to electric energy. At low alternator speeds and low road powers the heat engine is relatively inefficient. Also when the battery is fully charged at the start of the run, its high voltage prevents the alternator from producing much energy. The heat engine thus operates in an inefficient idle mode until the battery is partially discharged. This effect also introduces a possible error in the range estimates. The test data from 12-kilometer (7.5-mile) tests were extrapolated to the full range under the assumption that the alternator output and the road power remain constant for the full range. Actually as the battery state of charge drops, alternator output and heat-engine efficiency increase. Road power may also increase as the drive line and tires heat up. Both effects can increase range. Insufficient data are available to estimate these effects.

A similar effect occurs for the driving-schedule tests. Figure 28 is a plot of schedule B and C vehicle range versus fuel economy. The Kordesch hybrid's range increases significantly as more gasoline is consumed. Unfortunately, the Kordesch's fuel economy is much lower than that of a conventional Renault-5 LeCar tested under the same conditions (ref. 3) - except at very low ranges, where it operates almost like an all-electric vehicle. Fuel economy for the LeCar is shown (in fig. 28) to be 9.8 kilometers per liter for schedule B and 13.3 kilometers per liter for schedule C.

The range of a hybrid vehicle increases as more on-board electric energy is produced. This, in turn, results in an increase in the amount of gasoline consumed per unit of distance traveled and a decrease in the electric energy consumption as shown in figure 29. The converse is, of course, also true. Fuel consumption is decreased (or the distance traveled per gallon of gasoline increased) if more electric energy is consumed.

Electric energy can be used to decrease the consumption of on-board gasoline in the Kordesch hybrid vehicle. It does not, however, reduce the total amount of energy consumed in moving the vehicle. This is shown in figure 30, a plot of heat energy consumed per unit of distance traveled versus vehicle range. The heat energy is the heat content of the gasoline (assuming 122,000 Btu/gal) consumed plus the heat required to produce the electricity to recharge the battery, for a central-station heat-to-electricity conversion and transmission efficiency of 30 percent. Even though the data are scattered, they show that range for this hybrid is increased by increasing the total amount of energy consumed per unit of distance traveled. Because the heat-engine - alternator - rectifier system in the Kordesch vehicle operates at 10-percent efficiency or lower, using it to produce electricity for propelling a vehicle is less efficient than producing power in an efficient central powerstation.

For comparison, propulsion power was also measured for a conventional vehicle, a 2500-pound Renault-5 LeCar (ref. 3). Its heat energy consumption varied from 2230 to 2870 Btu/mile at constant speeds of 40 to 72 kilometers per hour (25 to 45 mph). At any range greater than 48 kilometers (30 miles) the Kordesch hybrid used more propulsion energy than the conventional vehicle.

The Kordesch hybrid was designed to provide greater range than an all-electric vehicle. It accomplished this objective, although the consumption of gasoline was high. A more efficient heat engine could probably be obtained and a more fuel-conservative operating mode developed. Both would reduce gasoline consumption.

APPENDIX A

VEHICLE SUMMARY DATA SHEET

1.0 Vehicle manufacturer Austin

2.0 Vehicle 1961 Austin A40 sedan

3.0 Price and availability

4.0 Vehicle weight and load
- 4.1 Curb weight, kg (lbm) 1138 (2510)
- 4.2 Gross vehicle weight, kg (lbm) 1410 (3110)
- 4.3 Cargo weight, kg (lbm)
- 4.4 Number of passengers 4
- 4.5 Payload, kg (lbm)

5.0 Vehicle size
- 5.1 Wheelbase, m (in.) 2.13 (84)
- 5.2 Length, m (in.) 3.66 (144)
- 5.3 Width, m (in.) 1.83 (72)
- 5.4 Height, m (in.) 1.45 (57)
- 5.5 Head room, m (in.) 0.94 (37)
- 5.6 Leg room, m (in.) 0.96 (38), front seat; 0.46 (18), rear seat
- 5.7 Frontal area, m^2 (ft^2)
- 5.8 Road clearance, m (in.) 0.16 (6.5)
- 5.9 Number of seats 2 bucket, front; 1 bench, rear

6.0 Auxiliaries and options
- 6.1 Lights (number, type, and function) 2 head, 2 park and tail; 2 turn signals; 1 dome
- 6.2 Windshield wipers 2
- 6.3 Windshield washers pushbutton
- 6.4 Defroster yes
- 6.5 Heater yes
- 6.6 Radio yes
- 6.7 Fuel gage 0 to 100 percent charge
- 6.8 Amperemeter yes, motor and rectifier
- 6.9 Tachometer none

6.10 Speedometer yes

6.11 Odometer yes

6.12 Right- or left-hand drive lift

6.13 Transmission manual; 4 speed

6.14 Regenerative braking no

6.15 Mirrors 1 inside; 2 outside

6.16 Power steering no

6.17 Power brakes no

6.18 Other ____________

7.0 Batteries

7.1 Propulsion batteries

7.1.1 Type and manufacturer EV-27; Globe-Union, Inc.

7.1.2 Number of modules 8

7.1.3 Number of cells 48

7.1.4 Operating voltage, V 96

7.1.5 Capacity, Ah 100 (2-h rate)

7.1.6 Size of each battery, m (in.) ____________

7.1.7 Weight, kg (lbm) 180 (397)

7.1.8 History (age, number of cycles, etc.) ____________

7.2 Auxiliary battery

7.2.1 Type and manufacturer EV-27 Die Hard; Globe-Union, Inc.

7.2.2 Number of cells 6

7.2.3 Operating voltage, V 12

7.2.4 Capacity, Ah ____________

7.2.5 Size, m (in.) ____________

7.2.6 Weight, kg (lbm) ____________

8.0 Controller

8.1 Type and manufacturer 3 electromechanical relays

8.2 Voltage rating, V 12

8.3 Current rating, A ____________

8.4 Size, m (in.) ____________

8.5 Weight, kg (lbm) ____________

9.0 Propulsion motor

9.1 Type and manufacturer DC series wound; Baker Co.

9.2 Insulation class ____________

9.3 Voltage rating, V 96

9.4 Current rating, A

9.5 Horsepower (rated), kW (hp) 8 (10) continuous; 16 (21) peak

9.6 Size, m (in.)

9.7 Weight, kg (lbm) 70 (154)

9.8 Speed (rated), rpm

10.0 Battery charger

10.1 Type and manufacturer built-in variac and rectifier

10.2 On- or off-board type on board

10.3 Input voltage required, V 120 AC

10.4 Peak current demand, A 15

10.5 Recharge time, h 10

10.6 Size, m (in.)

10.7 Weight, kg (lbm)

10.8 Automatic turnoff feature yes

11.0 Body

11.1 Type and manufacturer Austin A40 sedan

11.2 Materials steel

11.3 Number of doors and type 2; regular

11.4 Number of windows and type 4 on sides, 1 rear, 1 windshield

11.5 Number of seats and type 2 bucket, front; 1 bench, rear

11.6 Cargo space volume, m^3 (ft^3) none

11.7 Cargo space dimensions, m (ft)

12.0 Chassis

12.1 Frame

12.1.1 Type and manufacturer Austin A40

12.1.2 Steel

12.1.3 Modifications

12.2 Springs and shocks

12.2.1 Type and manufacturer

12.2.2 Modifications

12.3 Axles

12.3.1 Manufacturer

12.3.2 Front ______________________

12.3.3 Rear ______________________

12.4 Transmission

12.4.1 Type and manufacturer ______________________

____

12.4.2 Gear ratios ______________________

____

12.4.3 Driveline ratio ______________________

12.5 Steering

12.5.1 Type and manufacturer ______________________

12.5.2 Turning ratio ______________________

12.5.3 Turning diameter, m (ft) ______________________

12.6 Brakes

12.6.1 Front ______________________

12.6.2 Rear ______________________

12.6.3 Parking ______________________

12.6.4 Regenerative ______________________

12.7 Tires

12.7.1 Manufacturer and type Vredestein (Holland); Sprint

12.7.2 Size 145SR13

12.7.3 Pressure, kPa (psi):

Front 193 (28)

Rear 193 (28)

12.7.4 Rolling radius 1.74 (68.5)

12.7.5 Wheel weight, kg (lbm):

Without drum 12.0 (26.5)

With drum ______________________

12.7.6 Wheel track, m (in.):

Front ______________________

Rear ______________________

13.0 Performance

13.1 Manufacturer-specified maximum speed (wide-open throttle), km/h (mph)

____

13.2 Manufacturer-recommended maximum cruise speed (wide-open throttle), km/h (mph) ______________________

13.3 Tested at cruise speed, km/h (mph) ______________________

____

APPENDIX B

DESCRIPTION OF VEHICLE TEST TRACK

All the tests were conducted at the Transportation Research Center (TRC) of Ohio (fig. B-1). This facility was built by the State of Ohio and is now operated by a contractor and supported by the state. It is located 72 kilometers (45 miles) northwest of Columbus along U.S. route 33 near East Liberty, Ohio.

The test track is a 12-kilometer (7.5-mile) continuous loop 1.6 kilometers (1 mile) wide and 5.6 kilometers (3.5 miles) long. Three concrete lanes 11 meters (36 ft) wide in the straightaways and 13 meters (42 ft) wide in the curves make up the high-speed test area. The lanes were designed for speeds of 129, 177, and 225 kilometers per hour (80, 110, and 140 mph) with zero lateral acceleration in the curves. The 3-kilometer- (1.88-mile-) long straightaways are connected to the constant 731-meter- (2400-ft-) radius curves by a short variable-radius transition section. Adjacent to the inside concrete lane is a 3.66-meter- (12-ft-) wide asphalt berm. This berm is only banked slightly to provide a drainage slope. An additional asphalt lane 3.66 meters (12 ft) wide is located adjacent to the outside lane on the straightaways. The constant-speed and cycle tests were conducted on the inside asphalt lane because all tests were at relatively low speeds. The acceleration and coast-down tests were conducted on the straight outside asphalt lanes because these were more alike than the two inside asphalt lanes and because it was the portion of the track least likely to encounter traffic interference. The track has a constant 0.228-percent north-to-south downslope. The TRC complex also has a 20-hectare (50-acre) vehicle dynamics area and a 2740-meter- (9000-ft-) long skid pad for the conduct of braking and handling tests.

APPENDIX C

VEHICLE PREPARATION AND TEST PROCEDURE

Vehicle Preparation

When a vehicle was received at the test track, a number of checks were made to assure that it was ready for performance tests. These checks were recorded on a vehicle preparation check sheet, such as the one shown in figure C-1. The vehicle was examined for physical damage when it was removed from the transport truck and before it was accepted from the shipper. Before the vehicle was operated, a complete visual check was made of the entire vehicle including wiring, batteries, motor, and controller. The vehicle was weighed and compared with the manufacturer's specified curb weight. The gross vehicle weight (GVW) was determined from the vehicle sticker GVW. If the manufacturer did not recommend a GVW, it was determined by adding 68 kilograms (150 lbm) per passenger plus any payload weight to the vehicle curb weight.

The wheel alignment was checked and compared with the manufacturer's recommended alignment values. The camber and toe-in for the Kordesch hybrid vehicle were slightly out of specification. However, adjustments would have required a major disassembly of the main battery pack, so the tests were run with this misalignment. The battery was charged and specific gravities taken to determine if the battery cells were equalized. If not, an equalizing charge was applied to the battery. The integrity of the internal interconnections and the battery terminals was checked by drawing either 300 amperes or the vehicle manufacturer's maximum allowed current load from the battery through a load bank for 5 minutes. If the temperature of the battery terminals or interconnections rose more than 60 degrees Celsius above ambient, the test was terminated and the terminal was cleaned or the battery replaced. The battery was then recharged and a battery capacity check was made. The battery was discharged in accordance with the battery manufacturer's recommendations. To pass this test, the capacity must be within 20 percent of the manufacturer's published capacity at the published rate.

The vehicle manufacturer was contacted for his recommendations concerning the maximum speed of the vehicle, tire pressures, and procedures for driving the vehicle. The vehicle was photographed head-on with a 270-millimeter telephoto lens from a distance of about 30.5 meters (100 ft) in order to determine the frontal area.

Test Procedure

Each day, before a test, the driver was instructed to complete the pretest checklist (fig. C-2). Tests were conducted according to the run schedule shown in figure C-3. Data taken before, during, and after each test were entered on the vehicle data sheet (fig. C-4). These data include

(1) Average specific gravity of the battery

(2) Tire pressures

(3) Fifth-wheel tire pressure

(4) Test weight of the vehicle

(5) Weather information

(6) Battery temperatures

(7) Time the test was started

(8) Time the test was stopped

(9) Alternator rpm

(10) Ampere-hours out of the battery

(11) Ampere-hours into the battery

(12) Fuel temperature

(13) Total fuel flow

(14) Elapsed time of test

(15) Fifth-wheel distance count

(16) Odometer readings before and after test

(17) Watt-hours out of battery

(18) Watt-hours into battery

(19) Ampere-hours out of rectifier

During the cycle tests the following additional data were taken:

(20) Number of cycles

(21) Distance traveled for each cycle (cumulative)

(22) Fuel flow after each cycle (cumulative)

(23) Ampere-hours out of battery after each cycle

(24) Ampere-hours into battery after each cycle

(25) Watt-hours out of battery after each cycle

(26) Watt-hours into battery after each cycle

(27) Rectifier ampere-hours after each cycle

The battery charge data taken during the charge cycle were also recorded on this data sheet. These data include the average specific gravity of the battery after the test, the kilowatt-hours and ampere-hours put into the battery during the charge, and the total time of the charge.

To prepare for a test, the specific gravities were first measured for each cell and recorded. The tire pressures were measured and the vehicle was weighed. The weight was brought up to the gross vehicle weight (GVW) by adding sandbags. The instrumentation was connected, and power from the instrumentation battery was applied. All instruments were turned on and warmed up. The vehicle was driven to the starting point on the track. The fifth-wheel distance counter was reset to zero. The test was started and carried out in accordance with the test checklist. When the test lap was completed, the vehicle was brought to a stop and the vehicle data sheet was completed. The driver or navigator recorded tire pressures, weather, odometer reading, time the test was stopped, fuel temperature, total fuel flow, elapsed test time, number of cycles, ampere-hour integrator readings, and the fifth-wheel distance count. The same procedure was followed for each succeeding test lap, until the vehicle was returned to the workroom.

When the final test of the day was completed and the vehicle data sheet was filled out, post-test operations were commenced per the post-test checklist shown in figure C-5. All instrumentation power was turned off, the instrumentation battery was disconnected, and the fifth wheel was raised. The vehicle was then driven back to the workroom. The post-test specific gravities were measured for all cells, and the vehicle was placed on charge. Charge data were recorded on the charge data sheet shown in figure C-6.

The engineer conducting the test completed an engineering data sheet, shown in figure C-7, for each test lap completed. This data sheet provides a brief summary of the significant test information, including the engineer's evaluation of the test and a record of problems, malfunctions, changes to instrumentation, etc., that occurred during the test.

Weather Data

Wind velocity, ambient temperature, and uncorrected barometric pressure were measured at the beginning and end of each test. The wind anemometer was located about 1.8 meters (6 ft) from ground level near the center of the east straightaway (fig. B-1). The ambient air temperature and barometric pressure were measured in the control tower adjacent to the anemometer, but at a higher elevation. During many test runs the winds were variable and gusty. The wind conditions were displayed on undamped meters, making it virtually impossible to obtain accurate measurements under variable and/or gusty conditions. The ground elevation at the anemometer was 3 meters higher than the track elevation, which meant the wind was measured above the path of the vehicles. Also, the large physical size and high, banked curves of the track frequently resulted in local wind conditions that differed from the recorded values.

Determination of maximum cruise test speed. - The maximum speed of the vehicle was determined in the following manner. The vehicle was fully charged and loaded to gross vehicle weight. The vehicle was driven at wide-open throttle for one lap around the track. The minimum speed for the lap was recorded and the average was calculated. This average was called the vehicle maximum speed. This speed takes into account track variability and maximum vehicle loading. This quantity was then reduced by 5 percent and called the recommended maximum cruise test speed.

Cycle timer. - The cycle timer (fig. C-8) was designed to assist the vehicle driver in accurately driving SAE schedules B, C, and D. The required test profile is permanently stored on a programmable read-only memory (PROM), which is the heart of the instrument. This profile is continuously reproduced on one needle of a dual-movement analog meter shown in the figure. The second needle is connected to the output of the fifth wheel and the driver "matches needles" to accurately drive the required schedule.

One second before each speed transition (e.g., acceleration to cruise or cruise to coast), a signal sounds to forewarn the driver of a change. A longer duration signal sounds after the idle period to emphasize the start of a new cycle. The total number of test cycles driven is stored in a counter and can be displayed at any time with a pushbutton (to conserve power).

APPENDIX D

DETERMINATION OF RANGE FOR A BATTERY-POWERED VEHICLE

The range of a battery-powered vehicle can be estimated from the battery characteristics and the measured rate at which current is removed from the battery. This appendix presents a calculation procedure for performing this extrapolation.

Constant-Speed Range

At constant speed on a flat test track a vehicle operates at constant power except for the reduction in road load that occurs as the tires and vehicle mechanical components heat up. The battery current is almost constant for the duration of a constant-speed test, although it does tend to increase toward the end of the test as the battery voltage decreases. This current increase may be partially compensated for by the reduction in road power.

The available capacity of a lead-acid storage battery can be determined from the equation

$$C = bI^{n+1} \qquad \text{(D1)}$$

where

C capacity of battery, Ah

I current drawn from the battery, A

and b and n are empirical battery constants.

The time t that a battery can deliver a current I can be determined by dividing equation (D1) by the current to get

$$t = bI^{n} \qquad \text{(D2)}$$

The range of a vehicle at constant speed R can be calculated by multiplying equation (D2) by the vehicle speed V.

$$R = VbI^{n} \qquad \text{(D3)}$$

The current can be approximated as the measured integrated current in ampere-hours divided by the duration of the test in hours. This technique was used to estimate the range for six electric vehicles previously tested. The calculated and measured range results are compared in table D-1. The agreement is within 16 percent on all the data, with most of the results within 15 percent.

Driving Schedule Range

During an SAE J227a electric vehicle driving-schedule test a vehicle accelerates to a specified speed, cruises for a short time, coasts, and then brakes to a stop. The vehicle remains stopped for a short time and the process is repeated until the vehicle is no longer able to meet the acceleration or speed requirements. During a cycle, the battery current is high during acceleration, moderate during cruising, and zero for the rest of the cycle (unless the vehicle is a hybrid or has regenerative braking). The range of the vehicle for a driving-schedule test can be estimated from equation (D1) by using a suitable current and the measured distance traveled per ampere-hour removed from the battery, or

$$R = \beta (bI_c^{n+1}) \qquad \text{(D4)}$$

where

R distance traveled during driving-schedule test

β specific distance (distance traveled per ampere-hour)

I_c a representative current

The value of β is the measured distance that a vehicle travels divided by the total number of ampere-hours removed from the battery while traveling that distance. It should be obtained from a test involving many cycles.

The value of the current I_c to be used in equation (D4) was determined from six (driving schedule B and C) electric vehicle tests (codes from ref. 4) where the vehicle was run until the battery was depleted. The value of this current was found to be approximately equal to the cruise current. The measured range for these six electric vehicles over SAE J227a driving schedules B and C is compared with the range calculated by using the cruise current in equation (D4) in table D-2. The correlation seems to be accurate as the agreement between measured and calculated results was less than 12 percent for all but one data point.

Further confirmation of this calculation technique was obtained from laboratory tests with a golf car battery. The battery was discharged to simulate the discharge rates that occur during driving schedule B and C tests. The test conditions, the measured battery capacity, and the capacity calculated by using equation (D1) are shown in table D-3. The calculated battery capacity was within 8 percent of the measured battery capacity, a further confirmation of the calculation techniques.

For hybrid vehicles where the battery is charged from a heat engine-driven alternator or for electric vehicles with regenerative braking, the range will increase because the battery is charging during the test. This effect can be approximated by adjusting equation (D4) to include the capacity returned to the battery. Equation (D4) becomes

$$R = (1 + \alpha)\ \beta a I_c^{n+1} \qquad \text{(D5)}$$

where α is the measured ratio of the battery capacity in ampere-hours returned to the battery by the alternator or regenerative braking system per cycle, divided by the capacity in ampere-hours removed for the same cycle. For these calculations, the coulombic efficiency of battery recharge is assumed to be 100 percent, and any enhancement of the battery due to the reversal of current flow is also neglected.

APPENDIX E

CALCULATION OF RANGE FOR THE KORDESCH HYBRID VEHICLE

The vehicle fuel consumption tests were run for one lap of the track, only partially depleting the battery. The vehicle range achievable assuming full depletion of the battery (and assuming that the on-board fuel supply was not limiting) was calculated from the theoretical battery capacity by using the techniques developed in appendix D. This appendix presents the results of these calculations.

Constant-Speed All-Electric Tests

The all-electric tests were terminated when any one battery voltage (nominal 12 V) dropped to less than 9 volts. The Kordesch battery had deteriorated during previous vehicle tests, so the all-electric vehicle tests were always terminated by low battery voltage before the full manufacturer's rated battery capacity was removed.

The theoretical vehicle range was calculated from the test data by using equation (D3).

$$R = VbI^n \tag{D3}$$

The calculated battery constants b and n are 147 and -1.222, respectively, for the EV-27 battery. The current I was calculated from the measured ampere-hours removed from the battery during the test from table II divided by the test time. The calculations of the 40- and 72-kilometer-per-hour (25- and 45-mph) ranges are based on single tests, and the calculation of the 56-kilometer-per-hour (35-mph) range is based on the average of these tests.

The results of these calculations are shown in table E-1. The measured range varies from 19 to 31 kilometers (12 to 19 miles) and the calculated range from 37 to 43 kilometers.

Constant-Speed Hybrid Tests

The theoretical ranges for the Kordesch hybrid operating in the hybrid mode were calculated from the data obtained from a one-lap test by using a procedure similar to the one used for the all-electric tests.

The results of these calculations are presented in table E-2. All results shown in table E-2 were obtained from the data presented in table III of the text. The battery discharge current was obtained from the measured integrated ampere-hours out of the battery, divided by the test time.

Driving Schedule B and C Hybrid Tests

The ranges for the Kordesch hybrid vehicle when driven over driving schedules B and C were calculated by using equation (D5).

$$R = (1 + \alpha)\ \beta b I_c^{n+1} \qquad \text{(D5)}$$

where the symbols are defined in appendix D. The current I_c is approximately equal to the battery current during the cruise portion of the cycle. This current was obtained from constant-speed vehicle tests. The average battery discharge current for each test condition was obtained by averaging the current data from the tests run with the highest and lowest battery depths of discharge. These data are tabulated in table E-3 for the three constant-vehicle-speed tests and the three alternator speeds. The currents for the two battery depths of discharge were then averaged and plotted in figure E-1 as functions of alternator speed and vehicle test speed. From these curves the expected cruise currents for driving schedules B and C for each alternator speed were estimated.

The schedule B cycle current was taken as the 32-kilometer-per-hour (20-mph) constant-speed current and the schedule C current as the 48-kilometer-per-hour (30-mph) constant-speed current. These values are shown in table E-4. The values of the discharge fraction α and the specific distance β were calculated from data in table III. The discharge fraction is the ratio of the battery recharge capacity for a one-lap test. The specific distance is the distance traveled divided by the capacity removed from the battery while traveling this distance. These calculated values are shown in table E-4. Also shown in this table are the ranges of the Kordesch hybrid calculated by using equation (E1).

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TABLE I. - GLOBE-UNION BATTERY CHARACTERISTICS

Characteristic	EV-27	EV-27 (Die Hard)
Length, m (in.)	0.31 (12.04)	0.31 (12.04)
Width, m (in.)	0.17 (6.83)	0.17 (6.83)
Height, m (in.):		
To top of case	0.20 (7.90)	0.20 (7.90)
To top of terminal	0.22 (8.62)	0.22 (8.62)
Weight, kg (lbm):		
Dry	------------	36 (79)
Wet	56 (123)	53 (117)
Electrolyte specific gravity at full charge	$1.265 \pm \begin{pmatrix}0.010\\0.015\end{pmatrix}$	$1.265 \pm \begin{pmatrix}0.010\\0.015\end{pmatrix}$
Battery capacity (to 1.75-V cutoff):		
Current, A	37.5	25
Time, min	105	159
Capacity, Ah	65.6	66.3
Plates per cell	15	15
Cells per battery	6	6
Voltage per battery, V	12	12

TABLE II. - KORDESCH HYBRID VEHICLE INSTRUMENTATION

Parameter	Measuring device	Shunt valve
Vehicle speed	Strip-chart recorder	------------
Vehicle distance	↓	------------
Battery voltage	↓	------------
Motor voltage	↓	------------
Motor current	↓	200 A/50 mV
Rectifier voltage	↓	------------
Rectifier current	↓	100 A/50 mV
Integrated rectifier current	Curtis integrator	500 A/100 mV
Battery current in and out	Curtis integrator	500 A/100 mV
Battery energy in and out	DAUG watt-hour meter	250 A/60 mV
Fuel consumption	FluiDyne flowmeter	------------
Duration of test	FluiDyne flowmeter	------------

TABLE III. - HYBRID-MODE RANGE AND FUEL CONSUMPTION TEST RESULTS FOR KORDESCH HYBRID

(a) At constant speed; measured distance, 12.1 kilometers

Test date	Test speed, km/h	Test speed, mph	Average wind velocity, km/h	Alternator rotational speed, rpm	Battery depth of discharge, percent	Test duration, s	Test flow, cm³/min	Rectifier output, Ah	Integrated battery current, Ah: Discharge	Integrated battery current, Ah: Charge	Battery energy, Wh: Discharge	Battery energy, Wh: Charge
8/24/77	40	25	11	2800	80	1090	27.5	5.0	10.2	---	912	16
8/31/77	40	25	5 - 8	2800	10	1100	24.2	.8	14.9	---	1422	1
8/19/77	[a]40	25	8	3000	75	1100	45.0	8.2	7.1	1.1	844	130
9/1/77	40	25	11	3000	70	1070	44.8	7.4	7.4	.1	782	91
8/22/77	[a]40	25	5	3000	45	1080	38.3	6.7	8.9	---	884	48
8/31/77	40	25	6 - 11	3200	30	1080	79.1	10.1	5.4	.1	737	226
9/1/77	40	25	10	3200	5	1080	81.6	9.8	5.7	---	771	202
8/25/77	56	35	6 - 8	2800	45	780	24.0	1.6	13.3	---	1267	0
8/31/77	56	35	8 - 10	2800	40	770	23.9	.9	14.2	---	1291	1
9/7/77	56	35	5	2800	25	770	24.4	.5	14.6	---	1359	1
8/22/77	[a]56	[a]35	5	3000	35	770	39.4	5.0	10.5	---	985	11
8/24/77	[a]56	[a]35	8	3000	10	780	33.6	3.4	10.1	0.2	1037	14
9/21/77	56	35	6 - 8	3000	10	780	34.9	5.4	11.6	.1	1108	21
8/30/77	↓	↓	3 - 5	3200	35	770	96.4	8.7	8.4	.2	808	108
8/31/77	↓	↓	5 - 10	↓	65	↓	80.4	8.9	6.3	.1	681	131
9/7/77	↓	↓	6 - 8	↓	15	↓	72.2	7.6	7.5	.2	820	126
9/21/77	↓	↓	5	↓	30	↓	68.5	5.3	7.8	.1	814	103
8/25/77	72	45	11	2800	15	610	18.7	0.1	17.5	---	1644	1
9/6/77	72	45	6	2800	0	600	28.6	2.9	15.0	---	1334	6
8/22/77	[a]72	[a]45	8	3000	15	600	44.8	4.7	13.9	0.3	1282	7
9/2/77	72	45	6	3000	40	600	60.7	5.6	13.2	.2	1162	30
8/30/77	↓	↓	5	3200	10	610	93.6	6.0	11.0	.1	1056	35
9/1/77	↓	↓	10 - 13	3200	55	610	70.1	7.0	11.6	.3	1088	71
9/2/77	↓	↓	8 - 13	3200	40	610	72.9	6.6	11.6	.2	1118	50

(b) Under driving schedules

Test date	Driving schedule	Average wind velocity, km/h	Alternator rotational speed, rpm	Battery depth of discharge, percent	Measured distance, km	Measured distance, miles	Number of complete cycles	Test duration, s	Fuel flow, cm³/min	Rectifier output, Ah	Integrated battery current, Ah: Discharge	Integrated battery current, Ah: Charge	Battery energy, Wh: Discharge	Battery energy, Wh: Charge
8/25/77	B	6 - 8	2800	65	12.1	7.5	36	2750	34.8	12.4	15.6	2.1	1644	511
8/31/77	B	10 - 14	2800	60	12.6	7.8	35	2540	26.4	6.9	19.3	---	1777	150
8/22/77	[a]B	10 - 11	3000	70	12.4	7.7	36	2660	41.6	16.5	9.3	2.4	1242	732
8/19/77	[a]B	8	3000	50	12.2	7.6	38	2710	37.8	15.6	10.6	2.1	1525	657
9/1/77	B	10 - 13	3000	80	12.8	8.0	36	2590	43.6	18.7	11.2	2.8	1391	783
8/31/77	B	5 - 11	3200	70	12.7	7.9	36	2610	74.2	22.2	8.4	5.2	1373	1143
8/31/77	B	8 - 14	3200	55	12.8	8.0	36	2640	70.2	22.3	8.9	5.6	1473	1195
9/2/77	C	6	2800	0	12.4	7.7	22	1790	25.5	1.2	24.5	---	2200	9
9/7/77	C	5	2800	10	12.6	7.8	↓	1800	27.0	4.1	23.1	0.1	2042	58
8/22/77	[a]C	5 - 8	3000	55	12.2	7.6	↓	1790	55.0	13.1	17.4	4.5	1699	660
9/1/77	C	11 - 13	3000	25	12.7	7.9	↓	1780	40.9	10.6	17.6	1.9	1769	440
9/1/77	↓	11	3200	10	12.7	7.9	↓	1790	76.1	14.4	14.7	3.8	1604	647
9/2/77	↓	8 - 13	3200	20	12.4	7.7	↓	1760	74.4	15.7	15.3	4.7	1686	778
9/2/77	↓	6 - 8	3200	60	9.6	6.0	17	1380	77.3	13.0	12.3	3.5	1165	570

[a]Automatic choke fluctuating.

TABLE IV. - RANGE, FUEL ECONOMY, AND BATTERY ENERGY CONSUMPTION

FOR KORDESCH HYBRID

Test condition (constant speed or driving schedule)		Alternator rotational speed, rpm	Calculated range		Fuel economy		Net battery energy consumed	
km/h	mph		km	mile	km/liter	mpg	Ah/km	Wh/km
40	25	2800	64	40	24.9	58.7	0.19	18.1
		3000	116	72	14.9	35.0	.06	6.4
		3200	162	101	8.9	21.0	.03	3.3
56	35	2800	53	33	34.9	82.1	0.26	24.6
		3000	62	39	20.8	49.0	.17	16.6
		3200	116	72	12.5	29.5	.06	5.7
72	45	2800	40	25	45.1	106.0	0.40	37.1
		3000	51	32	26.8	63.0	.26	23.6
		3200	59	37	16.2	38.0	.19	17.5
B		2800	53	33	10.6	25.0	0.31	26.0
		3000	126	78	6.4	15.2	.06	6.8
		3200	201	125	3.9	9.1	.02	1.3
C		2800	32	20	15.7	37.0	0.74	65.2
		3000	51	32	9.4	22.2	.28	23.2
		3200	77	48	5.5	13.1	.13	10.6

TABLE V. - RANGE OF KORDESCH HYBRID IN

ALL-ELECTRIC MODE

Test date	Test speed		Battery capacity removed		Measured range[a]		Calculated range	
	km/h	mph	Ah	Wh	km	mile	km	mile
9/12/77	40	25	43.5	3683	30.8	19.1	43	27
[b]9/13/77	56	35	36.4	3106	24.0	14.9	39 (9/13/77–9/20/77)	24
9/14/77	56	35	33.3	2915	23.3	14.5		
9/20/77	56	35	34.5	3099	24.3	15.1		
9/9/77	72	45	26.6	2364	19.1	11.9	37	23

[a]Measured to point where any single battery was discharged to 9 volts.
[b]Wet track.

TABLE VI. - ACCELERATION TIMES FOR KORDESCH HYBRID

Vehicle speed		Time to reach designated vehicle speed, s	Vehicle speed		Time to reach designated vehicle speed, s
km/h	mph		km/h	mph	
0.0	0	0	36.0	22.4	8.6
2.0	1.2	.6	38.0	23.6	9.1
4.0	2.5	1.0	40.0	24.9	10.2
6.0	3.7	1.3	42.0	26.1	11.6
8.0	5.0	1.5	44.0	27.4	12.4
10.0	6.2	1.8	46.0	28.6	13.1
12.0	7.5	2.1	48.0	29.8	14.1
14.0	8.7	2.2	50.0	31.1	14.8
16.0	9.9	2.6	52.0	32.3	15.6
18.0	11.2	3.3	54.0	33.6	16.4
20.0	12.4	3.9	56.0	34.8	17.4
22.0	13.7	4.3	58.0	36.1	18.4
24.0	14.9	4.6	60.0	37.3	19.6
26.0	16.2	5.3	62.0	38.5	21.0
28.0	17.4	6.1	64.0	39.8	22.5
30.0	18.7	6.8	66.0	41.0	24.3
32.0	19.9	7.4	68.0	42.3	26.4
34.0	21.1	8.0	70.0	43.5	29.0

TABLE VII. - ACCELERATION CHARACTERISTICS

OF KORDESCH VEHICLE

Vehicle speed		Acceleration		Vehicle speed		Acceleration	
km/h	mph	m/s^2	mph/sec	km/h	mph	m/s^2	mph/sec
0	0	0	0	36.0	22.4	0.96	2.14
2.0	1.2	1.18	2.63	38.0	23.6	.74	1.66
4.0	2.5	1.67	3.73	40.0	24.9	.47	1.06
6.0	3.7	2.15	4.81	42.0	26.1	.54	1.21
8.0	5.0	2.14	4.80	44.0	27.4	.70	1.57
10.0	6.2	1.98	4.44	46.0	28.6	.66	1.48
12.0	7.5	3.00	6.71	48.0	29.8	.69	1.54
14.0	8.7	3.75	6.15	50.0	31.1	.73	1.63
16.0	9.9	1.22	2.73	52.0	32.3	.67	1.51
18.0	11.2	.84	1.88	54.0	33.6	.63	1.41
20.0	12.4	1.22	2.73	56.0	34.8	.56	1.25
22.0	13.7	1.59	3.56	58.0	36.1	.49	1.10
24.0	14.9	1.22	2.73	60.0	37.3	.44	.98
26.0	16.2	.76	1.71	62.0	38.5	.39	.87
28.0	17.4	.75	1.67	64.0	39.8	.34	.76
30.0	18.7	.89	1.98	66.0	41.0	.29	.65
32.0	19.9	.93	2.08	68.0	42.3	.24	.53
34.0	21.1	.93	2.07	70.0	43.5	.21	.47

TABLE VIII. - GRADEABILITY OF KORDESCH HYBRID

Vehicle speed		Grade-ability, percent	Vehicle speed		Grade-ability, percent
km/h	mph		km/h	mph	
0	0	0	36.0	22.4	9.8
2.0	1.2	12.2	38.0	23.6	7.6
4.0	2.5	17.3	40.0	24.9	4.9
6.0	3.7	22.6	42.0	26.1	5.6
8.0	5.0	22.5	44.0	27.4	7.2
10.0	6.2	20.8	46.0	28.6	6.8
12.0	7.5	32.3	48.0	29.8	7.1
14.0	8.7	29.4	50.0	31.1	7.5
16.0	9.9	12.6	52.0	32.3	6.9
18.0	11.2	8.6	54.0	33.6	6.5
20.0	12.4	12.6	56.0	34.8	5.7
22.0	13.7	16.6	58.0	36.1	5.0
24.0	14.9	12.6	60.0	37.3	4.5
26.0	16.2	7.8	62.0	38.5	4.0
28.0	17.4	7.7	64.0	39.8	3.5
30.0	18.7	9.1	66.0	41.0	3.0
32.0	19.9	9.6	68.0	42.3	2.4
34.0	21.1	9.5	70.0	43.5	2.1

TABLE IX. - ROAD ENERGY CONSUMPTION FOR KORDESCH HYBRID

Vehicle speed		Road energy		Vehicle speed		Road energy	
km/h	mph	MJ/km	kWh/mile	km/h	mph	MJ/km	kWh/mile
72.0	44.7	0	0	36.0	22.4	0.25	0.11
70.0	43.5	.41	.18	34.0	21.1	.24	.11
68.0	42.3	.41	.18	32.0	19.9	.23	.10
66.0	41.0	.41	.18	30.0	18.6	.23	.10
64.0	39.8	.38	.17	28.0	17.4	.24	.11
62.0	38.5	.37	.17	26.0	16.2	.22	.10
60.0	37.3	.37	.16	24.0	14.9	.22	.10
58.0	36.0	.36	.16	22.0	13.7	.22	.10
56.0	34.8	.35	.15	20.0	12.4	.20	.09
54.0	33.6	.33	.15	18.0	11.2	.18	.08
52.0	32.3	.31	.14	16.0	9.9	.19	
50.0	31.1	.28	.13	14.0	8.7	.19	
48.0	29.8	.30		12.0	7.5	.19	
46.0	28.6	.30		10.0	6.2	.18	
44.0	27.3	.28		8.0	5.0	.18	
42.0	26.1	.27	.12	6.0	3.7	.17	.07
40.0	24.9	.26	.12	4.0	2.5	.14	.06
38.0	23.6	.26	.12	2.0	1.2	.13	.06

TABLE X. - ROAD POWER REQUIREMENTS

FOR KORDESCH VEHICLE

Vehicle speed		Road power		Vehicle speed		Road power	
km/h	mph	kW	hp	km/h	mph	kW	hp
72.0	44.7	0	0	36.0	22.4	2.52	3.38
70.0	43.5	7.87	10.56	34.0	21.1	2.23	2.99
68.0	42.3	7.77	10.42	32.0	19.9	2.02	2.71
66.0	41.0	7.43	9.96	30.0	18.6	1.94	2.60
64.0	39.8	6.69	8.97	28.0	17.4	1.83	2.46
62.0	38.5	6.38	8.56	26.0	16.2	1.61	2.15
60.0	37.3	6.08	8.16	24.0	14.9	1.47	1.97
58.0	36.0	5.78	7.75	22.0	18.7	1.33	1.78
56.0	34.8	5.37	7.20	20.0	12.4	1.10	1.47
54.0	33.6	4.95	6.64	18.0	11.2	.91	1.22
52.0	32.3	4.45	5.97	16.0	10.0	.83	1.12
50.0	31.1	3.95	5.30	14.0	8.7	.73	.98
48.0	29.8	3.98	5.33	12.0	7.5	.62	.83
46.0	28.6	3.84	5.15	10.0	6.2	.49	.65
44.0	27.3	3.47	4.66	8.0	5.0	.39	.53
42.0	26.1	3.15	4.22	6.0	3.7	.28	.37
40.0	24.9	2.88	3.86	4.0	2.5	.16	.21
38.0	23.6	2.79	3.74	2.0	1.2	.08	.10

TABLE XI. - CALCULATED ENERGY CONSUMPTION FOR KORDESCH HYBRID IN HYBRID MODE

(a) SI units

Test condition (constant speed, km/h; or driving schedule)	Alternator rotational speed, rpm	Calculated range, km	Calculated capacity removed, Ah	Calculated capacity restored, Ah	Calculated charger input energy, MJ	Calculated energy consumption, MJ/km
40	2000	64	66	73	34	0.54
	3000	121	75	83	39	.34
	3200	169	80	88	41	.25
56	2000	55	61	67	32	0.58
	3000	64	62	68	32	.49
	3200	121	71	78	37	.31
72	2800	39	52	57	27	0.69
	3000	51	55	61	29	.56
	3200	60	57	63	30	.48
B	2800	45	59	65	31	0.67
	3000	87	62	68	32	.36
	3200	154	66	73	35	.22
C	2800	26	48	53	25	0.96
	3000	42	52	57	27	.65
	3200	58	53	58	28	.47

(b) U.S. customary units

Test condition (constant speed, mph; or driving schedule)	Alternator rotational speed, rpm	Calculated range, miles	Calculated capacity removed, Ah	Calculated capacity restored, Ah	Calculated charger input energy, kWh	Calculated energy consumption, kWh/km
25	2800	40	66	73	9.4	0.24
	3000	69	75	83	10.9	.15
	3200	104	80	88	11.5	.11
35	2800	31	61	67	8.8	0.26
	3000	40	62	68	8.9	.22
	3200	69	71	78	10.2	.14
45	2800	25	52	57	7.5	0.31
	3000	32	55	61	8.0	.25
	3200	38	57	63	8.3	.22
B	2800	28	59	65	8.5	0.30
	3000	54	62	68	8.9	.16
	3200	96	66	73	9.6	.10
C	2800	16	48	53	6.9	0.43
	3000	26	52	57	7.5	.29
	3200	36	53	58	7.7	.21

TABLE XII. - CALCULATED ELECTRICAL ENERGY CONSUMPTION FOR KORDESCH HYBRID IN ALL-ELECTRIC MODE

Test date	Test speed		Measured range		Capacity removed, Ah	Charger input		Charger output, Ah	Indicated energy consumption	
	km/h	mph	km	miles		MJ	kWh		MJ/km	kWh/mile
9/12/77	40	25	30.8	19.1	43.5	60.0	16.1	46.3	1.88	0.84
9/13/77	56	35	24.0	14.9	36.4	38.1	10.6	39.2	1.56	.70
9/14/77	56	35	23.3	14.5	33.3	46.8	13.0	34.9	1.92	.86
9/20/77	56	35	24.3	15.1	34.5	----	----	----	----	----
9/9/77	72	45	19.1	11.9	26.6	41.8	11.6	38.8	2.17	.97

TABLE XIII. - CHARGER EFFICIENCY RESULTS FOR KORDESCH HYBRID

Test date	Charger input		Charger output		Charger efficiency, percent
	MJ	kWh	MJ	kWh	
8/22/77	26.6	7.4	19.8	5.5	0.74
8/24/77	29.9	8.3	22.7	6.3	.76
8/25/77	31.7	8.8	21.6	6.0	.68
8/26/77	31.0	8.6	24.5	6.8	.79
8/31/77	29.2	8.1	21.9	6.1	.76
9/1/77	36.7	10.2	27.7	7.7	.76
9/2/77	22.7	6.3	19.1	5.3	.84
9/6/77	29.5	8.2	23.0	6.4	.78
9/7/77	18.4	5.1	14.7	4.1	.80
9/8/77	23.0	6.4	16.9	4.7	.74
9/9/77	41.8	11.6	32.7	9.1	.78

TABLE XIV. - KORDESCH HYBRID COMPONENT DATA AT TWO DIFFERENT BATTERY STATES OF CHARGE

[Test speed, 40 km/h (25 mph).]

Test date	Fuel consumption, cm^3/min	Test duration, s	Battery depth of discharge, percent	Motor voltage, V	Motor current, A	Rectifier voltage, V	Rectifier current, A
8/24/77	27.5	0 - 1090	80	93 - 80	45 - 55	110 - 98	10 - 32
8/31/77	24.2	0 - 1090	10	96 - 95	47 - 48	96 - 95	1 - 4

TABLE D-1. - MEASURED AND CALCULATED RANGES OF ELECTRIC VEHICLES FOR CONSTANT-SPEED TESTS

Electric vehicle code[a]	Test speed		Battery type	Measured capacity, Ah	Average current removed from battery, A	Battery constants		Calculated range		Measured range	
	km/h	mph				b	n	km	mile	km	mile
P-7	40	25	GC-2-19	143	68	302	-1.193	79	49	85	53
	56	35	↓	110	88	↓	↓	82	51	71	44
	72	45	↓	102	136	↓	↓	63	39	55	34
	82	51	↓	105	171	↓	↓	47	29	50	31
	40	25	EV-106	153	78	499	-1.308	68	42	79	49
P-3	56	35	EV-106	128	127	499	-1.308	50	31	56	35
	72	45	EV-106	105	192	499	-1.308	37	23	40	25
P-1	40	25	EV-106	144	61	499	-1.308	93	58	95	59
	50	31	EV-106	130	70	499	-1.308	97	60	93	58
C-2	40	25	EV-27-66E-11	259	135	2218	-1.456	71	44	77	48
	48	30	EV-27-66E-11	136	180	2218	-1.456	56	35	63	39
P-2	40	25	EV-106	166	36	499	-1.308	185	115	188	117
	56	35	EV-106	146	64	499	-1.308	122	76	129	80
C-9	32	20	EV-106	129	88	499	-1.308	47	29	47	29

[a]Codes from ref. 4.

TABLE D-2. - MEASURED AND CALCULATED RANGES OF ELECTRIC VEHICLES

FOR DRIVING SCHEDULE B AND C TESTS

Electric vehicle code[a]	Driving schedule[b]	Measured capacity removed from battery, Ah	Calculated cruise current, A	Battery constants		Calculated range[c]		Measured range	
				b	n	km	mile	km	mile
P-7	B	140	65	302	-1.193	47	29	48	30
	C	127	76	302	-1.193	50	31	48	30
P-3	B	166	60	499	-1.308	45	28	51	32
	C	126	102	499	-1.308	37	23	37	23
P-1	B	122	55	499	-1.308	80	50	66	41
C-2	B	163	92	2218	-1.456	55	34	53	33
P-2	B	181	22	499	-1.308	137	85	129	80
C-9	B	133	88	499	-1.308	34	21	35	22

[a]Code from ref. 4.
[b]Defined in SAE J227a (ref. 2).
[c]Calculated by using eq. (D4).

TABLE D-3. - LABORATORY BATTERY DISCHARGE TEST RESULTS AND CALCULATED BATTERY CAPACITY FOR A GOLF-CAR BATTERY (EV-106)

[Battery constants: b, 499; n, -1.308.]

Simulated driving schedule[a]	Acceleration current, A	Acceleration time, s	Cruise current, A	Cruise time, s	Calculated battery capacity,[b] Ah	Measured battery capacity, Ah
B	140	19	60	19	141	134
C	250	20	90	18	125	116

[a]Defined in SAE J227a (ref. 2).
[b]Calculated from eq. (D1).

TABLE E-1. - RANGE OF KORDESCH HYBRID IN ALL-ELECTRIC MODE

Test speed		Average battery current, A	Measured range[a]		Calculated range	
km/h	mph		km	mile	km	mile
40	25	56	31	19	43	27
56	35	82	24	15	39	24
72	45	102	19	12	37	23

[a]Measured to point where any single battery was discharged to 9 V, not to the full potential capacity of the battery.

TABLE E-2. - CALCULATED RANGE OF KORDESCH HYBRID

IN CONSTANT-SPEED TESTS

Test speed		Test date	Alternator rotational speed, rpm	Average battery current discharge, A	Calculated range[a]	
km/h	mph				km	mile
40	25	8/24/77	2800	34	79	49
		8/31/77	2800	50	50	31
		8/19/77	3000	24	123	77
		9/1/77	3000	25	117	73
		8/22/77	3000	30	94	58
		8/31/77	3200	18	173	107
		9/1/77	3200	19	162	101
56	35	8/25/77	2800	62	53	33
		8/31/77	2800	66	48	30
		9/7/77	2800	68	48	30
		8/22/77	3000	49	71	44
		8/24/77	3000	47	75	46
		9/21/77	3000	54	63	39
		8/30/77	3200	39	93	58
		8/31/77	↓	29	133	82
		9/7/77	↓	35	107	67
		9/21/77	↓	36	102	64
72	45	8/25/77	2800	105	36	22
		9/6/77	2800	90	44	27
		8/22/77	3000	83	48	30
		9/2/77	3000	79	51	32
		8/30/77	3200	66	63	39
		9/1/77	3200	70	60	37
		9/2/77	3200	70	60	37

[a]Calculated using eq. (D3).

TABLE E-3. - BATTERY CURRENT FOR CONSTANT-SPEED

OPERATION OF KORDESCH HYBRID AT VARIOUS

DEPTHS OF DISCHARGE

Test speed		Alternator rotational speed, rpm	Battery depth of discharge, percent	Battery discharge current, A	Average of two battery currents, A
km/h	mph				
40	25	2800	80	34	42
		2800	10	50	
		3000	75	24	27
		3000	45	30	
		3200	30	18	18.5
		3200	5	19	
56	35	2800	45	62	65
		2800	25	68	
		3000	35	49	51.5
		3000	10	54	
		3200	65	29	32
		3200	15	35	
72	45	2800	15	105	97.5
		2800	0	90	
		3000	40	79	81
		3000	15	83	
		3200	55	70	68
		3200	10	66	

TABLE E-4. - CALCULATED RANGE OF KORDESCH HYBRID IN DRIVING-SCHEDULE TESTS

Driving schedule	Test date	Alternator rotational speed, rpm	Estimated cruise current, A	Specific distance,[a] β		Recharge fraction,[a] α	Calculated range[b]	
				km/Ah	mile/Ah		km	mile
B	8/25/77	2800	30	0.77	0.48	0.13	59	37
	8/31/77	2300	30	.64	.40	0	45	28
	8/22/77	3000	15	1.35	.84	.26	137	85
	8/19/77	3000	15	1.16	.72	.20	113	70
	9/1/77	3000	15	1.14	.71	.25	116	72
	8/31/77	3200	12	1.51	.94	.62	207	129
	8/31/77	3200	12	1.45	.90	.63	199	124
C	9/2/77	2800	54	0.50	0.31	0	31	19
	9/7/77	2800	54	.55	.34	0	34	21
	8/22/77	3000	39	.71	.44	.26	58	36
	9/1/77	3000	39	.72	.45	.11	53	33
	9/1/77	3200	25	.87	.54	.26	79	49
	9/2/77	3200	25	.80	.50	.31	76	47
	9/2/77	3200	25	.76	.47	.28	72	45

[a]Defined in appendix D.
[b]Calculated by using eq. (D5).

Figure 1. - Kordesch hybrid vehicle.

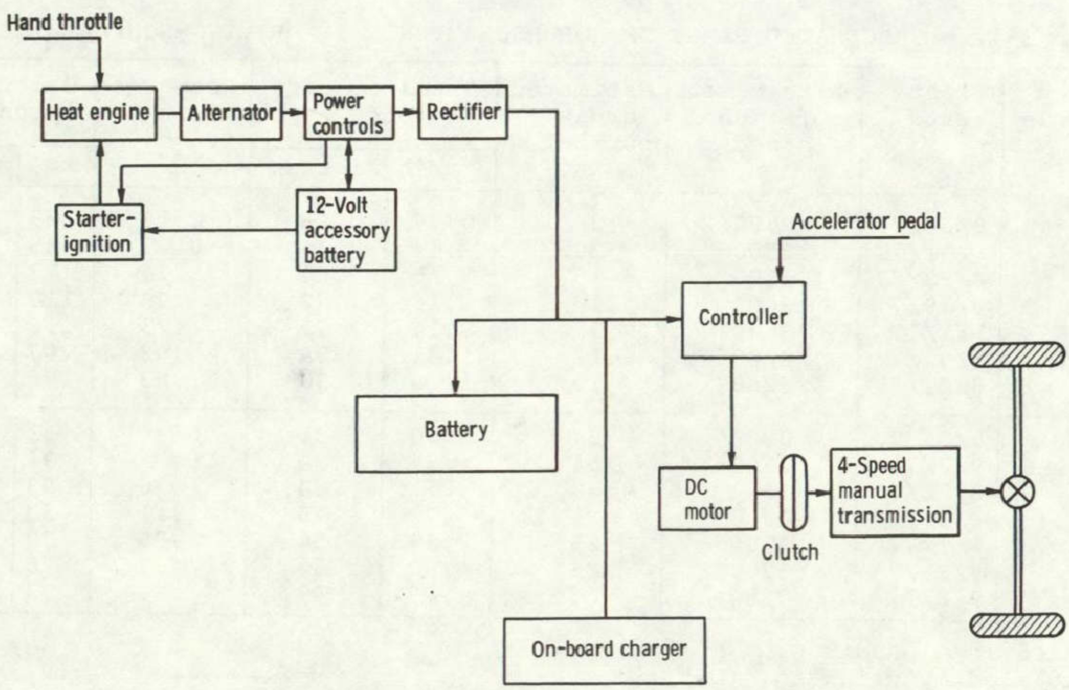


Figure 2. - Block diagram of Kordesch hybrid.

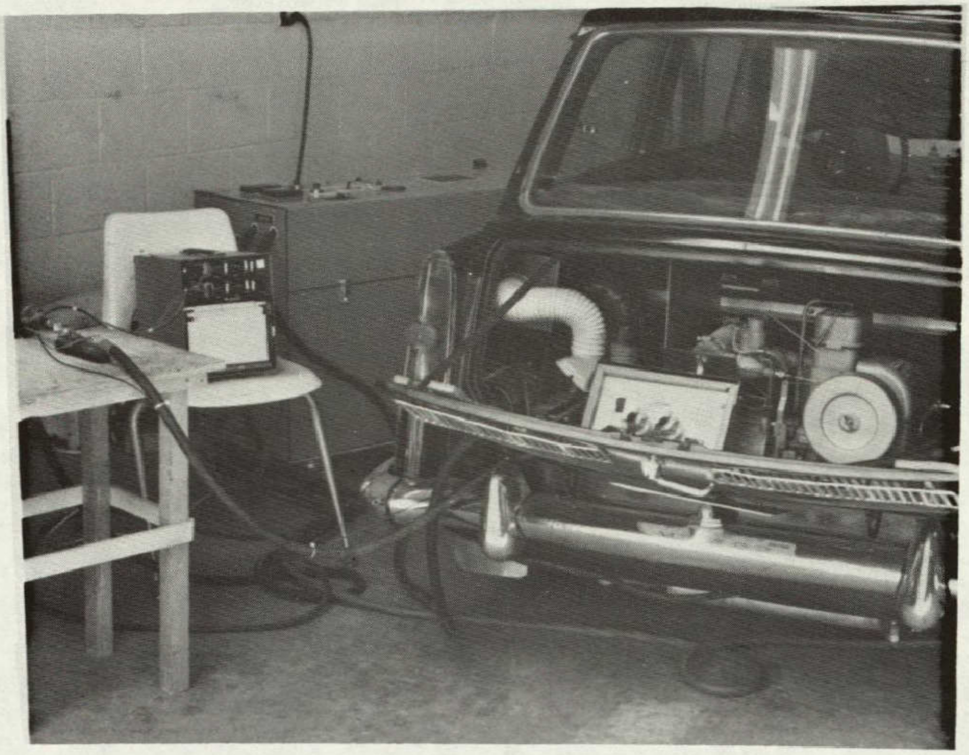


Figure 3. - Heat-engine - alternator system shown installed in trunk of Kordesch hybrid.

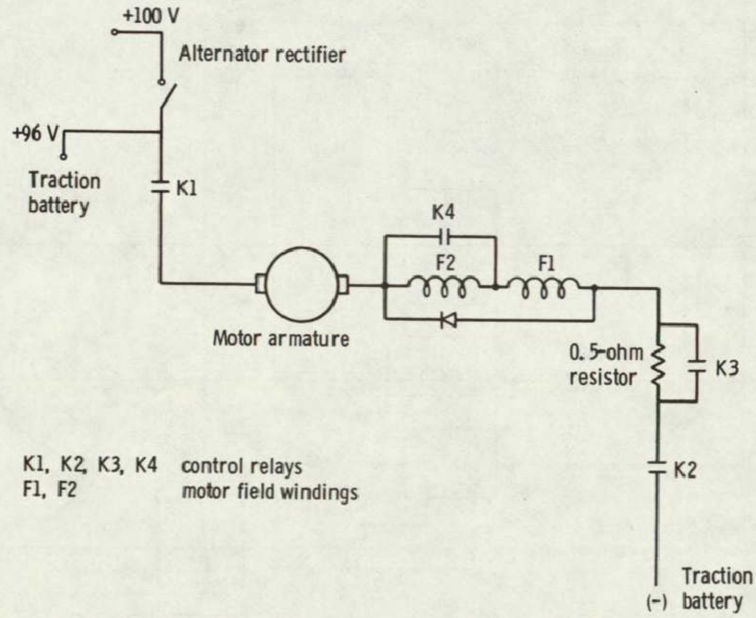


Figure 4. - Electrical schematic of traction motor and motor speed control.

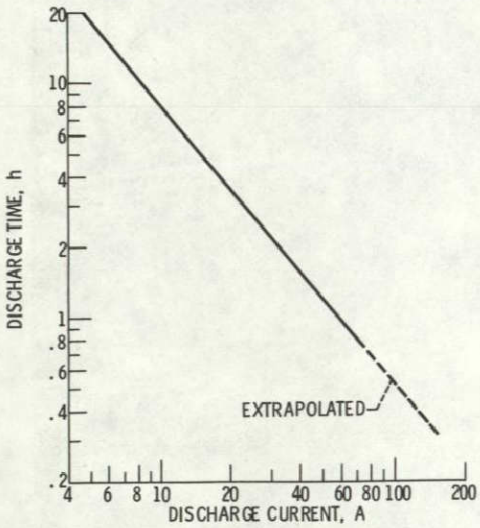


Figure 5. - Globe-Union EV-27 six-cell-battery discharge current-time characteristics.

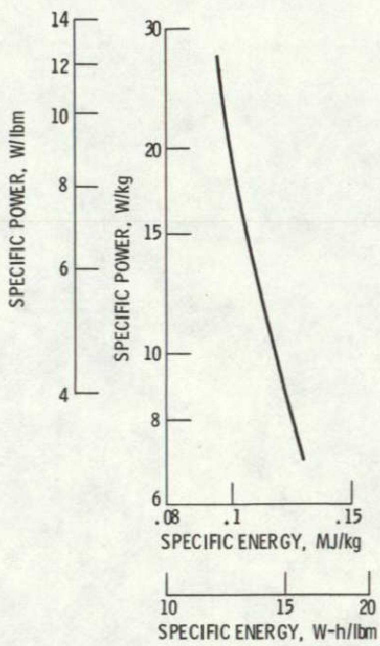


Figure 6. - Globe-Union EV-27 six-cell-battery discharge energy-power characteristics.

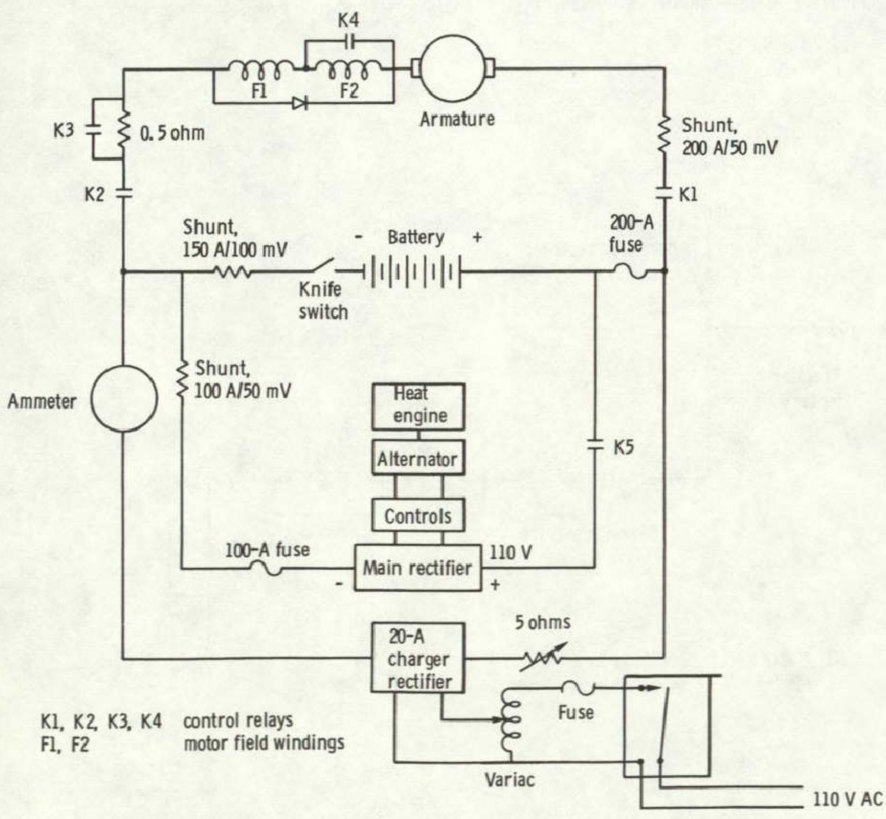


Figure 7. - Schematic of main electrical system of Kordesch hybrid.

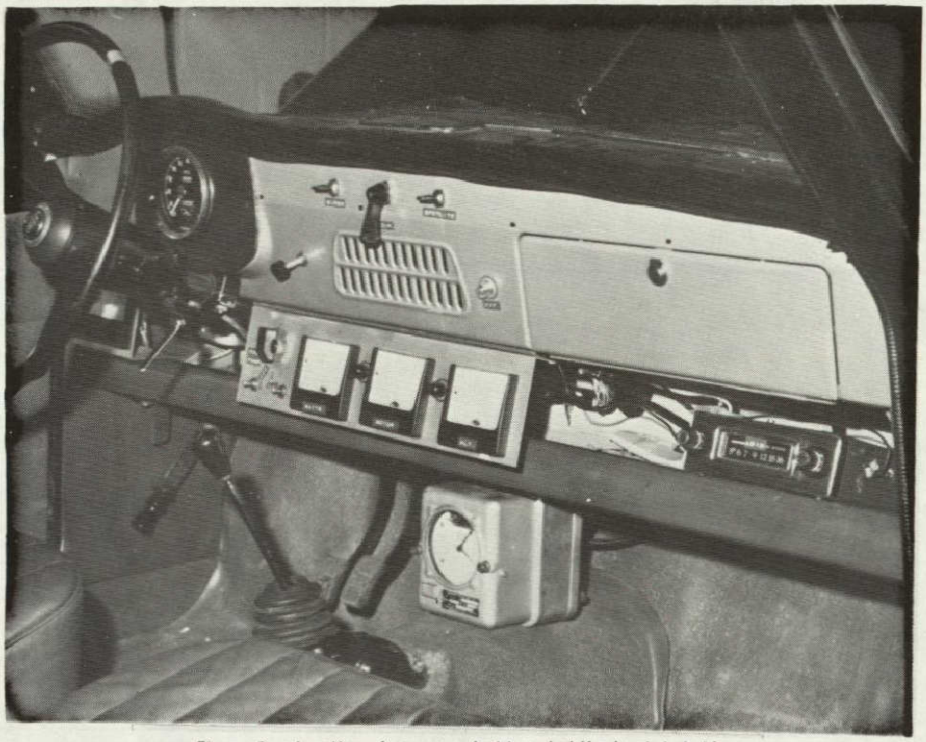


Figure 8. - Location of gages on dashboard of Kordesch hybrid.

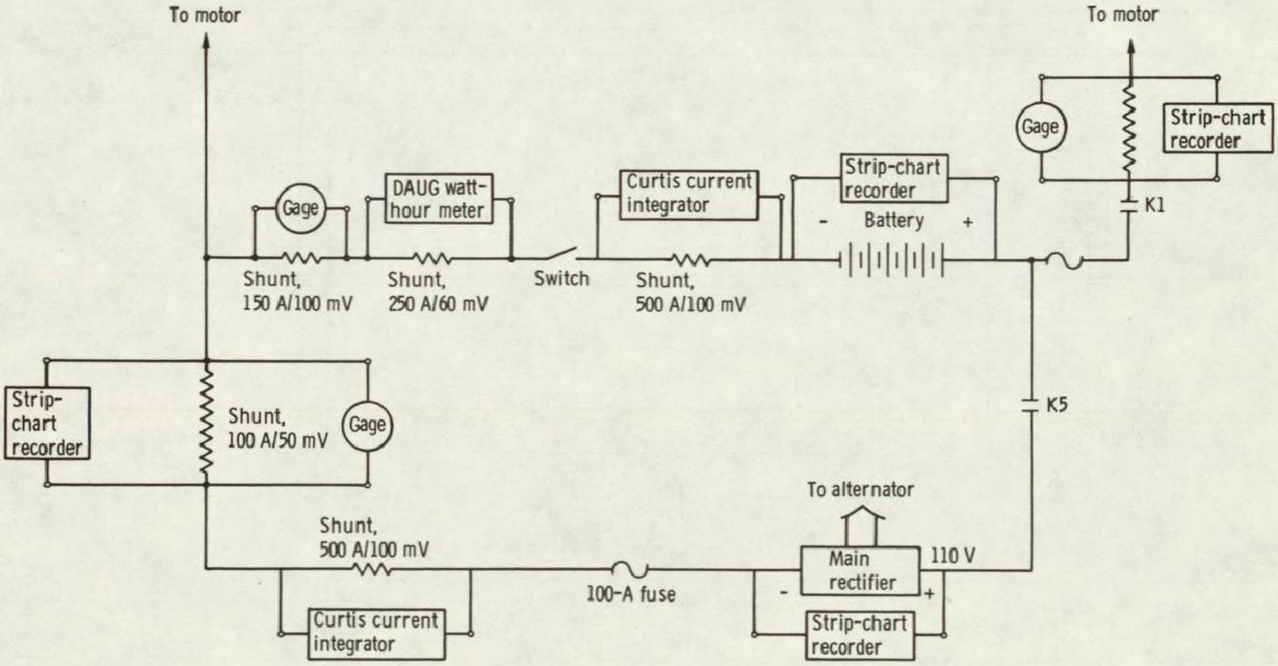
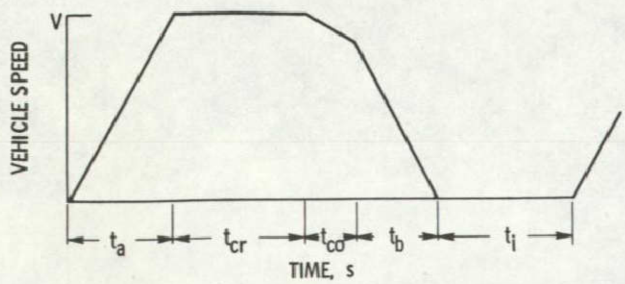


Figure 9. - Partial vehicle wiring diagram showing location of instruments.



TEST PARAMETER	SAE SCHEDULES		
	B	C	D
MAX. SPEED, V, mph	20	30	45
ACCEL. TIME, t_a, s	19	18	28
CRUISE TIME, t_{cr}	19	20	50
COAST TIME, t_{co}	4	8	10
BRAKE TIME, t_b	5	9	9
IDLE TIME, t_i	25	25	25

Figure 10. - SAE J227a driving cycle schedules.

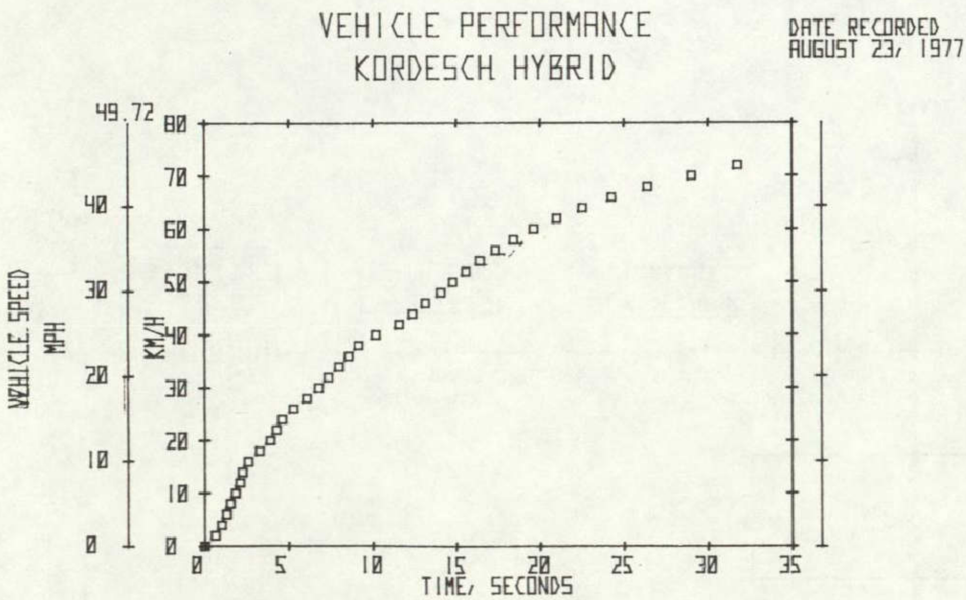


Figure 11. - Vehicle acceleration.

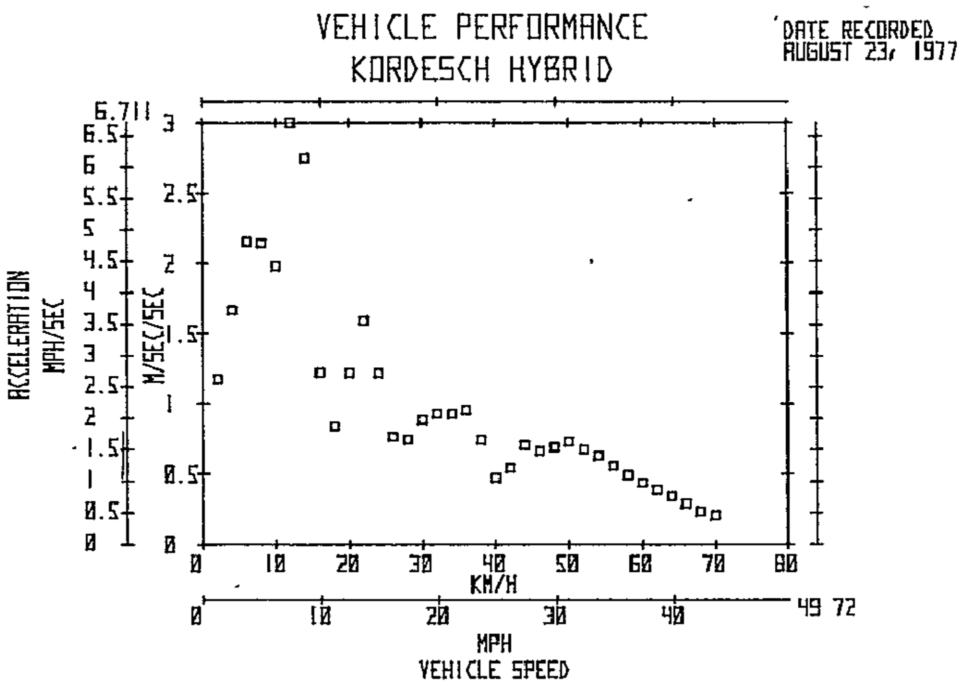


Figure 12. - Acceleration as a function of speed.

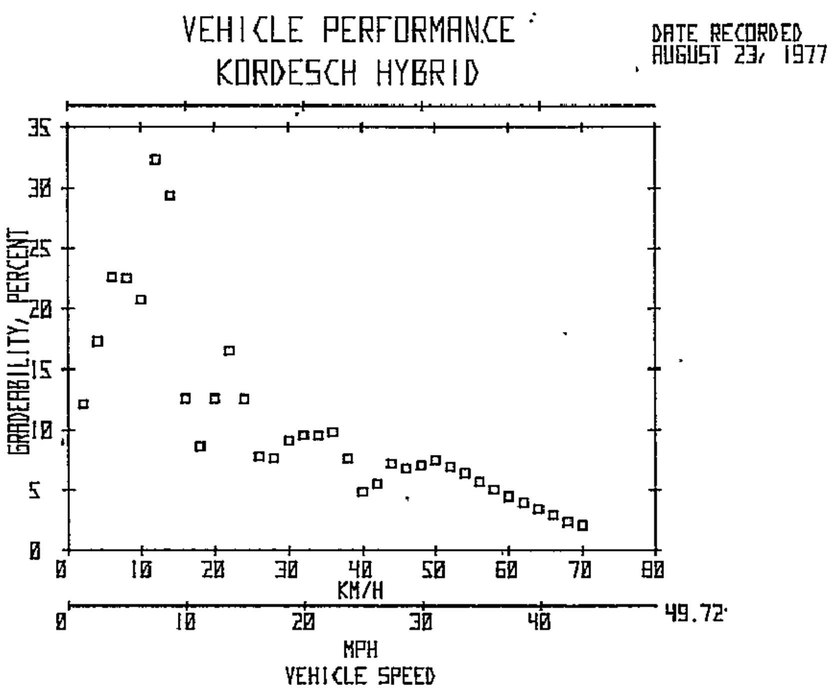


Figure 13. - Gradeability as a function of speed.

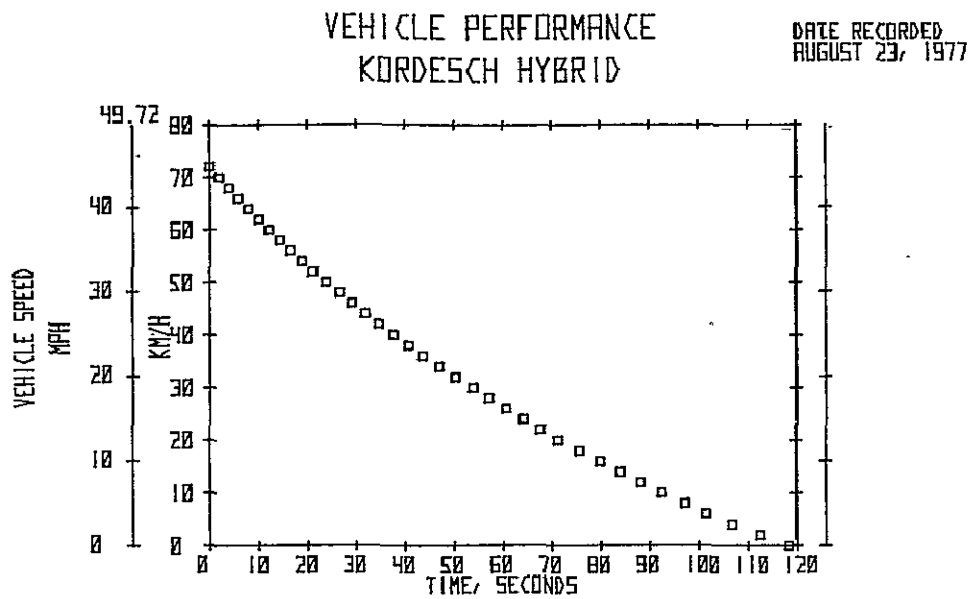


Figure 14. - Vehicle deceleration.

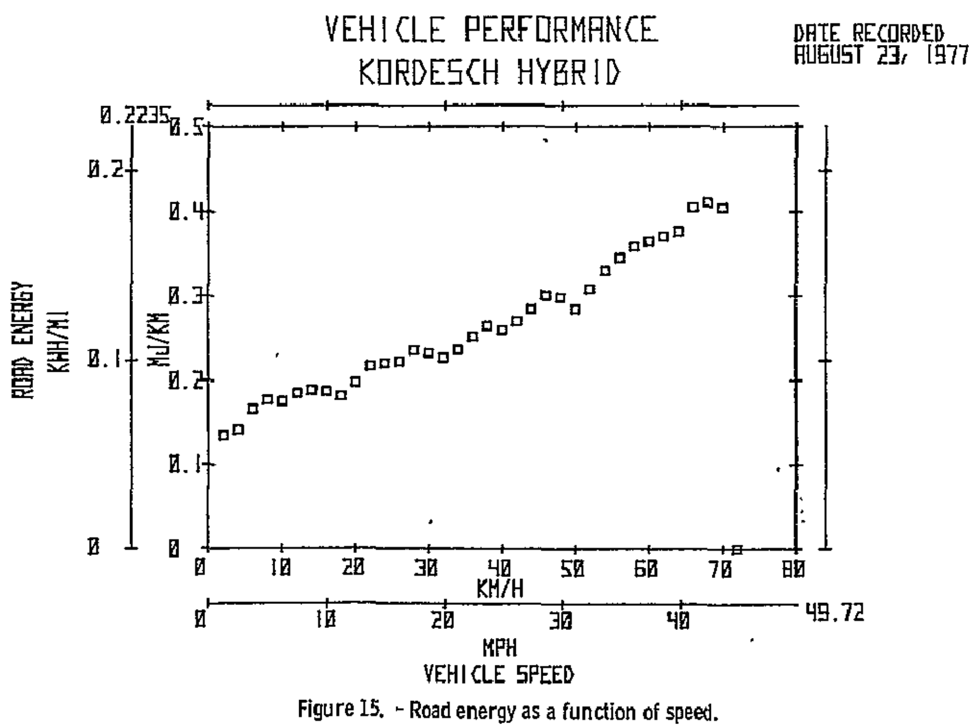


Figure 15. - Road energy as a function of speed.

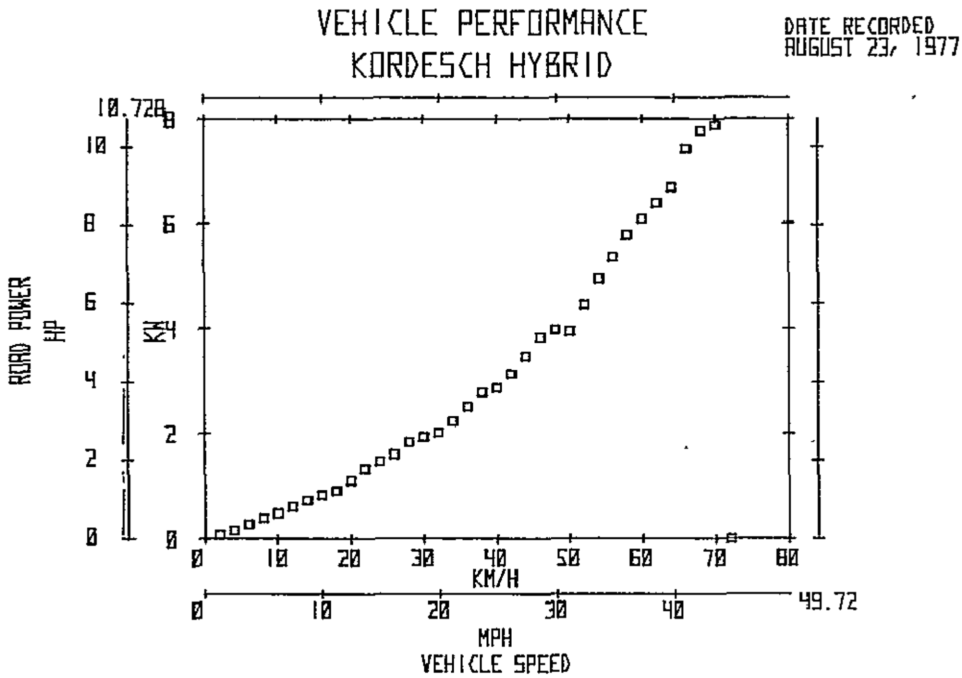


Figure 16. - Road power-as a function of speed.

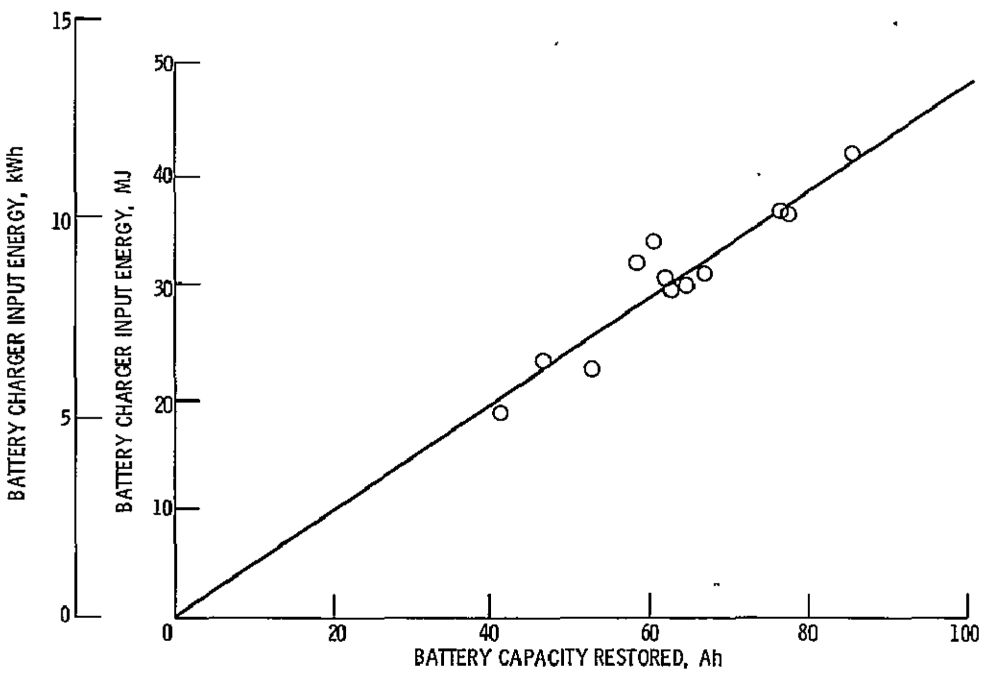


Figure 17. - Kordesch hybrid vehicle battery and battery charger characteristics.

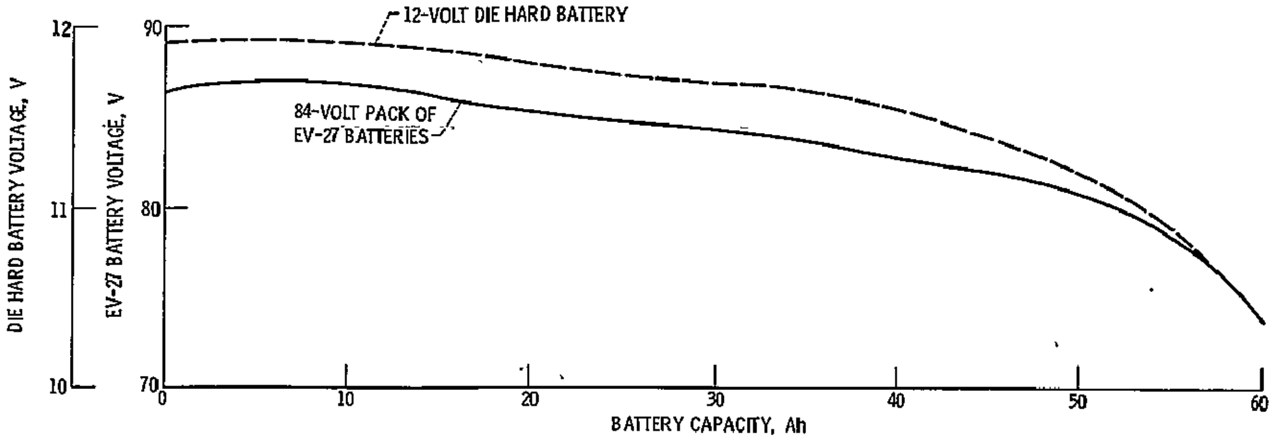


Figure 18. - Battery capacity checks of EV-27 batteries at 37.5-ampere discharge current.

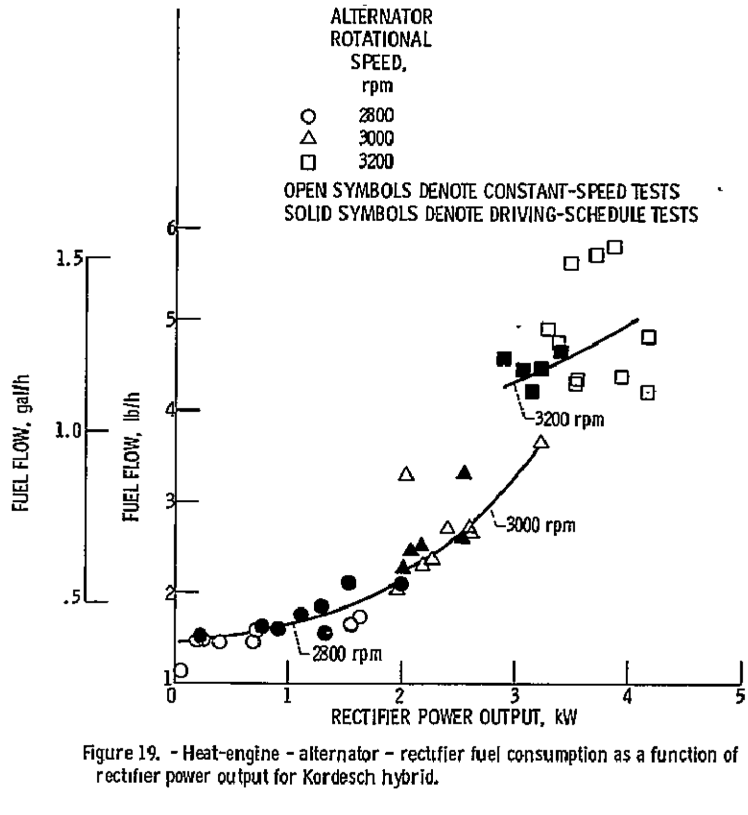


Figure 19. - Heat-engine - alternator - rectifier fuel consumption as a function of rectifier power output for Kordesch hybrid.

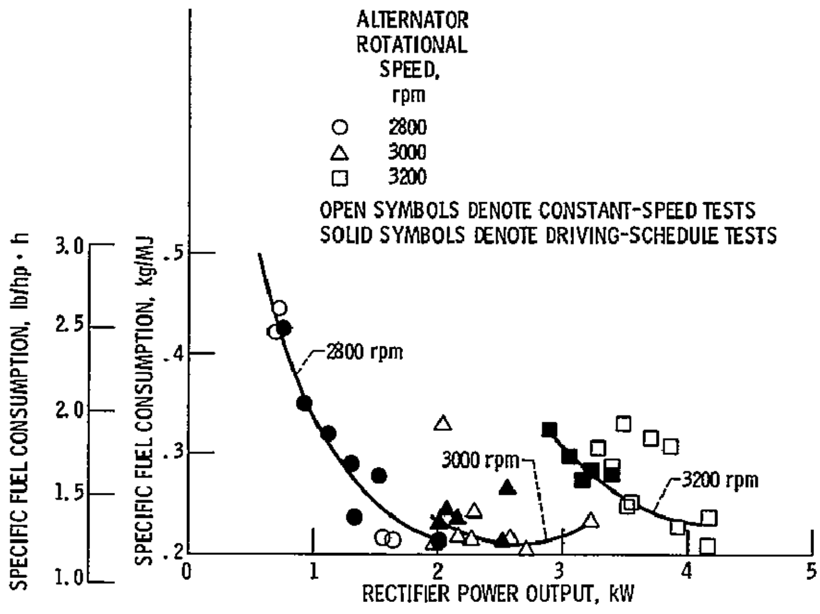


Figure 20. - Heat-engine - alternator - rectifier specific fuel consumption as a function of rectifier power output for Kordesch hybrid.

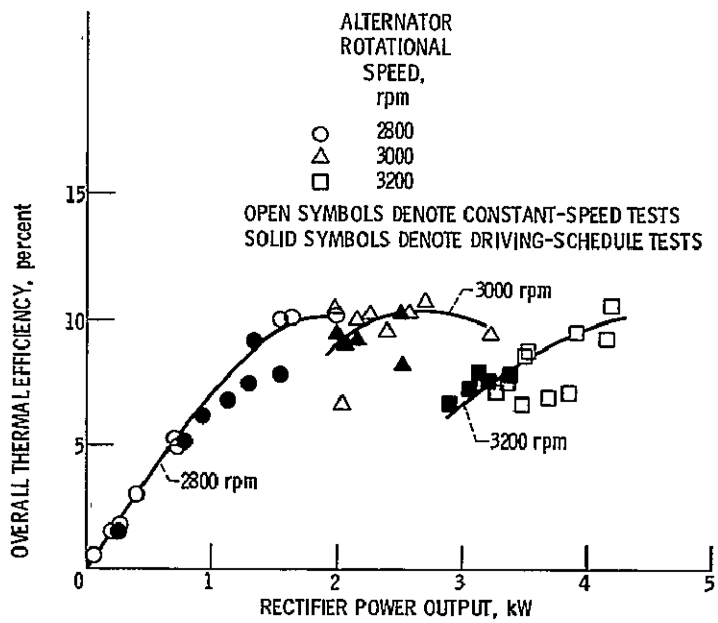


Figure 21. - Heat-engine - alternator - rectifier overall thermal efficiency as a function of rectifier power output for Kordesch hybrid.

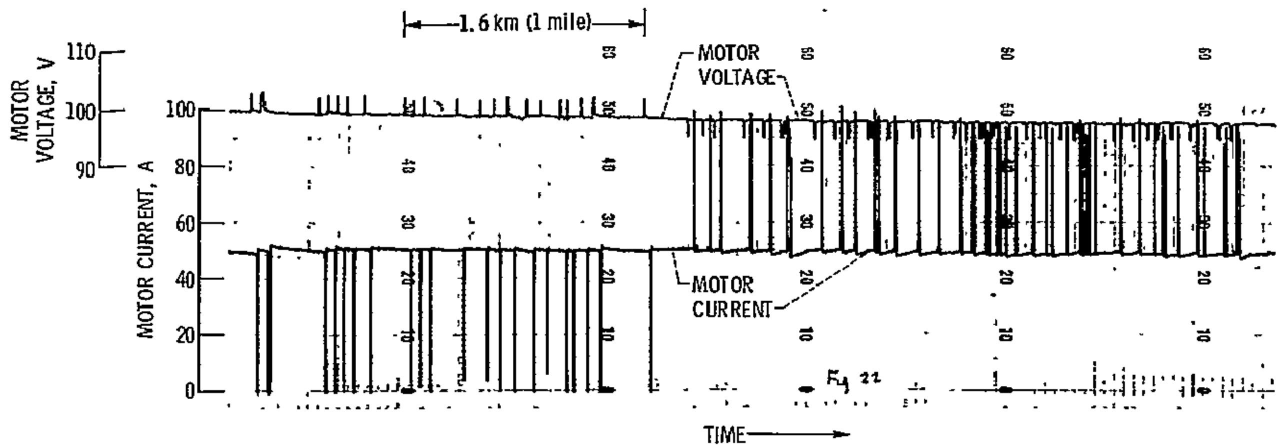


Figure 22. - Motor voltage and current during a 40-kilometer-per-hour (25-mph) vehicle constant-speed test of Kordesch hybrid. Battery discharge, 30 percent.

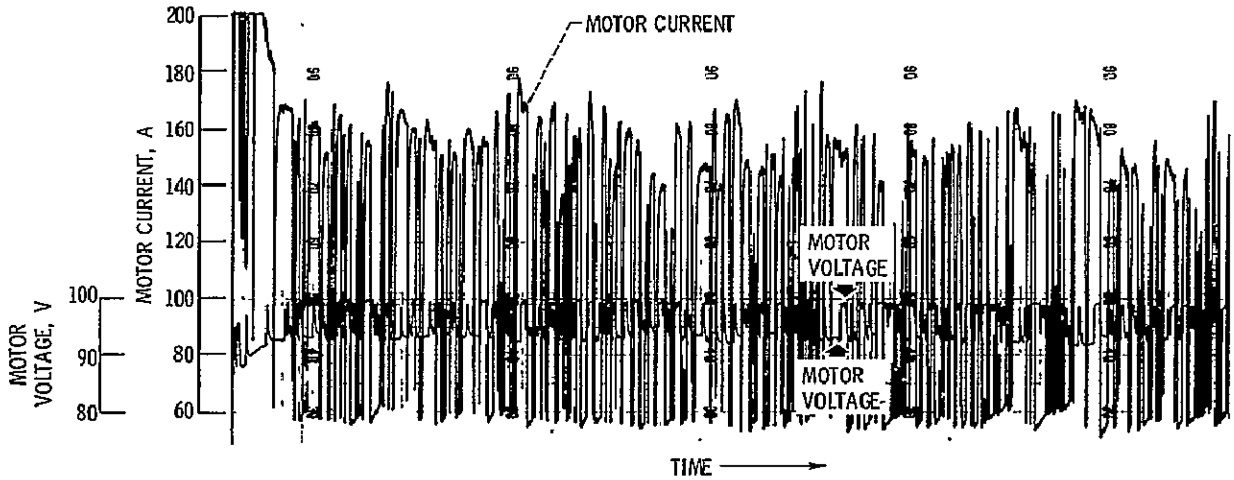


Figure 23. - Motor voltage and current during a 72-kilometer-per-hour (45-mph) vehicle constant-speed test of Kordesch hybrid. Alternator rotational speed, 2800 rpm.

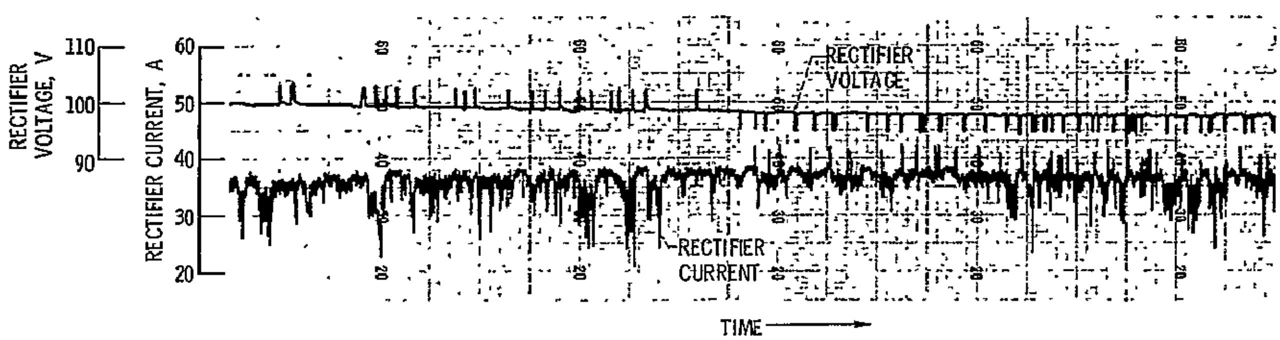


Figure 24. - Rectifier voltage and current during a 40-kilometer-per-hour (25-mph) vehicle constant-speed test of Kordesch hybrid. Alternator rotational speed, 3200 rpm.

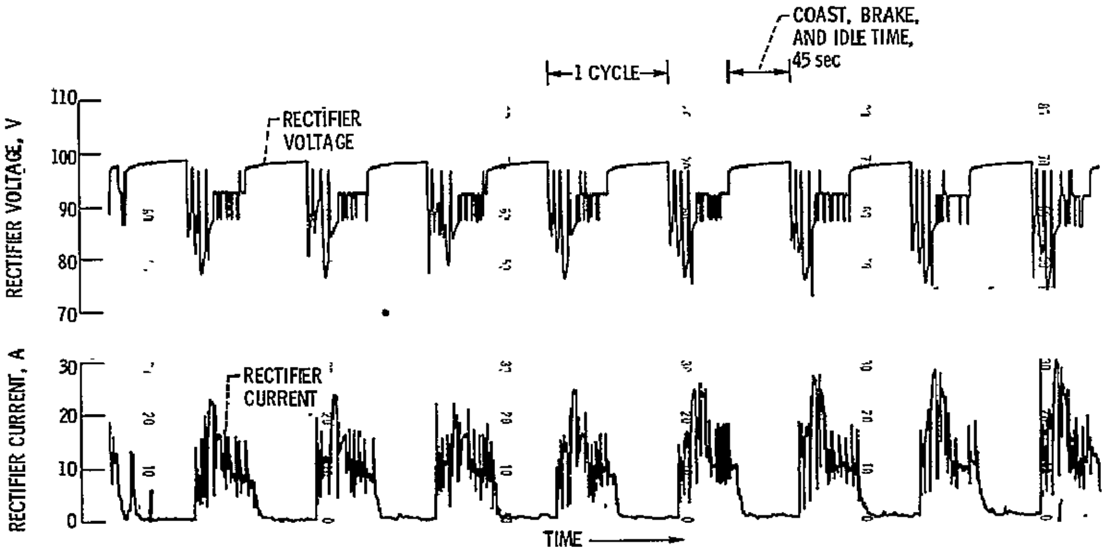


Figure 25. - Rectifier voltage and current during driving schedule C tests of Kordesch hybrid. Battery discharge, 8 percent; alternator rotational speed, 2800 rpm.

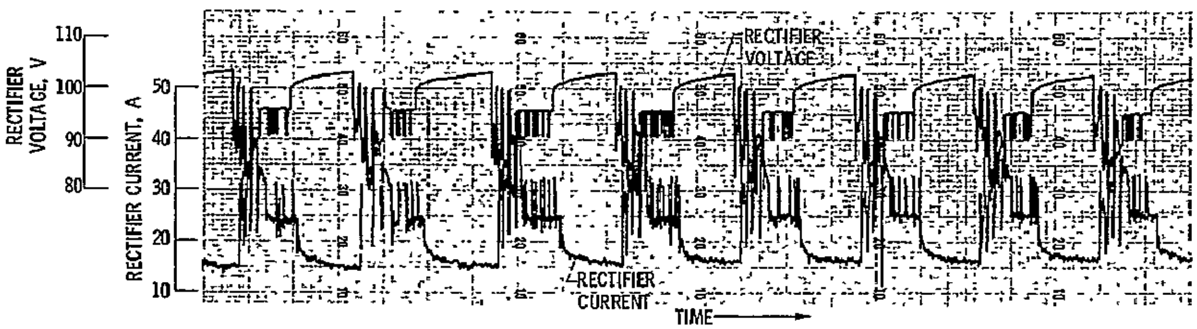


Figure 26. - Rectifier current and voltage during driving schedule C test of Kordesch hybrid. Alternator rotational speed, 3000 rpm.

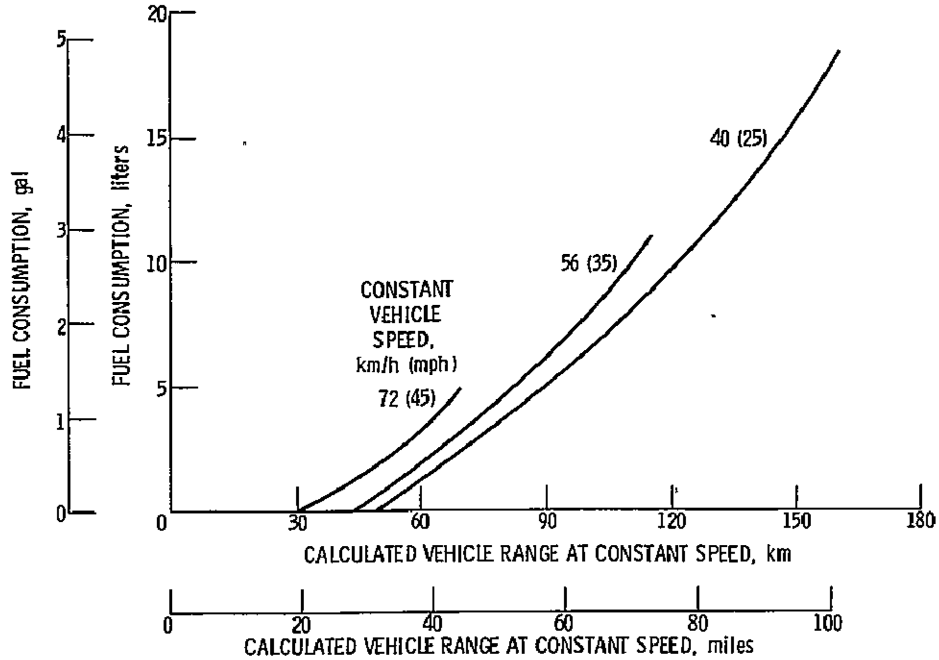


Figure 27. - Kordesch hybrid vehicle range at constant speed as a function of gasoline consumption.

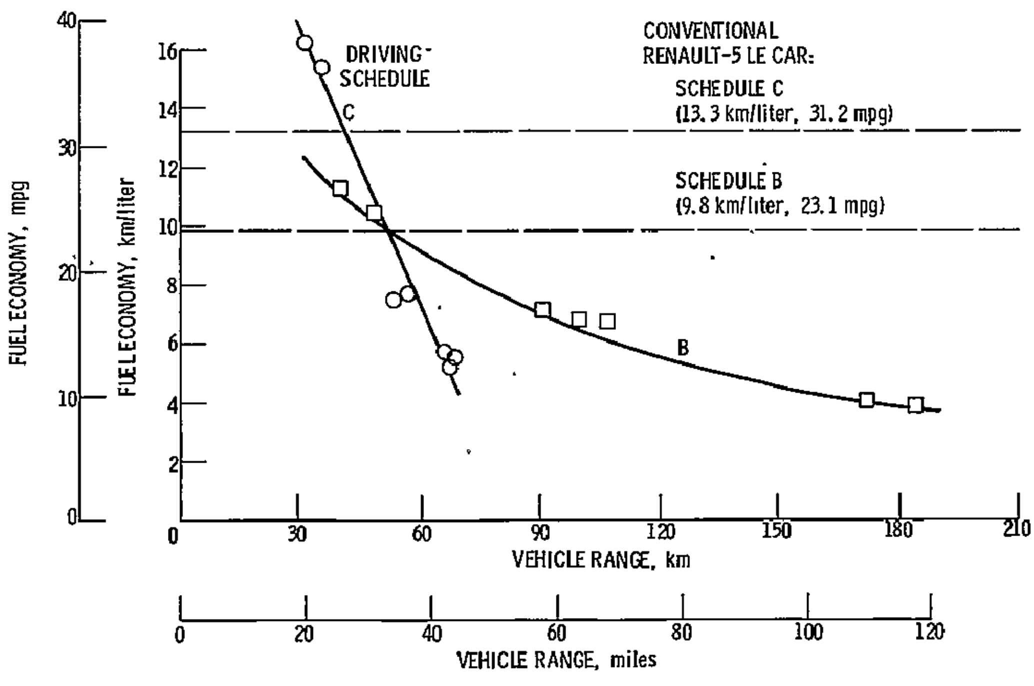


Figure 28. - Driving-schedule range as a function of fuel economy for Kordesch hybrid.

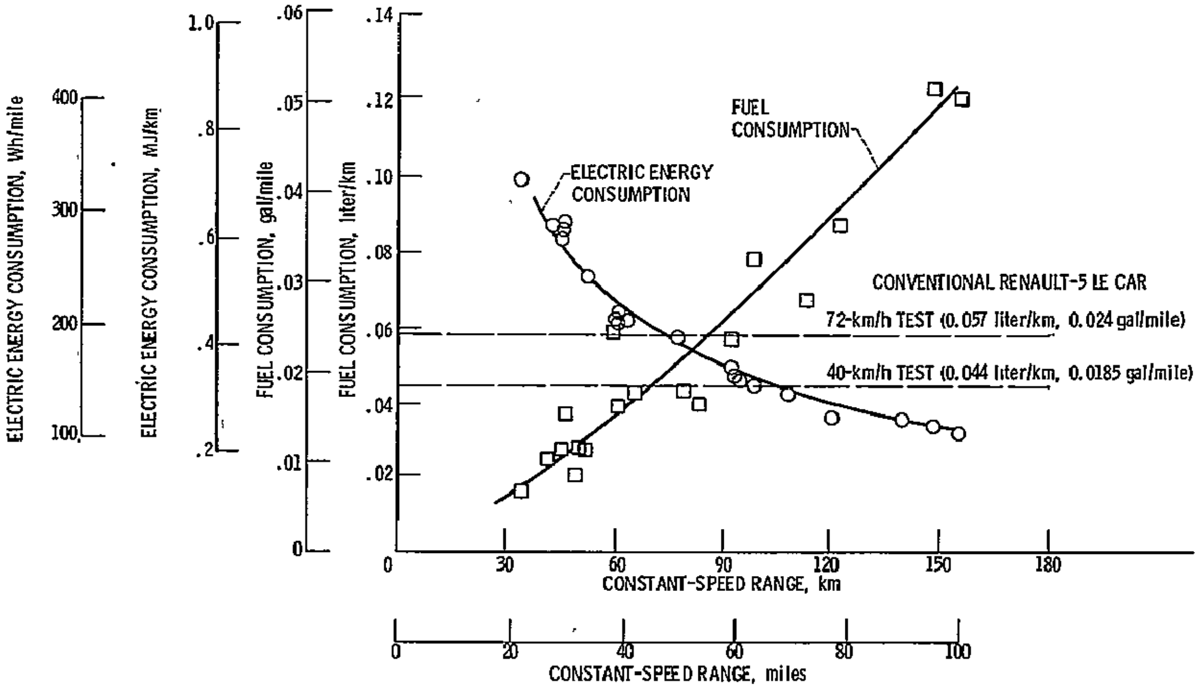


Figure 29. - Fuel and electric energy consumption for Kordesch hybrid.

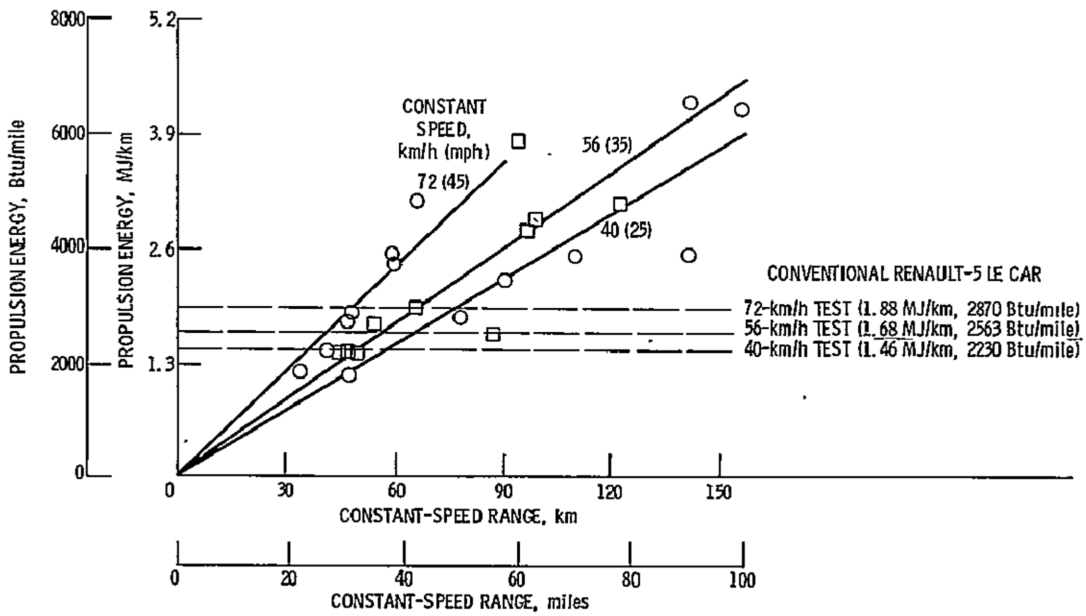


Figure 30. - Propulsion energy as a function of range for Kordesch hybrid.

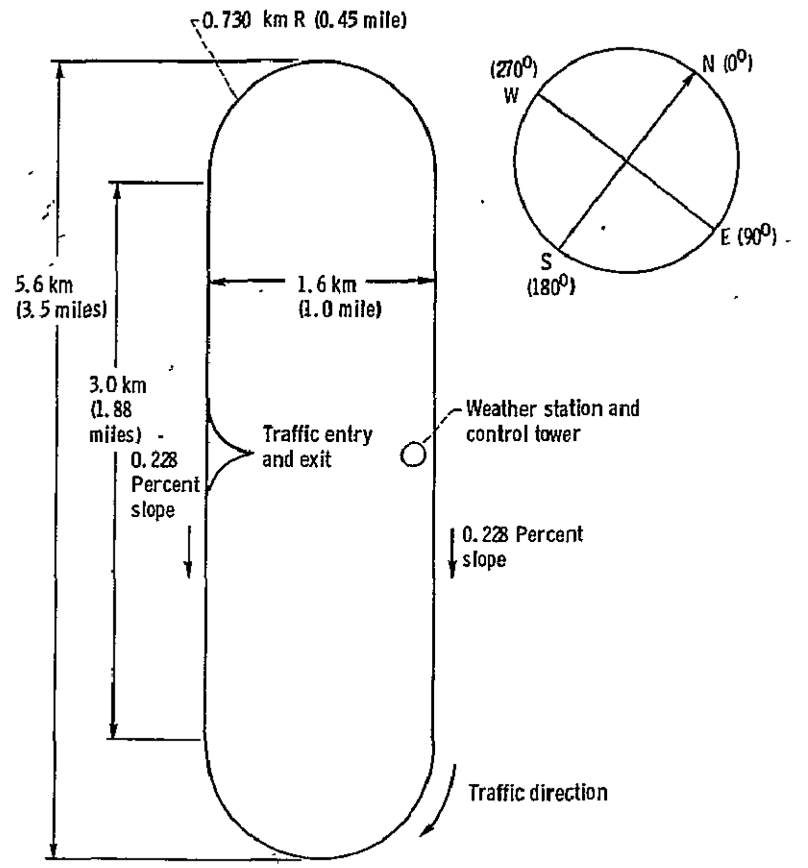


Figure B-1. - Characteristics of Transportation Research Center Test Track, East Liberty, Ohio.

1. Vehicle ____________________
2. Date received ____________________
3. Checked for damage - date ____________________
4. Wheel alignment - date ____________________
5. Battery checked and equalized - date ____________________
6. Curb weight determined, lbm ____________ Date __________
7. Gross vehicle weight, lbm ____________________
8. 300-Ampere test - date ____________________
9. Manufacturer's recommendations:
   Maximum speed, mph ____________________
   Tire pressures, psi: Front __________; Rear __________
   Driving procedures ____________________

Figure C-1. - Vehicle preparation check sheet for Kordesch hybrid.

1. Check 5th-wheel tire pressure and vehicle tire pressure.
2. Take 12-volt batteries off charge. Check water; add water if necessary.
3. Plug in 12-volt power to 5th wheel.
4. Check operations and settings of 5th wheel:
   Light expanded scale and set to test to be performed.
   Light and zero distance readout.
   Set interface box for distance readout at 1.0, on, and reset.
   Set interface box for strip chart at 10, on, and reset.
5. Spin up 5th wheel and check -
   Speedometer reading
   Distance counter recording
   Speed indication on strip chart
   Distance indication on strip chart
   Speed and timing indication on beeper
6. Reset interface box for strip chart to 1000.
7. Plug strip charts and integrator into inverter.
8. Switch on inverter.
9. Turn on strip charts and check for inking and paper; set if chart drive is working (zero setting).
10. Switch on integrators and zero. Make sure readings are recorded.
11. Turn off integrators, strip charts, and inverter. Unplug 5th wheel from 12-volt source. Turn off interface boxes and distance counter readout.
12. Remove charge current input from rectifier recorder (blue pen).
13. Install run current input - labeled "charge curr" - to rectifier recorder current input (blue pen).
14. Set chart scales.

	Zero	Span	Units
Battery power:			
Battery power - red	50 V	100 V	50 - 150 V
Battery current - blue	0 mV	50 mV	0 - 200 A
Rectifier power:			
Motor voltage - red	50 V	100 V	30 - 130 V
Motor current - blue	0 mV	50 mV	0 - 100 A
Vehicle speed - red	0 V	4.44 V	0 - 50 mph
Vehicle distance - blue	0 V	50 V	1000/pulse

   Chart speed, 1 min/in.
15. Put documents on strip charts: time, date, vehicle red and blue units, test to be performed, and chart speed.
16. Tow vehicle onto scales. (Test weight includes driver.) Ballast; raise 5th wheel.
17. Lower 5th wheel. Set hub loading (5 lb above hub weight).
18. Tow vehicle onto track.
19. Turn on -
   Inverter
   Recorders (Document time on chart paper.)
   Integrator to on position (zeroed).
   Interface box for distance readout (Reset. Check that selector is in "100" position.)
   Interface box for distance recorder (Reset. Check that selector is in "1000" position.)
   Distance readout. (Reset, count "on.")
   Plug 5th wheel into 12-volt supply.
20. Be sure data sheet is properly filled out to this point.
21. Proceed with test.

Figure C-2. - Pretest checklist for Kordesch hybrid.

1. Complete pretest checklist.
2. Complete 1/2 lap at 45 mph for warmup immediately prior to beginning test runs, with alternator lever in 3400-rpm position and knife switch closed.
3. Range tests - one full lap at each vehicle speed, in the order listed, with alternator lever in 3000-rpm position:
   a. 45 mph
   b. 35 mph
   c. 25 mph

   Chart speed, 1 in./min. Do not begin test run until desired constant range speed is attained. Start fuel and distance count. Place alternator lever in 3400-rpm position between tests. Do not shut off engine.
4. Cycle tests - one full lap (minimum) of each cycle, in the order listed, with alternator lever in 3000-rpm position:
   a. Schedule C
   b. Schedule B

   Chart speed, 20 sec/in. for the first three cycles and the last three cycles. The remaining cycles should be run with chart speed at 1 min/in. Record fuel data cumulative readings for each cycle, per special data sheet.
5. Maximum acceleration (without spinning wheels) to 45 mph and coast down to full stop with transmission in neutral. Perform a minimum of two accelerations and coastdowns on each outside track straight section. Chart speed at 5 sec/in. Record fuel flow at end of each acceleration and at end of each coastdown. Record distance for one acceleration on each track straightaway and for one coastdown on each track straightaway.
6. Place alternator lever in 3400-rpm position between test laps. Do not turn off engine.
7. Complete post-test checklist.

Figure C-3. - Run schedule for tests of Kordesch hybrid.

Vehicle ______ Test ______ Date ______

Driver ______ Navigator ______

Tire pressure before test, psi:
Right front ______ Left front ______ Right rear ______ Left rear ______

Tire pressure after test, psi:
Right front ______ Left front ______ Right rear ______ Left rear ______

Fifth-wheel tire pressure, psi ______ (calibrated, ______ psi)

Test vehicle weight, lbm:
Right front ______ Left front ______ Right rear ______ Left rear ______
Total front ______ Total rear ______ Total ______

Weather conditions:	Initial	During test	Final
Temperature, ^{o}F			
Wind speed, mph			
Wind direction			
Barometric pressure, in. Hg			

	Start	Stop
Time, s		
Odometer reading, miles		
Fuel flow, cm^3/mile		
Tire pressure, kPa		
Fuel temperature, ^{o}C		

Number of cycles ______ Fifth-wheel distance count, ft ______

DAUG meter:	Entladen	Laden
Start		
At speed		
End		
Stop		

Battery integrator:	Discharge	Charge
Start		
At speed		
End		
Stop		

Rectifier integrator discharge:
Start ______
At speed ______
End ______
Stop ______

Vehicle ampere-hour meter ______
Range, miles ______
Fuel flow, cm^3/min ______
Fuel temperature, ^{o}C ______
Fuel pressure, kPa ______

Alternator setting, rpm ______ Gear ______

Figure C-4. - Track data.

1. Note time immediately at completion of test. Turn off key switch.
2. Complete track data sheet. Do not turn off instrument power until all test run readings have been documented:
   - Odometer at stop
   - Ampere-hour integrator in and out
   - 5th-wheel counter
   - Motor temperature
   - Weather data
   - Number of cycles (if applicable)
   - Watt-hour integrator in and out
3. Turn off distance counter, interface boxes, strip-chart recorders, and inverter. Disconnect 5th wheel from 12-volt source.
4. Raise 5th wheel.
5. Tow vehicle off track.
6. Record specific gravities of traction batteries.
7. Check specific gravity on instrument batteries and note average reading on specific-gravity record sheet.
8. Check water level in accessory battery. Add water if necessary.
9. Put 12-volt instrument batteries on charge.
10. Zero integrators. Make sure reading is recorded.
11. Remove input jack for current on rectifier recorder (blue pen).
12. Plug in lead from battery integrator input to rectifier current input (blue pen).
13. Set strip charts as in summary:

	Zero	Span	Units
Battery voltage - red	50 V	100 V	50 - 150 V
Battery current - blue	0 mV	4 mV	0 - 20 A

    Chart speed, 10 min/in.

14. Document on strip charts the time, date, vehicle, red and blue units, after what test charging is being done, chart speed, and that it is a post-test charge.
15. Turn on strip-chart power and chart drive, and place integrator in "operate" position.
16. Turn on charger. Record time on track sheet and strip charts.

Figure C-5. - Post-test checklist for Kordesch hybrid.

Vehicle ________________ Battery system ________________

Test ________________ Date ________________

Average post-test specific gravity ________________

Open-circuit voltage, V ________________

Charger used ________________

Charger input voltage, V ________________

Battery temperature, °F: Before charge ______ After charge ___

Power, kWh: Start ________ End ________ Total ________

Time: Start ________________ End ________________

Total charge time, min ________________

Current input, Ah ________________

Average specific gravity after charge ________________

Approval ________________

Figure C-6. - Charge data for Kordesch hybrid.

Vehicle ____________ Test ____________ Date ____________

Engineer ____________

Reason for test (checkout, component check, scheduled test, etc.) ____________

____

Limitation on test (malfunction, data system problem, brake drag, etc.) ____________

____

Changes to vehicle prior to test (repair component, change battery, adjust brakes, etc.)

____

Weather conditions:

Temperature, ^{o}F ____________ Wind speed, mph ____________

Wind direction ____________ Barometricpressure, in. Hg ____________

Other ____________

Test results:

Test duration, h ____________ Range, miles ____________

Number of cycles ____________ Fueltemperature, ^{o}C ____________

Fuel flow (total), cm^3 ____________

Fuel economy, mpg ____________ Fuel consumption, cm^3/mile ____________

Current out of battery, Ah ____________ Current into battery, Ah ____________

Current out of generator, Ah ____________ Power into battery, kWh ____________

Charge time, hr ____________ Unit power, kWh/mile ____________

Was planned driving schedule followed? ____________

General comments: ____________

____

____

____

____

____

Figure C-7. - Engineering data sheet.

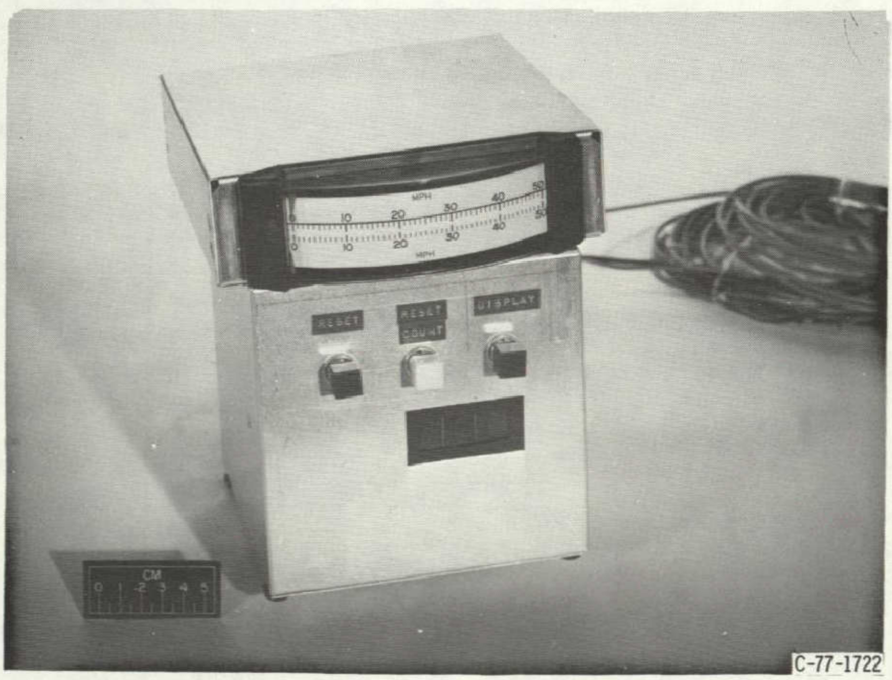


Figure C-8. - Cycle timer.

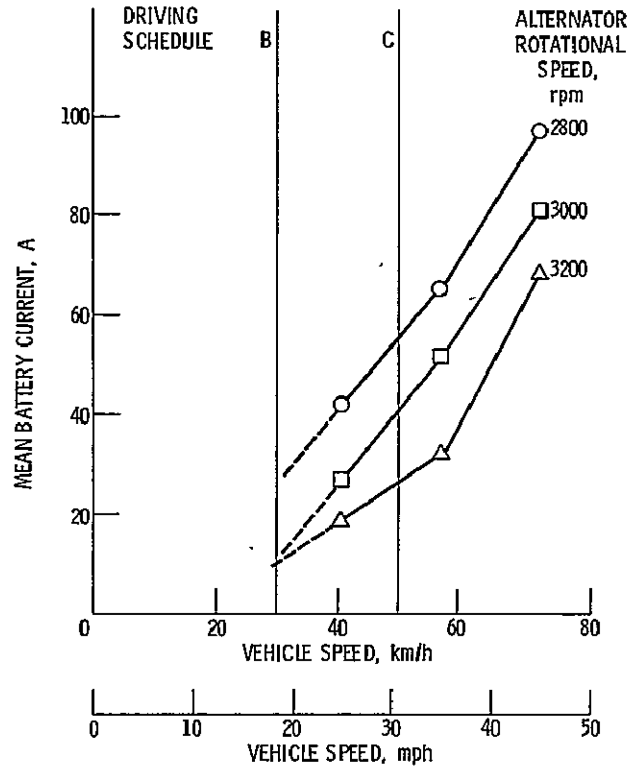


Figure E-1. - Average battery current during constant-speed tests.

1. Report No NASA TM-73769	2 Government Accession No.	3. Recipient's Catalog No
4. Title and Subtitle BASELINE TESTS OF THE KORDESCH HYBRID PASSENGER VEHICLE		5 Report Date June 1978
		6 Performing Organization Code
7. Author(s) Richard F. Soltis, John M. Bozek, Robert J. Denington, and Miles O. Dustin		8. Performing Organization Report No E-9604
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		10 Work Unit No
		11 Contract or Grant No
		13 Type of Report and Period Covered Technical Memorandum
12 Sponsoring Agency Name and Address Department of Energy Division of Transportation Energy Conservation Washington, D.C. 20545		14 Sponsoring Agency ~~Code~~ Report No. CONS/1011-14
15 Supplementary Notes Prepared under Interagency Agreement EC-77-A-31-1011.		

16 Abstract

The Kordesch hybrid passenger vehicle is propelled by an electric motor that receives its energy from a spark-ignition-engine-driven alternator and an electric battery system. It was developed and is owned by Dr. Karl V. Kordesch, formerly of Lakewood, Ohio, and now living in Graz, Austria. It was tested at the Transportation Research Center of Ohio Test Track, East Liberty, Ohio, between August 17 and September 22, 1977. The tests are part of an Energy Research and Development Administration (ERDA) project to assess the state-of-the-art of electric and hybrid vehicles. The Kordesch hybrid vehicle performance test results are presented in this report. The Kordesch hybrid is a four-passenger Austin A40 sedan that has been converted to a heat-engine-alternator- and battery-powered hybrid. It is propelled by a conventional, gasoline-fueled, heat-engine-driven alternator and a traction battery pack powering a series-wound, 7.5-kilowatt (10-hp) direct-current electric drive motor. The 12-kilowatt (16-hp) gasoline engine drives the 7-kilowatt alternator, which provides electrical power to the drive motor or to the 96-volt traction battery through a rectifier. The propulsion battery consists of eight 12-volt batteries connected in series. The electric motor is coupled to a four-speed standard Austin transmission, which drives the rear wheels. Power to the motor is controlled by a three-step foot throttle, which actuates relays that control armature current and field excitation. Conventional hydraulic brakes are used. There is no regenerative braking.

17 Key Words (Suggested by Author(s)) Electric vehicle Car Test and evaluation Battery		18. Distribution Statement Unclassified - unlimited STAR Category 85 DOE Category UC-96	
19. Security Classif. (of this report) Unclassified	20 Security Classif (of this page) Unclassified	21 No. of Pages 68	22 Price* A04

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

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