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NEAR TERM HYBRID PASSENGER VEHICLE DEVELOPMENT PROGRAM, PHASE I

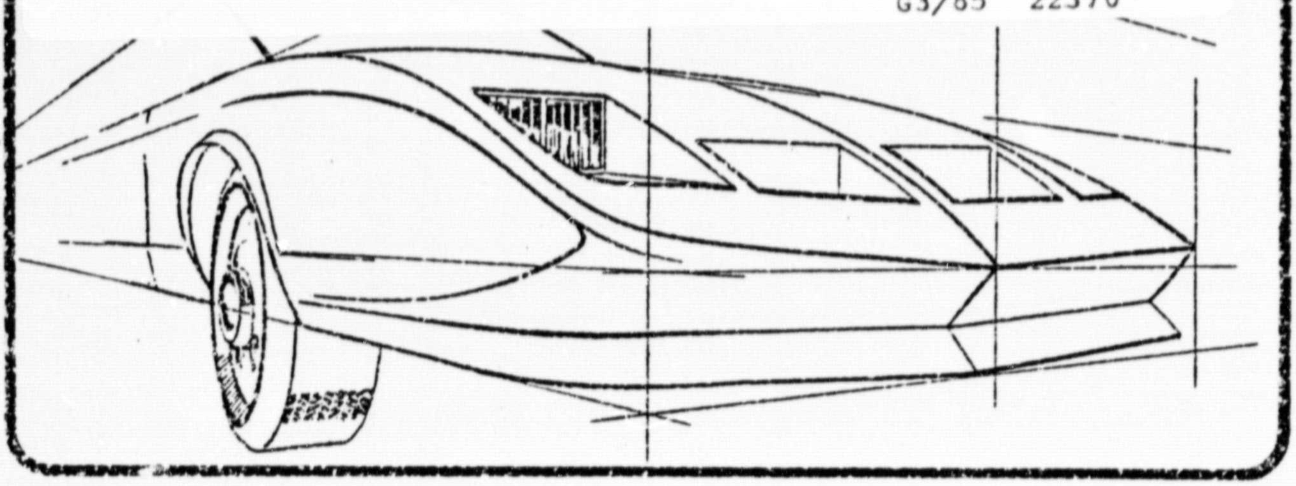
CONTRACT NUMBER 955188

FINAL REPORT

JANUARY 1980

PREPARED BY

MINICARS, INC.
55 DEPOT ROAD
GOLETA, CALIFORNIA 93017



This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration (NASA) under Contract NAS7-100, pursuant to an interagency agreement between the Department of Energy (DOE) and NASA.

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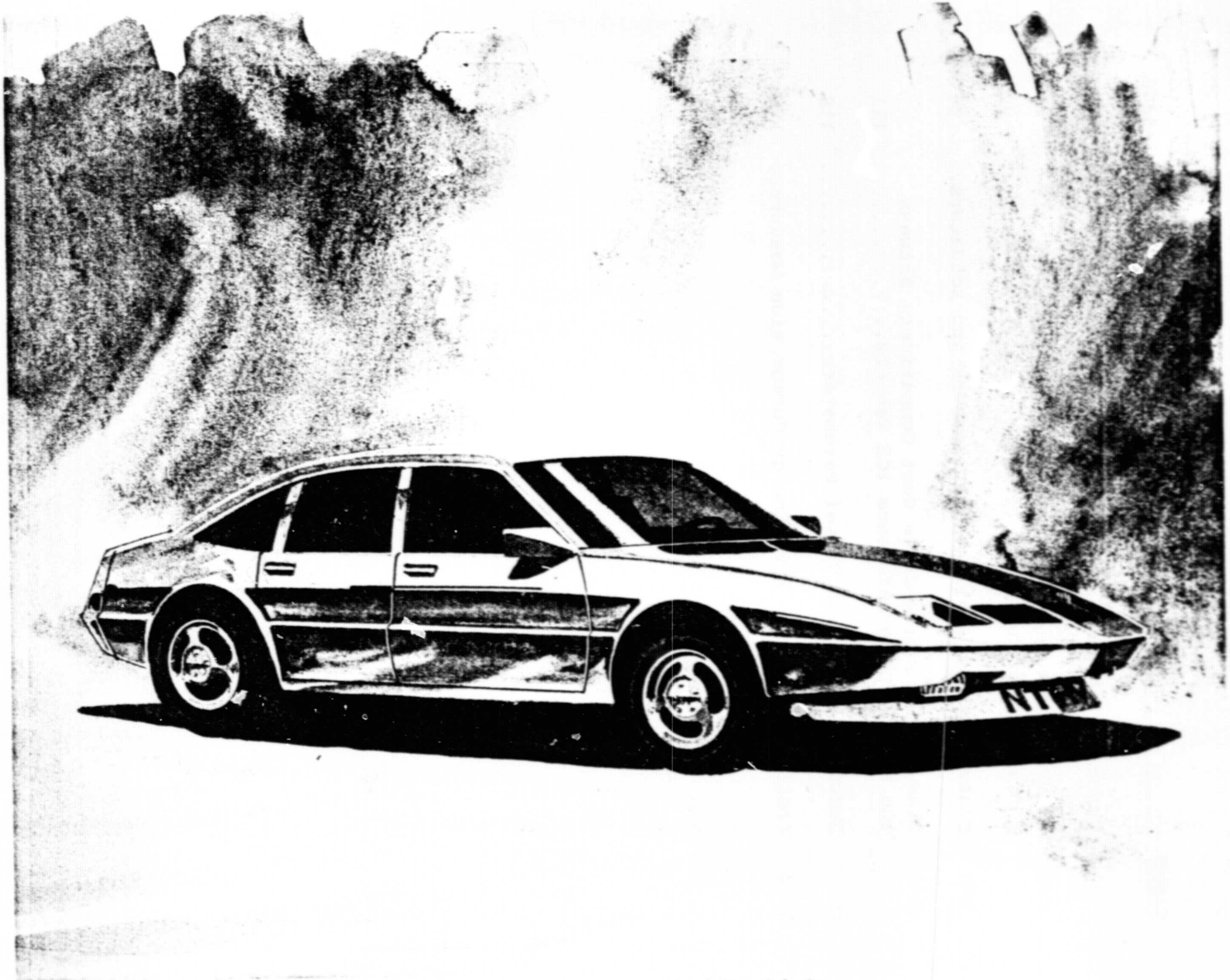

Minicars Near Term Hybrid Vehicle

SUMMARY

Under contract to the Jet Propulsion Laboratory of the California Institute of Technology, Minicars conducted Phase I of the Near Term Hybrid Passenger Vehicle (NTHV) Development Program. This program led to the preliminary design of a hybrid (electric and internal combustion engine powered) vehicle and fulfilled the objectives set by the Jet Propulsion Laboratory:

- Identify missions for hybrid vehicles that promise to yield high petroleum impact.
- Develop, through trade-off studies, a hybrid vehicle preliminary design that satisfies the mission requirements and performance specifications.
- Identify technologies that are critical to successful vehicle design, development and fabrication.

One mission identified in this program is "All Purpose City Driving." This mission includes over 98 percent of the automotive trips taken. An NTHV designed for this mission is expected to consume 60 percent less petroleum than would a conventional vehicle of similar size.

Trade-off studies to maximize fuel savings were used to develop initial design specifications of the NTHV. Various designs were "driven" through detailed computer simulations which calculate the petroleum consumption in standard driving cycles, the petroleum and electricity consumptions over the specified missions, and the vehicle's life cycle costs over a 10 year vehicle lifetime. Particular attention was given to the selection of the electric motor, heat engine, drivetrain, battery pack and control system.

Building on the trade-off studies, we developed a preliminary hybrid design. The vehicle incorporates production components wherever feasible (a "ground up" design of an entirely new automobile would be nearly impossible in the near term). The base vehicle is a modified General Motors X-body car, which represents the state of the art in lightweight automotive packaging. The vehicle is powered by a 48.5 kW turbocharged Volkswagen Rabbit diesel engine and a 24 kW (peak) compound dc electric motor in a parallel drive. Consumer acceptance considerations dictated the inclusion of a three speed automatic transmission, although a manual would be more cost-effective. The transmission is coupled to the engine through a lock-up torque converter and to the motor through either a slipping clutch or a variable-fill fluid coupling. The selection of the best motor/transmission mechanical interface is of particular importance and should be given high priority as NTHV development progresses.

For maximum efficiency, the NTHV design includes an on-board microcomputer based control system. This system decides whether the vehicle is to use the engine, the motor, or both, and controls the transmission shift sequences in order to maximize fuel economy. The same control system is also well suited to the monitor and control of numerous other functions in the vehicle. The evolution of a practical, reliable and inexpensive control system is critical to the development of a successful NTHV.

Although optimal sizes for the engine and motor were specified by the trade-off studies, the best battery pack size was not readily discernible. A larger battery capacity (up to approximately 16 kW-hr) would increase the all-electric range and improve petroleum economy. But somewhat smaller packs are more cost-effective. The preliminary design includes twelve 6 volt lead-acid batteries, whose combined capacity is 14.7 kW-hr at a 3 hour rate. This size was chosen primarily on the basis of packaging constraints. Lead-acid, nickel-iron and nickel-zinc batteries were evaluated for use in the NTHV. At the current level of development, the nickel-iron battery exhibits serious deficiencies while charging, and the nickel-zinc battery has an unacceptably short lifetime. These considerations leave the lead-acid battery as the only feasible choice in the near term, but nickel-iron or nickel-zinc batteries may eventually become more desirable as battery technology progresses.

The trade-off studies also showed that the NTHV accessories can require a substantial amount of power, with deleterious effects on fuel economy. Accessories are most efficiently powered by a drive which can couple to either the engine or motor. In addition, innovative design of accessory systems and drives can have a significant impact on fuel economy. A regenerative braking system and a turbine-driven generator which reclaims engine exhaust should also provide cost-effective fuel economy improvements.

The program's final results indicate that a hybrid vehicle would use substantially less petroleum than a hypothetical 1985 reference automobile. We calculated the 10 year life cycle costs of both the NTHV and the reference vehicle. Assuming that each car is driven a mean annual distance of 19,073 kilometers and petroleum is priced at $0.252 per liter ($0.955 per gallon), we found that the NTHV would cost $0.131 per kilometer--approximately 25 percent higher than the conventional vehicle's expected cost of $0.106 per kilometer. Higher petroleum prices do make the hybrid more attractive, however, and breakeven prices for petroleum fuel were calculated for some possible missions. In all purpose city driving, the NTHV becomes competitive at $0.67 per liter ($2.45 per gallon), and, for a family and civic business mission, the breakeven price drops to $0.30 per liter ($1.13 per gallon).

Table 1 summarizes the NTHV preliminary design, and Table 2 lists the hybrid performance specifications. The preliminary performance specifications were calculated in the trade-off studies (Section 3) through the use of the computer simulations described in Section 9. Appendix B explains, in detail, the assumptions which lay behind the specifications in Table 2. For comparison, we have included the applicable JPL vehicle performance requirements.

Table 1. Summary of Preliminary Design Component Specifications

Weight	
Curb Weight	1746 kg
Inertia Weight	1890 kg
Dimensions	
Length	493 cm
Width	173 cm
Height	139 cm
Wheelbase	266 cm
Battery	
Type	ISOA lead-acid
Capacity (3 hour rate)	12.6 kW-hr
Voltage	72V
Weight	336 kg
Size	242 DM^3
Heat Engine	
Type	4-cylinder turbocharged VW diesel
Displacement	1475 cc
Power	48.5 kW @ 5000 rpm
Torque	119 Nm @ 3000 rpm
Maximum Speed	5000 rpm
Electric Motor	
Type	Compound wound dc
Power Rating	24 kW intermittent; 15 kW continuous
Field Control	Transistor
Maximum Speed	10,000 rpm
Transaxle	
Type	Computer controlled automatic with lock-up torque converter
Number of Gears	3
Gear Ratios - 1	2.84:1
2	1.60:1
3	1.00:1
Final Drive Ratio	2.53:1
Brakes	
Type	Diagonal split hydraulic system with regenerative braking
Suspension	
Type	Front independent; rear beam axle
Steering	
Type	Powered rack and pinion
Tires	
Type	Radial ply P205/75 R14
Microprocessor	
Type	Distributed processing system utilizing the Motorola 6800 processor family

Table 2. Preliminary Design NTHV Performance Specifications

			Minicars' NTHV	JPL Minimum Requirements
P1	Minimum non-refueled range (km)			
P1.1	Federal Highway Driving Cycle (FHDC)		718	
P1.2	Federal Urban Driving Cycle (FUDC)		505	
P1.3	SAE J227a(B) Driving Cycle		413	
P2	Cruise speed (km/hr)		88	90
P3	Maximum speed			
P3.1	Maximum speed (km/hr)		180	
P3.2	Length of time maximum speed can be maintained on level road (minutes)		5	
P4	Accelerations (sec)			
P4.1	0-50 km/hr (0-30 mph)		5	6
P4.2	0-90 km/hr (0-56 mph)		13	15
P4.3	40-90 km/hr (25-56 mph)		10	12
P5	Gradeability (engine only)**			
		Grade (%)	Speed (km/hr)	
P5.1		3	118	90
P5.2		5	86	50
P5.3		8	80	50
P5.4		15	25	25
P5.5	Maximum grade	25		
P6	Payload capacity (kg)		520	520
P7	Cargo capacity (m^3)		0.5	0.5
P8	Consumer costs			
P8.1	Consumer purchase price (1978 $)		9,212	
P8.2	Consumer life cycle cost (1978 $/km)		0.131	

*72 volt Near Term Hybrid Vehicle with the accessories on.

**Distance is not included, because in diesel drive the distance is limited only by the fuel tank capacity.

Table 2 (Cont'd)

		Minicars' NTHV	JPL Minimum Requirements
P9	Emissions (gm/km)		
	P9.1 Hydrocarbons (HC)	0.13	
	P9.2 Carbon monoxide (CO)	0.31	
	P9.3 Nitrogen oxides (NO_x)	0.56	
P10	Ambient temperature capability - temperature range over which minimum performance requirements can be met (°C)	-20 to +40	
P11	Rechargeability - maximum time to recharge from 80 percent depth-of-discharge (hr)	6 to 8	
P12	Required maintenance - routine maintenance required per month (hr)	1	
P13	Unserviced storeability - unserviced storage over ambient temperature range of -30 to +50 °C (-22 to +122 °F)		
	P13.1 Duration (days)	120	
	P13.2 Warm-up required (minutes)	1 to 2	
P14	Reliability - mean usage between failures (km)		
	P14.1 Powertrain	40,000	
	P14.2 Brakes	40,000	
	P14.3 Vehicle	40,000	
P15	Maintainability - time to repair (hr)		
	P15.1 Mean	5.0	
	P15.2 Variance	2.0	
P16	Availability - minimum expected utilization rate [i.e., 100 x time in service ÷ (time in service + time under repair)]	97%	
P17	Additional accessories and amenities		
	Fuel-burning heater air conditioner, power steering, and power brakes		

SECTION 1

INTRODUCTION

The need to reduce petroleum consumption in the United States is now recognized as a national goal, and promises to become even more important in the future. Because over 30 percent of our petroleum is burned as fuel in automobiles, improvements in automotive fuel economy can be of significant aid.

The substitution of electricity for petroleum is one straightforward way to improve fuel economy. Nevertheless, our ability to efficiently store electrical energy is still a problem; state-of-the-art batteries have specific energies considerably below those of fossil fuels. Consequently, electric vehicles cannot offer a range comparable to conventional cars.

One possible solution to this problem is the hybrid vehicle, which is powered by both an electric motor and a heat engine. In the interest of fuel economy, the hybrid's power during short trips is primarily furnished by an electric motor coupled to a battery pack. But its engine is available when acceleration demands exceed the motor capacity or when trip requirements exceed its electric range.

This report addresses several questions about the development of hybrid vehicles in the near future. Do the petroleum savings that might accrue justify the added cost, weight and complexity of such vehicles? Would the hybrid be an acceptable alternative for the American people's transportation needs, and if so, would they perceive it as such? Do we have the technology now to build these vehicles and to make them safe, affordable and maintainable?

In the first task in this research (the "mission analysis") we attempted to find if there is a place for the hybrid in the nation's transportation picture. We examined the uses of automobiles in detail and refined the driving patterns into identifiable missions. These were quantified according to such variables as trip length, trip frequency and number of passengers. Each mission was analyzed for its suitability for hybrid vehicles and, when suitable missions were found, the resulting petroleum savings of a hybrid fleet were estimated.

With an established mission as a guideline, we refined the NTHV in terms of ultimate goals. This refinement occurred through trade-off studies, which were essentially a series of computer-assisted optimizations of petroleum savings in terms of the various design parameters and constraints (specified by JPL). To aid in the analysis, we calculated the net benefit (additional savings less additional cost) of each change. The trade-off studies also helped to pinpoint the parameters which are most critical to the design.

Finally, the trade-off results were meshed into a preliminary design package. In this task the theoretical package from the trade-off studies had to be transformed into a potentially producible automobile. Preliminary design often dictates that basic parameters (for instance, battery capacity) be changed; consequently, this process frequently reverted to additional trade-off studies in order to reoptimize the design. The resulting preliminary design is therefore a direct product of both theoretical calculation and practical knowledge.

JPL requested[1] that this report address certain specific topics; the locations of the discussions are listed below.

1. A brief summary of all Phase I activities is given at the front of this report.
2. The hybrid vehicle preliminary design is described in Sections 4, 5 and 6. Table 2 of the Summary lists performance projections for the overall vehicle and some of its subsystems. Section 4.5 gives references to the more detailed design information found in the Preliminary Design Data Package (Appendix C).
3. Alternative hybrid vehicle design options are discussed throughout Sections 3 through 6. A listing of the tradeoff study alternatives is included in Section 3.
4. Computer simulations are discussed in Section 9.
5. Section 8 describes the supporting economic analyses.
6. Reliability and safety considerations are specifically discussed in Section 7 and are mentioned in Sections 4, 5 and 6.
7. Section 10 lists conclusions and recommendations arrived at during the performance of Phase I.
8. A complete bibliography follows the list of references.

SECTION 2

MISSION ANALYSIS

2.1 INTRODUCTION

The assessment of the performance requirements and fuel consumptions of conventional and hybrid vehicles over a variety of driving conditions requires an identification of automobile usage. The usual way to identify usage is to evaluate vehicle performance over "cycles" characteristic of specific environments, such as highway or city driving. The approach used in the mission analysis study involved the construction of multidimensional probability distributions describing observed vehicle usage. Assessing the performance and fuel consumption of reference and hybrid vehicles over such distributions yielded a better understanding of the NTHV's potential as a replacement for conventional automobiles. The objectives of the analysis were

1. To characterize city, suburban and highway driving and to compare the fuel consumptions of the conventional and hybrid vehicles in each
2. To characterize missions, to estimate their associated fuel consumptions, and to specify a range of missions over which the hybrid is suitable.

Conceptually, the mission analysis was a constrained optimization problem. The objective function to be minimized was petroleum consumption, and the constraints, defined at length by JPL in Reference 1, concerned the minimal levels of passenger capacity, performance, comfort, safety and public acceptability. These constraints were so tight that for some otherwise promising missions, either no feasible solution existed or the solution was non-optimal. Our general approach was to emphasize the optimal constrained solution, but also to consider what may have been the case if the constraints had been relaxed.

The hybrid vehicle should show a maximum potential for reducing petroleum consumption. This includes both the amount of fuel that could be saved (a question amenable to analysis) and the amount that will be saved (which must remain, in part, a question of judgment). The first refers to the fuel that would be saved if a certain type of vehicle were to assume a certain portion of the auto market. The second must also consider the likelihood that such vehicles will, in fact, achieve a certain level of customer acceptance.

Given that the NTHV meets the minimum performance and comfort levels specified by JPL and the range and reliability requirements determined by the mission, trade-off and design analyses, the key variable in determining acceptability is cost. Cost must be interpreted in the very broadest sense and must be related to the social and economic circumstances which may exist in, say, the period from 1985 to 2000. Future circumstances which determine the background of studies are often called "scenarios." Some of the more obvious scenarios are

1. The price of gasoline and diesel fuel reaches what today would be considered astronomical levels, say $10 per gallon.

2. Gasoline is rationed or becomes totally unavailable, except to certain sectors of the population (for example, doctors).

3. Each family is restricted to one car, or there is some other method of car rationing.

None of these possibilities should be rejected out of hand. The one thing that is certain about the future is that it will be different.

In our study, however, we considered a scenario much like the present. It included only the relatively minor variations specified by JPL.[1] We believe, nevertheless, that it is important to keep radically different circumstances in view. A plan which takes into account only one possibility cannot be adequate.

2.2 MISSION DEFINITION

The basic idea of the analysis by missions is, of course, to uncover and define some subset of the automobile market particularly suited to hybrid vehicles. It goes without saying that missions do not provide the only way to subdivide the market. Much more commonly, one thinks of automobile types (station wagons, family sedans, sports cars) or customer characteristics (young "swingers," suburban middle income family heads of household, and so on). One can also characterize market sectors by engineering performance characteristics--as is done, for example, by Friedman,[2] who classifies cars by their weight to power ratio--and in any number of other ways.

We attempted to integrate the results and methods of all approaches to automobile market analysis with our mission analysis, whenever possible. There were several excellent reasons, however, for making the missions approach our central theme.

1. It was specifically requested by JPL.[1]

2. The best available statistics relating to auto travel have been broken down by trip purpose and, therefore, by mission.

3. Missions can be combined into new missions in a systematic and organized manner.

Surber and Deshpande[3] define missions as combinations of trip purposes. Trip purposes, in turn, are defined by enumeration by the U.S. Department of Transportation, Federal Highway Administration (FHWA).[4] Table 2-1 lists trip purposes and presents some of their characteristics. Any number of missions can be formulated by combining these trip purposes in various proportions.

No one would claim that a person who purchases a car for a particular mission will never use that car for other purposes. Rather, our idea was to proceed as if the customer thinks primarily of that mission in defining the characteristics of the car that meets his needs. We could then judge the market penetration and the petroleum savings attainable, and could modify our results by making allowance for the fact that the car will be used for other missions as well.

In order to learn as much as possible about how people drive, we studied the most comprehensive automobile usage data available. These included the Nationwide Personal Transportation Study (NPTS),[4] a Systems Development Corporation Survey of Urban Driving,[5] and origin-destination surveys made in Los Angeles and Washington, D.C. Analysis of the various data by Minicars and our subcontractor, General Research Corporation, showed that, while yearly mileage may vary significantly from survey to survey, the number of trips per day and the distributions of both trips

Table 2-1. Trip Purposes and Their Attributes

Trip Purpose	Frequence (%)		Approximate Daily Range Requirement (km)	Number of Passengers	Cargo Requirements	Performance
	Trips	Travel				
1 Home to work and return	36	42	100	2		medium
2 Family business	31	19	50	4	medium	low
3 Civic, educational, religious	9	5	50	4 to 6	medium	low
4 Social and recreational	22	33	100	4 to 6	medium	medium
5 Vacation	1	2.5	500	4 to 6	high	high

and daily travel by length remain essentially the same. The similarity of trip length distributions for three data sets can be seen in Figure 2-1. A rule of thumb can, in fact, be suggested for all travel: the 75th percentile is about equal to the average trip length, and the 90th and 95th percentiles are two and three times the average length, respectively. The observed distribution similarities give us confidence in our models and make it easier to study the effects of changes in such variables as average daily travel.

If the trip purposes in Table 2-1 are combined with trip length distribution data, various missions can be specified. We selected three candidate missions for the NTHV (while keeping in mind the advantages and disadvantages peculiar to hybrid vehicles). The three candidates are summarized in Table 2-2.

We selected Mission A, "All Purpose City Driving," to provide the largest possible petroleum savings. Mission A, which served as the primary basis for evaluating hybrid designs in the remainder of this contract, includes all trips shorter than 80 kilometers. Presumably, the NTHV owner would use mass transit or, possibly, a second family car for longer trips. The 80 kilometer trip length ceiling is not as restrictive as one might think; it still encompasses 98.8 percent of all trips and 96.3 percent of the total distance driven. Mission A is characterized by 18,596 kilometers of travel per year, consisting of trips averaging 13.6 kilometers in length.

Another candidate is Mission BB, the commuting mission. Based on the average trip length and average daily travel data in Table 2-2, there would seem to be no reason to produce a vehicle aimed at the commuter market segment. However, the vehicle

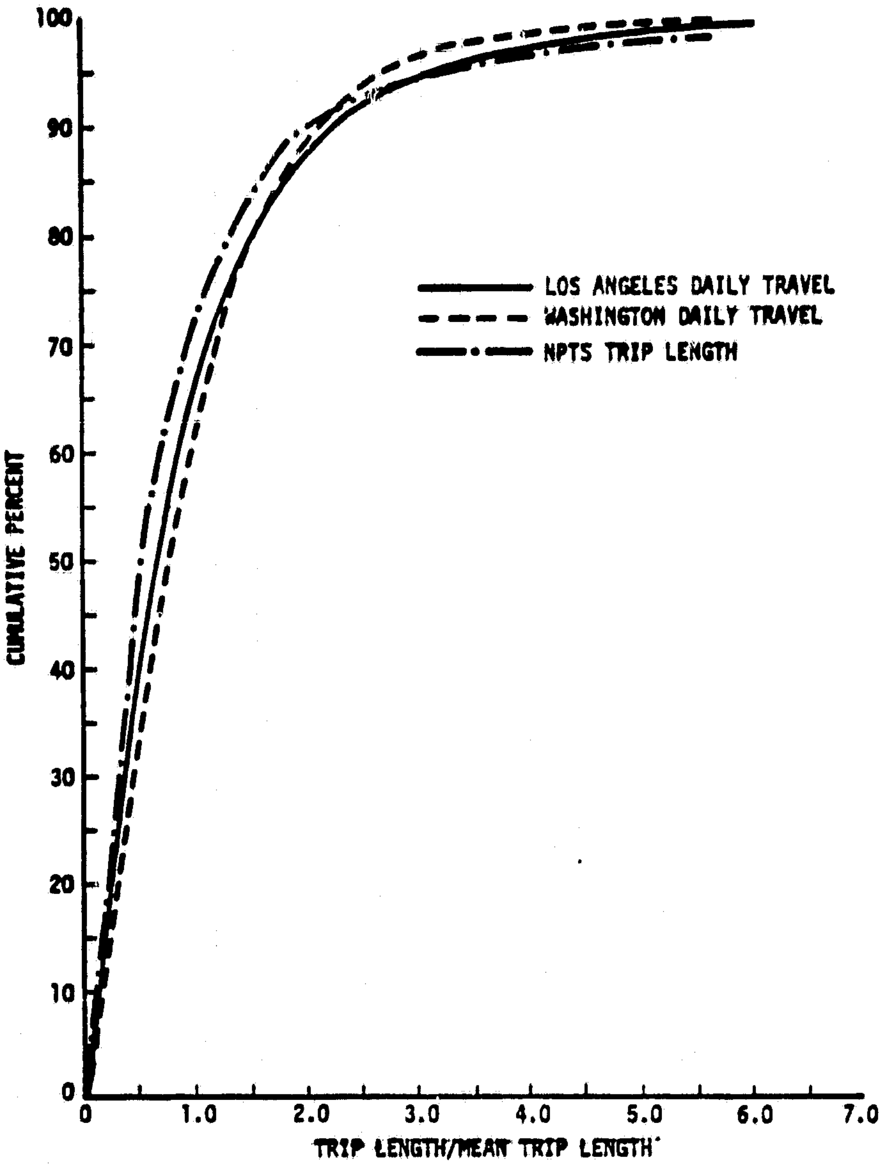

Figure 2-1. Actual Trip Length and Daily Travel Distributions

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Table 2-2. Summary of Candidate Missions

	Mission A (All Purpose City Driving)	Mission BB (Commuting)	Mission C (Family and Civic Business)
Trip purposes	1,2,3,4	1	2,3
Average trip length (km)	13.6	14.6	8.65
Average trips per day	3.74	1.76	1.47
Distance traveled per day (km)			
50th percentile	50.9	43*	12.7
95th percentile	153	65*	38
Average yearly travel (km)	18,596	5,890	4,635
Vehicle occupancy (no. passengers)			
95th percentile	4.79	2.62	4.41
98th percentile	5.44	3.72	5.51
Reference ICE vehicle**			
Average fuel economy (km/ℓ)	10.74	11.0	9.62
Average yearly fuel consumption (ℓ)	1,730	854	483
Potential number of vehicles in use as a percentage of total vehicle fleet	100	70	100

*These numbers represent distance traveled on a work day, including one 10 km after-work trip.

**The reference ICE vehicle is defined in Section 3.1.

occupancy data suggest that a significant portion of the commuter market could be served by a two passenger car. We initially considered Mission B, which only included commuting, but it seems likely that the consumer would use his or her car for other purposes as well. Therefore, we included three 10 kilometer trips per week in Mission BB to represent such uses as shopping, meals out, and after-work socializing.

In addition, we selected Mission C, Family and Civic Business, to represent the short range driving for which electric vehicles are well suited. Like Mission B, Mission C was chosen to satisfy the needs of a particular segment of automobile purchasers. One would expect hybrid vehicles to be most competitive with conventional automobiles in this mission.

2.3 POTENTIAL PETROLEUM SAVINGS

A necessary step in our methodology was to determine how much petroleum the hybrid would consume while driving a particular mission for a year, and to compare it to the fuel consumed by a hypothetical 1985 reference vehicle. (The reference vehicle is discussed in Section 3.1.)

National fuel consumption data exist for three standard driving cycles: the Federal Highway Driving Cycle (FHDC), the Federal Urban Driving Cycle (FUDC), and the Society of Automotive Engineers J227a(B) Electric Vehicle Driving Cycle. Unfortunately, such data do not exist for the missions we have specified. Therefore, it was necessary to break each mission down into some combination of the three standard cycles. We accomplished this (in general) by assuming that a trip begins with an FUDC segment, has an intermediate FHDC segment, and ends with another FUDC segment. We made this assumption because driving on freeways or other major arteries will most likely occur during the middle of a trip.

The two FUDC components were assumed to be of equal length, and the combination of city and highway driving was chosen such that the average speed and trip length of the combined cycles matched the trip under analysis. For trips shorter than 8.0 kilometers, an FUDC cycle was sandwiched between two SAE J227a(B) cycles, and for trips longer than 48.3 kilometers we used the FHDC cycle alone. The methodology of combining driving cycles is discussed in detail in Section B.2.4 of Appendix A.

After subdividing missions into driving cycles, we could determine both how much petroleum the reference vehicle burns in each trip and how much it burns in a year. We first calculated the hybrid vehicle petroleum consumption by simply assuming that the NTHV operated on electric power alone, and then switched to heat engine power when its electric range had been exceeded. This assumption provides a conservative estimate of fuel economy, since the NTHV will be operated on a more refined strategy. Table 2-2 also shows the reference vehicle fuel economies and yearly consumptions for the candidate missions.

Figure 2-2 shows the fuel consumption, plotted as a function of trip length, for the reference vehicle and hybrid vehicles of various ranges. The curves show that, even after the battery supply is exhausted, NTHVs continue to demonstrate superior fuel economy. This is due to the small, highly efficient NTHV engine (see Section 5.2), which must have help from the electric motor to provide fully adequate performance.

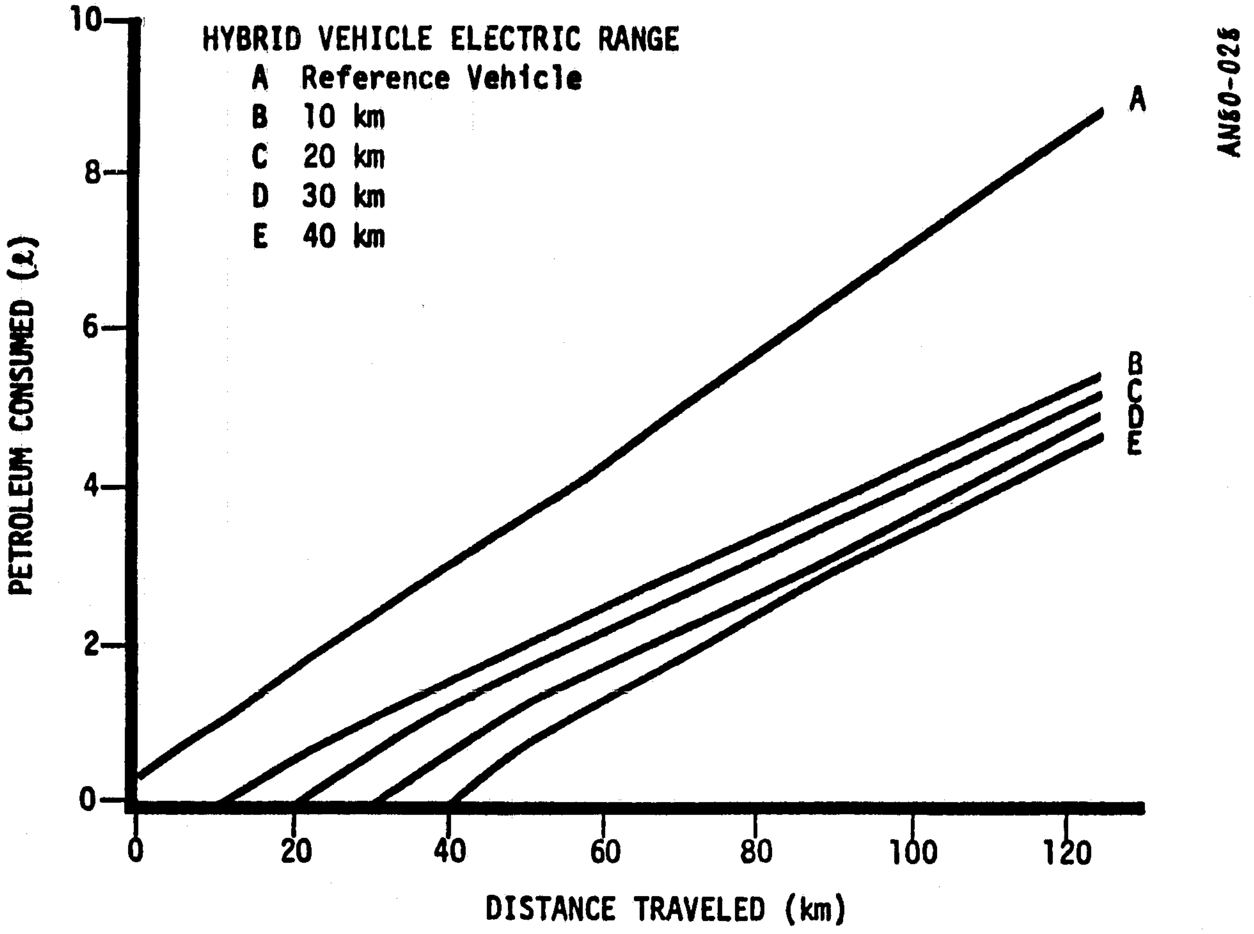

Figure 2-2. Hybrid Vehicle Fuel (Petroleum) Consumption

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SECTION 3

BASIC TRADE-OFF ANALYSES

3.1 METHODOLOGY

The goal of the design trade-off analyses is the development of a hybrid vehicle design which best achieves the potential for petroleum savings found by the mission analysis. Fundamentally, a trade-off study provides a systematic means of estimating the effects of design parameters on vehicle performance. The methodology we constructed (and implemented) to evaluate the advantages and disadvantages of all hybrid subsystems and components is outlined in Figure 3-1.

To provide a starting point in the design procedure, we specified a baseline NTHV. An evaluation of all conceivable NTHV designs would be impossible, so we began with our best estimate of what a hybrid vehicle would be, and then changed parameters one at a time to see how each affected the total package. The baseline hybrid specifications are given in Table 3-1.

Since the selected mission, Mission A, includes most of the trip purposes (and virtually all of the trips taken), the NTHV performance specifications must satisfy the needs of most automobile owners most of the time. The JPL vehicle performance requirements, listed in Table 2 of the Summary, provide a good estimate of an NTHV that should satisfy most owners. Nonetheless, conformance to the performance requirements does not guarantee that the NTHV will gain wide acceptance, and such considerations as marketability must be addressed independently.

To help gauge the desirability of introducing hybrid vehicles into the automobile fleet, we specified a reference vehicle to

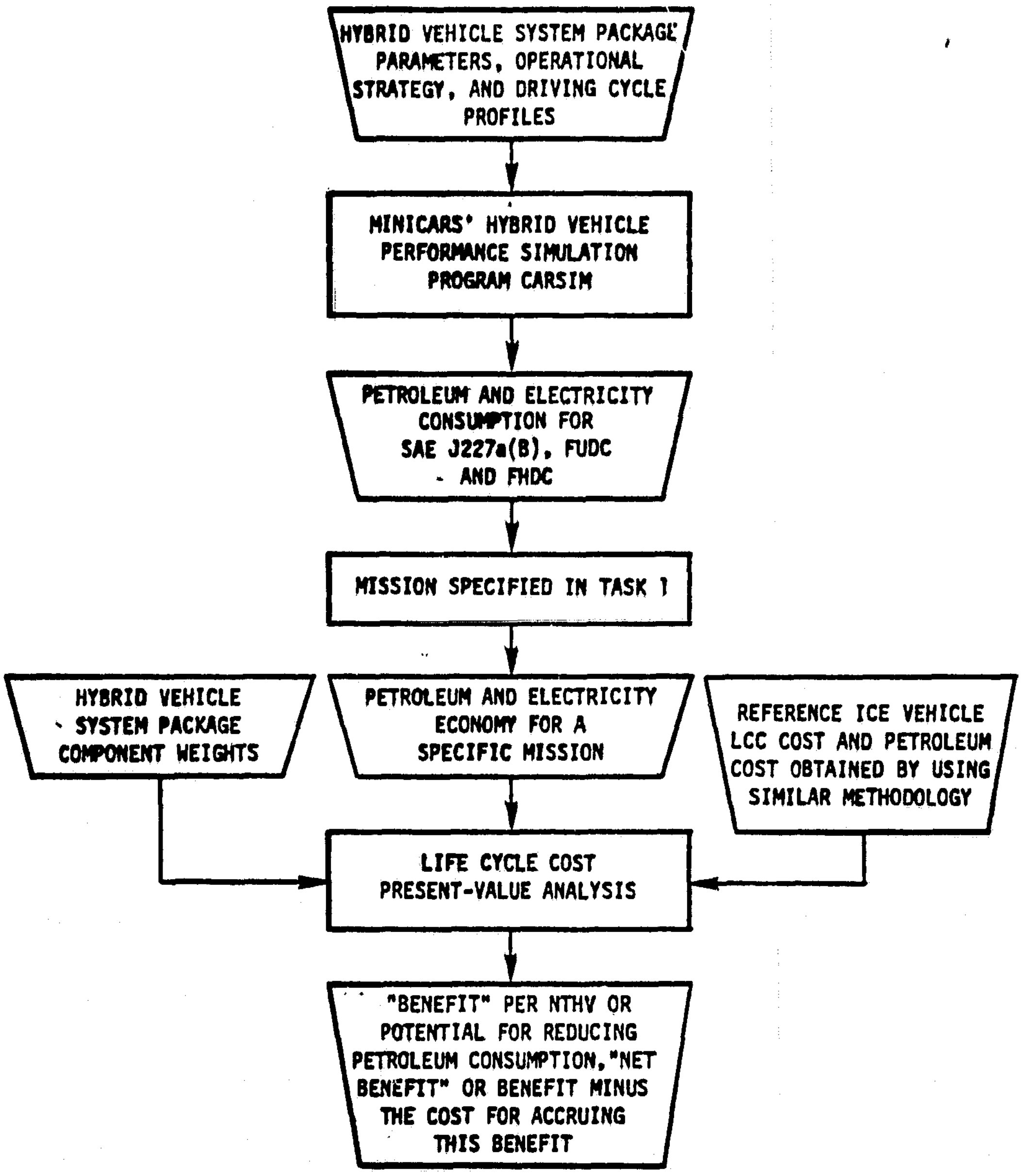

Figure 3-1. Trade-Off Studies Methodology for Each NTHV System Package

Table 3-1. NTHV Preliminary Specifications

Vehicle	Modified 1980 GM X-Body
Wheelbase (cm)	265
Curb weight (kg)	1894
Engine	Turbocharged Volkswagen Rabbit Diesel
Displacement (cc)	1471
Bore (mm)	76.5
Stroke (mm)	80.0
Compression ratio	23:1
Maximum power	48.5 kW @ 5000 rpm
Maximum torque	119 Nm @ 3000 rpm
Motor	dc shunt motor
Power (kW)	29
Maximum speed (rpm)	10,000
Base speed (rpm)	1650
Controller	Transistorized field chopper
Battery	Improved state-of-the-art lead-acid
Voltage	84 volts (fourteen 6-volt batteries)
Capacity (kW-hr)	12.6 (3 hour rate)
Weight (kg)	336
Transaxle	Computer controlled automatic with lock-up torque converter
Number of gears	3
Ratios - 1st	2.84:1
2nd	1.60:1
3rd	1.00:1
Final drive ratio	2.53:1
Tires	P205/75 R14

represent the near term vehicles which the NTHV might replace. The size requirement for the proposed NTHV puts a practical limitation on the vehicles which can be replaced. The proposed hybrid will be a five passenger car which, even with downsizing and weight reductions, would not have the efficiency required to replace small or subcompact cars. On the other hand, the NTHV would be too small to replace the largest vehicles. Therefore, the required size limits its potential to that of a replacement for compact and full-sized vehicles. Since each of these sizes of vehicles is estimated in the JPL Guidelines[6] to make up 30 percent of the vehicle market in 1985, a replacement would have the potential of capturing up to 60 percent of the total vehicle market.

Although automotive design has changed substantially in the past few years, it is still possible to predict with some accuracy what the 1985 cars will be like. We began with data (developed by Burke[7]) which project new car parameters for the period 1975-1985. Burke's analysis included the following variables:

Vehicle
    Price
    Weight
    Length
    Width
    Wheelbase
    Occupant packaging space

Engine
    Type
    Displacement
    Weight
    Emissions levels

Transmission
    Type
    Weight

Safety performance.

Projections of these parameters are not as hard as might first be guessed. Federal law has placed constraints on many parameters. The long lead times required to develop new automobiles have already established other parameters. And there are clear trends in the present marketplace--for instance, toward smaller size, lighter weight, better fuel economy and increased utilization of electronic control systems.

Our evaluation of these parameters in accordance with the JPL constraints led to the reference internal combustion engine (ICE) vehicle outlined in Table 3-2. This table also includes the relevant data for the 1980 Chevrolet Citation, one of the new General Motors X-body cars. The X-body cars are the product of a 5 year multibillion dollar effort which had fuel economy as a primary objective. As the data in Table 3-2 suggest, we expect the typical 1985 five passenger automobile to be quite similar to the Citation. The Citation is also noteworthy because we selected it as the base vehicle for the NTHV (Section 4).

For each candidate system package we simulated the hybrid's performance through three driving cycles (SAE J227a(B), FUDC and FHDC). The results of the hybrid vehicle simulation were used to evaluate the petroleum and electricity consumptions and the electric range when the vehicle is taken through the missions specified in the mission analysis. Then the results of the mission simulation (the average petroleum and electricity economies) were used in the evaluation of the life cycle cost (LCC) for each NTHV system package. Net benefit (the difference between the LCC of the reference vehicle and the LCC of the NTHV) was also calculated for each hybrid.

Table 3-2. Reference ICE Vehicle and Chevrolet Citation Performance Specifications

	1985 Reference ICE Vehicle	1980 Chevrolet Citation
Vehicle type	Mid-size, five-passenger	Mid-size, five-passenger
Inertia weight (kg)	1360	1307
Length (cm)	470	449
Width (cm)	185	174
Height (cm)	137	135
Engine	Gasoline, 63-67 kW	Gasoline, 67-86 kW
Transmission	4-speed manual or 4-speed overdrive automatic with lockup torque converter	4-speed manual or 3-speed automatic
Acceleration (0 to 966 km/hr)	14 sec	10-14 sec
Fuel economy (km/ℓ)		
Combined	12.1	9.8-12.3
City	10.8	8.5-10.2
Highway	14.3	11.5-14.9
SAE J227a(B)	7.1	N/A

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Using this methodology as a standard, we investigated the following factors:

1. Hybrid power sizing
   a. Battery capacity
   b. Heat engine peak power
   c. Electric motor peak power
2. Battery types
   a. Lead-acid
   b. Nickel-zinc
   c. Nickel-iron

3. Battery parameters
    a. Cycle life
    b. Initial state of discharge
    c. Final depth of discharge
4. Heat engine types
    a. Turbocharged diesel
    b. Naturally aspirated diesel
    c. Reciprocating spark ignition
    d. Stratified charge reciprocating spark ignition
5. Electric motor types
    a. dc shunt
    b. dc series
    c. dc compound
6. Controller
7. Charger
8. Transmission types
    a. Five speed manual
    b. Three speed automatic
9. Transmission parameters
    a. Transmission ratios
    b. Final drive
10. Drivetrain configurations
11. Regenerative braking
12. Hybrid accessories
    a. Air conditioning
    b. Other accessories
    c. Accessory operational strategy
13. Hybrid and vehicle cold start
14. Heating and defrosting
15. Vehicle operational strategies
16. Microcomputer
17. Vehicle inertia weight
18. Aerodynamic drag resistance
19. Rolling resistance

20. Electric range
21. Acceleration
22. Gradeability
23. Hybrid vehicle marketability
24. Life cycle costs

We began the investigation of the NTHV system packages using the most promising operational strategy. The object was the depletion of the batteries to their maximum allowable state of discharge at the end of the day. In this strategy the motor is used as the primary drive component until the batteries are depleted to their maximum allowable discharge. Then the engine becomes the primary drive component.

The initial trade-off studies, whose results are given below, did not include accessories, and worked under the assumption of a warm start. We performed all the trade-off studies by taking the NTHV system packages through Mission A, which covers 98.8 percent of all trips. The NTHV is assumed to start each morning with a fully charged battery pack which is depleted through subsequent driving. Minicars' computer system MISSIM was used to simulate the mission and to make the trade-off calculations (see Section 9). All of the costs used in this work are reported in 1978 dollars.

3.2 RESULTS

Initially, the trade-off studies concentrated on three major governing parameters of an NTHV system: battery capacity, electric motor peak power and heat engine peak power. During these studies the peak power to weight ratio was assumed to be 0.04 kW/kg, which is a necessary precondition to achieving the

JPL minimum performance constraints. The GM X-body vehicle, specified for the baseline NTHV, weighs 1090 kg. If the total weight of the NTHV is higher than this, then the X-body will have to be reinforced. To account for the reinforcements, we took the difference of the two weights and added 30 percent of that number to the total weight of the NTHV.

In this simulation we used ISOA lead-acid batteries with a battery life of 800 cycles.[8] The lead-acid battery capacities were taken to be 8.4, 10.5, 12.6, 14.7, 15.75 and 16.8 kW-hr. The electric dc shunt motor peak powers were assumed to be 14, 19, 24, 29 and 34 kW. The corresponding peak powers for a turbocharged diesel engine vary between 31.2 and 64.6 kW, depending on the peak power of the electric motor. And the NTHV inertia weights vary between 1630 and 1964 kg, depending on the system package used.

Each system package was put through CARSIM (see Section 9) by using the base operational strategy discussed above. Regenerative braking was included in all modes of operation. Figure 3-2 shows the range when the electric motor is the primary drive component and the heat engine secondary. The range increases as battery capacity increases and electric motor peak power decreases. The variations in range become less sensitive to changes in the electric motor peak power at high motor peak powers.

Each system package was put through Mission A, and the resulting yearly petroleum economies are shown in Figure 3-3. For any given battery capacity, the figure indicates the motor and engine combination that maximizes petroleum economy. Not surprisingly, Figure 3-3 indicates that small motors work best with small battery packs, and large motors with large packs

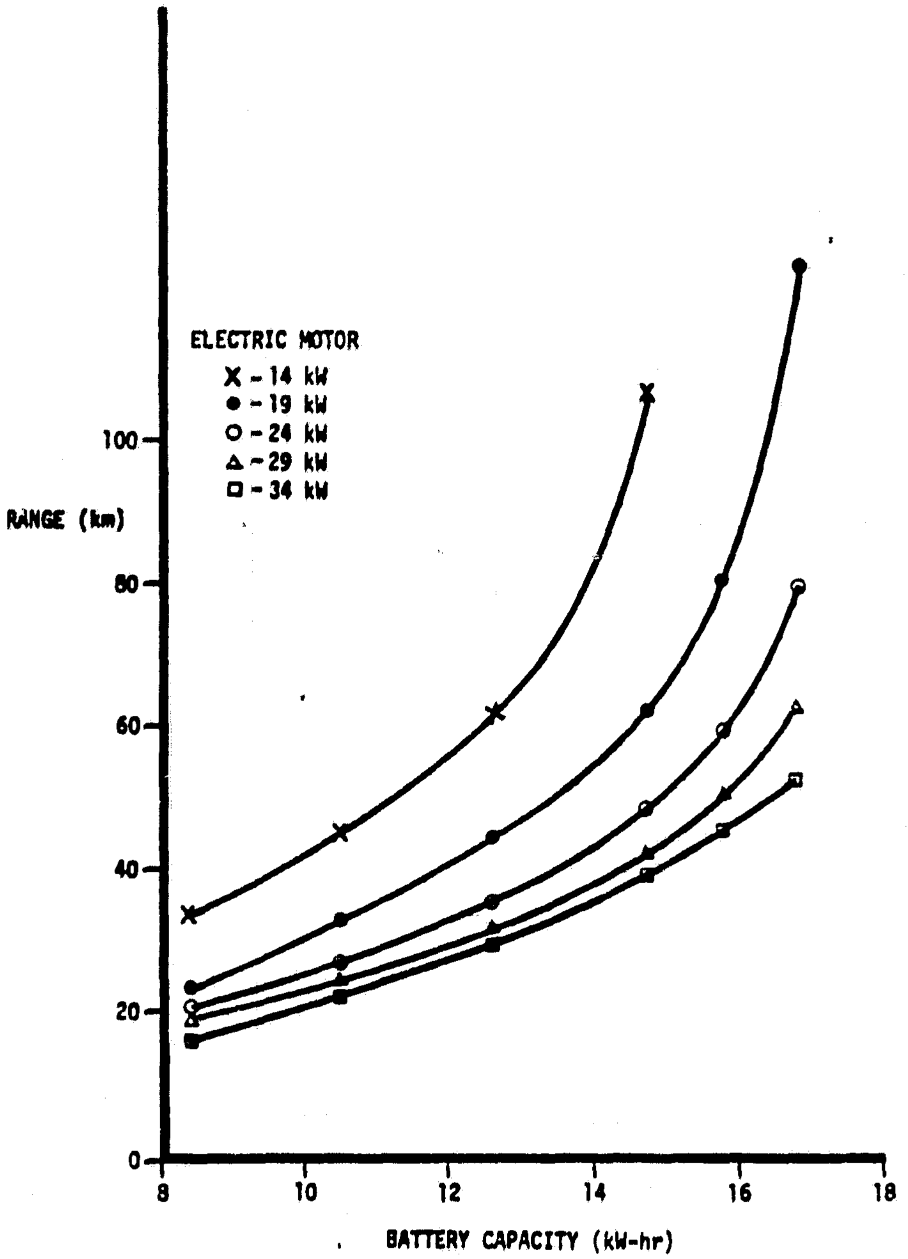

Figure 3-2. Range for the Electric Motor as the Primary Drive Component for Different NTHV System Packages

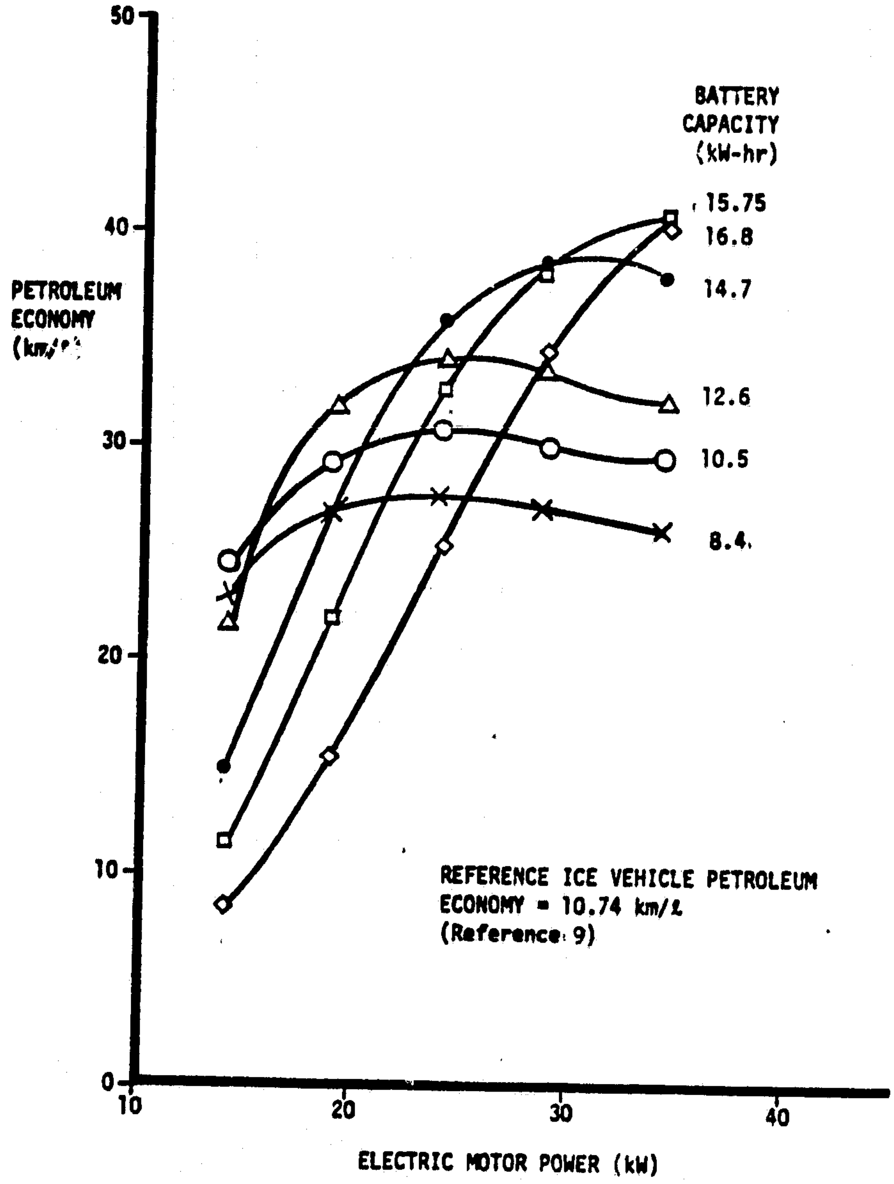

Figure 3-3. Averaged Petroleum Economy in Mission A for Different NTHV System Packages

(therefore the crossover of curves). These curves are a good illustration of the trade-offs that confront the hybrid vehicle designer. For a given size battery pack, an undersized motor will not sufficiently exercise the battery capacity; but the reduced range and added weight of an oversized motor more than offset the benefit of greater available power.

The petroleum consumption and life cycle costs for each configuration were calculated and compared to those of the reference vehicle. In all cases the resulting net benefit was found to be negative; that is, the cost of accruing the benefit is always greater than the benefit itself. Nevertheless, once petroleum prices reach some level, life cycle costs for the NTHV will be less than the reference vehicle, and net benefit becomes positive. This fact led us to calculate the breakeven petroleum prices. Figure 3-4 shows these prices, as a function of benefit, for various system packages.

Figure 3-4 provided a useful tool for starting the hybrid design. The 24 kW motor offers the most benefit over a wide range of battery capacities. If the desired power to weight ratio is maintained, the corresponding engine size is almost exactly that of the turbocharged Volkswagen Rabbit Diesel (48.5 kW). In the preliminary design studies (Section 5.2 below), this engine was found to be the most desirable for the NTHV. That is, we have the luxury of having a stock engine available in just the size we want.

The choice for the optimum battery capacity was less clear, however. Larger packs save more petroleum (up to a point), but using a smaller pack lowers the breakeven price. The absence of

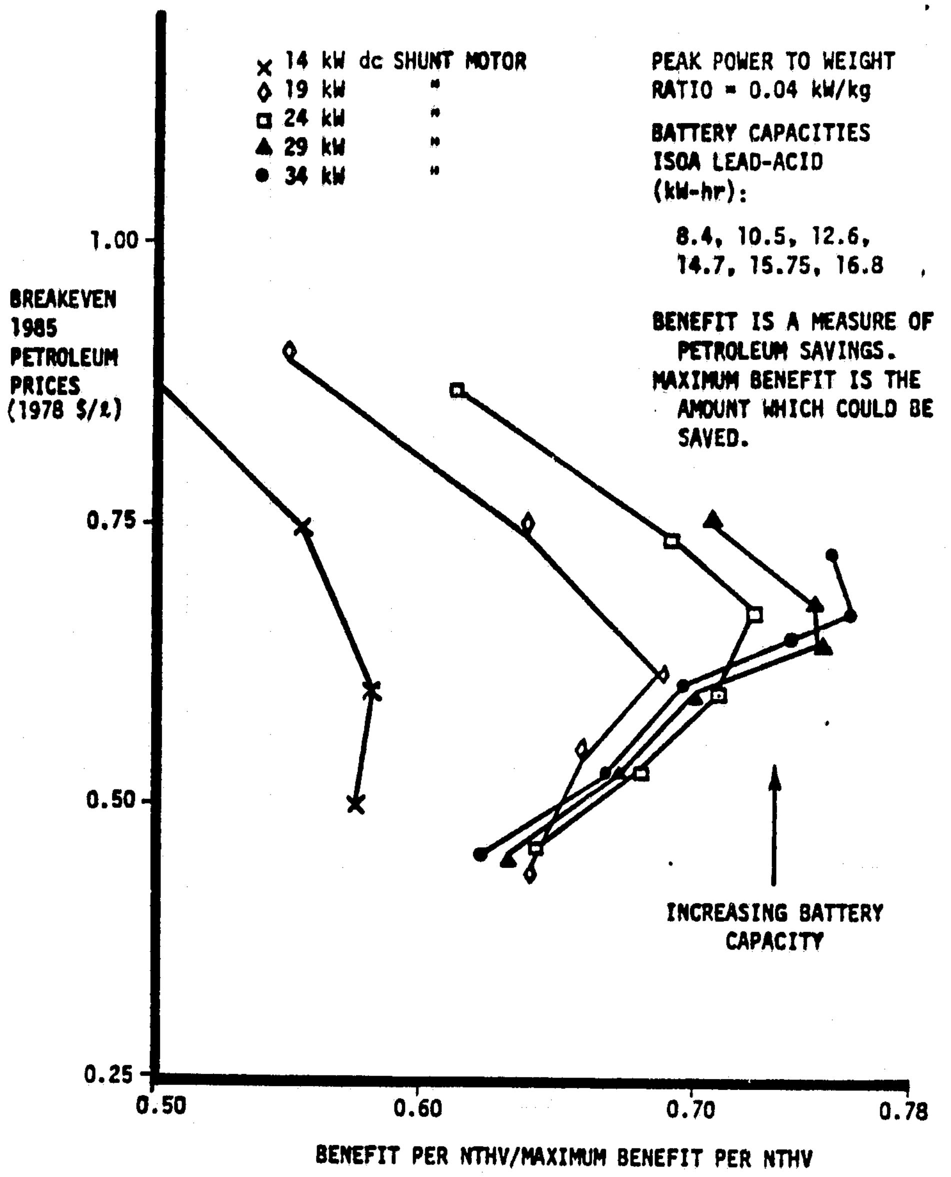

Figure 3-4. Breakeven 1985 Petroleum Prices at Which the LCC of an NTHV System Package Equals the LCC of the Reference ICE Vehicle

a clear cut choice for battery capacity allowed us to base the selection on other criteria--most notably packaging.

The engine and motor combination which maximized the benefit for a given battery package yields the curve shown in Figure 3-5. The upper portion of the curve is extrapolated to the full-size electric vehicle breakeven petroleum price obtained from Reference 6. Figure 3-5 verifies that the rate of increase in benefit decreases as the battery capacity increases.

3.3 OPERATIONAL STRATEGIES

Two basic modes of operation were used during the trade-off computer simulations: electric primary drive and engine primary drive. In electric primary drive the NTHV control system operates the powertrain in such a manner that the electric motor provides as much power as possible. If the hybrid were equipped with a 24 kW motor, for example, the motor alone would satisfy power requirements below 24 kW, and the engine would supply any incremental power required beyond that level. In engine primary drive the opposite strategy is employed, with the heat engine supplying all the power up to its capacity.

For a trip or series of trips which are shorter than the NTHV's all-electric range, the electric primary mode will yield the greatest petroleum savings. For some trips, in fact, the vehicle will burn no petroleum at all. Accordingly, we formulated a basic operational strategy which utilized electric primary drive until the batteries became 80 percent depleted. When that occurred, the operational strategy switched to engine primary drive. This basic strategy was employed throughout the trade-off studies. It should be mentioned that the FUDC, FHDC and

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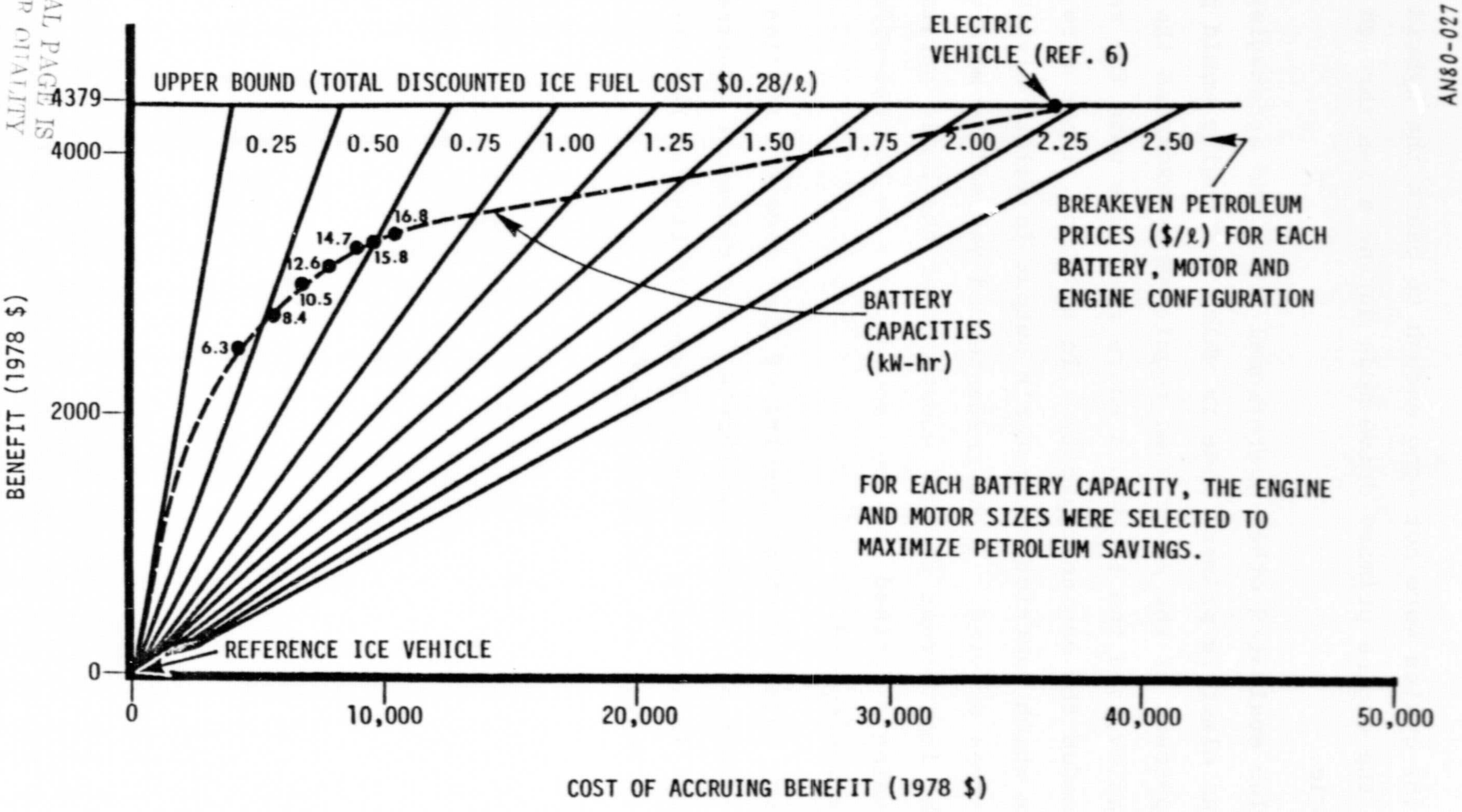

Figure 3-5. Benefit Versus Life Cycle Costs for Possible NTHV Configurations

SAE J227a(B) cycles were not long enough to cause the hybrid to switch to the engine primary drive mode during a run through a single cycle.

We also evaluated other operational modes and strategies. We tried an electric primary mode in which the engine would provide 100 percent of the power when requirements exceeded the motor capacity, and the two would share the loads when the requirements exceeded the engine capacity. In addition, there were strategies which restrict the motor's output in relatively long distance urban driving. In no instance did we realize more than a 5 percent improvement in fuel economy over the basic strategy, although using a refined strategy could prove to be cost-effective in a prototype hybrid.

We have detailed other results of the trade-off studies in subsequent sections, where applicable. Comprehensive treatment can be found in Appendix B (Design Trade-Off Studies Report) and Appendix D (Sensitivity Analysis Report).

SECTION 4

VEHICLE LAYOUT

4.1 DESIGN CONCEPT

In any automotive development program, there are two basic approaches: design the vehicle from the ground up, or modify an "off the shelf" (a current production) car. The ground up design offers the potential for a vehicle more specifically tailored to the needs of the program, as well as a more unified (and perhaps better integrated) product. But it also requires much attention to the design and integration of "routine" components, and this causes higher program costs.

In the NTHV program the highest priority goes to powertrain development, and it appears that this effort will suffer little, if any, compromise from a vehicle modification approach. Moreover, such an approach will distribute program costs more in keeping with the program priorities. It was, therefore, a straightforward decision to generate the NTHV design by modifying a production vehicle.

4.2 BASE VEHICLE SELECTION

A wide range of domestic and foreign production cars was examined for suitability as a base vehicle. The main objective was to find a lightweight car that would meet the JPL minimum requirements[6] for passenger and luggage volume. The search for low weight essentially meant that the base vehicle would have to have been introduced recently (because of the recent weight reduction programs for production vehicles) and would have to have front wheel drive. The top candidates are listed in Table 4-1.

Table 4-1. Capacity and Weight of Candidate Vehicles

Description	Volume[10] (m^3) Passenger Compartment	Luggage	Curb Weight[11]
Audi 5000	2.55	0.42	1,225
Chevrolet Citation	2.44	0.57	1,117
Dodge Omni	2.29	0.48	983
Volkswagen Rabbit	2.26	0.42	833
Volkswagen Dasher	2.38	0.34	981

Among the General Motors X-body cars, the Citation was selected because its hatchback configuration gives it more luggage volume and better aerodynamics. We eliminated the Audi 5000 because of its higher curb weight, and the Omni and Rabbit because they are not five passenger vehicles. Restructuring either of them to accommodate five passengers would be a major undertaking. This narrowed the choice to the Dasher and the Citation. The Citation is heavier, but has passenger and cargo volumes larger than those of the Dasher. The Citation was chosen as the base vehicle.

4.3 BATTERY PACK CONFIGURATION

Our basic approach to configuring the battery pack was to study the volumes in the vehicle and to use them in such a way as to avoid major changes in the vehicle's architecture. The major factors used in locating batteries were

1. Commercial battery case sizes that are available
2. Effect on vehicle architecture

3. Ease of service and access
4. Effect on vehicle dynamics
5. Effect on crashworthiness.

Four specific battery pack configurations were evaluated. These configurations, designated A through D, are shown in Figures 4-1 through 4-4. Configurations A through C contain 12 batteries, and D contains 11. These battery capacities are consistent with the trade-off results given in Section 3 and Appendix B.

Of the four specific configurations, we eliminated A because its polar moment of inertia was higher than the others, and B because it involved severe interference with rear seating. Configuration B would have been retained (being the only alternative without a lengthened nose) only if the forward battery location had been found unacceptable.

The remaining choice, between C and D, was largely dependent on the actual height of the batteries selected. Configuration D offers improved safety (from acid release in a rear crash), plus a reduced polar moment of inertia, but battery service and access are not as good. In Configuration C both the front and rear battery containers could be designed to be removed from either the top or the bottom. However, C requires a low-profile battery in order to avoid significant reductions of luggage volume, while D could accommodate the tallest batteries with room to spare. All factors considered, Minicars chose Configuration C for its preliminary design. Configuration D will be held as a backup, if battery height becomes a problem.

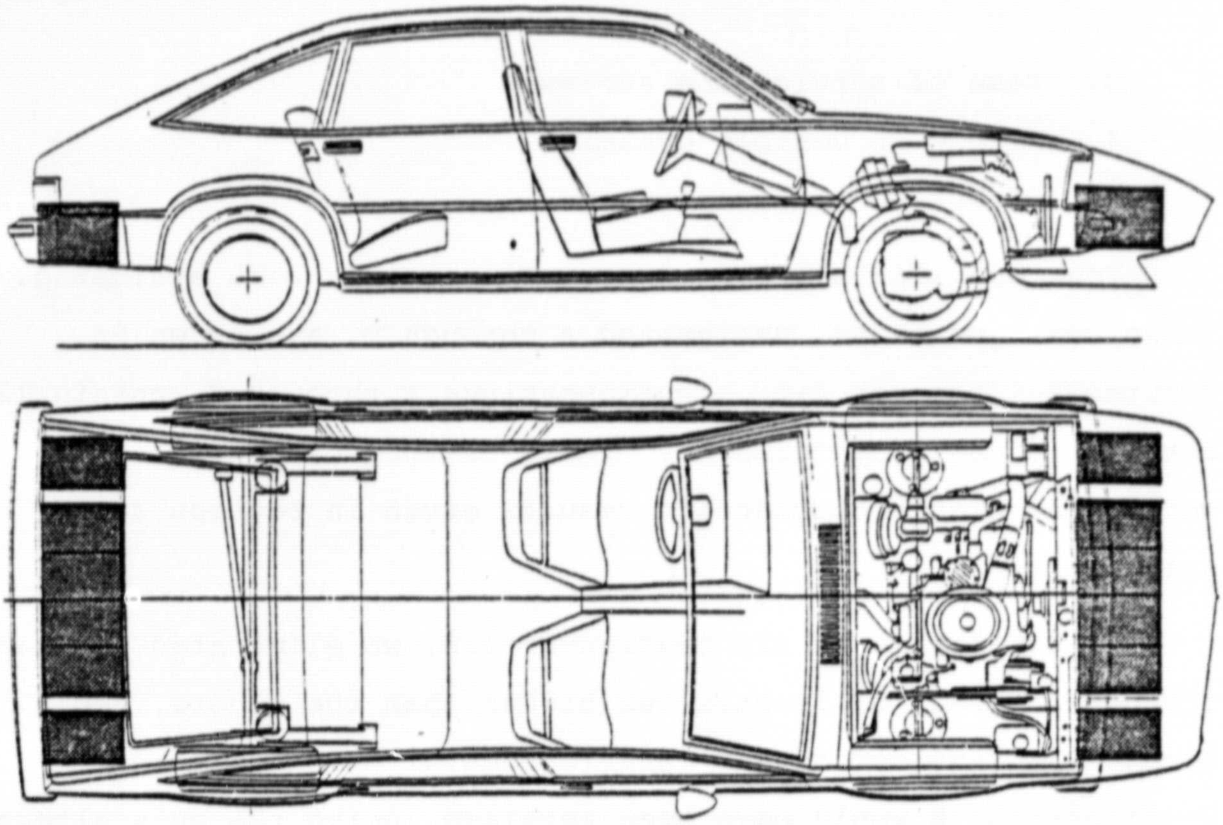

Figure 4-1. Configuration A

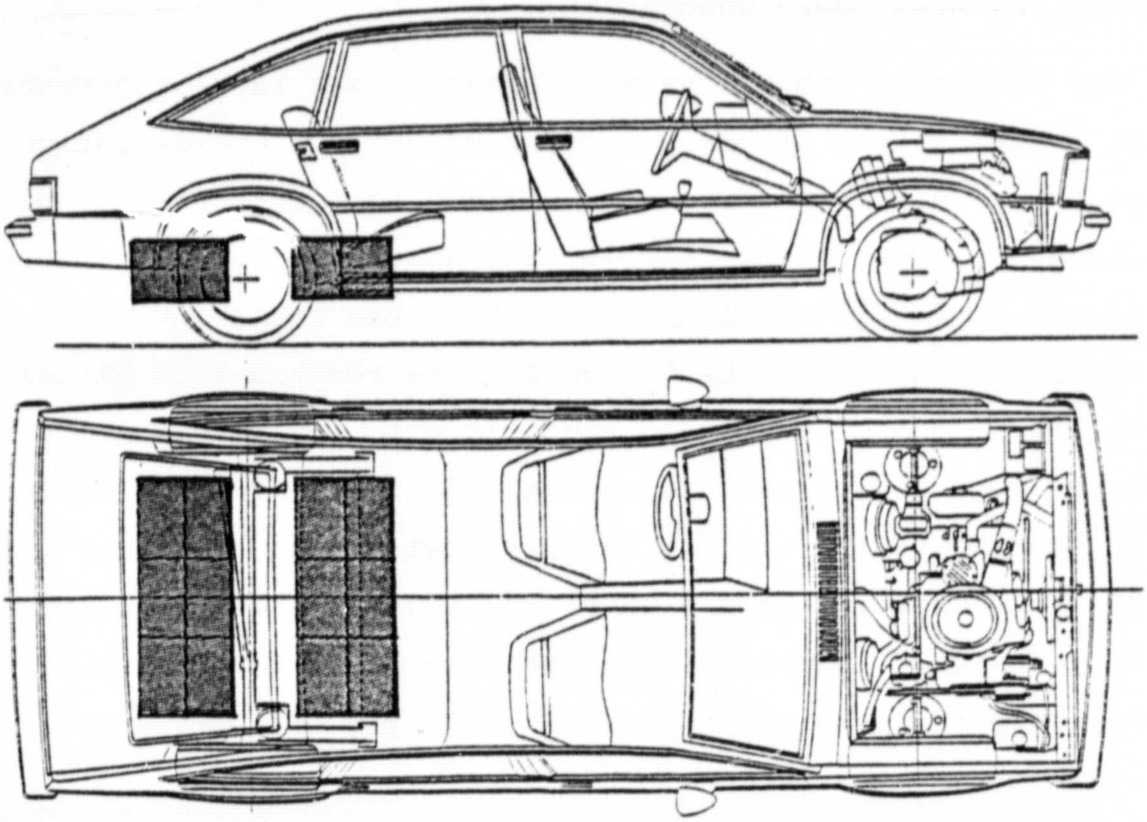

Figure 4-2. Configuration B

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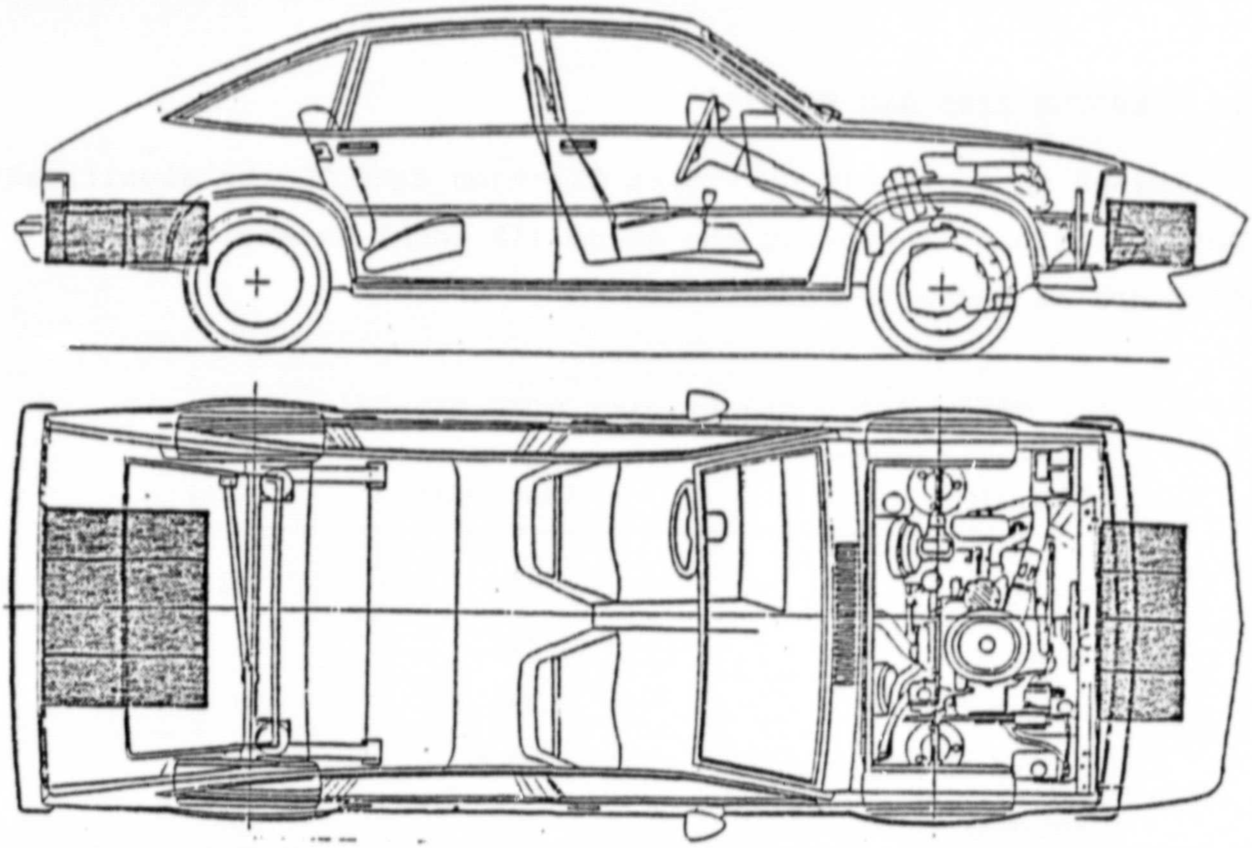

Figure 4-3. Configuration C

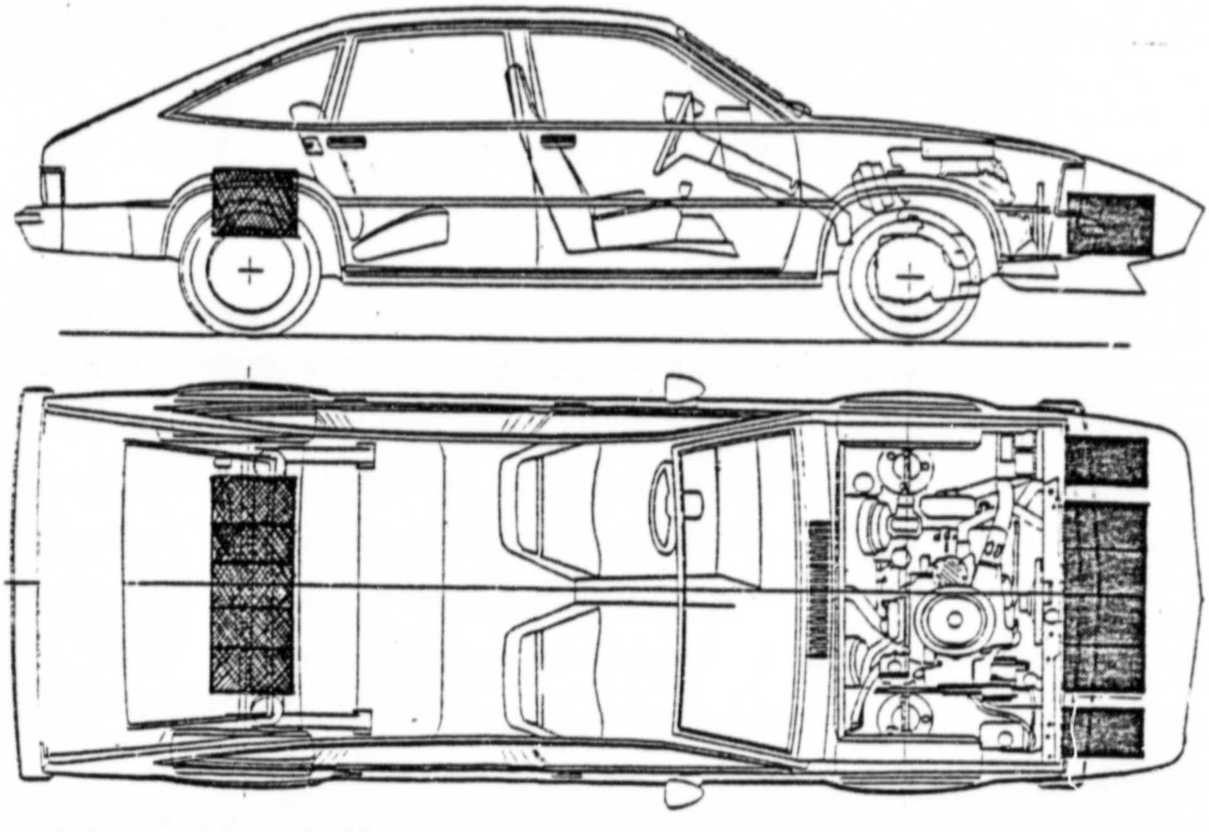

Figure 4-4. Configuration D

4.4 VEHICLE SIZE AND WEIGHT

Based on available Chevrolet Citation data,[12] the significant NTHV dimensions (including the 46 cm [18 inch] extension of the nose) are as shown in Table 4-2.

Table 4-2. Significant NTHV Dimensions

Dimension	Centimeters	Inches
Length	493	194
Width	173	68
Height	135	53
Ground clearance	13.6	5.4
Wheelbase	266	105
Track width, front/rear	149/145	59/57
Headroom, front/rear	97/95	38/37
Leg room, front/rear	107/88	42/35
Shoulder room, front/rear	143/142	56/56
Hip room, front/rear	140/137	55/54

The effect of vehicle weight on the hybrid's performance characteristics was investigated in the baseline NTHV. For this analysis we specified a 44 kW engine and ran vehicles weighing between 1364 kg (3000 pounds) and 2273 kg (5000 pounds) through Mission A. We found that heavier vehicles had modest increases in electricity consumption, but the change in petroleum economy was much more pronounced. Petroleum economies ranged from 51.21 km/ℓ in the lightest car to 25.19 km/ℓ in the heaviest, suggesting that weight reduction be given a high priority. Figure 4-5 illustrates the effect of weight on a hybrid's annual fuel consumption. The curve's slope (0.4137 ℓ/kg) provides a valuable guide for determining if weight reduction in specific areas will be cost effective.

Based on the trade-off studies and preliminary design, Table 4-3 was constructed to indicate how different subsystems affect the base vehicle weight.

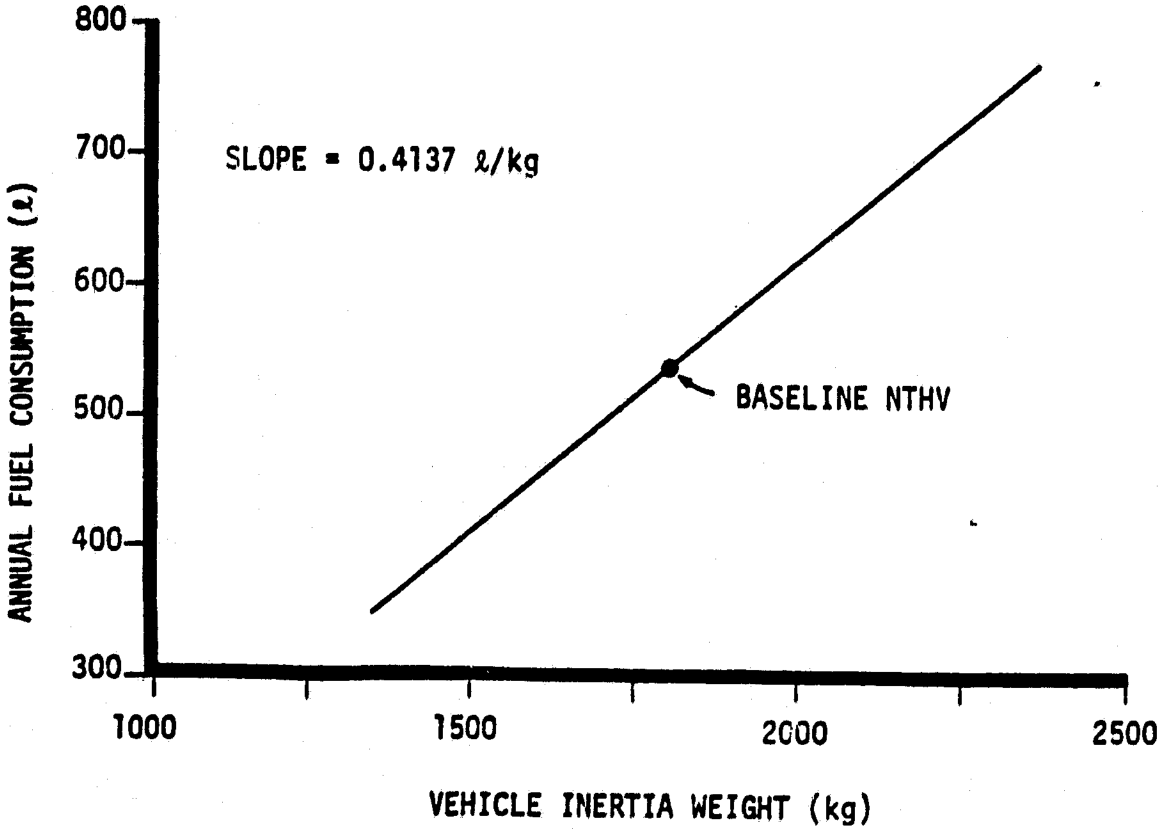

Figure 4-5. Effect of Vehicle Inertia Weight on Annual Fuel Consumption

Table 4-3. Comparison of Citation and NTHV Curb Weights

Description	Kilograms	Pounds
Curb weight of 4-door Citation with options	1,165	2,568
Engine change	- 40	- 87
Transmission modifications	+ 26	+ 58
Electric motor	+ 91	+ 200
Chain, clutch and housing	+ 25	+ 55
Controller, on-board charger, wiring	+ 23	+ 50
Computer and power supply	+ 13	+ 30
Batteries (12 6-volt units)	+ 336	+ 740
Structural modifications	+ 107	+ 236
NTHV curb weight	1,746	3,850

The total vehicle weight increase is 581 kg (1282 pounds); the batteries comprise 19 percent of the curb weight.

4.5 AERODYNAMICS AND ROLLING RESISTANCE

The trade-off studies required that the aerodynamic drag and rolling resistance be estimated for candidate vehicles. The published Chevrolet Citation drag coefficient is 0.417, and we would expect the addition of the front nose extension (battery compartment) to slightly improve the vehicle's aerodynamics. Minor changes to the vehicle exterior could also lower the drag coefficient. We therefore assume the drag coefficient of the NTHV to be 0.39. Multiplying this times the frontal area of the NTHV (1.96 m^2) yields a vehicle drag factor of 0.76 m^2. Major restyling could, of course, lower this figure, but it would not be expedient in this program.

Combined rolling resistance and bearing drag were calculated according to the following equation, supplied by Firestone:

$$D = (0.0123 + 3.26 \times 10^{-5} V) W \quad ,$$

where D is the rolling and bearing drag, V is velocity (in m/sec) and W is the vehicle weight (kg).

4.6 SUBSYSTEMS

The powertrain and electronic control system are discussed in some detail in Sections 5 and 6, respectively. Detailed descriptions of the primary hybrid vehicle subsystems may be found on the following pages of the Preliminary Design Data Package (Appendix C):

Front Suspension	C-32, -54
Rear suspension	C-32, -54
Battery Support Structure Design	C-36
Passive Restraints	C-37
Driver Air Cushion System	C-38 to -46
Passenger Restraint System	C-46
Door Interior Padding	C-46 to -53
Steering System	C-54 to -56
Brake System	C-56 to -59
Tires and Wheels	C-59 to -60
Drivetrain (Engine, Motor and Transmission	C-62 to -123
Power Conditioning Unit	C-124 to -135
Battery Subsystem	C-136 to -141

Sections 3 through 8 of the Preliminary Design Data Package offer a complete description of the hybrid vehicle design.

SECTION 5

POWERTRAIN

5.1 INTRODUCTION

Powertrain design is widely regarded as the most critical aspect of successful hybrid vehicle development. This section addresses the selection of a heat engine, electric motor and controller, battery pack, and, possibly most important, the mechanical connection between the two powerplants and the drive wheels. More comprehensive treatments of these choices can be found in Sections 5 through 9 of Appendix B and Sections 4 through 6 of Appendix C.

The Minicars NTHV will be a parallel rather than a series hybrid. That is, both the heat engine and the electric motor will propel the vehicle directly, either separately or together--rather than the electric motor providing all of the propulsion and the heat engine driving only a generator. The parallel system is more efficient than the series because it eliminates the double efficiency loss which occurs when the heat engine is the primary source of power.

We decided to use stock or modified stock components for the major drivetrain components (the heat engine, motor and transmission). As with the base vehicle, a total redesign of these components would divert a large portion of our resources away from areas in which they could be put to better use. In addition, a total redesign would seriously jeopardize near term availability.

5.2 HEAT ENGINE

The heat engine for the NTHV must meet three major requirements--low specific fuel consumption, light weight and low cost. There are five basic types of heat engine that could be used:

1. Otto cycle spark ignition
2. Diesel or compression ignition
3. Rankine cycle or steam engine
4. Brayton cycle or gas turbine
5. Stirling cycle.

The Rankine cycle engine was eliminated because of its high weight and poor specific fuel consumption, and the Sterling cycle because it is not likely to be developed to the necessary level in the near term. The Brayton cycle, while lightweight, will probably not be available with low enough specific fuel consumption in the near term. The two remaining heat engine types--the spark ignition and the diesel--are the most likely engines for the NTHV.

The spark ignition Otto cycle engine includes reciprocating and rotary engines, with carburetors or fuel injection, homogenous or stratified charge, and normal aspiration, supercharging or turbocharging. Several of these combinations were eliminated, since minimum fuel consumption is a major factor. A stratified charge rotary engine is the only rotary that could be competitive with the more fuel efficient reciprocating engines.

The diesel's fuel consumption rate is better than all but the very best spark ignition engines. At other load and speed conditions, and particularly at idle, the diesel engine tends to have better specific fuel consumption than the best spark ignition. Diesel engines are better than spark ignition engines for the same level of power output, but recent work by General Motors and Volkswagen has narrowed, though not eliminated, the weight gap between diesel and spark ignition engines.

With either a diesel or spark ignition engine, the use of a supercharger or turbocharger would allow the use of a smaller displacement, and therefore lighter, engine for a given power output. Frequently, this is accompanied by an improvement in specific fuel consumption. But the addition of a supercharger or turbocharger would add significantly to the cost of either internal combustion (IC) engine.

Four specific IC engines were selected for trade-off studies. These are described in Table 5-1.

The engine specifications, the fuel consumption curves and the maximum torque data were entered into the Minicars hybrid vehicle performance simulation program. The engines were scaled to 48.5 kW in order to meet the baseline NTHV system package performance requirements. For example, the 96 percent Honda stratified charge spark ignition evaluated in the trade-off studies was 4 percent lighter, had 4 percent less maximum torque, but provided the same fuel economy as the standard production engine.

The hybrid was taken through Mission A with each of the four different engines. Table 5-2 shows that the electricity consumptions varied no more than a few percent, but the petroleum consumptions varied considerably. The diesel engines had better petroleum economies than did the spark ignition engines, and the turbocharged diesel gave the best economy of all.

The results of a net benefit analysis for the same engines can be seen in Table 5-3. Fuel costs are the dominating effect

Table 5-1. Engines Considered in the Trade-Off Studies

Engine	Displacement (cm^3)	Bore (mm)	Stroke (mm)	Compression Ratio	Maximum Power (kW)	Maximum Torque (Nm)	Engine Scale Factor (%)	Scaled Maximum Power (kW)	Scaled Maximum Torque (Nm)
1. Turbocharged Volkswagen Rabbit diesel	1,475	76.5	80.0	23:1	48.5 @ 5000 rpm	119 @ 3000 rpm	100	48.5 @ 5000 rpm	119 @ 3000 rpm
2. Naturally aspirated Rabbit diesel	1,475	76.5	80.0	23:1	35.8 @ 5000 rpm	79 @ 2500 rpm	135	48.5 @ 5000 rpm	106 @ 2500 rpm
3. Stratified charge Honda, spark ignition	1,606	73.9	93.0	8:1	50.7 @ 5000 rpm	115 @ 3000 rpm	96	48.5 @ 5000 rpm	110 @ 3000 rpm
4. Volvo spark ignition	2,130	91.9	80.0	8.5:1	73.8 @ 5200 rpm	141 @ 2500 rpm	56	48.5 @ 5200 rpm	93 @ 3000 rpm

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Table 5-2. Results of Taking the Baseline NTHV Through Mission A With the Four Engines

Engine	Annual Fuel Consumption (ℓ)	Fuel Economy (km/ℓ)	Annual Electricity Consumption (kW-hr)	Electricity Economy (km/kW-hr)
Turbocharged Volkswagen Rabbit diesel	540	34.42	3,225	5.77
Naturally aspirated Rabbit diesel	604	30.80	3,281	5.67
Stratified charge Honda, spark ignition	700	26.57	3,281	5.67
Volvo spark ignition	739	25.15	3,279	5.67

Table 5-3. Results of the Economic Analysis of the Baseline NTHV With the Four Engines

Engine	Benefit (1978 $)	Net Benefit (1978 $)	Breakeven Petroleum Price	
			1978 $/ℓ	1978 $/gal
Turbocharged Volkswagen Rabbit diesel	3,101	-4,567	0.62	2.35
Naturally aspirated Rabbit diesel	2,951	-4,652	0.65	2.45
Stratified charge Honda, spark ignition	2,723	-4,939	0.71	2.67
Volvo spark ignition	2,630	-5,205	0.75	2.83

on net benefit, and the turbocharged diesel saves enough fuel to more than pay for its extra cost and weight. Therefore, the turbocharged Volkswagen Rabbit diesel is the best choice for a hybrid heat engine. Furthermore, this engine should have little difficulty meeting 1981 EPA emission standards (see Section 4.6 of Appendix C).

5.3 ELECTRIC MOTOR AND CONTROLLER

The complete range of electric drive system candidates for the NTHV study is shown in Figure 5-1. The unique requirements of low voltage, high current, maximum efficiency, near term availability, low noise and low cost quickly narrowed this field.

In the past both synchronous and asynchronous ac motor drives have been considered for electric vehicle propulsion, primarily because of the elimination of the commutator associated with dc motors. These drives have recently found application in rail vehicles. However, we excluded them from further consideration in the NTHV program because they will not be available for automobiles in the near term.

In recent years the permanent magnet (PM) dc motor has received renewed interest because of the increasing commercial availability of high strength rare-earth permanent magnets. However, PM motors in the power range required for the NTHV are not expected to be available in the near term, and hence were eliminated.

Thus the requirement of near term availability essentially limits the viable options to series dc, shunt dc and compound dc motors. These drives have similar manufacturing costs (approximately \$1.80/kg); we therefore evaluated them primarily on the

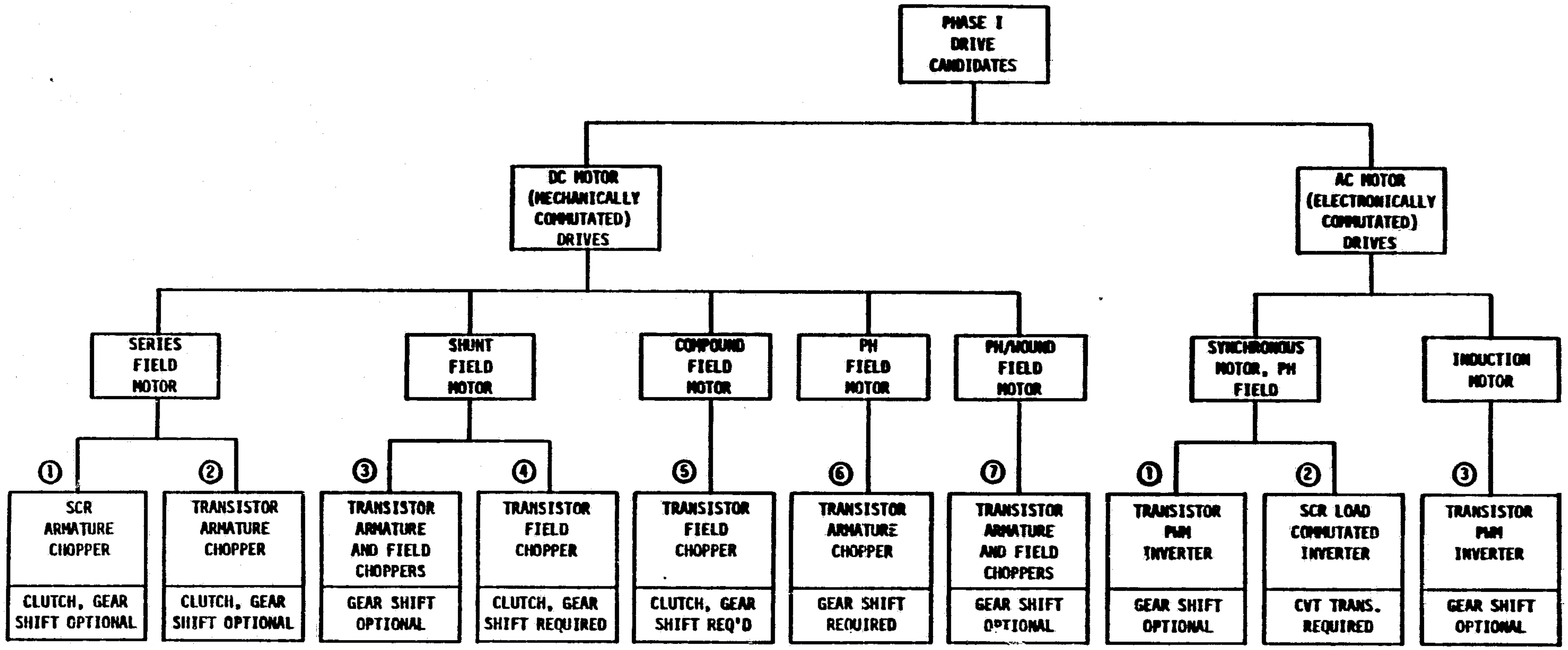

Figure 5-1. Candidate Motor Drives

complexity of their control system design, their performance characteristics and their regenerative braking capability.

The control of the speed and power of dc electric motors for vehicle propulsion systems is generally accomplished by varying either the effective voltage applied to the armature or the effective motor field excitation--or a combination of the two. The three types of dc motors provide three different approaches to the control function.

In the series dc motor the armature and field coils are wired in series; thus the current flowing through the two coils is always equal. This gives the motor the advantage of inherent stability. But the payment for this stability is slightly poorer efficiency and the added complexity necessary for regenerative braking.

The major problem for our application, however, is the requirement for an armature controller with a series motor. Because of the hybrid's relatively low voltage supply, armature control requires a controller capable of handling currents on the order of 400 to 500 A. Therefore the consideration of the series motor depends primarily on the features of the controllers available.

There are two sorts of armature control on dc motors: contactor and chopper control. The series motor with contactor control is widely used in low speed industrial and recreational vehicles. However, contactor control has problems with discontinuous acceleration; it therefore was excluded from consideration for the NTHV.

The chopper controller must have switches capable of sustained operation under high current loads. Either Metal Oxide

Semiconductor Field Effect Transistors (MOSFETs) or bipolar transistors could function as switching devices, but the high currents demand extensive paralleling. With MOSFETs, paralleling would be impractical and with bipolar transistors would produce an unstable and potentially unreliable design (see Section 7.2.2 of Appendix C). A more workable solution, widely used in electric locomotives and rapid transit cars, is the use of silicon-controlled rectifiers (SCRs) as power switching devices. Unfortunately, SCR controllers tend to be complex, noisy and expensive--constraints which might not deter the locmotive designer, but which preclude their use in passenger cars.

Because of the problems with controllers, therefore, we had to eliminate series dc motors from consideration; the selection narrowed to either shunt or compound dc motors. In a shunt motor the field coils are electrically independent of the armature coils, and the control function can be accomplished by field control alone. The compound motor is identical to the shunt motor, except that some of the field winding is wired in series with the armature. An NTHV with either motor would employ a field controller which could give speed ratios of about 3:1.

In the shunt motor the field current controller must provide a minimum value of field excitation to control armature reaction effects at all times and load conditions. When the motor is subject to sudden speed changes or transient loads, the required excitation changes may have to be accomplished very quickly, to prevent the motor from entering an unstable commutation range. Hence the control circuitry may need to include anticipatory, or closed servo loop, field forcing.

Unstable commutation could also be prevented by using a compound motor (see Section 7.1 of Appendix C). The compound drive, to work best in the NTHV, would have only enough series windings to insure stability. Thus it would allow the use of a simpler, more reliable field controller, although the added series coils would cause a small loss of efficiency during regenerative braking.

In either motor design, shunt or compound, the minimum practical field magnetization (and hence maximum effective power output) will be essentially the same--it will be governed by the armature reaction problem. Therefore, given otherwise similar motor designs, there is no power advantage to be obtained from eliminating the series field. The total field excitation power requirement also does not change, for it does not matter whether this is obtained by shunt or series field coils. However, the shunt motor requires a more complex field current control in order to meet the minimum field excitation needs of the motor. It is only the ease of designing the overall motor, engine and transmission control system that emphasizes advantages of the compound over the shunt motor.

The motor field controller is expected to be considerably simpler and cheaper than the armature choppers discussed earlier. Again, either bipolar transistors or MOSFETs could be used as switching devices. MOSFETs have the advantages of higher switching speed, low drive power requirements, relative ease of paralleling and, most important, the absence of the secondary breakdown failure mode which is inherent in the bipolar transistor. Moreover, MOSFET technology is rapidly advancing, and increased power handling capability may soon make paralleling unnecessary.

The motor field controller functions as a step-down dc-dc converter, or chopper, applying a variable fraction of the battery voltage to the motor shunt field winding. Such choppers can operate with variable off time and variable frequency, variable on time and variable frequency, or variable on and off times and constant frequency. The variable off time/variable frequency approach was selected by one contractor in the Near Term Electric Vehicle Program.[13]

Constant frequency MFC operation was selected by Minicars for two reasons: electromagnetic interference (EMI) is easier to suppress when confined to fixed fundamental and harmonic frequencies, and audible noise originating in the chopper or motor magnetic elements can best be eliminated by using a constant chopper frequency above the audible range. Field choppers in the size ranges under consideration can and do emit highly noticeable noise in the audible frequency range, which could prove to be objectionable to drivers and passengers.

A detailed circuit description of the proposed motor control (which is combined with the battery charger) is given in Section 5 of Appendix C.

5.4 DRIVETRAIN

Drivetrain Configurations

Five different drivetrain options were evaluated for the NTHV system package. Drivetrain configurations have a strong influence on a vehicle's efficiency, cost and weight, and the different alternatives include some wide ranging possibilities:

A. An automatic transmission with the engine connected through a torque converter and the motor connected to the transmission through a slipping clutch or a variable fill fluid coupling

B. An automatic transmission with both the engine and motor connected to the transmission through the same torque converter and a starting resistor for the motor

C. An automatic transmission with the engine connected to the torque converter and the motor connected to the transmission output through a slipping clutch, variable fill coupling, or directly, using a starting resistor

D. An automated manual transmission under computer control

E. A manual transmission controlled by the driver.

These options reflect the assumption that the problems of efficiently transmitting power from the engine to the wheels have already been solved, and that that section of the drivetrain should essentially be left intact. A design that would efficiently connect the motor drivetrain to the engine drivetrain made from stock components would certainly be less expensive than would a complete redesign of all components.

We conducted an initial trade-off analysis to compare a five-speed manual transmission with a three-speed automatic. The shift schedules for each transmission were specified to yield the most efficient regime for the power required. As with the other trade-off studies, the baseline NTHV was taken through Mission A with each transmission. The results are shown in Tables 5-4 and 5-5.

Not surprisingly, the five-speed manual is quite a bit cheaper and more fuel efficient than the three-speed automatic. This finding led, first of all, to Option E, the fully manual

Table 5-4. Results of Taking the Baseline NTHV Through Mission A with Manual and Automatic Transmissions

Transmission Type	Annual Fuel Consumption (ℓ)	Fuel Economy (km/ℓ)	Annual Electricity Consumption (kW-hr)	Electricity Economy (km/kW-hr)	Electric Range (km)
5-speed manual	540	34.42	3,225	5.77	36
3-speed automatic	667	27.89	3,667	5.07	30

Table 5-5. Economic Analysis of the Baseline NTHV with Manual and Automatic Transmissions

Transmission Type	Benefit (1978 $)	Cost of Accruing This Benefit (1978 $)	Life Cycle Cost (1978 $)	Breakeven Petroleum Price ($/ℓ)	($/gal)
5-speed manual	3,101	7,668	24,495	0.62	2.35
3-speed automatic	2,802	8,047	25,173	0.72	2.73

transmission. Option E would couple both the motor and engine through slipping clutches to a standard manual transmission. As in a conventional car, the driver could apply and remove power at his discretion, but the on-board computer would decide whether to use the engine, the motor or both.

This system would be the simplest, lightest, cheapest, most reliable, and easiest to develop of any of the combinations considered. However, it requires a certain level of competence to drive (as with any manual transmission), and a certain level of driver understanding to obtain the potential high efficiency from the powertrain. For improved operation, the control computer could signal (display) the optimum gear to use in the current driving condition. If the driver followed these recommendations, the overall vehicle efficiency would be outstanding; if he did not, the powertrain efficiency would suffer.

Option D, the computer controlled manual transmission, is a variation of the computer controlled "high technology" transmission that Minicars has developed and is now running in one of our Research Safety Vehicles (RSVs). This transmission operates the clutch and engine throttle and shifts gears according to inputs from the accelerator pedal position, vehicle speed and engine speed. The computer selects the best gear ratio for petroleum economy under the conditions called for by the driver. The overall package gives the ease of driving of an automatic transmission, with petroleum economy equal to or better than a manual transmission. The potentially better economy comes from the ability of the computer to do a better job of selecting the optimum transmission ratio than the driver is likely to do. The unit provides a very driveable package, with smooth operation of the clutch, engine throttle and gear shifts. Nonetheless, it would require the most development work of any of the combinations.

While the two manual transmission options provide the best potential fuel economy, both suffer marketability problems. The fact that the vast majority of cars are sold with automatic transmissions indicates that the average car buyer is willing to pay a great deal not to have to shift gears. Thus, Option E was eliminated for lack of customer acceptance. Even though Option D will shift gears automatically, each shift is accompanied by a short power loss. The public is accustomed to the smooth continuous power shifting of automatic transmissions and may find unexpected power losses to be unacceptable. We therefore eliminated Option D also.

Options A, B and C all use a torque converter to couple the engine to an automatic transmission. The torque converter is a hydrodynamic device that not only couples the engine to the transmission, but also multiplies the torque produced by the engine while the converter is slipping. Although a torque converter suffers some power losses (which can be reduced with a lock-up clutch), it can provide good start-up characteristics to an engine at all throttle openings. The excellent driveability and control which it provides have resulted in the almost universal use of the torque converter in automatic transmissions all over the world. This makes the torque converter an easy choice for the engine to transmission coupling. Therefore, the three remaining alternatives essentially are answers to the questions of how and where to connect the motor.

In Option B both the motor and the engine are connected to the torque converter input. This configuration would allow us to leave the transmission essentially intact, and therefore would provide advantages in terms of cost, packaging and simplicity. Its major drawback lies in the inherently poor match between the characteristics of a hydrodynamic torque converter and an electric motor which uses field control alone. This problem manifests itself in all-electric driving. The motor/torque converter system will only start from zero speed at maximum motor torque, so it would be impossible to ease away from rest very slowly. Electrical modifications (such as the use of a starting resistor) would help solve this problem, but only by adding complexity to the motor controller.

In Option C the motor is connected directly to the transmission output through a slipping clutch. The slipping clutch, unlike the torque converter, will not multiply the input torque at low speeds, since its input torque always equals its output torque. Thus, coupling the motor through a slipping clutch eliminates the all-electric starting problem. In Option C, as in Option B, the transmission remains intact and the packaging is simplified. The drawback here is that the transmission can no longer provide varying gear ratios for the motor, and, consequently, the motor is forced to operate at less than ideal speeds.

Option A specifies that the motor drive be connected through a slipping clutch between the torque converter and the automatic transmission. This option is better than B and C in terms of efficiency, performance and driveability because it uses both the slipping clutch and the transmission for the motor drive. However, it requires relatively extensive transmission modifications, and would be the most expensive to develop.

Although all five of the options discussed above could be developed into suitable drivetrains, we believe Option A is the most desirable to pursue. It offers the best compromise between performance, ease of development, cost and consumer acceptance. A schematic of the Option A powertrain configuration is shown in Figure 5-2. Figure 5-3 is a photograph of the NTHV engine compartment mockup, using this powertrain.

Automatic Transmissions

Currently, there are three production transverse-engine automatic transmissions suitable for the NTHV. These are the Volkswagen transmission used in the VW Rabbit and the Fiat Strada,

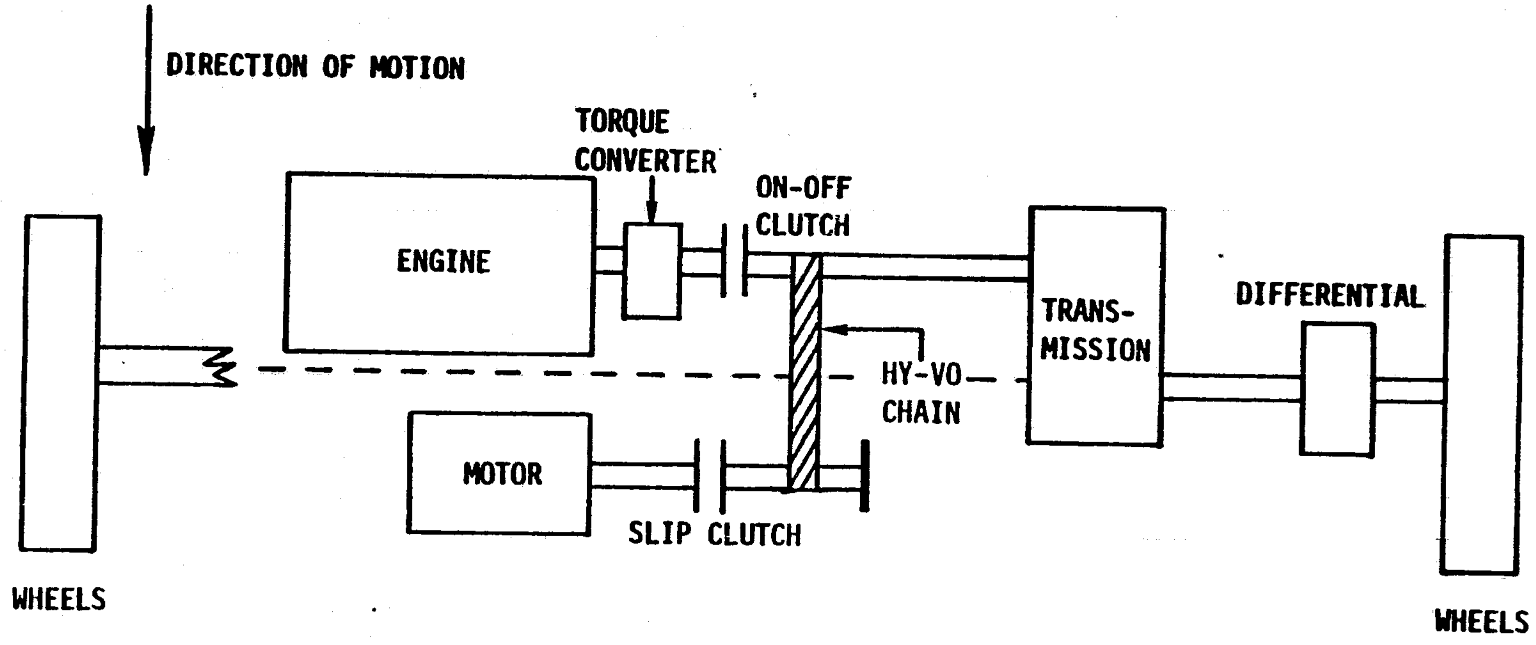

Figure 5-2. Schematic of Option A Powertrain Configuration Which Couples the Electric Motor Through a Slipping Clutch, a Chain, and Automatic Transmission

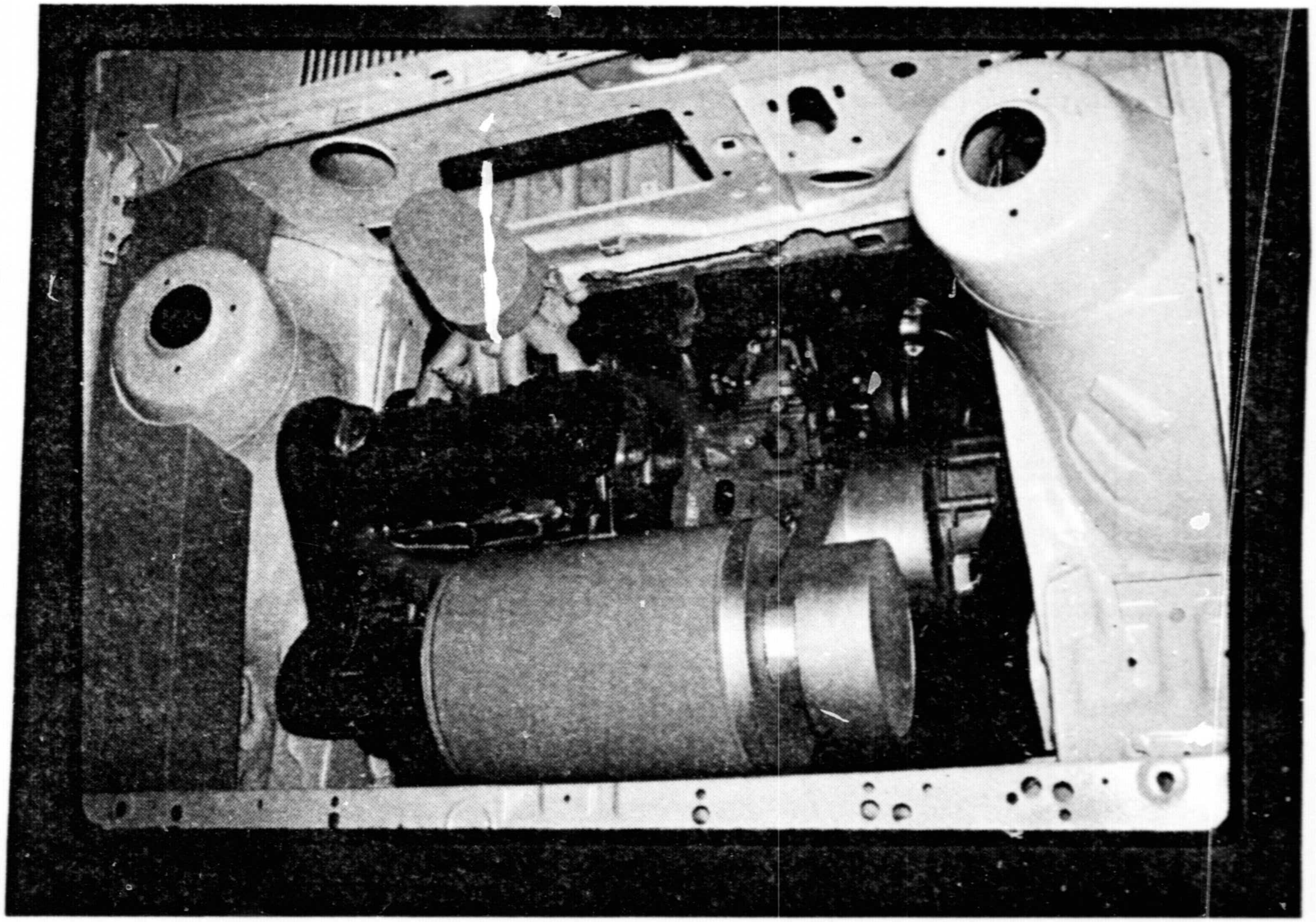

Figure 5-3. Hybrid Vehicle Engine Compartment, Showing the Electric Motor, Volkswagen Rabbit Diesel Engine, and Turbocharger

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the Chrysler A-404 used in the Omni and Horizon, and the Turbo-Hydramatic 125 used in the GM X-body cars. The other transverse-engine automatic transmissions made in Europe have various shortcomings in adaptability and reliability.

All three of the candidate transmissions could be modified for use in the NTHV. All are three-speed planetary designs which use torque converters and are representative of the latest practice in automatic transmission design. Each could be adapted for use in the NTHV, and none has a marked superiority over the others. The Volkswagen unit has the fewest advantages for a hybrid, both because of the complexity of its multiple concentric shafts and the somewhat greater difficulty of adapting it for input from an electric motor. The General Motors and Chrysler units are essentially equal in adaptability--neither transmission has a major advantage over the other. There is a small benefit to the General Motors unit because its wider gear ratio spacing would be of some advantage in fuel economy when the diesel is running. Further, this transmission would have the room for a friction, rather than an overrunning, clutch to connect the engine to the transmission--thereby avoiding one possible area of additional development.

The actual operation of the transmission will remain hydraulic, since a complete design change would be required to apply the various transmission clutches and brakes electrically. But then a question arises about the level at which to interface the electric and hydraulic systems. This question has two possible answers: the hydraulic control level and the shift valve level.

While the Minicars computer control system is completely capable of controlling the entire shifting sequence, such a development would be of little benefit to the NTHV. It would take a great deal of computer simulation and test bed development for the computer control system to reach the level of shift control that General Motors has already designed into the hydraulic control system. And, since the potential gains in efficiency with computer controlled clutches and brakes is very small, it would not appear to be worth the considerable effort. Rather, it is much better to control the shifts at the shift valve input level and to use the General Motors hydraulic control system to actually shift gears.

In an effort to use as much of the original hydraulic system as possible, we decided to employ the standard control system for the Park, Reverse and Neutral positions, and probably for the Intermediate and Low positions as well. The computer control will be used only to control the shifts when the transmission is put in the Drive range. The inputs will control the shift valves and the kickdown control for downshifting. The computer will also control the line pressure of the transmission, which normally is a function of the accelerator pedal position. The line pressure is a factor in the control of the shifts and in minimizing the power consumed in driving the transmission pump.

This system could be developed with a minimum of transmission modification, so that the major effort of the transmission program could be devoted to improving the driving efficiency of the NTHV.

Clutches and Couplings

Preceeding discussions referred to the use of a slipping clutch in the electric motor drive and, possibly, the heat engine drive. We investigated both spring applied (as in standard shift automobiles) and spring released clutches. A hydraulically applied spring release clutch would definitely be the best choice for coupling the field controlled motor to the transmission. It is simpler in this application, suffers lower hysterisis losses, and also has the advantage of being disengaged when the entire system is turned off. A fully manual transmission, should it be used, would of course require the more common spring applied slipping clutch to couple and decouple the engine.

A possible alternative to the slipping clutch would be a variable fill fluid coupling. A fluid coupling is similar to a torque converter, but has no reactive member; consequently, input and output torques are equal, as in a clutch. By changing the quantity of oil in the coupling, the characteristics of the coupling can be changed. If the on-board computer controls the oil fill, then the coupling can be made to behave exactly like a slipping clutch and, in fact, replace it. Section 4 of Appendix C contains a detailed discussion of torque converters and variable fill fluid couplings.

The variable fill coupling has some advantages over the slipping clutch. It would, however, be larger and heavier, and less is known about coupling control than clutch control. Based on these considerations, we prefer the slipping clutch, but recommend that both devices be carried forward into the development program until bench tests indicate a clear advantage to one.

5.5 ACCESSORY DRIVE

The NTHV requires a power steering pump, engine water pump, alternator, brake vacuum pump and air conditioning compressor. Table 5-6 gives the power requirements for these accessories.

Table 5-6. NTHV Accessory Power Requirements at Two Different Accessory Driveline Speeds

Accessory Name	Power Requirement at 1000 rpm (kW)	Power Requirement at 2500 rpm (kW)
Fan	0.37	1.50
Water pump	0.15	1.19
Power steering pump	0.37	1.34
Alternator	0.60	1.27
Brake vacuum pump	0.15	0.75
Air conditioning compressor (average)	1.50	3.58
Transmission pump	0.15	1.04
Total	3.29	10.67

Accessory power requirements for the NTHV are substantial, requiring as much as 40 percent of the total vehicle power at low driving speeds. To find the most efficient means of driving the accessories, we calculated several alternative drive mechanisms. The possibilities included the heat engine, electric motor, transmission, a separate electric motor, engine cooling, an exhaust Rankine cycle engine, an exhaust gas turbine, regenerative braking, and combinations of these. To evaluate petroleum economy, we conducted trade-off studies with the baseline hybrid in Mission A.

The best accessory drive we found would use power from both the motor and engine. This configuration is shown in Figure 5-4. There is an accessory drive shaft on the extension of the motor centerline. All of the accessories, except the air conditioner, are driven from this shaft; the shaft, in turn, is powered directly by the motor or by a belt from the engine. The drive

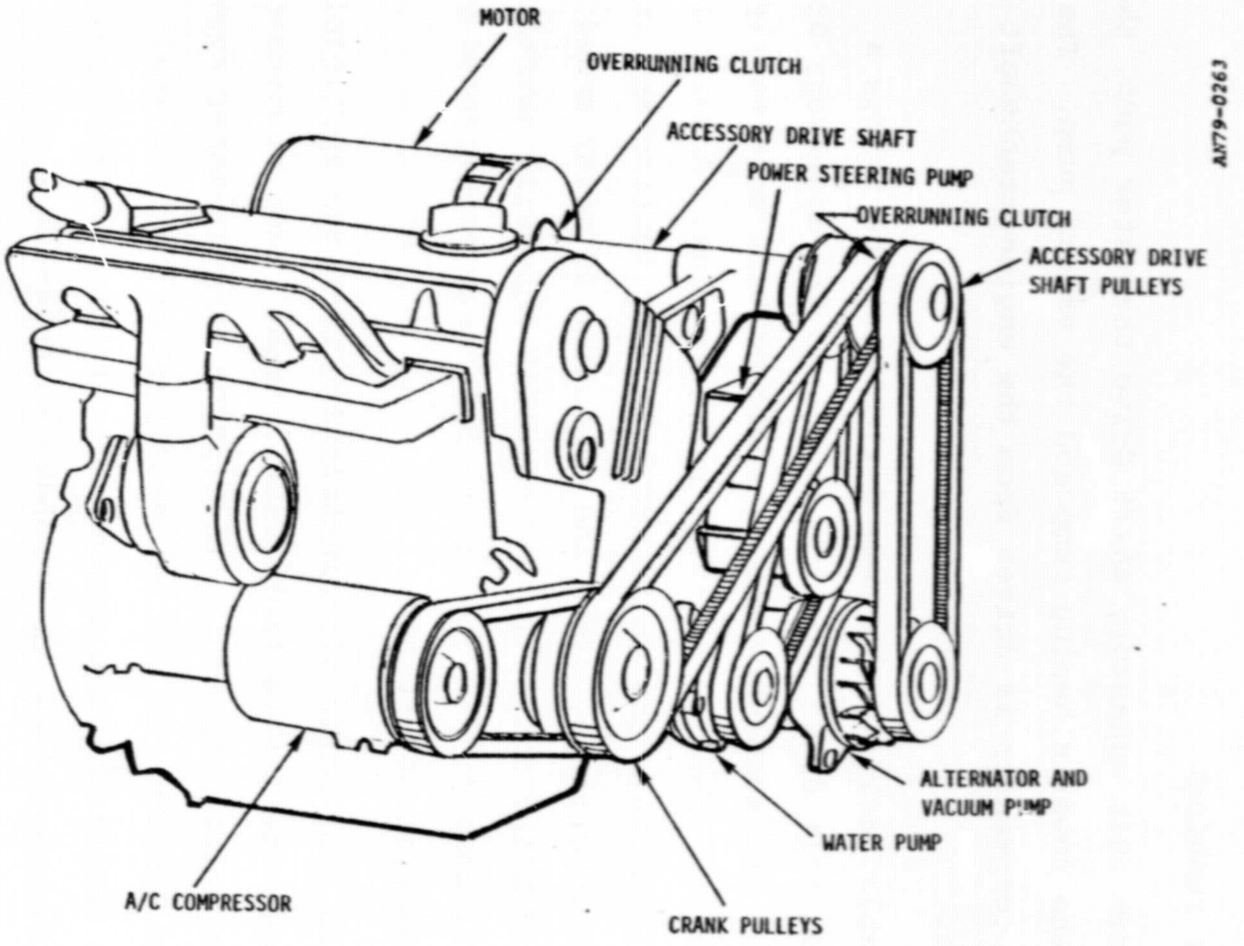

Figure 5-4. Accessory Drive Concept

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from the engine has a 2:1 ratio, to match the 2:1 ratio in motor to engine speeds. Both the drive from the motor and the accessory shaft pulley from the engine are powered through overrunning (freewheel) clutches, so that the shaft is driven by whichever powerplant is running.

Belts from this accessory shaft drive the water pump, the alternator, the power steering pump and the vacuum pump. The air conditioning compressor is driven from the engine crankshaft by a separate belt.

A desirable variation on this design would be to use a variable speed belt drive from the engine to the accessory drive shaft, so that the accessory speeds would be kept more nearly constant when the vehicle is driven by the engine. A variable speed drive from the motor would add more complication and is of somewhat less importance, since the variation of motor speed when the vehicle is being driven in the electric mode will normally be less than 2:1, compared to the 3:1 to 5:1 range experienced with an internal combustion engine.

There are four basic air conditioning concepts applicable to an NTHV. These are the variable displacement Freon compressor, Rankine cycle turbo-compressor, absorption ammonia-water system, and air-cycle system. On the basis of performance and fuel economy, the selected Freon compressor air conditioning system has a firm advantage (see the Addendum to Appendix B).

5.6 BATTERIES

It has been widely recognized that the practicality of electric and hybrid vehicles depends primarily on the availability of low cost, long life batteries with high specific energy and high specific power. The near term battery alternatives for the hybrid vehicle were effectively limited to the three batteries involved in the Argonne National Laboratory Near Term Electric Vehicle battery program: the lead-acid, nickel-iron, and nickel-zinc batteries.

The specific energy and power relationships shown in Figure 5-5 illustrate the superiority of the nickel-zinc battery. Interestingly, the specific energies of the lead-acid and nickel-iron batteries behave similarly and drop drastically at high specific power levels, while the nickel-zinc battery maintains a fairly constant specific energy even at high specific power levels.

We ran computer simulations of the three batteries through Mission A. The results, given in Table 5-7, show the impact of the high specific energy levels of the nickel-zinc batteries.

Table 5-7. Results of Taking the Baseline NTHV System Package Through Mission A for Three Near Term Batteries

Battery Type	Annual Fuel Consumption (ℓ)	Fuel Economy (km/ℓ)	Annual Electricity Consumption (kW/hr)	Electricity Economy (km/kW-hr)	Electric Range (km)
Lead-acid	540	34.42	3,225	5.77	36.0
Nickel-zinc	346	53.81	2,771	6.71	52.4
Nickel-iron	447	41.60	3,143	5.91	38.9

As expected, the nickel-zinc batteries demonstrated the highest potential to reduce petroleum consumption. Life cycle cost, however, is greatly affected by battery cycle life. The cycle lives of the lead-acid, nickel-zinc and nickel-iron batteries

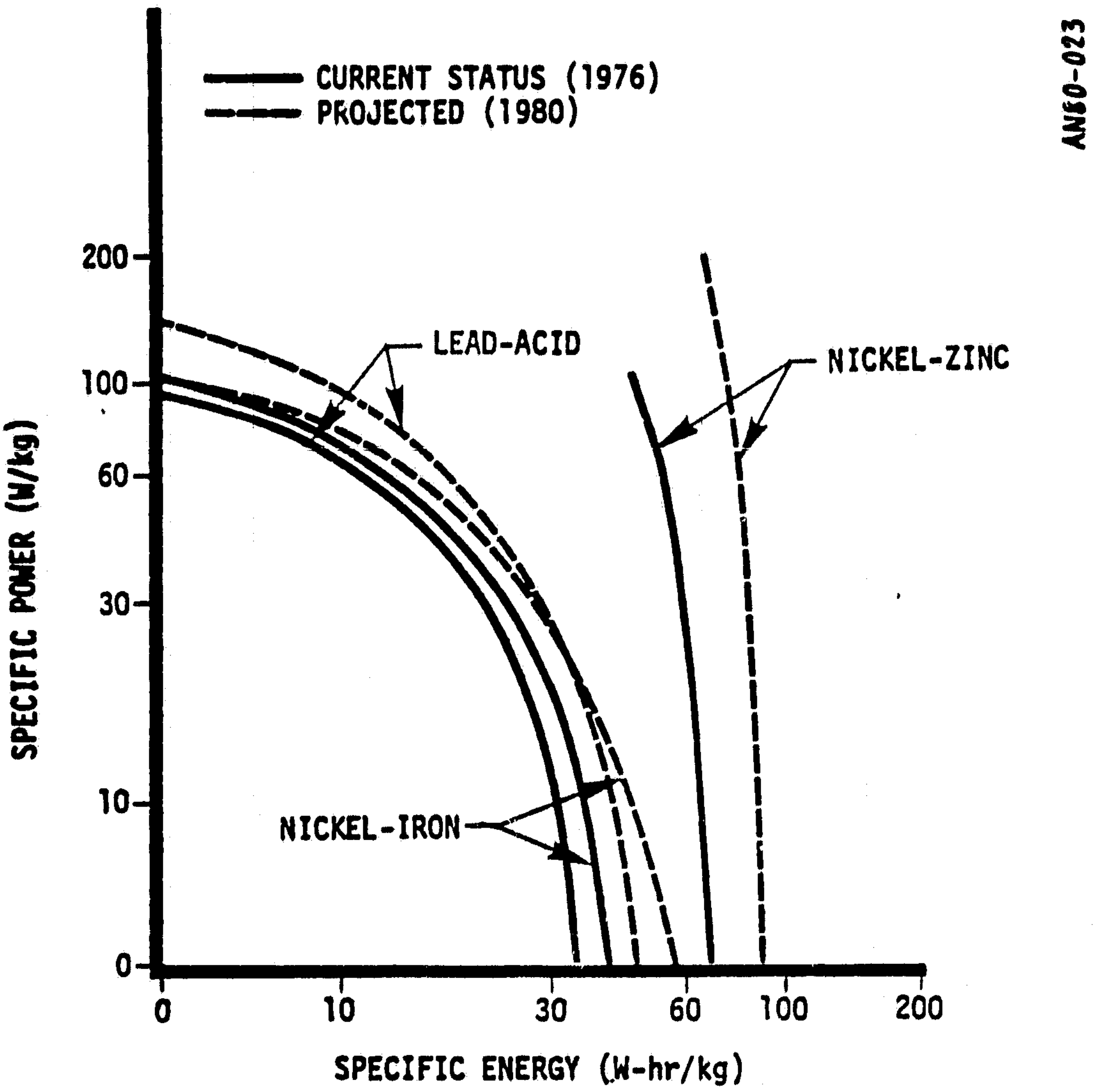

Figure 5-5. Specific Power Versus Specific Energy for Near Term Battery Candidates[14]

were taken to be 1000, 500 and 2000, respectively. Although nickel-zinc accords more benefit (petroleum savings), its replacement costs increase the breakeven petroleum price to \$0.99/ℓ, which is considerably higher than either nickel-iron (\$0.43/ℓ) or lead-acid (\$0.62/ℓ).

These figures suggest that nickel-iron batteries are the best choice for the NTHV. Practical considerations, however, indicate otherwise. The nickel-iron battery takes almost twice the volume of the lead-acid battery (thereby causing packaging problems), has poor low temperature performance, and has high rates of self discharge, internal heating, and charge and discharge gassing. Because of these difficulties, the U.S. industry ceased commercial production of nickel-iron batteries in 1974.

If a single battery could have both the specific energy of the nickel-zinc and the potential long life of the nickel-iron, the NTHV life cycle costs would be comparable with those of the conventional reference vehicle. Unfortunately, the nickel-iron and nickel-zinc batteries still require too much development to be feasible in the near term. Accordingly, we must recommend the use of lead-acid batteries in the NTHV.

Battery Charger

Through proper design, the on-board charger (120 V, 60 Hz input; 15 Adc and 30 Adc maximum outputs) can be combined with the field supply controller (especially since the charger and controller have approximately the same power ratings). This combination can save about 18 kg. Further weight savings are possible if the charger is designed to elevate the frequency pulses above the 60 cycles used in direct line conversion models; this reduces the iron mass requirements.

Cold Starts

The performance of conventional lead-acid batteries is significantly degraded at low temperatures. An NTHV which started at 0°C would have less than half the electric range of one starting at room temperature. Consequently, we evaluated four alternative heat sources for the battery pack:

- Engine (self contained warm-up)
- Battery pack itself (self contained warm-up)
- Separate petroleum burning heater (self contained warm-up)
- Wall plug electricity (external warm-up).

Battery warm-up with wall plug electricity is the cheapest of these alternatives, and has the additional benefit of zero petroleum consumption. When external power is not available, a separate petroleum-burning heater would provide the best solution. Compared to running the engine, the savings in petroleum consumption which would accrue from such a heater would more than offset its initial cost (approximately $300). Moreover, the thermal stresses which accompany each engine restart would shorten the engine's life. The other alternative, using the battery pack itself, consumes such a large quantity of energy that the electric range would be substantially reduced (see Section 10.2 of Appendix B).

SECTION 6

ELECTRONIC CONTROL SYSTEM

6.1 INTRODUCTION

There are three key reasons a microcomputer based electronic control system (ECS) is required for the NTHV control functions. First, an adaptive operational strategy is needed. This strategy considers the likely mission to be driven, the recent daily driving patterns, the driver trip input, the current mission experience to present, and the vehicle powertrain parameters and state. It decides whether the most appropriate mode is diesel or electric primary drive, and then specifies the maximum power contribution of the motor. Second, because neither powerplant can meet all the NTHV performance constraints by itself, at times the second powerplant must be automatically brought on line. Third, variable transmission shift points are necessary in order to accommodate the varying power contributions supplied by the individual powerplants.

The primary functions of the NTHV electronic control system are to

- Provide control of the hybrid powertrain, including the transmission, clutches and torque converter, engine, and electric motor
- Select the operational strategy
- Provide a safe, reliable, and driveable vehicle
- Provide visual diagnostic and vehicle status information to the driver
- Facilitate maintenance and repair.

Figure 6-1 shows the major subsystems controlled and monitored by the ECS. Table 6-1 lists the functional responsibilities by subsystem.

Table 6-1. Functional Responsibilities of the ECS

System Monitor and Control	System Monitor
Diesel engine	Accessory & engine battery
Electric motor & motor controller	Brake pedal & lines
Transmission	Accelerator pedal
Motor clutch	Accessories
Engine clutch	Fuel tank
Lock-up torque converter	Environmental conditions
Driver display	Power batteries state of charge
Power battery on board & off board charging	
Power battery compartment temperature	

6.2 MICROCOMPUTER HARDWARE SPECIFICATION

6.2.1 Electromagnetic Interference/ Compatibility (EMI/EMC)

One of the most severe requirements for automotive electronics is reliable operation in the typical vehicle environment of electromagnetic interference and power line transients. This is particularly true of the present day microcomputers, whose metal oxide silicon (MOS) logic interfaces are more sensitive than those of bipolar transistors; i.e., transistor-transistor logic

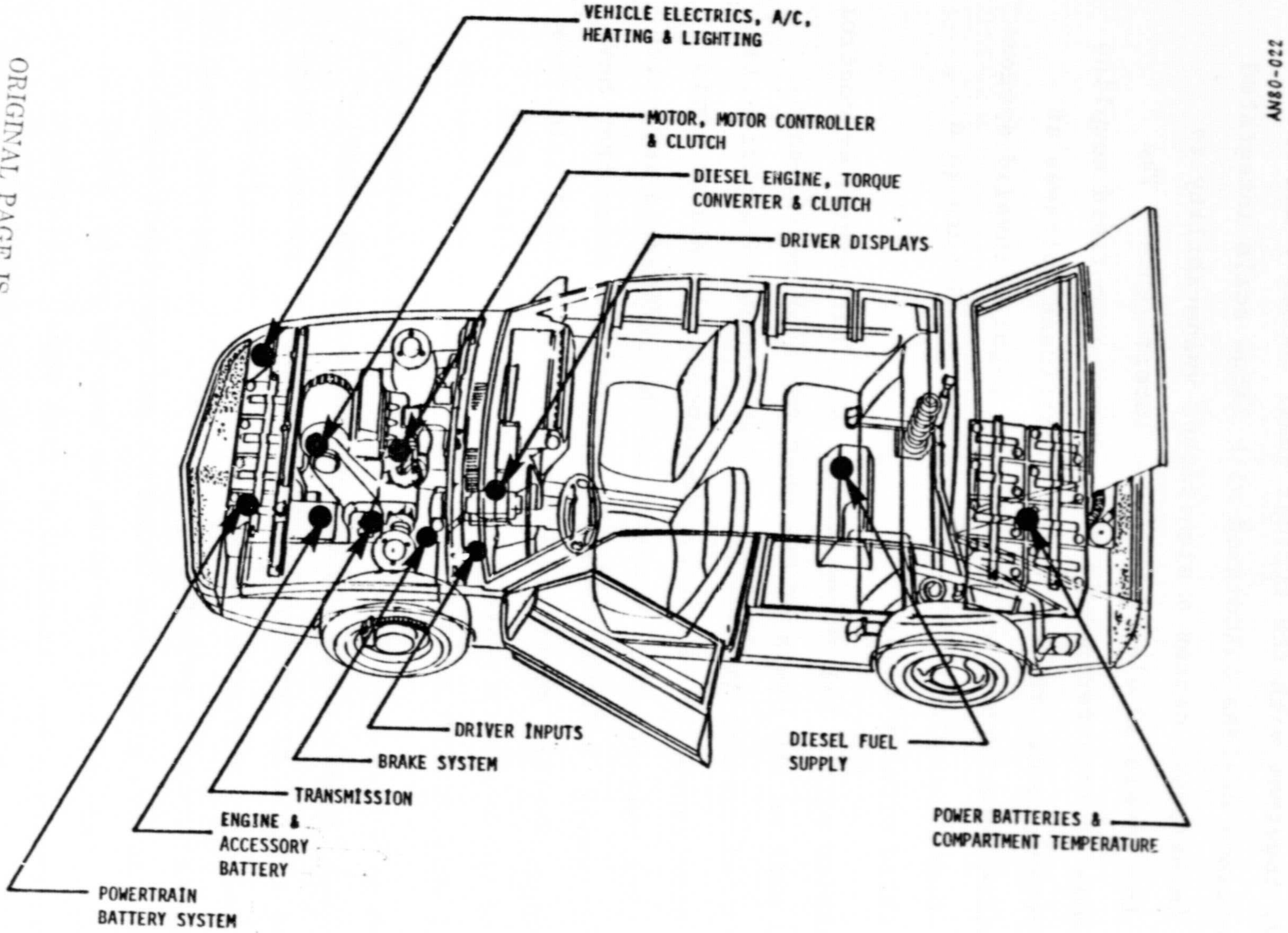

Figure 6-1. Major Components Controlled or Monitored by the Computer System

(TTL). The MOS device is a voltage sensitive element. Voltage sensitivity, together with the typical small geometry and low input capacitance devices associated with large scale integrated (LSI) chip interfaces, causes a significant vulnerability to relatively low levels of electromagnetic interference. The prevalent mode of interference is through magnetic field coupling into the system cables; this produces significant voltages at high impedance interface circuits, thereby causing invalid system response. Direct coupling through the system enclosure is a second or third order effect.

The choice of MOS LSI chips for the NTHV microcomputer control system was made on the basis of the need for high performance, high functional density and low unit cost. These three criteria could not simultaneously be met by the bipolar transistor logic families. The only notable exception is the integrated injection logic (IIL) family; unfortunately, IIL devices, because they have a low voltage, current summation logic, require special interface devices and power supply voltages. They also presently lack peripheral support devices and multiple sources in the industry.

We chose N-type MOS (NMOS) over the wider temperature range and relatively higher noise immune complementary MOS (CMOS) because of functional density considerations. At present there are very few CMOS microcomputer designs having the performance and functional density required by the NTHV. In addition, the typical automotive electronic interface can experience electromagnetically induced noise of volts to tens of volts, which is well above the response threshold of even CMOS. Interference is an important enough problem that the "electromagnetic hardening" of automotive electronics cannot be achieved simply by device technology selection.

We selected the microcomputer chip set technology on the basis of

- High performance (processor throughput)
- High functional density (functions per chip)
- Low cost
- Availability of development support equipment.

The electromagnetic hardening of the system will be accomplished at the system level.

There are two additional problem areas. Power line transients are severe in the contemporary production vehicle. These are primarily caused by the solenoid and motor loads, which usually are unsuppressed (e.g., the air conditioner clutch) or which require large currents (e.g., the starter motor). This problem necessitates special design considerations for power interface circuits. The second problem occurs because the typical microcomputer operates over a clock frequency range of 1 to 10 MHz. The logic switching transients at these clock rates are particularly effective in coupling into other automotive accessory electronics, such as radio and even tachometer circuits. This is a severe problem for automotive radios, which can have front end sensitivities down to 0.5 microvolts. The result is highly audible noise on AM and station blanking on FM. Again, hardening can only be effectively accomplished at the system level.

6.2.2 Microcomputer Selection

The Phase I ECS design is described in Appendix C. The microprocessor must meet the following general requirements:

- Distributed independent system for use in development

- Distributed master-slave independent system for production
- Maximum flexibility (ability to convert developmental software to production system)
- Memory referenced architecture (desirable in the control function due to use of table look-up functions)
- Integrated modular software utilizing an executive monitor system (to enhance the software development and provide flexible, structured and disciplined coding)
- Availability of a software and hardware development system
- Hardware multiply and double precision instructions to accommodate the control system function (particularly necessary for providing fast throughput and keeping total electronics system error below 1 to 3 percent)
- A comprehensive design for EMI/EMC, in conjunction with an NMOS microprocessor buffered with CMOS integrated circuits (to effectively minimize the problems due to EMI)
- Throughputs on the order of 200 KOPS (thousand operations per second) for control of the powertrain elements
- Low cost production microprocessor chip set or single chip microcomputer for automotive applications (desirable).

After evaluating the various microprocessors available, we found that the Motorola MC6801 family of single chip computers met all of the requirements. This family has the following features:

- Enhanced MC6800 processor with multiply and double precision instructions
- Memory referenced based architecture
- 2K bytes of on-chip read only memory (ROM)
- Erasable programmable ROM (EPROM) version soon to be available
- 128 bytes of on-chip random access memory (RAM)
- Capability to mask program RAM to provide non-volatile function
- On-chip clock
- Expandable address data bus for external memory and input/output (I/O)
- Programmable I/O port configuration
- On-chip timer
- Single 5V supply operation, compatible with both TTL and CMOS
- Availability of a software and hardware development system using a high order language compiler and incircuit emulator
- Availability of cross-assembler, cross-compiler and simulator for timesharing computers
- Average instruction speeds of 4 µsec and an effective typical throughput of 300 KOPS.

The MC6801 has been designed for use in a distributed operating mode to provide separate processors for separate functions. As a result, all of the requirements of the NTHV ECS microcomputer are met by the use of the MC6801 family of single chip microprocessors.

6.2.3 Hardware Design

Figure 6-2 shows that the NTHV ECS is partitioned into two functions: control and supervision. The associated hardware design is shown in Figure 6-3. The control function is the larger and more complex of the two and is responsible for centralized control of the diesel engine, electric motor, transmission, torque converter and clutches. The controller also performs limited diagnostics and self-test functions. Since its inputs include virtually all of the control system sensors, these data are transmitted to the supervisor for its shared use. In return, the controller receives its basic operation strategy commands from the supervisor.

The supervisor uses another 6801 microcomputer. The supervisor system, whose hardware is less complex, provides

- NTHV vehicle operational strategy
- Display of vehicle/engine/control system parameters
- System level diagnostics
- Resources management (displays of fuel and electricity consumptions and range remaining).

The distributed processor design was deliberately chosen to take advantage of the natural separation of the controller and supervisor functions. The high speed control function algorithms are processed by the controller, and the slower operating mode and resources management algorithms, along with operator interfaces and displays, are processed by the supervisor. This division

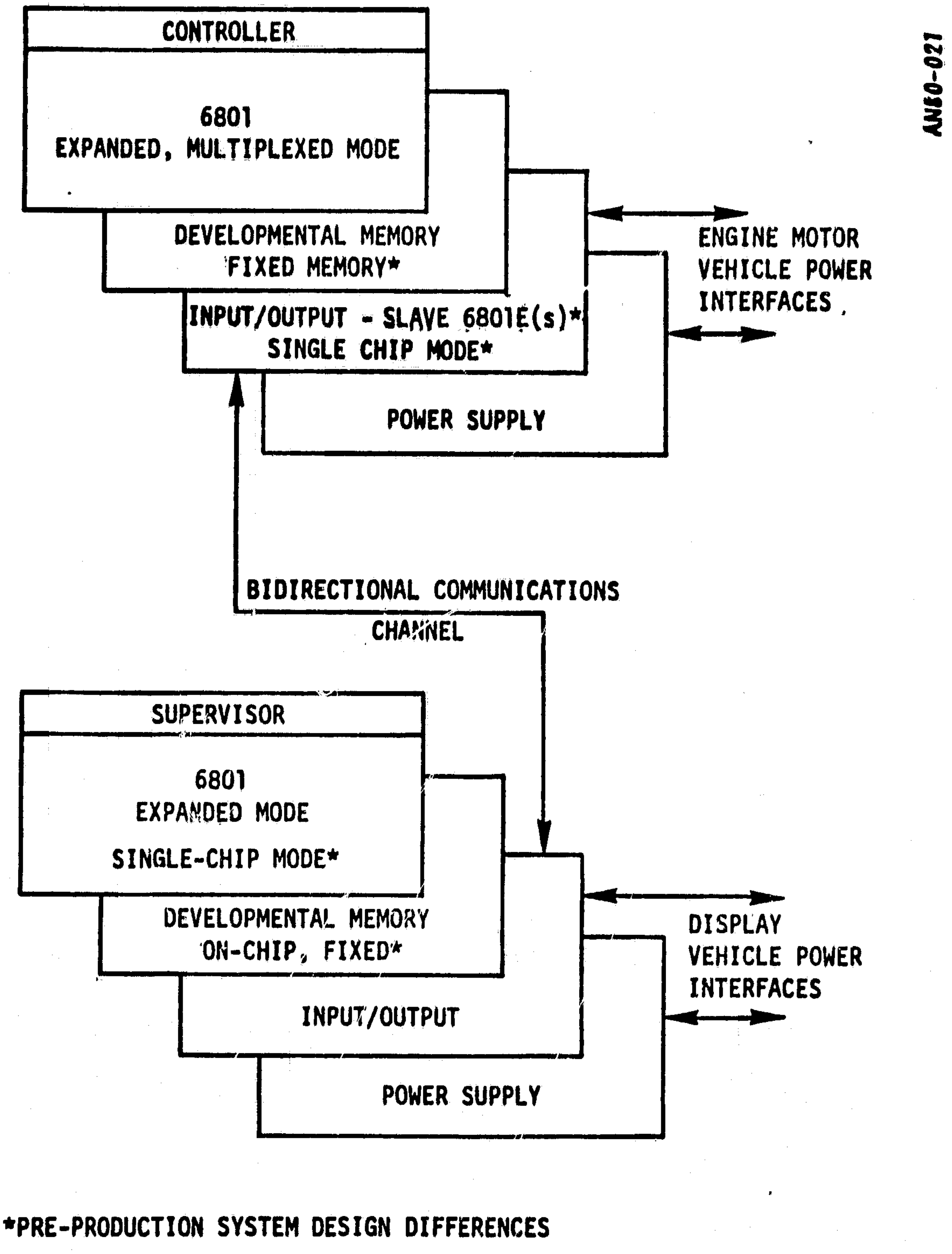

Figure 6-2. Developmental NTHV ECS Microcomputer Functional Partitioning

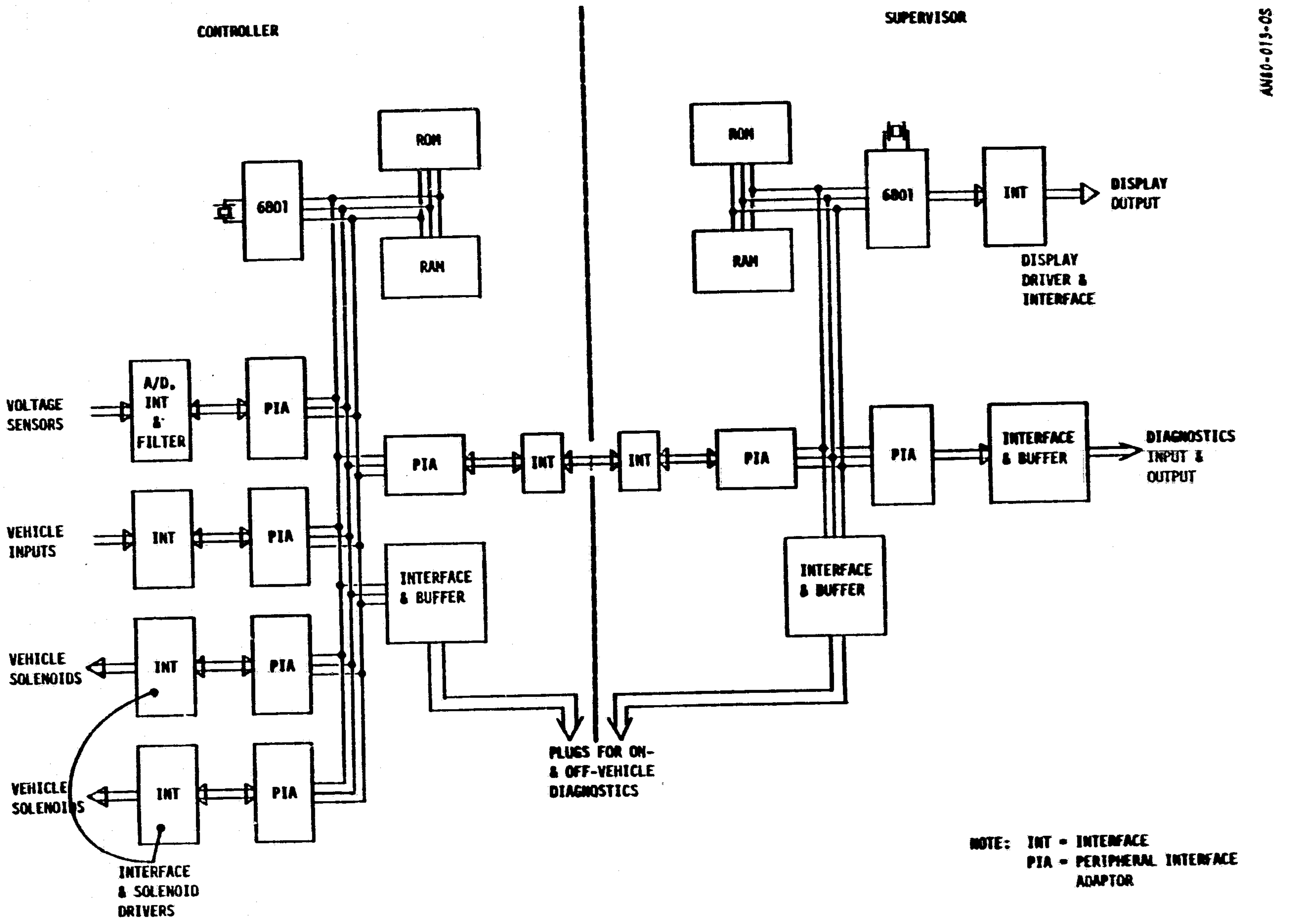

Figure 6-3. ECS Hardware Design

effectively reduces the processing throughput demands on the controller processor; it also reduces controller design risk by allowing all of the 6801 computational power to be used for controlling. The hardware complexity of the supervisor is minimized by sharing the controller data on a limited, slow rate, low interference basis. It is important to note that both subsystems use the 6801, and only their bus and I/O pin assignments are different. Therefore, the same hardware design aids and software development tools can be used. This would obviously not be the case if non-identical microcomputers were used.

The developmental hardware memory design should be configured around industry standard ultraviolet EPROM devices for both the controller and supervisor. This will facilitate the generation, debugging and checkout of the software in the developmental system. Since this design would not be cost effective for production, metal mask ROM will be used in the production design. Table 6-2 itemizes the most significant hardware differences between the development and production designs. The production design is a direct extension of the developmental controller/supervisor concept, except that the controller has imbedded slave 6801E processor(s), as shown in Figure 6-4. These slave 6801Es are configured as single chips and serve to reduce the extent of the master I/O hardware and associated software. In effect, the imbedded 6801Es act as I/O data pre- and post-processors.

6.2.4 Processor and Memory Design

As shown in Figure 6-5, both the controller and supervisor are expanded and multiplexed; this provides the capability of using off-board memory. If this design proves to be unnecessary

Table 6-2. NTHV Microcomputer Control System Hardware Configuration Summary

Subsystem	Development System	Production Design
<u>Controller</u>		
Processor	6801	6801
Memory:		
ROM	EPROM	NMOS ROM (in addition to 6801)
RAM	NMOS RAM	NMOS RAM (in addition to 6801)
RAM (N/V)*	CMOS RAM	6801 on-chip
CAL DATA/ROM PATCH	EPROM	Bipolar fusible link PROM
Input/Output	CMOS LOGIC Single supply, low voltage operational amplifiers Bipolar transistor drivers	Slave 6801E(s) to replace I/O hardware and to reduce I/O data software burden of Master Processor. Some CMOS logic will still be used.
Power Supply	Three-terminal regulator	Three-terminal regulator
<u>Supervisor</u>		
Processor	6801	6801
Memory:		
ROM	EPROM	6801 on-chip plus NMOS ROM**
RAM	NMOS RAM	6801 on-chip
RAM (N/V)*	CMOS RAM	6801 on-chip
Input/Output	CMOS LOGIC Single supply, low voltage operational amplifiers Bipolar transistor drivers	CMOS LOGIC Single supply, low voltage operational amplifiers Bipolar transistor drivers
Power Supply	Three-terminal regulator	Three-terminal regulator

*N/V = non-volatile.

**As needed, depending on the complexity of the final operation strategy.

C-2

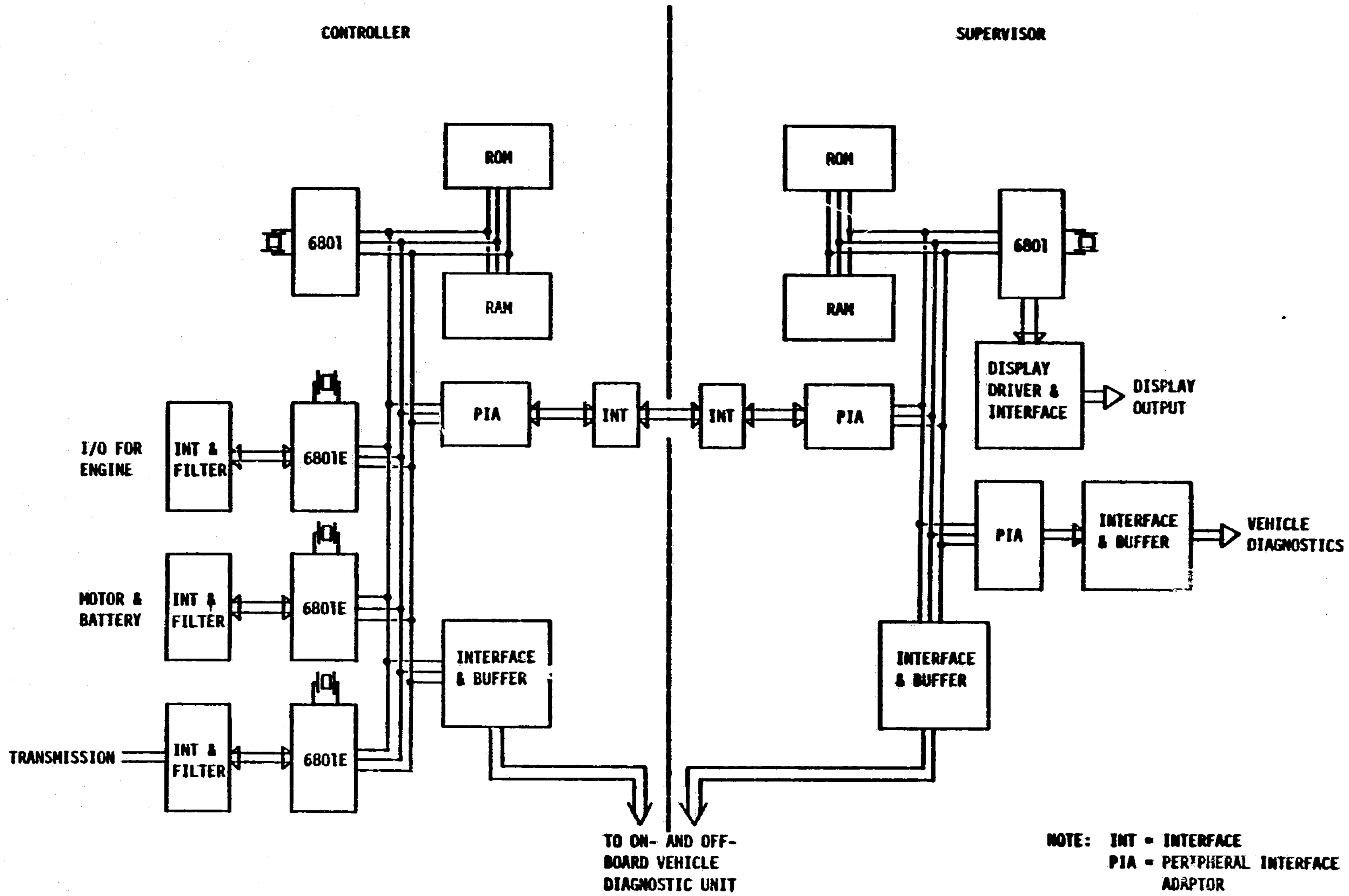

Figure 6-4. ECS Production Design

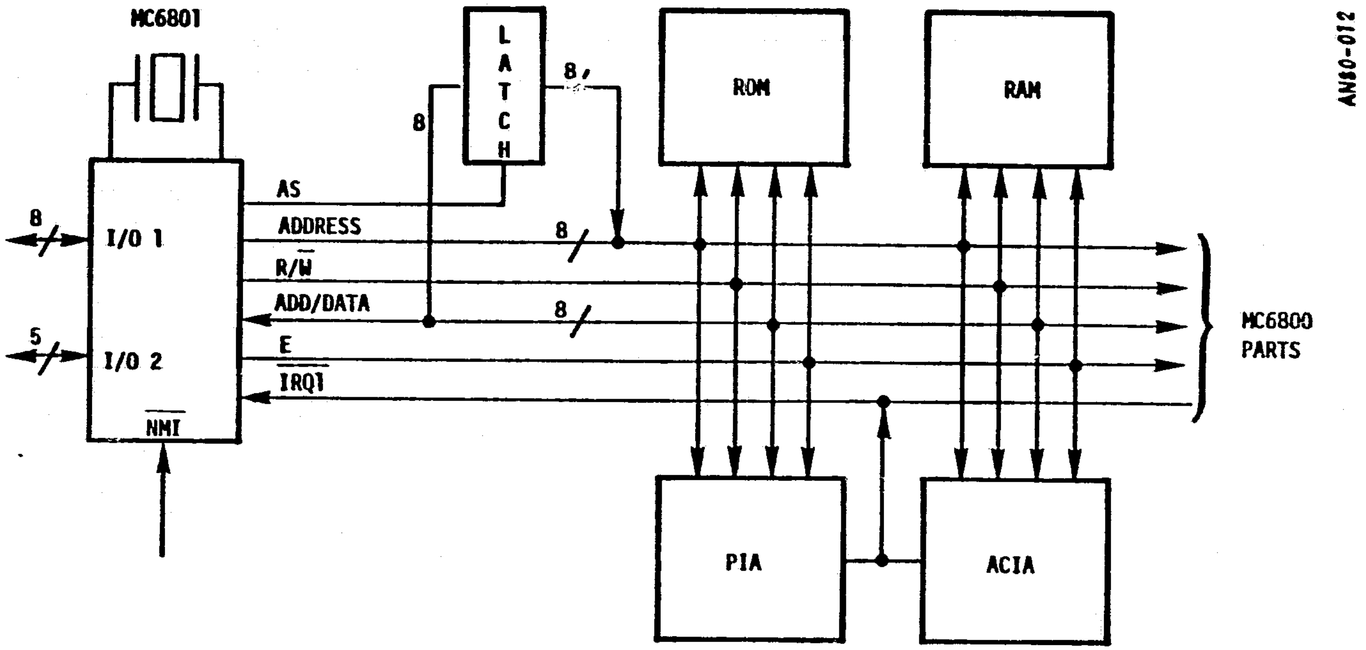

Figure 6-5. Expanded, Multiplexed Mode

in production in either system, the single-chip mode shown in Figure 6-6 could be used.

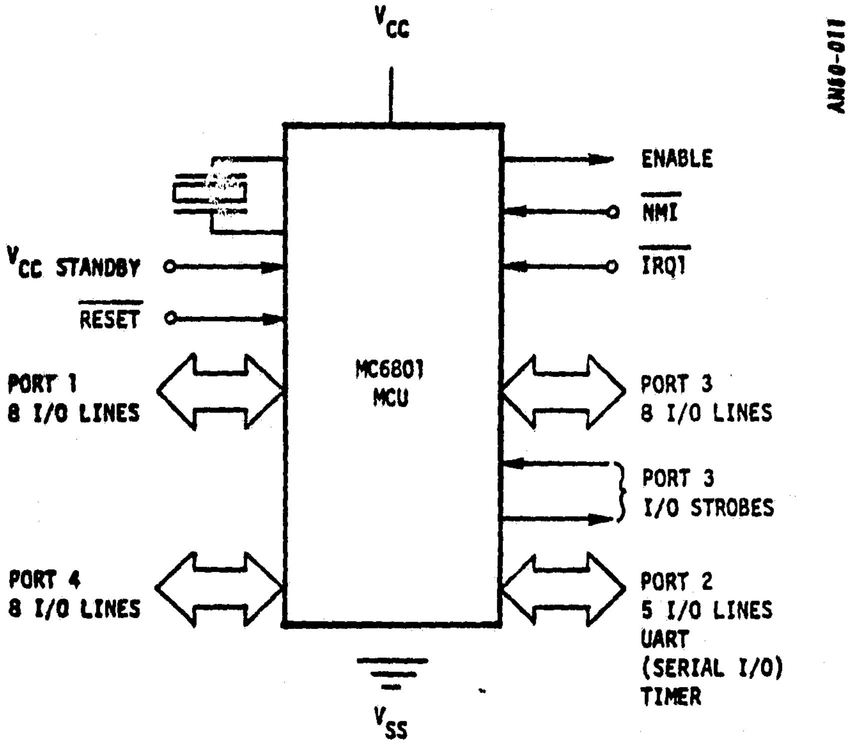

Figure 6-6. MC6801 MCU Single-Chip Mode

The controller memory in the development design consists of 16K of EPROM, 4K of static RAM and 2K of non-volatile CMOS RAM. Provision can be made for additional memory, if useful for development, in the developmental system.

In the production design, the 2K on-board 6801 ROM is supplemented by off-board NMOS static ROM and RAM. The non-volatile RAM functions are assumed by the on-board RAM. The use of bipolar fusible link PROM, such as the National Semiconductor DM54S472, is retained in order to provide calibration data and ROM patches.

The important feature of fusible link PROM is that it allows field or late modification changes without affecting the mask programming runs made by the bulk of the system. Thus, problems discovered late in the production process are not disastrous.

The supervisor memory in the development hardware consists of 16K of EPROM, 4K of static RAM and 2K of non-volatile RAM. The production version will utilize the on-chip 6801 ROM supplemented with off-board static NMOS ROM, as needed.

6.2.5 Technical Risk Minimization

In summary, the key features of the ECS computer design which minimize technical risk in development are

- Flexible developmental hardware design
- Development system paralleled by a production-oriented design
- Established production, yet state-of-the-art microcomputer
- Available software development system compatible with the selected microcomputer
- Modular software
- Comprehensive design for EMI/EMC.

6.3 DIAGNOSTIC SYSTEM

Three levels of diagnostic capabilities are provided for the ECS:

- Built-in test equipment
    - On-board diagnostics
    - I/O wraparound (to verify that commands have been executed

  - Reasonableness testing
  - Control system state checking
  - Actuator monitoring

- Portable diagnostic display unit
  - On-vehicle problem evaluation
  - On-vehicle performance monitoring
  - Digital/Analog (D/A) capability

- Support diagnostic test equipment
  - Detailed ECS system troubleshooting.

In the built-in test function the testing is an ongoing process. The detection of a problem causes further diagnostic checking, and the ECS may automatically select fail degraded, fail safe, or override operation. (See Section 7.2 for more details.) The driver of the NTHV can identify any specific problems via a request switch which will cause display of general diagnostic messages on the main display. No additional hardware is required for this system. The NTHV's on-board limited diagnostic capability will be based, in part, on the capabilities and performance already demonstrated in a production automotive system--the computer controlled catalytic converter (C4) developed by General Motors.

The diagnostic display unit (DDU) is a device which can be connected to the test connector/vehicle harness. It is small enough to be stored in the dash. The DDU enables fairly detailed evaluation of vehicle problems through the use of switch selectable monitoring of various vehicle functions. It also allows the interface of off-board monitors.

The support diagnostic test equipment is designed to provide detailed troubleshooting of the ECS system. This equipment comprises a sophisticated microprocessor-based system designed for intelligent evaluation and diagnosis by a parallel computer.

6.4 SENSORS AND ACTUATORS

A simplified schematic of the sensors and actuators applicable to the ECS is shown in Figure 6-7. Table 6-3 gives a detailed list of them. Many of the sensors and actuators to be used will represent state-of-the-art pre-production units. The majority of the sensors are resistive, thus enabling the use of a ratiometric A/D converter approach. This results in lower costs and simplified hardware design. There are no large power solenoids--only small (50-100Ω) units which control on/off functions or which pulse-width modulate a large hydraulic valve or actuator. This is power efficient, thus providing low battery drain.

6.5 DISPLAYS AND CONTROLS

The NTHV has displays and controls similar to those in the Minicars Research Safety Vehicle (RSV). The emphasis is on digital and digital analog displays. The vehicle speed and remaining fuel resources are displayed in a digital analog form. The oil pressure, odometer, water temperature, etc. are displayed digitally, as are the diagnostic messages.

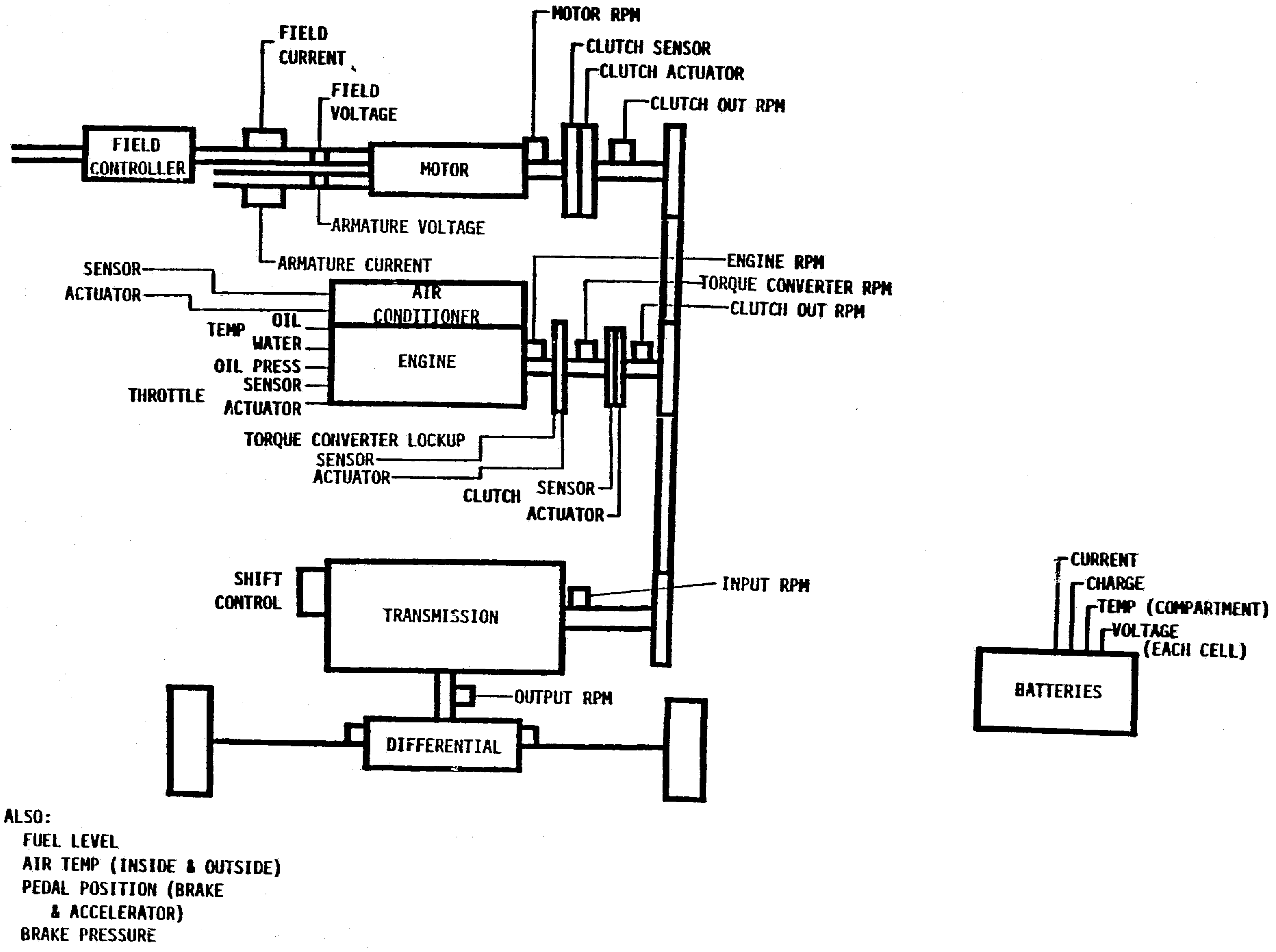

Figure 6-7. Sensor and Actuator System

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Table 6-3. Control System Applications, Sensors and Actuators

		Sensors		Actuators	
Application	Purpose	Function	Description	Function	Description
Engine	Control speed and power of engine and monitor engine operating system parameters and fuel level	RPM*	Magnetic pickup and interface	Throttle position	Two solenoid valves for hydraulic ram--small
		Throttle position	Potentiometer and interface	Starter	Starter relay
		Oil pressure	Pressure transducer and interface	Fuel pump	Fuel pump relay
		Fuel level	Potentiometer and interface		
		Water temperature*	Thermistor and interface		
		Oil pressure	Thermistor and interface		
Engine torque converter	Control torque converter lock-up	Lock-up	Microswitch showing lock-up	Lock-up control	Solenoid valves for lock-up clutch actuation
		Engine speed*	Magnetic pick-up and interface		
		Converter out RPM*	Magnetic pick-up and interface		
Engine clutch	Control engine clutch	Clutch	Pressure switch showing clutch open or closed	Clutch control	Two solenoid valves controlling hydraulic ram
		Clutch input RPM*	Magnetic pick-up and interface		
		Clutch output RPM	Magnetic pick-up and interface		
Electric motor and controller	Control speed and power of motor	Field current armature	Current sensor and interface	Field current	Serial I/O line to field controller
		Armature current	Current sensor and interface		
		Field voltage	Voltage sensor and interface	Armature current	Relay to turn on/off
		Armature voltage	Voltage sensor and interface	Armature current	Relay for starting motor
		Motor speed*	Magnetic pick-up and interface		

*Sensor shared with another function.

Table 6-3 (Cont'd)

Application	Purpose	Sensors		Actuators	
		Function	Description	Function	Description
Motor clutch		Clutch input RPM*	Magnetic pick-up and interface	Clutch closure and opening	Two solenoid valves controlling hydraulic ram
Transmission	Control transmission shifting and gear selection	Transmission input RPM	Magnetic pick-up and interface	Shifting	Six solenoid actuated hydraulic valves
		Transmission output RPM	Magnetic pick-up and interface		
		Accelerator pedal*	Pot		
		Gear select*	Switches		
Driver inputs	Monitor and control information to and from the driver	Brake position	Potentiometers and interface		
		Accelerator position	Potentiometers and interface		
			Full out and idle		
			Switches		
			Accelerator Pedal		
			Circuit monitor		
		Transmission shift position			
		Manual input	Key-in system		
		Key position	Circuit monitor		
Power batteries and battery environment	Control and monitor battery conditions	State of charge	Battery state of charge	Battery charger	Battery charger control from wallplug
		Battery compartment temperature*	3 thermistors and interface	Temperature	Solenoid controlling air flow
		Battery module voltage	13 voltage sensor circuits		
		On-board charger	Switch		

*Sensor shared with another function.

Table 6-3 (Cont'd)

		Sensors		Actuators	
Application	Purpose	Function	Description	Function	Description
Engine and accessory battery	Monitor charging and voltage of engine battery	Alternator output voltage	Alternator output voltage interface	Diagnostic Display	Indicate vehicle status and problems
Environmental conditions	Control air temperature for passengers	Inside air temperature	3 thermistors and interface	A/C control	Air conditioner clutch control solenoid
		Outside air temperature	3 thermistors and interface		
		Engine temperature*	1 thermistor and interface	Combustion heater control	Combustion heater control relay plus additional actuators required for motor and engine control
		Battery compartment temperature*	1 thermistor and interface		
		Environmental control switches	Circuit status monitoring		
Accessories and diagnostics	Control accessories and diagnostic checks	Lights	Interfaces to detect bulb or circuit failures	Diagnostic display	Indicates vehicle status and problems
		Brakes	Circuit to monitor brake system failure sensor	Diagnostic interface	Interface to plug-in diagnostic box
			Brake system - pressure transducers		
			Brake pressure transducers		

*Sensor shared with another function.

SECTION 7

RELIABILITY AND SAFETY

7.1 BASIC CONSIDERATIONS

Some of the previous sections have addressed reliability and safety criteria in the various aspects of NTHV design. In this section we review the design specifically in these terms.

Reliability was an important consideration in the selection of a production base vehicle over an entirely new design. Likewise, off-the-shelf components were specified wherever possible--most importantly, for the engine, transmission and batteries. In this respect lowering the development costs and improving reliability are non-conflicting goals.

The unique characteristics of the NTHV require special consideration. It would appear that the overall complexity of the powertrain would hurt reliability. However, dual powerplants should actually be beneficial in this regard, since the vehicle is still operable in either mode alone. We have taken care to route the high amperage battery cables through safe, inaccessible locations and to use interlocks in all major connections. In addition, the batteries are externally vented to keep hazardous gases from accumulating.

7.2 MICROPROCESSOR-BASED CONTROL SYSTEM

Reliability and safety were very important concerns in the design of the microprocessor-based control system. There are four levels of system design which pertain to these concerns.

Self Test. Numerous routine software checks were called for to check system operation. A diagnostic package would perform continuous reasonableness tests to check operation. Sensor readings must be within specified limits, which may vary during vehicle operation. For example, with either drivetrain clutch activated, input and output shaft speeds should be equal. Input/output wraparound, which uses electrical feedback to confirm that an actuator change of state has occurred, is also incorporated at this level.

Fail-Degraded Mode. In this mode, when there are minor or temporary software or system failures, backup hardware will automatically take over. The resulting operation will not be optimal, but will allow the continued use of the vehicle. This need might arise, for example, because of transients associated with strong external power sources, such as high voltage power lines.

Fail-Safe Mode. If a major failure occurs in the powertrain or in the ECS, the vehicle will go through a prescribed shutdown sequence, allowing the vehicle to come to some safe base condition--such as a slow stop on the side of the road. The diagnostic system and driver manual will allow the driver to identify the cause of the failure, so that appropriate action may be taken.

Manual Override Mode. A manual override can be used by the driver in the event that the fail-safe mode was activated by a failure in the electric power or in the ECS. The driver can override the ECS and lock out the electric power plant, thus using the engine alone for power and selecting the gear ratios through direct linkage.

The combined operation of the three safety and reliability modes is shown in Figure 7-1. This configuration maximizes the

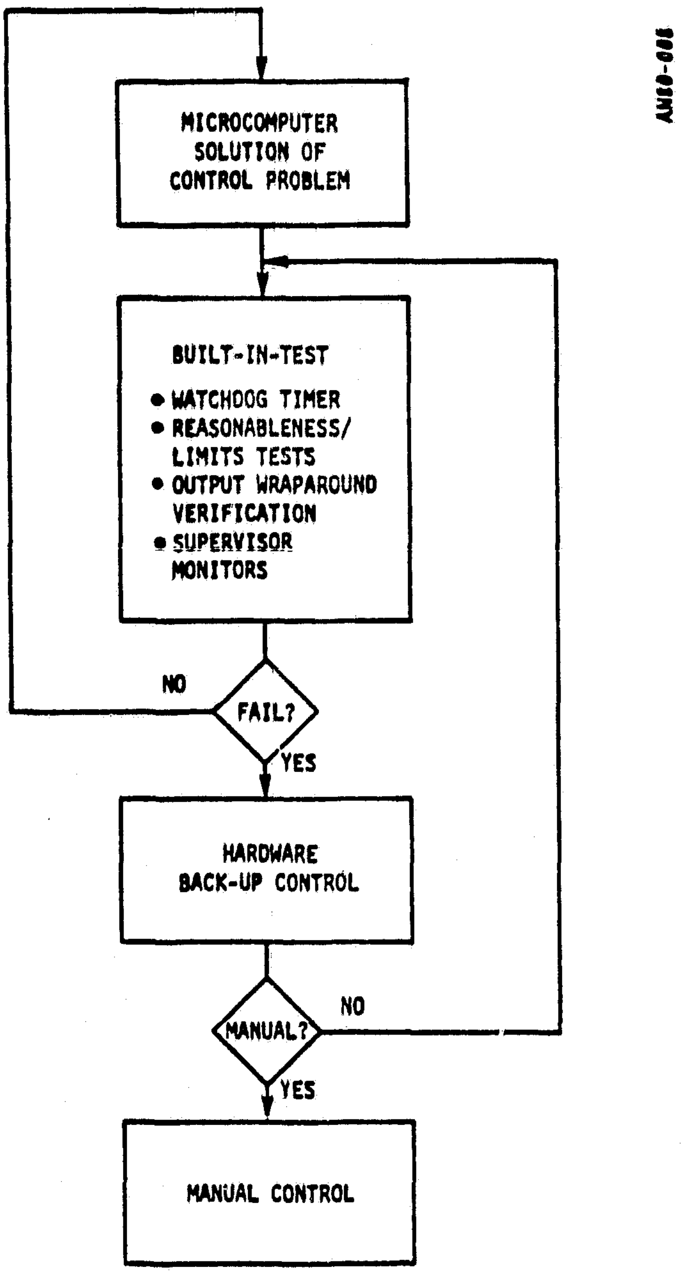

Figure 7-1. NTHV Microcomputer Control System Operating Modes

petroleum savings whenever the system is operating normally, yet promotes customer acceptance by allowing manual operation if the entire microcomputer control system fails.

7.3 CRASHWORTHINESS AND OCCUPANT PROTECTION

A major advantage of using the Chevrolet Citation for the hybrid base vehicle is the crashworthiness of its design. The Citation has been tested in frontal impacts at speeds up to 48 mph and was found to have one of the best crash pulses (acceleration versus time plots) in any production vehicle.

The hybrid's extra mass, most of which is in the engine compartment, will have a deleterious effect on crashworthiness unless the structural design is modified appropriately. The general procedure is to assess the amount of crush space available (allowing for non-crushable elements like the engine), establish a force versus crush characteristic that will generate controlled collapse of the available space at sufficient force levels to absorb the crash energy, and then provide for the transmittal of those forces through or around the passenger compartment (so as to maintain compartment integrity). These steps are accompanied by careful consideration of the vehicle architecture, computer simulations, static and dynamic crush tests of elements and whole structures, and, finally, by vehicle crash tests. All of these steps will have to be applied in the conversion of a Citation into an NTHV.

To be a socially responsible vehicle, the NTHV has to possess a degree of occupant protection equal to or greater than those vehicles which it is replacing. From the schedule of NTHV production and the NHTSA's near-term rulemaking plan, it is clear that complying with the 1978 safety standards will be insufficient.

By 1983, FMVSS 208 will require vehicles of the size of the NTHV to possess so-called "passive" occupant frontal impact protection. This protection is to be confirmed in a 30 mph fixed flat barrier impact with dummies representing 50th percentile males at all designated front seat positions. The automobile industry is currently reacting to FMVSS 208 requirements by developing either air cushion restraint systems or passive belts for their vehicles--the choice of system being dictated by marketing factors, vehicle particulars, and corporate research resources. In the case of the X-body, GM seems to be preparing to introduce passive belts into the vehicle at least in the early years of the standard.

Nevertheless, studies have shown a strong consumer dislike for any belt restraint system. Air cushions, on the other hand, do not suffer the same customer acceptance problems and would certainly be more effective than disconnected belt systems. This consideration, together with the fact that the Citation was designed to easily accommodate air cushions, led us to select air cushions for the NTHV.

Sections 3.5 and 3.6 of Appendix C discuss vehicle crashworthiness in greater detail.

SECTION 8
ECONOMIC ANALYSIS

8.1 INTRODUCTION

In previous sections we have reported life cycle costs (LCCs) for hybrid and reference vehicles. These costs, for the most part, will be incurred from 5 to 15 years into the future. They are, therefore, quite speculative, and could vary substantially if different assumptions are made. In this section we explain how the life cycle costs were determined.

The life cycle cost analyses were divided into five groups: the first calculated the manufacturing and acquisition costs for an NTHV; the second dealt with the research and development costs; the third concentrated on the propulsion system maintenance costs; the fourth calculated the total operating costs; and the fifth group combined all the previously detailed LCC items and conducted a present-value analysis for each item. Finally, knowing the present-value of the total LCC for an NTHV, we compared the results with the LCC of a conventional internal combustion engine (ICE) vehicle and determined the net benefit per NTHV.

8.2 MANUFACTURING AND VEHICLE ACQUISITION COSTS

The manufacturing cost of a vehicle component or system was obtained from its unit cost estimating relationship. This relationship was considered as a second order polynomial:

$$\text{UNIT COST} = f(W_c) = A_0 + A_1 \times W_c + A_2 \times W_c \times X_c \quad , \qquad (1)$$

where W_c is the vehicle curb weight (which could be replaced by $\ln(W_c)$ or $\sin(W_c)$, if desired). The unit cost estimating relationship can also be extended to higher order polynomials and to other functional relationships, if necessary. The result of Equation 1 is the manufacturing unit cost (in 1978 dollars) for the vehicle component or system; for example, \$/kg or \$/kW. The unit cost was multiplied with the appropriate characteristic of the component or system (weight of the system, power of the system, etc.) in order to obtain the manufacturing cost.

After the manufacturing costs were calculated, the mark-up factor for the vehicle was analyzed using an estimating relationship similar to Equation 1, but this time the independent variable was the total manufacturing cost. The mark-up factor (which in this analysis equaled 2.0) was multiplied with the total manufacturing cost in order to obtain the purchase price of the vehicle.

We then included the financing terms (such as the interest rate and the finance duration), the sales tax and the salvage value at the end of 10 years (as percentages of the vehicle purchase price), and the discount rate for the present-value calculations. The cost of financing the vehicle purchase price was calculated by the formula

$$\text{INTEREST} = P \times \{i \times n \times [1 - (1 + i)^{-j}] - 1\} \quad , \qquad (2)$$

where P is the purchase price, i is the interest rate, and n is the finance duration in years.

All the present-value calculations in this economic analysis were performed for each year, as follows:

$$\text{PRESENT-VALUE} = S/(1 + j)^{m} \quad , \qquad (3)$$

where S is the value to be discounted in the m^{th} year after 1985, and j is the discount rate.

The battery replacement costs were calculated in this section because they are treated similarly to the vehicle manufacturing costs. The battery manufacturing cost was obtained with an estimating relationship having the form of Equation 1, but the independent variable was the total battery weight that has to be replaced periodically.

The mark-up factor for the batteries was also analyzed with an estimating relationship similar to Equation 1. This time the independent variable was the battery manufacturing cost, and the mark-up factor was multiplied by the battery manufacturing cost in order to obtain the purchase price for the replacement batteries.

We assumed that the purchase price of a new automobile is financed over 48 months and batteries over 26 months, both at 12 percent interest. The 10th year salvage value for a car was assumed to be 5 percent of the original price, and the batteries were assumed to retain 10 percent of their original value when sold at the end of their life cycles. For all items a 5 percent sales tax was included.

8.3 RESEARCH AND DEVELOPMENT COSTS

The additional research and development costs for the NTHV relative to a conventional automobile can be estimated by dividing them into any number of elements. In this program each element's cost was calculated according to the formula

$$\text{R\&D ELEMENT COST} = (T \times R + C)(1 + L) \quad , \qquad (4)$$

where T is the research and development element's man-hour estimate in hours, R is the man-hour composite rate in \$/hr, C is the man-hour related costs in dollars, and L is the contractor's profit percentage.

For each research and development element, the value of T, R, C and L have to be known. In the present-value calculations of the total research and development cost, equal annual costs were assumed, and the total research and development cost was divided by the number of research and development years in order to obtain the annual research and development cost. The research and development cost amortization duration (in years) and the annual vehicle production rate also had to be known in order to calculate the research and development amortization per NTHV vehicle.

Total research costs for the baseline NTHV were calculated to be $23,914,000. Apportioned among 500,000 cars, the amortized discounted cost is $67.65 per car.

8.4 PROPULSION SYSTEM MAINTENANCE COSTS

The propulsion system maintenance costs are a portion of the operating cost. They can be estimated by dividing them into any number of elements. Required data include the total distance driven over the vehicle's lifetime, the scheduled maintenance interval in kilometers, mean time to repair, mean time to replace, mean time to inspect, labor rate, and parts cost per maintenance interval for each maintenance cost element. From these data we calculated the lifetime total cost of each element and the total propulsion system maintenance cost for each year.

8.5 TOTAL OPERATING COSTS

The total operating costs were divided into four subsystems--energy, maintenance and repair, battery replacement, and other operating costs. The battery replacement costs were calculated in the manufacturing cost group, and the propulsion system maintenance costs were determined in their own group.

The operating costs also included tires, insurance, license and registration, accessories, garage, parking and tolls, and, of course, petroleum and electricity. These costs were calculated in units of dollars per kilometer. They varied for different vehicles; the specific values may be found in Appendix C of Appendix B.

8.6 PRESENT-VALUE OF TOTAL LIFE CYCLE COSTS

All of the costs discussed above were discounted to present-value, assuming a 2 percent discount rate, as specified by JPL.[13] The apportionments of costs in the NTHV and the reference ICE vehicle are shown in Table 8-1.

Table 8-1. Present-Value Life Cycle Cost Comparisons Between the NTHV and the Reference ICE Vehicle (1978 Dollars)

Costs	Baseline NTHV	Percent of Total	Reference ICE Vehicle	Percent of Total
1. Total acquisition cost	10,753	43.74	8,372	43.02
2. Total energy cost	2,678	10.39	4,379	21.97
3. Total maintenance and repair cost	2,154	8.76	2,020	10.13
4. Total battery replacement cost	3,621	14.73	-	-
5. Total other operating cost	5,312	21.60	5,158	25.88
6. R&D cost	68	0.28	-	-
Total LCC	24,586	100.00	19,929	100.00

SECTION 9

COMPUTER SIMULATIONS

A number of computer programs were devised or modified to aid in this analysis. These will be briefly described in this section. All four appendices contain further, more comprehensive information about the computer programs.

CARSIM, the Minicars vehicle performance simulation program, has been used in several U.S. Department of Transportation programs and has been found to be an excellent model for estimating fuel consumption. In this application CARSIM was modified to model NTHV performance over the Federal Urban Driving Cycle (FUDC), the Federal Highway Driving Cycle (FHDC), and the SAE J227a(B) electric vehicle driving cycle.

CARSIM was first programmed with the appropriate driving cycle represented as a function of velocity versus time. The vehicle data input into the calculation was

- Vehicle weight, drag coefficient and tire dimensions
- Transmission gear and final drive ratios
- Inertia and friction loss characteristics for the powertrain
- Torque versus rpm versus fuel consumption curves for the engine
- Battery characteristics and initial state of discharge
- Motor characteristics
- Optimal shift curves for each mode
- Operational strategy.

The important outputs of the program included the vehicle's petroleum consumption and economy, electricity consumption and economy, and final state of battery charge.

The program MISSIM was used to simulate the performance of a vehicle driving one of the yearly missions. Instead of running the vehicle through each trip, one at a time, as CARSIM does, MISSIM uses the CARSIM petroleum and electricity economies as inputs. A specific mission (Mission B, for example) consists of a known distribution of trip lengths. This distribution was divided into trip length bins, and the mean length of each bin was used as an input. From average velocity versus trip length relationships, MISSIM calculated the average velocity for each bin. The next step was to divide each bin's total travel into three fractions, represented by the FHDC, FUDC and SAE J22a(B) driving cycles. Since we knew how a vehicle performed in each cycle, it was then a straightforward matter to sum the different CARSIM outputs into totals for a year.

After a particular NTHV configuration was driven through CARSIM and MISSIM, it went through the Minicars Life Cycle Cost Program. This program calculates life cycle costs and net benefit using the technique discussed in Section 8 above.

Another program, OPSTRAT, helped us to evaluate operational strategies. OPSTRAT produces information about the hybrid's expected fuel consumption over a range of distances. Its results are based on five factors: the probability of density of the instantaneous power required to propel a vehicle over a driving cycle, the power demands of the accessories, the rate of petroleum consumption as a function of power, the rate of battery consumption as a function of power, and the vehicle's mean speed. Predictions from CARSIM and OPSTRAT correlate well, which makes the combination of their results possible.

The principal tool used in the sensitivity studies (Appendix D) was a Monte Carlo trip making program similar to the one described in Reference 15. The program, originally written by the General Research Corporation of Santa Barbara, California, was expanded and adapted to the new Minicars Vax 11/780 computer. The chief program modifications were the simulation of trips by individual missions and the ability to assign variations in annual travel to trip length and trip frequency in arbitrary proportions. The modified program is called TRAVEL. The term "Monte Carlo" comes from the program's methodology--in which all trips are selected randomly from a pre-programmed distribution.

The approach used in TRAVEL is essentially the following: first, the program calculates the ratio of the assumed annual distance (which is to be studied) to a baseline annual distance. It then stretches the trip length and trip frequency by appropriate factors. (The NTHV to be analyzed is assumed to start each day with a freshly charged battery pack.) TRAVEL chooses the number of trips to be taken during the day. It then selects the first trip from the trip length distribution and tests whether it can be driven in the electric mode; it next selects the second trip and repeats the procedure until all of the trips for that day have been accomplished. Once the vehicle electric range has been reached, the remainder of the current trip and all subsequent trips are driven using diesel primary drive. Finally, TRAVEL tallies the results for each day and finds the yearly averages and totals.

More comprehensive treatments of these computer programs, including complete listings and sample printouts, may be found as follows:

CARSIM - Appendix A of Appendix B
MISSIM - Appendix B of Appendix B

LIFE CYCLE COST - Appendix C of Appendix B

OPSTRAT - Appendix D of Appendix B

TRAVEL - Appendix A of Appendix D

SECTION 10

PHASE I CONCLUSIONS AND RECOMMENDATIONS

10.1 MISSION ANALYSIS/SENSITIVITY ANALYSIS

Conclusions

1. The three most promising missions were found to be

	Mission	Primary Reason for Selection
A	Restricted General Purpose Travel (City Driving)	Maximum potential market penetration
BB	Commuting	Smaller, two-passenger car*
C	Family and Civic Business	Minimal range requirements

2. Hybrid vehicles could indeed save substantial quantities of petroleum.

3. A review and synthesis of previous studies led to the summary of trip making behavior shown in Table 10-1.

4. Mission analysis results are quite sensitive to the large uncertainties in the "tails" of the trip length distributions, i.e., in the length and frequency of very long trips.

5. Mission analysis results are insensitive to the manner in which increased travel is apportioned between longer trips and more frequent trips.

6. Variations in annual travel of the magnitude given by JPL[17] (of the order of ± 10 percent) do not strongly affect the choice of the preferred candidate system, but they do affect the

---

*Does not meet JPL minimum requirements.

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Table 10-1. Summary of Trip and Travel Parameters

Location	Source (Reference)	Approximate Date	Average Trip Length (km)	Average Number Trips/Car/Day	Average Daily Distance per Car (km)	Average Annual Distance/Car (km): Estimated as 365 x Daily Distance	and	Average Annual Distance/Car (km): Estimated from Gas Tax Data
Los Angeles	GRC (**)	1967	12.9	3.64	47.0	17,155		
Los Angeles*	SDC (5)	1970	11.7	3.40	38.6	14,089		
Six Cities	SDC (5)	1970	12.0	3.45	41.5	15,148		
Nationwide	NPTS (4)	1969-1970	14.3	3.05	43.8	15,987		
Nationwide	Schwartz (16)	1972	14.3	3.145	44.9	16,[illegible]6		
Nationwide	Highway Statistics (**)	1969						15,749
		1972						16,396
		1974						15,285

*Trips longer than 50 miles were not considered.

**See General Research Corporation addendum to Appendix A.

total fuel consumed. The change in fuel used can be approximated by assuming that the incremental distances are driven on the internal combustion engine only.

7. Variations in fuel and electricity prices in the range specified by JPL[17] (of the order of ± 30 percent) do not significantly affect the design trade-off study results.

8. Larger variations in fuel prices do have important effects. The breakeven prices for petroleum fuel (at which the NTHV 10 year life cycle costs become less than those of the reference vehicle) are

Mission AA, All Travel	55¢/liter, or $2.08/gallon
Mission A, Restricted General Purpose Travel	65¢/liter, or $2.45/gallon
Mission C, Family and Civic Business	30¢/liter, or $1.13/gallon.

9. The number of passenger cars affects the national petroleum consumption and thus, indirectly, the total petroleum imports and the balance of payments. Within the range specified by JPL[17] (on the order of ± 10 percent), these effects are moderate.

Recommendations

1. At this writing, the price of petroleum fuel is already higher than the projected 1985 price used in our analyses. Additional sensitivity analyses should more fully investigate the effects of even higher prices.

2. The negative net benefit and high petroleum breakeven price for all purpose travel make the introduction of NTHVs en masse into the American automobile fleet doubtful under normal

circumstances. More attention should be given to improbable, but still possible, scenarios--such as an acute petroleum shortage.

3. Hybrid vehicles appear to be better suited for special purpose missions (for instance, commuting or short range city driving) than for all purpose travel. The feasibility of vehicles detailed for such missions should be further investigated.

4. The Phase I NTHV Program considered the potential effects of replacing in the near term a large fraction of the automobile fleet with hybrid vehicles. Because such a replacement would require several years, a study should be made of the time phasing effects of NTHV introduction. Could hybrid vehicles be integrated into the fleet quickly enough to have any appreciable effect in the near term?

10.2 TRADE-OFF STUDIES

Conclusions

1. The preliminary design NTHV has the potential of saving at least 60 percent of the petroleum that will be used by a reference ICE vehicle in 1985.

2. For a given battery capacity, there is one engine and motor size combination that maximizes the petroleum savings.

3. The purchase price of the preliminary design NTHV is 30 percent higher than the purchase price of the reference ICE vehicle.

4. The life cycle cost of the preliminary design NTHV is 25 percent higher than the life cycle cost of the reference ICE vehicle, at the JPL specified nominal petroleum prices. The cost

of operating the preliminary design NTHV is $0.131 per kilometer, compared to $0.106 per kilometer for the reference ICE vehicle.

5. The breakeven petroleum price (at which the life cycle cost of the preliminary design NTHV equals the life cycle cost of the reference ICE vehicle) is $0.60 per liter.

6. The NTHV accessory loads can consume a significant portion of the total available power. The accessory power demands have adverse effects, both on the range with electric motor primary drive (20 percent) and on the overall petroleum consumption rates (26 percent).

7. Two waste energy recovery methods can improve the petroleum economy of an NTHV in a cost effective manner. One is the use of regenerative braking, which improves the NTHV fuel economy by 5.6 percent, and the other is the use of exhaust waste energy via a turbine-generator system, which improves the fuel economy by 12 percent.

8. The life cycle costs, and the overall practicality, of hybrid vehicles depend on the availability of long-life batteries.

9. When the cycle life of the battery is reached, the batteries can be left in the hybrid vehicle and can be used with degraded capacity until they short out. The average fuel economy for such usage (assuming a linear decrease to 30 percent capacity over 10 years) would be 23 km/liter, while the life cycle cost would be 6 percent higher than that of the reference ICE vehicle.

10. The battery subsystem has to be insulated and thermally controlled. Otherwise, the batteries will lose 60 percent of their capacity if the battery temperature drops to -20°C.

11. The effect of NTHV weight is more severe on vehicle performance characteristics than on the petroleum consumption. The preliminary design NTHV saves 0.4137 liters of petroleum per year for each kilogram of weight removed from the vehicle.

12. Simple operational strategies give very good fuel economies--in excess of 34 km/liter (80 mpg) for the preliminary design NTHV (for Mission A). Additional petroleum savings may accrue by switching to more sophisticated operational strategies, but the benefit would not exceed 5 percent for all travel.

Recommendations

1. The design trade-off studies were conducted for a five-passenger hybrid vehicle to be used in Mission A. The studies should be extended to different size vehicles--ranging from one-passenger vehicles to buses--and to different vehicle missions, so that the complete vehicle and mission spectrum is covered.

2. The effects (on fleet petroleum consumption) of introducing different size hybrid vehicles into the market should be investigated.

3. The availability of crucial materials (such as lead) should be investigated.

4. The government and automotive manufacturing scenarios that would affect the marketability of the hybrid vehicles should be analyzed.

5. The lifetime primary energy consumption should be determined for the full spectrum of hybrid vehicles and should be compared to that of the reference ICE vehicle.

10.3 PRELIMINARY DESIGN

Conclusions

1. The NTHV should be based on a stock vehicle rather than a new design from the ground up. The development of a new design requires an extensive effort that does nothing to advance the development of electric and hybrid vehicles, and yields no significant improvement in performance. The General Motors X-body automobile is the best choice as a base vehicle.

2. The best configuration for the NTHV battery pack is to divide the batteries between the front and the rear of the vehicle, with the front pack ahead of the radiator and the rear pack recessed in the trunk floor.

3. The NTHV should have a passive restraint system for the driver and front passenger, in accordance with the safety standards of 1983 and beyond.

4. The most critical consideration in transmission design is the method of starting the vehicle from rest with the field control electric motor.

5. At the current state of battery development, the use of lead-acid batteries is the only practical choice for the NTHV.

6. The environmental system (to heat and cool the passenger compartment and to heat the battery compartments) must be designed for a minimum usage of energy (whether derived from petroleum or electricity). Energy must also be conserved by means of effective insulation.

7. A microcomputer based electronic control system is necessary to safely and reliably operate the NTHV with minimum energy consumption. This system, which will control the major vehicle

subsystems, will be a distributed processing system based on state-of-the-art microcomputer components.

10.4 CRITICAL TECHNOLOGIES

One of the objectives of the Phase I NTHV program was to identify technologies important to successful hybrid vehicle development. Our work has found four that we feel are comparatively important:

1. Development of the appropriate mechanical interfaces between the engine, motor and transmission, including a means for starting from rest with motor power only
2. Development of the improved state-of-the-art lead-acid battery (or equivalent) to a satisfactory performance and durability level
3. Development of a high efficiency accessory drive, low power consumption accessories, and thermal control system
4. Integration of the various computer and control components into a practical, reliable system.

The design deals with these technologies as follows:

1. The preliminary design effort considered five powertrain options (described in the Preliminary Design Data Package and its Addendum [Appendix C] and in Section 5 above). These include a manually controlled transmission and clutch and four automated transmissions under computer control. All of the options could be developed into satisfactory drivetrain packages. We selected the one in which the electric motor is coupled to the transmission through either a slipping clutch or a variable fill coupling,

since it should give the best overall results, with an acceptable level of risk.

2. Inadequate battery performance would not in and of itself nullify the NTHV program; it would simply degrade the life cycle cost and fuel economy of an NTHV. As battery technology improves, new batteries can be substituted, and vehicle performance will improve.

3. Failure to develop a high efficiency accessory drive or low power consumption accessories would not remove the attractiveness of the NTHV. It would still have better fuel economy than the reference ICE vehicle--but perhaps not three times as good. Nevertheless, the potential for high petroleum savings implies that this development be pursued vigorously. The sensitivity of fuel economy to weight for this vehicle is low, which means that extra accessory weight that improves efficiency is probably a very good investment.

The thermal control system is not critical to the total success of the design; it only affects the overall efficiency (fuel economy) of the vehicle. Two alternatives have been identified for recovering additional energy from the engine exhaust, and various options exist for pre-heating the engine during charging, heating the batteries during charging, etc. The variety of available approaches minimizes the implementation risk.

4. The development program for the electronic control system is designed to minimize risk through the incorporation of a flexible developmental, yet production oriented, hardware design, an established production, yet state-of-the-art microcomputer, modular software, and a comprehensive approach to electromagnetic interference and compatibility. Risk is also minimized by the

fact that there are various alternatives that could lower the operational requirements on the control system. For example, the use of a manual transmission would greatly reduce the computational workload, permitting more attention to other applications (such as engine control). Severe problems with the control system could also be circumvented by exercising an option with relaxed operational requirements.

10.5 ENERGY CONSUMPTION

An estimate of potential petroleum savings was obtained through the mission analysis described in Section 2.3. More accurate evaluations of energy consumption became available as the baseline NTHV was developed during the trade-off and preliminary design studies. Table 10-2 shows our best estimate of the NTHV's energy consumption, obtained by driving the preliminary design through the MISSIM computer program.

Table 10-2. Preliminary Design NTHV Energy Consumption Measures

1. Annual petroleum based fuel energy consumption per vehicle compared to reference ICE vehicle over Mission A

   NTHV = 753 liters/year   Reference ICE = 1730 liters/year

   NTHV = 28,672 MJ/year   Reference ICE = 65,873 MJ/year

2. Annual total energy consumption per vehicle compared to reference ICE vehicle over Mission A

   NTHV = 42,435 MJ/year   Reference ICE = 65,873 MJ/year

3. Potential annual fleet petroleum based fuel energy savings compared to reference ICE vehicle over Mission A

   11.16×10^{10} MJ/year

4. Potential annual fleet total energy consumption compared to reference ICE vehicle over Mission A

   15.29×10^{10} MJ/year

5. Average energy consumption over maximum non-refueled range

   FHDC = 2.19 MJ/km

   FUDC = 3.12 MJ/km

   SAE J227a(B) = 3.79 MJ/km

6. Average petroleum based fuel energy consumption over maximum non-refueled range

   FHDC = 2.12 MJ/km

   FUDC = 3.03 MJ/km

   SAE J227a(B) = 3.68 MJ/km

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