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ELECTRIC AND HYBRID VEHICLE PERFORMANCE AND DESIGN GOAL DETERMINATION STUDY

Final Report

August 1977

Work Performed Under Contract No. EY-76-C-03-1215

GENERAL RESEARCH CORPORATION

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Prepared For
U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Transportation Energy Conservation
Washington, D.C.

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**ELECTRIC AND HYBRID VEHICLE PERFORMANCE
AND DESIGN GOAL DETERMINATION STUDY**

Final Report

by

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August 1977

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PREFACE

The authors wish to acknowledge the capable assistance of Mssrs. Michael Pocobello and Daniel Armstrong of Triad Services, Inc., and Mr. Wally E. Rippel, for their contributions to this study.

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ABSTRACT

Recommendations are set forth for performance standards for near-term and advanced electric and hybrid vehicles which are to be leased or purchased by the U.S. Energy Research and Development Administration pursuant to Public Law 94-413. Private and commercial applications in urban and rural areas are considered. The underlying analytical basis is derived. Limited market surveys and interviews with present owners of electric vehicles indicated that the most important criterion for private vehicles is low operating cost. This criterion, combined with the low specific energy density and relatively short life of present storage batteries, was the key factor in the minimum performance specified for near-term private electric vehicles: two or more passengers, 50 km range over the SAE J227a/C driving schedule, with a maximum energy use of about 0.9 MJ/km (0.4 kWh/mi). Near-term commercial vehicles have even lower recommended minimum performance, including 50 km on the (less demanding) SAE J227a/B schedule.

Advanced batteries with up to 2.8 times the energy density of present batteries, if they become available, will allow the performance of advanced electric vehicles' to approach that of conventional subcompact vehicles, except in range. Ranges of 165 km (SAE J227a/D driving schedule) for the private vehicles and 220 km (J227a/C) for the commercial vehicles are specified. Operating costs for the advanced vehicles, including battery depreciation, should be competitive with comparably sized conventional vehicles if battery development goals are achieved.

Heat-engine battery-electric hybrid vehicles may provide the driving range lacking in electric vehicles and use appreciably less fuel than conventional vehicles. Performance standards recommended for near-term hybrid vehicles call for essentially the same performance as for comparably sized near-term electric vehicles, except for increased range capability.

Development specifications recommended for advanced hybrids call for substantially reduced petroleum fuel consumption and the same acceleration capability exhibited by present conventional subcompact cars.

Performance standards for a light agricultural utility vehicle are developed.

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1 INTRODUCTION AND EXECUTIVE SUMMARY

1.1 INTRODUCTION

In September of 1976, Congress passed the "Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, Public Law 94-413." Among the purposes of this act is included a provision to "demonstrate the economic and technological practicability of electric and hybrid vehicles for personal and commercial use in urban areas and for agricultural and personal use in rural areas...." To this end, the administrator of ERDA is to "promulgate rules establishing performance standards for electric and hybrid vehicles to be purchased or leased..." within 15 months of enactment. Within six months after the performance standards are released, contracts for the lease or purchase of up to 2500 near-term electric and hybrid vehicles are to be let. These vehicles shall be delivered by December 1979.

The performance standards are to be revised periodically until September 1980. Contracts for the lease or purchase of up to 5000 advanced electric and hybrid vehicles are to be let no later than March 1982, except that under special provisions the ERDA administrator is allowed to delay the delivery of some vehicles until February 1983.

General Research Corporation (GRC) has conducted a study to assist ERDA in developing the performance standards to be used for PL 94-413. (For the advanced vehicles, the standards are termed "development specifications" to differentiate between the current state of technology and that predicted for the 1980-1983 period.) The purpose of this report is to detail GRC's methods and findings, and the rationale on which the recommended performance standards and development specifications are based.

The method used to develop the performance standards consisted of three main tasks. First, the operation of electric vehicles was analyzed to determine the relationship of vehicle range and energy usage to key parameters: battery specific energy density, motor-driveline efficiency, battery mass ratio (battery mass/vehicle mass), and the driving schedule. Second, available test data on electric and hybrid vehicles were analyzed (using the analytical relationships just mentioned) to determine the state of the art. Third, hypothetical vehicle designs were used to determine the performance standards.

1.2 EXECUTIVE SUMMARY

Near-term battery-electric cars will generally have substantially less performance and moderately higher operating costs* than comparably

* Operating costs in this report consist of maintenance, electricity, and battery depreciation; interest, insurance, taxes, parking, tolls, and vehicle depreciation are not included. Note that operating costs are appreciably less than life-cycle costs.

sized conventional cars. These shortcomings are primarily due to the low specific energy density of presently available lead-acid storage batteries. Advanced lead-acid batteries which are projected by battery developers to become available in the mid-1980s would allow a doubling of travel range between battery chargings and perhaps a 30 percent decrease in operating costs.

To keep operating costs as close as possible to those for subcompact conventional vehicles, near-term electric cars should probably be small (800 kg curb mass) and carry only two passengers. A four-passenger electric car would be appreciably more massive and expensive to operate.

Near-term electric commercial vehicles will also have shortcomings in performance, particularly in range. However, for applications in which conventional vehicles perform a great many starts and stops with attendant engine idling, electric vehicles may be cost-competitive. As with electric cars, advanced lead-acid batteries would allow a substantial increase in range and a moderate decrease in operating cost for commercial electric vehicles.

Table 1.1 summarizes the recommended performance standards for near-term electric vehicles.

TABLE 1.1
SUMMARY OF RECOMMENDED PERFORMANCE STANDARDS FOR
NEAR-TERM URBAN ELECTRIC VEHICLES*

<u>Standard</u>	<u>Vehicle</u>	
	<u>Private</u>	<u>Commercial</u>
Acceleration	0-50 km/h in 12 s	0-50 km/h in 15 s
Gradeability	30 km/h on 10%	25 km/h on 10%
	40 km/h on 7%	35 km/h on 7%
Minimum Top Speed, [†] km/h	75	75
Minimum Passengers (inc. driver)	2	2
Minimum Cargo Capacity	30 kg and 0.2 m ³	230 kg and 1.5 m ³
Minimum Urban Driving Range, ^{**} km	50	50
Maximum Energy Input to Charger [*]	0.90 MJ/km	7 kJ/km per kg of cargo payload
	(0.4 kWh/mi)	(2.8 kWh/ton·mi)

* Test conditions are given in Table 9.5.

** For the SAE J227a/C and J227a/B driving schedules, respectively. These schedules are described in Appendix G.

[†] All top speed specifications in this report require that the speed be maintained for at least five minutes.

Advanced batteries, typified by nickel-zinc cells with a specific energy density nearly three times that of present lead-acid batteries, are projected by battery developers to be available by 1985. Such batteries would allow four-passenger electric cars to operate at freeway speeds and travel about 165 km (100 mi)* in urban traffic conditions. Operating costs are expected to be slightly below those for comparable conventional vehicles. It is not likely that these vehicles will be competitive with conventional cars among single-car families, since they cannot be used for the relatively infrequent long trips such as vacations. However, by 1980, there will be over 24 million multicar families who are potential users of electric cars. Even with advanced batteries, it probably will not be feasible to operate conventional air-conditioners in electric vehicles unless these conditioners are petroleum fueled. Table 1.2 summarizes the recommended development specifications for advanced electric vehicles.

Battery-electric vehicles cannot provide the performance and amenities (primarily air conditioning) of conventional vehicles. For this reason, hybrid vehicles (heat engine, battery, and electric motor) may be an attractive alternative to electric vehicles. Performance standards are developed for both near-term and advanced hybrids. Near-term hybrids will probably have about the same performance as near-term electric vehicles except for a greater range. Advanced hybrids appear to have the potential for substantial fuel savings in urban traffic.

Recommended performance standards for hybrid vehicles are summarized in Tables 1.3 and 1.4.

Recommended safety standards for electric and hybrid vehicles are patterned after the Federal Motor Vehicle Safety Standards (FMVSS) applicable to conventional cars and trucks. It is envisaged that near-term electric and hybrid vehicles can meet all applicable FMVSS with only minor exceptions. Advanced vehicles should meet all applicable FMVSS. Safety standards not covered by the FMVSS which are peculiar to battery-operated vehicles are specified. These standards are not expected to interfere with the orderly development of either near-term or advanced vehicles.

The development of comprehensive standards for agricultural vehicles was hampered by lack of standard driving schedules comparable to the SAE J227a series for electric vehicles and the EPA City cycle for conventional and hybrid vehicles. Nevertheless, performance standards were developed for a light-duty agricultural vehicle, based on the most appropriate electric vehicle driving schedule available. These standards are summarized in Table 1.5.

* In conformance with the policy of ERDA and Public Law 94-168 to encourage use of the metric system, this report uses SI (International System of Units) units. Where convenient, the equivalent value in conventional units is given in parentheses. Appendix K contains conversion factors which will be useful to those readers unfamiliar with SI units.

TABLE 1.2

SUMMARY OF RECOMMENDED DEVELOPMENT SPECIFICATIONS FOR
ADVANCED URBAN ELECTRIC VEHICLES*

Specification	Vehicle	
	Private	Commercial
Acceleration	0-65 km/h in 10 s	0-65 km/h in 10 s
Gradeability	55 km/h on 10% 70 km/h on 7%	55 km/h on 10% 70 km/h on 7%
Minimum Top Speed, km/h	105	105
Minimum Passengers (inc. driver)	4	2
Minimum Cargo Capacity	60 kg and 0.3 m ³	500 kg and 2.5 m ³
Urban Driving Range, km**	165	220
Maximum Energy Input to Charger*	1.08 MJ/km (0.48 kWh/mi)	3.1 kJ/km per kg of cargo payload (1.26 kWh/ton·mi)

* Test conditions are given in Table 9.5.

** For the SAE J227a/D and J227a/C driving schedules, respectively. These schedules are described in Appendix G.

TABLE 1.3

SUMMARY OF RECOMMENDED PERFORMANCE STANDARDS FOR
NEAR-TERM HYBRID VEHICLES[§]

Standard	Vehicle	
	Private	Commercial
Minimum Urban Range, km ^{§§}	200	200
Maximum Energy Input to Charger, MJ/km	0.45 MJ/km [†]	0.8 MJ/km ^{††}
Max Petroleum Fuel Consump, l/100 km	4	6.7
Max Petroleum Fuel Use, % ^{†††}	75	75

[§] Acceleration, gradeability, and maximum speed standards are the same as given in Table 1.1 for near-term electric vehicles.

^{§§} On the SAE J227a/C and J227a/B driving schedules, respectively.

[†] After 33 km on SAE J227a/C schedule followed by 33 km at 75 km/h.

^{††} After 100 km on SAE J227a/B schedule.

^{†††} Maximum allowable ratio of petroleum to total energy input to vehicle fuel tank and battery charger, based on 32.7 MJ/l for energy equivalent of petroleum.

TABLE 1.4
SUMMARY OF RECOMMENDED DEVELOPMENT SPECIFICATIONS
FOR ADVANCED HYBRID VEHICLES

<u>Standard</u>	<u>Vehicle</u>	
	<u>Private</u>	<u>Commercial</u>
Acceleration	0-90 km/h in 17 s	0-90 km/h in 17 s
Maximum Speed, km/h	105	105
Minimum Passengers (inc. driver)	4	2
Minimum Cargo Capacity	100 kg and 0.4 m ³	500 kg and 2.5 m ³
Maximum Energy Input to Charger, MJ/km*	0.71	1.0
Maximum Petroleum Fuel Consumption After Urban Range Test, l/100 km*	2.1	2.7
Maximum Petroleum Fuel Use, %**	50	50

* After 73 km and 90 km, respectively, in the EPA City Driving Schedule.

** Maximum allowable ratio of petroleum to total energy input to vehicle fuel tank and battery charger, based on 32.7 MJ/l for energy equivalent of petroleum.

TABLE 1.5
SUMMARY OF RECOMMENDED PERFORMANCE STANDARDS FOR
A LIGHT-DUTY AGRICULTURAL ELECTRIC VEHICLE

<u>Standard</u>	
Minimum Top Speed, km/h	20
Minimum Range on SAE J227a/A, km	15
Gradeability at 35%, km/h	5
Maximum Gradeability, percent	50
Minimum Payload, kg	1000
Energy Consumption (input to Charger, SAE J227a/A, MJ/km·t of payload)	3.3

2 CATEGORIES OF PERFORMANCE STANDARDS AND DEVELOPMENT SPECIFICATIONS FOR ELECTRIC AND HYBRID VEHICLES

This section defines important categories of standards and specifications which are generally applicable to electric and hybrid vehicles. These categories provide a framework for the performance standards and development specifications set forth in subsequent sections. The categories are comprehensive, and as nearly all-inclusive as time would permit. It is not intended that values should actually be specified for every category--and the standards presented in this report do not cover every category--but the comprehensiveness of the categories serves the purpose of organizing in a logical manner the large number of standards required to define an electric or hybrid vehicle.

Standards and specifications constitute a vital form of communication between buyer and seller, or between sponsor and developer. They should be explicit, detailed, complete, and unambiguous, defining precisely what the buyer seeks or the seller offers. The categories of standards and specifications set forth in this section were chosen with these objectives in mind.

Because there is no widely accepted terminology, Sec. 2.1 discusses the meaning of standards. It differentiates between performance standards and design standards, and it distinguishes constructively among several terms which are often used ambiguously or interchangeably: standards, criteria, goals, objectives, specifications, and characteristics. Section 2.2 identifies overall qualitative objectives for electric and hybrid vehicles. Section 2.3 categorizes standards and criteria relevant to each overall objective.

2.1 THE MEANING OF STANDARDS

A standard is generally an authoritative example, model, or rule to be followed. Thus standards for electric vehicles should describe qualities or characteristics of the vehicles desired by prospective buyers.

In practice two kinds of standards have become common. Design standards describe a vehicle in terms of its materials, its components, and its shape or configuration. Performance standards, in contrast, describe a vehicle in terms of its function or operation. A design standard might require 30 percent of the curb mass of an electric car to be devoted to batteries. A corresponding performance standard might require an 80-km driving range for a specified driving schedule between recharges instead.

Design standards are easy to write and easy to enforce for simple systems of common components. Often a simple inspection suffices to judge compliance with design standards. Application of performance

standards, on the other hand, often involves relatively elaborate testing, and the standards are correspondingly difficult to define.

The great advantage of performance standards is that they facilitate and encourage progress and improvement. Unlike design standards, they offer no impediment to the innovator who offers new materials and techniques for accomplishing a desired function. Moreover, they do not require their authors to foresee the best design for a builder to undertake.

In this study, emphasis was placed on performance standards. Performance standards are especially desirable now for electric and hybrid vehicles because optimized designs have yet to be established and underlying technology is expected to advance significantly. As a means of communication between buyer and builder, performance standards are much more likely to lead to the most satisfactory vehicle within technical and economic reach. As defined in Section 7(2) of P.L. 94-413, "... performance standards shall represent the minimum level of performance which is required with respect to any vehicles purchased or leased...". The performance standards developed in subsequent sections are consistent with this definition.

It is impractical, however, to avoid design standards entirely. Limitation of the vehicles considered here to those utilizing electric energy is itself a de facto design standard. Moreover, design standards may be the most efficient means of describing aspects of electric and hybrid vehicles which employ conventional components such as lights and accessories.

Performance standards for the advanced vehicles (to be leased or purchased in 1981 and later) are to be updated periodically. For this reason, they are in the nature of goals and are termed a development specification.

2.2 OVERALL OBJECTIVES

As an aid in identifying comprehensive performance standards for electric vehicles, it is convenient now to list overall objectives for such vehicles. Objectives commonly associated with electric and hybrid vehicles include lower air pollution and lower petroleum use. In addition, electric vehicles must meet objectives served by the conventional vehicles they replace--utility, economy, safety, and so on.

Table 2.1 presents a comprehensive list of overall objectives for electric vehicles. It may be interpreted to include the objectives noted above and many others. It is arranged in three sections. The first section includes six overall objectives principally of interest to users of electric vehicles, ranging from utility and durability to such less-quantifiable objectives as amenity and pleasurability. The second section

adds a broad societal objective which individual users sometimes ignore: ecological compatibility. The final section adds marketability, an issue of concern primarily to suppliers; it includes considerations of institutional acceptability and profitability not included in user or societal objectives.

TABLE 2.1
OVERALL OBJECTIVES FOR ELECTRIC VEHICLES

For Users:	Utility
	Durability
	Economy
	Safety
	Amenity
	Pleasurability
For Society:	Ecological Compatibility
For Suppliers:	Marketability

Standards relevant to these objectives are outlined and discussed, objective by objective, in Sec. 2.3. Since completeness is important, and both private and commercial vehicles are under consideration, not every standard from the lists of Sec. 2.3 is necessarily appropriate for every vehicle. For each standard listed, a characteristic is suggested except where quantification is impractical, or where a design standard is introduced and a simple equipment requirement is suggested. In most cases, there are alternative possible characteristics relevant to a given standard; those listed appeared both easy to measure and accurately descriptive of the vehicle quality or attribute in question.

Because emphasis is on performance standards, numerous commonplace design standards do not appear in the following pages. These include vehicle mass, battery type, battery mass, motor mass, motor power, controller type, transmission type, and many others. This is entirely intentional. The performance standards offered instead suffice to ensure that satisfactory vehicles are describable. The builder or

developer is deliberately left free to select and demonstrate the design parameters he considers best for meeting or exceeding these performance standards.

2.3 CATEGORIES OF STANDARDS

Utility

Table 2.2 categorizes and defines standards for a vehicle's utility in performing its basic function: moving its payload through urban or rural areas. Performance and payload standards are intended to assure that in normal operation, the vehicle can transport sufficient passengers and cargo in representative driving conditions without impeding traffic. Range standards, stated separately because of their crucial importance for electric vehicles, are intended to assure sufficient total movement capability between recharges. Driveability standards are intended to assure that only reasonable demands are made on the driver. Handling standards are intended to assure responsiveness to lateral control. Operability standards are to ensure adequate functioning in adverse conditions which may arise occasionally. Rechargeability standards are to ensure rechargeability from electric outlets ordinarily available in representative recharging situations. Finally, a set of equipment standards assures devices (and capabilities) often taken for granted in conventional vehicles.

Since utility refers to basic function, the niceties of passenger and cargo accommodations are treated subsequently under standards for amenities. Similarly, performance under abnormal conditions such as collisions is considered under standards for safety.

Durability

Standards for durability are categorized and tabulated in Table 2.3. These standards are intended to ensure that the vehicle performs its basic function for a long period of time with little routine maintenance, infrequent failures, and low downtime. Because they may pose special problems, batteries and other electric drive components are singled out for special attention. A design standard is suggested for vehicle life because of the impracticality of verifying a performance standard.

Economy

Standards for economy are categorized and tabulated in Table 2.4. It is assumed that the vehicle owner will also own the propulsion battery; if not, battery cost standards would be replaced by a lease cost standard. The life-cycle cost standards single out those aspects of electric vehicle costs which may significantly differ from conventional vehicle costs. In addition, they include a total life-cycle cost figure, since it is this (together with life-cycle benefits) which eventually determines whether the electric vehicle is cost-effective.

TABLE 2.2
STANDARDS FOR UTILITY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Performance	Acceleration	Time to travel a given distance or reach to a given speed from a standing start
	Gradeability	Maximum grade on which a given speed can be maintained
	Braking	Stopping distance from a given speed
	Cruising Speed	Maximum speed regularly sustainable for a stated time
	Top Speed	Maximum attainable speed
Payload	Passenger	Number of seated passengers (including driver) accommodated
	Cargo Capacity	Mass and volume of maximum load accommodated
Range	Urban Range	Range on an urban driving cycle such as SAE J227a/C
	Constant Speed Range	Range at a constant moderate speed
Driveability	Speed Control	Number of discrete vehicle speeds selectable by driver on level road
	Steering Effort	Steering torque for a given turn and speed
	Braking Effort	Pedal force for maximum deceleration at a given speed
	Maneuverability	Minimum turn radius
Handling	Steady-State Yaw Response	Yaw gain versus speed at a given lateral acceleration
	Transient Yaw Response	Yaw velocity versus time for a given steering input
	Steering Returnability	Time for yaw velocity to decay after release of steering wheel during a given maneuver
	Steady-State Lateral Acceleration	Lateral acceleration attainable in a given turn at a given speed

Table 2.2 (cont.)

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Operability	Adverse Weather	Extremes of temperature, humidity, and precipitation ranges within which vehicle shall be operable
	Vital Accessories	Length of time lights and warning signals are operable following complete discharge of the propulsion battery in stated driving conditions.
Rechargeability	Full Charge	Time for full recharge from a given ac supply after a specified discharge
	Charge Control	Automatic charging initiation and termination
	Charge Compatibility	Harmonic and reactive components of current drawn by charger
Equipment:	Headlights	Design requirement.
	Brake Lights	"
	Running Lights	"
	Backup Lights	"
	Warning Lights	"
	Interior Lights	"
	Speedometer	"
	Odometer	"
	Ammeter	"
	Voltmeter	"
	State-of-Charge Meter	"
	Windows	"
	Wipers	"
	Washers	"
	Rearview Mirrors	"
	Defroster	"
	Horn	"
	Turn Signals	"
	Sunshades	"
	Reflectors	"
	Backup Warning (Commercial vehicles)	"

TABLE 2.3

STANDARDS FOR DURABILITY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Longevity	Battery Life Cycle	Number of deep-discharge cycles before excessive loss of capacity
	Battery Service Life	Number of years battery can support a representative given daily drive
	Vehicle Life	Design Standard
	Engine Life ^A	Distance or time between overhauls
Reliability	Vehicle Reliability	Mean time between failures in representative daily driving
	Electric Drive Reliability	Mean time between failures of battery, controller, or motor in representative daily driving
	Hybrid Drive Reliability	Mean time between failures of engine and associated mechanical drive
	Charger Reliability	Mean time between failures of battery charger in representative daily use
Maintainability	Battery Maintenance	Frequency and amount of routine maintenance activity
	Motor-Controller Maintenance	Frequency and amount of routine maintenance activity
	Engine Maintenance [*]	Frequency and amount of routine maintenance activity
	Other Vehicle Maintenance	Frequency and amount of routine maintenance activity
Repairability	Drive Repairability	Times required to replace engine, battery, motor, or controller
	Vehicle Repairability	Times required to replace other equipment (transmission, U-joints, brake cylinders, brake linings, fenders, etc.)

^A Hybrid vehicles

TABLE 2.4

STANDARDS FOR ECONOMY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Initial	Vehicle Cost	Sticker price.
	First Battery Cost	Sticker price
Life-Cycle Cost	Battery Replacement Cost	Price of replacement battery with trade-in allowance
	Battery Replacement Labor	Hours required to replace battery
	Routine Maintenance Cost	Estimated price of parts and labor for recommended maintenance, per unit travel
	Energy Cost	Price of energy required per unit of travel under typical conditions
	Life-Cycle Cost	Estimated life-cycle cost per unit of travel including all expenses of ownership and operation.

Safety

Standards for safety are categorized and tabulated in Table 2.5. Since this field is thoroughly covered by current and projected Federal Motor Vehicle Safety Standards (FMVSS), individual standards and characteristics are detailed in Table 2.5 only to deal with safety conditions peculiar to electric vehicles. All major categories of protection, however, are included in the table for the sake of completeness.

Standards for safe electrical propulsion in Table 2.5 include an overload warning system to enable the driver to avoid damage to the electric drive itself, plus provision for minimization of electric-drive hazards such as shock, explosion, corrosion, and runaway. One peculiar hazard of electric drive systems is that failures frequently do not stop or stall the motor, but lead to uncontrolled full-power or full-torque output instead. The "panic switch" standard provides a last resort in the event of runaway.

Amenity

Standards for amenity are categorized and tabulated in Table 2.6. Those contributing to comfort describe the driver or passenger environment within the vehicle. Both a performance standard and a design standard are offered for heating; to minimize heating energy, it may be preferable to employ seat and radiant heating rather than air heating as is customary in conventional cars, but the performance of such heating is very difficult to measure quantitatively. Standards contributing to convenience are also slated in terms of design rather than performance, again because performance standards are difficult to define.

Pleasurability

Standards for pleasurability are categorized and tabulated in Table 2.7. Pleasurability, the last and least tangible objective of standards primarily impacting the user of the vehicle, refers to the ability of the vehicle to induce pleasure. This ability cannot be ignored, since for fifty years it has been a primary factor in automotive design, advertising, and sales. It seems feasible to describe, even with design standards, only the few dimensions of pleasurability categorized in Table 2.7. There are many others, of course: novelty, status, prestige, freedom, power, and opportunity are among the pleasurable sensations invoked by or attributed to automobiles.

Ecological Compatibility

Standards for ecological compatibility are categorized and tabulated in Table 2.8. These standards are of primary concern to society rather than individual users, since the individual user by his actions alone cannot change the ecological balance. They cover the most important

TABLE 2.5

STANDARDS FOR SAFETY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Accident Avoidance	(Safety Design)	(FMVSS 100 series)
	Automatic Braking	Deceleration when foot removed from accelerator
Occupant Protection	(Safety Design)	(FMVSS 200 series)
	(Crash Protection)	(FMVSS 208)
	(Flammability)	(FMVSS 300 series)
	Fuel Tank Integrity *	(FMVSS 301)
Pedestrian Protection	Impact Control	(Possible FMVSS)
	Pedestrian Retention	(Possible FMVSS)
Property Protection	Theft Protection	(FMVSS 114-115)
	Damage Limitation	(FMVSS 215)
Electrical System Hazard Control	Shock Avoidance	(Design standard: insulation, electrical interlocks, and grounding)
	Explosive Gases	(Design standard: battery, cell caps, and battery compartment ventilation)
	Corrosive Vapors	(Design standard: battery, cell caps, gas exhaustion, enclosure)
	Dangerous Materials	Escape of Corrosive, explosive, toxic, or heated material from battery in specified crashes
	Circuit Protector	Maximum current flow from battery
	Panic Switch **	(Design standard: controls including master disconnect independent of all other wiring devices)
	Overload Warning	(Design standard: warning device to show that motor, controller, or battery is overloaded)

* Hybrid vehicles and electric vehicles with petroleum fueled heaters.

** Not required on vehicles with manual clutches.

TABLE 2.6

STANDARDS FOR AMENITY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Comfort	Seating	(Design standard for dimensions, padding, upholstery, adjustability)
	Ventilation	Exterior-to-interior airflow volume and distribution
	Heating & Cooling	Interior temperature under given conditions; or design standard for coat heating
	Air Conditioning	Interior temperature and humidity under given summer driving conditions
	Noise	Interior noise levels under given driving conditions
	Ride Quality	Occupant vibrational acceleration amplitude versus frequency under given driving conditions
Convenience	Accessibility	(Design standard for door sizes and handles)
	Charger Connection	(Design standard for recharger cord deployment, storage, and connectors)
	Glove Box	(Design standard)
	Ash Trays	(Design standard)
	Window Operation	(Design standard)
	Clock	(Design standard)
	Trip Odometer	(Design standard)
	Instrument legibility	(Design standard)
	Vision	(Design standard)
	Luggage Space Access	(Design standard)
	Spare Wheel & Jack	(Design standard)

TABLE 2.7

STANDARDS FOR PLEASURABILITY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Style	Body Style	(Design standard)
	Color	(Design standard)
	Trim	(Design standard)
	Styling	(Design standard)
Luxury	Upholstery	(Design standard)
	Carpets	(Design standard)
	Paneling	(Design standard)
Entertainment	Radios (AM,FM,CB)	(Design standard)
	Tape Deck	(Design standard)
	EMI Noise	EMI noise picked up by radio from propulsion system

TABLE 2.8

STANDARDS FOR ECOLOGICAL COMPATIBILITY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Energy	Propulsion Energy	Energy input to the recharger and fuel tank per unit of specified driving schedule
	Manufacturing Energy	Energy required to extract, transport, fabricate, and deliver materials, components, and the completed vehicle
	Recycling Energy	Energy required to recycle or dispose of vehicle materials
Materials	Inventory	(Design standard: maximum allowable content per vehicle of such materials as lead, antimony, nickel, titanium, lithium, and rare earths)
	Recyclability	(Design standard: maximum allowable content per vehicle of materials unsuited for recycling)
Emissions	Air Pollutants	Maximum emissions in the EPA city driving cycle of hydrocarbons, carbon monoxide, nitrogen oxides, ozone, sulphates, and other noxious materials
	Noise	Noise power levels for specified driving and measurement conditions
	Electromagnetic Interference (EMI)	Power spectral density of electromagnetic radiation from the operating vehicle

aspects of energy use, materials use, and objectionable emissions. Air pollutant emissions are already governed by Federal and state standards, but for the pure electric vehicle, much more stringent goals and criteria may be appropriate. Moreover, there is the possibility of emission species not covered by existing standards, such as ozone and sulfate or sulfuric acid.

Marketability

Standards for marketability are categorized and tabulated in Table 2.9. These involve factors important to the commercial success of electric vehicles which have not already been treated in relation to user or societal objectives. They include institutional acceptability (which is not necessarily congruent with societal interests), service availability during and beyond a warranty period, profitability to dealer, ability to use improved batteries, and potential of the design to grow into models with new capabilities.

TABLE 2.9

STANDARDS FOR MARKETABILITY

<u>Category</u>	<u>Standard</u>	<u>Description</u>
Institutional Acceptability	Licensability	Licensable in all states of the US
	Insurability	Acceptable to a reputable insurance company for liability and collision damage insurance at stated rates
	Financeability	Acceptable to a major lending institution for financing on stated terms
Supportability	Service Availability	Commitment of suppliers to offer parts and skilled labor for stated periods in stated places
Warranty	Warranty	Guarantee of manufacturer/dealer to provide parts and labor for certain adjustments and repairs needed in a stated period
Profitability	Dealer Markup	Percent increase from dealer cost to sticker price
Growth Potential	Versatility	(Design standard: adaptability of design to other body styles, capacities, and intended functions)
	Upgrading	(Design standard: adaptability of design to improved materials, battery systems, motors, and controllers, transmissions, and other components improving performance)

3 ANALYTICAL RELATIONSHIPS FOR ELECTRIC VEHICLES

Published performance goals and test data are presented in varying formats. For example, one reference may give an acceleration goal of 30 km/h in 3 s, while another may have 40 km/h in 6 s. One reference reporting test results may give a range in a given cycle with a payload of 300 kg, while another similarly-sized vehicle is reported to have a particular range in the same driving cycle, but with a 75 kg payload. Even more difficult to compare are results over different driving cycles. In this case, one cannot be certain of comparability even if the energy requirement per kilometer is equal for the two cycles, because the battery output is very sensitive to power density.

To deal with these types of comparability problems, scaling and simulation have been employed. The purpose of this section is to develop the equations used in scaling and simulation. Most of these relationships are neither original nor difficult to derive. However, several of the equations developed for range and operating cost are quite useful, and are believed to be original.

3.1 ACCELERATION

Acceleration is almost always included among performance goals and test results; but several formats are used. Most often, a speed-time pair is given; less frequently distance-time or speed-distance is presented.

An accurate analytical representation of acceleration (or velocity as a function of time) is readily derived, but the data required to apply such a representation to a particular car exceeds the data available in almost every instance. However, for scaling purposes the following simplified approach has proven very useful for maximum acceleration from rest. Neglecting drag and assuming constant power delivered to the wheels* results in

$$M_V \frac{dV}{dt} V = P_W \quad **$$

which can be integrated directly to give

* For vehicles with separately excited motors, the constant-power assumption is very good. For series-connected motors, it is only an approximation, but is still very useful for scaling.

** See Appendix A for the definition of symbols used in this report.

$$V^2 = 2P_W t / M_V \quad (3.1)$$

For a given vehicle, P_W and M_V are fixed, so t scales as V^2 . Thus a vehicle which takes 20 seconds to reach 60 km/h could reasonably be expected to reach 50 km/h in 13.9 seconds. Scaling to or from very low speeds or up to high speeds should be done with caution. The former may be in error because Eq. 3.1 implies infinite acceleration at $t = 0$. Scaling to high speeds may be in error because aerodynamic drag has been neglected, and the motor/gear combination may be such that the constant-power assumption is seriously violated.

Distance as a function of time is obtained by solving Eq. 3.1 for V and integrating, which gives

$$S = \left(\frac{8P_W}{9M_V} \right)^{1/2} t^{3/2} \quad (3.2)$$

Thus the vehicle used in the above example would travel 129 m in 13.9 s and 222 m in 20 s.

3.2 GRADEABILITY

Gradeability, the maximum grade at which a given speed can be maintained, is not generally measured directly. Rather, data from the acceleration test is used to infer gradeability.¹ This approach results in

$$\sin \theta = \dot{V} / g \quad (3.3)$$

where $\dot{V}$ is the maximum acceleration attainable at speed V on level ground. If a plot of $\dot{V}$ versus V is available from tests, $\dot{V}$ can be determined as a function of speed and Eq. 3.3 can be used to determine gradeability for various speeds. However, the V - $\dot{V}$ relationship is usually not available, particularly for vehicles where only performance goals are given. In these instances, the approach of Sec. 3.1 can be used to obtain two relationships useful for scaling and estimating gradeability.

First, if gradeability for one speed is known (θ_1, V_1),

$$\sin \theta = V_1 \left(\frac{\sin \theta_1}{V} \right) \quad (3.4)$$

Second, if only acceleration is known ($\dot{V}_1$ in t_1),

$$\sin \theta = \frac{V_1^2}{2gt_1V} \quad (3.5)$$

Equations 3.4 and 3.5 are subject to the same caveats as Eqs. 3.1 and 3.2. Note that Eq. 3.5 has the same functional dependence upon V as Eq. 3.4 and is really only another form of Eq. 3.4.

3.3 MAXIMUM SPEED

Accurate estimation of maximum speed requires data on the losses, motor, gearing, and battery. However, a simple calculation is easily made and is often useful. In addition to acceleration data (a V - t pair), an estimate of the vehicle drag-area product is required. Equating the power available at the wheels as determined from the acceleration data to the aerodynamic drag power, and solving for V_{MAX} , yields

$$V_{MAX} \approx \left(\frac{M_V V_1^2}{t_1 \rho C_D A} \right)^{1/3} \quad (3.6)$$

Since tire and gear friction are neglected in Eq. 3.6, it usually predicts a V_{MAX} which is too high. Also, if the motor cannot deliver full power at higher vehicle speeds because of a limited gear ratio, Eq. 3.6 will predict a too-high V_{MAX} (assuming the V_1 - t_1 pair is chosen for a speed at which full motor power is developed).

Appendix B compares results using Eqs. 3.4-3.6 with test data for two electric vehicles.

3.4 RANGE

The critical issue for near-term electric vehicles is range. This will continue to be the case until substantially better batteries are developed. The purpose of this section is to develop a closed-form analytic equation for range which can be used for scaling purposes and to illuminate the effects on range of the main parameters of the vehicle system:

- Battery specific energy density
- Battery mass ratio (battery mass/gross vehicle mass)
- Vehicle friction losses (rolling, viscous, and aerodynamic)
- Motor-driveline-controller efficiency
- Gross vehicle mass

Figure 3.1. Power and Energy Densities of Representative Batteries

There are four key elements of analysis which are introduced in this section. First is the method of representing battery specific power density as a function of discharge time. Second is the representation of battery discharge, which we call the Fractional Utilization Model. Third is the range parameter, k_1 , a figure of merit for a given electric vehicle which is essentially independent of the type of battery used and the gross vehicle mass. Fourth is the equation for range in a specific driving cycle as a function of just three elements: the range parameter, the battery mass fraction, and the battery (primarily the specific energy density, but also a measure of the relationship between specific energy and specific power).

The key to developing the range model is the representation of the battery; the vehicle dynamics and the driveline, motor, and controller subsystems are relatively straightforward to handle. One problem with battery models is that some of them require data which are difficult to obtain, or to estimate for batteries which have yet to be developed. The data most readily available, particularly for advanced batteries, are (estimates of) the specific energy and power densities. Usually power density is plotted versus energy density on log-log paper, producing the familiar curve with a pronounced knee, as shown in Fig. 3.1.² However, if power density is plotted as a function of available discharge time, the resulting curve is more nearly linear on log-log paper. Such curves for the batteries represented in Fig. 3.1 are shown in Fig. 3.2. The relationships of power density to time shown in Fig. 3.2 are well described by an equation of the form

$$\log P_D = \log P_1 + b \log \tau + c(\log \tau)^2 \quad (3.7)$$

The significant aspect of Fig. 3.2 is that all of the curves have about the same slope.* As will be shown, this slope plays an important part in range and cost estimates.

Because the discharge rates of electric-vehicle batteries fall within a relatively narrow range, the last term in Eq. 3.7 can be dropped with little loss in accuracy.** When this is done, P_D takes on a particularly simple form:

$$P_D = P_1 \tau^b \quad (3.8)$$

* Data for other lead-acid batteries are given in Appendix C.

** This term is included in the computer simulation that was used in analyzing test data (Sec. 5), but is dropped in what follows.

Figure 3.2. Power Density of Representative Near-Term and Advanced Batteries

Solving Eq. 3.8 for τ allows us to write specific energy density, equal to $P_D \tau$, as a function of power density:

$$E_D = P_D \tau = E_D(P_D) = P_D^{(1 + 1/b)} P_1^{-1/b} \quad (3.9)$$

We are now in a position to develop an expression for range over a specified driving schedule, using a model for battery discharge which is based upon a fractional utilization of the battery.³ Let the battery discharge rate during a small time interval be P_B . The basis of the fractional utilization model is that the increment of battery "used up" during dt is equal to the energy output of the battery divided by the specific energy density at that specific power density, i.e.,

$$dM_B = (P_B dt) / [E_D(P_B/M_B)] \quad (3.10)$$

which can be rewritten, using Eq. 3.9, as

$$dM_B = \frac{P_B dt}{3600 (P_B/M_B)^{(1+1/b)} P_1^{-1/b}} \quad (3.11)$$

[The factor 3600 appears because τ (in Eqs. 3.7 and 3.8) is in hours, while dt is in seconds.]

The battery discharge rate P_B is found from the equation of motion:

$$P_B = M_V \dot{V}(\dot{V} + C_1 + C_2 V + C_3 V^2/M_V)/\eta_{MD} \quad (3.12)$$

When Eqs. 3.11 and 3.12 are combined and the resulting equation integrated over a specific driving cycle, the battery mass used for one cycle is

$$M_{BC} = (fP_1)^{1/b} M_B/k_1 \quad (3.13)$$

where

$$k_1 = 3600/\int [V(\dot{V} + C_1 + C_2 V + C_3 V^2/M_V)/\eta_{MD}]^{-1/b} dt \quad (3.14)$$

Equation 3.12 only applies when the battery is discharging. Thus the integration in Eq. 3.14 must be interpreted carefully. If regenerative braking is not present, the integration is performed only for periods of acceleration and cruising. If regeneration is present, the period of braking must be included (when $\dot{V} < 0$), but the efficiency term η_{MD} must be moved to the numerator of the integrand since power is going from the wheels to the battery. Actually, there is evidence that the amount of energy that can be withdrawn from the battery increases when regeneration is used by an amount greater than the regeneration energy returned to the battery, as reported by Rippel^{4*} and Menga.⁵ The net effect of this phenomenon, which is probably related to polarization and sulfation, is to slightly increase the charge-discharge efficiency of the battery. For our purposes, data in Rippel's report indicates that this effect, which we call the regenerative utilization factor, increases the effect of that portion of energy returned during regeneration by about 50 percent over what would normally be expected. This factor must be included with η_{MD} in the numerator of the integrand, as mentioned above. This effect is discussed more fully in Appendix D.

The number of cycles which can be driven is assumed to be the ratio of battery mass to the mass of battery used for one cycle, M_{BC} . Thus

* W.E. Rippel was a consultant to General Research Corporation for this study.

$$R = k_1 R_C (f P_1)^{-1/b} \quad (3.15)$$

The factor b is -0.734 ,^{*} so the exponent in Eq. 3.15 is 1.36. Note in Eq. 3.14 that if η_{MD} were constant, it could be factored out and would appear in the same relationship as f and P_1 , i.e., to the $(-1/b)$ th power. (With regeneration, the situation is more complicated, but basically range is still proportional to $\eta_{MD}^{-1/b}$, if η_{MD} is relatively constant during battery charge and discharge.) Note also that k_1 is weakly dependent on M_V since C_3 includes the vehicle frontal area which scales as $M_V^{2/3}$. However, as long as M_V is not greatly different from the value used to determine k_1 , Eq. 3.15 is accurate.

Parameter k_1 is a measure of the range capability of a given vehicle for a specific driving schedule. It is independent of the battery used (to the extent that the exponent in Eq. 3.15 is the same for different batteries), and of the battery fraction, and only weakly dependent upon gross vehicle weight. It can be argued that two of the factors upon which k_1 does depend--tire friction and motor-driveline efficiency--really are dependent upon gross vehicle weight and therefore k_1 cannot be treated as a constant. However, in Sec. 5, we show data for existing vehicles which indicate that there is no discernible trend with gross vehicle weight within the range of interest. Thus Eq. 3.15 turns out to be a very useful relationship.

There is evidence, based on preliminary tests at Jet Propulsion Laboratory of EV-106 batteries discharged with current profiles based on the J227a schedule (B, C, and D), that the fractional utilization battery model upon which Eq. 3.15 is based is conservative, i.e., predicts less range than is actually achieved (see Appendix E). This is not surprising, since the model makes no allowance for recuperation during the periods of no current drain (during 44 s out of 122 s of the J227a/D cycle there is no current). Thus Eq. 3.15 should be conservative. However, because we seldom have the data required (particularly the motor-driveline efficiency as a function of load and speed) to evaluate k_1 directly (by Eq. 3.14), it is usually determined from Eq. 3.15. That is, knowing the range (from tests), R_C , f , and P_1 allows determination of k_1 . Done in this manner, the under-prediction of the fractional utilization model is corrected by a k_1 which is slightly too high. This procedure allows us to use Eq. 3.15 to determine the effect on range of changes in battery fraction (f), power density (P_1), and vehicle gross mass ($f = M_B/M_V$).

* This value applies to the ESB EV-106 golf-cart battery in the one to two hour discharge region. The ESB EV-106 is representative of present electric vehicle batteries. As can be seen from Fig. 3.2, the slope (and thus b) for other batteries is similar. Specific power-discharge time relationships for other lead-acid batteries are given in Appendix C.

3.5 COST RELATIONSHIPS

For a given driving schedule, the initial battery cost is amortized over its useful life of N_C discharge cycles. The normalized (on a per-unit-mass and per-unit-distance basis) amortization cost is the initial cost of the battery divided by the total range driven over the N_C cycles. Thus, using Eq. 3.15

$$C_K = C_B f / (N_C R) = C_B f^{(1+1/b)} P_1^{1/b} / (k_1 N_C R_C) \quad (3.16)$$

The normalized electricity cost is given by

$$C_E = k_2 C_W / (\eta_C \eta_B) \quad (3.17)$$

where

k_2 = normalized battery energy output over the driving cycle, kJ/(kg·km)

$$= \frac{1}{R_C} \int \frac{V(V + C_1 + C_2 V + C_3 V^2 / M_V)}{\eta_{MD}} \quad (3.18)$$

(The same rules apply to evaluating k_2 as apply to calculating k_1 , defined by Eq. 3.14.)

The operating cost per unit distance traveled per unit vehicle mass is the sum of the battery amortization and electricity costs. To this must be added maintenance, vehicle depreciation, finance, parking and tolls, insurance, and taxes to get life-cycle costs.

4 REVIEW OF PERFORMANCE GOALS FOR ELECTRIC VEHICLES CONTAINED IN LITERATURE

A review of the literature produced 24 papers in which performance goals for electric vehicles are given. Different formats and degrees of completeness make it necessary to recast some of the goals in a different format to facilitate comparison.*

This section is divided into three parts. Section 4.1 defines our use of four terms which are used with various meanings in the references: goals, objectives, criteria, and characteristics. Section 4.2 presents the data on goals obtained from the 24 papers. Section 4.3 compares published goals with theoretical goals based on 1976 and 1980 battery technology.

4.1 DEFINITIONS

In discussing electric vehicles, the words "goals," "objectives," "criteria," and "characteristics" are often used interchangeably. For the purposes of this study, however, the following definitions will apply:

- Characteristics are quantitative, measurable descriptors, e.g., speed, range.
- Criteria are minimum or maximum acceptable values of characteristics, e.g., minimum speed of 60 km/h on the level.
- Goals are desired values of characteristics.
- Objectives are qualitative aims, e.g., high materials recyclability, safety, low initial cost, etc.

4.2 PUBLISHED PERFORMANCE GOALS

Performance goals vary with the intended application of the vehicle. To categorize the vehicles studied, we used the six classes of electric vehicle applications designated in an earlier study,⁶ as follows:

- Utility car -- a subcompact, low-price, low-performance electric vehicle for urban use (e.g., a vehicle the size of a two-passenger Honda 600, but with less performance and shorter range)
- Commuter car -- an electric vehicle competitor to the ICE compact (e.g., Pinto)

* For example, one reference had an acceleration goal of 335 feet in 10 seconds. Using a method described in Sec. 3, this is shown to be equivalent to reaching 55 km/h in about 10 seconds.

- Family car -- an electric vehicle competitor to the ICE standard sedan (e.g., Impala)
- Delivery van -- an electric vehicle suitable for short-range urban deliveries (e.g., milk truck, telephone repair van, postal delivery van)
- Taxi -- an electric vehicle for short-range urban commercial passenger transportation
- Bus -- a large electric vehicle suitable for urban passenger transportation

In compiling the data, the goals were converted into consistent units. However, many of the data are difficult or impossible to compare, because they are presented for different performance criteria. The acceleration and gradeability goals were scaled to comparable criteria using the methods summarized in Sec. 3.

The values for acceleration, in terms of maximum speed attainable within various times, were scaled into maximum speed attained after 10 seconds. Similarly, the gradeability values were scaled to maximum velocity on an 11-percent grade (the maximum grade normally found on good mountain roads).⁷

The maximum range of the electric vehicle is dependent on the choice of battery and its energy density. Almost all of the published range goals were established by considering the capabilities of the lead-acid battery, rather than general goals for the several types of electric vehicles. The exceptions are the ADL goals published in 1969,⁶ which do not consider battery limitations, and some commuter-car goals published by Argonne National Laboratories in 1976,⁸ based on future lithium/iron-sulfide batteries.

The various range goals are specified for many different driving cycles. Some are based on constant velocities, but with no common value; in some cases, no velocity is given. Others are given for an inadequately described driving cycle. An attempt was made, using an electric vehicle simulation based on the approach described in Sec. 3, to scale these given range goals into some comparable format (e.g., range at a constant 48 km/h). However, because of the lack of detailed data, this effort was generally unsuccessful.

The energy consumption goals are presented for total energy used, including battery charger losses. The payloads are given in number of passengers for the cars, taxis, and buses, and net payload weight for the delivery van. When not specified, the passenger weight is assumed to be that of a 50th percentile male (68 kg) in accordance with FMVSS 110.

The remaining goals, such as safety, cost, reliability, and maintenance, are included as "other" under "characteristics."

Five examples were found which best fit into the utility car category. Goals for these vehicles are shown in Table 4.1. Each column is headed by a reference number, an abbreviation of the country of origin and company, and the year in which the report was published, or if specified, the year in which the goals were to be met. Entries omitted in the table were not given in the report reviewed.

Twelve sets of commuter car goals are shown in Table 4.2. The scaled acceleration goals are remarkably similar for seven of the twelve. Much less agreement is shown for the other characteristics.

Only two examples were found which fit into the family car category; they are shown in Table 4.3.

Goals for fifteen delivery vans are shown in Table 4.4. In contrast with the rather close agreement shown in Table 4.2 for commuter cars, Table 4.4 exhibits a much wider spread for every characteristic reported.

Tables 4.5 and 4.6 include the published goals for taxis and buses, respectively.

In regard to meeting the Federal Motor Vehicle Safety Standards (FMVSS), Refs. 6, 10, 12, 13, and 27 indicated the FMVSS or equivalent to be one of their objectives. References 9 and 15 (GMC and Ford) noted that their vehicles would not meet the FMVSS.

Cost was mentioned as a goal in only four instances: Reference 10, \$2977 for the commuter car, in 1973 dollars; Reference 12, less than \$5000 in 1975 dollars; Reference 17, 1.25 times the equivalent ICE vehicle cost; and Reference 27, \$5600). Reliability and maintainability goals were never quantified, and only mentioned occasionally.

The specific rationale used in selecting the goals is given in only a few of the references. However, these rationales, when stated, include the following:

- Utility Car: Acceleration (48 km/h in 10 s) should at least equal 1954 Volkswagen (30 hp), and is required to maintain an acceptable traffic flow rate through a light-controlled intersection.¹⁰
- Commuter Car: Acceleration (64 km/h in 10 s) is minimum for merging into freeway traffic.¹² For gradeability, it should be noted that to maintain minimum freeway speed (64 km/h) on a maximum freeway grade (6 percent) requires a capability of maintaining 35 km/h on an 11-percent grade.

TABLE 4.1
PERFORMANCE GOALS FOR UTILITY CARS

	<u>6/USA</u> <u>ADL</u>	<u>9/Jpn</u> <u>Govt</u>	<u>10/Jpn</u> <u>Govt</u>	<u>11/USA</u> <u>GMC</u>	<u>12/USA</u> <u>GRC</u>
Year Report Published:	1969	1969	1977	1976	1974
<u>Characteristic</u> ^(A)					
Acceleration, V in t					
Reported	48/10	30/4	40/7	48/20	48/10
Scaled (V in 10 s)	48	47	48	34	48
Gradeability, % at V					
Reported	*	*	12.3/40	5/24 (20% max)	
Scaled	30 ^(E)	29 ^(E)	44	13	30 ^(E)
Range, R at V	80/*	140/40	*	40 ^(B)	56 ^(C) (132/48)
Maximum Speed, km/h	105	80	80	72	72
Payload, No. Passengers	2	2 ^(D)	4	2	2
Gross Vehicle Mass, kg	771	1000	1622	*	953
Battery Fraction, % GVM	*	30	30	*	26
Energy Consumption, MJ/km	*	*	*	*	1.58 ^(C)
Other				Does not meet FMVSS	Does meet FMVSS

- A. V is velocity in km/h; t is time in seconds; R is range in km.
 B. For an undefined central business district cycle.
 C. SAE J227 Residential Cycle (see Appendix G).
 D. Two passengers + 100 kg, or four passengers.
 E. Calculated using Eq. 3.5.

* Not specified

TABLE 4.2

PERFORMANCE GOALS FOR COMMUTER CARS

	References											
	6/USA ADL	9,13/Jpn Govt	10/Jpn Govt	11/USA GMC	14/USA AMF	12/USA GRC	15,16/USA CDA	17/USA Ford	18/USA A-C	19/USA EVC	8/USA ^(G) Argonne	
Year Report Published:	1969	1973	1977	1976	1976	1974	1975	1974	1971	1971	1978 ^(J)	1981 ^(J)
<u>Characteristic</u> ^(A)												
Acceleration, V in t												
Reported	97/30	30/3	40/6	72/30	43/7.8	64/10	50/12	102 ^(E)	96/30	48/30	64/15	89/15
Scaled (V in 10 s)	56	55	52	42	54	64	46	55	55	28	52	73
Gradeability, % at V												
Reported	*	10.5/40	12.3/40	5/24 (20% max)	5/45 (30% max)	10/75	30% max	*	*	*	*	*
Scaled, V at 11%	41 ^(I)	38	44	13	24	69	27 ^(I)	39 ^(I)	40 ^(I)	10 ^(I)	35 ^(I)	68 ^(I)
Range, R at V	161/*	190/40	*	80 ^(B)	72 ^(C)	87 ^(C) 294/48	110 ^(D) 190/65	50 ^(D) 63/64	96/96	32/80 80/32	171 ^(G,H) 600/40	254 ^(G,H) 975/40
Maximum Speed, km/h	129	80	80	97	105	105	90	129	120	80	97	129
Payload, No. Passengers	4	5	4	2	4	4	2	2	4	1 ^(F)	2	2
Gross Vehicle Mass, kg	1225	2000	1772	--	1663	1804	1393	1452	--	--	1136	1136
Battery Fraction, % GVW	--	<30	<30	--	36	38	33	30	--	--	31	31
Energy Consumption, MJ/km	--	--	--	--	2.5 ^(C)	2.5 ^(C)	--	--	--	--	--	--
Other	--	--	--	Does not meet FMVSS	Meet FMVSS <\$5000 '75\$	Meet FMVSS 2977 '73\$	Meet FMVSS	Does not meet FMVSS	--	Cost < ICE + 25%	Meet "required" safety standards	

NOTES:

- A. V is velocity in km/h; t is time in seconds; R is range in km.
 B. Undefined "suburban" driving cycle.
 C. SAE J227 Metropolitan Cycle (Appendix H).
 D. Undefined "city" driving cycle.
 E. 102 meters in 10 seconds.
 F. Plus 227 kg payload.
 G. Lithium/Iron Sulfide Batteries.
 H. SAE J227 Residential Cycle (Appendix G).
 I. Calculated using Eq. 3.5.
 J. Year goals to be met.

* Not specified

TABLE 4.3

PERFORMANCE GOALS FOR FAMILY CARS

	<u>6/USA</u> <u>ADL</u>	<u>11/USA</u> <u>GMC</u>
Year Report Published:	1969	1976
<u>Characteristic</u> ^(A)		
Acceleration, V in t		
Reported	97/15	72/30
Scaled (V in 10 s)	79	42
Gradeability, % at V		
Reported	*	5/24 (20% max)
Scaled, V at 11%	81 ^(C)	13
Range, R at V	322/*	120 ^(B)
Maximum Speed, km/h	161	97
Payload, No. Passengers	6	4
Gross Vehicle Mass, kg	1996	*
Other		Does not meet FMVSS

NOTES

- A. V is velocity in km/h; t is time in seconds; R is range in km.
 B. Undefined "suburban" driving cycle.
 C. Calculated using Eq. 3.5.

* Not specified

TABLE 4.4
PERFORMANCE GOALS FOR DELIVERY VANS

	References														
	6/USA ADL	20/Brit	21/USA CDA	22/USA EVC	23/Brit Lucas	24/Germ Bosch	9/Jpn Govt	10/Jpn Govt	11/USA GMC	25/Brit Chloride	25/Can Quebec	27/Germ VW	28/Ital Fiat	13/Jpn Toyota	29/USA USPS
Year Report Published:	1965	1972	1973	1971	1976	1972	1973	1977	1976	1976	1976	1976	1973	1976	1975
<u>Characteristic (A)</u>															
Acceleration, V in t															
Reported	64/20	8 ^(I)	48/14	40/10	48/10	>Diesel	30/5	40/9	48/15	45/20	*	50/15	30/7	*	48/20
Scaled, V in 10 s	45	25	41	40	48	*	42	42	39	32	*	41	36	*	34
Gradeability, % at V															
Reported	*	*	*	*	*	7/40 ^(C)	10.5/40	12.3/40	5/24 20 max	17 max	*	7/35 16 max	16 max	*	10/16 ^(G)
Scaled, V at 11%	27 ^(K)	*	21 ^(K)	21 ^(K)	30 ^(K)	27	38	44	15	13 ^(K)	*	24	17 ^(K)	*	15
Range, R at V	96/*	56 ^(E)	151/64	64 ^(B)	121 ^(F)	51/*	145-193 /40	160-225 /40	80 ^(D)	64/*	120/*	*	50 ^(E)	45 ^(E) 90 ^(F)	32 ^(H)
Maximum Speed, km/h	90	105	80	72	80	74	70	70	86	64	*	70	55	60	53
Payload, kg	1134	*	454	590	750-1250	*	300-1100	300-1100	454	2080	550	*	446	486	306
Gross Vehicle Mass, kg	3175	2722	2722	*	*	*	1100- 3500	1400- 3700	*	6250	*	4000	*	*	1950
Other	--	--	--	--	--	--	Batt 30%	--	Does not meet FMVSS	Note J	--	--	--	--	Meet FMVSS \$5600

NOTES:

- A. V is velocity in km/h; t is time in seconds; R is range in km.
- B. With five stops/mile.
- C. For 10 minutes.
- D. Undefined "suburban" driving cycle.
- E. Undefined "city" driving cycle.
- F. Unspecified "working range."
- G. For 120 m.
- H. USPO Driving Cycle, 300 stops/mile.
- I. Initial acceleration in km/h per second.
- J. Cost "low"; reliability "high"; maintenance "low".
- K. Calculated Using Eq. 3.5.

* Not specified

TABLE 4.5
PERFORMANCE GOALS FOR TAXIS

	<u>6/USA</u> <u>ADL</u>	<u>23/Brit</u> <u>Lucas</u>
Year Report Published:	1969	1975
<u>Characteristic</u> ^(A)		
Acceleration, V in t		
Reported	64/14	*
Scaled, V in 10 s	52	*
Gradeability, % at V		
Reported	*	*
Scaled, V at 11%	35 ^(D)	*
Range, R at V	241/*	161 ^(B)
Maximum Speed, km/h	124	88
Payload, No. Passengers	6	Note C
Gross Vehicle Mass, kg	1996	*
Other	--	Safety ^(C)

NOTES

- A. V is velocity in km/h; t is time in seconds; R is range in km.
- B. "Working range."
- C. Meet requirements of London Metropolitan Police Carriage Office.
- D. Calculated using Eq. 3.5.

* Not specified

TABLE 4.6
PERFORMANCE GOALS FOR BUSES

	<u>6/USA ADL</u>	<u>9/Jpn Govt</u>	<u>10/Jpn Govt</u>	<u>30/Germ Bosch</u>
Year Report Published	1969	1973	1977	1972
<u>Characteristic</u> ^(A)				
Acceleration, V in t				
Reported	48/15	30/8	30/6.2	50/20
Scaled (V in 10 s)	39	34	38	35
Gradeability, % at V				
Reported	*	10.5/25	10.5/30	16/20
Scaled (V at 11%)	20 ^(D)	24	29	29
Range, R at V	193/*	240/40	330/40	60-100 ^(B)
Maximum Speed, km/h	88	60	68	70
Payload, No. Passengers	67 ^(C)	60 80	70	--
Gross Vehicle Weight, kg	13612	15000	13600	--
Other		Batt < 30%	Batt < 30%	Batt < 30%

NOTES:

- A. V is velocity in km/h; t is time in seconds; R is range in km.
- B. "Operating range."
- C. With 68 kg/passenger (FMVSS 100).
- D. Calculated using Eq. 3.5.

* Not specified

- A small truck should have the same acceleration (41 km/h in 10 s) and gradeability (22-25 km/h on an 11-percent grade) as an equivalent diesel-powered vehicle.^{24,27}

In general, the published goals lack rationale and completeness. In a number of references, a range goal is given with no corresponding driving cycle or speed. There is no clear trend in the goals with either time or country of origin. Finally, with only a few exceptions, the battery technology assumed to derive the goals, if that method was used, is not specified.

5 REVIEW AND ANALYSIS OF RECENT ELECTRIC VEHICLE TEST DATA

This section summarizes the important data derived from a review and analysis of recent vehicle test data. Over thirty reports describing electric vehicles were reviewed to determine the state-of-the-art. From these, thirteen passenger vehicles and five light vans suitable for commercial use were selected for further analysis, primarily on the basis of test data availability.* The purpose of the review was to establish a technology baseline on which to base the near-term performance standards.

The result of the review and analysis was an assessment of how each vehicle would perform over a specific test driving cycle. Passenger vehicle performance was estimated for the SAE J227a/C driving schedule; commercial vehicle performance was estimated for the SAE J227a/B schedule.¹ Appendix G gives the details of the various J227a schedules.

The methods used to estimate each vehicle's performance over either schedule varied considerably with the type of primary data available. In order of increasing confidence, the five methods employed are described below.

First, for the majority of the vehicles considered, test data were not available for either range or energy usage on the J227a schedules. Only constant-speed ranges and basic descriptors (gross vehicle mass, battery type and mass, vehicle dimensions, etc.) were available for these vehicles. To estimate J227a range and energy usage in these instances required that we first estimate vehicle losses (tire and viscous friction, aerodynamic, and motor-controller-driveline) which were consistent with the constant-speed range data provided. Then, using a detailed electric vehicle simulation, the J227a range and energy consumption were estimated. Clearly, this procedure is not as accurate as one would like, but so few data are provided in most papers on electric vehicle performance that we had no alternative. The estimated errors in this method are ± 25 to 30 percent.

The second method of performance estimation was used when additional data on motor performance, driveline losses, and road power losses were available, but J227a test data were not included. In these instances, simulation was again used, but with the details of the various losses included. Again, simulation results were checked against the test data provided. The estimated errors in this method are ± 15 to 25 percent.

The third method was used for the few vehicles for which we were able to obtain results of road tests over the J227a schedules in which range, but unfortunately not energy usage, was measured. In these

* Vehicles for which insufficient data were available are listed in Appendix F.

instances we simulated the performance (adjusting losses until the test-measured ranges were obtained) in order to obtain energy usage. Here, the estimated errors are ± 5 to 15 percent.

The fourth method consisted of being able to use data from the report as given. The estimated errors are ± 5 to 15 percent for measured data.

The fifth method consisted of scaling test results at other conditions; this was used in some cases to estimate gradeability and constant speed range.

Table 5.1 summarizes the estimates of the accuracy of the above methods.

In most cases, the reports reviewed contained acceleration and top speed. However, the acceleration data were seldom in the format which we chose to use: time to reach 50 km/h (31 mi/h) from a standing start. Fortunately, we were able to scale the given acceleration data to the required format by using Eq. 3.1. The accuracy of this scaling technique is quite good for small changes in time and speed.

Gradeability data were not always given. The results presented here are in many cases estimates, although we were often able to scale given values to our format (the grade on which a vehicle could maintain 30 km/h steady speed, using Eq. 3.4).

Top speed was usually given. When it was not, we estimated it using Eq. 3.6.

Tables 5.2 and 5.3 summarize the results of the review of test data on private and commercial electric vehicles. Figures 5.1 and 5.2 show the relationship of range parameter k_1 and energy usage parameter k_2 (which are defined in Sec. 3) to vehicle test mass for the private vehicles. Corresponding values for commercial vehicles are shown in Figs. 5.3 and 5.4.

The overall energy economy figures shown in Tables 5.2 and 5.3 were based on the assumption that battery charge-discharge efficiency was 75 percent and battery charger efficiency was 70 percent. For comparisons among the vehicles, normalized energy usage (k_2) is more meaningful, as it essentially removes the effect of vehicle weight. Note that k_2 is based upon battery output energy, rather than on battery charger input energy. The range parameter k_1 is an inverse measure of vehicle losses (not including battery and battery charger losses); range increases with k_1 .

The computer simulation used to estimate performance also produces average driveline, motor, and motor-controller efficiencies over one

TABLE 5.1

APPROXIMATE ACCURACY OF METHODS USED FOR PERFORMANCE ESTIMATION

Symbols Used in Tables 5.2 & 5.3	Short Description	Percentage Error (+/-)					
		Acceleration	Gradeability	Top Speed	Range (Constant Speed)	Range (J227a)	Energy Consumption ^A
a	Estimate all efficiencies, tire and viscous losses, and aerodynamic drag; check simulation results against constant-speed range tests	20	25	15	5-10	25	30
b	Use detailed models for some or all of the system components; check simulation results against constant-speed range tests	15-20	20-25	15	5-10	15-20	25
c	Adjust efficiencies and losses in simulation to reproduce test ranges on J227a schedules; use simulation to obtain energy consumption	20	25	15	5	5	15
d	Test data provided	5	5	5	5	5	10
e	Scale from other test data	10	20	20	20	20	25

^AEnergy usage data appear to be less repeatable than range data. We suspect that this may be related to inadequate control of the battery charging process, which allows occasional overcharging.

TABLE 5.2

PERFORMANCE SUMMARY FOR PASSENGER VEHICLES

Vehicle:	Ford ³¹ Comuta	GM-512 ³²	Citicar ^{33,*}	Sundancer ³⁴	Fiat ³⁵	Enfield ^{36,37} 8000	Anderson ³⁸ 3rd Gen.	CDA ^{13,33,**} Town Car	Ripp- ^{4,†} Electric	Toyota ¹³ EX-1	EVA ³³ Metro	Mars ¹¹ 39,40	Electro- ⁴¹ Sport
Mass, kg													
Curb:	544	567	626	726	800	960	1143	1339	1314	1375	1429	1860	2350
Test:	703	74E	708	907	930	1121	1533	1452	1493	1667	1701	1932	2690
Battery													
Fraction: ^A	0.25	0.20	0.33	0.38	0.21	0.27	0.22	0.34	0.39	0.30	0.28	0.45	0.37
Voltage:	48	84	48	72	108	96	72	108	120	96	96	120	144
Approximate Energy Density, l-h rate, Wh/kg:	23	31	23	33	23 ^B	21	27	24	23	41	23	23	23
No. Passengers (incl. driver):	2+2 ^C	2	2	2	2	2	4	2	4	4	4	4	5
Time to Accelerate to Speed: t(s)/V(km/h)	12/48(d)	12.48(d)	30-40/48 ^H (d) 16.7/48(d)	8.3/40(c)	9/50(d)	12.5/48(d)	10/48 ^D (a)	11.8/48(d)	14/48(d)	++	16/48(d)	13.8/48(d)	12.5/48(d)
Gradeability Grade at 30 km/h, %:	11(b)	12(b)	6(d)	12(b)	18(a)	10(e)	14(a)	11(b)	14(d)	13.9(e)	11(d)	10(d)	12(b)
Maximum Speed, km/h:	>64(d)	60	48 ^H (d) 57(d)	95(d)	77(d)	64(d)	95 ^D (a)	95(d)	90-95(d)	95(d)	88(d)	89(d)	100(d)
Range, km													
50 km/h:	40(b)	86(d)	85(b)	165(d)	65(d)	75(a)	95(a)	211(d)	152(d)	143(b)	61(d)	191(d)	100(d)
70 km/h:	1	1	1	117(d)	35	1	50 ^D (a)	136(d)	114(d)	88(b)	48(d)	130(d)	75(d)
J227a/C:	37(b)	57(b)	53 ^G (b)	100(b)	47(a)	50(a)	68(a)	105(b)	110 ^F (d)	92(b)	32(d)	113(b)	64(b)
Overall Energy Usage ^F J227a/C, MJ/km:	0.79(b)	0.55(b)	0.82(d)	0.70(b)	0.72(a)	1.08(a)	1.10(a)	1.11(b)	1.11 ^E (d)	2.05(b)	2.00(c)	1.58(b)	2.33(b)

^A Battery mass/test mass^B EV-106 performance assumed for this battery, as no descriptive data were given.^C Children^D Range of 100 km at 70 km/h and a top speed of 105 km/h were listed as achieved values, but were actually design goals. Estimates given here are consistent with the technology employed.^E With regenerative braking; range without regenerative braking is 94 km and energy use is 1.28 MJ/km. Actual battery-battery charger efficiency was 0.72 with regeneration and 0.686 without regeneration, giving 0.31 MJ/km and 0.99 MJ/km for regeneration and no regeneration, respectively.^F Assumed charger efficiency is 70 percent, and battery efficiency is 75 percent. Thus, these values are referenced to the "wall."^G A range of 31 km was obtained in tests (Ref. 33), but the simulated value of 53 is used here because it is more consistent with other tests.^H The performance reported in Ref. 33 is generally poorer than that reported in personal communication. Two values shown are from Ref. 33 and personal communication, respectively.^I Not capable of required speed.^{*} D. Armstrong, personal communication, "Citicar Data and Performance Test Results," Triad Services, Inc., 23 September 1976.^{**} D. Armstrong, personal communication, "Characteristics and Performance Data--CDA Town Car," Triad Services, Inc., 6 August 1976.[†] W. Rippel, personal communication, 19 May 1977.[‡] 2.3/30(d); 14.2/200 m; 22.8/400 m.**NOTE:** The lower case letters in parentheses (a-e) refer to the estimate of error; see Table 5.1.

TABLE 5.3

PERFORMANCE SUMMARY FOR COMMERCIAL VEHICLES

Vehicle:	Jet Industries ³³ Electra-Van	Otis ³³ P-500 Van	AM General ^{*,27,42} Electruck	Battoradic ^{43,44,45} Mini-Van	Lucas ⁴⁶ Limousine
Mass, kg					
Curb:	1134	1642	1644	2520	2780
Test:	1429	2016	1950	2860	3500
Battery					
Fraction ^A	0.29	0.23	0.31	0.37	0.26
Voltage	84	96	54	112	216
Approximate Energy Density, l-h rate, Wh/kg	23	23	20	23	23
No. Passengers (inc driver)	2	2	1	2	2
Payload (inc passengers), kg	295	340	318	363	720
Time to Accelerate to Speed, t(s)/V(km/h)	17/48(d)	12.5/48(d)	20/48(d) 23.4/48(d) ^C	10.7/48(c)	14.7/50(d)
Gradeability Grade at 30 km/h, %	8(d)	17(d)	6.2(d)	10.3(e)	10(b)
Maximum Gradeability, %	--	--	14.5(d)	>30(d)	16.5(e)
Maximum Speed, km/h	70(d)	63(d)	65(d), 48(d) ^C	88(d)	89(b)
Range, km					
32 km/h	112(d)	47(d)	96(e)	113(e)	254(b)
48 km/h	72(d)	29(b)	72(e), 63(d) ^C	97(e)	163(d)
J227a/B	75(d)	40(d)	70(b), 54(d) ^C	79.4(d)	119(b)
Overall Energy Usage ^B J227a/B, MJ/km	1.13(c)	2.4(c)	1.53(b), 1.76(d)	2.45(d)	2.65(b)

^A Battery mass/test mass^B Assumed charger efficiency is 70 percent, and battery efficiency is 75 percent. Thus these values are referenced "to the wall."^C First value from Ref. 27; second value from Ref. 42.^{*} George Scharbach, personal communication, "AM General Electruck Characteristics" (included coastdown data), AM General Corporation, 11 October 1976.NOTE: The lower-case characters in parentheses (a-e) refer to the estimate of error; see Table 5.1.

Figure 5.1. Range Parameter k_1 for Private Vehicles on J227a/C Driving Schedule

Figure 5.2. Normalized Energy Usage Parameter k_2 for Private Vehicles on J227a/C Driving Schedule

Figure 5.3. Range Parameter k_1 for Commercial Vehicles on J227a/B Driving Schedule

Figure 5.4. Normalized Energy Usage for Commercial Vehicles on J227a/B Driving Schedule

driving cycle (in cases for which no detailed loss data are available, Method a in Table 5.1, these efficiencies are input constants). Tables 5.4 and 5.5 show the average combined efficiencies on the appropriate driving schedules for passenger and commercial vehicles, respectively. Based on these average efficiencies, 0.6 (for passenger vehicles on the J227a/C schedule) and 0.55 (for commercial vehicles on the J227a/B schedule) were chosen as conservative, yet representative, values to use in the hypothetical vehicle designs described in Sec. 6.

The performance summary for passenger vehicles shown in Table 5.2 is based on payloads which vary from 82 to 181 kg and from 72 to 390 kg for the two- and four-passenger vehicles, respectively. However, as shown in Sec. 3, range varies as battery fraction to about the 1.36th power ($f^{1.36}$) and energy consumption is proportional to gross vehicle weight. To allow comparison on an equal-payload basis, the acceleration

TABLE 5.4
COMBINED CONTROLLER-MOTOR-DRIVELINE EFFICIENCIES
AVERAGED OVER A J227a/C SCHEDULE FOR SELECTED PASSENGER VEHICLES

<u>Vehicle</u>	<u>Efficiency, η_{MD}</u>	<u>Comments</u>
Comuta	0.61	
GM-512	0.64	
Citicar	0.55	
Sundancer	0.75	
Fiat	0.73	
Enfield	0.56	Conversion
Anderson	0.60	
CDA Town Car	0.69	
Ripp-Electric		
with regeneration	0.63	Conversion
without regeneration	0.55	Conversion
Toyota	0.44	Torque converter with 710 W pump
EVA Metro	0.59	Conversion
Mars II	0.68	Conversion
Electroport	0.63	Conversion

TABLE 5.5
COMBINED CONTROLLER-MOTOR-DRIVELINE EFFICIENCIES
AVERAGED OVER A J227a/B SCHEDULE FOR SELECTED COMMERCIAL VEHICLES

<u>Vehicle</u>	<u>Efficiency, η_{MD}</u>	<u>Comments</u>
Electra-Van	0.65	Conversion
Otis P-500	0.54	No transmission
AM General Electruck	0.70	Conversion
Lucas Limousine	0.65	Conversion
Battronic Mini-Van	0.51	

range, and energy usage were scaled by using the following relationships. In addition, acceleration was scaled to the time required to reach 50 km/h. Results of the scaling are shown in Table 5.6.

Acceleration (based upon Eq. 3.1)

$$t' = t(M'_V/M_V)(500/V)^2$$

Range (based on Eq. 3.15)

$$R' = R(M'_V/M_V)^{1.36}$$

Energy Usage (based on Eq. 3.18)

$$E'_c = (M'_V/M_V)E_c$$

TABLE 5.6

ESTIMATED PASSENGER VEHICLE PERFORMANCE BASED ON STANDARD PAYLOADS

Vehicle	Adjusted ^A Gross Vehicle Mass, kg	Number of Passengers	Acceleration 0-50 km/h, s	Range, km		Energy Usage ^B on J227a/C, MJ/km
				J227a/C	50 km/h	
Comuta	694	2	12.9	38	41	0.79
GM-512	717	2	12.5	60	91	0.61
Citicar	776	2	19.9	47	75	0.90
Sundancer	876	2	12.5	105	173	0.69
Fiat	950	2	9.2	46	63	0.72
Enfield 8000	1110	2	13.4	51	76	1.08
CDA Town Car	1489	2	13.1	101	204	1.20
Anderson	1443	4	10.2(9.2)	74(86)	103(120)	1.08(0.97)
Ripp-Electric	1614	4	16.4(14.9)	106(121) ^C 84(97)	112(156)	1.15(1.01) 1.48(1.30)
Toyota EX-1	1675	4	6.4(5.8)	91(104)	142(161)	2.05(1.80)
EVA Metro	1729	4	17.6(16.1)	31(35)	60(68)	2.13(1.87)
Mars II	2160	4	16.7(15.6)	97(107)	164(181)	1.76(1.66)
Electroport	2650	4	13.4(12.6)	65(71)	102(111)	2.81(2.56)

^A Adjusted gross vehicle mass obtained by adding 150 kg to curb mass for 2-passenger vehicles, 300 kg to curb mass for 4-passenger vehicles.

^B Input to charger.

^C With and without regeneration, respectively.

NOTE: Values shown in parentheses are for the 4-passenger vehicles with only two passengers (150 kg).

6 REQUIREMENTS FOR ELECTRIC VEHICLES^{*}

We believe that the key questions pertaining to the initial acceptance of electric vehicles are:

- Who might buy an electric vehicle?
- What should its performance be (range, speed, operating cost^{**})?
- How many passengers should it carry?

We addressed these questions by a combination of studying available data, talking to electric vehicle dealers and one manufacturer,[†] and analyzing a limited number of electric vehicle owner questionnaires.

6.1 OWNER PROFILE

There are believed to be about 1500 electric cars in daily use in the United States, based on the sales of Sebring-Vanguard (1500 Citicars), Elcar^{††} of Elkhart, Indiana (300 vehicles), and a few conversions from small manufacturers.

Both Citicar and Elcar are two-passenger, specially-manufactured (not conversions), limited-performance cars. Top speed is about 50-65 km/h, and range at a steady 40 km/h is about 75 km. The Citicar retailed for about \$2900, the Elcar for about \$3200.

^{*}Most of the work reported in this section was performed by Harry Fox, a consultant to General Research Corporation. A major portion of it was done pursuant to Contract E(04-3)-1180 with the Energy Research and Development Administration.

^{**}Ideally, a potential purchaser would be concerned with life cycle cost. However, in practice most people seem to be concerned only with initial price and out-of-pocket expenses (fuel, and perhaps maintenance). Because it appears likely that the purchase price of electric cars will be high (relative to similarly sized conventional cars) during their introductory years, we felt that operating cost is the key cost issue to be dealt with initially. Also, it is quite possible that for the P.L. 94-413 demonstration the vehicle's cost will be in effect subsidized for some users. Indeed, Section 11 of P.L. 94-413 specifically authorizes this for Federal agencies.

[†]Sebring-Vanguard, Inc., manufacturer of the Citicar, which interrupted production in 1976. Cars are still being sold by a number of dealers.

^{††}Elcars were manufactured by Zagato of Milan, Italy. Elcar ceased sales in 1976.

Based on fifty questionnaires completed by Citicar owners (and supplied to us by Sebring-Vanguard) and personal and telephone interviews by us with about fifty additional Citicar dealers and owners, we compiled the following statistics about the Citicar owners surveyed: 72 percent bought the car because they believed it would be more economical to own than a conventional car; 23 percent bought because of environmental concerns. Forty-nine percent used the vehicle to commute to work (the Citicar's range is 40-55 km in traffic); 43 percent used it for short trips and errands; the remainder of the vehicles were used for inter-office errands, etc. Sixty-nine percent of the owners were in the 25-to-54 age bracket; 26 percent were older. Fifty-eight percent had an annual income between \$10,000 and \$25,000; 31 percent had a higher income. Although not addressed specifically in the questionnaire, we believe from the interview survey that essentially all the Citicar purchasers we surveyed also owned one or more conventional automobiles.

The only other known survey of electric vehicle owners was conducted in October 1975 by Power-Robertson & Company, a Los Angeles market research firm.* Responses were received from 116 Citicar owners and 13 Elcar owners.^{47,48} The novelty factor was significant, as 87 percent would not have purchased any automobile if the electric were not available. The median age was 48 years and the median income was \$24,500. Fifty-eight percent had occupational classifications of professional, technical, managerial, official, or proprietor.

6.2 POTENTIAL APPLICATION

Near-term electric passenger cars, because of range limitations, will primarily find applications in multi-car households. Accordingly, projections of the number of husband-wife multicar households in 1980 were made. In 1972 there were 45.7 million husband-wife households,⁴⁹ of which 39.7 percent had two or more cars.⁵⁰ Thus the potential number of electric car households was 18.2 million in 1972. Taking into account the shifting participation of females in the work force, we estimate that the corresponding number of potential electric-car households will be 24 million in 1980.

6.3 RANGE

Two approaches are taken here to determine the range requirements for electric and hybrid vehicles. First, the range requirements of the "average" car are estimated, based upon work by Schwartz.⁵¹ These

* An update to the October 1975 survey was released in June 1977 by J.D. Power & Associates. The latter survey included responses from 184 Citicar and 11 Elcar owners. Findings of the two studies were quite similar.

requirements are beyond the capability of near-term electric vehicles, so a second approach investigates the travel requirements of the average secondary car (the car driven least in a two-car household).

The average car makes 3.14 trips with a total range of about 47 km each day.⁵² Schwartz, using a Monte Carlo simulation process, has constructed a relationship for the "usefulness" of an electric vehicle as a function of its range.⁵¹ Usefulness is the percentage of days in the year on which the electric vehicle could be used for all trips by an individual (without recharging between trips). This relationship is shown in Fig. 6.1. The assumptions used by Schwartz in arriving at Fig. 6.1 were:

1. The number of trips made by a vehicle on a given day is Poisson distributed with a mean of 3.135. (The average trip is 14.3 km long.)
2. The distribution of automobile trips is as shown in Table 6.1.
3. The average vehicle driving distance is 16,386 km (10,184 mi) annually.

Hamilton, using data from a 1969 Los Angeles origin-destination survey, found that secondary drivers in two-car households drive considerably less than the average car is driven (about 47 km/day).¹² Figure 6.2 shows the results of this analysis, which indicates that a range of 50 km will satisfy secondary drivers on about 85 percent of their driving days.

6.4 MAXIMUM SPEED

Attaining a top speed of 88 km/h (the current 55 mi/h speed limit) with even modest electric cars is potentially possible. Assuming a tire friction factor of 1.6 percent and a drag area of 0.93 m^2 (10 ft^2), the required road power is only 12.3 kW for a 1000-kg vehicle. An electric car with a 60-percent motor-driveline efficiency and 0.3 battery mass fraction would require a specific power output of 68 W/kg, which could be maintained for perhaps 12 minutes with present golf-cart batteries. However, the range at this speed would be only about 18 km. The question is, then, what speed is required?

One of the most comprehensive sources of urban transportation data is provided by the 1967 survey conducted by the Los Angeles Transportation Study.⁵³ Based on this study, the average speed for non-freeway trips was 44.4 km/h; for freeway trips, the corresponding average was 79.2 km/h.¹² Comparison of these data for 1972 with data from the 1974 National Transportation Study,⁵² for 44 urbanized areas throughout the United States, indicates that the Los Angeles figures are typical. Unfortunately, none of these data give any information on requirements

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Figure 6.1. Electric Vehicle Usefulness (Ref. 51)

TABLE 6.1
DISTRIBUTION OF AUTOMOBILE TRIPS (FROM REF. 51)

<u>One-Way Trip Length, km(mi)</u>	<u>Percent of Annual Trips</u>	<u>Total Trips/Year</u>	<u>Percent of Annual Vehicle Travel</u>	<u>Average Trip Length, km</u>
Under 8(5)	54.1	616	11.1	3.0
8(5) - 16(9)	19.6	233	13.8	10.1
16(9) - 24(15)	13.8	157	18.7	19.5
24(15) - 32(20)	4.3	49	9.1	30.4
32(20) - 48(30)	4.0	46	11.8	42.0
48(30) - 64(40)	1.6	18	6.6	60.0
64(40) - 80(50)	0.8	9	4.3	78.4
80(50) - 160(100)	1.0	11	7.6	113.3
150(100) and Over	<u>0.8</u>	<u>9</u>	<u>17.0</u>	308.9
	100.0	1138	100.0

Figure 6.2. Distribution of Daily Driving Distance in Los Angeles Region, Secondary Drivers with Cars in Two-Car Household (Ref. 12)

for cruising or top speed, but the average speed requirement is quite modest. Top speed and acceleration are both functions of the power available at the wheels. Thus it turns out in some instances that the speed which is consistent with the acceleration requirement appears adequate. This will be examined more carefully in Sec. 7.6.

6.5 ACCELERATION

Near-term electric vehicles generally will not have the capability to operate on freeways. Thus their acceleration requirement can be based on a combination of what is possible and what is needed to stay up with average traffic. Figure 6.3 shows velocity profiles measured in Detroit under various traffic conditions. Based on this figure, 12 s to reach 50 km/h is a reasonable acceleration requirement; this value is also consistent with the existing vehicles described in Table 5.2.

For the near-term commercial vehicle, the requirement is relaxed to 15 s to reach 50 km/h (which is still consistent with Fig. 6.3), to be more nearly consistent with the existing electric vans described in Table 5.3. Three of the five vehicles shown in Table 5.3 meet or exceed this requirement.

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Figure 6.3. Measured Urban Traffic Acceleration Characteristics (Ref. 21)

Acceleration requirements for advanced vehicles should be higher because they are more likely to be operated on at least short stretches of freeways. In order not to impose a traffic hazard at merge points, the electric vehicles must be able to accelerate to about 65 km/h (40 mph) while on the entrance ramp. This requirement is made more difficult to meet by uphill entrance ramps in urban areas to freeways which are raised above surface streets.

Figure 6.4 shows the length requirements for uphill ramps for vehicles with various acceleration capabilities. Also indicated in Fig. 6.4 is the region of ramp length and grade prevalent in the Los Angeles region.* The equations used to generate Fig. 6.4 are derived in Appendix H.

From Fig. 6.4 we conclude that advanced vehicles will require the capability to accelerate to 65 km/h in 10 seconds to merge safely with traffic on most urban freeways.

* Personal communication between Mr. Parker Hall of the California State Transportation Department (CALTRANS) and Mr. Charles Graver of GRC.

Figure 6.4. Length of Ramp Required for Vehicle to Enter Freeway

6.6 GRADEABILITY

We have few data on which to base gradeability requirements. Urban streets seldom exceed ten-percent grade; freeways are limited to six percent.⁵⁴ Thus the near-term vehicles should be able to move at safe speeds on ten-percent grades. Rather than specify a minimum speed on a ten-percent grade, we will defer this item until Sec. 7.6 where we calculate the speed consistent with the acceleration requirement set forth in Sec. 6.5.

Advanced electric vehicles should be able to maintain a minimum speed of 65 km/h (40 mi/h) on a six-percent grade to provide safe freeway operation.

Maximum gradeability should be at least twenty percent, as short ramps in parking garages can be as steep as seventeen percent.⁵⁵

6.7 VEHICLE CAPACITY

Automobile occupancy varies with trip purpose and trip length. Ninety-two percent of home-to-work trips and 77 percent of all trips

involve only one or two occupants.* Based on trip length, only average occupancies are available. For one-way trips of 24 km or less, average occupancies are 1.3 to 1.4 for home-to-work, and 1.8 to 1.9 for all trips.**

In summarizing electric vehicle requirements, the most important issue (based on surveys) in the view of owners is economy. There appears to be a sizable potential market among multi-car households, but the electric car must compete economically with a secondary car, which is likely to be older and thus relatively inexpensive to purchase.† Trip speed data provided little on which to base speed requirements, since they were available only as averages. Occupancy data strongly suggests that a two-passenger capacity is adequate for a large portion of trips. Of course, a few people would purchase a vehicle which met only their "average" needs if their "peak" needs could be met by another vehicle in the same price bracket. For conventional automobiles, this is almost always possible. However, for electric cars, every unit of increased payload will increase the vehicle's gross mass by up to two units. Of this increase, about 30 percent will be in batteries, which adds appreciably to operating costs, and probably maintenance requirements as well.

* Unpublished Table P-8 from the National Personal Transportation Survey conducted by the Bureau of Census for the Federal Highway Administration, 1967-1970.

** Ibid., Table T-5.

† In many cases the secondary car is an older first car. It is unlikely that a new car--conventional, electric, or hybrid--can compete economically with the older first car in these cases.

7 HYPOTHETICAL VEHICLE DESIGN AND RATIONALE--NEAR-TERM ELECTRIC VEHICLES

We develop here a gross design for two hypothetical vehicles and the rationale for many of the performance standards to be specified. The reason for this approach is to insure that the resulting performance standards are realistic, self-consistent, and compatible with the vehicles described in Sec. 5.

7.1 PRIVATE VEHICLES--RANGE

The range parameters k_1 shown in Fig. 5.1 vary from about 5.5 for the Toyota electric to just under 11 for the Sundancer. We chose seven as a representative yet conservative value of what can be achieved by near-term vehicles. Based on a value of seven for k_1 , and an SAE J227a/C cycle length of 0.54 km/cycle (this value varies slightly with aerodynamic drag and friction, but 0.54 km/cycle is conservative), Fig. 7.1 shows how range varies with battery mass fraction and battery energy density. Also shown in Fig. 7.1 are the energy densities of present batteries and the 1985 goal for lead-acid batteries, based on a recent study.²

Figure 7.1. Range on J227a/C Driving Schedule for Hypothetical Private Vehicle

Two points are apparent from Fig. 7.1. First, to reach a range of 70 to 80 km* with present batteries will require a battery fraction greater than about 0.38. Second, we can look forward to about a 100-percent range increase for any given battery fraction if the 1980 energy density goal for lead-acid batteries is achieved.

To require a range of 70 to 80 km over the J227a/C schedule with present batteries means that the same vehicle will have about 150 km range with the advanced lead-acid batteries. Unfortunately, 150 km range is still inadequate for first-car use. Thus a requirement of 70 to 80 km for near-term vehicles appears to be a poor choice. Also, increased costs and maintenance are associated with high battery fractions, and these too, are disadvantageous.

However, a range requirement of 50 km appears to be a good compromise for the following reasons:

- . 50 km on the SAE J227a/C schedule is over two hours of driving. It should be enough to meet the requirements of two-car households on 80 to 85 percent of driving days, according to Fig. 6.2.
- . A battery mass fraction of about 0.3 is required. This is a reasonable compromise based on the state-of-the-art vehicles summarized in Table 5.2.
- . If the 1985 energy density goal is achieved, the range can be increased to over 100 km, which is adequate for almost all second-car driving days. Even if the 1985 goal is only half-way achieved (100 kJ/kg or 30-31 Wh/kg), the vehicle's range will increase to about 75 km, which is nearly the 95 percent level in Fig. 6.2.

7.2 PRIVATE VEHICLES--ENERGY USAGE

Cost of operation** is perhaps the most important parameter to consider. To calculate cost, a representative value of the energy usage parameter k_2 is required. From the definitions of the range and cost parameters k_1 and k_2 , given by Eqs. 3.14 and 3.18, one would expect a high degree of correlation. This turns out to be the case, as the private vehicle k_1 and k_2 have a correlation coefficient of -0.762. For the commercial vehicles, the coefficient is -0.737. Thus we are not free to

*The 95-percent point in the second-car daily travel distribution shown in Fig. 6.2.

**Includes battery depreciation and electricity cost.

independently pick representative values of both k_1 and k_2 from Figs. 5.1 through 5.4. Unfortunately, the possible effect of the correlation of k_1 and k_2 was not recognized at the time this work was performed. However, upon checking, it turned out that the value of k_2 chosen for the private vehicles ($k_2 = 0.54$) is the best value (based on a linear regression analysis) for $k_1 = 7$. Thus for the private vehicle analysis, k_2 is consistent with the correlation of k_1 and k_2 . However, for the commercial vehicle case, a range parameter k_1 of 16 was selected, and the value of k_2 chosen independently ($k_2 = 0.50$) turned out to be 10 percent higher than indicated by a regression analysis. This error, which increases electricity costs by the same margin, was not considered serious enough to require redoing the analysis, since electricity costs represent only about 30 percent of operating costs. (This is shown in Fig. 7.2). Thus the overall cost of operation is high by about three percent, well within the uncertainty of the parameters used in the rest of the analysis.

NOTE: OPERATING COST SHOWN HERE DO NOT INCLUDE INTEREST, INSURANCE, TAXES, PARKING, TOLLS AND DEPRECIATION (EXCEPT BATTERY).

Figure 7.2. Private Electric Vehicle Operating Cost, SAE J227a/C Schedule

Based on Eqs. 3.16 and 3.17, Fig. 7.2 compares the operating cost of our hypothetical 1000-kg vehicle with that of an ICE subcompact. In addition to the parameter values shown in Fig. 7.2, initial battery cost C_B (for replacement batteries, with trade-in) was assumed to vary linearly with specific energy density from \$1.35/kg at $F_1 = 81.7$ kJ/kg (22.7 Wh/kg) to \$1.85/kg at $E_1 = 137.9$ kJ/kg (38.3 Wh/kg.) The prices are in 1975 dollars, taken from the 1985 goals, Ref. 2.

The ICE subcompact cost of operation shown in Fig. 7.2 is estimated to be 3¢/km on a 10-year-life basis.⁵⁶ This subcompact is approximately equivalent to a Honda Civic in size and performance. Note that the near-term electric car would not have equivalent performance in almost any category--range, acceleration, top speed, or gradeability--only in operating cost.

Two factors emerge from Fig. 7.2. First, battery amortization, electricity, and maintenance costs are roughly equal. Improving battery life by 50 percent has about the same effect on costs as meeting the 1985 energy density goal. (The 1985 battery life goal is 1000 cycles; current battery life is 300-400 cycles.) Second, and most important, the costs for the electric vehicle in Fig. 7.2 scale directly with the vehicle mass, with the possible exception of maintenance costs. If the gross vehicle mass is greater than the 1000 kg assumed here, there is no chance of near-term electric cars competing with the conventional subcompact in operating costs. We thus conclude that our hypothetical private vehicle should have a curb mass of about 820 kg in order that its gross mass be about 1000 kg with two occupants and 20 to 30 kg of luggage.

To specify a vehicle mass limit is inconsistent with providing performance standards as opposed to design standards. Energy use, however, is a performance characteristic which is nearly proportional to vehicle mass. Furthermore, it should be kept low for reasons in addition to dollar economy. Thus a "wall" consumption of 0.90 MJ/km on the SAE J227a/C cycle will be specified. This is arrived at by assuming battery and battery charger efficiencies of 0.75 and 0.8, respectively: $0.90 \text{ MJ/km} = (0.54 \text{ kJ/km} \cdot \text{kg}) \times 1000 \text{ kg} / (0.75 \times 0.8)$.

7.3 COMMERCIAL VEHICLES--RANGE

The scope of possible commercial electric vehicles is great, ranging from one-person meter-maid runabouts to large buses and heavy-duty trucks. However, we have limited our consideration to relatively light delivery vans for reasons enumerated here.

There appears to be a limited market for golf-cart-size, one-person vehicles. A number of electric vehicles of this type are already available, so it seems ill-advised to spend money on a demonstration of this type of vehicle. Furthermore, even if all vehicles of this size were replaced with their electric counterparts, the effect on nationwide petroleum consumption would be negligible.

Taxis were not considered specifically because only 0.6 percent of urban travel (in 1970, passenger-miles) was by this mode.⁵⁷

At the other end of the commercial electric vehicle spectrum are buses and perhaps large trucks. However, buses are built in relatively small volume and tend to be custom-designed for the purchaser. It would be difficult to specify performance standards for them which would be accepted by more than one transit district. Further, in 1970 only 2.7 percent of urban travel (passenger-miles) was by bus.⁵⁷ Thus the potential petroleum saving due to electric buses is small.

Large electric trucks were not considered for several reasons. First, there are few examples of them to be found. Second, range limitations preclude their operation in any intercity role, so the potential applications are much reduced. Third, they would be extremely expensive, because of their size and custom construction, so that perhaps one large truck might cost as much as five to ten private or small commercial vehicles. Fourth, since only a few vehicles would be involved, they could not be used widely in a demonstration program.

The size of the hypothetical commercial vehicle chosen on which to base performance standards is one which will carry two passengers and 230 kg (500 lb) of payload. There are many applications which such a vehicle could satisfy, including postal deliveries. These applications are now being filled by ICE vehicles getting relatively poor fuel economy due to the multi-stop routine of their driving schedule. The SAE driving schedule which comes closest to describing these types of driving is probably the SAE J227a/B. This schedule is shown in Fig. G.1. The average speed is about 15 km/h, and the length of each cycle about 0.31 km.

In order to coexist with urban traffic, commercial vehicles should be able to perform the SAE J227a/C schedule as well as the SAE J227a/B, but a number of existing commercial electric vehicles cannot meet the acceleration requirements (48 km/h in 18 s) when fully loaded. Thus it appears reasonable to specify range requirements based on the SAE J227a/B schedule, but require acceleration and cruising speeds great enough to allow them to function in most urban traffic situations.

Proceeding as we did for private vehicles, Fig. 7.3 shows the range of a hypothetical commercial vehicles, based on Eq. 3.15, with $k_1 = 16$.

We were unable to find a distribution of commercial vehicle travel distances comparable to the distribution for second cars shown in Fig. 6.2. Thus we are not in a position to be able to pick a battery mass fraction which will satisfy a given percentage of commercial travel days. However, based on the battery fractions for existing small vans tabulated in Table 5.3, it appears as though a fraction of 0.25 is a reasonable compromise. It will allow our hypothetical vehicle to go 50 km on a SAE J227a/B schedule with present batteries; the range will increase to over 100 km

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Figure 7.3. Range Over SAE J227a/B Driving Schedule for Hypothetical Commercial Vehicle

if 1985 lead-acid battery goals² are met. Actually, these ranges may be conservative, since in most applications the vehicle will not travel fully loaded throughout the day.

7.4 COMMERCIAL VEHICLES--ENERGY USE

Figure 7.4 shows operating costs (excluding taxes, parking, insurance, tolls, interest, and all depreciation except battery) for the hypothetical commercial vehicle over the SAE J227a/B schedule. Comparison with Fig. 7.2 (passenger vehicle costs) indicates substantially greater costs for the commercial vehicle. This is primarily due to the difference in vehicle masses, a factor of 1.9.

Figure 7.4 indicates that the largest single component of operating cost is battery amortization, at least until better batteries are produced. Figures 7.2 and 7.4 are based on an electric energy cost of 1.11¢/MJ (4¢/kWh), which is about the national average. The electricity cost is inversely proportional to battery and battery charger efficiencies. The former is about 0.75, and is not expected to vary for the advanced lead-acid batteries; the latter is presently 0.6-0.7 for many golf-cart battery chargers, although 0.8 was assumed for these calculations. Rippel has demonstrated an average efficiency of 0.95 for a transformerless charger,⁴ so the 0.8 value can be improved if safety considerations do not preclude such a device.

To arrive at an overall energy consumption for the commercial vehicle, we will assume that the payload represents about 20 percent of the gross vehicle mass. (The average payload for the five vans summarized in Table 5.3 is 17.4 percent of the payload.) Since the payload of our hypothetical vehicle is 380 kg (230 kg freight plus two passengers at 75 kg each), the gross vehicle mass is 1900 kg. This is about the same gross vehicle mass as the Otis P-500 Van and the AM General Electruck. Since 25 percent of the 1900 kg is batteries, the battery pack will consist of about 16 of the golf-cart types, or equivalent. Energy consumption at the wall plug can be obtained by

$$\begin{aligned}\text{Energy Consumption} &= \frac{0.50 \text{ kJ/kg} \times 1900 \text{ kg}}{0.8 \times 0.75} \times 10^{-3} \text{ MJ/km} \\ &= 1.53 \text{ MJ/km (SAE J227a/B schedule)}\end{aligned}$$

which we round up to 1.6 MJ/km. Since a vehicle with a 230 kg cargo payload may not be appropriate for all applications, we will normalize the energy consumption to the payload capacity. Thus

Figure 7.4. Commercial Electric Vehicle Operating Cost, SAE J227a/B Schedule

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$$\text{Normalized Energy Consumption} = \frac{1.6 \text{ MJ/km}}{230 \text{ kg}}$$

$$= 6.95 \text{ kJ/km} \cdot \text{kg (SAE J227a/B schedule)}$$

which we will round up to 7 kJ/km·kg of payload.

Near-term vehicle parameters and operating costs are summarized in Table 7.1.

7.5 CONSTANT-SPEED RANGE

Sections 7.1 and 7.2 estimated the range of the hypothetical near-term vehicles in urban driving. However, it is also useful to estimate the range at constant speeds. To do this, we will need to estimate representative values for the vehicle system losses: tire, viscous, and aerodynamic friction, and motor (including controller) and driveline losses. Table 7.2 shows these estimates and the resulting constant-speed ranges. The first three losses (tire, viscous,* and aerodynamic) are based on coastdown tests of several electric vehicles described in Appendix I; the motor-driveline efficiency estimate shown is based upon Tables 5.4 and 5.5.

7.6 GRADEABILITY AND TOP SPEED

In Sec. 6, the requirements for acceleration were developed for the near-term vehicles. These requirements were based on keeping up with urban traffic. Top speed and gradeability (except for maximum gradeability) were not developed independently; we chose to see what the acceleration requirements implied for these measures rather than choose values which would be largely arbitrary. Now that the hypothetical vehicle design is specified, we will estimate gradeability and top speed based on the acceleration capability.

The friction coefficients needed to produce these estimates are the same as those given in Table 7.2. The details of the method used are given in Appendix H. Table 7.3 shows the gradeability and top speed estimates for the near-term vehicles. Note that the near-term vehicles are estimated to have about a 30 km/h capability on a ten-percent grade. Since such grades do not occur frequently in most urban areas, we assume that such a capability is adequate.

*The viscous loss is a catchall term for all losses proportional to speed. Some tires exhibit such a loss; the remainder is in the bearings, seals, and gears.

TABLE 7.1

SUMMARY OF OPERATING PARAMETERS AND OPERATING COSTS FOR
HYPOTHETICAL NEAR-TERM VEHICLES

	<u>Vehicle</u>	
	<u>Private</u>	<u>Commercial</u>
Battery:		
Specific Energy Density (1-h rate), kJ/kg		83 (23 Wh/kg)
Charge-Discharge Efficiency		0.75
Battery Charger Efficiency		0.8
Life, discharge cycles		400
Initial User Cost, \$/MJ		14 (\$50/kWh)
Vehicle:		
Battery Mass Fraction	0.30	0.25
Gross Vehicle Mass, kg	1000	1900
SAE Driving Schedule	J227a/C	J227a/B
Operating Costs, * ¢/km:		
Maintenance (estimated)	1.0	1.0
Electricity [at 1.11¢/MJ (4¢/kWh)]	1.0	1.8
Battery Amortization	<u>2.1</u>	<u>3.1</u>
Total	4.1	5.9
Energy Input to Charger, MJ/km	0.9	1.6
Energy Input to Charger, normalized to Cargo Payload Capacity, kJ/km·kg	--	2.0

* Does not include interest, insurance, taxes parking tools, and depreciation (except battery).

TABLE 7.2
ESTIMATED RANGE AT CONSTANT SPEED FOR HYPOTHETICAL
NEAR-TERM VEHICLES

	<u>Vehicles</u>	
	<u>Private</u>	<u>Commercial</u>
Gross Vehicle Mass, kg	1000 (2205 lb)	1900 (4185 lb)
Tire Friction C_1 , N/kg	0.16 (1.6%)	0.12 (1.2%)
Viscous Friction C_2 , N·s/kg·km	0.001 (4.5×10^{-3} %/mi/h)	
Drag Area Product $C_D A$, m ²	0.9 (10 ft ²)	1.5 (16 ft ²)
Motor-Driveline Efficiency, η_{MD}	0.65	
Battery Specific Energy E_1 , kJ/kg	83 (23 Wh/kg)	
Battery Mass Fraction f	0.3	0.25
Range, km at speed, km/h		
70	40	35
60	50	50
50	60	60
40	90	95

TABLE 7.3

THEORETICAL GRADEABILITY AND TOP SPEED BASED ON ACCELERATION CAPABILITY
FOR HYPOTHETICAL NEAR-TERM VEHICLES

<u>Vehicle</u>	<u>Acceleration Capability, V(km/h) in t(s)</u>	<u>Average Specific Power At Wheels, W/kg</u>	<u>Gradeability</u>		
			<u>Speed on 7% Grade, km/h</u>	<u>Speed on 10% Grade, km/h</u>	<u>Top Speed, km/h</u>
Private	50 in 12	10.3	40	31	81
Commercial	50 in 15	8.7	36	23	81

8 HYPOTHETICAL VEHICLE DESIGN--ADVANCED ELECTRIC VEHICLES

Several improvements in electric vehicle subsystems can be expected during the next few years which will allow substantially better performance, even with present batteries. First, regenerative braking or fly-wheel energy storage may become commonplace in vehicle design. (Only the Ripp-Electric and AM General Electruck have regenerative braking among the vehicles discussed so far, although many European electric vehicles incorporate it.) Second, motor design can be expected to be improved to provide higher efficiencies. This will probably be achieved by using separately-excited motors, which have lower losses than series-wound motors with chopper-armature current control. Separately excited motors may, however, increase transmission requirements. Regeneration is also less complex with separate excitation. Third, as specially designed vehicles are developed, aerodynamic and tire friction losses should decrease somewhat. Fourth, battery charger efficiency should approach 95 percent. Table 8.1 shows the current and anticipated values of the parameters related to these improvements. The rationale and data upon which Table 8.1 is based are described in Appendix I.

TABLE 8.1

DESCRIPTORS FOR HYPOTHETICAL ADVANCED ELECTRIC VEHICLE

	<u>Vehicle</u>	
	<u>Private</u>	<u>Commercial</u>
Tire Friction C_1 , N/kg	0.12	0.10
Viscous Friction C_2 , N·s/kg·m	0.001	
Drag Area Product $C_D A$, m ²	0.82	1.5
Motor-Driveline Efficiency η_{MD}	0.75	

8.1 PRIVATE VEHICLES

Using the values shown in Table 8.1 and a vehicle mass of 1500 kg, range performance characteristics (J227a/D) for a vehicle with and without electrical regenerative braking are shown in Fig. 8.1. In modeling the vehicle with regenerative braking, efficiencies are assumed to be the same in either direction for the driveline and motor (generator). The energy returned to the battery during braking is assumed to be multiplied by a regenerative utilization factor, χ (discussed more fully in Appendix D). Values of χ greater than unity are consistent with test data reported by Rippel⁴ on a dynamometer⁴ and on a track* for the J227a/C cycle, and by Menga⁵ in Italy for an urban driving cycle. This phenomenon apparently occurs because the regeneration energy makes available some of the active material that is present in the battery, but normally unavailable at high discharge rates. The relatively short pulses of regeneration energy will tend to decrease both polarization and sulfation effects.

In the dynamometer tests reported by Rippel⁴, a total recharge of 11.9 A·h during regenerative braking resulted in an increase in total discharge of 20.4 A·h. During the track tests of the Ripp-Electric, comparable figures were 16.1 A·h recharge for a total increase of 20.1 A·h. Assuming a charge-discharge efficiency of 75 percent, the regenerative utilization factor, χ , was 2.29 and 1.67 for dynamometer and track tests, respectively. The average of these values, 1.99, gives good agreement when it is used in a detailed simulation, and the results are compared with the test data. Of course, χ would be somewhat less than indicated here if calculated on the basis of energy rather than charge, since terminal voltage drops during discharge and rises during regeneration. Unfortunately, the instrumentation required to measure discharge and regenerative braking recharge energy was not available during the tests.

In tests on a small Italian urban vehicle reported by Menga⁵, battery energy output increased from 100 to 110.6 units (the results are normalized, so the absolute amounts are not stated) when regenerative braking was used. The energy returned to the battery was 10.2 units, so the regenerative utilization factor χ was 1.39, assuming a charge-discharge efficiency of 75 percent. Equation 3.11 was assumed to be valid during regeneration if the sign of the numerator was reversed.

Also shown in Fig. 8.1 is the range performance which could be expected of a flywheel-battery-electric vehicle. The flywheel-battery-

* W. E. Rippel, personal communication, "Summary of Track Tests Performed on Ripp-Electric Vehicle at Ontario Motor Speedway," 18-20 December 1976, preliminary report from Jet Propulsion Laboratory.

Figure 8.1. Range Comparison of Flywheel-Battery-Electric and Battery-Electric Vehicles

electric vehicle modeled here has a flywheel coupled to the vehicle's wheels by a continuously variable ratio transmission (CVRT). The flywheel is assumed to be lossless, but the CVRT consists of a motor-generator combined with a set of mechanical gears such that energy goes through the transmission in both mechanical and electrical forms. Thus for the purpose of modeling this vehicle, all of the flywheel system losses are treated as if they occur in the flywheel transmission.

The battery is used for two purposes. One, during the acceleration and cruise periods, the battery provides some or all of the energy needed to propel the vehicle. Two, during the coast and dwell periods, battery power is used to recharge the flywheel.

During braking, the regenerative energy is stored in the flywheel rather than in the battery.

The battery power is limited to a level of $P_{\max}$. During the initial acceleration, the battery provides all the required power up to a maximum level of $P_{\max}$. At that time, the flywheel system cuts in and provides the additional power needed.

During the cruise period, the battery power level remains at $P_{\max}$, which partially recharges the flywheel and provides cruise power. During the coast period, the flywheel is recharged at a rate equal to $P_{\max}$ (less losses in the flywheel transmission). During braking, all kinetic energy (less driveline and flywheel transmission losses) is stored in the flywheel via the driveline and the flywheel transmission; no battery energy is used. During the dwell period, the battery power level is again set at $P_{\max}$ to complete recharging the flywheel (less flywheel transmission losses). The energy from the battery during a complete driving cycle exactly equals all the system losses (motor, controller, transmission, tires, aerodynamic, and flywheel transmission).

Energy losses in this hypothetical system are due to five sources: motor (80 percent efficiency); flywheel transmission (losses occur each time energy is taken from or put into the flywheel); driveline (efficiency in each direction 94 percent); and other friction losses shown in Table 8.1.

The flywheel-battery-electric vehicle has three potential advantages over the battery-electric vehicle. One, since the battery is discharged at a nearly constant power level which is almost equal to the average power required, maximum energy is available. Two, since the flywheel system has a very high specific power density compared to lead-acid batteries, higher acceleration should be possible. Three, battery life may be enhanced since peak loads are less. Offsetting these potential advantages are increased cost and complexity and the losses in the flywheel system (here all lumped into the flywheel transmission).

Figure 8.1 indicates that the flywheel-battery-electric vehicle may not be competitive with the battery-electric vehicle (with regenerative braking) on a range basis for the SAE J227a/D schedule unless the flywheel system efficiency is 70 percent or higher averaged over the cycle. Such average flywheel system efficiencies may not be attainable in the near future with continuously variable ratio transmissions, which are needed for this application.

Based on Fig. 8.1, we can set a goal of 165 km range for the SAE J227a/D schedule, corresponding to a regenerative utilization factor of about 1.4 and the 1985 nickel-zinc energy density goal of 230 kJ/kg (64 Wh/kg).² This range goal can be revised downward in the future if it appears that the new batteries are not going to meet the goals set forth in Ref. 2.

8.2 COMMERCIAL VEHICLES

Advanced batteries will allow an increase in payload to 500 kg (freight) and increased range on a more difficult driving schedule (SAE J227a/C instead of SAE J227a/B). Allowing for a driver and passenger, the total payload will be 650 kg. Assuming that this represents 20 percent of the gross vehicle mass, as for the near-term vehicle, this results in a gross vehicle mass of 3250 kg. Figure 8.2 shows the variation in range for three different battery fractions and both the SAE J227a/B and SAE J227a/C driving schedules.

Based on Fig. 8.2, we chose a range goal of 220 km on the SAE J227a/C schedule. This corresponds to a battery fraction of 0.25 and the 1985 Ni-Zn battery goals.

8.3 OPERATING COSTS

Pertinent parameters and operating costs for the advanced vehicles are summarized in Table 8.2. Note that the resulting 3.6¢/km is a little less than the 4.1¢ shown for the near-term private vehicle in Fig. 7.2 (with 400 cycle battery life). Thus advanced technology may allow us to more than triple the range on a more difficult driving cycle (SAE J227a/D versus SAE J227a/C), increase the gross vehicle mass by 50 percent, double the passenger capacity, and end up with about the same operating cost on a per-unit-distance basis.

For the commercial vehicle, advanced technology may allow a two-thirds increase in gross vehicle mass (doubling of freight payload), over a four-fold increase in range on a more difficult driving schedule (SAE J227a/C versus SAE J227a/B). Operating costs are about the same, 6¢/km.

Figure 8.2. Range Tradeoffs for Advanced Commercial Vehicle

TABLE 8.2

SUMMARY OF OPERATING PARAMETERS AND OPERATING COSTS
FOR HYPOTHETICAL ADVANCED VEHICLES

	Vehicle	
	<u>Private</u>	<u>Commercial</u>
Battery:		
Specific energy density (1-h rate), kJ/kg		230 (64 Wh/kg)
Regenerative utilization factor		1.0
Charge-discharge efficiency		0.7
Battery charger efficiency		0.95
Life, discharge cycles		600
Initial user cost, \$/MJ		14 (\$50/kWh)
Vehicle:		
Battery mass fraction	0.25	0.25
Gross vehicle mass, kg	1500	3250
Driveline efficiency, average	0.94	0.94
Motor & controller efficiency, average	0.80	0.80
SAE driving schedule	J227a/D	J227a/C
Range, km	165	220
Operating cost, * c/km:		
Maintenance (estimated)	1.0	1.5
Electricity [1.11¢/MJ(4¢/kWh)]	1.0	1.7
Battery amortization	<u>1.6</u>	<u>2.9</u>
Total	3.6	6.1
Energy input to charger, MJ/km	0.90	1.55
Energy input to charger, normalized to cargo payload, kJ/km.kg)	==	3.1

* Does not include interest, insurance, taxes, parking, tolls, and depreciation (except battery).

8.4 RANGE AT CONSTANT SPEEDS

Table 8.3 shows estimated constant-speed ranges for the hypothetical advanced vehicles. These ranges are approximately four times greater than comparable ranges for the near-term vehicles. The increased battery specific energy accounts for about 75 percent of the increase, and the remainder is due to lower friction and increased motor-driveline efficiency.

The fact that the ranges are the same for both private and commercial vehicles is coincidental (ranges were rounded to the nearest five kilometers).

8.5 GRADEABILITY AND TOP SPEED

Gradeability and top speed estimates for the hypothetical advanced vehicles are shown in Table 8.4. These values are based on the average specific power at the wheels required to produce the required acceleration (65 km/h in 10s). The method used to obtain gradeability and top speed estimates is described in Appendix H.

TABLE 8.3
ESTIMATED RANGE AT CONSTANT SPEED FOR
HYPOTHETICAL ADVANCED VEHICLES

	Vehicle	
	Private	Commercial
Gross vehicle mass, kg	1500 (4846 lb)	3250 (7159 lb)
Tire friction C_1 , N/kg	0.12 (1.2%)	0.10 (1%)
Viscous friction C_2 , N·S/kg·m	0.001 (4.5×10^{-3} %/mi/h)	
Drag area product $C_D A$, m ²	0.82 (8.8 ft ²)	1.5 (16 ft ²)
Motor-driveline efficiency η_{MD}	0.75	
Battery specific energy E_1 , kJ/kg	230 (64 Wh/kg)	
Battery mass fraction	0.3	0.25
Range, km at speed, km/h		
90	175	175
80	215	215
70	260	260
60	315	315
50	375	375

TABLE 8.4
THEORETICAL GRADEABILITY AND TOP SPEED
BASED ON ACCELERATION CAPABILITY
(HYPOTHETICAL ADVANCED VEHICLES)

Vehicle	Acceleration Capability V(km/h) in t(s)	Average Specific Power At Wheels, W/kg	Gradeability		Top Speed km/h
			Speed on 7% Grade, km/h	Speed on 10% Grade, km/h	
Private	65 in 10	18.8	71	56	123
Commercial	65 in 10	18.6	73	57	131

9 PERFORMANCE STANDARDS AND DEVELOPMENT SPECIFICATIONS

Sections 7 and 8 developed gross designs for hypothetical vehicles upon which performance standards and development specifications will be based. Rechargeability, battery life, and safety, three categories not considered thus far, will be developed here as a preliminary to setting forth the recommended performance standards and development specifications for electric vehicles. Standards and specifications specific to hybrid vehicles will be developed in Sec. 10.

9.1 BATTERY CHARGING

To be of maximum utility to the average user, near-term private electric vehicles must be capable of being recharged from a 120 Vac outlet by an on-board charger. The charger should also be able to operate on 240 Vac, for those users who have it available. Further, this charger should be capable of unattended operation which will provide automatic cutoff when the batteries have completed charging.

The charger input power available, assuming a 20 A circuit capacity and unity power factor, is 2.4 kW. The maximum requirements for recharge energy for the 1975-technology private vehicles is (Table 7.1)

$$\begin{aligned}\text{Recharge Energy} &= 0.90 \text{ MJ/km} \times 50 \text{ km} \\ &= 45.0 \text{ MJ}\end{aligned}$$

The minimum recharge time would be 5.2 hours at constant power level. Allowing for a non-constant power level and less than unity power factor, 8 hours should be sufficient to recharge the batteries.

When the advanced batteries (1980 lead-acid) are introduced, the charger will have to provide up to twice as much energy to provide the projected range:

$$\begin{aligned}\text{Recharge Energy} &= 0.9 \times 100 \text{ km} \\ &= 90 \text{ MJ}\end{aligned}$$

so a higher-voltage charger will be required.

For the near-term commercial vehicle, the recharge energy is much greater than for the near-term private vehicle, 81 MJ, and a 120 Vac charger is marginal at best. Thus commercial on-board chargers should

be able to operate from either single-phase or three-phase 240/480 Vac distribution systems. Except for the 240 Vac single-phase system, these combinations have the growth potential to handle advanced lead-acid batteries which may require as much as 170 MJ recharge energy. Even the 240 Vac single-phase system would be adequate if the current capacity were increased to 30 A.

For the advanced private vehicle, the maximum recharge energy is 178.2 MJ (1.08×165), so even a charger fed by a 240 Vac, 20 A single-phase circuit will require over eight hours to recharge the battery. However, it is unlikely that the battery will be fully depleted each day, so we will not require a three-phase 240 V or 480 V charger, which would cause a considerable wiring problem for many households.

The recharge requirement for the advanced commercial vehicle is 341.0 MJ (1.548×220). This will require a minimum time of 11.4 h with a three-phase 240V/20A system and 7.6 h with a three-phase 240V/30A system. Thus we will require that the charger input be three-phase 480V/20A. A three-phase 240 V input to the charger should also be provided for those users not requiring a full charge. Recharge requirements are summarized in Table 9.1.

9.2 BATTERY LIFE

Battery life is probably the aspect of electric vehicle technology about which least is known. Battery manufacturers appear reluctant to publish claims for electric-vehicle battery life--perhaps because the conditions under which the batteries are used (and charged) vary so much. Commonly quoted figures of 300-400 deep discharge cycles for present golf cart batteries may be meaningless if these batteries are subjected to average discharges which exceed the 75A upon which the batteries are rated.

What is needed, but not available at this time, is a standard test by which battery life could be measured. This test should specify a specific power density profile representative of that drawn by electric vehicles, and precisely define the battery charger characteristics. Additionally, provisions should be made for regenerative braking and a method developed to derate (or uprate) the standard life-cycle value for non-standard specific power density profiles.

The development of the above tests and methods should be actively pursued. However, in the meantime we are faced with the problem of specifying battery life for the vehicles to be used in the P.L. 94-413 demonstrations.

Test apparatus is available which automatically cycles a battery through a given specific power density profile (JPL has recently begun tests of this type). Since only one or two batteries need be tested at one time, the overall power requirements are not great. For near-term

TABLE 9.1
BATTERY CHARGING REQUIREMENTS

	Near-Term				Advanced	
	Private		Commercial		Private	Commercial
	1975 Battery	1980 Lead-Acid	1975 Battery	1980 Lead-Acid		
Energy Requirements, MJ	45.0	90.0	81.0	170.2	178.2	341.0
Input to Charger	Minimum time to recharge, h - - - - -					
120V/1 ϕ /20A	5.2	10.4	9.4	19.7	20.6	--
240V/1 ϕ /20A	2.6	5.2	4.7	9.9	10.3	19.7
240V/3 ϕ /20A	--	3.0	2.7	5.7	6.0	11.4
240V/3 ϕ /30A	--	--	--	--	4.0	7.6
480V/3 ϕ /20A	--	--	--	--	--	5.7
Specified Maximum Charging Conditions	120/20/12* 240/20**		240(3 ϕ)/20/8		240(1 ϕ)/20/12 480(3 ϕ)/20/8	

* Voltage(phase)/Current/Time

** Can be provided as option, but 120V/20A capability must be provided.

batteries, which are discharged in one to three hours of a SAE J227a schedule, perhaps two to three complete charge-discharge cycles could be completed each 24-hour period. This would allow about 20 charge-discharge cycles a week. If it can be shown that the charging process can be accelerated without affecting battery life, then the life-cycle test of a 400-600 cycle battery could be completed in a few months.

The method which is recommended for battery life tests consists of the following steps:

1. During the specified SAE J227a driving cycle test, record the profile of battery power. Convert this into a profile of specific power density.
2. Test several of the same type of batteries over the specific power density profile determined in Step 1. The batteries are to be charged in the same manner as by the on-board or external charger supplied by the vehicle manufacturer.
3. Terminate each discharge test when the battery cannot supply at least 95 percent of the power called for by the test apparatus. Each test terminated in this manner constitutes one deep discharge cycle.
4. The life cycle test is to be terminated when the simulated driving range falls to 75% of the original minimum range specification. For example, if the range requirement which the vehicle must meet is 50 km on the SAE J227a/C schedule and that is equivalent to 147 cycles, then the life of the battery is considered over when it can achieve fewer than 110 discharge cycles as defined in Step 3.

9.3 SAFETY REQUIREMENTS

Near-term vehicles may have difficulty meeting certain current Federal Motor Vehicle Safety Standards (FMVSS). Conversions of ICE-powered vehicles will be tested at the modified curb mass, which generally will be about 30 percent greater. Specially designed vehicles will generally not have the benefit of the large design and testing programs employed by the automobile manufacturers.

The FMVSS can be grouped into two broad categories: direct-injury related and "other." In the direct-injury related category are rules like FMVSS 201 (occupant protection), 202 (head restraints), 208 (occupant crash protection), etc. In the "other" category are many of the crash avoidance standards (101-118) and damageability standards, e.g., 215.

There is no reason why electric (and hybrid) vehicles cannot meet most of the standards, and there should be no exceptions allowed in the injury-related category. However, in the "other" category are two possible exceptions for near-term vehicles.

One exception is FMVSS 109, on tires, which requires testing up to 85 mph. This requirement should be modified for near-term vehicles if a tire with lower rolling friction would result.

A second exception relates to FMVSS 102 (transmission shift lever sequence, starter interlock, and transmission braking effect). FMVSS 102 requires that the engine must brake in one of the lower gears below 25 mph. This requirement should be waived for electric vehicles without regenerative braking.

Advanced vehicles should meet all applicable FMVSS.

There are at least five areas peculiar to electric and hybrid vehicles which must be addressed from a safety aspect.

First is shock hazard. The main propulsion battery should be electrically isolated from the vehicle chassis to reduce the chance of a person receiving a shock if a battery terminal is touched.

Second is explosion hazard. Lead-acid batteries may emit hydrogen and oxygen when they are charged, or during discharge if one or more cells have been reversed. Adequate ventilation must be provided to ensure that explosive mixtures do not accumulate. Additionally, the batteries must have explosion-proof caps, a standard item for automotive batteries.

Third, is electrolyte containment in a roll-over type of accident. It may be unrealistic to require that the battery electrolyte be contained in all accidents. However, in an accident in which the vehicle comes to rest upside down or on its side, the amount of corrosive or hazardous material entering the passenger compartment must be kept small.

Fourth is a motor runaway. Solid-state controllers sometimes fail in a short-circuit mode, which could have disastrous consequences if provision is not made for disconnecting the propulsion battery. Whether manual or automatic, this feature must be provided, and must also be checkable by the driver on a routine basis. For vehicles with a clutch, motor runaway presents less of a safety hazard, but the disconnect mechanism should still be provided.

Fifth is battery shorting, which could create high temperatures and fire hazards. Possible failure mechanisms are control circuit failures, electrical shorts caused by external objects during maintenance, and traffic accidents.

9.4 ACCESSORY LOADS

Accessories will impose additional electrical loads which must be furnished by either the propulsion battery or a separate accessory battery.

Representative accessory loads are shown in Table 9.2. Because passenger compartment heaters can require up to 1640 W (Ref. 11), this function will probably be provided by a gasoline or diesel-fuel heater. This still leaves the following loads to be supplied electrically: radio, blower, lights, wipers, power brakes, and power steering.

Air conditioners are also estimated to require about 1640 W, so it is not feasible to operate them on battery-electric vehicles, even with the nickel-zinc batteries. They can be operated from petroleum, however. The advanced hybrid vehicles described in Sec. 10 will be able to support the additional load of an air-conditioner.

TABLE 9.2
REPRESENTATIVE ACCESSORY LOADS FOR ELECTRIC VEHICLES¹¹

	<u>Load, W</u>
Radio	31
Blower	144
Headlights	154
Brake Lights	48
Wipers	55
Air Conditioner	1640
Power Brakes	10
Power Steering	70
Heater	<u>1640</u>
Total (with either air conditioner or heater)	2152
Total (without heater or air conditioner)	512

9.5 SUMMARY OF PERFORMANCE STANDARDS FOR NEAR-TERM VEHICLES

At this time it is unrealistic, and possibly ill-advised, to attempt to specify a value for each of the many criteria developed in Sec. 2. As one of the stipulations of the Electric and Hybrid Vehicle R&D Act of 1976 is to "assure that small business concerns have a realistic and adequate opportunity to participate in the project," the standards have been limited to those which we feel are the most important. These standards, then, do not constitute complete specifications for the vehicles, but rather specify the required performance. Performance, however, is interpreted to include factors such as number of passengers, payload; and safety.

Tables 9.3 and 9.4 summarize the standards developed in preceding sections for near-term and advanced vehicles. In some instances the criteria have been rounded up or down slightly. Also given are a number of design standards covered by various FMVSS.

The standards shown in Table 9.3 are limiting acceptable values. That is, they are minimums (maximums) which must (must not) be exceeded. In some instances, the appropriate Federal Motor Vehicle Safety Standard is specified, rather than a quantitative performance standard.

Table 9.5 shows test conditions which differ from those of SAE J227a.

TABLE 9.3

RECOMMENDED PERFORMANCE STANDARDS FOR NEAR-TERM ELECTRIC VEHICLES

<u>Standard</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Acceleration	Time to reach given speed	12 s to reach 50 km/h	15 s to reach 50 km/h
Gradeability	Speed which can be maintained on a given grade	30 km/h on 10% 40 km/h on 7%	25 km/h on 10% 35 km/h on 7%
	Maximum grade (forward and reverse directions)	20%	20%
Top Speed (for 5 min.)	Forward speed	75 km/h	75 km/h
	Reverse speed	10 km/h	10 km/h
Passenger Seating	Minimum number of seated passengers accommodated (including driver)	2 (75 kg each)	2 (75 kg each)
Cargo Capacity	Minimum load accommodated, mass and volume	30 kg and 0.2 m ³	230 kg and 1.5 m ³
Urban Range	Range on SAE urban driving schedule	50 km on J227a/C	50 km on J227a/B
	Range at constant speed	35 km at 70 km/h	45 km at 60 km/h
Rechargeability	Maximum allowable time for recharge	8 h using 120 Vac/20A source*	8 h using 240(3 ϕ) Vac/20A source**
	Automatic cutoff when full charge is reached	Required	Required

* On-board charger; additional 240 Vac capability may be provided.

** Charger need not be on board. On-board emergency 120 Vac charger may be provided.

Table 9.3 (Cont.)

<u>Standard</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Energy	Maximum energy input to charger for SAE schedule	0.90 MJ/km on J227a/C	7 kJ/km per kg of cargo capacity on J227a/B
Battery Cycle Life	Number of deep discharge cycles before excessive loss of capacity. See Sec. 9.2	400	400
Braking	--	FMVSS 105	FMVSS 105
Speed Control	Minimum number of vehicle speeds selectable by driver for driving on level roads	6	6
Maneuverability	Minimum turning diameter (curb to curb)	10 m	12 m
Adverse Weather	Extremes of ambient temperature within which vehicle shall meet acceleration, gradeability, top speed, and range requirements	-18°C to +50°C	-18°C to +50°C
Vital Accessories	Length of time lights and signals are operable following termination of range test	1 h	1 h
Exterior Lights	--	FMVSS 108	FMVSS 108
Odometer	--	Resettable trip	Resettable trip
State of Charge Meter	Current integrator or equivalent to indicate both charge and discharge Ah	Required	Required

Table 9.3 (Cont.)

<u>Standard</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Windows	--	FMVSS 205	FMVSS 205
Wipers	--	FMVSS 104	FMVSS 104
Washers	--	FMVSS 104	FMVSS 104
Rearview Mirrors	--	FMVSS 111	FMVSS 111
Defroster	--	FMVSS 103	FMVSS 103
Heating	Passenger Compartment Heating	Required as option	Required as option
Horn	--	Required	Required
Turn Signals	--	FMVSS 108	FMVSS 108
Sunshades	--	Required	Required
Reflectors	--	FMVSS 108	FMVSS 108
Battery Maintainability	--	Maintenance to require less than 2 h/month	
Safety	Crashworthiness	FMVSS 113, 201-212, 214, 216, 219, 301, 307	
	Damageability	FMVSS 215	
	Crash Avoidance	FMVSS 101-112, 114-116, 118, 124; see Sec. 913 for possible modifications to FMVSS 102 and FMVSS 109	
	Shock Hazard	Main propulsion battery must be electrically isolated from vehicle chassis	

Table 9.3 (Cont.)

<u>Standard</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
	Explosive Gas Accumulation	Positive ventilation to prevent accumulation of hazardous gas mixtures. Explosion-proof battery caps required	
	Corrosive Material	FMVSS 301 modified to include battery contents	
	Motor runaway	Provide positive mechanism for disconnecting propulsion battery from motor in the event of motor-controller short-circuit failure or loss of field current.	
	Battery Shorts	Provide automatic disconnect in event of battery short circuit	

TABLE 9.4

RECOMMENDED DEVELOPMENT SPECIFICATIONS FOR ADVANCED ELECTRIC VEHICLES

<u>Specification</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Acceleration	Time to reach given speed	10 s to reach 65 km/h	10 s to reach 65 km/h
Gradeability	Speed which can be maintained on a given grade	55 km/h on 10% 70 km/h on 7%	55 km/h on 10% 70 km/h on 7%
	Maximum grade (forward and reverse directions)	20%	20%
Top Speed (for 5 min.)	Forward speed	105 km/h	105 km/h
	Reverse speed	10 km/h	10 km/h
Passenger Seating	Minimum number of seated passengers accommodated (including driver)	4 (75 kg each)	2 (75 kg each)
Cargo Capacity	Minimum load accommodated, mass and volume	60 kg and 0.3 m ³	500 kg and 2.5 m ³
Urban Range	Range on SAE urban driving cycle	165 km on J227a/D	220 km on J227a/C
	Range at constant speed	170 km at 90 km/h	170 km at 90 km/h
		250 km at 70 km/h	250 km at 70 km/h
			370 km at 50 km/h
Rechargeability	Maximum allowable time for recharge	12 h using 240(1 ϕ) Vac/ 20A source*	8 h using 480(3 ϕ) Vac/ 20A source**

* On-board charger must have 120 V input in addition.

** Charger need not be on board; should have connection for 240 Vac(3 ϕ) input also. On-board 120V emergency charger provided.

Table 9.4 (Cont.)

<u>Specification</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Energy	Maximum energy input to charger	1.08 MJ/km on J227a/D	1.62 MJ/km on J227a/C
Battery Cycle Life	Number of deep discharge cycles before excessive loss of capacity; see Sec. 9.2	1000	1000
Braking	--	FMVSS 105	FMVSS 105
Speed Control	Minimum number of vehicle speeds selectable by driver for driving on level roads	6	6
Maneuverability	Minimum turning diameter (curb to curb)	10 m	12 m
Adverse Weather	Extremes of ambient temperature within which vehicle shall meet acceleration, gradeability, top speed, and range requirements	-18°C to +50°C	-18°C to +50°C
Vital Accessories	Length of time lights and signals are operable following termination of range test	1 h	1 h
Exterior Lights	--	FMVSS 108	FMVSS 108
Odometer	--	Resettable trip	Resettable trip
State of Charge Meter	Current integrator or equivalent to indicate both charge and discharge Ah	Required	Required

Table 9.4 (Cont.)

<u>Specification</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Windows	--	FMVSS 205	FMVSS 205
Wipers	--	FMVSS 104	FMVSS 104
Washers	--	FMVSS 104	FMVSS 104
Rearview Mirrors	--	FMVSS 111	FMVSS 111
Defroster	--	FMVSS 103	FMVSS 103
Heating	Passenger Compartment Heating	Required as option	Required as option
Horn	--	Required	Required
Turn Signals	--	FMVSS 108	FMVSS 108
Sunshades	--	Required	Required
Reflectors	--	FMVSS 108	FMVSS 108
Battery	--	Propulsion battery shall have a single-point watering and gas venting system	
Maintainability			
Safety	Crashworthiness	FMVSS 113, 201-212, 214, 216, 219, 301, 307	
	Damageability	FMVSS 215	
	Crash Avoidance	FMVSS 101-112, 114-116, 118, 124; see Sec. 9.3 for possible modifications to FMVSS 102 and FMVSS 109	
	Shock Hazard	Main propulsion battery must be electrically isolated from vehicle chassis	

Table 9.4 (Concl.)

<u>Specification</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
	Explosive Gas Accumulation	Positive ventilation to prevent accumulation of hazardous gas mixtures, explosion-proof battery caps required	
	Corrosive Material	FMVSS 301 modified to include battery contents	
	Motor Runaway	Provide positive mechanism for disconnecting propulsion battery from motor in the event of motor-controller short circuit failure or loss of field current	
	Battery Shorts	Provide automatic disconnect in event of battery short circuit	

TABLE 9.5
TEST CONDITIONS

<u>Standard</u>	<u>Condition</u>	<u>Criteria</u>
Acceleration	Battery state	Acceleration requirements are to be met at full charge and 80% discharge.*
Top Speed	Battery state	Tables 9.3 and 9.4 requirements to be met at full charge and 40% discharge.*
Acceleration, Top Speed, and Range	Ambient Temperature	Tables 9.3 and 9.4 requirements to be met throughout range of ambient temperature, with preheating of vehicle to 20°C and batteries to 27°C prior to tests allowed.
All	Payload	All tests to be performed with load equivalent to maximum required payload (passengers plus cargo)
All		SAE J227a Electric Vehicle Test Procedure shall apply to cases not covered by above criteria
All	Accessory load during acceleration, grade-ability, top speed, and range tests	Near-term electric and hybrid vehicles: 512 W Advanced electric vehicles: 512 W Advanced hybrid vehicles: 2152 W

* See SAE J227a Specification, Paragraph 3.2.4 for definition of battery discharge.

10 HYBRID VEHICLES

The standards set forth in the previous section indicate that the performance of electric vehicles, particularly for the near-term period, will be substantially below that of ICE-powered vehicles. A question which naturally arises is, "Can hybrid vehicles provide some of the performance and amenities lacking in near-term electric vehicles and still have the potential of meeting the primary goal of PL 94-413"? (The primary goal of PL 94-413 is to reduce the nation's dependence upon foreign sources of petroleum through the substitution of [non-petroleum-generated] electricity for petroleum in the transportation sector.)

Section 3 of PL 94-413 defines a hybrid vehicle as "...a vehicle propelled by a combination of an electric motor and an internal combustion engine or other power source and components thereof." For the purposes of this study, we have assumed that a hybrid vehicle is "refueled" by both electrical energy and petroleum and must derive a "substantial" portion of its range from the electrical source. The definition of "substantial" will be discussed in Sec. 10.4.

Ideally, a hybrid vehicle should meet the following goals:

1. Have the performance of a conventional car
2. Use less petroleum than a conventional car of comparable size and performance (by substituting electrical energy for petroleum)
3. Have first cost and life-cycle costs competitive with those of conventional cars

From the limited test data available and the few detailed simulations of hybrids reported in the literature, it appears that building a vehicle meeting even the first two of these goals may be a difficult task.

It is apparent that a heat-engine hybrid can be designed which will be competitive with conventional cars in acceleration (and gradeability), top speed, and amenities. If the size of the heat engine is not restricted, any reasonable standards for these performance characteristics should present no problem to the designer. The key issues which we will address, then, are keeping the heat engine's fuel consumption low, and obtaining an appreciable fraction of the range from the electric motor. Unfortunately, these requirements appear to be inherently incompatible for the following reasons.

The basic principle used to achieve low fuel consumption in a hybrid vehicle is to operate the heat engine in an efficient regime.* Several methods have been proposed to do this:

1. To use an on-board reversible energy storage system to permit (more nearly) optimum engine operation over a wide load range

* All fuel consumption values in this section are "on-board" or input to the fuel tank and not fuel consumption at the utility generating station.

by sharing the load between the engine and the energy storage system. (This also permits a smaller heat engine to be used, which is generally more efficient to operate since it runs nearer its capacity.)

2. To use the energy storage system for regenerative braking.
3. To shut off the heat engine during deceleration and dwell, and to use the stored energy to accelerate the vehicle to a speed at which the heat engine operates efficiently and to start the heat engine.

Inherent in these strategies is the use of the energy storage device as a peak leveler. Thus in a heat-engine/battery-electric hybrid, the batteries are used to provide the peak loads so that the heat engine can provide the "average load." But the nature of storage batteries is that the total energy delivered decreases rapidly with increasing rate of delivery. This is easily seen from Fig. 3.1 which shows, for example, that the energy available at the five-hour rate is about 1.4 times that available at the one-hour rate (this ratio applies to all four of the batteries shown in Fig. 3.1).

Thus to minimize fuel consumption we need to use the batteries as a peak leveler, but to maximize the energy delivered by the batteries (and the range from electricity) we need to use the heat engine as a peak leveler. The extent to which these opposing goals can be simultaneously achieved is not clear at this time.

The remainder of this section discusses the state of the art of hybrids, and then develops the rationale for the hybrid vehicle performance standards which are recommended.

10.1 HYBRID STATE OF THE ART

Few reports are available on hybrid-fueled vehicles. This lack of data reflects to some extent the changing priorities in our urban transportation system. In the 1960s and early 1970s, several hybrid vehicles were designed or proposed to reduce exhaust emissions. Some of these vehicles used batteries for temporary energy storage, but they generally were designed to recharge the batteries with the heat engine, using petroleum fuel as the source of energy. Although these vehicles could be modified to have the batteries recharged from an external source, and thus be hybrid-fueled vehicles, sufficient information is not generally available to predict how well they would perform with substantially discharged batteries. Generally, though, it appears that the energy carried in the batteries was only enough to provide up to 30 kilometers additional range, with considerable deterioration in acceleration and top speed.

In 1974, emphasis shifted somewhat from reducing emissions to reducing petroleum usage. Few, if any, vehicles have been designed which accomplish this goal and still retain performance comparable to that of ICE vehicles.

This section describes several hybrid vehicles which have been built. Test data is generally lacking. Table 10.1 summarizes the characteristics and performance of the hybrids discussed in this section. Several other hybrids for which less information is available are listed in Appendix J.

Three hybrid vehicles were designed by General Motors in the late 1960s. Two were series-configuration hybrids,* Stir-Lec I and II, using Stirling heat engines.⁵⁸ Stir-Lec I used a three-phase alternator and a rectifier to charge the battery, which powered an inverter and three-phase AC traction motor. In Stir-Lec II the inverter and AC motor were replaced by a SCR chopper and a DC motor.

The third GM hybrid vehicle was one of the three GM-512 special-purpose urban cars (the other two were ICE- and battery-powered).³² This vehicle had very little range on batteries alone (60 kg of batteries for a mass fraction of 0.085 with two passengers) and traveled only 24 km in city traffic (two stops per mile, maximum speed of 50 km/h in the hybrid mode. This was about one-half the range achieved by the electric GM-512 (see Table 5.2) on the same driving schedule.

A more recent hybrid is the Volkswagen hybrid bus described by J.P. Altendorf at the Fourth International Automotive Propulsion System Symposium.⁵⁹ This vehicle uses a parallel configuration, and was designed primarily to minimize noise and emissions. Its acceleration, top speed, and range are superior to that of a similar all-electric vehicle developed by Volkswagen. However, it uses more fuel than the equivalent ICE-only Volkswagen bus. Two reasons are given for the increased fuel consumption. First, the portion of total energy which flows from the gas tank through the engine to the motor-generator to the battery, and then back through the motor-generator to the wheels, is not being used efficiently. Second, a hybrid vehicle will always be heavier than a conventional vehicle with the same payload.

The fuel consumption of the conventional (ICE-powered) Volkswagen bus is about 0.120 l/km (19.6 mpg), or only about 60 percent of that required by the hybrid vehicle.

A series-hybrid which is very unsophisticated when compared with the Volkswagen just described was built by Dr. Karl V. Kordes of

* A series configuration is one in which all energy to the wheels must go through the traction motor; a parallel configuration has two paths by which energy can reach the wheels, usually some form of power-splitter transmission which essentially sums the outputs of the motor and the heat engine.

TABLE 10.1
SUMMARY OF HYBRID VEHICLE CHARACTERISTICS

Vehicle (Ref.):	Stir-Lec I ⁵⁸	Stir-Lec II ⁴³	GM-512 ³²	Volkswagen ⁵⁹	Kordesch [*]	Petro- ⁶⁰⁻⁶² Electric	AM ^{63,64} General DJ-5C
Gross Mass, kg	1455	1455	731	2369	1000	2040	1775
Heat Engine, Cycle	6kW, Stirling	6kW, Stirling	3.75kW, Otto	40kW, Otto	7kW, Otto	97kW, Wankel	18.6kW, Otto
Battery:							
Type	SLI	SLI	SLI	SLI	SLI	SLI	SLI
Mass Fraction	0.153	0.153	0.082	--	0.18	0.067	0.11
Configuration	Series	Series	Parallel	Parallel	Series	Parallel	Parallel
No. Passengers (inc. driver)	4	4	2	8	2	4	2
Time to Accelerate to 50 km/h:							
Batteries alone	--	--	33	--	--	--	--
Engine Running	10.7	9.1	16.7	8.5	12	6.0	15.7
Max Speed, km/h:							
Batteries only	48	48	50	70	--	--	--
With Heat Engine	88	97	50	104	100	--	79
Range (at 50 km/h):							
Batteries only, km	40	40	8	--	40	--	15-30
With Heat Engine	320	320	300	80 ^{**}	>100	--	--
Fuel Consumption:							
l/100/km	5.9-7.8 [†]	5.9-7.8 [†]	4.7-5.9 ⁻	2.09 ^{**}	5.†	25.	7-29 ⁺⁺
(mi/gal)	(30-40)	(30-40)	(40-50)	(11.3)	(50)	(9.4)	(8.1-33.6)

* Information obtained from Dr. Karl V. Kordesch, (216) 221-6870.

** Fakra cycle (See Appendix C), maximum charging current 30A.

† At 50 km/h

++ "City traffic"

Lakewood, Ohio.* This is essentially an all-electric vehicle to which a commercially available (Sears) gasoline engine and alternator have been added. The maximum alternator output is 7 kW. When rectified (120 VDC), this is sufficient to power the vehicle at about 70 km/h. On batteries alone, the Kordesch vehicle will go about 40 km at 50 km/h. With the heat engine running, the range is increased to about 230 km, with a fuel consumption of about 0.05 l/km (50 mpg). The acceleration capability with the alternator running and fully charged batteries is 0-65 km/h in 20 s, or 0-50 km/h in about 12 s.

Vehicle mass (two passengers) is 1000 kg, of which the batteries (eight 12V, 100 Ah Globe-Union SLI units) constitute 18 percent and the engine-alternator about 9 percent.

In addition to the Volkswagen bus and the Kordesch hybrid, which represent extremes in hybrid sophistication, there have been several other hybrids built in recent years. Of these, one for which appreciable testing has been reported is the Petro-Electric Motors hybrid.⁶⁰ The Petro-Electric uses a parallel-configuration hybrid with a Wankel engine and an electric motor-generator on a common shaft. The basic control strategy is to maintain the Wankel's manifold pressure at a preselected value throughout the driving cycle.

Gould Laboratories modified and tested for the US Postal Service an AM General DJ-5C postal van.^{63,64} A parallel configuration, the vehicle used an 18.6 kW Onan gasoline engine directly coupled to a 72 VDC separately excited motor-generator. These combined units drive a continuously variable ratio hydrostatic transmission which is connected to the differential. Twelve automotive batteries with a total mass of 196 kg are the energy storage system.

This vehicle had improved acceleration, gradeability, top speed, and constant-speed range compared to the AM General DJ-5E electric postal van. However, when compared with its ICE-powered counterpart (the DJ-5D), the hybrid was less promising. Fuel consumption was 0.14 l/km (16.8 mpg) versus 0.12 l/km (19.6 mpg) for the DJ-5D, both at 40 km/h. Curb weights for the vehicles were 1498 kg (DJ-5C) and 1174 kg (DJ-5D). The greater fuel consumption is probably due to the increased vehicle weight, which can account for as much as 0.06 l/km.**

* The information reported here on the Kordesch hybrid was obtained from Dr. Kordesch.

** Assuming a tire friction coefficient of 0.15 N/kg (1.5 percent), the increased power at the wheels is 540 W. The engine-transmission efficiency at 40 km/h is 0.105 and the engine specific fuel consumption is 0.34 kg/kWh (0.56 lb/hp-h), 64 resulting in fuel consumption of 0.06 l/km.

Gould concluded that the tests of the DJ-5C hybrid demonstrated the potential of the system. Recommended improvements included an improved engine with reduced noise and emissions, a different hydrostatic transmission with reduced weight and losses and higher torque, and the development of methods to eliminate the high-no-load losses which occurred during the fast idle periods.

Although none of the vehicles summarized in Table 10.1 were designed to run on batteries alone for their primary mode of travel, it is interesting to estimate their range on the SAE J227a/C schedule, based on their battery mass fractions. Using Eq. 3.15 with the range factor $k_1 = 7$ (the state of the art value for the electric vehicles reviewed in Sec. 5), $R_c = 0.55$ km, and $P_1 = 23$ W/kg, the estimated "batteries only" ranges are shown in Table 10.2. (The hybrids in Table 10.1 all used SLI batteries, for which P_1 is greater than 23 W/kg, the present value for golf-cart batteries. However, SLI batteries cannot be discharged as deeply as golf-cart batteries without severely curtailing their life, so the above range estimates are probably reasonable.) The significance of Table 10.2 is the indication that some hybrids could derive a substantial portion of their average daily range from electrical sources: the average car travels about 47 km each day (Sec. 6.3). It is not clear that their power-related performance (acceleration, top speed, gradeability) would remain the same with substantially discharged batteries.

TABLE 10.2
ESTIMATED RANGE OF HYBRIDS OPERATING ON
BATTERIES ALONE (SCHEDULE SAE J227a/C)

<u>Vehicle</u>	<u>Battery Mass Fraction</u>	<u>Range, km</u>
Petro-Electric	0.067	7
GM-512	0.082	9
AM-General DJ-5C	0.110	14
Stir-Lec	0.153	21
Kordesch	0.180	27

In summary, most hybrids which have been demonstrated were built to lower exhaust emissions. The few which were designed to lower fuel consumption have not yet been able to do so. However, hybrids are in a less developed state than electric vehicles, and it is possible that significant improvements will occur with further development.

10.2 REVIEW OF KEY HYBRID SIMULATIONS

The preceding section indicated that the few hybrids which have been built and tested have generally exhibited relatively high fuel consumption. To see if this problem is inherent, it is worthwhile to review briefly the results of computer simulations of hybrid performance.

Unnewehr and his coworkers at Ford have conducted detailed simulations of many vehicles to determine which, if any, configurations and strategies are promising (in terms of emissions and fuel consumption) relative to conventional and electric vehicles.⁶⁵ They took into account the effect of regenerative braking (assuming an increase of 1.135 in range for the EPA city cycle) and the net increase in vehicle mass (due to hybrid components) to define a vehicle system efficiency:

$$\eta_{\text{sys}} = \eta_{\text{net}} \frac{\text{regenerative factor}}{\text{mass penalty factor}} \quad (10.1)$$

The mass penalty factor was applied to the denominator of Eq. 10.1 because the energy used on the city cycle scales nearly directly with vehicle mass for the range of vehicle sizes considered (1134 kg - 2495 kg). Table 10.3 shows the comparative efficiencies of conventional vehicles and several series hybrids. The "on-off" strategy refers to cutting off fuel flow to the engine during periods of coasting, braking, and dwell. Efficiencies are shown in Table 10.3 for a "continuous" strategy with the heat engine/generator providing 25, 50, or 75 percent of the average required power. Note that the trend in Table 10.3 is for efficiency to increase as less energy is put through the battery. Also, in the more efficient configurations, the hybrid vehicle is benefiting mostly from regenerative braking rather than from operating the heat engine in a more efficient mode.

It is generally recognized that parallel-configuration hybrids have the potential for greater economy since the relatively insufficient path from the heat engine through the motor is eliminated for some of the energy. Table 10.4 compares system efficiencies for parallel hybrids from the study by Unnewehr and coworkers.⁶⁵

Table 10.4 indicates that several of the parallel hybrids considered have greater estimated system efficiencies than a conventional vehicle. The Bosch hybrid in Table 10.4 operates with the engine off

TABLE 10.3²²
CONVENTIONAL AND SERIES-HYBRID VEHICLE STRATEGIES
(EPA City Cycle)

<u>Configuration</u>	<u>Strategy</u>	<u>Energy Through Battery, %</u>	<u>η_{NET} *</u>	<u>Regener- ative Braking Factor</u>	<u>Weight Penalty Factor</u>	<u>η_{SYS}</u>
Conventional	--	--	0.136	1.	1.	0.136
Hybrid	on-off	100	0.120	1.135	1.4	0.097
"	"	100	0.120	1.135	1.2	0.113
"	continuous	75	0.126	1.135	1.4	0.102
"	"	50	0.134	1.135	1.3	0.117
"	"	25	0.141	1.135	1.2	0.133

* Assumes a differential efficiency of 0.95 for all vehicles.

below about 30 km/h.⁶⁶ Nickel-cadmium batteries with a mass of 202 kg provide the electrical energy. The hybrid components increase the vehicle mass by 400 kg. If the batteries become totally discharged the vehicle must be stopped and the batteries recharged through the motor-generator. It does not appear that this type of hybrid would lend itself well to saving fuel by the substitution of electrical energy, as the range on batteries only is just 21 km.

The Ford A strategy in Table 10.4 is one in which no transmission is used. Nickel-cadmium batteries sufficient to provide 45 kW power and 1.8 MJ (0.5 kWh) are the energy storage system.⁶⁵ As shown in Appendix G, the approximate battery energy requirement for the EPA city cycle is about 0.420 MJ/km·t. Thus for the vehicle (total mass of 2041 kg) the energy requirement is 0.86 MJ/km. By discharging the batteries, the range increment would be no more than about 2 km. With lead-acid batteries, both the acceleration and range extension would be less.

The Ford B strategy is one in which the regenerative braking energy is enough to keep the battery charged (on the EPA City Cycle). Additional energy from external sources is not required for battery charging.

TABLE 10.4⁶⁵
CONVENTIONAL AND PARALLEL-HYBRID VEHICLE STRATEGIES

(EPA City Cycle)						
Strategy	Heat Engine Energy Through Electrical System, %	Electrical Energy Through Battery, %	η_{NET}^*	Regener- ative Factor	Weight Penalty Factor	η_{SYS}
Conventional	--	--	0.136	1.0	1.0	0.136
Hybrid, continuous	75	50	0.155	1.135	1.4	0.126
" "	50	50	0.187	1.135	1.3	0.163
" "	25	50	0.219	1.135	1.2	0.208
" "	25	50	0.210	1.135	1.1	0.226
Hybrid, on-off (Bosch)	75	100	0.141	1.135	1.2	0.133
Hybrid, on-off (Bosch)	50	100	0.174	1.135	1.1	0.179
Hybrid, on-off (Ford A)	15	100	0.199	1.135	1.02	0.221
Hybrid on-off (Ford B)	0	100	0.233	1.135	1.06	0.240

* Assumes a differential efficiency of 0.95 for all vehicles.

The Ford work indicates that hybrid vehicles have a substantial potential for saving fuel, although not necessarily by substitution of electricity for petroleum. In Sec. 10.4 we will investigate the potential of substitution.

10.3 DESIGN OF HYPOTHETICAL NEAR-TERM HYBRIDS

Table 10.1 indicates that the existing hybrids with performance near that of conventional vehicles (Volkswagen, Petro-Electric, and DJ-5C) have relatively high fuel consumption. However, the work reported in Sec. 10.2 indicates that hybrids with lower fuel consumption may be feasible, although substitution (of electrical for petroleum energy) may not be the method employed.

Based on these observations, we believe that it would be ill-advised to specify performance like that of conventional vehicles (specifically acceleration, top speed, and capacity) for near-term hybrids.

For this reason we consider in this section a hybrid which is essentially an electric vehicle with extended range. To achieve a low average petroleum fuel consumption, it is envisaged that the vehicle would operate on batteries alone for a specified range, switching to the hybrid mode when the batteries are discharged to a given level. Note, though, that the resulting performance standards will not require battery-only operation.

To determine what portion of annual driving could be done in the electric mode, we used techniques similar to those used to produce Fig. 6.1.

Using a Monte Carlo simulation technique, we went through the following process:

1. For a given day of the year, the number of trips is drawn from a Poisson distribution (average 3.135 trips per day).
2. For each trip a trip length is drawn from the distribution of percent of annual trips versus trip length in Table 6.1.
3. When the total of trip lengths exceeds the electric-mode range, the vehicle is assumed to switch to the hybrid mode for the remainder of the day.*
4. Steps 1 through 3 are repeated for 365 days.
5. Steps 1 through 4 are repeated 100 times.**

* This can occur during a trip. From then on, the batteries may be used for short periods requiring more power than available from the heat engine, but on the average no more energy is drawn from the batteries.

** Schwartz used 400 iterations to arrive at Fig. 6.1. We found only negligible differences in the travel statistics after 100 iterations, so to save computer time all trials were terminated at that point.

The above procedure was performed for two annual driving distances: 16,386 km (10,184 miles) as used by Schwartz for his base case and 26,401 km (16,409 miles). The latter distance is believed to be representative of the distances traveled by newer cars.⁷⁰ Lacking specific data on the distributions of trip frequency and trip length for the increased annual distance, we assumed that both the frequency of trips and the average trip length would increase by the square root of the increased distance factor. For example, in the case of 25,744 km/year, the average number of trips/day was increased from 3.135 to 3.934 and the average trip lengths shown in Table 6.1 were each increased by a factor of 1.255 ($= \sqrt{25,747/16,386}$). This assumption was adopted because it seems reasonable that new cars are used more frequently and for longer trips than older cars.

Figure 10.1 shows the results of the above analysis. Based on the distributions shown on Fig. 10.1, a hybrid vehicle which can be operated in an electric mode has the potential to conserve appreciable petroleum because about 50 percent of the annual driving can be done in the electric mode. Presumably much of the driving done in the hybrid mode would be on the highway, where the heat engine can operate efficiently. Thus the annual fuel consumption of a vehicle with an electric/hybrid mode could potentially be less than half of that used by a conventional vehicle. The hypothetical design of such a hybrid will be addressed in the remainder of this section.

Figure 10.1. Distance Traveled in All-Electric Mode by Battery Heat-Engine Hybrid

Table 10.5 shows the characteristics assumed for the near-term hybrid vehicles. Note that the first three are the same as those assumed for electric vehicles. The following approach consists of replacing some of the batteries from the electric vehicles described in Secs. 7 and 8 with a heat engine and alternator/rectifier (for the series configurations) of equivalent mass.* Thus the total weight of the vehicle is held constant so that we can compare the hybrid vehicle's performance with its electric counterpart. Note, too, that the structural weight fraction is the same for the near-term hybrids and their electric counterparts. All vehicles are assumed to have the capability for operation on batteries alone for a range which will be less than that of electric vehicle because of the reduced battery fraction.

The remainder of this section is devoted to a gross design of near-term hybrids. The purpose of including the resulting detail is to show that successful hybrids are feasible, although there are difficulties related to the maximum power density of near-term (lead-acid) batteries. Figure 10.2 is a block diagram which will help the reader follow the design steps.

The near-term private electric vehicle specified in Table 9.3 has a minimum-range standard of 50 km on the SAE J227a/C schedule. Assume that it is desired to extend its capability by the addition of a heat-engine alternator combination which will allow indefinite cruising (subject to the amount of fuel carried) at the top speed of 75 km/h. The specific power at the wheels required for steady speed is

$$P_W/M_V = V \left(C_1 + \rho \frac{C_D A V^2}{2M_V} \right) \quad (10.2)$$

which gives 8.3 W/kg for the near-term private electric vehicle.

The heat engine output (for series configuration) will be

$$\begin{aligned} P_{HE} &= \frac{P_W}{\eta_D \eta_M \eta_G} + P_{ACC} \\ &= \frac{8300}{0.8 \times 0.75 \times 0.85} + 512 \\ &= 16.8 \text{ kW} \end{aligned}$$

* Parallel-type hybrids would not necessarily have an alternator, as the heat engine could be coupled directly to the driving wheels.

TABLE 10.5
CHARACTERISTICS OF HYPOTHETICAL NEAR-TERM HYBRID VEHICLES

	<u>Private</u>	<u>Commercial</u>
Minimum Capacity, passengers (including driver)	2	2
Gross Vehicle Mass, kg	1000	1900
Capacity, freight, kg	30	230
Battery-Heat Engine-Alternator Mass, kg	300	475
Tire Friction, N/kg	0.16	0.12
Drag-Area Product, m ²	0.9	1.5
Battery Energy Density (l-h), kJ/kg	83(23 Wh/kg)	83(23 Wh/kg)
Battery Charger Efficiency	0.7	0.7
Battery Charge/Discharge Efficiency	0.75	0.75
Regenerative Braking	no	no
Average Motor-Controller Efficiency*	0.75	0.75
Average Driveline Efficiency*	0.8	0.8
Alternator-Rectifier Efficiency	0.85	0.85
Heat Engine SFC, l/MJ (lb/bhp·h)	0.148(0.66)	0.148(0.66)
Accessories Load, W**	512	512

* Averaged over the appropriate J227a driving schedule.

** Included in accessory load are radio, heater blower, lights, wipers, power brakes, and power steering. These values are taken from Table 9.2.

Figure 10.2. Design Process for Near-Term Hybrid Vehicles

From Fig. 10.3, the specific mass of the heat engine is 2.9 kg/kW. To the mass of the engine must be added the mass of oil, water, radiator, and fuel. Let the total mass of the heat engine and its accessories be

$$2.9 \times 16.8 + (10)_{\text{radiator}} + (3)_{\text{water}} + (1)_{\text{oil}} + (15)_{\text{fuel}} = 78 \text{ kg}$$

The alternator output will be $\eta_{\text{G}} P_{\text{HE}}$, which is 14.3 kW. The mass of the alternator, based on Fig. 10.4, is 20.5 kg. Thus the total mass of the hybrid components is 98.5 kg. The battery fraction in the hybrid will be

$$f = \left(\frac{300 - 98.5}{1000} \right) = 0.201$$

Before proceeding with fuel consumption calculations, it is necessary to check the power density required for the hybrid. The maximum power density will most probably occur at the end of the 0-50 km/h acceleration. The specific power at the wheels is composed of the steady-speed drag portion (Eq. 10.2) and the power required to accelerate the vehicle. Assuming constant power at the wheels, we can use Eq. 3.1 to calculate the latter component. Thus the specific power at the wheels is*

$$P_{\text{W}}/M_{\text{V}} = v \left(C_1 + \frac{C_{\text{D}} A v^2}{2M_{\text{V}}} \right) + \frac{v^2}{2t} \quad (10.3)$$

For $v = 50 \text{ km/h}$ (13.8 m/s) and $t = 12 \text{ s}$, Eq. 10.3 gives

$$P_{\text{W}}/M_{\text{V}} = 11.7 \text{ W/kg}$$

The required specific power density of the battery will be

$$P_{\text{D}} = \frac{11.7}{\eta_{\text{D}} \eta_{\text{M}} f} = \frac{11.7}{0.8 \times 0.75 \times 0.201} \\ = 97.3 \text{ W/kg.}$$

* The power required at the wheels during acceleration is strongly dependent upon the acceleration profile used (constant acceleration, decreasing acceleration, etc., see Appendix G). The approach used in Eq. 10.3 yields results which are reasonably accurate.

Figure 10.3. Specific Mass of Reciprocating Spark Ignition Engines⁶⁷

Figure 10.4. Mass of 6000-rpm Generators Not Designed for Overload⁶⁸

To see if this is reasonable, it is necessary to determine the power density of near-term lead-acid batteries as a function of state of charge. As lead-acid batteries are discharged, their open-circuit terminal voltage decreases and their internal resistance changes, generally increasing. Quantitative data for electric-vehicle batteries are contained in the Gould Battery Handbook.⁶⁹ Based on these data, we show in Table 10.6 the characteristics which can be expected of near-term lead-acid electric vehicle batteries. The table indicates that maximum power densities in excess of 100 W/kg are possible if the battery is discharged less than 60-70 percent. However, since most existing electric vehicles limit the maximum current to 200-400A, it appears that the high power densities shown in Table 10.6 are achievable only at considerable cost due to higher-capacity power electronics, probably reduced battery life, and possibly a different motor design.*

The maximum power densities shown in Table 10.6 are not unrealistic for lead-acid batteries. For example, a Gould HDP (Heavy Duty Power) 24F-GP-81 12V tractor battery has a 450A rating of 30 seconds at 0°F temperature. During this period, the terminal voltage must remain above 7.2V, so the power output is at least 3240 W. Based on a battery mass of 20.4 kg, the power density is 158.5 W/kg. At a higher temperature the power density would be even greater.

Table 10.6 indicates that an EV-106 might provide the hybrid with the power for the 0-50 km/h acceleration in 12 seconds, but only to a depth of discharge of 60 percent. The current at maximum power density is very high, higher than allowed in any designs of which we are aware. Thus an alternative approach will be taken. The following approaches are possible:

1. Decrease the required acceleration. It is already very modest, so this does not appear to be attractive.
2. Use an air-cooled engine/alternator which is appreciably lighter than shown in Figs. 10.3 and 10.4. We will leave this approach to the vehicle designer.
3. Consider a parallel configuration. This will decrease the load on a battery by lessening the mass of the heat engine and eliminating the alternator altogether.

The third approach appears potentially viable. Repeating the appropriate steps, we get

* Since maximum power occurs when the terminal voltage is one-half the open-circuit value, motors would have to be designed to deliver maximum power at reduced voltage. Generally low-voltage, high-current motors are more expensive and less efficient than high-voltage, low-current motors of the same power rating.

TABLE 10.6
CALCULATED CHARACTERISTICS FOR AN EV-106 GOLF CART BATTERY
AS A FUNCTION OF PERCENTAGE OF DISCHARGE

Depth of Discharge, [*] percent	Open-Circuit Voltage, V	Internal Resistance, [†] m Ω	Maximum Power ^{**} Density, W/kg	Current at Maximum Power Density, A
0	2.18	1.50	133	727
20	2.07	1.37	131	755
40	2.02	1.37	125	737
60	1.98	1.56	105	635
80	1.94	1.89	83	513
90	1.91	2.36	65	405

^{*} Discharged at a 6-hour rate for a 100 Ah battery at 77°F.

^{**} The EV-106 weighs 29.5 kg and has a 6-h capacity of 165 Ah. To calculate maximum power density, it was assumed that a 6V battery with the characteristics shown here would weigh $29.5 \times (100/165) = 17.9$ kg.

[†] The internal resistance shown here is that exhibited for currents of up to 300A from a 100-Ah golf-cart battery. The comparable current level for an EV-105 is $300 \times 1.65 = 495$ A. We have no data to indicate whether these internal resistances will remain constant up to the current at maximum power density.

$$P_{HE} = \frac{8.3}{0.8} + 0.5 = 10.9 \text{ kW}$$

The specific mass is 3.4 kg/kW (Fig. 10.3). Keeping the same masses for water, oil, radiator, and fuel, and adding 15 kg for a more complicated transmission,* gives a total heat engine weight of 81 kg. Since no alternator is needed, the battery fraction is

$$f = \frac{219}{1000} = 0.219$$

The maximum specified power density for the battery is now

$$P_D = \frac{11.7}{0.8 \times 0.75 \times 0.219} = 89 \text{ W/kg}$$

Reference to Table 10.6 indicates that we can now discharge to a depth of 70 percent. Since there is uncertainty in many of the parameters given in Table 10.5, we will accept the above alternative (parallel configuration) as our hypothetical design, recognizing that it may be marginal.

Since battery-powered range scales as battery fraction to the 1.36 power (Eq. 3.15), the battery-only range will be

$$R = 50 \times \left(\frac{0.219}{0.300} \right)^{1.36} = 33 \text{ km}$$

From Fig. 10.1, the fraction of electric driving during the year will be 0.50.

The petroleum consumption when the engine is operating will be

$$W_F = w_F \times 10.9 = 5.81 \text{ l/h}$$

At a speed of 75 km/h, the petroleum consumption is

$$F_P = 5.81/75 = 0.08 \text{ l/km (30 mpg)}$$

* With a parallel configuration, some form of continuously-variable ratio transmission may be required.

On an annual basis the vehicle will travel 50 percent on batteries and 50 percent on petroleum. Thus the average fuel (petroleum) consumption will be

$$F_p = 0.50 \times 0.08 = 0.04 \text{ l/km (59 mpg)}$$

To arrive at an urban range performance standard for this vehicle, we will require that it complete at least 50 cycles of the J227a/C schedule (about 33 km). After completing 50 cycles of the SAE J227a/C schedule the vehicle must be able to maintain 75 km/h for at least 33 km. The electrical energy (input to the charger) for this test must not exceed

$$0.9 \times 0.5 = 0.45 \text{ MJ/km}$$

where 0.9 MJ/km is the energy specification for the electric vehicle. The fuel consumption for this test is not to exceed

$$0.08 \times 0.5 = 0.04 \text{ l/km (59 mpg)}$$

The total energy required to refuel and recharge the vehicle after the above range test should not exceed (using 32.7 MJ/l as the energy equivalent of gasoline):⁶⁵

$$(0.45 + 32.7 \times 0.04)66 = 116 \text{ MJ (32 kWh)}$$

of which at least 26 percent ($0.45 \times 66/116$) must be electrical.

Hypothetical Near-Term Commercial Hybrid

It is not clear that the heat engine for this vehicle should be sized for the capability to cruise at the top speed, as we did for the private hybrid vehicle. It probably makes more sense to try to extend the range on the J227a/B schedule. Let us assume that we want to have the basic acceleration capability of the electric, 0-50 km/h in 15 seconds. Proceeding as we did previously,

$$P_w/M_v = 9.9 \text{ W/kg}$$

And (for the parallel configuration),

$$P_{HE} = \frac{9.9 \times 1900}{0.8} + 512 = 24 \text{ kW}$$

From Fig. 10.3, the heat engine specific mass is 2.5 kg/kW. The total heat engine mass is about

$$24 \times 2.5 + (15)_{\text{radiator}} + (7)_{\text{water}} + (2)_{\text{oil}} + (20)_{\text{fuel}} \\ + (15)_{\text{trans}} = 119 \text{ kg}$$

The battery fraction will be

$$f = \frac{1900 \times 0.25 - 119}{1900} = 0.187$$

Checking the maximum battery specific power density, we get

$$P_D = \frac{9.9}{0.8 \times 0.75 \times 0.187} = 88 \text{ W/kg}$$

which is considerably higher than we would like to have. However, with this vehicle we have a margin of battery fraction. The near-term commercial design was based on a battery fraction of 0.25. Structurally, 0.3 is still reasonable. Thus if we back off to $f = 0.3$ to base the hybrid design on, the battery fraction becomes

$$f = \frac{1900 \times 0.3 - 119}{1900} = 0.237$$

and

$$P_D = \frac{9.9}{0.8 \times 0.75 \times 0.237} = 70 \text{ W/kg}$$

which is still higher than we would like, but perhaps adequate.

The range over the J227a/B schedule is 46 km, slightly less than the 50 km estimated for the electric vehicle, since the latter design was

based on $f = 0.25$ and the hybrid fraction is now $f = 0.237$. Thus we can expect about 49 percent of the annual travel to be electric (based on a 46 km range and 26,401 km annual travel in Fig. 10.1).

Although the heat engine is sized to provide the peak acceleration, the fuel consumption is determined primarily by the energy required to propel the vehicle through the driving schedule. The heat engine energy requirement (at its output) can be estimated from the normalized energy requirement ($k_2 = 0.5$ kJ/km·kg for the near-term commercial vehicle) and the estimated motor efficiency of 0.75 (Table 10.5). This results in (driveline efficiency is assumed to be the same for both the electric and hybrid vehicles)

$$\frac{0.5 \text{ kJ/km kg} \times 1900 \text{ kg} \times 0.75}{1000 \text{ kJ/MJ}} = 0.71 \text{ MJ/km}$$

Thus the fuel consumption is

$$0.71 w_F = 0.105 \text{ l/km (22 mpg)}$$

To this value must be added the fuel consumed during the coast, brake, and dwell periods. For the SAE J227a/B cycle, these periods total 34 seconds. The "idle" fuel consumption is 0.016 l/h for each kilowatt of maximum output.⁶⁶ Thus the idle fuel consumption of the engine is

$$\frac{0.016 \text{ l/h} \cdot \text{kW} \times 24 \text{ kW} \times 34 \text{ s}}{3600 \text{ s/h}} = 3.6 \times 10^{-3} \text{ l/cycle}$$

or

$$\frac{3.6 \times 10^{-3} \text{ l/cycle}}{0.33 \text{ km/cycle}} = 0.011 \text{ l/km}$$

The average total fuel consumption is

$$0.105 + 0.011 = 0.116 \text{ l/km (20 mpg)}$$

The urban range performance standards for this vehicle can be expressed as a range of 100 km on the SAE J227a/B schedule with an electrical consumption at the charger not to exceed

$$\frac{1.6 \times 50}{100} = 0.80 \text{ MJ/km}$$

and a fuel consumption not to exceed

$$\frac{0.133 \times 50}{100} = 0.67 \text{ l/km (36 mpg)}$$

The total energy required to refuel and recharge the vehicle after the above range test should not exceed (using 32.7 MJ/l for the energy equivalent of gasoline):⁶⁵

$$(0.8 + 0.067 \times 32.7)100 = 299 \text{ MJ (83 kWh)}$$

of which at least 27 percent (80/299) must be electrical.

10.4 DESIGN OF HYPOTHETICAL ADVANCED HYBRIDS

The previous section developed gross designs for hybrid vehicles with limited performance. This approach appears consistent with the state of hybrid technology. Section 10.2 indicated, however, that it should be possible to develop hybrids with the acceleration, top speed, and amenities of a conventional vehicle which simultaneously achieve superior petroleum fuel economy. The purpose of this section is to derive development specifications for such advanced hybrid vehicles which use appreciable stored electrical energy.

Fuel consumption goals for advanced hybrids should be based on the anticipated state of the art hybrid in the early 1980s. A good point of departure for this approach is the Ford work described in Sec. 10.2, in which a system efficiency of 0.249 was estimated for a parallel on-off strategy (Ford B in Table 10.4).⁶⁵ The vehicle which achieved the 0.249 efficiency had a gross mass of 2041 kg. Other sized vehicles, however, were nearly as efficient, as indicated in Table 10.7.

Potential purchasers of advanced hybrids will likely compare them with new or nearly new conventional vehicles. Certainly advanced hybrids will be at least as expensive as conventional vehicles for the next decade or more. Thus it seems reasonable that advanced hybrids will be driven as far as new conventional vehicles are believed to be driven, about 26,400 km (16,408 mi) annually.⁷⁰ This amounts to an average of 73 km/day (45 mi/day).

TABLE 10.7⁶⁵
PARALLEL HYBRID FUEL CONSUMPTION
(Ford B Strategy)

Gross Vehicle Mass, kg	Road Energy,* kJ/km·kg	Engine Displacement, ℓ	0-90 km/h** Accel, s	Fuel Consumption, ℓ/100 km (mi/g)	Overall [†] Efficiency
2495	0.281	6.56	17	8.83 (26.6)	0.243
2268	0.287	5.75	18	8.22 (28.6)	0.243
2041	0.314	4.95	21	7.86 (29.9)	0.249
1814	0.308	4.1	18	7.10 (33.1)	0.241
1588	0.326	2.8	22	6.60 (35.6)	0.240
1361	0.346	2.3	21	6.06 (38.8)	0.238

* Calculated from overall efficiency, using 32.7 MJ/ℓ for the energy equivalent of gasoline; EPA City driving schedule.

** Scaled from 0-60 mi/h times, using Eq. 3.1.

[†] Differential efficiency assumed to be 0.95.

Hypothetical Private Hybrid

In what follows we derive petroleum fuel and electrical consumption specifications for a hypothetical hybrid which is based on these assumptions:

1. The basic vehicle (before batteries to extend the range are added) is the 1361-kg one of Table 10.7.
2. Batteries, in addition to the high-power-density one required to implement the Ford B strategy, will be added to allow the "modified hybrid" to obtain various portions of its travel from stored energy.
3. The portion of stored energy will be based on the expected average daily travel, 73 km.

4. Every unit of battery mass added will require a fractional unit of supporting structure (the mass compounding factor). Mass compounding factors of 0.3 and 0.5 will be investigated. The value of 0.5 was used in a recent comparison of electric with conventional vehicles,¹¹ and the value of 0.3 is believed to represent a lower bound.
5. The added batteries will be assumed to discharge at the 2.35-hour rate, regardless of how much battery mass is added. (This is the time it takes to drive 73 km in the EPA City schedule.) Based on Eq. 3.8, the 2.35-hour specific energy density is assumed to be $1.26 E_1$.
6. The additional mass allowed for the electric motor is assumed to be three percent of the vehicle gross mass.
7. The motor-driveline efficiency of the electrical system is assumed to be 0.75.
8. The road energy for the resulting hybrid (all calculations will be based on the EPA City driving schedule) is assumed to be 0.325 kJ/km·kg. This will result in conservative results (estimating too much energy) for gross vehicle masses greater than about 1600 kg.
9. The overall efficiency for the petroleum-fueled heat engine is assumed to remain 0.238 for all vehicles.

The range available from the stored electrical energy is

$$R_S = \frac{1.26 E_1 M_B \eta_{MD}}{0.325(1321 + F_C M_B) 1.03} = 2.82 \frac{E_1 M_B}{1321 + F_C M_B}$$

where

E_1 = battery specific energy density (1-h rate), kJ/kg

M_B = mass of the batteries added for range extension, kg

F_C = mass compounding factor

The fuel consumption when the batteries are not being used is

$$\begin{aligned} E_P &= \frac{0.325(1321 + F_C M_B) 1.03}{0.238 \times 32.7 \times 10^3} \\ &= 4.30 \times 10^{-5} (1321 + F_C M_B) \end{aligned} \quad (10.4)$$

We assume that the fuel consumption averaged over a day's travel is E_p as given by Eq. 10.4 weighted by the ratio of travel on petroleum fuel to total travel:

$$E'_p = E_p \frac{(73 - R_s)}{73}$$

The electrical energy required at the charger input is

$$E_c = \frac{1.26 E_1 M_B}{0.7 \times 0.9 \times 73} = 0.0274 E_1 M_B$$

where 0.7 and 0.9 are the assumed battery charge/discharge and charger efficiencies respectively.

Figures 10.5 and 10.6 show the equivalent fuel consumption as a function of battery specific energy density for the two mass compounding factors. These figures indicate that fuel consumption is not greatly sensitive to battery energy density. However, the vehicle mass is much more sensitive to energy density, as indicated in Fig. 10.7.

To be consistent with the hypothetical advanced electric vehicle designs discussed in Sec. 9, we will base the advanced hypothetical hybrid designs on batteries with a specific energy density of 230 kJ/kg (64 Wh/kg). Note, however, that Fig. 10.7 indicates a relatively small decrease in vehicle mass beyond 150 kJ/kg. Thus the success of the advanced hybrid designs does not appear to be as sensitive to battery development as is the case for successful advanced electric vehicles. According to Ref. 65, the principal limitation on realizing the type of hybrid used as the basis for the hypothetical design discussed here is the energy storage system. The minimum rating for this system is 441 W/kg and 108 kJ/kg (30 Wh/kg). However, if batteries are to be added for range extension, these power and energy density minimums on the "power" battery can possibly be relaxed by combining the batteries, although just how much would require detailed analysis.*

Although Figs. 10.5 and 10.6 indicate that these hypothetical designs offer the potential for substantial fuel savings, there are disadvantages which should be mentioned. First are higher initial and maintenance costs; second is greater complexity and the accompanying lower reliability; third is the relatively high fuel consumption when the range

* It may not be desirable to combine the power and range extension batteries because of the severely degraded performance that would result when the combined battery was fully discharged.

Figure 10.5. Petroleum Fuel Consumption of Hypothetical Advanced Hybrid Private Vehicle

Figure 10.6. Petroleum Fuel Consumption of Hypothetical Advanced Hybrid Private Vehicle

Figure 10.7. Mass of Hypothetical Advanced Hybrid Private Vehicle

extension batteries are discharged. We are not able to make quantitative statements about the first two of these disadvantages, but can readily estimate the fuel consumption when the batteries are discharged.

We will select 67 percent as the goal for the portion of daily travel on stored electrical energy and use the 50 percent mass compounding factor. The resulting gross vehicle mass from Fig. 10.7 is about 1550 kg (for 230 kJ/kg batteries). The basic vehicle (without range extension batteries) has a mass of 1361 kg, so we can expect the fuel consumption to be about 6.5 l/100 km (36.2 mi/gal) ($5.7 \times 1550/1361 = 6.5$) when the range extension batteries are discharged. That is still very low consumption by present standards.

Commercial Vehicles

Development specifications for commercial advanced hybrid vehicles can be approached in the same manner as for the private vehicle. The primary differences are that the vehicle is larger and the average daily travel is greater. The energy requirement (in kJ/km·kg) is essentially the same as for the smaller private vehicle, because the increased mass tends to cancel the effect of higher aerodynamic loads.

We estimate average daily travel as follows. The EPA city driving schedule has 17 stops per cycle. Although these stops were intended to simulate traffic lights and congestion, we will assume that eight of them are stops for deliveries--or pickups--which take an average of five minutes each. Thus the time to drive through one cycle of the commercial driving schedule is 40 minutes greater than the time required for the EPA city schedule. This results in a total time of 3772 seconds or 62.8 minutes. The average speed is now 11.3 km/h. In an eight-hour day a vehicle will thus travel an average of 90 km. However, rather than assume that the range extension batteries discharge at an average eight-hour rate, we will use the four-hour rate to be conservative.

Figures 10.8 and 10.9 show the results of calculations for fuel consumption and vehicle mass, similar to those that produced Figs. 10.5-10.7.

Table 10.8 summarizes the two hypothetical vehicle designs at the operating point goal: 67 percent of average travel by stored electrical energy.

10.5 PERFORMANCE STANDARDS AND DEVELOPMENT SPECIFICATIONS

The hypothetical vehicle designs developed in Secs. 10.3 and 10.4 are intended to rectify deficiencies in the predicted performance of electric vehicles. In addition, the advanced hybrid vehicles have the capability of supporting the power requirements for air conditioning. Thus most of the standards and specifications for the hybrids are the same as for the electrics. Those hybrid standards which differ from electric-vehicle standards are given in Tables 10.9 and 10.10.

Figure 10.8. Petroleum Fuel Consumption of Hypothetical Advanced Commercial Vehicle

Figure 10.9. Mass of Hypothetical Advanced Commercial Vehicle

TABLE 10.8
CHARACTERISTICS OF HYPOTHETICAL ADVANCED HYBRID VEHICLES
(EPA City Driving Schedule)

	<u>Private</u>	<u>Commercial</u>
Gross Mass, kg	1550	2270
Road Energy, MJ/km	0.904	0.681
Overall Efficiency for Propulsion by Heat Engine	0.238	0.249
Average Daily Travel, km	73	90
Portion of Daily Travel on Stored Electrical Energy	0.67	0.67
Average Fuel Consumption, ℓ/100 km	2.1(112 mi/gal)	2.7(87.0 mi/gal)
Fuel Consumption After Batteries Discharged, ℓ/100 km	6.5(36.2 mi/gal)	8.4(28.1 mi/gal)
Average Motor-Driveline Efficiency	0.75	
Battery Mass, kg	112	170
Battery Specific Energy Density, kJ/kg	230 (64 Wh/kg)	
Battery Charge/Discharge Efficiency	0.7	
Charger Efficiency	0.9	
Average Electrical Consumption (Input to Charger), MJ/km	0.71	1.0
Maximum Petroleum Energy Input, % [*]	49	47

* After test in EPA City schedule with a range equal to average daily travel. Petroleum fuel heating equivalent 32.7 MJ/ℓ used.

TABLE 10.9
NEAR-TERM HYBRID PERFORMANCE STANDARDS WHICH DIFFER
FROM THOSE FOR ELECTRIC VEHICLES (Table 9.3)

<u>Standard</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Range	Range on SAE Cycle	200 km on J227a/C	200 km on J227a/B
Energy	Maximum Energy Input to Charger, MJ/km	0.45 [*]	0.80 ^{**}
	Maximum Petroleum Fuel Consumption, ℓ/100 km	4 [*]	6.7 ^{**}
	Maximum Petroleum Fuel Use, % [†]	75	75
Emissions	Exhaust and Evaporative Emission Limits	As specified in Sections 86.077-1 through 86.077-39 and 86.078-8 of the Federal Register, Vol. 40, No. 126, 30 June 1975.	

^{*} Range test for energy consumption: 33 km (50 cycles) of SAE J227a/C schedule followed by 33 km at 75 km/h or faster.

^{**} Range test for energy consumption: 100 km of SAE J227a/B.

[†] Maximum allowable ratio of energy into vehicle fuel tank (calculated at 32.7 MJ/ℓ) to the total petroleum and electrical energy input (to charger) for the range test for energy consumption.

NOTE: Refer to Table 9.5 for test conditions.

TABLE 10.10
ADVANCED HYBRID DEVELOPMENT SPECIFICATIONS
WHICH DIFFER FROM THOSE FOR ADVANCED ELECTRIC VEHICLES (Table 9.4)

<u>Specification</u>	<u>Description</u>	<u>Private</u>	<u>Commercial</u>
Acceleration	Time to Reach Given Speed	17 s to Reach 90 km/h	17 s to reach 90 km/h
Gradeability	Maximum Gradient for Starting	30%	30%
Speed	Minimum Top Speed, (for 5 min), km/h	105	105
Passenger Seating	Minimum Number of Passengers (incl. driver)	4	2
Cargo Capacity	Minimum Load Accommodated, Mass and Volume	100 kg and 0.4m ³	500 kg and 2.5m ³
Energy	Maximum Input to Charger after Urban Range Test, MJ/km*	0.71	1.0
	Maximum Petroleum Fuel Consumption After Urban Range Test, l/100 km*	2.1	2.7
	Maximum Petroleum Energy Input after Urban Test, %**	50	50
Emissions	Exhaust and Evaporative Emission Limits	As specified in Sections 86.077-1 through 86.072-39 and 86/078-8 of the Federal Register, Vol. 40, No. 126, 20 June 1975	

* After 73 km and 90 km, respectively, on the EPA City Driving Schedule.

** Based on petroleum heating equivalent of 32.7 MJ/l.

11 AGRICULTURAL APPLICATIONS OF ELECTRIC AND HYBRID VEHICLES

The types of electric and hybrid vehicles which would be useful for agricultural applications and still meet the stated intent of PL-94-413 are not readily apparent. Certainly, applications requiring high power levels such as heavy tillage are not consistent with existing or projected battery technology. At the opposite end of the spectrum are very small vehicles which can be steered by the driver's knees, leaving his hands free to gather eggs. Such vehicles are already developed; their potential impact on petroleum consumption is nil. However, between these extremes there are applications which could be served by electric or hybrid vehicles.

In recent years the trend has been for the average size of tractors to increase.* In 1965, the 162,482 wheel-type tractors sold had an average power of 47 kW. Ten years later fewer tractors (161,145) were sold, but the average power was up 54 percent to 73 kW. This trend is expected to continue. The apparent problem in this trend is that more and more large tractors are being used inefficiently for light-duty work which could be done by much smaller units. Applications now being handled by large tractors which might be handled by electric or hybrid vehicles include:

- Mowing
- Spraying
- Light cultivation
- Haulage of feed, seed, chemicals, etc.
- Scraping manure
- Snow removal
- Bulk materials handling
- Feedlot operation
- Moving trailers
- Fence and outbuilding construction
- Farmstead transportation
- Woodyard operations in forestry

A potential advantage of using electric vehicles for agricultural applications (as compared to urban uses) is that wind-powered generators could be used to charge the batteries.

* Information in this paragraph was obtained from Malcolm E. Wright, Assistant Professor of Agricultural Engineering, Virginia Polytechnic Institute and State University.

Vehicle parameters are shown in Table 11.1 for a hypothetical agricultural electric vehicle which could be used for many of the above applications. Table 11.2 gives performance standards for this vehicle. The range and energy standards are based on the SAE J227a/A schedule for lack of an appropriate agricultural schedule.

Development of additional performance standards for electric and hybrid agricultural vehicles is hampered by the lack of one or more basic agricultural driving schedules. These schedules would allow investigators to establish energy consumption and power requirement patterns for vehicles of various sizes. Only then can meaningful hypothetical designs be developed.

TABLE 11.1
HYPOTHETICAL LIGHT-DUTY AGRICULTURAL ELECTRIC VEHICLE PARAMETERS

Curb Mass, kg	1000
Payload, kg	1000
Tire and Chassis Friction, N/kg	0.2 [*]
Driveline Efficiency ^{**}	0.7
Motor and Controller Efficiency	0.7
Battery Efficiency	0.75
Charger Efficiency	0.8
Energy Requirements for SAE J227a/A, MJ/km·t of gross vehicle mass	1.65
Energy Requirements for SAE J227a/A, MJ/km·t of payload	3.30
Battery Mass Fraction (based on gross vehicle mass)	0.25

^{*} This value was chosen purposely high to allow for off-road operation.

^{**} Averaged over the SAE J227a/A schedule.

NOTE: Aerodynamic and viscous losses are assumed to be negligible for low-speed vehicles.

TABLE 11.2
RECOMMENDED PERFORMANCE STANDARDS FOR A LIGHT-DUTY
AGRICULTURAL ELECTRIC VEHICLE

<u>Standard</u>	<u>Description</u>	<u>Value</u>
Speed	Minimum Top Speed (for 5 min), km/h	20
Gradeability	Speed on 35% Grade, km/h	5
	Maximum Grade, %	50
Passenger Seating	Minimum Number of Seated Passengers (Including Driver)	2
Minimum Payload	Mass of Payload Accommodated, kg	1000 (open bed)
Maneuverability	Maximum Space Required for minimum Radius turn, wall-to-wall, m	7
Range	SAE J227a/A range, km	15
Energy	Maximum Input to Charger (J227a/A Schedule), MJ/km·t of payload	3.3

APPENDIX A DEFINITION OF SYMBOLS

A	Reference area for aerodynamic drag coefficient, m^2
b,c	Coefficients used to fit Eq. 3.7 to the curves in Fig. 3.2
C_D	Aerodynamic drag coefficient
C_1	Tire friction, N/kg (also includes chassis friction extrapolated to zero speed)
C_2	Viscous friction, W·s/m·kg) (primarily tire friction, but includes chassis friction)
C_3	Aerodynamic drag factor, $N \cdot s^2/m^2$
C_B	Initial battery cost, \$/kg
C_E	Vehicle electricity cost, normalized to vehicle mass, \$/kg·km
C_K	Amortized battery energy cost, normalized to vehicle mass and range, \$/kg·km
C_W	Cost of energy at wall socket, \$/kJ
$d(\cdot)$	Infinitesimal element of $(\cdot)$
E_1	Battery specific energy density at 1-h discharge rate, kJ/kg
E_C	Energy required to propel vehicle over one cycle of a specific driving schedule, normalized to R_C (input to charger), kJ/km
$E_D(X)$	Battery specific energy density corresponding to a specific power density X, kJ/kg
f	Battery mass/gross vehicle mass ratio
F_C	Mass compounding factor (ratio of additional structure mass required to support batteries to mass of batteries supported)
F_P	Hybrid fuel consumption, l/km
F_T	Tractive force on vehicle due to motor/heat engine, N

g	Gravitational acceleration, 9.8 m/s^2
k_1	Parameter used in range calculations, Eq. 3.14
k_2	Normalized energy consumption (from the battery) for a specific driving cycle, $\text{kJ/kg}\cdot\text{km}$
M_B	Battery mass, kg
M_{BC}	Incremental battery mass required to propel vehicle through one driving cycle, kg
M_V	Vehicle mass, kg
M_{VE}	Effective vehicle mass (incl. rotating inertia effects), kg
N_C	Battery life, charge/discharge cycles
P_1	P_D at the 1-h discharge rate, W/kg
P_{ACC}	Accessory power, W
P_B	Battery discharge rate, W
P_D	Battery specific power density, W/kg
P_{HE}	Hybrid heat engine output, W
P_{MAX}	Battery discharge rate for flywheel-battery-electric vehicle, W
P_W	Power delivered to wheels, W
R	Range over a specified driving cycle
R_C	Distance driven when covering one cycle of a driving schedule
R_S	Range available from stored electrical energy in a hybrid, km
S	Distance traveled during acceleration, m
t	Time, s
V	Speed, m/s
V_{MAX}	Maximum vehicle speed, m/s
$\dot{V}$	Acceleration, m/s^2

w_F	Hybrid engine specific fuel consumption, kg/MJ
$\dot{w}_F$	Hybrid engine fuel consumption, kg/h
η_B	Battery charge/discharge efficiency
η_C	Battery charger efficiency
η_D	Driveline (transmission and differential) efficiency
η_F	Flywheel transmission efficiency
η_G	Hybrid alternator/rectifier efficiency
η_M	Motor (generator) efficiency
η_{MD}	(= $\eta_M \eta_D$)
η_{SYS}	Net vehicle system efficiency for hybrid (includes effects of regenerative braking and increased vehicle mass)
η_{NET}	Net engine/motor efficiency for vehicles
θ	Roadway gradient, rad
τ	Time for the battery to discharge at constant power level to a given end condition, h
ρ	Atmospheric density, 1.225 kg/m ³ at sea level

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APPENDIX B

VALIDATION OF EQUATIONS 3.4, 3.5, AND 3.6 USED TO ESTIMATE GRADEABILITY AND MAXIMUM SPEED

Equation 3.4 is used to scale gradeability at one speed and grade to another. Equation 3.5, which is used to estimate gradeability when only acceleration is known (the time to accelerate from rest to a given speed) is just another form of Eq. 3.4. Equation 3.6 is used to estimate maximum speed when only acceleration data are known. The equations are repeated here for convenience.

$$\sin \theta = V_1 \frac{\sin \theta_1}{V} \quad (3.4)$$

$$\sin \theta = \frac{V_1^2}{2gt_1V} \quad (3.5)$$

$$V_{MAX} \approx \frac{M_V V_1^2}{t_1 \rho C_D A} \quad (3.6)$$

Figure B.1 shows the gradeability as determined by the J227a procedure and by Eq. 3.4 for the Lucas Limousine and the Ripp-Electric. The data from these tests was obtained during September 1976 for the Lucas⁴⁶ and March-April 1977 for the Ripp-Electric.* Table B.1 shows the acceleration data obtained. Two observations about Fig. B.1 are in order. One, there is considerable scatter in the gradeability as determined from the acceleration data. Two, if Eq. 3.4 (or equivalently, Eq. 3.5) is used to scale the gradeability at 50 km/h, the agreement is reasonable for speeds from about 25 km/h to 60 km/h.

Using coastdown data from the same series of tests mentioned above, we calculate that the drag-area product for the Lucas and Ripp-Electric vehicles is as given in Table B.2. Using Eq. 3.6, maximum speed is calculated and also shown in Table B.2. Also shown for comparison is the measured maximum speed measured during the test series.

* Preliminary Data Report for the Ripp-Electric Passenger Car, 20 May 1977. Prepared by JPL for NASA-LeRC.

Figure B.1. Comparison of Gradeability Using J227a Procedure and Eqs. 3.4 or 3.5

The rather poor agreement in predicted maximum speed obtained for the Lucas vehicle appears to be caused by the lack of a transmission for changing the drive ratio as speed is increased. Thus the motor is unable to deliver as much power at the high speeds as at 50 km/h, from which the speed-time pair for Eq. 3.6 was chosen.

Conversely, the Ripp-Electric has a four-speed transmission which allows the motor to develop nearly full power at the higher speeds. Thus V_{MAX} as determined by Eq. 3.6 is in good agreement with the measured maximum speed.

TABLE B.1
ACCELERATION TESTS

Ripp-Electric *		Lucas Limousine **	
Time, s	Speed, km/h	Time, s	Speed, km/h
3.0	16.1	1.0	5.6
7.4	32.2	2.0	11.2
10.1	40.2	4.0	20.1
14.0	48.3	6.0	27.2
18.4	56.3	8.0	33.8
23.0	64.4	10.0	39.1
29.2	72.4	15.0	49.1
37.4	80.5	20.0	57.9
		25.0	63.9
		30.0	68.5
		35.0	71.4
		40.0	74.0
		50.0	77.6
		60.0	80.1
		70.0	81.7
		80.0	82.9
		84.0	82.9

* Controller was using temporary transistors with limited motor current to 190 A. These have been replaced with transistors which allow 240 A motor current. The effect of this change will be to increase the motor torque by about 35 percent below 40 km/h.

** At zero and 40 percent discharge levels.

TABLE B.2
ESTIMATED TIRE AND AERODYNAMIC LOSS FACTORS

	<u>Vehicle</u>	
	<u>Lucas Limousine</u>	<u>Ripp-Electric</u>
Drag-Area Product, m^2	1.59 (17.1 ft^2)	1.14 (12.3 ft^2)
Test Mass, kg	3496	1493
Maximum Speed, * km/h	101.2	86.2
Maximum Speed, ** km/h	82.9	90.9

* Based on Eq. 3.6 and the time to accelerate to 50 km/h.

** Measured maximum top speed.

APPENDIX C

CONSTANT POWER DISCHARGE CHARACTERISTICS FOR REPRESENTATIVE
LEAD-ACID ELECTRIC VEHICLE BATTERIES

Much of the analysis upon which the performance standards are based use the constant power discharge curves shown in Fig. 3.2. The purpose of this appendix is to show that other electric vehicle and golf cart lead-acid batteries have similar characteristics. Figure C.1 shows characteristics for two German (Varta) and three domestic (two Gould and one ESB) batteries. The characteristics for all of these batteries are quite similar.

Figure C.1. Constant Power Discharge Characteristics for Various Golf-Cart and Electric-Vehicle Batteries

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APPENDIX D

PREDICTION OF BATTERY BEHAVIOR DURING REGENERATIVE BRAKING

A number of investigators have concluded that the benefit from regenerative braking for most urban driving schedules does not justify the added complexity and cost.^{32,35} However, recent tests indicate that, even with a relatively low-speed driving schedule such as the SAE J227a/B (maximum speed 32 km/h), more than a 10-percent increase in range can be achieved with regenerative braking. In some of these tests there are indications that for every unit of energy put into the battery during regeneration, more than one unit can be withdrawn (relative to the amount of energy available from the battery without regenerative braking).

One way to view the above phenomenon is to visualize a separate and higher battery efficiency for energy flowing into the battery. However, this approach results in "apparent" battery efficiencies exceeding 100 percent, a fundamental impossibility. Thus we have defined the regenerative utilization factor χ as the increase in discharge energy divided by the regenerative energy and the battery efficiency.

Table D.1 shows results obtained with the Ripp-Electric vehicle during the NASA/LeRC series of tests conducted in Phoenix, Arizona, in early 1977. Unfortunately the test personnel did not have the instrumentation required to measure regenerative and discharge energy during the Ripp-Electric tests. However, the range increases measured are appreciable. For comparison, a "charge" regenerative utilization factor has been computed in Table D.1. To get a rough estimate of the actual regenerative utilization factor for the Ripp-Electric, assume an average discharge voltage during the run of 1.9 V/cell and an average voltage during the regenerative braking of 2.3 V/cell (1 m Ω internal resistance, 300 A charging current, and 2.0 V/cell open voltage). Then the ratio of (discharge Ah/recharge Ah) to (discharge energy/recharge energy) is $1.9/2.3 = 0.83$. Thus the regenerative utilization factors for the J227a/B and J227a/C schedules in Table D.1 would be $0.83 \times 1.55 = 1.28$ and $0.83 \times 2.36 = 1.95$, respectively.

One test has been reported in which recharge energy was measured rather than charge. Menga reported that 10.2 units of energy returned to the battery by regenerative braking increased the battery output from 100 to 110.6 units (the results have been normalized to the amount of energy delivered without regenerative braking).⁵

TABLE D.1
RIPP-ELECTRIC REGENERATIVE BRAKING TESTS

SAE J227a Schedule	Regenerative Braking	Range, km	Input to Charger, MJ	Battery Discharge, Ah	Regenerative Braking Charge, Ah	Regenerative* Utilization Factor
B	No	105.2	95.4	170.7	--	--
B	Yes	105.2	120.7	192.3	18.7	1.55
C	No	89.6	90.0	153.2	--	--
C	No	97.7	92.9	163.2	--	--
C	Yes	107.0	100.4	177.2	17.0	
C	Yes	119.2	102.6	196.7	21.0	2.36**
C	Yes	127.0	96.1	202.6	19.5	

* The regenerative utilization factor (based on charge)

$$\frac{(\text{Ah}) \text{ w/regeneration} - (\text{Ah}) \text{ wo/regeneration}}{\eta_B (\text{Ah})_{\text{recharge}}}$$

** Based on the average of the two C schedule runs without regeneration and the average of the three C-schedule runs with regeneration. η_B assumed to be 0.75.

Assuming a battery efficiency of 0.75, the resulting regenerative utilization factor is

$$x = \frac{110.6 - 100}{0.75 \times 10.2} = 1.39$$

The driving schedule used by Menga is not defined, except as "urban."

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APPENDIX E
BATTERY DISCHARGE: COMPARISON OF THE FRACTIONAL UTILIZATION
AND HOXIE MODELS

The method used in Sec. 3 to determine electric vehicle range is based upon a fractional utilization model of battery discharge.³ The basis of this model is the assumption that an increment of battery is "used up" during each small time interval. The magnitude of this increment is (Eq. 3.10):

$$dM_B = P_B dt / [E_D (P_B / M_B)] \quad (E.1)$$

To determine range, increments are summed until the result equals M_B . Note that P_B in Eq. 3.1 is a function of time. E_D , the specific energy density, is a function of the specific power density, equal to P_B / M_B . This model does not take into account the effect of recuperation on energy available from a battery. That is, during periods of low or no discharge the polarization effect in the battery tends to decrease so that more energy can be drawn subsequently. Recuperation is the effect which allows one to repeatedly crank an (internal combustion) automobile engine with the starter until the battery is apparently "dead." However, after a wait of several seconds to a few minutes, the engine can be cranked some more (this only works a few times).

Taylor and Siewk proposed a modification of an earlier battery discharge model to allow for the recuperation effect.⁸⁸ The resulting model, referred to as the Hoxie Model,^{*} can be best explained with the aid of Fig. E.1. The mass of battery required to furnish the power profile specified in Fig. E.1 is

$$dM_B = \frac{P_1}{P_D(\tau_1)} + \frac{P_2 - P_1}{P_D(\tau_2)} + \frac{P_3 - P_2}{P_D(\tau_3)} + \frac{P_4 - P_3}{P_D(\tau_4)} \quad (E.2)$$

where

$P_D(\tau)$ = specific power density that battery can sustain
for time τ

^{*}Hoxie's original model was proposed to predict the size of a battery (number of plates) required for a specific discharge current profile.⁸⁹

Figure E.1. Sample Power Profile

The range of the vehicle is found by summing mass increments based on Eq. E.2 until the result equals M_B . The $P_D(\tau)$ are obtained from Eq. 3.7:

$$\log P_D = \log P_1 + b(\log \tau) + c(\log \tau)^2 \quad (E.3)$$

The only restriction in using Eq. E.2 is that the battery must be capable of providing the maximum power density encountered. In the profile shown in Fig. E.1, this restriction would mean that

$$P_2/M_B < P_{D_{MAX}}$$

To compare the range calculated by the fractional utilization and Hoxie models, the battery current profile for the Ripp-Electric was measured for the B, C, and D cycles of the SAE J227a driving schedules. The general profile and its constant current approximation is shown in Fig. E.2.⁹⁰ Table E.1 gives the specific values for each driving schedule.

Figure E.2. Generalized Current Profile for Ripp-Electric in SAE J227a Schedule

TABLE E.1⁹⁰

MEASURED AND STEPWISE APPROXIMATIONS FOR RIPP-ELECTRIC
BATTERY CURRENT PROFILES IN THE SAE J227a B, C, D, DRIVING
SCHEDULES

(Refer to Figure E.2)

Schedule J227a	Measured Profile					Stepwise Approximation		
	I_a	t_a	I_b	t_b	t_c^*	I_1	t_1	I_2
	A	s	A	s	s	A	s	A
B	100	19	35	38	72	25	9.5	75
C	216	18	54.6	38	80	54	9	162
D	375	28	88.7	78	122	94	14	218

* t_c is the period of each cycle

Although the models described above are based upon power profiles, the data in Fig. E.1 and Table E.2 are current profiles. However, the analogy is straightforward, and both models can be used to predict the number of current profile cycles which can be provided by a battery. * Figure E.3 shows the constant current which can be sustained to cutoff by an ESB EV-106 battery. (This figure is analogous to Fig. 3.2.) The discharge characteristic shown in Fig. E.3 can be represented by

$$\ln I = 4.787 - 0.74 \ln \tau - 0.0482 (\ln \tau)^2 \quad (E.4)$$

Application of Eq. E.4 to the above models (appropriately modified for current rather than power) yields the results shown in Table E.2. The results indicate that the fractional utilization model underpredicts the number of cycles by 9 to 20 percent, while the modified Hoxie model is quite accurate for the J227a/B and J227a/C schedules, and 12 percent over for the J227a/D schedule.

TABLE E.2
COMPARISON OF BATTERY DISCHARGE MODELS
(Ripp-Electric/JPL Tests)

Driving Schedule Simulated, J227a	Number of Driving Cycles		
	Model		Measured
	Frac Util	Mod Hoxie	
B	334(9)*	367(1)*	369
C	148(20)*	187(2)**	184
D	39(20)*	55(12)**	49

* Percent error (low).

** Percent error (high).

* Cutoff is 1.75 V/cell for currents of 75A or less; 1.0 V/cell otherwise.

Figure E.3. Constant Current Discharge Characteristics for ESB EV-106 (Data from Manufacturer)

Unnewehr reported on similar tests using EV-106 batteries.⁹¹ The current profile for a Ford Cortina electric vehicle conversion driving the SAE metropolitan schedule was measured and approximated as follows:

<u>Current, A</u>	<u>Interval, s</u>	<u>Time from Beginning, s</u>
20	46	46
170	6	52
250	6	58
350	6	64
400	3	67
350	4	71
250	7	78
170	26	104
20	46	150

Using the EV-106 discharge characteristic represented by Eq. E.4, we obtain the following results:

	<u>Model</u>		<u>Ford Measurements</u>
	<u>Frac Util</u>	<u>Mod Hoxie</u>	
Number of Cycles	21	31	24.8 - 25.8

Thus we tentatively concluded that the fractional utilization model may be conservative in predicting range. However, more experiments are needed, particularly using power rather than current profiles.

APPENDIX F

VEHICLES NOT ANALYZED IN SECTION 5

This appendix contains lists of electric vehicles which were not included in the analysis reported in Sec. 5, primarily because insufficient data were available. Tables F-1 and F-2 cover passenger vehicles and light trucks, vans, and buses, respectively. The order of listing within each table is not significant.

TABLE F.1

PASSENGER VEHICLES FOR WHICH INSUFFICIENT DATA WERE AVAILABLE FOR
DETAILED ANALYSES IN SECTION 5

<u>Name</u>	<u>Curb Weight, kg</u>	<u>Passengers</u>	<u>Manufacturer</u>	<u>Remarks</u>	<u>Reference</u>
Braun Electric	816	4	Braunlich/Roessle Co.	Converted Honda Civic	72
Electra King PFS 125	500	2	B&Z Electric Car		72
Electra King PFS 135	907	2	B&Z Electric Car		72
Lucas Electric Taxi	2640	5	Lucas Electric Co., England	Specially designed prototype	72,23
Mazda Electric Family Van	1345	5	Toyo Kogyo Co., Japan	Conversion	72
Transformer I	2994	6	Electric Fuel Propulsion	Conversion	72
General Electric Delta	450	2+2(child)	General Electric Co.	New design	73
Markette	915	2	Westinghouse Electric	New design	*
Elcar	495	2	Elcar Corp., Indiana	New design	**,74
Gregoni	816	2	Compagnie Generale d'Electricite, France	New design	75
Electrovair	1542	6	General Motors	Converted Corvair, silver- zinc batteries	76
Linear Alpha	--	5-6	Linear Alpha	Conversions	

* Press release, Westinghouse Electric Corp., circa 1967.

** Promotional literature, Elcar Corp., Elkhart, Indiana 46514.

† Promotional literature, Linear Alpha, Inc., Skokie, Illinois 60076.

TABLE F.2

LIGHT TRUCKS, VANS, AND BUSES FOR WHICH INSUFFICIENT DATA WERE AVAILABLE FOR
DETAILED ANALYSES IN SECTION 5

<u>Name</u>	<u>Curb Weight, kg</u>	<u>Payload, kg</u>	<u>Manufacturer</u>	<u>Remarks</u>	<u>Reference</u>
Daihatsu EH S40	835	200	Daihatsu Motor Co., Japan	Conversion	72,77
Daihatsu EH S40VM	900	200	Daihatsu Motor Co., Japan	Conversion	72,77
Bedford CF Sliding Pack	3070	950	Lucas Industries, England	Conversion, similar to Bedford CF Fixed Pack review in Section 3	72,23
Lucas Electric CFI Pulman	3070	770	Lucas Industries, England	Conversion	72
Lucas Electric Midi-Bus	9943	2223	Lucas Industries, England	Conversion	72
Mazda Electric Bongo Van	1625	380	Toyo Kogyo Co., Japan	Conversion	72
Mazda Electric Porter Cab Truck	1270	430	Toyo Kogyo Co., Japan	Conversion	72
Silent Karrier	6350	1814	Chloride Technical Ltd., England	Conversion	72
Silent Rider (bus)	16257	50 pass.	Chloride Technical Ltd.	Conversion	72
THEV No. 2	1400	200	National Tsing Hua Univ., Japan	Conversion	72
Townobile 120 (bus)	6560	116 pass.	Elroy Engineering Pty, Ltd., Australia	Special design	78
OE 302 (bus)	16000- 19000	110 pass.	Daimler-Benz AG, W. Germany		79
Electro-Van	2805	500	Volkswagenwerk AG., W. Ger.	VW Pickup conversion	80
Marathon Van	3300	900	Messerschmitt-Bolkow-Blohm, W. Germany	New designs, fiberglass bodies	75
MAN Bus	8200	99 pass.	Maschinenfabrick-Ausburg- Nurnburg, W. Germany	Batteries in trailer pulled by bus	75,81
Osaka Bus	15000	60-80 pass.	Hino Motor Co., Japan		75
Harbuilt Truck			Harbuilt Electric Co., Ltd., England	Used for mail delivery in Cupertino, California	
EM-0466	1700	500	USSR	Prototype	75
Zaphorozhet	1500	500	USSR	Prototype, nickel-iron batteries	75

Table F.2 (Cont.)

<u>Name</u>	<u>Curb Weight, kg</u>	<u>Payload, kg</u>	<u>Manufacturer</u>	<u>Remarks</u>	<u>Reference</u>
Electromobil-73	1200	600	USSR	Prototype	75
Linear Alpha		340-1100	Linear Alpha	Conversions to Dodge vans	*
T/3 Delivery Van	1651	317 or 4 pass.	Electromotion, Inc.	New design	**
Bedford Conversion	2740 [†]	--	Electricity Research Council, England	Converted Bedford, torque converter	82
Fiat ENEL Vans	1375-1415	350+ driver	Fiat, Italy	Converted Fiat vans	83
EMA 1 and EMA 2	680, 2240	250, 860	Research Institute for Rotating Electrical Machines, Czechoslovakia	Converted vans	84

* Promotional literature, Linear Alpha, Skokie, Illinois 60076

** Promotional literature, Electromotion, Inc., Bedford, Massachusetts 01730.

GVW

APPENDIX G

DRIVING SCHEDULES

A number of driving schedules have been used for testing of electric and urban vehicles. The most prevalent of these are the SAE (Society of Automotive Engineers) J227 series. In 1973, the SAE J227 Residential and Metropolitan schedules were published.⁸⁵ These are defined in Table G.1.

In February 1976, the SAE published a revised test procedure SAE J227a which contains four driving schedules: A, B, C, and D.¹ These schedules, defined in Fig. G.1. are basically designed for milk trucks (A), bakery trucks or shuttle buses (B), parcel post delivery vans (C), and commuter cars (D).

The Department of Health, Education and Welfare published an Urban Driving Cycle in 1970.⁹² This schedule, which is not reproduced here because of its great length, defines a vehicle trajectory 1372 seconds long, with a maximum speed of 91.2 km/h (56.7 mi/h). This schedule is now referred to as the EPA City Cycle for purposes of emissions and fuel economy tests.⁹³ Its length is about 11.8 km (7.34 mi) and the average speed is 31 km/h (19.3 mi/h).

In Germany, the Fakra driving schedule is often used to simulate urban driving conditions.⁵⁹ This schedule consists of an acceleration averaging 1 m/s^2 to 50 km/h, a cruise of about 22.1 seconds at 50 km/h, deceleration at 1 m/s^2 to zero speed, and a dwell time of 30 seconds. Total distance traveled is 0.5 km at an average speed of 22.5 km/h (14 mi/h).

To get a clearer picture of the demands each of these driving schedules imposes on a vehicle, Table G.2 shows for a hypothetical advanced vehicle the road energy, maximum road power, and percentage losses for various subsystems. Also shown is the approximate range such a vehicle would achieve with EV-106-type batteries.

Comparison of the road energy and specific power requirements in Table G.2 indicates that the SAE Metropolitan J227a/D and Fakra schedules are quite similar. Although requiring less energy than several other schedules, the EPA city schedule requires nearly double the power density of the next most difficult schedule, the SAE J227a/D.

The specific power requirement for the other schedules is reduced considerably by using an exponential acceleration profile. For example, in the SAE J227a/D schedule, the average acceleration required from 0 to 28 seconds is 0.71 m/s^2 . If the vehicle accelerates with constant acceleration, maximum power is needed at 28 seconds. For the hypothetical

TABLE G.1

SAE METROPOLITAN AND RESIDENTIAL DRIVING SCHEDULES

Mode	Time Interval, s		Average Acceleration, m/s ²		Speed at End of Interval				Cumulative Time, s	
	Met	Res	Met	Res	km/h		mi/h		Met	Res
					Met	Res	Met	Res		
Dwell	20	20	0	0	0	0	0	0	20	20
Accelerate	14	14	0.96	0.96	48	48	30	30	34	34
Cruise	15	15	0	0	48	48	30	30	49	49
Decelerate	11	11	-0.61	-0.61	24	6.7	15	15	60	60
Cruise	15	15	0	0	24	6.7	15	15	75	75
Accelerate	25	12.5	0.54	0.54	72	48	45	30	100	87.5
Cruise	21	46.5	0	0	72	48	45	30	121	134
Decelerate	21	8	-0.53	-0.56	32	32	20	20	142	142
Decelerate	8	8	-1.12	-1.12	0	0	0	0	150	150

AN-47646

SAE J227a SCHEDULE				
TEST PARAMETER	A	B	C	D
MAXIMUM SPEED V , km/h	16 ± 1.5	32 ± 1.5	48 ± 1.5	72 ± 1.5
ACCELERATION TIME t_a , s	4 ± 1	19 ± 1	18 ± 2	28 ± 2
CRUISE TIME t_{cr} , s	0	19 ± 1	20 ± 1	50 ± 2
COAST TIME t_{co} , s	2 ± 1	4 ± 1	8 ± 1	10 ± 1
BRAKE TIME t_b , s	3 ± 1	5 ± 1	9 ± 1	9 ± 1
IDLE TIME t_i , s	30 ± 2	25 ± 2	25 ± 2	25 ± 2
TOTAL TIME, s	39 ± 2	72 ± 2	80 ± 2	122 ± 2

Figure G.1. SAE J227a Driving Cycle Schedules

TABLE G.2
COMPARISON OF VARIOUS DRIVING SCHEDULES

	SAE J227						EPA City	Fakra
	Res	Met	A	B	C	D		
Length, km	1.42	1.67	0.028	0.33	0.57	1.61	11.8	0.52
Period, s	150	150	39	72	80	122	1372	80
Battery Output Energy, kJ/km·t	355	444	576	326	298	463	420	463
Maximum Road Power, W/kg	13.7	16.0	4.9	5.0	11.1	17.7	32.4	14.7
Losses, percent								
Tires	37.4	30.5	21.2	39.2	33.2	29.9	31.8	28.5
Aerodynamic	14.1	18.6	0.9	6.8	12.4	25.3	17.0	11.4
Motor-Driveline	26.3	26.1	27.9	27.0	24.7	25.9	26.7	25.8
Brakes	22.2	24.8	49.9	27.1	28.3	19.0	24.5	34.5
Maximum Battery Specific Power Density, W/kg	45.7	53.2	16.2	16.7	36.8	59.1	108.3	49.0
Approximate Range, [†] km	62.9	42.1	42.9	84.7	54.9	41.2	45.0	44.6

* Vehicle: $C_1 = 0.12 \text{ N/kg}$ $M_V = 1500 \text{ kg}$
 $C_2 = 10^{-3} \text{ N·s/kg·m}$ $\eta_{ML} = 0.75$
 $C_D A = 0.82 \text{ m}^2$ $f = 0.3$
 No regenerative braking

[†] Using EV-106 batteries

vehicle, this is 28.1 W/kg (at the wheels). However, suppose we taper the acceleration profile exponentially, such that

$$a_o = \frac{1}{\tau} \int_0^{\tau} a_1 e^{-ku} du = \frac{a_1}{k\tau} (1 - e^{-k\tau}) \quad (G.1)$$

where

a_o = average acceleration required, m/s

a_1 = initial acceleration, m/s

k = acceleration time constant, s^{-1}

τ = time for acceleration, s

u = dummy integration variable

Further, let the acceleration at the upper limit (28 s in Eq. G.1) be αa_o where α is a factor less than unity. Thus

$$a_1 e^{-k\tau} = \alpha a_o \quad (G.2)$$

Combining Eqs. G.1 and G.2 yields

$$\alpha(e^{k\tau} - 1) - k\tau = 0 \quad (G.3)$$

For any given α , Eq. G.3 can be solved for $k\tau$.

Use of the exponential acceleration results in considerable reduction in peak power requirements. For the SAE J227a/D cycle, the differences are shown in Table G.3 for $\alpha = 0.5$ (a value found to result in a nearly constant power profile).

All runs tabulated in Table G.2 used $\alpha = 0.5$ except that for the EPA City schedule, in which acceleration is not specified, only pairs of speed and time.

TABLE G.3
COMPARISON OF CONSTANT AND EXPONENTIAL TAPER
ACCELERATION PROFILES
(SAE J227a/D Schedule)

	$\alpha = 1$ <u>Constant Acceleration</u>	<u>$\alpha = 0.5$</u>
Road Energy, kJ/km•t	466	463
Maximum Power, W/kg	28.1	17.7
Length of One Cycle, km	1.55	1.61

APPENDIX H

GRADEABILITY, TOP SPEED, AND FREEWAY RAMP LENGTH REQUIREMENTS AS A FUNCTION OF VEHICLE ACCELERATION CAPABILITY

Electric and hybrid vehicles generally have limited acceleration capability. A possibly serious effect of this limitation will be to prevent these vehicles from entering freeways at safe speeds.

The purpose of this appendix is to derive a relationship which allows us to study the effect of acceleration limitation on freeway merging when the freeway ramp is at grade. In addition, the same equations can be used to determine gradeability and top speed capability. The fundamental equation governing vehicle motion is

$$M_V \dot{V} = F_T - M_V(C_1 + g\theta) - M_V C_2 V - 0.5 \rho C_D A V^2 \quad (H.1)$$

The tractive force, F_T , is equal to the power applied to the wheels divided by the speed V . If this relationship is used and Eq. H.1 is rearranged, we have

$$\dot{V} = P_W/M_V - (C_1 + g\theta) V - C_2 V^2 - 0.5 \rho C_D A V^3/M_V \quad (H.2)^*$$

Separating the variables (V and t , which is explicit) and rearranging Eq. H.2 gives

$$\int \frac{V dV}{V^3 + C_2 V^2/C_3 + (C_1 + g\theta) V - P_W/M_V C_3} = -C_3 t + \text{cons.} \quad (H.3)$$

where

$$C_3 = 0.5 \rho C_D A/M_V$$

Since we are not interested in the actual acceleration profile, there is no need to solve Eq. H.3 formally. However, the greatest real root (generally there will be only one real root) of the denominator of the integrand in Eq. H.3 is the top speed for a given grade θ . Thus by factoring the cubic equation in Eq. H.3, we can determine a vehicle's top speed and gradeability.

* We assume that P_W is constant during acceleration.

To determine freeway on-ramp length requirements, we want to use distance instead of time as the independent variable in Eq. H.2. This is accomplished by noting that

$$\dot{V} = \frac{dV}{dt} = \frac{dV}{dS} \cdot \frac{dS}{dt} = V \frac{dV}{dS}$$

which allows us to rewrite Eq. H.2 as

$$\int \frac{V^2 dV}{V^3 + C_2 V^2 / C_3 + (C_1 + g\theta) / C_3 V - P_W / M_V C_3} = -C_3 S + \text{cons.} \quad (\text{H.4})$$

The integrand of Eq. H.4 can be expanded by partial fractions, and the result integrated to give

$$S = -\frac{A}{C_3} \ln(1 - V/V_1) - \frac{B}{C_3} \ln(1 - V/V_2) - \frac{C}{C_3} \ln(1 - V/V_3) \quad (\text{H.5})$$

where

$$V_1, V_2, V_3 = \text{roots of denominator of integrand, Eq. H.4}$$

$$A = V_1^2 / (V_1 - V_2)(V_1 - V_3)$$

$$B = V_2^2 / (V_2 - V_1)(V_2 - V_3)$$

$$C = V_3^2 / (V_3 - V_1)(V_3 - V_2)$$

Note that the initial condition $S = 0$ when $V = 0$ has been fulfilled in Eq. H.5 and that in general two of the three roots and coefficients (A,B,C) are complex.

Equation H.5 is the desired relationship between acceleration capability (P_W/M_V), grade (θ), and ramp length (S). To produce Fig. 6.4, Eq. H.3 was integrated iteratively on P_W/M_V to get the desired acceleration capability, e.g., 65 km/h in 10 s. Then the resulting ratio P_W/M_V was used in Eq. H.5 to obtain pairs of ramp lengths and grades.

In passing, it is worth noting that less accurate, but still good, results can be obtained by assuming that $C_2 = C_D A = 0$ in Eq. H.1. This approach results in

$$\frac{V^2}{2} + V_0 V + V_0^2 \ln(1 - V/V_0) = -(C_1 + g\theta) S \quad (\text{H.6})$$

where V_o is the maximum speed of the vehicle on a grade equal to θ :

$$V_o = \frac{P_W}{M_V(C_1 + g\theta)} \quad (H.7)$$

The ratio P_W/M_V is the specific power delivered to a vehicle's wheels during acceleration. Using Eq. 3.1,

$$P_W/M_V = \frac{V_1^2}{2t_1} \quad (H.8)$$

For example, suppose we want to determine ramp length requirements for the following vehicle (to reach 65 km/h at the end of the on-ramp):

$$C_1 = 0.12 \text{ N/kg}$$

$$C_2 = 10^{-3} \text{ N}\cdot\text{s/kg}\cdot\text{m}$$

$$C_D A = 0.82 \text{ m}^2$$

$$M_V = 1500 \text{ kg}$$

$$\text{Acceleration} = 0\text{-}65 \text{ km/h in } 10 \text{ s (on level)}$$

The required power-to-mass ratio (based on Eq. H.4) is

$$P_W/M_V = 18.8 \text{ W/kg} \quad (H.9)$$

The approximate power-to-mass ratio based upon Eq. 3.1 is

$$P_W/M_V = \frac{(65/3.6)^2}{2 \times 10} = 16.3 \text{ W/kg} \quad (H.10)$$

Equations H.9 and H.10 in Eqs. H.5 and H.6, respectively, result in the ramp lengths in Table H.1, which indicates that the approximate equation produces slightly conservative results.

TABLE H.1

RAMP LENGTH REQUIRED TO ACCELERATE FROM 0 TO 65 km/h

<u>Grade, %</u>	<u>Eq. H.4, m</u>	<u>Eq. H.5, m</u>	<u>Difference, %</u>
0	122.1	133.8	9.6
1	133.7	147.5	10.3
2	148.1	164.5	11.1
3	166.4	186.6	12.2
4	190.7	216.5	13.6
5	225.0	259.9	15.5
6	278.7	330.5	18.6
7	381.1	476.4	25.0
Maximum Grade, %	7.89	8.00	1.4

APPENDIX I

ESTIMATION OF TIRE FRICTION, VISCOUS FRICTION, AERODYNAMIC DRAG, AND MOTOR-DRIVELINE FACTORS

In Sec. 3, a range parameter k_1 and a battery energy output parameter k_2 were derived to characterize the state-of-the-art for existing electric vehicles. These parameters are useful for determining range and energy usage, but they are driving-schedule-dependent. To determine range over other driving schedules (including at constant speed), acceleration, and gradeability, we need estimates of the fundamental losses. The first three of these items can be determined from coast-down tests. Fortunately, coastdown runs were made for the vehicles tested by NASA/LeRC and JPL for ERDA. These data have been made available to GRC, and we have estimated the loss factors C_1 , C_2 , and $C_D A$ for several vehicles.

The purpose of this appendix is to briefly outline the method used to determine the loss factors, present the results obtained, and our estimates of the motor-driveline efficiencies. In addition, estimates are made for advanced vehicles of these losses and efficiencies.

During a coastdown run, there is no tractive force because the motor is not energized (and disengaged, if possible). Thus the equation of motion for the vehicle is*

$$M_{VE} \dot{V} = -(C_1 + g\theta) M_V - C_2 M_V V - 0.5 \rho C_D A V^2 \quad (I.1)$$

The roadway gradient θ varies throughout the length of the test section. For the Dynamic Sciences, Inc., track in Phoenix, Arizona, where most of the tests were run, we have used a survey of the track which allows us to calculate θ for each 30.3-m (100-ft) segment of track. The solution of Eq. I.1 is

$$V = \frac{V_1(V_o - V_2) - V_2(V_o - V_1) \exp[-C_3(V_1 - V_2)(t - t_o)]}{V_o - V_2 - (V_o - V_1) \exp[-C_3(V_1 - V_2)(t - t_o)]} \quad (I.2)$$

where

$$V_o = \text{speed at time } t_o, \text{ m/s}$$

$$V_1, V_2 = -(C_2/2C_3) \pm \sqrt{(C_2/2C_3)^2 - 2M_V(C_1 + g\theta)/\rho C_D A}$$

* Equation I.1 does not include the effects of wind velocity of the lift developed by the vehicle (proportional to V^2). These effects can be included if they are known for the vehicle and test being considered.

$$C_3 = \rho C_D A / 2M_{VE}$$

(The remainder of the variables are defined in Appendix A.)

Data from coastdown runs consist of speed-time pairs. To determine C_1 , C_2 , and $C_D A$, Eq. I.2 is "fit" to these data on a minimum sum-of-squared-error basis. Results for several vehicles are tabulated in Table I.1.

TABLE I.1
LOSS COEFFICIENTS DERIVED FROM COASTDOWN TESTS

<u>Vehicle</u>	<u>C_1, N/kg</u>	<u>C_2, N·s/kg·m</u>	<u>$C_D A$, m²</u>
Vans:			
Lucas Van	0.0686	5.95×10^{-4}	1.74
Electra-Van	0.0811	*	0.94
Otis P-500	0.0635	2.66×10^{-3}	0.24
DJ-5E	0.128	6.98×10^{-3}	0.45
Battronics Minivan	0.154	1.31×10^{-2}	1.12
Cars:			
EVA Metro	0.0686	4.40×10^{-3}	0.4
Citi-Car	0.159	4.53×10^{-3}	0.97
EVA-Contactor	0.134	4.12×10^{-3}	1.08
Ripp-Electric	0.127	1.49×10^{-3}	0.89
EPC Hummingbird	0.143	*	1.61
Elcar	0.203	3.78×10^{-3}	1.22
Waterman DAF	0.104	1.11×10^{-2}	*

* Negative values

The appreciable scatter in the results of Table I.1 is believed due to three main factors. First, we are uncertain of the location of the beginning of each coastdown run relative to the track survey. Second, we are uncertain of the magnitude and direction of winds during runs. Detailed expansion of Eq. I.1 to include the effect of either headwinds or tailwinds indicates that the apparent C_1 and C_2 are quite sensitive to winds and that the apparent C_{DA} can be decreased substantially by a tailwind. Third, the standard deviation of the coefficients is believed to be large in some cases.

However, for the purpose of defining hypothetical near-term and advanced vehicles, the coefficients shown in Table I.2 are based upon our judgment at this time.

TABLE I.2

ESTIMATES OF LOSS COEFFICIENTS FOR HYPOTHETICAL VEHICLES

<u>Vehicle</u>	<u>C_1, N/kg</u>	<u>C_2, N·s/kg·m</u>	<u>C_{DA}, m²</u>	<u>η_{MD}</u>
Near-Term:				
Private	0.16	10^{-3}	0.9	0.65
Commercial	0.12	10^{-3}	1.5	0.65
Advanced:				
Private	0.12	10^{-3}	0.82	0.75
Commercial	0.10	10^{-3}	1.5	0.75

The rationale for picking the coefficients and efficiencies shown in Table I.2 is as follows. Coefficient C_1 is primarily due to tire friction, but also includes any bearing, seal, and gear drag which remains constant with speed. Radial tires exhibit a coefficient of friction of about 0.12 to 0.14 for car tires and 0.1 to 0.12 for medium size truck tires⁹⁴ (lower because of higher pressure and greater radius). Advanced tires should be a little better; thus the decrease shown.

Coefficient C_2 includes the viscous term in tire drag plus bearing, seal, and gear viscous drag. Little is known about this term, so only a small amount has been included. Table I.2 indicates that C_2 may be even higher.

The drag-area product $C_D A$ depends upon the frontal area A , and C_D . The latter will presumably decrease some with cleaner designs; it is about 0.4 for the best current conventional car designs, and is estimated to average near 0.6 for present electric cars. We have predicted a 50 percent increase in the mass of the advanced cars (relative to the near-term design). As frontal area is proportional to $(\text{mass})^{2/3}$, this indicates an increase of 1.31. Thus the implied decrease in C_D is $(0.82/0.9)/1.31 = 0.69$. That means that the average C_D of advanced cars will have to be about $0.69 \times 0.6 = 0.42$.

For commercial vehicles, we are predicting a growth in mass of 1.71 (3250/1900). Thus the average C_D must decrease by a factor of 0.7 ($= 1.71^{-2/3}$). That is essentially the same as the reduction estimated for the private cars.

Motor-driveline efficiency is driving-schedule-dependent. However, based upon Tables 5.4 and 5.5, we have estimated 0.65 for near-term vehicles. For advanced vehicles we estimate a driveline efficiency of 0.94 (without torque converters) and an average motor efficiency of 0.8 for a combined efficiency of 0.75.

APPENDIX J

DUAL-FUEL HYBRID VEHICLES NOT DISCUSSED IN SECTION 10

TABLE J-1

DUAL-FUEL HYBRID VEHICLES NOT DISCUSSED IN SECTION 10

<u>Name</u>	<u>Curb Weight,</u> <u>kg</u>	<u>Passengers</u>	<u>Manufacturer</u>	<u>Remarks</u>	<u>References</u>
Gemini II	N/A	6	National Motors	Converted Oldsmobile Royale 6-cylinder engine; parallel operation	*
OE 302/305	N/A	N/A	Daimler-Benz	Diesel powered generator runs 45% of time; series operation	86
Hybrid Electrobus	6810	21	Tork-Link Corp/ U of Florida	45 kW diesel/30 kW alternator added to Electrobus; series configuration	87
Transformer I	N/A	6	Electric Fuel Propulsion	Converted General Motors car which can operate as a battery-electric or with a trailer-mounted internal-combustion engine and generator, as a series hybrid	**
Robert Bosch	N/A	4	Robert Bosch	On-off battery/heat engine	66

* Assorted press releases from Donohue & Company, Inc., Bala Cynwyd, Pennsylvania.

** Assorted press releases from Electric Fuel Propulsion Corporation, Troy, Michigan.

APPENDIX K

SUMMARY OF KEY CONVERSION FACTORS FOR THE INTERNATIONAL SYSTEM OF UNITS (SI)

ERDA policy and Public Law 94-168 encourage the use of the metric system, specifically SI units. The purpose of this appendix is to provide conversion factors to allow one to get from SI units back to more familiar units for comparison. Table K.1 contains a summary of useful conversion factors.

TABLE K.1

<u>Parameter</u>	<u>Parameter Name</u>	<u>To Convert From</u>	<u>To</u>	<u>Multiply By</u>
Mass	kilogram	kg	lb	2.205
	ton	t	kg	1000.
Length	meter	m	ft	3.28
	kilometer	km	mi	0.621
Area	--	m ²	ft ²	10.8
Volume	--	m ³	ft ³	35.3
	liter	ℓ	gal	0.264
Speed	meter/second	m/s	mi/h	2.23
	kilometer/hour	km/h	mi/h	0.621
Acceleration	--	m/s ²	mi/h·s	2.23
Force	Newton	N	lb _f	0.225
Energy	megajoule	MJ	BTU	948.
	--	MJ	kW·h	0.278
	--	MJ	kJ	1000.
Energy	--	MJ/km	BTU/mi	1525.
Consumption	--	MJ/km	kW·h/mi	0.447
Specific Energy	kilojoule/ kilogram	kJ/kg	Wh/lb	0.126
Power	kilowatt	kW	hp	1.34
Specific Power	--	W/kg	W/lb	0.454
	--	kW/kg	hp/lb	0.608

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