Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Alternative Propulsion Systems Inputs

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-95-086
October 1994

FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations Research and Development

NOTICE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This study was conducted under contract to the Federal Highway Administration for the Intelligent Vehicle/Highway Systems Research Division. The purpose of the study was to assess the Impact of Alternative Propulsion Systems (APS) on Automated Highways (AHS).

Research Overview

The study was based on the assertion that concepts for automated highways and initial implementations will be influenced, primarily, by the design characteristics and limitations of modern vehicles. The study assumed a possible AHS design evolution, then using the functional and performance requirements for these AHSs, constructed a list of APS operational conditions which in turn, constrain the design of APSs. The reasonable APS vehicle will 'look' similar to today's automobile in terms of size, passenger area, storage space, weight, maneuverability and complexity of operation. The study examined these reasonable vehicles in terms of their operability and impact on a set of likely AHSs, over a range of operational scenarios. Subsequently, the research assessed infrastructure impacts of APSs and speculated on alternative AHS configurations that would be necessary to explicitly support APS traffic.

Research Activities

The research defined a set of representative system configurations (RSCs) for automated highway systems (AHS), then parameterized those configurations to provide a range of variability within each RSC, and finally established an evolutionary timeline for automated highways. The timeline was used in the consideration of a possible scenario for the concurrent evolution of AHSs and APSs, and to assess the dynamic interaction between these developing systems.

In parallel with the definition and specification of RSCs, the research into alternative propulsion systems identified and evaluated candidate APS technologies. A set of technology and performance baselines for APSs were established using APS vehicles that are currently in existence and undergoing evaluation. This baseline provided a realistic point of divergence for the analysis. The study then focused on applying the results of the research into enabling technologies, in conjunction with an assessment of market forces, to synthesize, from that baseline, the evolution of APSs over a time frame comparable to that defined for the RSC evolutionary scenario.

Methodology

The following is a description of the research approach taken for the AHS definition and APS analysis activities:

a. Several current, and well-researched AHS concepts were chosen for evaluation. Models were constructed for several AHS RSCs. These models were expressed in terms of vehicle performance requirements related to the vehicle operation and interaction with the roadway.

AHS configuration and performance parameters considered in the study included: vehicle control concept, typical acceleration ramp lengths, roadway speeds, inter-vehicle spacing, roadway grades and grade lengths, inter-vehicle spacing, urban and rural travel, guideway configurations, and vehicle restrictions. This portion of the research activity made use of the RSCs defined for a concurrent PSA study[1], by extracting data that was most relevant to APS/AHS interaction.

b. The modern internal combustion engine was used as a baseline from which to measure the relative performance and function of advanced APS vehicles considered in the study. Each APS concept was modeled to provide numerical estimates of power and energy requirements for every reasonable combination of APS vehicle and AHS concept considered in the study.

The modeling approach was central to our research methodology for the quantitative assessment of the interaction between the APS vehicle and the roadway. APS vehicle performance envelopes were developed to allow impacts to be evaluated for a range of AHS and APS configurations and parameters. Vehicle parameters considered in this analysis were: vehicle chassis and subsystem weights and volumes, type of fuel, fuel or energy storage capacity and weight, vehicle shape (drag coefficient), accessory load, cruising speed, acceleration capacity, power train configuration, engine or power source efficiency, and transmission efficiency, and, in the case of hybrid vehicles, vehicle operating mode.

Summary of Key Results

Most of the key analytical results from the study are summarized in figures ES-1 and ES-2. Figure ES-1 illustrates the relationships between the different types of driving missions and the power and energy envelopes required of the primary power and energy source(s). The example shown is for a 1814 kg (4000 lb) vehicle. The power and energy capacities for current and potential vehicle batteries are also plotted and include some of the most advanced battery concepts currently being investigated. The batteries were sized for the vehicle, based on measured or estimated battery specific power and energy and estimates of the vehicle weight and volume which could be allocated to battery storage. The driving missions that a particular battery can perform are represented by the mission descriptions falling below and to the left of the dot representing that battery.

Figure ES-2 focuses on the bottom line for the EV, illustrating the primary battery characteristics required for non-stop rural travel (241 km/150 mi) at nominal freeway speeds. The figure clearly shows that even the most advanced battery technologies fall short of meeting the specific energy (energy per unit weight of the battery) requirements. Obviously, the demand for battery performance can be reduced by sacrificing more of the vehicle payload for batteries or reducing the performance expectation of EVs, or a combination of the two approaches.

[1]The PATH PSA for Activity Area A, Urban and Rural Comparison.

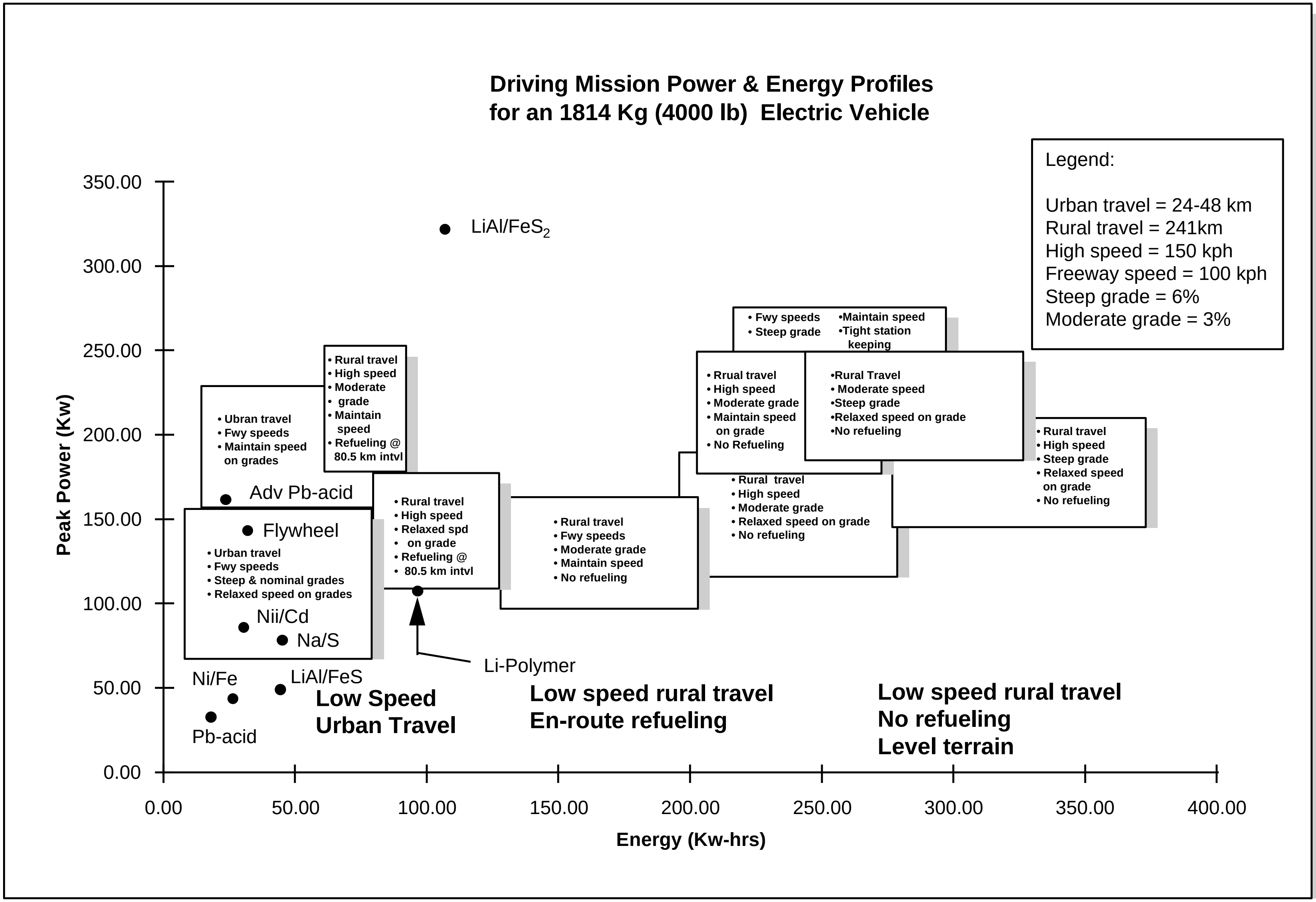

Figure ES-1. Driving Mission Power and Energy Profiles for an 1814 Kg Electric Vehicle

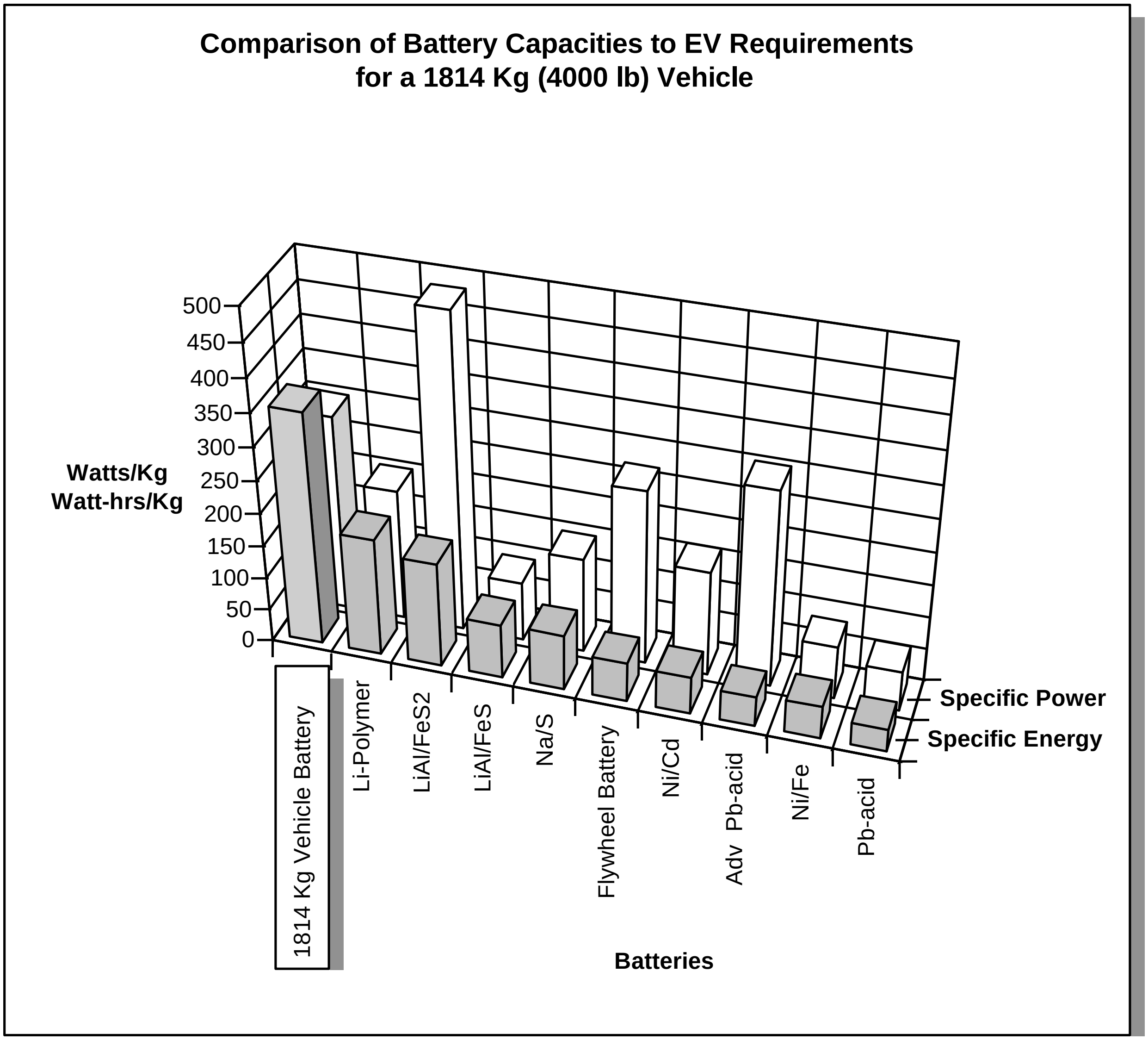

Figure ES-2. Comparison of Battery Capacities to EV Requirements for 1814 Kg Vehicle

These results, along with analyses of other types of fuels, analyses of other propulsion system concepts and more qualitative analyses pointed to the following conclusions:

- The EV will be limited to urban travel for the foreseeable future.

- The EV is not expected to significantly influence AHS in the next 20 years. The EV is expected to be a minority player into the year 2015, where we project that EVs will represent, at most 7% of the total vehicle population in the United States.

- EVs require high performance, high efficiency components. EV performance is very sensitive to the efficiency of vehicle power management and power train. In some of the driving scenarios examined, the energy requirements varied as much as 35-37% between high and low efficiency vehicle systems.

- AFVs and hybrid vehicles are inherently better suited for high-speed cruising and long haul scenarios than EVs.

- Research into current battery technology suggests that the most advanced battery technologies will yield only two to seven times the power of today's conventional lead-acid battery and two to five times the specific energy. In the initial analysis, several of these battery technologies appeared suitable for moderate rural travel, on level roadways, at today's highway speeds. However, in the final analysis these conditions are ideal and not representative of typical travel; none of the battery technologies provided the sustained power necessary to meet today's typical on-ramp accelerations demands or the power and energy to maintain high speeds over grades during rural travel.

- The results suggest that vehicles with limited on-board power and energy sources would benefit from platooning, provided station keeping maneuvers were designed for power and energy conservation. Station keeping within platoons can have a measurable cost in terms of added power required and energy consumption. The added energy consumption for typical 150 mile (241 km) trip can be on the order of 33-38%. Drafting effects within the platoon can benefit vehicles and nearly offset the added energy required for station keeping.

- Hybrid vehicles will not be feasible until advanced batteries are available with sufficient power to get the battery weight down to within 15-25% of the total vehicle weight. Hybrid vehicles with combustion engines (CEs) as primary power sources and contemporary technology batteries as secondary power boost sources were found to be impractical due to the added weight of batteries required. However, Ni/Cd, Na/S and lithium batteries promise power densities that will meet the weight and volume constraints of the hybrid.

- Flywheel batteries could provide the power densities necessary for certain hybrid vehicle designs.

- Alternative fueled vehicles (AFVs) are expected to be a more significant factor after 1998, as a result vehicle fleet purchases due to the federal Clean Air Act Amendment (CAAA) and the Energy Policy Act (EPACT) of 1992, with its tax incentives. Their performance, handling and controllability are similar enough to those of gasoline powered vehicles so that they do not pose special AHS operation or control issues. They do, however, impact the infrastructure in terms of availability of refueling stations, fuel production, handling and, to a lesser extent, vehicle maintenance.

- APSs pose special check-in problems due to their reliance on power and energy sources that are less predictable than conventional combustion engines. This factor has the potential for further reducing the EV range on automated highways, due the necessity for the AHS to apply some safety factor to the information extracted from the vehicle.

- AFVs and EVs will not provide gasoline fuel taxes. This will cause a proportionate drop in tax revenues from gasoline taxes and the public and/or commercial operations shift to alternative propulsion systems. There will need to be a means established for including these vehicles in the road tax revenue structure.

Document Organization

Section 1.0 , Introduction, provides a background and states the objectives of the study.

Section 2.0, Study Scope, describes the technical scope and rationale.

Section 3.0, APS Impact Analysis Approach, provides a discussion of the structure of the study and a description of the specific research and analysis tasks.

Section 4.0, Research Activities, discusses the research activities performed and results, focusing on the quantitative analyses of the roadway, vehicle and roadway vehicle interaction.

Section 5.0, APS Impacts, provides a qualitative discussion of the impacts of APSs in terms of issues, concerns and risks that were inferred from the quantitative analyses, surfaced during study team interaction. These results are organized into the following categories:

Section 5.1, Population Projections for APS-Powered Vehicles, discusses the market penetration of APS over the next twenty years.

Section 5.2, Impacts of APS Vehicles, discusses the potential impacts of APS vehicle introduction from the standpoints of the environment, utility infrastructure, AHS interaction, vehicle design and administrative issues.

1.0 INTRODUCTION

1.1 Background

Alternative propulsion systems cover the spectrum of automotive technologies, from conventional internal combustion engines to alternative fuels, electric propulsion, fuel cells and electrified guideways. The focus of our concern in this study is the dynamic interaction of evolving vehicle propulsion systems and Automated Highway Systems (AHSs). The target technology for the time frame considered in this study is the electric vehicle (EV). The EV is assumed to have limited introduction as a passenger vehicle over the next 10 to 25 years.

As vehicle propulsion systems transition from conventional power to the EV, requirements will be imposed on AHSs to support them. Each new generation of vehicle will most likely have some operational, performance and safety characteristics which will be unique to that class of vehicle and propulsion system. Therefore, AHS planning must not only take into account the evolution of enabling AHS technologies, but must also consider the evolution of the vehicles the AHS will be supporting.

1.2 Objectives

The primary objectives of this activity were to assess the impact of Alternative Propulsion Systems on the deployment of automated highway systems in terms of issues and risks, including; cost/benefit tradeoffs, operational and performance issues and requirements, infrastructure impacts and associated risks. The assessment of risks included the analysis of factors in selected APS technologies, their implementation, deployment and operation that may impose risks in the AHS environments considered in the study.

A secondary objective was to identify and evaluate alternative AHS configurations which would support the APSs defined in the study.

2.0 STUDY SCOPE

The study consists of a multidimensional, parametric analysis of the impact of selected alternative propulsion systems on automated highway systems. The primary dimensions defining the study environment were technology, time and competing configurations for AHSs and APSs. Within this environment the study assessed the impact of APSs on the deployment, operation and safety of AHSs. The study identified some risks and requirements imposed on AHSs by APSs over several evolutionary time frames (1990's, 2000-2009, 2010 and out). This time period was selected because it is considered likely to span much of the continuing evolution of EV battery technology. The last time frame, 2010 and out, is expected to mark the beginning of the introduction more advanced propulsion systems into the public fleet.

The study considered the characteristics and deployment of four AHS concepts and evaluated the impact of a probable APS evolutionary scenario on those concepts. These AHS approaches follow a four-step evolutionary process consisting of an initial vehicle-centered concept that is evolved in three stages to a platooning concept with intelligence distributed between the vehicle and the roadway. This combination of AHS concepts was selected for the following reasons:

(a) Each AHS concept has been researched and documented;

(b) The combination offers a broad spectrum of infrastructure impacts by considering varying degrees of vehicle control, differing performance characteristics, varied distributions of system instrumentation and complexity, from enhanced on-board intelligence to an enhanced intelligent guideway, and varying degrees of intelligence centralization, and

(c) This approach promised to surface a wide range of useful results related to system performance, deployment and safety impacts.

3.0 APS IMPACT ANALYSIS APPROACH

The study was comprised of four distinct research and analysis tasks. The tasks were to:

- Evaluate and Assess Alternative Propulsion Systems;
- Define Representative AHS Configurations;
- Perform Impact Analysis of APS on AHS;
- Postulate on Alternative AHS Configurations.

The tasks and their relationships are illustrated in figure 3-1, and are discussed in sections 3.1 through 3.4. One of the important features of the study approach was that parallel, but somewhat independent activities of APS and AHS definition, characterization and evaluation were conducted during the initial stages of the effort. This was done in an effort to maintain the objectivity of the study, and avoid the possibility of tailoring an AHS concept to a specific APS evolutionary scenario. As part of the impact analyses, the APSs and AHSs were be played together in a scenario of multiple APSs which were deployed and operated in multiple AHS environments, which were analyzed over several discrete deployment time frames.

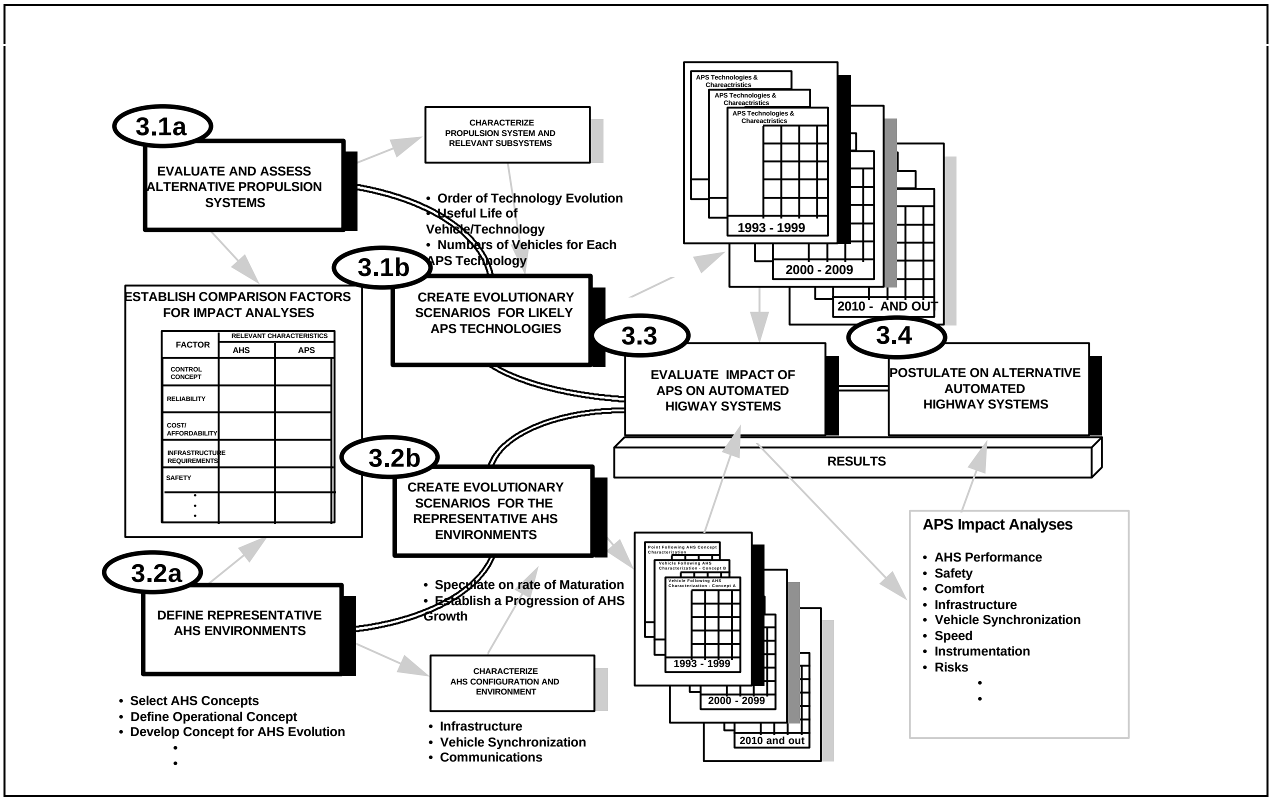

Figure 3-1. APS Impact Analysis Methodology

3.1 Evaluate and Assess Alternative Propulsion Systems

This activity consisted of a limited research of APS technologies, assessing their levels of maturity and projecting the evolution of APS technologies over the time frame established for the study. The results of this activity were used to assess the impact of APSs on AHSs (section 3.3) and to define potential alternative AHS configurations for the activity described in section 3.4. The most likely APS technologies for commercial and private vehicles were selected based on a limited research of commercial and government data and in-house research.

This portion of the study considered alternative fuels, alternative fuel vehicles, current battery technology and expected battery developments, as well as vehicle technologies and developments, such as ultra light composite body materials, regenerative braking, air conditioning and power steering. An evolutionary deployment scenario was established for the EV and battery technologies in order to examine the impact of EVs on evolving AHS capabilities.

Each of the APSs selected has been described in parametric and quantitative terms. The study defined APS characteristics, identifying likely subsystems, system efficiencies, power consumption, and energy storage requirements. These were subsequently used to evaluate system performance and function of the AHS Representative System Configurations (RSCs) defined in the activity described in section 3.2. The study has also identified malfunctions, types of failures, and provided qualitative estimates of the reliability of each APS as they were likely to impact an AHS. Performance factors such as maximum speed, acceleration and range were assessed and AHS infrastructure requirements imposed by each APS were identified.

3.2 Define Representative AHS Configurations

The study defined a mix of AHS Representative System Configurations (RSCs) which offer a range of vehicle and roadway complexities, and operational variables such as capacity, safety and speed. These are discussed in detail in section 4.1.1 and approach the definition of AHS configurations in a logical progression from an initial vehicle-centered approach and continuing with progressively more enhanced vehicle intelligence. In parallel, the guideway begins a phased development, starting with passive support features and progressing through four stages of increasing guideway intelligence into an active guideway supporting high-speed platooning.

Evolutionary timelines have been estimated for each of the representative AHS configurations, which overlap those of the APS analysis in described in section 3.1. Each of the representative AHSs was configured to meet the eight Baseline Assumptions for AHS function, operation, performance defined in the original PSA Studies request for proposal.

3.3 Perform Impact Analysis of APS on AHS

This phase of the study conducted a comparative analysis of the results of the APS and AHS definition efforts described in sections 3.1 and 3.2. The activity assessed the impacts and risks to the deployment and operation of AHSs imposed by APS vehicles. In order to provide some insight into APS-AHS interaction, as both technologies evolve, the analyses was conducted for the time intervals, 1993-1999 and 2000-2009. Additionally, the activity attempts to provide some insight into the impacts of APSs for the years 2010 and out.

AHS variables considered in the APS impact analyses included:

- AHS Check-in and Check-out configuration and procedures
- Lane configurations
- Vehicle headway
- Instrumentation and intelligence allocations among vehicles and roadway
- Driver training and ability
- State of the infrastructure
- Speeds, flows and capacities
- Urban and rural travel
- Road grade
- System safety assumptions and requirements
- State of development of AHSs and APSs at each time frame
- Vehicle mix, including conventional, low emission vehicles (LEVs), ultra-low emission vehicles (ULEVs) and zero emission vehicles (ZEVs).

3.4 Postulate on Alternative AHS Configurations

The study determined which of those issues and requirements identified in the impact analyses (section 3.3) would be essential to an AHS that both (a) supports evolving APS vehicles and (b) meets the Baseline Assumptions for an AHS stated in the RFP. These results were then used to suggest and evaluate alternative AHS configurations, deployment approaches and operational considerations necessary to support APSs.

Subsequently, several more detailed assessments were made. One analysis attempted to identify and evaluate, the AHS requirements and configuration alternatives necessary to mitigate the risks associated with individual APS technologies, and a second identified alternatives necessary for AHS operation with mixed propulsion system vehicles. The feasibility, maturity and cost/benefits of alternative AHS configurations was assessed.

4.0 RESEARCH ACTIVITIES

4.1 AHS Representative System Configurations

As discussed in the project objectives, one of initial tasks in this research activity was to develop specifications/descriptions of competing AHS configurations, or Representative System Configurations (RSCs). For consistency, the AHS Operating Mode Input Matrix[2], table 4.1-1, was used to define combinations of AHS configurations and vehicle operation and demand variables. The matrix in the figure relates RSCs to vehicle operating and demand variables. The RSCs defined in this matrix are consistent with those defined by Calspan for the PSA studies.

The matrix precludes certain combinations, such as mixed manual and AHS instrumented vehicles operating highly automated roadways. Additionally, some of the configurations identified in the matrix were considered either unsafe or unreasonable and were discarded from consideration; for example high-speed platooning with mixed heavy and single passenger vehicles, at moderate spacing was disallowed (modes 79, 87 and 95). Shaded areas in the matrix represent those cells excluded from consideration.

It was found that vehicle propulsion systems were sensitive to only one of the primary operating variables: speed. However, secondary variable considerations, such as road grade, trip length, peak acceleration requirements and on-ramp configurations have a significant impact on the evaluation of APS-AHS interaction.

4.1.1 AHS Concept Definitions

Several operating mode alternatives were developed for analysis by assessing combinations of RSCs with different operating concept variables and selecting the most likely combinations. The methods for defining the RSCs, operating and demand variables are described in this section.

Representative system configurations were specified/described in terms of the following distinguishing characteristics:

(1) Alternative Guideway Configurations. There are two concepts, one for mixed manual and AHS equipped vehicles (G1) and separate AHS lanes (G2).

(2) Alternative Instrumentation, Authority/Intelligence Distribution. Four successive stages of AHS progression were considered, each building on the earlier stage:

I1: Vehicle based system, AICC available (longitudinal control - similar to "autobrake + autogap", minor guideway sensor instrumentation. Guideway provides routing advice and emergency support.

---

[2]The AHS Operating Mode Input Matrix was developed at the Transportation Research Group at California Polytechnic State University at San Luis Obispo.

I2: Same as I1 plus guideway passive support for lateral vehicle guidance, advisories on road surface conditions and hazards, increased possible continuous video monitoring of right of way.

I3: Same as I2 plus AHS support of lane change maneuvers and overall flow coordination at a local and network level, limits to operator/driver intervention capabilities appear at this stage, entry-exit responsibility/activities increase, system steady state operation designed for AHS traffic only.

I4: Same as I4 plus platooning[3], extremely complex and critical activities in entry/exit, operator/driver intervention at the panic button level, only, very powerful guideway instrumentation, possible powered roadway and EVs.

(3) Heavy Vehicle Strategy. Another variable considered important is the possible inclusion of heavy vehicles. Two heavy vehicle strategies were added for consideration, one for mixed passenger and heavy vehicle traffic (M) and one for separate lanes for heavy vehicles (S). This combination of vehicle and instrumentation/intelligence, guideway configuration and heavy vehicle strategies yielded eight RSCs for consideration.

The four concepts for vehicle and roadway intelligence, I1 through I4, were combined with guideway concepts for lanes having mixed AHS-equipped and manual vehicles (G1) and for separate lanes for AHS-equipped vehicles, only. The mixed traffic concept, G1, was not considered in combination with the more complex AHS configurations of I3 and I4.

The Operating Variables selected were speed, vehicle spacing and travel demand. These were defined as follows:

(1) Maximum operating speed. This Operating Variable is coupled with average vehicle spacing. Two maximum operating speed options were examined, 100 and 150 kph.

(2) Vehicle spacing. Two average "spacing" alternatives were examined. The "moderate spacing" alternative is compatible with the recent longitudinal control demonstration by PATH in San Diego, which yielded an average separation of 10 meters at 34 meters/second. A "long" spacing alternative was examined which was, on the average, twice the distance of "moderate spacing".

(3) Travel demand. Three alternative travel demand scenarios were considered for each speed-spacing pair. These were "low", "moderate" and "high", representing approximately 3000 vph, 6,000 vph and 12,000 vph respectively.

---

[3]Platooning was unofficially defined at the PSA Interim Results Workshop (IRW) as "very close" spacing, on the order of a few feet, requiring inter-vehicle communications and some form of mechanical, electromagnetic or "other" entrainment to keep the vehicles in a stable formation. This definition is different from just "closer than today" vehicle spacing which can/will be achieved safely through the reduction of the reaction times and standardization of vehicle braking ability. Both have the potential to increase throughput and overall network capacity with platooning creating more dramatic changes but requiring significantly more complex system structure. Initial estimation shows that "close spacing" can achieve throughput of 3,000 to 6,000 vehicles per lane per hour, while "platooning" can achieve throughputs of over 12,000 vehicles per hour. However, both alternatives will have only moderate impact to the overall network capacity without special arrangements and modification in the entry/exit facilities. The latter is more critical as the throughput reaches several multiples of today's system lane carrying abilities.

Table 4.1.1-1. AHS Operating Mode Input Matrix

Operating & Demand Variables ↓ / Representative System Configurations (RSCs) →			Guideway Configuration: G1 (Mixed with Manual)				G2 (Separate Lanes for AHS)			
			Instrumentation, Authority/Intelligence Distribution: I1		I2		I3		I4	
Speed	Spacing	Demand	Heavy Vehicle Strategy: M	S	M	S	M	S	M	S
Moderate	Long	D1	1	2	3	4	5	6	7	8
		D2	9	10	11	12	13	14	15	16
		D3	17	18	19	20	21	22	23	24
	Moderate	D1	25	26	27	28	29	30	31	32
		D2	33	34	35	36	37	38	39	40
		D3	41	42	43	44	45	46	47	48
High	Long	D1	49	50	51	52	53	54	55	56
		D2	57	58	59	60	61	62	63	64
		D3	65	66	67	68	69	70	71	72
	Moderate	D1	73	74	75	76	77	78	79	80
		D2	81	82	83	84	85	86	87	88
		D3	89	90	91	92	93	94	95	96

Legend:

Guideway Configuration (G) G1= mixed manual and AHS equipped vehicles G2= separate lanes for AHS equipped vehicle Heavy Vehicle Strategy (M & S) S= separate lanes for heavy vehicles (large trucks & buses) M= mixed heavy and passenger vehicles	Instrumentation, Authority/Intelligence Distribution (I) I1= vehicle based system, AICC for longitudinal control, minor guideway instrumentation I2= I1 plus Guideway passive support for lateral guidance I3= I2 plus AHS lane change support, local and network supported flow control, limited driver intervention, increased entry/exit control/support, automated lanes restricted to AHS equipped vehicles I4= I3 plus platooning, complex entry/exit, driver intervention restricted to panic/emergency mode, powerful guideway instrumentation, possible roadway power
Speed Moderate= 100 kph High= 150 kph Spacing Moderate= 10 meters Long= 20 meters	Demand per lane (D) D1= 3,000 vph D2= 6,000 vph D3= 12,000 vph

4.1.2 AHS Operating Mode Descriptions

A single AHS Operating Modes is defined by a specific RSC and Operating Variable pair, which is designated by a numbered cell in the Operating Mode Input Matrix. A set of secondary variables was defined for each Operating Mode selected for analysis. These variables appear to have the most impact on APS operations.

Nineteen operating modes were selected for final evaluation. The choice of secondary variables and the alternative values they can assume (degrees of freedom for the AHS operating mode development) was guided by APS evaluation requirements, as well as the need to consider a variety of AHS concepts. Operating mode descriptions will also include the following additional elements addressing specific APS evaluation needs:

- Configurations/Rules for Mixed (with non-AHS traffic) Operation
- Vehicle Size/Weight Strategy
- AHS Lane Availability
- Maximum Grades by Grade Length
- Check-in/out Times
- Averages and Distributions of Trip Lengths
- Refueling Station Availability
- AHS Market Penetration
- On/Off Ramp Configurations
- Daily/Seasonal AHS Traffic Demand Variations

The Operating Mode Input Matrix presents the AHS in progressively more complex, advanced, and effective stages as we move from left to right and from top to bottom of the matrix. As mentioned in the Instrumentation, Authority/Intelligence Distribution (Ix) descriptions, the introduction of separate AHS lanes almost coincides with the introduction of I3. What is certain, however is that manual traffic will be highly unlikely to be allowed in stage I4. Four areas of AHS progress were evaluated, one for each Ix instrumentation stage. The exclusion/inclusion of heavy vehicles introduces an added complexity that was examined separately for each Ix. The two alternative vehicle speeds also created some variability within the same instrumentation group that was evaluated. The following four subsections describe the characteristics of the Operating Mode Groups for each stage of AHS instrumentation[4]:

Group Under I1

Operating Mode Group O_{1M}: Cells #1,9,25,33
Operating Mode Group O_{1S}: Cells #10,18,34,42

[4]Numbers in the subscript show the "I" stage to which the operating mode belongs. Subscript M denotes heavy vehicles mixed with light duty vehicles in the same traffic stream. S denotes AHS activities in lanes where heavy vehicles are not allowed. For stages I1 and I2, where manual and AHS traffic are mixed, the separation of heavy vehicles occurs through prohibition of the use of the one or two left lanes in facilities with more than two lanes in one direction. In the case of only one lane in each direction it will not be feasible to separate heavy vehicles. This limitation is likely to reduce the likelihood of high speed capabilities in rural cases where high speed is desirable. Subscript F denotes high speed (150 KPH). Spacing and demand are not shown in subscript form.

Operating Mode Group O_{1SF}: Cells #50,58,82,90

This Operating Mode Group contains configurations similar to the highway system today plus automation of the longitudinal control of the vehicle. Longitudinal control features include systems such as autobrake and autogap and/or AICC. The longitudinal control systems provide the capability to reduce the headway between vehicles and relieve the driver of tactical activities in the control of the throttle and brakes for position keeping.

Several scenarios for the staging of implementations are discussed. The most likely one supported by the latest industry developments calls for the introduction of ICC first. The ICC will be able to follow a vehicle at a fixed time or space headway with a certain maximum speed restriction and only "soft braking" capabilities. Soft braking denotes that the driver will be responsible for hard deceleration maneuvers if needed.

In the future, ICC is expected to be enhanced with a collision avoidance capability where the trail vehicle will perform the hard deceleration maneuver automatically when needed. There are some additional implicit assumptions that need to go into the calculation of the "safe" autogap. Assumptions include the vehicle speed differential and the braking capability differential between the lead and trail vehicles. System reaction time is almost universally accepted to be a few tenths of a second (0.1 to 0.3 sec.). Uncertainty in this area is the overhead that the malfunction analysis teams will include to compensate for backup system reaction time. Initial indications are that it will not be more than two tenths of a second. However, the initial question on the absolute value as well as the differential of braking capabilities between the lead and trail cars in the absence of inter-vehicle communications is a major one. Detailed analyses are needed to assess the safety boundaries for each combination of speed and braking capability in terms of minimum space or time headway. The time headway, in turn, defines the theoretically maximum system throughput capacity. The driver is still responsible for lateral control (steering) of the vehicle.

Group Under I2

Operating Mode Group O_{2M}: Cells #11,19,35
Operating Mode Group O_{2S}: Cells #20,44
Operating Mode Group O_{2SF}: Cells #52,60,92

This operating mode group includes the addition of vehicle lateral control capabilities. It is expected that initially this will be performed through tracking of markers on or within the pavement. Alternatives include magnetic and/or visual markers or reference points. Several test and working installations (for transit systems) at this stage show that lateral control is technically feasible and provides a smoother ride with more accurate tracking than manual steering. Difficulties and uncertainties arise when automatic lateral control is combined with automatic longitudinal control, even for steady state operations. Such uncertainties include the impacts of automation activity on the other; like braking and acceleration initiatives while on a turn or tracking correction; or the other way around. Another issue is that this combination of longitudinal and lateral control will be the first time that the driver is able to "retire" from all driving duties, while being required to remain alert. Such concerns gave birth to the idea of prohibiting the ability to use both longitudinal and lateral control at the same time. This initial design will permit study of both systems and their potential interaction as well as human factors assessments on the ways to ensure driver alertness. This stage is initially expected to share lanes with manual driving, which adds another level of uncertainty requiring driver alertness. Vehicle to roadway communication capabilities are recommended, but not required in this phase, and inter-vehicle communications would help reduce the traffic stream instabilities and braking capability uncertainty.

<u>Group Under I3</u>

Operating Mode Group O_{3M}: Cells #13, 37
Operating Mode Group O_{3S}: Cells #22, 46
Operating Mode Group O_{3SF}: Cells #62, 70, 94

This operating mode group introduces the integration of longitudinal and lateral control systems to the point where complete maneuvers like lane changing and merging and weaving can be performed. It is possible that by this stage the market penetration of AHS will be able to justify separation of manual and automated traffic lanes. However, the system should be able to accommodate the occasional manual vehicle introduced by error or intention. Driver ability to take control of the vehicle will begin to be restricted and reactions will be limited to standardized emergency procedures or "panic button" level alternatives. Substantial infrastructure changes will be required including the addition and/or conversion of lanes, the development of special entry/exit configurations and considerable roadside instrumentation. Roadway to vehicle communications are required and inter-vehicle communications are also highly recommend and probable at this stage for maneuver coordination.

<u>Group Under I4</u>

Operating Mode Group O_{4M}: Cells #15, 39
Operating Mode Group $O4_{MF}$: Cell #63
Operating Mode Group O_{4S}: Cells #24, 48
Operating Mode Group $O4_{SF}$: Cells #64, 72, 96

This operating mode group introduces a more advanced AHS design. Although the exact system characteristics fade in the distant implementation horizon, it appears that in cases of only one AHS dedicated lane, platoons need to be formed at the entry/exit facilities and formations kept constant during the en-route sections in the presence of high demand. At this stage high demand is assumed to be the reason for the switch from I3 to I4. In cases of more than one AHS lane, platoon switching and formation could be achieved en-route as well. Platoon joining and braking will be performed through lateral merge of vehicles rather than longitudinal control maneuvers. Presently this appears to be a "safer" design. The driver reaction alternatives at this configuration will be at the "emergency button" level only. Alternative designs call for AHS-only lanes to be designed in pairs for each direction.

The "average trip" for the "urban" AHS system is a home-to-work trip of 15 miles each way, requiring approximately 30 minutes. Such trips are responsible for about half the vehicle miles in most urban environments and represent about one fourth to one third of the total number of trips.

Non-home-to-work trips are greater in number but are usually shorter and unlikely to be impacted by the introduction of AHS, at least in the initial stages. A high end (approximately 90th percentile) home-to-work trip of 30 miles was also considered. The "average" rural trip today is assumed to be inter-city travel of 150 miles at an average speed similar to "moderate" AHS speed (100 KPH). In the G1 configurations of mixed traffic, entry/exit facilities are assume to be similar to what the freeway system has today. In the G2 configurations entry/exit facilities are assumed to be spaced every two miles in the urban areas and every ten miles in the rural areas.

4.1.2.1 AHS Operating Mode Inputs to APS Analyses

A shorthand notation is used to characterize the operating modes. Trips are either urban (U) or rural (R). Urban trips are either of average length (U_a = 15 miles or 24 kilometers) or long (U_l = 30 miles or 48 kilometers). Rural trips are 150 miles (241 km) in length. Grades (G) are described in terms of their slope and length. Grades are either long (G_l = 6% grade for 2 miles, or 3.2 kilometers) or short (G_s = 3% for 1 mile or 1.6 kilometers).

<u>1. Operating Mode #9$U_a G_l$</u>

This operating mode has all of the above mentioned characteristics for the I1 group. Longitudinal accelerations and decelerations for position keeping are on the order of a maximum of 0.2g at 100 KPH (mixing with trucks and manual traffic), with average accelerations are on the order of 0.05g. Position keeping accelerations at higher speeds are on the order of .1g, with average accelerations of 0.025g. A grade of six percent grade and two miles long was considered. The average speed over the grade was assumed to be 60 KPH, although the average speed for level travel is 100 KPH. Trip length was assumed to be 15 miles (U_a). Check-in/out time at the ends of the ramps was assumed to be on the order of 30 seconds. On-ramp profiles were in accordance with current profiles measured on different California freeways during the recent project by Cal Poly.

System entries and exits were assumed to be spaced at two mile (3.2 km) intervals.

<u>2. Operating Mode #9$U_a G_s$</u>. Same as above, but grade is 1 mile (1.6 km) at 3 percent.

<u>3. Operating Mode #9$U_l G_s$</u>. Same as above but trip is 30 miles long (4.8 km).

<u>4. Operating Mode #9$U_l G_l$</u>. Same as above but grade is 2 miles (3.2 km) at 6 percent.

<u>5. Operating Mode #10$U_l G_l$</u>. Same as above but speeds do not drop over grade.

<u>6. Operating Mode #10U_aGl.</u> Same as above, but trip is 15 miles (24 km).

<u>7. Operating Mode #20RG_l.</u> This group is within AHS stage I2. All baseline inputs are the same as above, but this mode considers a rural trip of 150 miles (241.4 km) and assumes refueling availability every 50 miles (80.5 km).

<u>8. Operating Mode #11RG_l.</u> Same as above, but speed over grade is 60 kph (37.3 mph)

<u>9. Operating Mode #60RG$_l$</u>. Same as above but speeds over grade are at 100 kph (62 mph) and top speed is 150 kph (93 mph).

<u>10. Operating Mode #60RG$_S$</u>. Same as above but grade is 1 mile (1.6 km) at 3 percent.

<u>11. Operating Mode #52RG$_S$</u>. Same as above but speeds are not reduced over grades.

<u>12. Operating Mode #46U$_a$G$_l$</u>. The remaining operating modes all have I3 AHS characteristics. Longitudinal accelerations and decelerations for position keeping will be in accordance with the values observed during the San Diego test performed by PATH and will be on the order of 0.1g. A grade of 6 percent and 2 miles (3.2 km) in length should be considered part of the trip (G - long, mode indicator). Trip length should be assumed to be 15 miles (24.1 km) (U - average, indicator after the mode number). Check-in/out time at the ends of the ramps should be assumed to be on the order of 30 seconds. On-ramp speed profiles should be in accordance with current profiles measured in different California Freeway during a recent project by Cal Poly. System entries and exits will be spaced at 2 miles (3.2 km) intervals.

<u>13. Operating Mode #46U$_a$G$_S$</u>. Same as above but grade is 3 percent and one mile (1.6 km) long.

<u>14. Operating Mode #46U$_l$G$_S$</u>. Same as above but trip length is 30 miles (48.3 km).

<u>15. Operating Mode #46U$_l$G$_l$</u>. Same as above but grade is 6 percent and two miles (3.2 km) long.

<u>16. Operating Mode #94U$_l$G$_S$</u>. Same as above but speed is high at 150 kph (92 mph), and grade is 3 percent and one mile (1.6 km) long.

<u>17. Operating Mode #94RG$_S$</u>. Same as above but trip is 150 miles (241.4 km) long, with refueling availability every 50 miles (80.5 km).

<u>18. Operating Mode #46RG$_S$</u>. Same as above but speed is moderate at 100 kph (62 mph).

<u>19. Operating Mode #46RG$_l$</u>. Same as above but grade is at 6 percent and 2 miles (3.2 km) long.

Note: Stage I4 is expected to be very similar to I3 as far as characteristics that influence propulsion systems. One possible influence could be that because of the increased capital required to move from I3 to I4 it could become feasible to provide an electrified guideway which would solve the energy starvation problems that this analysis is highlighting.

In section 4.3 we evaluate APS performance in the AHS environment using the operating modes described above. However, in order to effectively assess APS sensitivities to individual roadway and driving mission factors, additional operating modes have been added which are subsets to those defined above. This resulted in a total of thirty-eight individual modes that were analyzed. Each of the modes in 7 through 11 above were separated into two modes, one with no refueling and a second with refueling stations at designated intervals. Similarly, each of the modes 12 through 19, above, have been partitioned into four modes; one mode with the vehicle operating independently with no refueling, a second independent operating mode, but with refueling, a third mode with platooning and no refueling, and a final mode that combines refueling and platooning.

4.1.3 Possible Evolutionary Concept for AHS

One possible evolutionary AHS growth model is illustrated Table 4.1.3-1. This approach reflects a likely economic scenario in which much of the initial burden of AHS cost will be placed on the individual user, through added vehicle costs incurred by AHS-related functions and features. However, as the infrastructure builds up and usage increases, the cost of AHS is shifted to the public sector. This concept is also consistent with public safety objectives, in that safety of automated highway travel becomes increasingly more observable and controllable through the centralization of vehicle monitoring and control.

1993 - 2004. The timeline begins with implementation of a vehicle-based system featuring longitudinal control based on an AICC concept and minor guideway sensor instrumentation. The guideway also provides advanced traveler information, such as routing advice and emergency support. This concept allows for a mixture of AHS-equipped and non-equipped vehicles. There is no supporting highway infrastructure in place at this point. It is expected that, during this period, the emphasis of AHS implementations would be on vehicle on-board systems which allow mixed traffic.

2005-2014. The assumptions made for this stage of AHS development are even more subjective than those for the prior phase, and were made in order to construct an environment in which for the assessment the impact of mixed AHS and non-AHS vehicles on automated highways. During this stage it is assumed that as the infrastructure begins to build up, additional roadway intelligence is added to allow mixed AHS and non-AHS equipped vehicles to operate on the same AHS roadway. The guideway is providing lateral guidance support to equipped vehicles. It is anticipated in this scenario that there would be a spacing penalty for the AHS-equipped vehicles, due to the combination of added lateral control feature in the presence of non-instrumented vehicles. At the present time, the combination of longitudinal and lateral control are considered technical challenges. An additional penalty in allowing non-AHS vehicles on the AHS is that there is no increase in average vehicle speed at this stage of AHS evolution.

During this time frame the goal of further infrastructure development is to enhance system performance, in terms of speed and capacity. The infrastructure becomes more mature with proliferation of instrumented roadways and AHS equipped vehicles.

During the latter part of this period it is assumed that the number of AHS-equipped vehicles begins to grow significantly, justifying increased investment in guideway intelligence. This scenario calls for increased infrastructure support of lane change maneuvers, flow coordination and entry/exit responsibilities.

2015 - 2024. During this stage the volume of demand for AHS access becomes sufficient to economically justify separate right-of-ways for AHS vehicles. With the latter comes improved vehicle speed the capability for closer vehicle spacing and the advent of platooning. Non-AHS vehicles, including large commercial vehicles operate on lanes and roadways dedicated to mixed vehicles, which may include AHS-capable vehicles. The evolutionary model allows for the co-existence of several AHS concepts, including an enhanced platooning concept with enhanced roadway intelligence.

The likelihood of two AHS system configurations existing concurrently, and in use by the same driving population is arguable, however, the concept is included for its potential to cause greater variability in the APS impact analyses. Another reason for including both concepts is that one is better suited for urban environments, while the other makes sense for inter-city travel where platooning is either unnecessary or undesirable.

The study makes some assumptions about the interoperability between I3 and I4; (a) Vehicles instrumented to operate in an I4 environment will be capable of operating in I3, however (b) vehicles instrumented solely for I3 will not be capable of operating in an I4 environment. The premise for (a) is the assumption that both concepts include intelligent roadways with vehicle-to-roadway communications and that inclusion of I3 functions in I4 equipment is a reasonable and cost-effective extension. The premise for (b) is that vehicles instrumented only for I3 do not have the inter-vehicle communications necessary for I4 operation.

It is expected that, during this period, the AHS infrastructure would begin to build to a point at which some AHS facilities would incorporate enhancements to roadway intelligence that would:

(a) Provide the capacity to sense the presence and location of a vehicle on the roadway,

(b) Discriminate between instrumented vehicles and non-AHS traffic vehicles, and

(c) Reduce the complexity of on-vehicle AHS systems.

4.2 APS Vehicle Research

APS Research and Analysis Approach

The process used to conduct APS research and analysis is illustrated in Figure 4.2-1. This process starts with development of AHS-dependent vehicle performance requirements which are derived from PATH studies. These requirements define the average trip distance, road grade, hill climb and in the case of platooning, vehicle station keeping. The latter would be required of the APS operating on an automated highway. These vehicle requirements are subsequently converted to wheel power and energy requirements which are expressed as functions of vehicle weight and aerodynamic drag and rolling friction.

The vehicle road power and energy data, together with selected APS power train concepts and subsystem characteristics, were used to estimate peak engine power and fuel capacity for each vehicle concept. This was accomplished by means of a process that traced the power flow and estimates power losses through the vehicle power train subsystem, from the driving wheels back up to the primary propulsion energy source. Subsequently, APS subsystem performance requirements, such as peak power levels and required power-level durations were derived for each APS-AHS concept combination. The study carried through with these same analyses for conventional internal combustion-powered vehicles to provide a comparative baseline.

Performance requirements were used to estimate vehicle subsystem physical characteristics, such as weight and packaging volume. A complete vehicle was synthesized for each APS concept, taking into account vehicle factors, such as structure, occupancy and cargo capacity. The resultant APS vehicle is then compared to the baselined conventional vehicle that it would be replacing to assess the viability of the APS. This analysis includes penalties of the APS in terms of: loss in performance due to increased vehicle weight, and reduced passenger or cargo capacity.

The viability analysis then addresses three APS impact areas; operability, technology and infrastructure. Operability relates to how the APS fits within the driver's and AHS modes of operation, such as check-in requirements, road handling, and instrumentation and displays. Technology needs refers to the prioritized improvement in subsystem performance that is needed to bring the APS vehicle up to acceptable conventional vehicle performance. Infrastructure impacts and requirements addresses APS-specific issues, in particular, the support infrastructure required to fuel and service the APS vehicles.

4.2.1 APS Vehicle Selection

<u>Potential APS Power Systems</u>

Figures 4.2.1-1 illustrates the family of possible power systems for vehicle propulsion. Vehicular primary energy sources can be classified into those in which the energy source is stored on board the vehicle and those in which primary energy is supplied from an external source, without the need for storage. The latter category includes all systems in which energy is transferred from some fixed guideway transmitter installation to the vehicle. Generally, these external energy transfers are made through direct contact, as in a "third rail", or non-contact transfer, such as inductive coupling.

AHS Concept Variables		**Automated Highway System Evolutionary Concept**						
		Evolutionary Time frame						
Variable	**Value**	**1993-1999**	**2000-2004**	**2005-2009**	**2010-2014**	**2015-2019**	**2020-2024**	**2025-?**
Authority/Intelligence Distribution								
I_1	Vehicle-based System/Minor Guideway Sensor Instrumentation	●	●					
I_2	Guideway Passive Support for Lateral Maneuvers			●	●			
I_3	Enhanced Guideway Support of Lane Change, Flow Coordination, Entry/Exit Control				●	●		
I_4	Enhanced Guideway Intelligence/Platooning						●	●
Vehicle Speed								
S_1	100 Kilometers/Hour	●	●	●				
S_2	150 Kilometers/Hour				●	●	●	●
Inter-Vehicle Spacing								
Mod	10 Meters	●	●			●	●	●
Long	20 Meters			●	●			
Guideway Configuration								
G_1	Mixed with non AHS Traffic	●	●	●	●			
G_2	Separate AHS right-of-way					●	●	●
Evolutionary Time frame		**1993-1999**	**2000-2004**	**2005-2009**	**2010-2014**	**2015-2019**	**2020-2024**	**2025-?**

Figure 4.1.3-1. Possible AHS Evolutionary Timeline

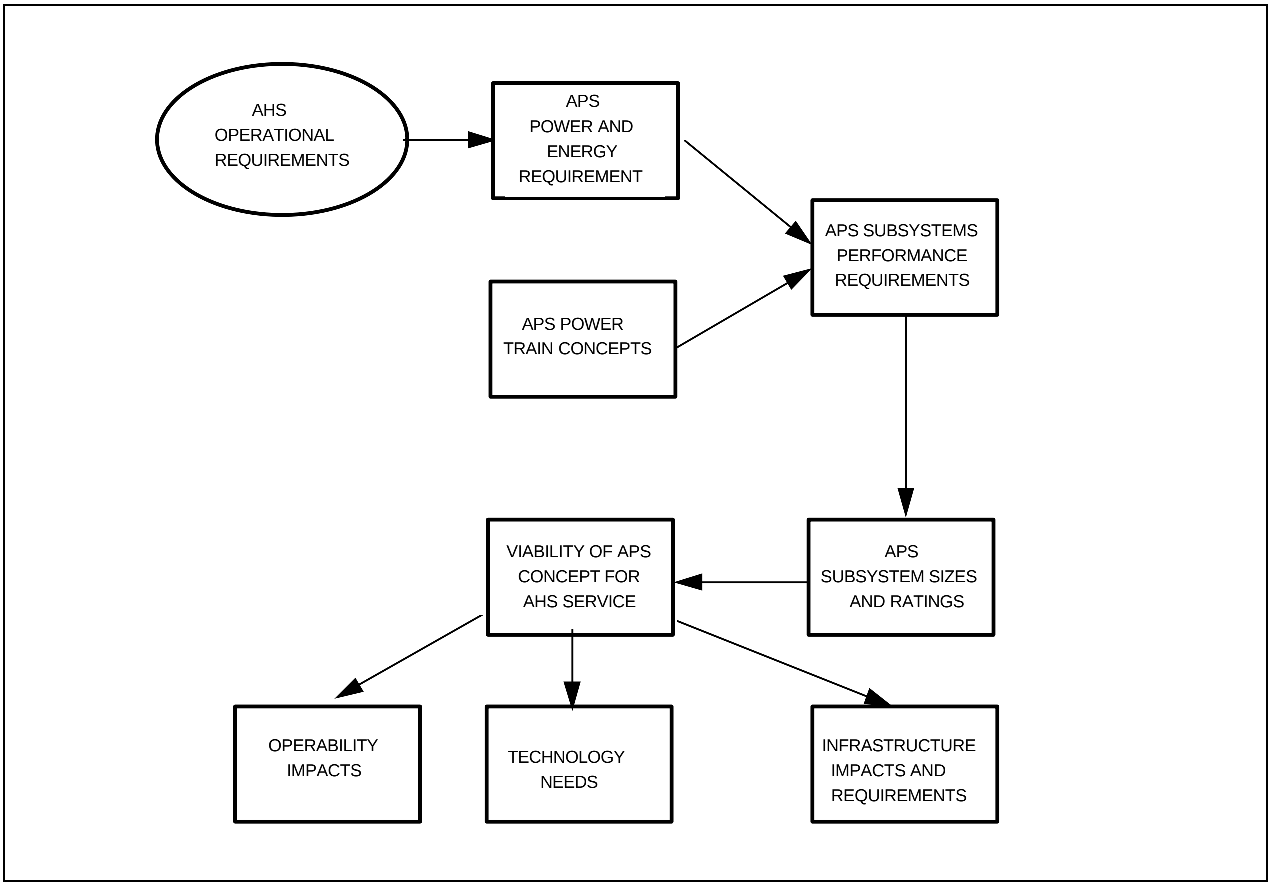

Figure 4.2-1. APS Research and Analysis Approach

Heat Engines. On-board energy sources include systems in which the primary energy is stored as chemical potential and then is transformed into thermal energy for subsequent use in a thermodynamic heat engine cycle. The thermal energy can be added "externally", as in quasi-Carnot (Stirling) or vapor expansion (Rankine) engines, or "internally", as in spark ignition (Otto), compression ignition (Diesel), or turbine (Brayton) engines. The fuel of choice for each of these heat engines is variable, and depends on considerations of flammability and combustion characteristics, as well as factors such as fuel storability, cost and availability. Historically, liquid petroleum products have been the fuel of choice for internal combustion engines, while external combustion engines, with their broader tolerance to combustion characteristics have been and are fueled with a wide range of materials ranging from wood and peat, through coal and bunker grade boiler oils and other distillates.

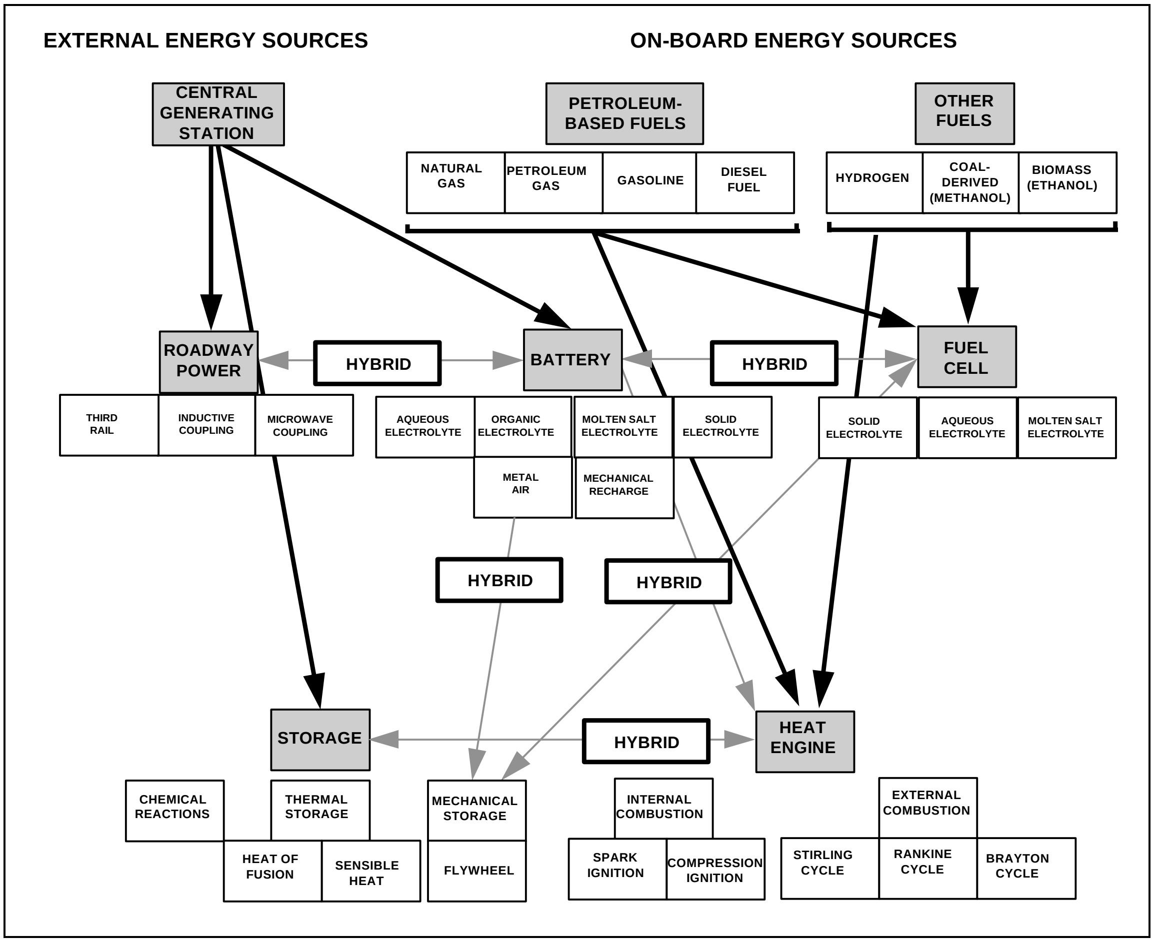

Figure 4.2.1-1. Family of Possible Vehicle Propulsion Systems

Fuel cells. Fuel cells and batteries represent systems wherein the primary energy is stored as chemical energy, but is transformed into thermodynamic work through electrochemical processes. The transformation does not generally impose high temperatures and pressures; factors which lead to the materials and emission problems associated with many heat engines. Fuel cells differ from batteries in that they are rechargeable through the addition of fresh fuels, and in most cases, require the removal of spent chemical products. Since recharging is accomplished through fuel replenishment, the "charging range" is limited only by the transfer rate of fresh reactants into the fuel cell. Most contemporary fuel cells require hydrogen, and complex hydrocarbon reformers are needed to create that fuel on board.

Batteries. Batteries are generally regarded as being rechargeable by reversal of the electrochemical conversion process, that is, electrical energy is used to transform reaction products back into fresh reactants. These types of systems are called secondary batteries. (Primary batteries are those in which the battery reactants are not electrically recharged, and the re-conversion of products back into reactants is done by other means, such as physical replacement of materials). Discharging and charging electrochemical reactions almost always involves undesirable side reactions, such as corrosion or poor specie distributions (dendrite formation) leading to finite battery cycle life.

A primary driver for consideration of secondary batteries as vehicle energy sources is that the base energy source, that is, the supplier of electrical energy for recharging, lies in the electrical power generating station, be it founded on petroleum, natural gas, coal, hydropower, nuclear, geothermal, wind or solar sources. This wide range of central generating sources reduces the consumption of petroleum for transportation purposes, and offers environmental pollution reduction through the substitution of non-polluting transportation energy sources and/or more readily controlled centralized stationary emission sources.

Hybrid Systems. There are hybrid electrochemical systems possessing both battery and fuel cell characteristics. For example, a hybrid system could be composed of an electrochemical system using oxygen from the air as the fuel cell oxidant, coupled with a reducing fuel, such as a reactive metal like magnesium.

Energy may also be stored as mechanical energy, through the use of flywheels and compressed gas, or as thermal energy in the form of sensible heat, or change of phase heat. Mechanical systems have the advantages of extremely high cycle life and charge/discharge rates. Thermal systems typically have low energy densities and suffer Carnot inefficiencies when transformed into mechanical work.

Figures 4.2.1-1 also shows that numerous hybrid systems are possible, with various combinations of onboard and external energy sources. In each case the conceptual hybrid system seeks to avoid the problems associated with a single energy source by augmenting it with beneficial characteristics of other energy systems. For example, combining fuel cells with batteries gives the high energy density and thus extended vehicle range associated with the chemical potential of fuel cell reactants, coupled with the benefit of rapid refueling. Batteries offer the high power-density needed for vehicle acceleration that is lacking in fuel cells. Similarly, heat engine-based hybrids relax many of the demands on heat engine drivability which tend to contribute to reduced fuel economy and increased emissions, while retaining the range and convenience of operation of contemporary vehicles. The secondary energy source, be it electrochemical or mechanical, provides power boost.

APS Selection Rationale

The research team conducted a review of possible APS combinations, as well as the most likely embodiments within the time frame of this study. Subsequently, due to the large number of possible combinations and specific implementations, it chose to focus the AHS impact analyses on a reduced set of APS configurations. This subset of possible APS configurations was selected based their of appraisal of the development status APSs and an assessment of the probability of new successes in the future.

It was recognized that the introduction and acceptance of any APS will be evolutionary, rather than revolutionary, and that the number of APS vehicles which might appear to have an impact on AHS, will be limited to those having, in the judgment of the researchers, the highest probability of near-term introduction. Sections 4.2.2 and 4.2.3 present analyses of candidate APSs which are based upon this line of reasoning. Subsequent analyses, presented later in this report, return to examine some of the other APS configurations and embodiments to provide an understanding of what technical and infrastructure hurdles would have to be overcome for their introduction.

One of the research team's early findings was that, through the next 30 year period, the reciprocating, internal combustion engine (ICE) most likely will continue to dominate the passenger and light weight fleet vehicle market. The ICE will continue to be refined, driven by increased pressure to reduce emissions and fuel consumption. Part of these objectives will be satisfied through refinements in other portions of the vehicle through the use of better aerodynamic design, higher specific strength materials, and general downsizing of the vehicles themselves.

Fuel substitution and emission reduction goals will cause moderate shifts toward natural gas, and coal- and bio-mass-derived fuels, such as methanol and ethanol. The rates of their introduction will ultimately be driven by geo-political issues and the realization that a petroleum-based transportation system is an unwise use of a limited natural resource.

While contemporary battery systems do not possess the necessary range for contemporary conventional vehicle substitution, it was assumed that over the period considered for this analyses, advancements will be made sufficient to overcome that short coming. However, the rate of introduction will be small in comparison with the total vehicle population.

Hybrid systems involving heat engines and mechanical or chemical storage subsystems appear to be an attractive pathway toward eventual transition to transportation energy supplied by central electrical generating stations, as discussed earlier. Hybrids allow the development of the major electrical subsystems which eventually would be incorporated into pure electrically propelled vehicles, and would pave the way for much of the support and service infrastructure that electric vehicles will require. In most cases hybrids would derive benefits from progress in ICE technology, as well.

For the above reasons, the study team chose to focus the research on three categories of APSs.

(1) ICE with non-petroleum fuels. This first category examines conventional internal combustion engine vehicles that are modified to operate with non-petroleum-derived fuels. In particular, we are attracted to natural gas as a substitution fuel, since a major portion of the fuel distribution infrastructure is in place, and the engine systems conversion technology from gasoline is well-understood. Natural gas also has advantages in cleaner combustion products, and reduced engine wear. On board storage of natural gas is the drawback, due to the reduced energy per unit volume when compared to gasoline, and the weight and packaging considerations for natural gas tankage.

(2) APSs with on-board batteries. The second category is an electric APS with on-board batteries supplying motive power and energy. For this study, we have established near-term lead acid batteries as the baseline for an electric APS. We recognize that this electrochemical system may not provide the total solution for a viable electric vehicle, however the other power train subsystems for this vehicle would change little with the further advancement of battery technology. Furthermore, there

have been sufficient lead acid battery vehicle demonstrations to form a good baseline for evaluating future battery technology improvements.

(3) ICE/battery hybrid APS. In this type of system the heat engine provides energy for vehicle range and the battery provides peak power for acceleration.

As a variant of the electrochemical energy storage, we believe the use of a flywheel for energy storage is worth considering, since the flywheel, by itself, eliminates much of the power and cycle life limitations near-term batteries might suffer in hybrid use.

4.2.2 APS Vehicle Analysis

APS Vehicle Baseline.

As discussed earlier, today's internal combustion engine powered vehicle was the baseline for APS comparative analysis. It was also assumed that the ICE vehicle would dominate the nation's roads well into the next century. Using the evolutionary history of the ICE-powered vehicle over the last 25-50 years as the model for the future, it was reasonable to assume that ICE technology progress will continue, and that the ICE will be steadily refined toward lighter weight, higher efficiency, lower emissions, and multi-fuel capability. It is obvious that any of the APS systems which incorporate ICEs will benefit from that progress, and that analyses of the substitution of any APS for today's ICE must recognize that the substitution will be done against the more technologically advanced, and better performing ICEs of the future.

Trends in vehicle design include lighter weight, higher strength structures and suspensions systems. There will be continuous improvement in vehicle systems: in occupant protection through better crash management and passenger safety systems, and in crash prevention through more sophisticated driver warning and collision avoidance systems. All of these improvements will be incorporated into APS-powered vehicles.

For the purposes of this research, several categories of vehicles were considered. The broadest was the passenger vehicle. The research team chose three curb weight passenger vehicles - 2000, 3000 and 4000 pounds, which span the range of weights for contemporary vehicles. A lower-end weight, light-duty commercial vehicle, around 6000 pounds curb weight, was also examined in order to provide representation for today's van and light delivery vehicles. In addition, this category was included because it is highly likely that APS vehicles will find initial acceptance among fleet operators, such as the gas and electric utilities, postal service, and vehicles serving homes and small businesses.

The weight budgets for contemporary automobiles is shown in figure 4.2.2-1[5]. The weights are shown for three weight classes of cars which correspond to a compact, a sedan and a luxury sedan respectively. The table presents component weight profiles for contemporary vehicles. These

[5]These allocations were made following discussions with members of TRW's Automotive staff and their contacts at several U.S. automobile manufacturers.

figures were subsequently used to determine specific components and weights that could be swapped out for APS components.

Table 4.2.2-1. Contemporary Vehicle Weight Budgets

Vehicle Subsystem	Weight Allowances for vehicles					
	907 kg (2000 lb) Vehicle		1360 kg (3000 lb) Vehicle		1814 kg (4000 lb) Vehicle	
	Weight in kg (lb)	% Total Weight	Weight in kg (lb)	% Total Weight	Weight in kg (lb)	% Total Weight
Suspension	**Suspension = 15% to 17.5%**					
Front Suspension	90.7	10.0%	136.1	10.0%	181.4	10.0%
Rear Suspension	45.4	5.0%	90.7	6.7%	136.1	7.5%
Body	**Body = 40% to 50%**					
Stripped Body	226.8	25.0%	272.1	20.0%	317.5	17.5%
Doors & Fenders	90.7	10.0%	136.1	10.0%	181.4	10.0%
Interior & Trim	136.1	15.0%	181.4	13.3%	226.8	12.5%
Power Train	**Power Train =28.3% to 35.8%**					
Transmission	45.4	5.0%	68.0	5.0%	113.4	6.3%
Drive Axles	22.7	2.5%	22.7	1.7%	36.3	2.0%
Engine	188.2	20.8%	362.9	26.7%	499.0	27.5%
Other Systems	**Other Systems = 3.63% to 3.75%**					
Exhaust System	9.1	1.0%	13.6	1.0%	18.1	1.0%
Cooling System	6.8	0.7%	9.1	0.7%	11.3	0.6%
Fuel Tank	9.1	1.0%	13.6	1.0%	18.1	1.0%
Wiring Harnesses	9.1	1.0%	13.6	1.0%	18.1	1.0%
Fluids	**Fluids = 3.00% to 3.13%**					
Fluids	27.2	3.0%	40.8	3.0%	56.7	3.1%
Totals	907.3	100.0%	1,360.9	100.0%	1,814.2	100.0%

The contemporary vehicle is getting lighter. The power train and the body, however, are not expected get any lighter in the near future. The power train has been lightened as much as possible and the body will continue to be made of steel for safety reasons. Steel absorbs more energy than either plastics or aluminum. The above weights will be used to determine the maximum allowable weight that can be used for alternative propulsion systems and alternative fuels for combustion engines.

The portions of the contemporary vehicle that can be removed for alternative propulsion systems and the corresponding weight are shown in table 4.2.2-2.

Table 4.2.2-2. Replaceable Components and Weights for Contemporary Vehicles

	2000 lb. Vehicle		3000 lb. Vehicle		4000 lb. Vehicle	
	Weight in kgs	% Total Weight	Weight in kgs	% Total Weight	Weight in kgs	% Total Weight
Transmission	45.35	5.00%	68.03	5.00%	113.38	6.25%
Drive Axles	18.14	2.00%	22.68	1.67%	36.28	2.00%
Engine	181.41	20.00%	340.14	25.01%	453.51	25.00%
Exhaust System	9.07	1.00%	13.61	1.00%	18.14	1.00%
Cooling System	6.80	0.75%	9.07	0.67%	11.34	0.63%
Fuel Tank	9.07	1.00%	13.61	1.00%	18.14	1.00%
Wiring Harnesses	6.80	0.75%	13.61	1.00%	18.14	1.00%
Fluids	40.82	4.50%	63.49	4.67%	102.04	5.63%
Totals	292.52	32.25%	507.94	37.35%	716.55	39.50%

Alternate Propulsion Systems can make use of 32.3% to 39.5% of car weight currently used by ICE-related components

Shaded portions may be replaced by alternative propulsion system components

The shaded areas in the table highlight the portions of contemporary vehicles in several weight classes that can be removed and replaced with another propulsion system. The remaining portions of the vehicle must remain the same for passenger comfort and to provide storage space. These data, along with APS component statistics for different vehicle weight classes were used later in the APS requirements analyses to establish propulsion system and energy storage device weight and volume sizing budgets for each weight class, for each APS concept.

Vehicle Performance Models

All road vehicles consume energy in order to overcome aerodynamic drag and rolling drag associated with tire flexure, to accelerate, and to climb grades. Aerodynamic resistance is a function of vehicle frontal area and the vehicle drag coefficient. The latter is dependent on the shape factor of the vehicle and the smoothness by which air passes about the vehicle. Road power required to overcome aerodynamic drag varies as the cube of vehicle speed.

Rolling drag is primarily dependent on tire design, construction and inflation pressure. Lower tire profile and radial construction, both introduced during the last decades, have reduced this form of drag. To a first order approximation, rolling drag power is directly proportional to vehicle weight and speed. (Note that tire flexure patterns vary with road speed, introducing second order power corrections. Also, steering forces distort the tire contact area and load distribution resulting in changes to tire rolling drag coefficients. It was assumed that these corrections to the basic tire drag model are sufficiently small to be neglected, particularly in view of the more coarse power train performance characteristics used in analyzing the APSs.)

Acceleration power is the rate at which a vehicle's kinetic energy increases. It is directly proportional to vehicle mass, acceleration rate and vehicle velocity. Hill climb power is that required to move the vehicle against gravity. It is proportional to the weight of the vehicle, the sine of the grade angle, and the speed on the grade. The resulting road load power for any vehicle may be approximated by the relationship shown in figure 4.2.2-1.

$$\mathbf{RdHp} = \underbrace{6.85\times10^{-6}(C_dA)V^3}_{\text{(aerodynamic drag)}} + \underbrace{4\times10^{-5}VW}_{\text{(tire \& rolling friction)}} + \underbrace{8.27\times10^{-5}VaW}_{\text{(acceleration)}} + \underbrace{2.67\times10^{-3}VW\sin\theta}_{\text{(hill climb)}}$$

RdHp	= road horsepower
C_dA	= product of the aerodynamic drag and frontal area (square feet) of the vehicle.
V	= velocity of the vehicle (mph)
W	= weight of the vehicle in pounds
a	= acceleration of the vehicle in ft/sec^2
θ	= grade angle

Figure 4.2.2-1. Simplified Vehicle Power Requirements

The energy required for a specific AHS scenario is computed as the sum of the energies required for each leg of the scenario, where a leg represents a distance traveled at constant power. This is shown in the relationship below:

$$\textbf{Energy Required} = \sum_{i=1}^{n} \mathbf{RdHp_i \bullet T_i}\,,$$

where i represents the ith leg traveled at constant power $RdHp_i$, T_i is the time to complete the ith leg, and n is the number of distinct legs traveled.

Vehicle Power Train Models

For this study, three APS power trains were selected for analysis:

1. A heat engine ICE, driving through an automatic transmission representative of the Figure 4.2.2-2 paths from On Board Energy Sources to Heat Engine;
2. A battery powered electric vehicle. Figure 4.2.2-3 represents the Central Generating Station to Batteries path;
3. Battery - Heat Engine Hybrid. Two models for hybrids are illustrated in figures 4.2.2-4 and 4.2.2-5.

The study has not included fuel cells since their near-term technology involves relatively bulky hydrocarbon reformer and post-reformer treatment equipment to produce on board hydrogen for use in the fuel cells themselves. The attendant weight and volume penalties suggest fuel cell technology is more appropriate to larger buses and trucks, in which the fuel cell might compete more favorably with large diesel engines. (Cryogenic hydrogen or metallic hydride hydrogen storage also appears to place a very heavy burden on the fuel distribution infrastructure and on-vehicle storage.)

We also carry consideration of flywheel energy storage within the context of both heat engine-flywheel hybrids, and battery-flywheel hybrids. Flywheels have attraction in their potential for extremely high rates of charge and discharge, and very high cycle lifetimes.

The study includes guideway powered systems. The guideway powered vehicle behaves in the same manner as a hybrid on the guideway. A secondary source of energy, heat engine or battery, would be needed for off-guideway operation. While on the guideway, the propulsion system will resemble much of a pure battery-powered vehicle, or a heat engine hybrid with the hybrid's engine-driven generator replacing the guideway pick-up source.

Systems employing thermal storage were rejected due to their inherently low, Carnot-limited heat conversion efficiency. External combustion engines were also rejected. Rankine systems require volume-consuming vapor generators and radiators; Stirling machines, while possessing high conversion efficiency, are large, heavy and have yet to demonstrate viable service lifetimes.

Brayton (gas turbine) systems might be attractive some time in the future when used within a hybrid system. Their multi-fuel capabilities are attractive, but NOx control is difficult. Hybridization would reduce much of the part load/part speed fuel and emission penalties of gas turbines. However, given the choice of a rational pathway to an all-electric transportation system in the future, it appears more realistic to stay with the ICE, rather than introduce another system which, in our view, may have limited usefulness for the class of vehicles being considered for AHS operation.

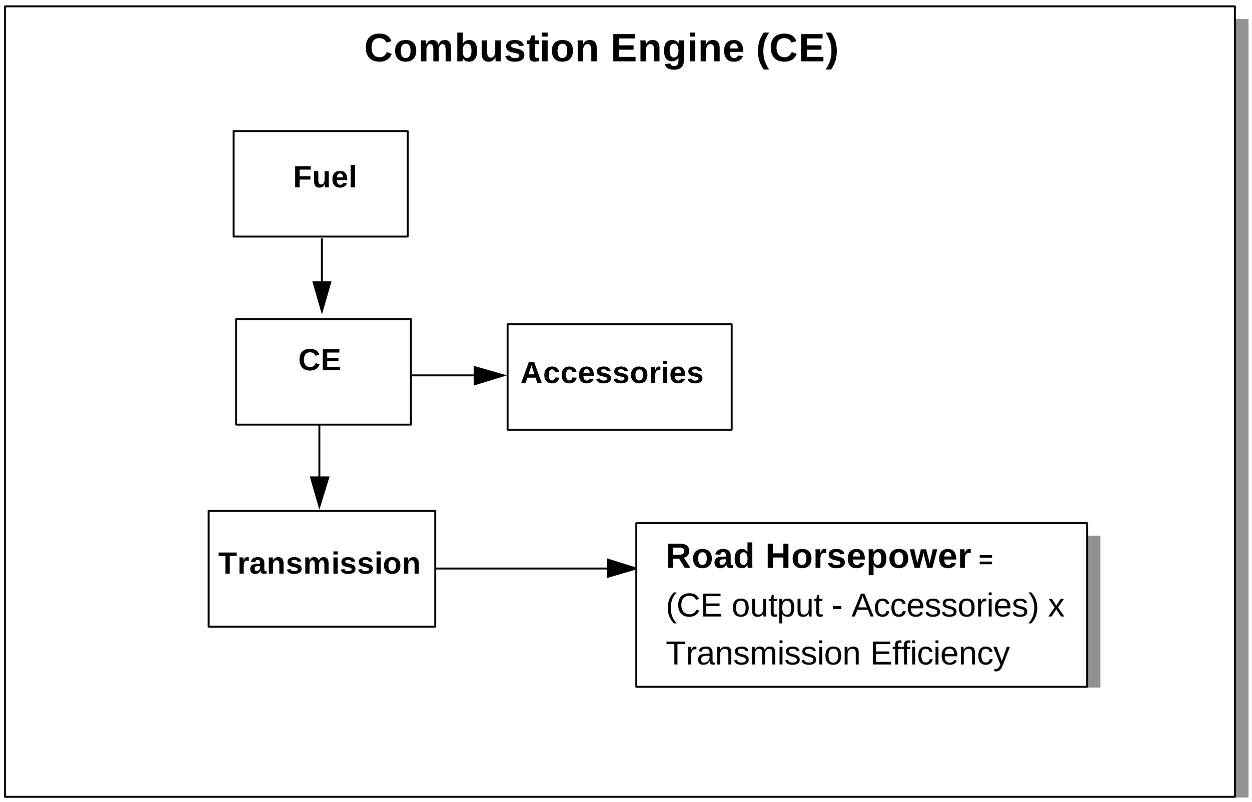

Figure 4.2.2-2. Combustion Engine Model

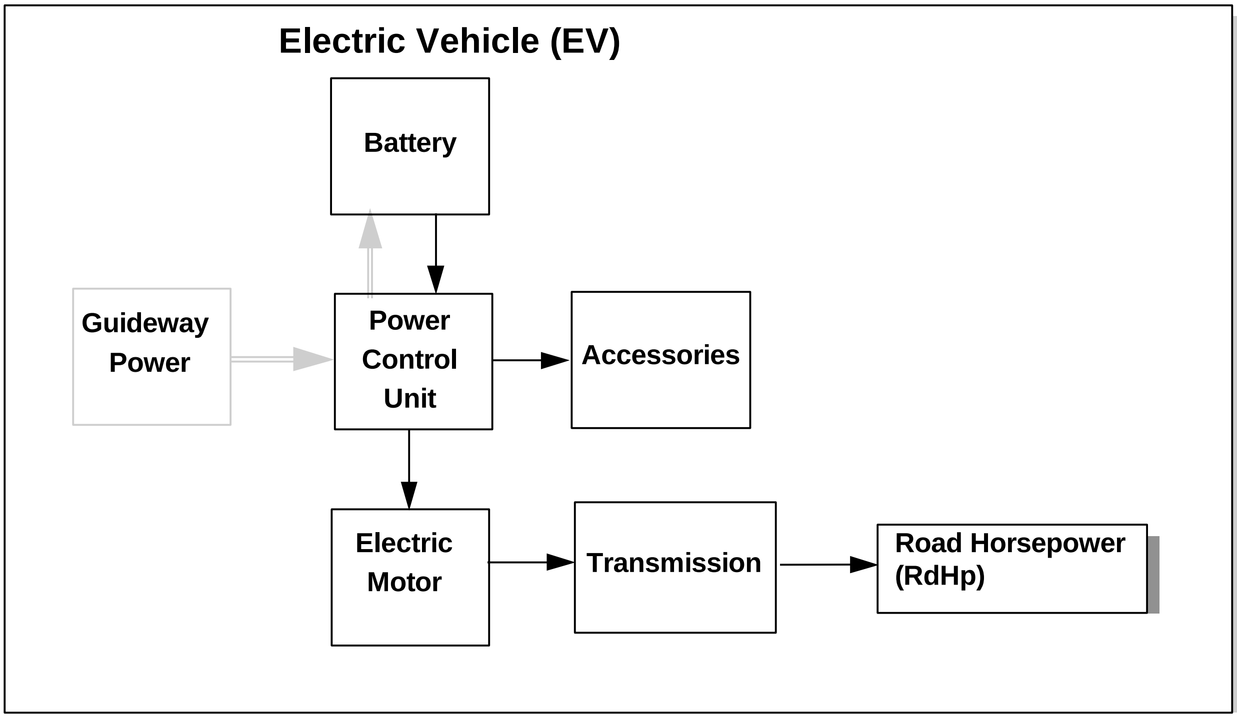

Figure 4.2.2-3. Electric Vehicle Power Train Models

The power train model in the figure above was constructed to assess the power and energy requirements for several electric vehicle concepts, including:

- Battery powered vehicle.
- Guideway powered vehicle.
- Guideway powered vehicle with the guideway supplying battery charging power, as well as vehicle power.

Electric Vehicle Power Train Models:

RdHp	=	Road Horsepower.
Access	=	Accessory power load.
Em	=	Motor efficiency.
Empcu	=	Motor power control unit efficiency.
Et	=	Transmission efficiency.
Ebat-chg	=	Battery discharge efficiency.
Ebat-dis	=	Battery charging efficiency.
Lbat	=	Battery charging load

<u>Battery Powered</u> RdHp = Pbat * Ebat-dis * Epcu * Em * Et - Access/Epcu

<u>Guideway Power</u> RdHp= Guideway Power * Epcu * Em * Et - (Access/Epcu)

<u>Guideway Power with Battery Charging</u>

RdHp= Guideway Power * Epcu * Em * Et - Access/Epcu - Lbat/(Epcu * Ebat-chg)

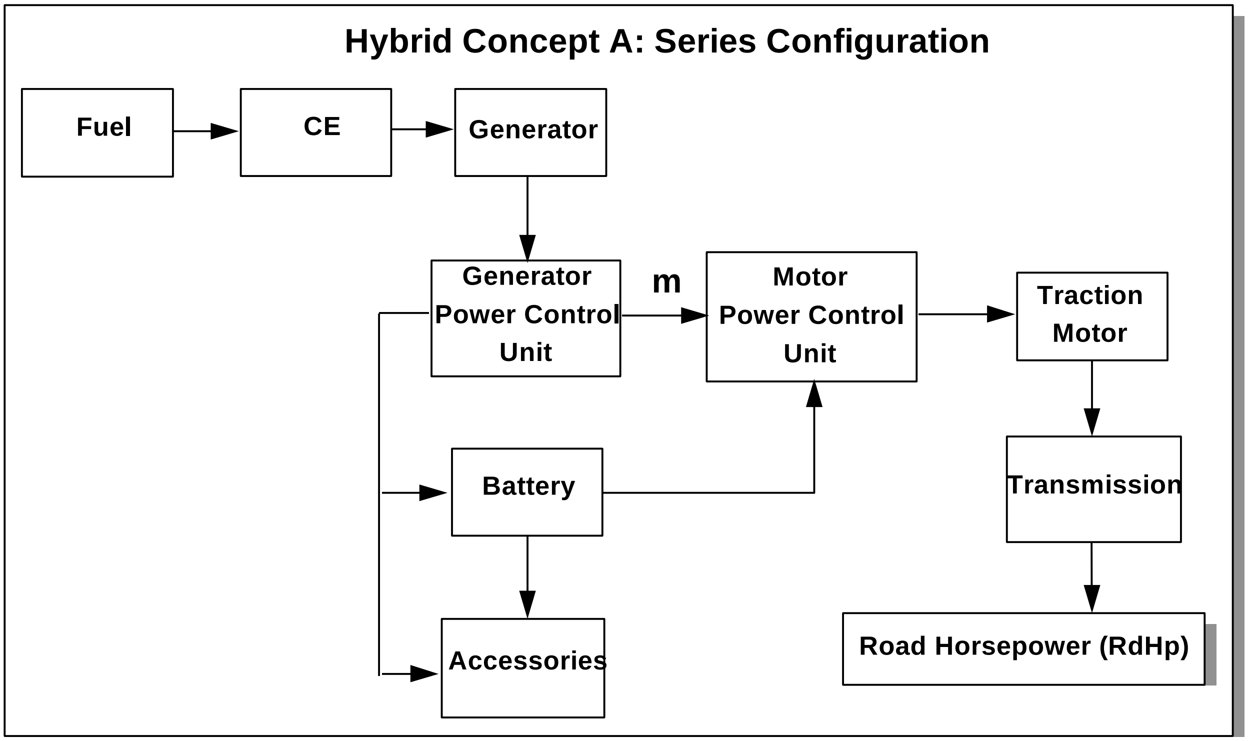

Figure 4.2.2-4. Hybrid Vehicle A - Series Configuration Power Train Model

Hybrid A Power Train Model:

RdHp	=	Road Horsepower.
Pce m	=	Fraction of the generator power control unit going directly to the motor power control unit, where m can assume values from zero to one.
Em	=	Motor efficiency.
Empcu	=	Motor power control unit efficiency.
Eg	=	Generator efficiency.
Egpcu	=	Generator power control unit efficiency.
Et	=	Transmission efficiency.
Pbat	=	Battery power output.
Ebat-chg	=	Battery discharge efficiency.
Ebat-dis	=	Battery charging efficiency.
Access	=	Accessory power load.

RdHp = Empcu * Em * Et * {Pce * Eg * Egpcu *
[m + (1 - m) * (Ebat-chg * Ebat-dis)] -
(1 - m) * (Access/Ebat-dis)}

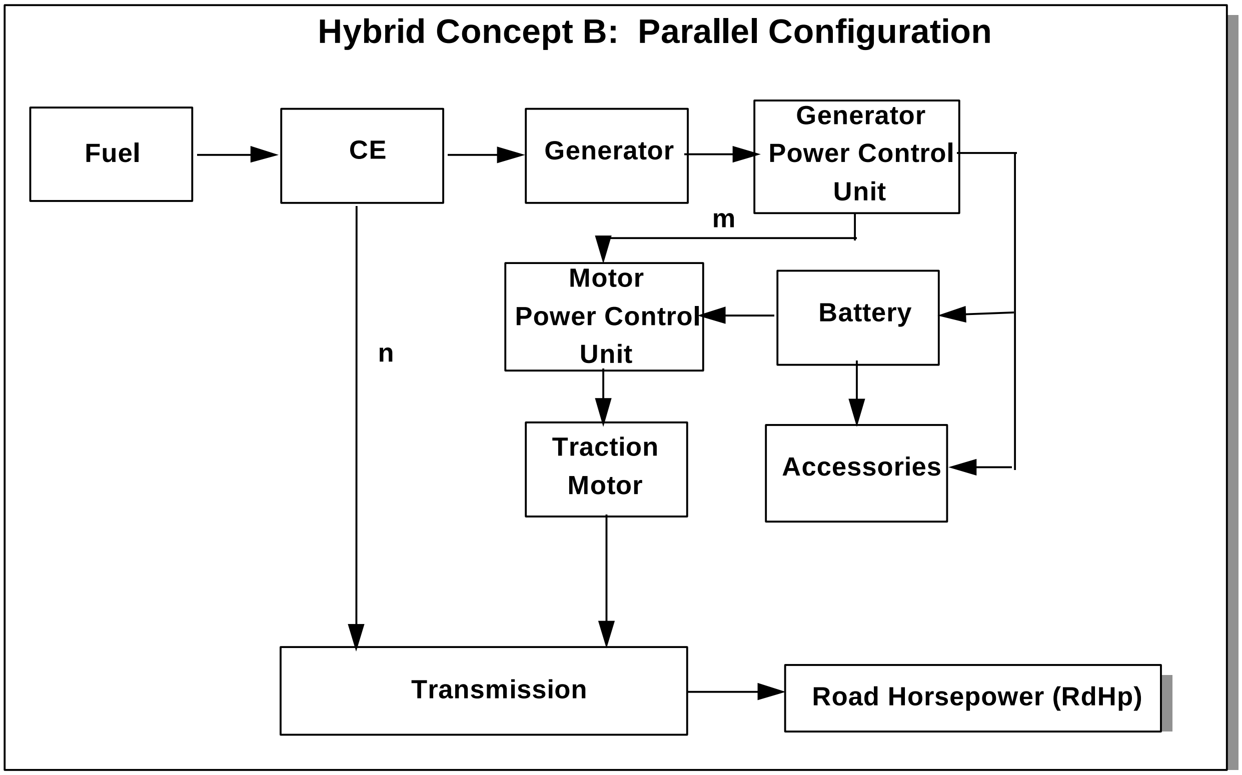

Figure 4.2.2-5. Hybrid Vehicle B - Parallel Configuration Power Train Model

Hybrid B Power Train Model:

RdHp = Road Horsepower.
Pce = Combustion engine power output.

m = Fraction of the generator power control unit going directly to the motor power control unit, where m can assume values from zero to one.
n = Fraction of the combustion engine power output going directly to the transmission, where n can assume values from zero to one.
Em = Motor efficiency.
Empcu = Motor power control unit efficiency.
Eg = Generator efficiency.
Egpcu = Generator power control unit efficiency.
Et = Transmission efficiency.
Pbat = Battery power output.
Ebat-chg= Battery discharge efficiency.
Ebat-dis = Battery charging efficiency.
Access = Accessory power load.

RdHp = {n * Pce * Et + (1 - n) * [(Pce * Eg * Egpcu * m * (Empcu * Em * Et)] +
(1 - m) * Ebat-chg * Ebat-dis - Access/Ebat-dis) +
(Pbat * Ebat-dis * Empcu * Em * Et)}

The parallel concept for a hybrid vehicle is an interesting approach because of the combinations of operating modes possible. When n = 1, the vehicle can operate as either a conventional combustion engine (CE) vehicle, or as a combustion engine with a battery power assist.

When n = 0, and the engine is running, all of the engine power is going to the generator and the vehicle is driven electrically with m controlling the amount of battery or generator power going to the wheels. However, if the engine is off, then the vehicle appears to operate as a EV.

4.2.3 Assessment of On-Board Storage Technology

4.2.3.1 Battery Technology

The study researched advanced battery developments to provide a technology baseline for the performance estimates of our baseline and projected EV configurations. Many of the automobile manufacturers have EV development programs. There are five major battery technologies being pursued under various development programs. These are: Sodium/Sulfur (Na/S), Lead/Acid (Pb-Acid),Nickel/Cadmium (Ni/Cd), Sodium/Nickel Chloride (Na/NiCl), and Nickel/Iron (Ni/Fe). These batteries are favored because the technologies for their development and evaluation are available today. These batteries are expected to provide 2 to 3 times the power of Lead/Acid batteries. However, even with this performance multiple over lead-acid batteries, these new technologies still present limitation in vehicle range and top speed when compared to those of today's conventional vehicles.

Table 4.2.3-1, below shows the development of advanced batteries in the near future and how they compare with Lead/Acid batteries. When they become commercially available, even the most advanced batteries will provide only 3 to 5 times the power of lead/acid batteries.

Table 4.2.3-2 provides estimates of the current and projected performance of these batteries. These figures suggest that lithium-polymer is the most promising technology that is likely to go through engineering and product development within the next 10 years. Lithium-polymer batteries are expected to provide 5 times the power of conventional lead-acid batteries of about the same physical volume. This implies that the battery pack could be limited in size and weight but provide 5 times the power of current battery packs. This will make the EV feasible, but it will be limited in range and top speed.

One of the drawbacks of batteries is that the penalty for continued deep discharging is a shorter battery life. Figure 4.2.3-1 illustrates the relationship between battery cycle life and the average depth of discharge.

The depth of discharge and the cycle life issue could be mitigated with an electro-mechanical (flywheel) battery. This type of battery does not have the same cycle-life problem because the energy is stored in a mechanical device and not a chemical one. The electro-mechanical battery energy performance is comparable to that of batteries in the range from nickel iron batteries to lithium-iron monosulfide batteries. However, electro-mechanical batteries will not resolve the energy storage problem for electric vehicles cycle life.

Table 4.2.3-1. Comparison of Advanced Battery Technologies to Lead-Acid Batteries

Advanced Technology Batteries compared with Lead-Acid*

	Relative Energy Capacity(range)	Relative Peak Power	Availability
Lead Acid	1.0	1.0	Now
Nickel-iron	1.5x	1.3x	Now
Sodium-sulfur	2-3x	2.5x	1995-2000
Lithium-iron monosulfide	2-3x	1.8x	1995-2000
Lithium-iron disulfide	3-5x	6-7x	2000+
Lithium-polymer	3-5x	3-4x	2000+

*Source: The Push for Advanced Batteries, EPRI Journal, April/May 1991

Table 4.2.3-2. Performance Estimates for Advanced Battery Technologies

Performance Status of EV Batteries*

	Pb-Acid	Ni/Fe	Adv. Pb-Acid+	Ni/Cd	Flywheel Battery	Na/S	LiAl/FeS	$LiAl/FeS_2$ (Bipolar)	Li-Polymer
Manufacturer/Developer	CMP	EPI	HTBI	SAFT	Various	ABB/ CSPL	ANL/ SAFT	ANL	H.Q./ERL/ Harwell
Specific Energy (Wh/kg) @c/3	34	50	45	57	60	85 **105**	83 **95**	200** **160**	-- **180**
Energy Density(Wh/l) @c/3	82	113	90	115		89 **120**	110 **140**	610** **480**	-- **250**
Specific Peak Power (W/kg)@80% DOD	60	80	300	160	266	145/85 **150**	90 **110**	600** **480**	-- **200**
Cycles	750^ **1000**	650^ **1100**	900	1500* **2000**	10,000+	1000/ 300*^ **600**	115* **600**	500** **600*** **	-- **700**

000 = Achieved 10/90 ^ In-vehicle testing to date(10/90) *Bench testing
000 = Projected **Achieved at cell level
***** Could increase 1000+ if molybdenum is used as the current collector in positive electrode**
Sources: *Battery Development for Electric Vehicles, EPRI, 12/92
+Electrosource HBTI Technical Summary

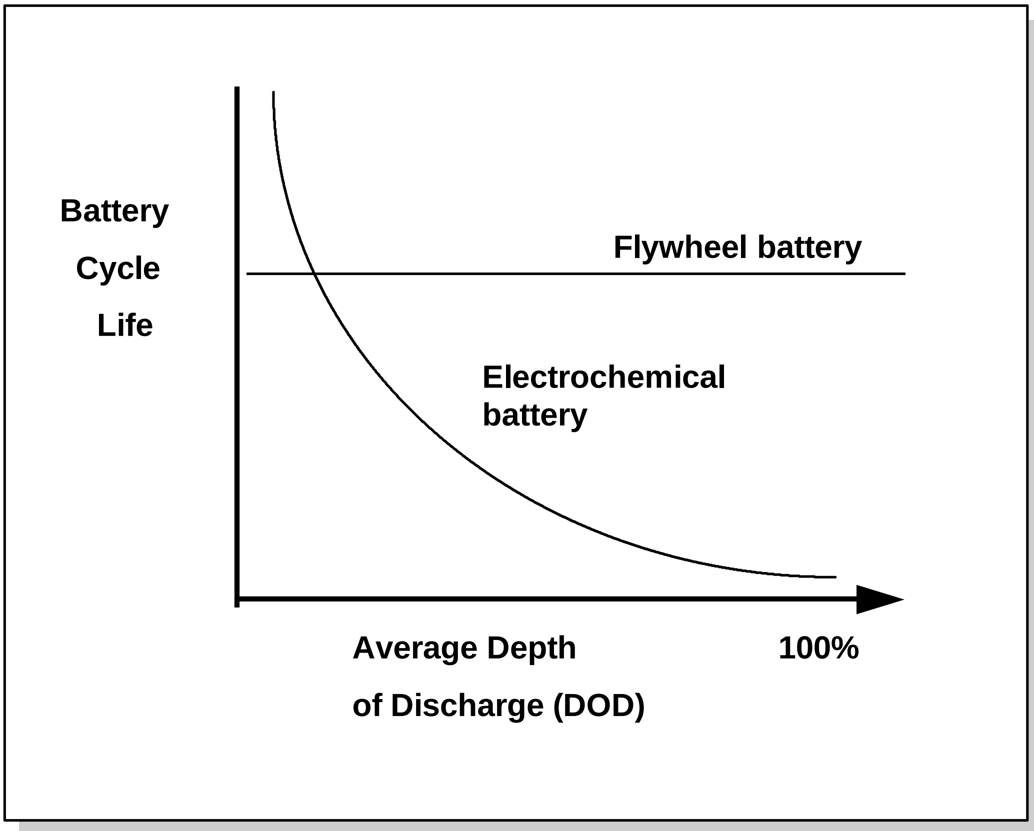

Figure 4.2.3-1. Relationship Between Battery Cycle Life and Depth of Discharge

4.2.3.2 Flywheel Technology

A flywheel is essentially a mechanical energy storage device. Modern flywheel batteries are electro-mechanical devices that store energy with a wheel spinning at speeds up to 100,000 RPM. The battery is charged by electrical energy through a frequency controlled brushless motor and stored energy is retrieved when the motor is reversed and used as a variable frequency generator. As energy is drawn from the flywheel its slows down rapidly. If the flywheel energy is not being used and energy is not added to the flywheel, the wheel eventually stops spinning due bearing and aerodynamic drag.

The power of a flywheel is dictated by its rate of change of angular momentum and therefore is limited only by the torque capability of the rotating electrical machine to which it is linked. The state of charge of a flywheel can be determined by the speed of the wheel. Its behavior is predictable because it is determined by the physical properties of the wheel, the coil and the rotational speed of the flywheel.

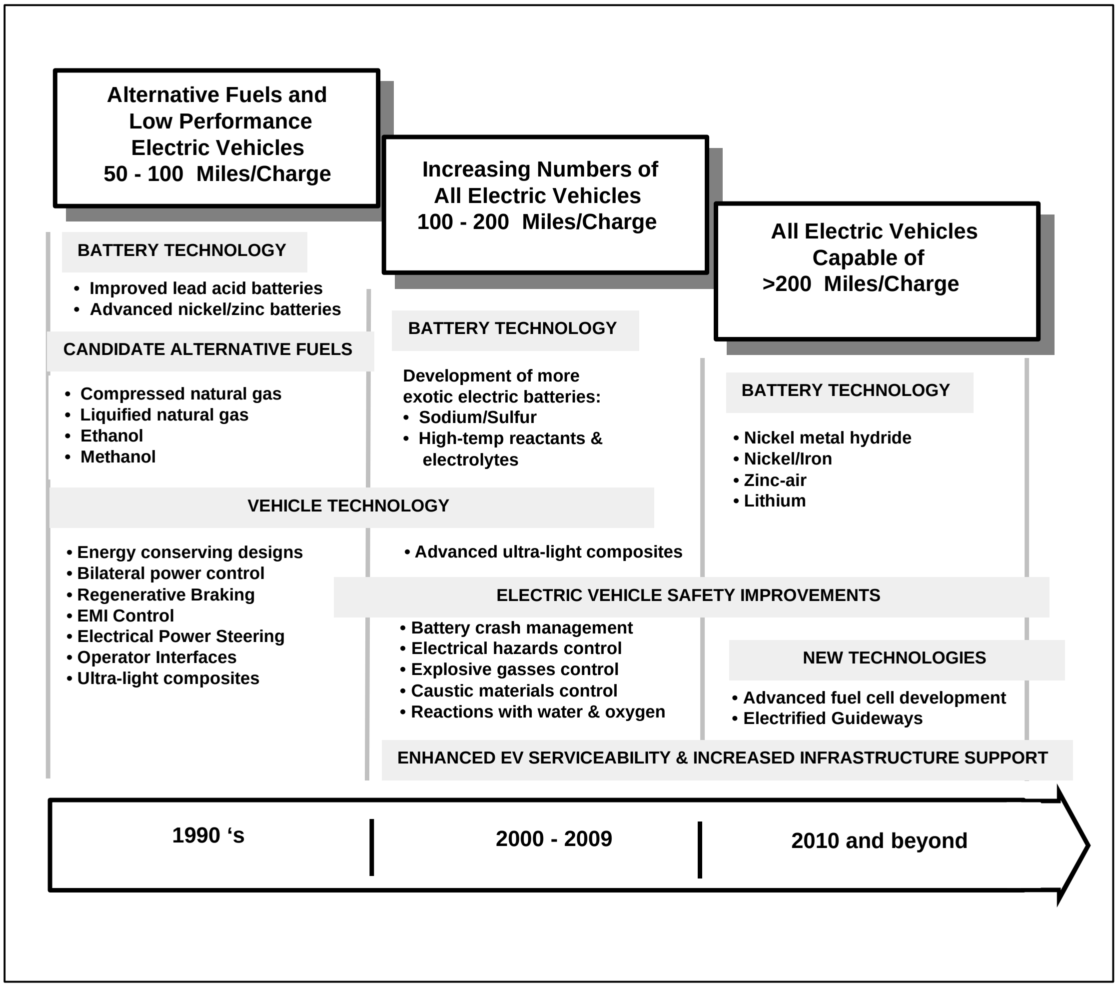

Figure 4.2.3-2. Possible Evolutionary Scenario for Battery Technology

The shaft of the wheel must be connected to the casing by some form of mechanical bearings or magnetic bearings. Mechanical bearings cause higher drag losses. Magnetic bearings do not have lower power losses, but are sensitive to road vibration.

Flywheels produce gyroscopic reactions to coupled movements and these reactions must be considered with any vehicle implementation. This precession can be compensated for in a number of ways, including; (a) the placement additional flywheel batteries along axes that will provide equal and opposite reactive forces or (b) the incorporation of a flywheel gimbal mechanism.

Flywheel batteries are promising replacements for chemical batteries, due to their power and energy densities. With present design and packaging technologies, flywheel energy densities on the order of 60 Wh/kg can be expected. This is equivalent to today's Ni/Cd battery energy densities. Power densities (taking all flywheel battery components into consideration) are estimated at 270 W/kg at 80% depth of discharge, which is close to that projected for Li-Polymer battery technology. Approximately half of the flywheel battery weight can be taken up by components external to the flywheel, including control electronics, motor, cooling hardware, bearings, and support and containment structures.

A typical performance profile for a flywheel battery might be:

- Peak Power 75 - 100 Kw
- Energy Storage -2.5 Kw-hrs
- Total weight - approximately 60 Kg.

Some of the technological hurdles to be overcome before their large scale introduction include: the gyroscopic reaction forces described above, materials engineering and design to achieve a high energy system that is light weight and able to achieve high rotational rates, the ultra-low friction bearing technology, and system safety standards.

4.3 APS Performance Requirements for AHS Operating Modes

The AHS Operating Modes, described earlier, defined operational and performance requirements that must be met by any vehicle in order to successfully complete a specific driving scenario within a specific AHS configuration. APS vehicle performance requirements were derived from these data and were expressed in terms of primary fuel storage requirements and horsepower output of the primary energy/power conversion source. These values represent the power necessary to meet the performance requirements imposed by the AHS, and the on-board energy needed to meet the endurance requirements of the AHS operational scenarios.

The AHS variables representing different Operating Modes are shown in tables 4.3-1a and 4.3-1b. The nineteen modes described in section 4.1 have been increased to 38 by adding more variability. This was accomplished by allowing and disallowing fueling stops for the scenarios of AHS Groups I2, and by considering platooning and non-platooning scenarios for Group I3 in combination with allowing and disallowing refueling stops. Note that the Operating Mode identification numbers (1 through 38) in the tables corresponding to the Operating Mode numbers shown later in the power and energy plots.

Translation of AHS Requirements into APS Requirements

The process for translating AHS operational and performance requirements into APS performance requirements consists of the following steps:

(a) Apply the quantified Operating Mode data for Modes 1 through 19 to the Simplified Vehicle Power Requirements model for each APS vehicle weight category and for the trip length and terrain defined for that mode, then,

(b) Apply the resultant road horsepower number to the appropriate APS power train model in a reverse computational process that considers power dissipation and energy conversion efficiencies. The computation is carried back up through the power train to the APS primary power source and the primary on-board energy storage component.

Table 4.3-1a. AHS Operating Modes for APS Analyses

Operational Mode	Trip Length	Average Speed[1]	Grade Characteristics		Station Keeping Accel.	Entry /Exit	Check-in/out times	Refueling Facilities
	(km, mi)	(km/hr, mi/hr)	Slope %	Length (km, mi)	max/avg g's	Dist. (km, mi)	(sec)	Interval Between (km, mi)
Mixed AHS & Manual Traffic								
#	**AHS Group I1**							
1	24.1, 15	100, 62 Note 2	6	3.2, 2	0.2/0.05	3.2, 2	30	No refuel
2	24.1, 15	100, 62 Note 2	3	1.6,1	0.2/0.05	3.2, 2	30	No refuel
3	48.3, 30	100, 62 Note 2	3	1.6,1	0.2/0.05	3.2, 2	30	No refuel
4	48.3, 30	100, 62 Note 2	6	3.2, 2	0.2/0.05	3.2, 2	30	No refuel
5	48.3, 30	100, 62	6	3.2, 2	0.2/0.05	3.2, 2	30	No refuel
6	24.1, 15	100, 62	6	3.2, 2	0.2/0.05	3.2, 2	30	No refuel
	AHS Group I2							
7	241.4, 150	100, 62	6	3.2, 2	0.2/0.05	16,10	30	No refuel
8	241.4, 150	100, 62	6	3.2, 2	0.2/0.05	16,10	30	80.5, 50
9	241.4, 150	100, 62 Note 2	6	3.2, 2	0.2/0.05	16,10	30	No refuel
10	241.4, 150	100, 62 Note 2	6	3.2, 2	0.2/0.05	16,10	30	80.5, 50
11	241.4, 150	150, 93.2 Note 3	6	3.2, 2	0.1/0.05	16,10	30	No refuel
12	241.4, 150	150, 93.2 Note 3	6	3.2, 2	0.1/0.05	16,10	30	80.5, 50
13	241.4, 150	150, 93.2 Note 3	3	1.6, 1	0.1/0.05	16,10	30	No refuel
14	241.4, 150	150, 93.2 Note 3	3	1.6, 1	0.1/0.05	16,10	30	80.5, 50
15	241.4, 150	150, 93.2	3	1.6, 1	0.1/0.05	16,10	30	No refuel
16	241.4, 150	150, 93.2	3	1.6, 1	0.1/0.05	16,10	30	80.5, 50

Table 4.3-1b. AHS Operating Modes for APS Analyses

Opera-tional Mode	Trip Length (km, mi)	Average Speed[1] (km/hr, mi/hr)	Grade Characteristics Slope %	Grade Characteristics Length (km, mi)	Station Keeping Accel. max/avg g's	Entry/ Exit Dist. (km, mi)	Check-in/out times (sec)	Refueling Facilities Interval Between (km, mi)	Platooning Yes/No
AHS-only Lanes									
#	**AHS Group I3**								
17	24.1, 15	100, 62	6	3.2, 2	0.1/0.025	3.2, 2	30	No refuel	No
18	24.1, 15	100, 62	6	3.2, 2	0.1/0.025	3.2, 2	30	No refuel	Yes
19	24.1, 15	100, 62	3	1.6, 1	0.1/0.025	3.2, 2	30	No refuel	No
20	24.1, 15	100, 62	3	1.6, 1	0.1/0.025	3.2, 2	30	No refuel	Yes
21	48.2, 30	100, 62	3	1.6, 1	0.1/0.025	3.2, 2	30	No refuel	No
22	48.2, 30	100, 62	3	1.6, 1	0.1/0.025	3.2, 2	30	No refuel	Yes
23	48.2, 30	100, 62	6	3.2, 2	0.1/0.025	3.2, 2	30	No refuel	No
24	48.2, 30	100, 62	6	3.2, 2	0.1/0.025	3.2, 2	30	No refuel	Yes
25	48.2, 30	150, 93.2	3	1.6, 1	0.1/0.025	3.2, 2	30	No refuel	No
26	48.2, 30	150, 93.2	3	1.6, 1	0.1/0.025	3.2, 2	30	No refuel	Yes
27	241.4, 150	150, 93.2	3	1.6, 1	0.1/0.025	16,10	30	No refuel	No
28	241.4, 150	150, 93.2	3	1.6, 1	0.1/0.025	16,10	30	80.5,50	No
29	241.4, 150	150, 93.2	3	1.6, 1	0.1/0.025	16,10	30	No refuel	Yes
30	241.4, 150	150, 93.2	3	1.6, 1	0.1/0.025	16,10	30	80.5,50	Yes
31	241.4, 150	100, 62	3	1.6, 1	0.1/0.025	16,10	30	No refuel	No
32	241.4, 150	100, 62	3	1.6, 1	0.1/0.025	16,10	30	80.5,50	No
33	241.4, 150	100, 62	3	1.6, 1	0.1/0.025	16,10	30	No refuel	Yes
34	241.4, 150	100, 62	3	1.6, 1	0.1/0.025	16,10	30	80.5,50	Yes
35	241.4, 150	100, 62	6	3.2, 2	0.1/0.025	16,10	30	No refuel	No
36	241.4, 150	100, 62	6	3.2, 2	0.1/0.025	16,10	30	80.5,50	No
37	241.4, 150	100, 62	6	3.2, 2	0.1/0.025	16,10	30	No refuel	Yes
38	241.4, 150	100, 62	6	3.2, 2	0.1/0.025	16,10	30	80.5,50	Yes

Notes:
1 Maintain maximum speed over grade unless indicated otherwise.
2 Maintain speed of 60 kph (37.3 mph) on grade.
3 Maintain speed of 100 kph, (62 mph) on grade.

The resulting numbers represent the output of the vehicle primary power source and the energy storage requirements necessary to meet the performance and operational requirements of a particular AHS configuration. Specific APS vehicle performance requirements for each of the AHS Operating Modes are discussed in sections 4.2.3.1 through 4.2.3.5.

Vehicle issues resulting from this quantitative analysis, as well as qualitative results, and an analysis of the impact of APSs on Automated Highways are summarized in Section 5.

Performance Factors Affecting All Vehicles.

Prior to discussing the performance of specific APS vehicle configurations, it is useful to examine some of the major factors affecting the performance of all vehicles, regardless of the propulsion system. These factors include vehicle weight, aerodynamic drag, road grade, grade length and speed over grade and trip length.

Aerodynamic Drag. Figure 4.3-1 illustrates the sensitivity of the road horsepower requirements for a typical 3000 lb (1360 kg) vehicle as a function of speed. Note that, for a speed of 100 kph (63 mph), the road horsepower consumed by drag is almost 19 horsepower (14 kilowatts). This figure increases dramatically (as the cube of velocity) to 50 road horsepower at 150 kph (93 mph). This figure implies that for a typical gasoline engine or alternative fuel vehicle approximately 65 horsepower at the engine output is needed just to overcome aerodynamic drag.

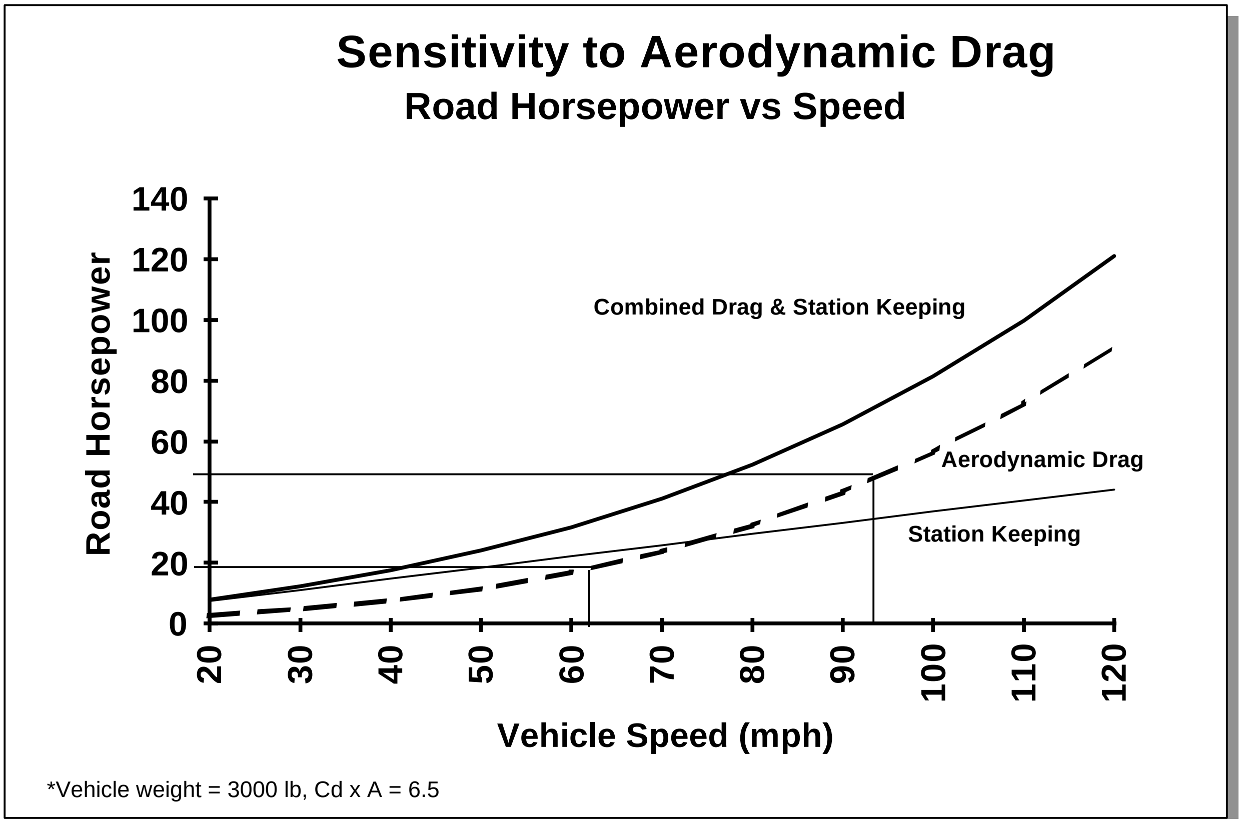

Figure 4.3-1. Road Horsepower Sensitivity to Drag for a Typical 3000 lb Vehicle

Vehicle Drag Coefficient and Frontal Area. Figure 4.3-2 illustrates the sensitivity of road horsepower to the product of drag coefficient and frontal area. Horsepower values are given for a range of vehicle weights at a constant speed of 100 kph (63 mph). The approximate drag factors are considered for two popular vehicle models, a light weight and heavier vehicle. This factor points to the approximate 20 horsepower differential between a smaller or more streamlined vehicle and a larger, less aerodynamic vehicle. Streamlining to reduce the drag coefficient (Cd) and a smaller frontal area will contribute to better power and energy efficiencies

in APSs and EVs. This is particularly important to EVs which have limited power and energy capacities.

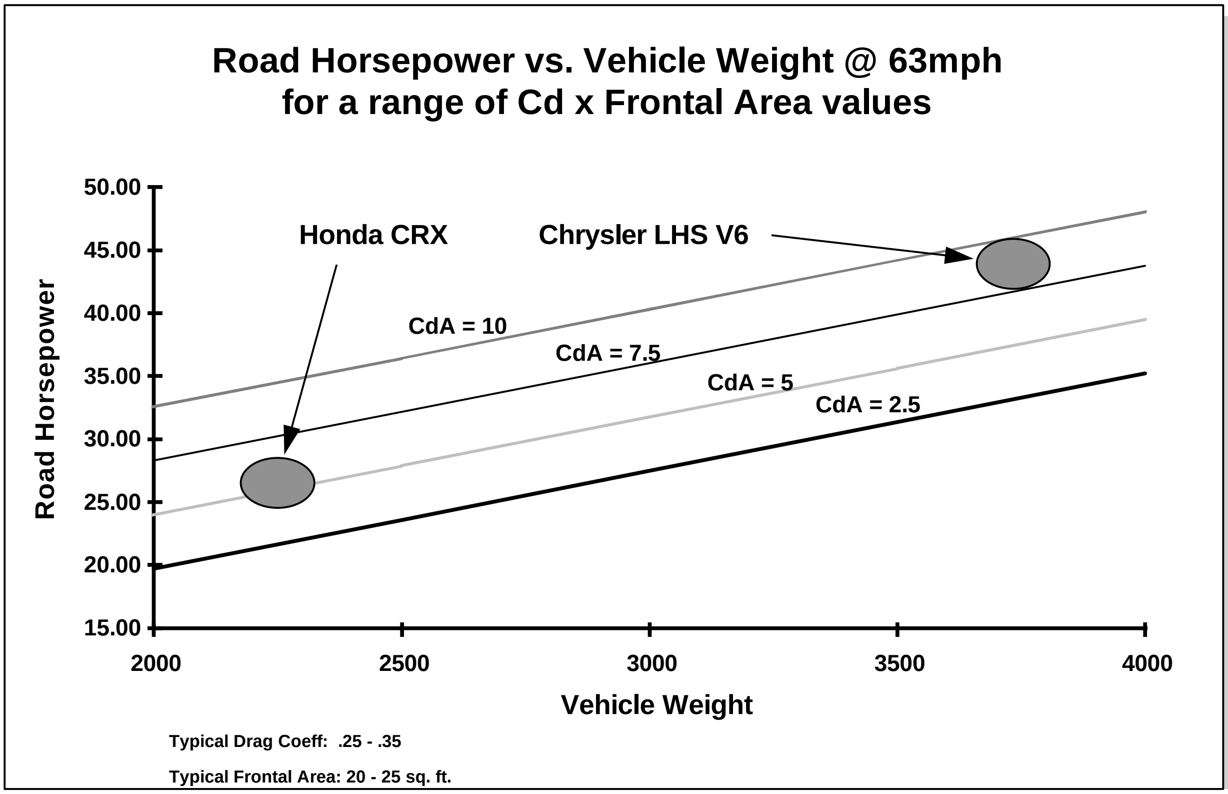

Figure 4.3-2. Road Horsepower Sensitivity to Aerodynamic Drag @ 100 kph (63 mph)

Grade and Speed on Grade impacts on Horsepower Consumption. Figure 4.3-3 illustrates the relationship among vehicle weight, speed and road grade, assuming a constant drag factor. The plots for the two production vehicles are used to illustrate where today's vehicles fall and were produced using the vehicle test weights and approximate drag figures. The figure shows that a light weight vehicle requires double the road horse power to go from level driving at 100 kph (63 mph) to a 6% grade at that speed. The figure also suggests that the light weight vehicle will not be able to achieve 150 kph on a 6% grade.

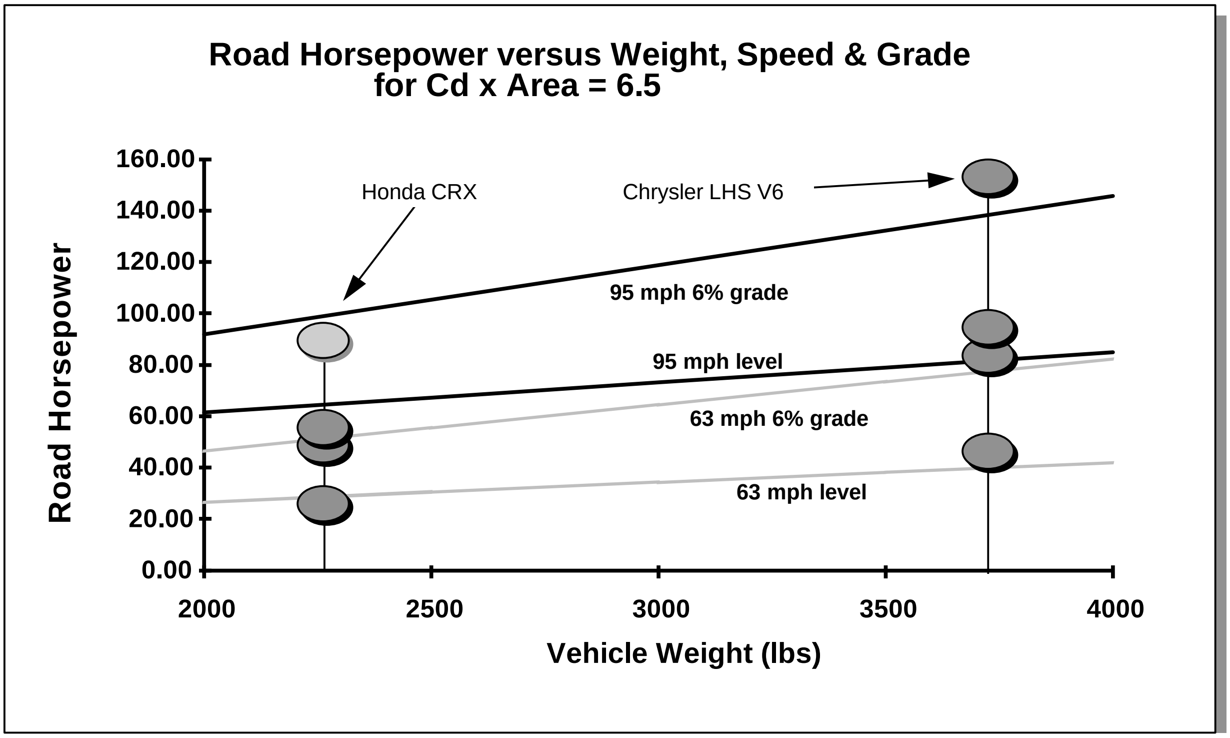

Figure 4.3-3. Road Horsepower Sensitivity to Road Grade

On-Ramps and Acceleration Lanes. Figure 4.3-4 illustrates the relationship between on-ramp length and the road horsepower required to achieve a 50 mph entry speed for several weight classes of vehicles. On-ramp length (and grade) will be a critical factor for lower powered vehicles. The example is for an existing on-ramp of 152.4 meters (500 feet). As the on-ramp length is decreased the road horsepower required to accelerate to a particular terminal or merging speed is increased.

To put on-ramp power requirements in another perspective, the peak road horsepower required to accelerate a 3000 lb vehicle to 50 mph by the time it reaches the end of the 500 ft ramp is approximately equivalent to the amount of power required to maintain the same weight vehicle at a speed of 100 kph (63 mph) on a 6% grade.

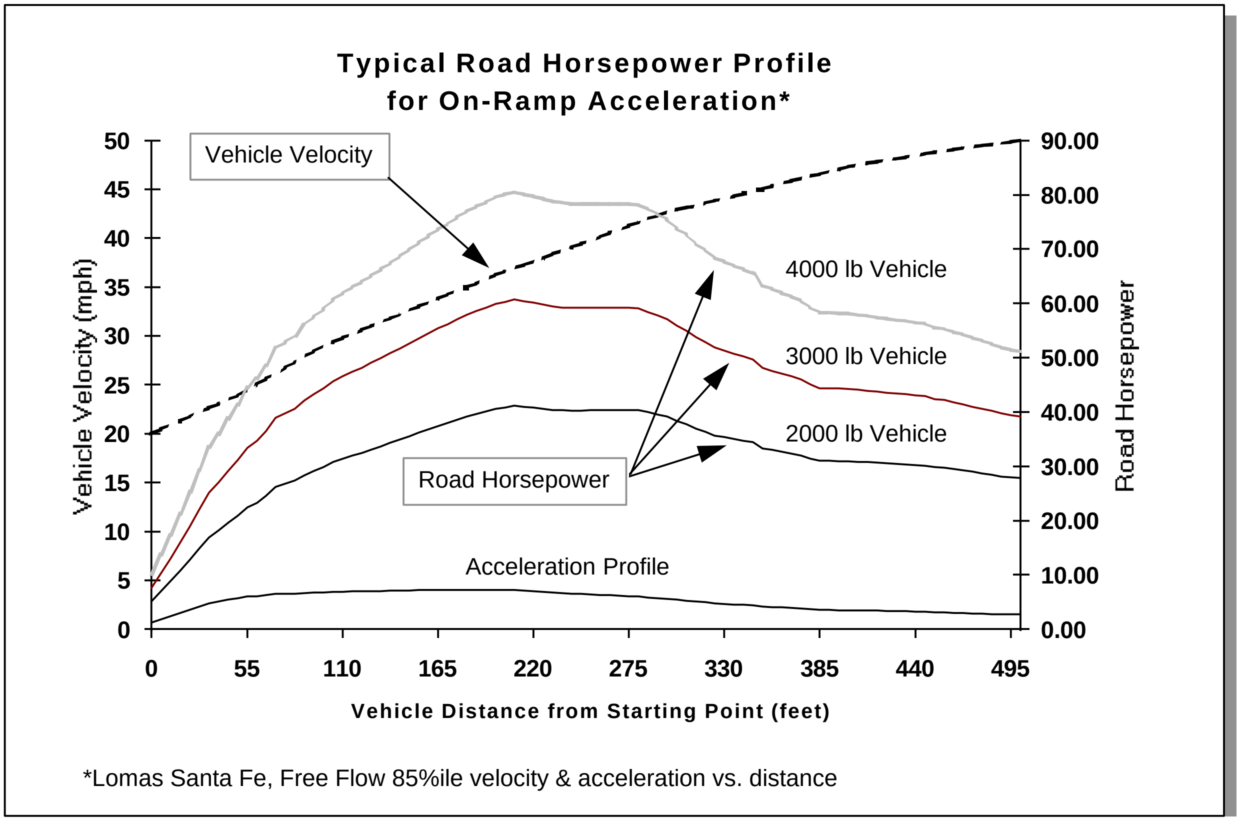

Figure 4.3-4. Typical On-Ramp Road Horsepower Requirements for Different Vehicle Weights

4.3.1 AHS Operating Mode Power and Energy Requirements

Operating Mode Power Requirements

The AHS Operating Modes describe driving missions for vehicles on different AHS configurations and operating conditions. These descriptions include distance traveled, speed, acceleration used for station keeping, and hill grades and distances. For scenarios that indicated that platooning was being used, the coefficient of drag on the following vehicle was reduced by approximately 25%. This figure is consistent with recent measurements and was used to estimate the reduction in power requirements for following vehicles in platoons.

Since there are refueling stations every 50 miles for the nine of the rural operating modes[6], the energy and power requirements for those modes were computed for 50 miles of the rural operating modes. Refueling was assumed to have no direct impact on power for these analyses. The AHS parameter values for the various operating modes were used to determine the maximum energy and total power required to successfully complete the driving mission specified for those modes.

Figure 4.3.1-1 shows the maximum amount of energy required to propel the vehicle for each operating mode, for each of the three vehicle weight classes. The prime mover in the vehicle must be able to provide sufficient power at the drive shaft to compensate for drive train losses and provide the required horsepower to the road. The figure allows the comparison of the relative power requirements platooning and non-platooning scenarios[7].

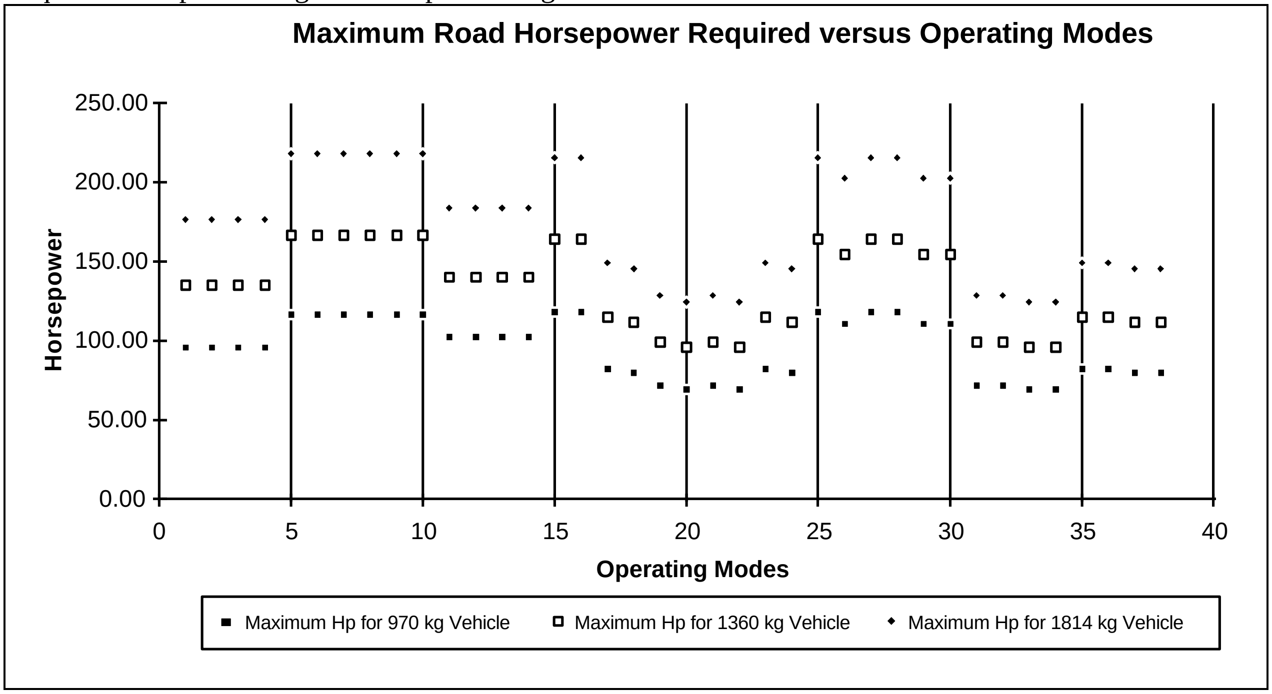

Figure 4.3.1-1. Maximum Power required for each Operating Mode

Energy Storage Requirements for Electric Vehicles on the AHS

The energy storage systems for Electric Vehicles and Hybrid Vehicles must be adequate for the vehicles to meet the peak power and energy requirements for each of the operating modes. Figure 4.3.1-2 shows the amount of energy required by a 907 Kg (2000 lb) electric vehicle to accomplish each operating mode.

The plots suggest that platooning could have a significant energy savings impact. It is estimated that for a 241 km trip at a speed of 100 kph, the 907 kg vehicle could save on the order of 12% over the energy required for the same trip without platooning. The same vehicle could save up to 30% for that

[6]Refueling is allowed for Operating Modes 8, 10, 14, 16, 28, 32, 36 and 38.

[7]Platooning scenarios with no refueling are operating mode numbers 18, 20, 22, 24, 26, 29, 33, 37. Non-platooning, non-refueling scenarios are 17, 19, 21, 23, 25, 27, 31, and 35.

same trip taken at a speed of 150 kph. These values are rough figures, but the physics and recent testing suggest that the drafting affect can have significant power and energy savings benefits.

Figure 4.3.1-3 shows the amount of energy required by a 1360 Kg electric vehicle to accomplish each operating mode.

Figure 4.3.1-4 shows the amount of energy required by a 1814 Kg electric vehicle to accomplish each operating mode.

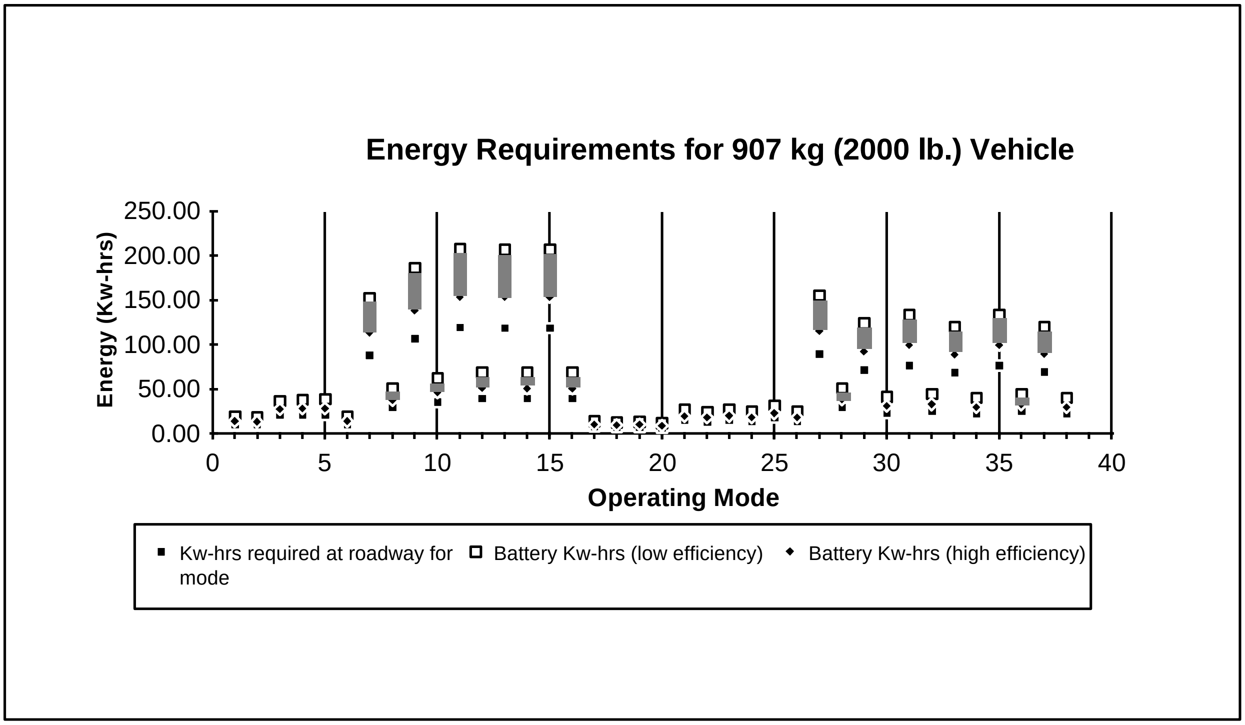

Figure 4.3.1-2. Energy Storage Requirements for 907 Kg Electric Vehicle

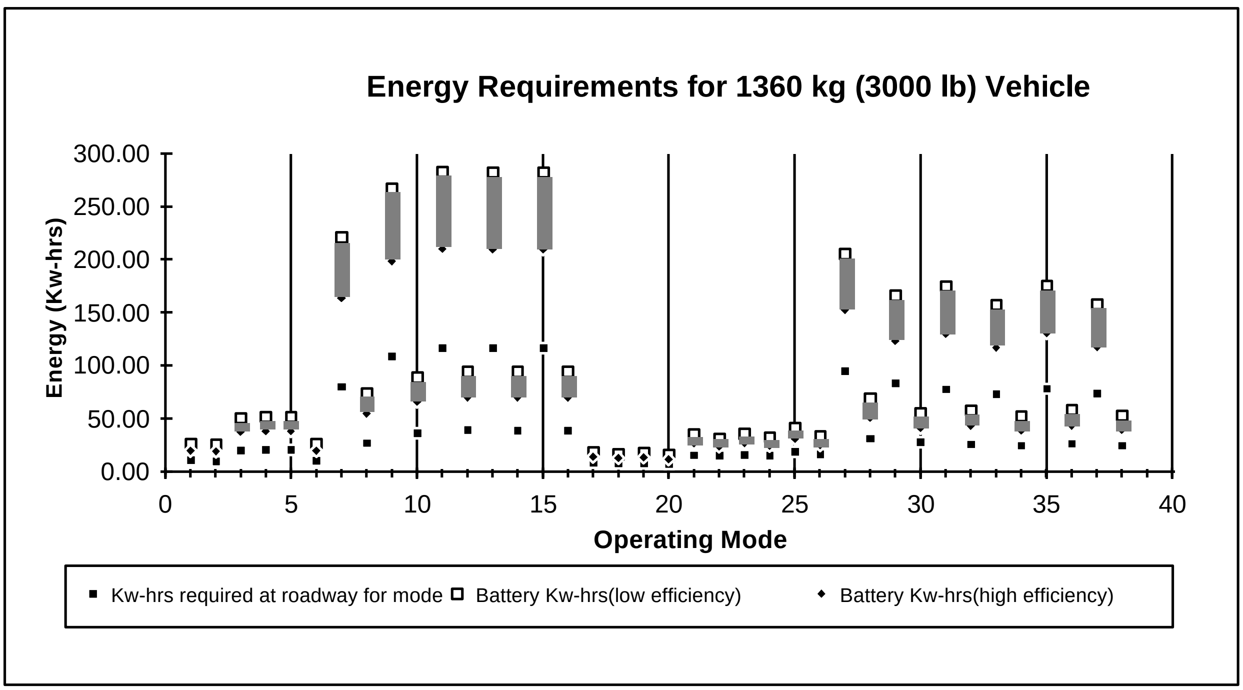

Figure 4.3.1-3. Energy Storage Requirements for 1360 Kg Electric Vehicle

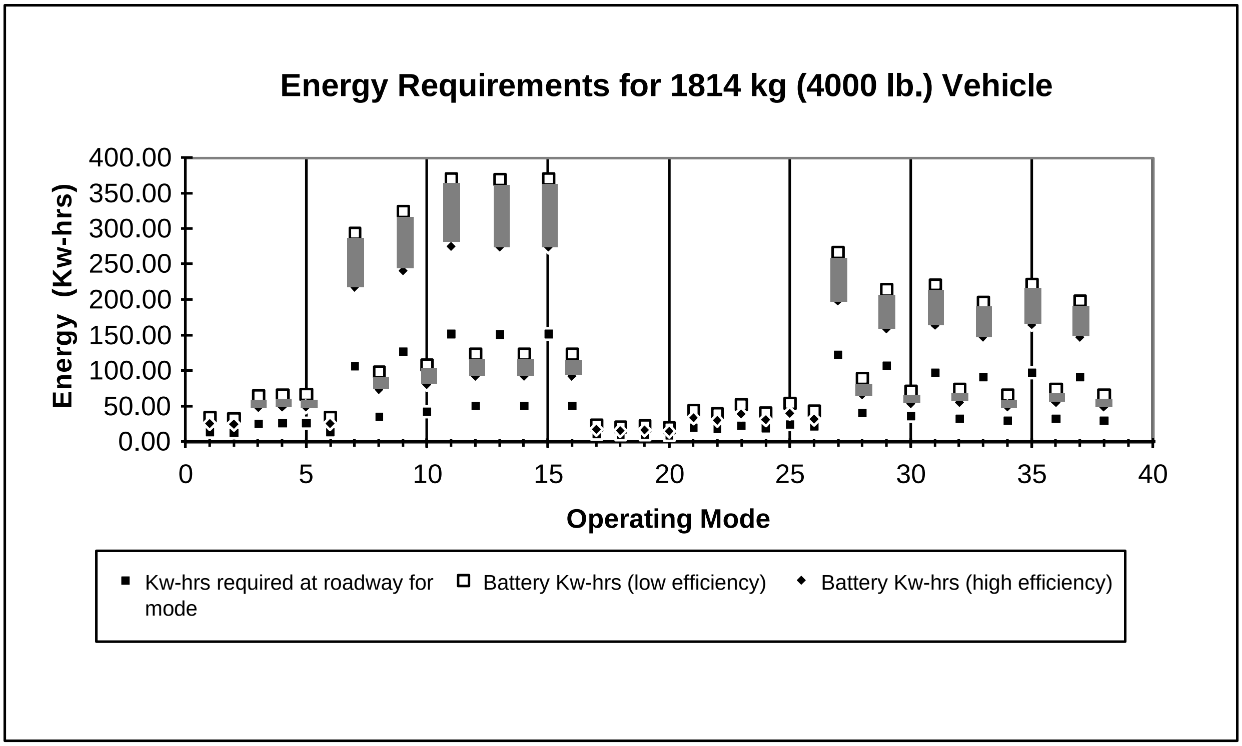

Figure 4.3.1-4. Energy Storage Requirement for 1814 Kg Electric Vehicle

The energy requirement differences are caused primarily by the weight of the vehicle and the efficiency of the propulsion system. There is a difference between the following car and the lead car in a platoon. These figures illustrate the obvious fact that larger cars will need more batteries. An analysis of available vehicle weight and volume budgets shows that larger vehicles have an advantage over smaller vehicles for battery capacity. This is due in part to the fact that there is a certain amount of fixed weight and volume overhead for EVs that is independent of vehicle size. This overhead has more impact on the smaller vehicle.

The figure also shows that platooning can have a dramatic effect on the range of electric cars, reducing energy losses due to aerodynamic drag by as much as 15-20% for long haul scenarios.

Energy Storage and Power Requirements for Hybrid Vehicles

The energy storage requirements for hybrid vehicles are different than those of the electric vehicle or the alternative fueled vehicle. The energy storage requirement is determined by the energy management algorithm that is developed for the vehicle.

The electric motor will provide 10% of the acceleration that is used for station keeping on level portions of the operating mode and the electric motor will provide the power difference between the level power and the hill climb power. (Note: In hill climb, the combustion engine provides the acceleration for station keeping.)

The combustion engine (CE) can produce sufficient power to maintain the vehicle at a constant speed on all level portions of the operating modes. In Hybrid A, the electric motor draws needed boosting power it needs from the battery. In Hybrid B, the electric motor is activated to provide the initial boost during acceleration and for hill climbs. All of the operating modes were analyzed and the one that placed the maximum demand on battery power and energy was selected as the battery requirement for our hybrids. The maximum amount of battery energy required for Hybrids A and B are shown in Table 4.3.1-1 for low and high power train efficiencies. The figures are identical for the two hybrids due to the use of similar power and energy control strategies. The most stringent operating mode was used to determine the battery and combustion engine requirements.[8]

Table 4.3.1-1. Hybrid Vehicle Battery Power and Energy Requirements

Hybrids A and B	**907 Kg Vehicle**		**1360 Kg Vehicle**		**1814 Kg Vehicle**	
	Kw	Kw-hr	Kw	Kw-hr	Kw	Kw-hr
Low Efficiency	25.7	.8	38.6	1.2	51.4	1.6
High Efficiency	19.1	.6	28.6	.9	38.1	1.3

The hybrid vehicle has a more stringent specific peak power requirement, than it has a specific energy requirement. This is because the battery recharges from an engine-driven generator. However, the battery sizing must meet the minimum boost power requirements for vehicle hill climbing. The battery power requirements for these vehicles is the dominating requirement for battery sizing, suggesting conventional lead-acid battery weights on the order 380, 570 and 760 kilograms, for the 970, 1360 and 1814 Kg vehicles, respectively. These are not practical battery weights when compared to the total weight of the vehicle, in that they make up approximately 40% of the total vehicle weight.

These results suggest that the hybrid vehicle will not be feasible until advanced batteries are available with sufficient specific power to get the battery weight down to the 15-25% of the total vehicle weight. The Ni/Cd, advanced Pb-acid, Na/S, LiAl/FeS2 and Li-Polymer batteries discussed earlier have sufficient specific power to meet these requirements. The flywheel promises to meet this peak power requirement as well as the advanced batteries, however it has low energy storage capacity. These features suggest that the flywheel battery is a good candidate as the secondary power source for hybrid vehicles.

[8]The most demanding operating mode is a high speed (150 kph) rural travel (150 km) with no refueling and one 6% grade that is two miles in length.

Table 4.3.1-2. Hybrid Vehicle Combustion Engine Power Requirements

	907 Kg Vehicle		**1360 Kg Vehicle**		**1814 Kg Vehicle**	
	Kw	Hp	Kw	Hp	Kw	Hp
Hybrid A						
Low Efficiency	82	110	119.4	160	149	200
High Efficiency	59.7	80	82	110	109.7	147
Hybrid B						
Low Efficiency	56	75	79.8	107	108	145
High Efficiency	59.7	80	78.3	105	104.4	140

The CE power requirements above suggest that hybrid A is more sensitive to the efficiencies in power conversion and transmission. However for high component efficiencies, the two hybrids have similar engine power requirements.

4.3.2 Gasoline and Alternative Fuel Vehicle Performance

Gasoline and Alternative Fuel Vehicles (AFVs) over the next ten to fifteen years are expected to retain the range that gasoline powered vehicles have today, since the bulk of these AFVs are expected to consist of converted Gasoline Fueled Vehicles. Automobile manufacturers can be expected to ensure that the AFVs carry sufficient fuel for the range requirements for all of the operating modes discussed in this analysis. The on-board energy storage system provides the energy for the vehicle to accomplish the mission. The energy from gasoline and alternative fuels were determined to high enough for these vehicles to successfully complete all modes[9].

Figure 4.3.2-1 provides the power requirements for the internal combustion engines for gasoline and alternative fueled vehicles. It also shows the typical power for engines that are provided for each weight class of vehicle. For engines that do not provide enough power to accomplish a mode, the mode power will appear above the line for the engine power in the figure. For example, 907 Kg vehicle with the specified engine cannot reach the speed of 150 kph so all of the modes that require 150 Kph are above the engine power line for the 907 Kg vehicle. The power of the engine for the 907 Kg Vehicle is 92 hp. The power for the 1360 Kg Vehicle is 190 hp and the power for the 1814 Kg Vehicle is 270 hp.

[9]This means that the volume and weight requirements associated with alternative fuel storage, management and propulsions systems fall within allowable limits for each weight class of vehicle, for each AHS scenario considered in this study.

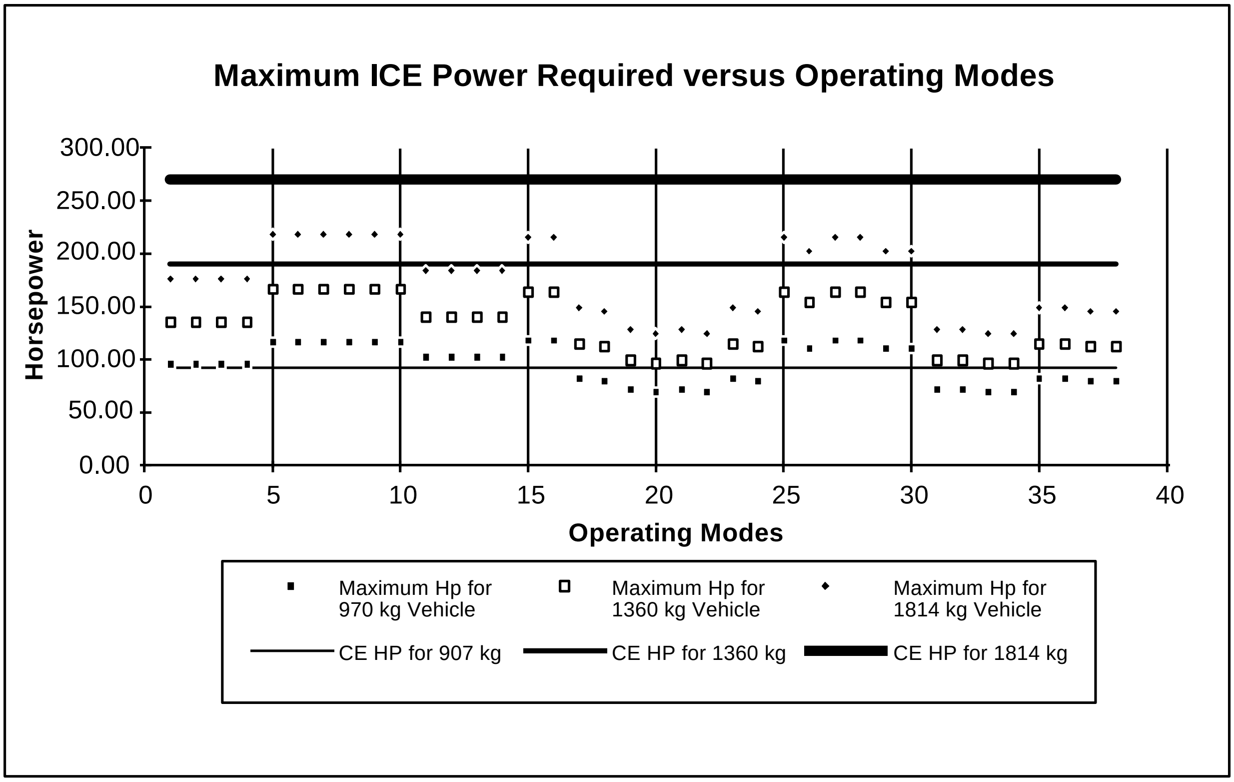

Figure 4.3.2-1. Combustion Engine Requirements and Capabilities

The primary difference between a gasoline powered vehicle and an alternative fueled vehicle is the fuel and the fuel tanks. Many alternative fuels are in a gaseous state rather than a liquid state like gasoline; one that is available and familiar to consumers is natural gas. The performance of natural gas-fueled vehicles is similar to that of gasoline powered vehicles. Natural gas powered vehicles may have lowered public acceptance due to the storage volume taken up by natural gas cylinders. It is estimated that approximately 30-50% of the trunk space is taken up for cylinder placement. The natural gas vehicle is also about 5% heavier than an equivalent gasoline powered vehicle for the same on-board energy storage capacity. Natural gas-fueled vehicles will also have to overcome the "Hindenberg complex."

A 907 kg vehicle would have to have 2 natural gas cylinders to have the equivalent energy of a 32 liter gasoline tank. The difference in weight between the gasoline with its fuel tank and the natural gas with its heavy cylinders is 18.85 kg added to the weight of the 907 kg natural gas powered vehicle. The cylinders would occupy 109 more liters of space than the fuel tank. This additional space is available in the vehicle storage compartment.

The 1360 kg vehicle would have to have 3 natural gas cylinders to have the equivalent energy of a 48 liter gasoline tank. The difference in weight between the gasoline with its fuel tank and the natural gas with its heavy cylinders is 28.3 kg of weight added to the 1360 kg. natural gas powered vehicle. The cylinders occupy 164 liters more space than the fuel tank and additional space is available in the storage compartment of the vehicle that can be used by the cylinders.

The 1814 kg vehicle would have to have 4 natural gas cylinders to have the equivalent energy of a 64 liter gasoline tank and the difference in weight between the gasoline with its fuel tank and the natural gas with its heavy cylinders is 37.73 kg of weight added to the 1814 kg vehicle. The cylinders occupy 218 liters more space than the fuel tank and additional space is available in the storage compartment of the vehicle that can be used by the cylinders.

AFV market influences. The federal Clean Air Act Amendment (CAAA) of 1990 is written to influence fleet purchases of "clean fuel" passenger vehicles, trucks and vans, and heavy duty vehicles beginning in 1998[10]. Clean fuels are defined by the CAAA to include natural gas, ethanol, methanol or other alcohols; mixtures of 85% or more methanol, ethanol or other alcohols; reformulated gasoline and diesel; propane, electricity and hydrogen. This law, coupled with the Energy Policy Act (EPACT) of 1992, with its tax incentives, is designed to encourage the availability of alternative fuels and reduce the United States' dependency on foreign oil, promises to influence the number of AFVs on the road.

4.3.3 Electric Vehicle Performance

This section provides a summary of the results of the performance analysis conducted for Electric Vehicles followed by a discussion of the analysis and data.

4.3.3.1 Summary of EV Performance Results

Current battery technology provides insufficient acceleration power for many of today's on-ramps. Today's lead-acid batteries provide only 25 to 30% of the power necessary to accelerate a vehicle from rolling speed to 80 kph (50 mph) on a 152 meter (500 feet) on-ramp. Equivalent weights of lithium polymer batteries almost meet the requirement, while Li/FeS batteries promise more than adequate power to meet most power requirements. The practicability of Li/FeS batteries for private vehicles is another issue.

Advanced battery technologies accommodate more Operating Modes. However, advanced battery technologies such as Lithium Polymer and bipolar LiAl/FeS can meet some moderate speed (100 kph), rural driving (241 km) scenarios where speeds over grade requirements are relaxed. This makes the assumption that rapid refueling can be practicably accomplished during the trip. The scenarios assumed refueling stations spaced at 80.5 km (50 mi) intervals. However, no assumptions are made as to the cost or safety of such batteries.

The study imposes a certain realism in vehicle design, which constrains the amount of vehicle weight and volume which may be allocated for batteries and the electric power train. However, the range and performance of the EV can be greatly extended if the private or commercial user is willing to sacrifice greater vehicle weight and volume payloads for more battery.

---

[10]The CAA of 1990 required AFV purchases as follows:

- 30% of new fleet purchases of passenger cars, light trucks and vans by model year 1998;
- 50% of new fleet purchases of passenger cars, light trucks and vans by model year 1999;
- 70% of new fleet purchases of passenger cars, light trucks and vans by model year 2000 and thereafter;
- 50% of new purchases of heavy-duty vehicles, including urban buses and delivery vans, beginning with model-year 1998.

EV power train and electric components efficiencies critical to power and range. The limited power and energy storage capacity of current batteries compared to most useful driving scenarios suggest that super efficient, light-weight electrical components will be required to maximize the amount of power delivered to the wheels. The study results suggest that EVs with efficient electrical components and power trains can require up to 40% less peak power than less efficient systems.

Braking regeneration capability for EVs. The benefit of regenerative braking for increasing vehicle range is marginal for AHS operation, since the opportunities for braking per mile should be very low for a well-controlled AHS. Typically, for stop and go urban driving, no more than 25% of the total tractive energy required at the wheels is available for conversion back into useful work through regenerative braking. Taking into account electrical braking inefficiencies and the inability of the on-board storage system to fully absorb the energy, it is estimated that no more than 15% of the total expended tractive energy could be recovered and re-used. Regenerative and less complicated dynamic braking can, however, reduce brake wear and, of course, are amenable to independent wheel braking effort and anti-skid braking.

Approaches to compensating for lower powered vehicles may include longer acceleration or merging lanes and different metering strategies than for higher powered vehicles.

Headway control in platooning can have a negative impact on EV range. Analyses indicate that attempting to maintain the same tight station keeping at high speed as at lower speeds can consume as much as 40% more energy for inter-city travel.

Current EV technology imposes operational limitations. Current battery technology limits EV operations to short-haul scenarios with limited hill climbing.

The results suggest that there is a certain economy of scale in favor of the larger EVs over the smaller, lighter weight EV. The projected battery energy capacities for each weight class vehicle for each battery technology show that the larger vehicles with more battery capacity can meet more of the AHS operating modes than smaller vehicles. This limits the smaller vehicles to short haul, local travel on the order of 24 to 48 Km (15 to 30 miles.)

4.3.3.2 EV Performance Analysis

This analysis examined the performance of several weight classes of EVs against a representative set of AHS operational scenarios, ranging from short hop urban driving missions to high-speed, inter-city travel A basic premise for the analysis was the assumption that Electric Vehicles would have the same physical volume and weight budgets for energy storage, electronics and power train as today's ICE vehicles in the same weight class. Individual vehicle component weight and volume budgets were established for 907, 1360 and 1814 kilogram vehicles based on a combination of published data and physical measurements. These figures were used determine the components weights and volumes of the ICE vehicle that could be removed and used for batteries, motor controller, electric motor and transmission. These figures were then used to size the power train and battery.

With the battery volume and weight limits determined for each vehicle weight class, it was then possible to determine the maximum battery power and energy output capacities for each weight class vehicle configured with different battery technologies. These capacities were subsequently compared with the power and energy demands of the AHS to determine which vehicle-weight/battery combinations met the demands of which AHS scenarios. The analysis considered both high and low power transfer efficiencies to identify those cases where marginal efficiency could affect the success or failure in a particular AHS scenario.

Typical weights for components for Electric Vehicle subsystems are shown in table 4.3.3-1 and are based on the vehicle weight allocations discussed in section 4.2.2. The power of the electric motors are 74.6 Kw (100 hp), 149.2 Kw (200 hp) and 186.5 Kw (250 hp) respectively. The power is adequate for most of the operating modes. However, a 74.6 Kw motor will not pull a 907 Kg vehicle up a hill at 150 Kph, but it will perform all other modes.

Table 4.3.3-1. Weights for Electric Vehicle Components

EV Component	Weights in Kilograms (pounds)		
Electric Vehicle Weight Class	907 kg (2000 lb)	1360 kg (3000 lb)	1814 kg (4000 lb)
Motor	45.4	90.7	136.1
Motor Controller	34.0	34.0	34.0
Transmission	11.3	11.3	11.3
Batteries	202.0	408.0	603.0

Table 4.3.3-2 provides the battery energy and volume for each battery type in each weight class of vehicle. The significance of this chart is that of the two battery constraints, battery weight and battery volume allocation, battery weight is the limiting parameter for the size of the battery for all of the battery types considered.

The battery weights in the above table 4.3.3-2 were used to compute the power and energy available to each weight-class of vehicle for each of the battery technologies. The battery power and energies were then compared to the power and energy demands for each of the operating modes in order to determine the operating modes that can be performed by the different battery technologies. Figures 4.3.3-1, 3 and 5 illustrate the vehicle power requirements and battery power capacities for 907, 1360 and 1814 kilogram vehicles. Figures 4.3.3-2,4 and 6 illustrate the vehicle energy requirements and battery energy capacities for the same weight classes.

Table 4.3.3-2. Battery Power and Volume Allocations for Different Vehicle Weight Classes

Vehicle Weight Class	907 Kg (2000 lb) Vehicle			1360 kg (3000 lb) Vehicle			1814 kg (4000 lb) Vehicle		
Allocated Battery Weight (kg)	202			373			536		
Allocated[11] Capacity (liters)	331			600			890		
Battery Type	Peak Power (Kw)	Total Stored Energy (Kw-hr)	Battery Volume (liters)	Peak Power (Kw)	Total Stored Energy (Kw-hr)	Battery Volume (liters)	Peak Power (Kw)	Total Stored Energy (Kw-hr)	Battery Volume (liters)
Pb-Acid	12.1	6.9	83.7	22.4	12.7	154.6	32.2	18.2	222.4
Advanced Pb-Acid	60.6	9.1	101.1	111.8	16.8	186.7	160.9	24.1	267.8
Ni/Fe	16.2	10.1	89.3	29.8	18.6	164.9		26.8	237.3
Ni/Cd	32.3	11.5	100.0	59.6	21.3	184.7	42.9	30.6	265.9
Flywheel Battery	53.7	12.1	N/A	99.2	22.4	N/A	142.7	32.2	N/A
Na/S	29.3	17.2	192.8	54.1	31.7	355.9	77.8	45.9	512.3
LiAl/FeS	18.2	16.8	152.3	33.6	30.9	281.2	48.3	44.5	404.7
LiAl/FeS (bipolar)	121.1	40.4	66.2	223.6	74.6	122.2	321.8	107.3	175.9
Lithium Polymer	40.4	36.3	145.3	74.6	67.1	268.4	107.3	96.6	386.2

Figures 4.3.3-1 through 4.3.3-6 illustrate that existing batteries, as well as those planned for development within the next 20 years, will not provide sufficient specific power and energy for electric vehicles applications requiring demanding inter-city travel at high-speeds, with steep road grades and sparse refueling stations. The space and weight for batteries will have be increased to have electric vehicles which will meet the operating modes. The figures also show that vehicle range can be increased by platooning and by carefully managing the accelerations needed for stations keeping.

The energy requirements shown do not consider reserve for depth of discharge. The greater the average depth of discharge, the shorter the cycle life of the battery. Therefore, a reserve must added

[11]Based on average physical measurments for variety of contemporary vehicles.

to the energy storage requirement for in order to provide a reasonable life-span. However, the added energy storage requirement carries the added penalty of increased weight and reduced vehicle range

Figures 4.3.3-1 and 4.3.3-2 illustrate the power and energy requirements and battery capacities for a 907 Kg (2000 lb) vehicle. A comparison of these charts reveals that the LiAl/FeS2 battery would just meet the peak power requirements for the demanding conditions of operating mode 15, which feature a 3% grade with no speed relaxation and tightly controlled inter-vehicle spacing. However, the LiAl/FeS2 does not meet the energy requirements (figure 4.3.3-2). None of the battery technologies meets both the energy and power requirements for rural travel. Some operating modes were at lower speeds (100 kph) and provided for refueling at 80.5 Km (50 mi) intervals, relaxed speed on grades, and included platooning in order to reduce the battery energy storage requirement and allow consideration of batteries with lower specific energies. However, none of the batteries that met even the lower energy requirement could provide the specific power to meet power demands of those lower energy modes.

Some of the more advanced battery technologies were close to meeting some of the more demanding urban operating modes examined. For example the Li-Polymer battery come close to being able to provide sufficient power and energy for urban travel at freeway speeds and steep grades.

Note that the flywheel battery is shown only as a point of reference because of its relatively high specific power. The flywheel battery has insufficient specific energy to be considered for a primary on-board energy source. A discussion of the flywheel battery as a secondary power source is contained in the section on hybrid vehicles.

Vehicle weight factors. Figures 4.3.3-3 through 4.3.3-6 illustrate the fact that vehicle weight is an important factor in determining the viability of a battery powered vehicle. As the vehicle weight increases, the battery payload weight to vehicle weight factor increases. This is due to a disproportionate increase in the available weight budget for batteries as the vehicle weight increases. The analysis assumed the weight and volume constraints of modern passenger vehicles. It was shown that battery volume is not the limiting factor and that battery weight is primary determinant for how much on board power and energy is available. If consumers and manufacturers are willing to settle for a compromise among such factors as added vehicle weight, reduced storage space and increased vehicle cost, then the LiAl/FeS2 and Li/Polymer batteries become candidates for most urban travel.

Platooning. EVs are particularly sensitive to constant station keeping maneuvers at high speeds. Reducing the accelerations required for station keeping by one-half can reduce the energy required for long haul, high-speed scenarios by as much as 40%, or between 40 and 70 Kw-hr, depending on the weight of the vehicle.

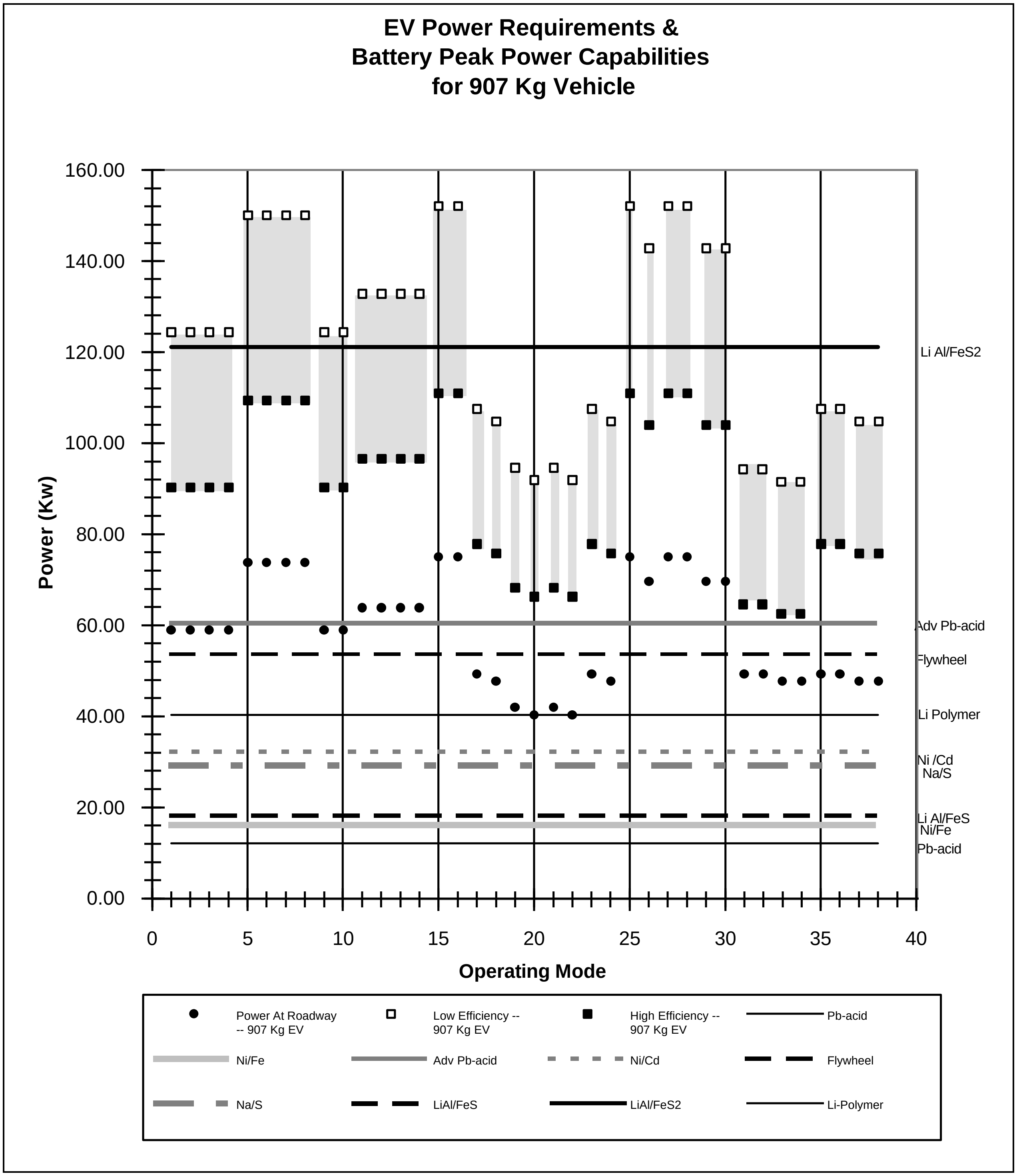

Figure 4.3.3-1. EV Power Requirements & Battery Peak Power Capabilities for 907 Kg Vehicle

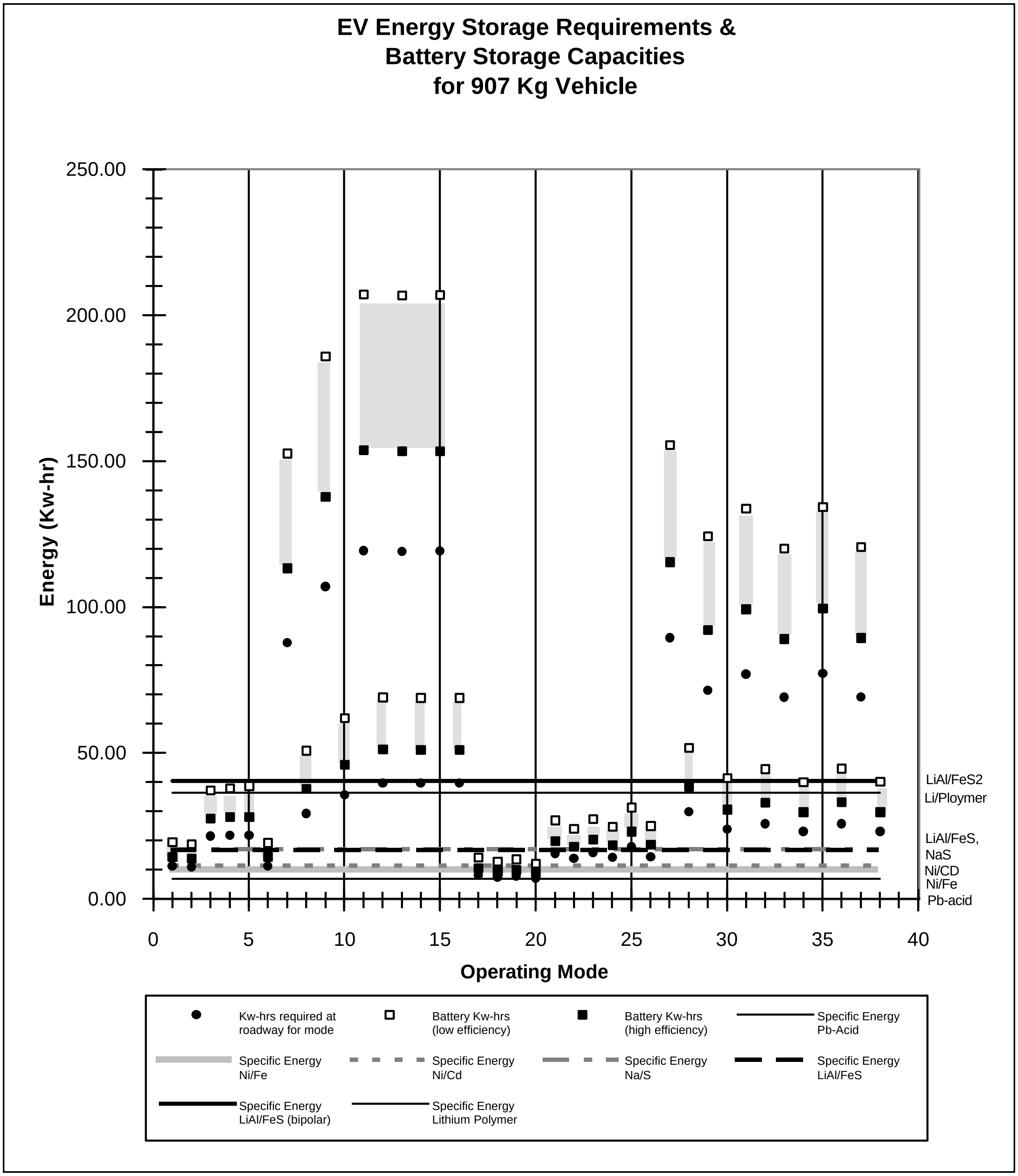

Figure 4.3.3-2. EV Energy Requirements & Battery Storage Capacities for 907 Kg Electric Vehicle

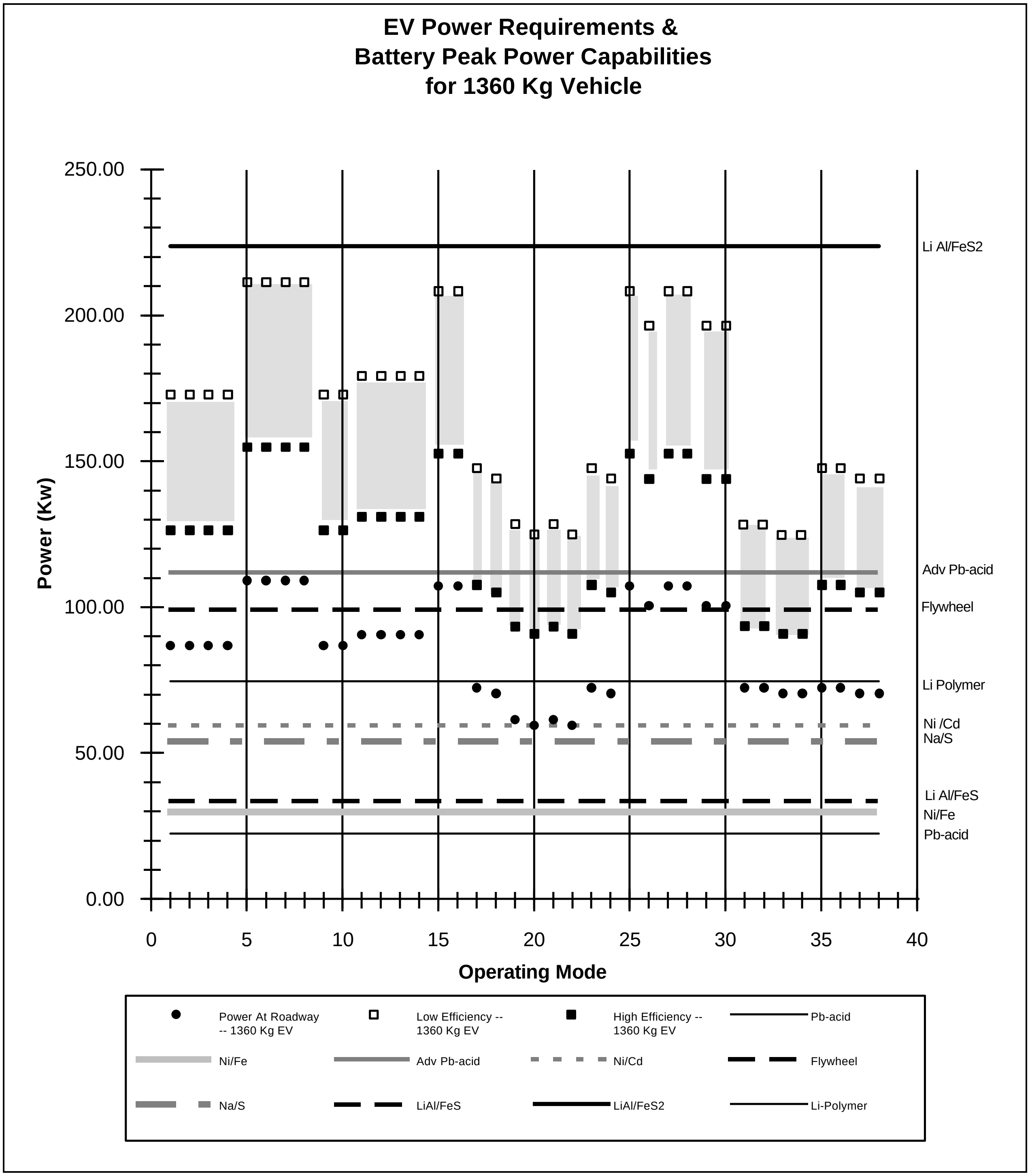

Figure 4.3.3-3. EV Power Requirements & Battery Peak Power Capabilities for 1360 Kg Vehicle

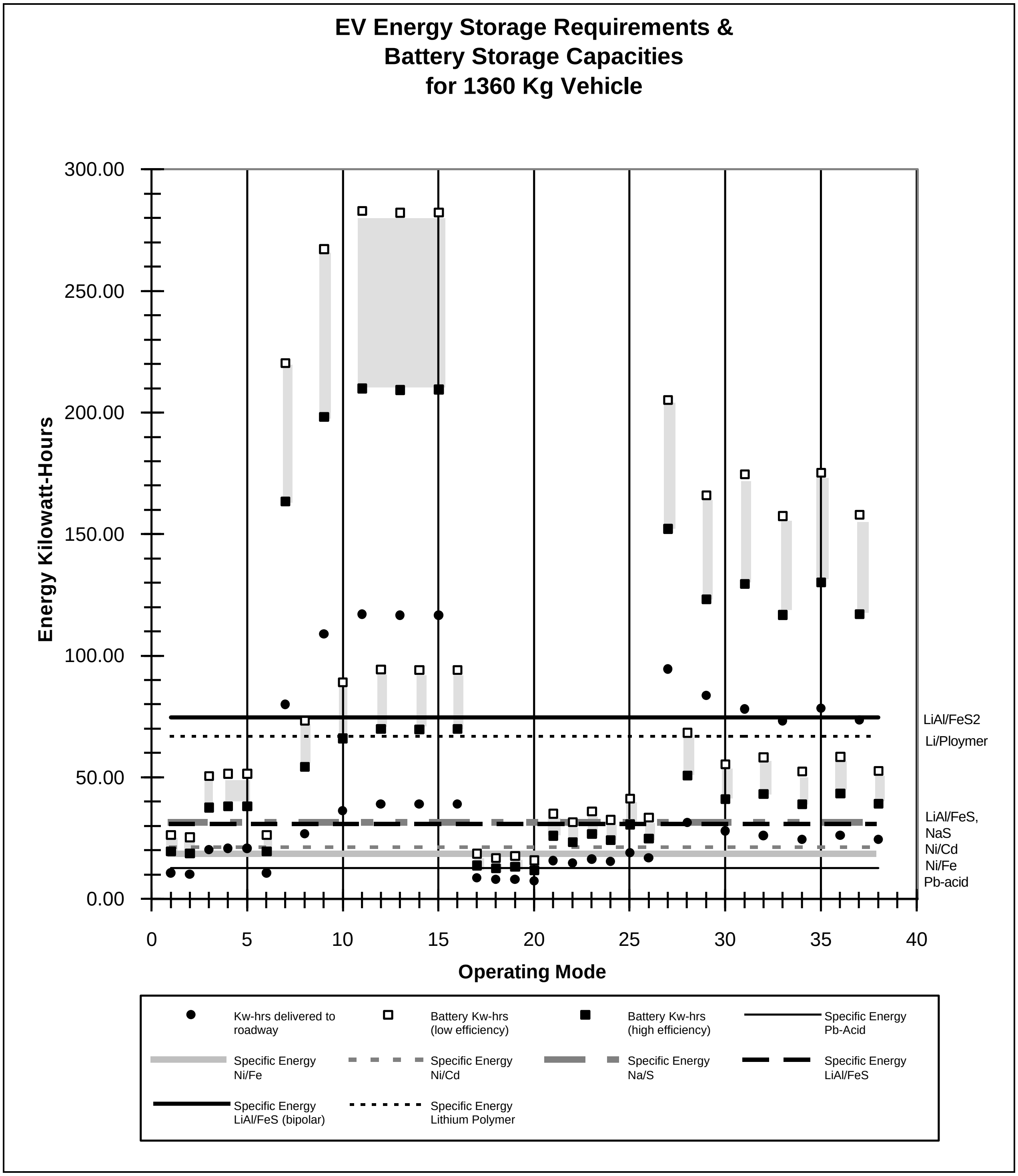

Figure 4.3.3-4. EV Energy Storage Requirements and Battery Storage Capacities for 1360 Kg Vehicles

.

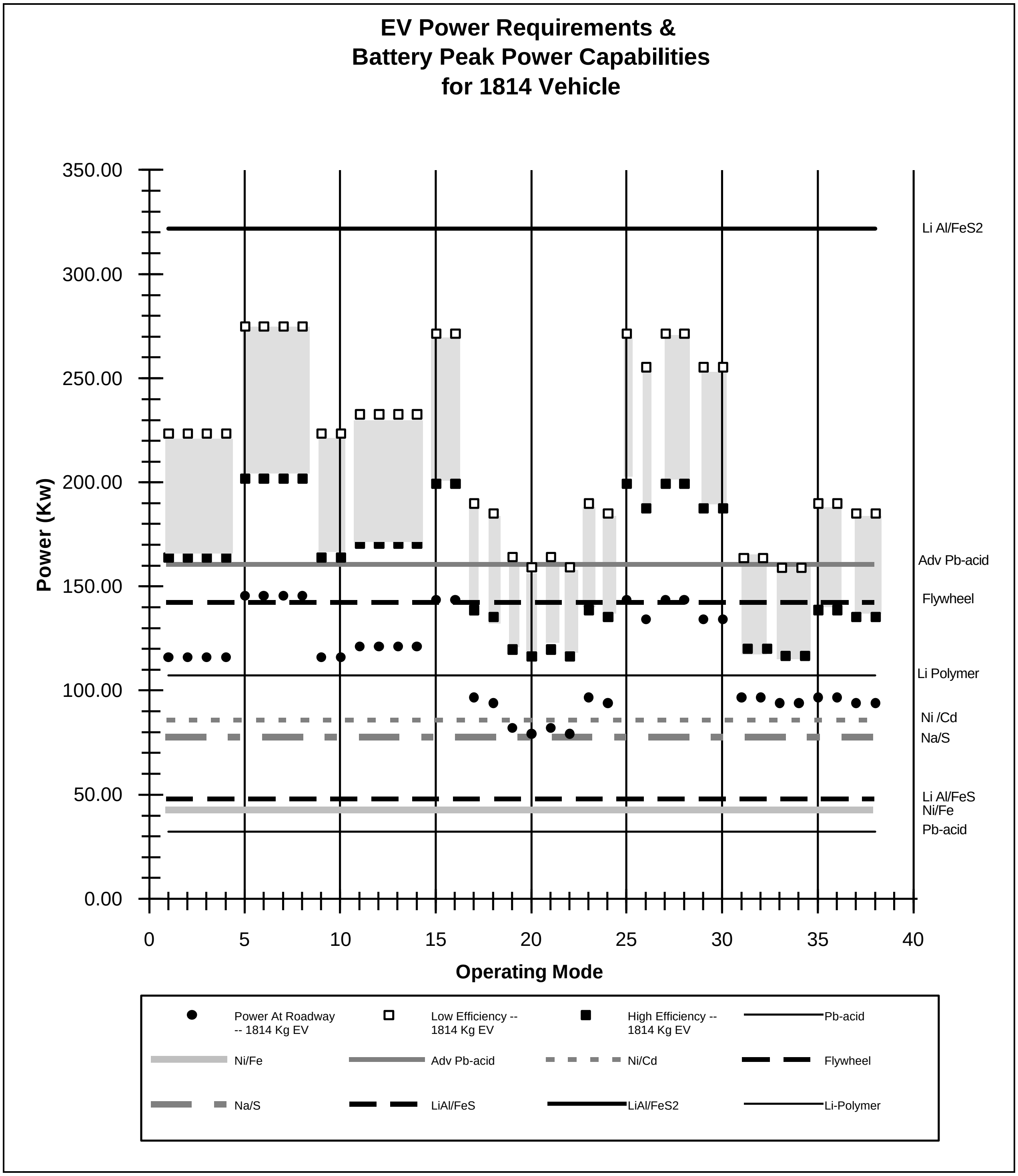

Figure 4.3.3-5. EV Power Requirements & Battery Peak Power Capabilities for 1814 Kg Vehicle

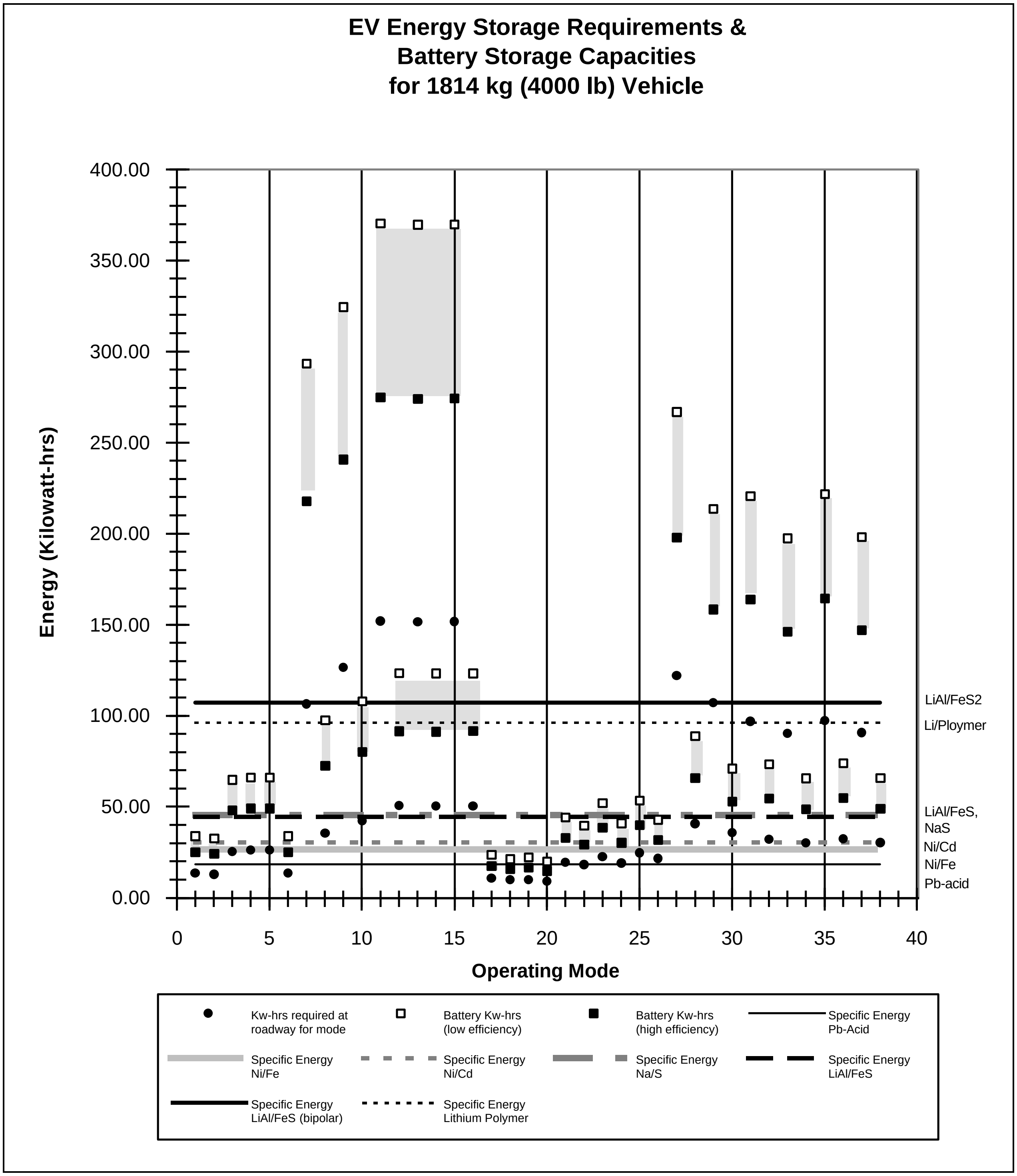

Figure 4.3.3-6. EV Energy Storage Requirements and Battery Storage Capacities for 1814 Kg Vehicles

4.3.4 Hybrid Vehicle Performance

4.3.4.1 Summary of Hybrid Vehicle Performance Results

Present-day battery technology does not offer the sufficient specific power required for hybrids designed for battery-powered boosts. Ni/Cd, advanced Pb-acid, Na/S, LiAl/FeS2 and Li-Polymer batteries are expected to meet the power boost needs of the hybrid.

Moderate to heavy hybrid vehicles offer performance similar to that of gasoline and other AFVs. Hybrids with advanced technology batteries as the secondary power source will perform better than light weight vehicles (907 Kg or 2000 lbs) given the weight and volume constraints of those vehicles.

Light weight hybrid vehicles may benefit from emerging flywheel technology. The specific power for flywheels is comparable to that of advanced battery technologies.

Hybrid performance sensitivity. The series design of Hybrid A makes it more sensitive to power train efficiencies, than Hybrid B, which has a parallel architecture that is less sensitive to those factors.

Hybrid vehicle is an excellent application for emerging flywheel technology. The high power, low energy requirements of certain hybrid designs makes the flywheel a promising candidate in terms of the specific power offered. This technology has an inherently greater cycle life than that of the chemical battery and eliminates the material handling, storage, disposal and crash hazard problems that are characteristic of chemical batteries. Flywheel battery cost factors were not evaluated as part of this study.

Hybrid vehicles can impact the AHS check-in procedure. The hybrid vehicle, because it has a primary, as well as a secondary power source, poses a more complex check-in problem. The AHS check-in system must assess a number of interrelated parameters to determine if the vehicle is AHS. These parameters include; the distance of the trip, speed(s), terrain, overall capabilities and performance of the vehicle, primary power capacity and fuel supply, and secondary power source capacity and state. For example, since the vehicle has the capacity to re-energize the secondary power source, a depleted secondary source may not necessarily be the basis for deciding to exclude the hybrid from entering the AHS. The hybrid would be allowed on the guideway in those cases where it is low on secondary energy, but has sufficient on-board primary fuel and is capable of restoring sufficient energy to the secondary energy source in time to meet the greater demands of terrain down the road.

4.3.4.2 Hybrid Vehicle Performance Analysis

The performance of the hybrid is constrained by the peak power of the battery. The energy requirements shown in Figure 4.3.4-1 suggest small batteries, requiring between .6 and .8 Kw-hr for the 907 Kg vehicle. This would be a conventional lead-acid battery of around 20 Kg, however, the power requirements for battery boost of 20-25 Kw would require a battery weight of nearly 400 Kg. The greatest demands on vehicle peak power are acceleration onto the roadway and high-speed hill climbing. For the hybrid vehicle, the peak battery power that is required to boost the vehicle on a grade is greater than the power needed to boost the vehicle during on-ramp acceleration onto the freeway. This is due to the fact that the combustion engine is providing most of the power for on-ramp acceleration. The hybrid will meet all of the operating mode performance requirements if the battery is sized to meet the demands of the hill climb. Otherwise, the hybrid will have sufficient energy to climb the hill, but at a reduced speed.

The more advanced batteries, as well as flywheel batteries, can be used in the medium and heavy vehicles to produce a hybrid with sufficient power to accelerate onto the freeway and to provide the boost needed for the hill climb in all modes. However, the flywheel battery is the lightest battery that meets the peak power requirements to boost the vehicle on the hill climb. Some flywheel designs are expected to provide approximately 80 Kw of power flywheel which can be sustained for .03 hrs, which is sufficient power to boost the vehicle over the hill. When considering flywheels, the lightest vehicles will have a weight penalty and will have to sacrifice storage space for the battery. Light weight flywheel hybrids be capable of successfully performing in all operating modes. This factor does not rule out hybrids, since some of the modes feature 6% grades at 150 kph, which represent more of an extreme.

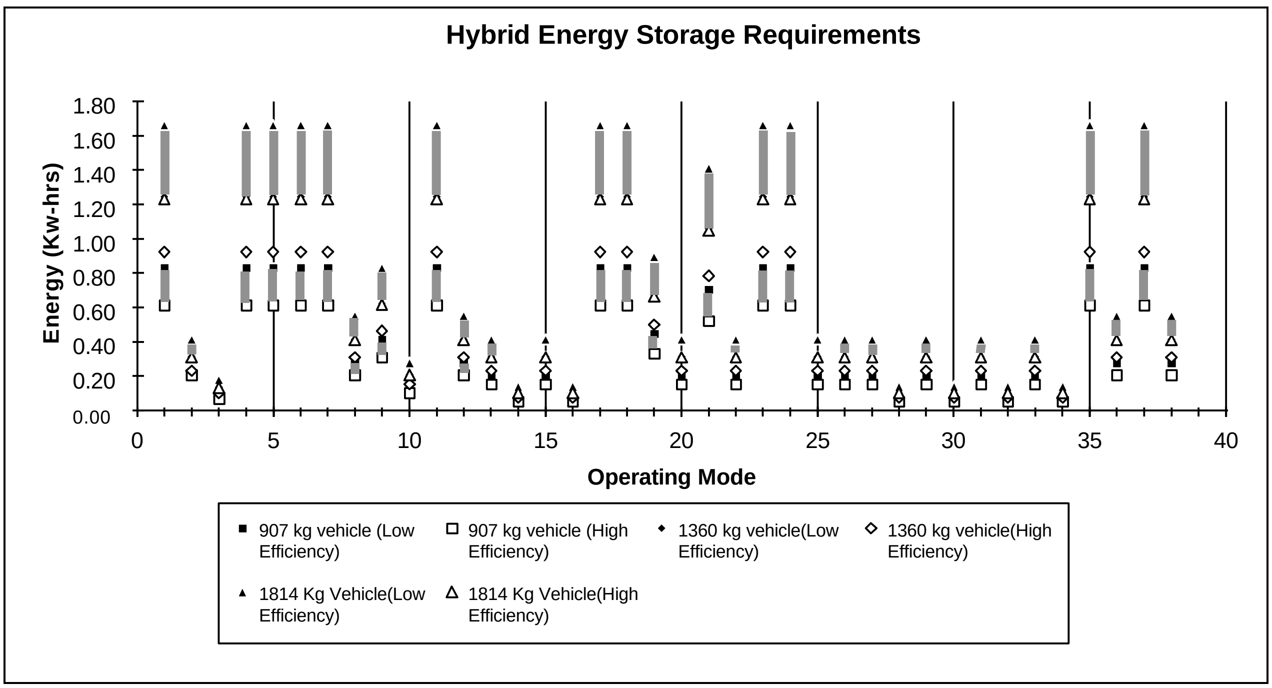

Figure 4.3.4-1. Hybrid Vehicle Energy Storage Requirements

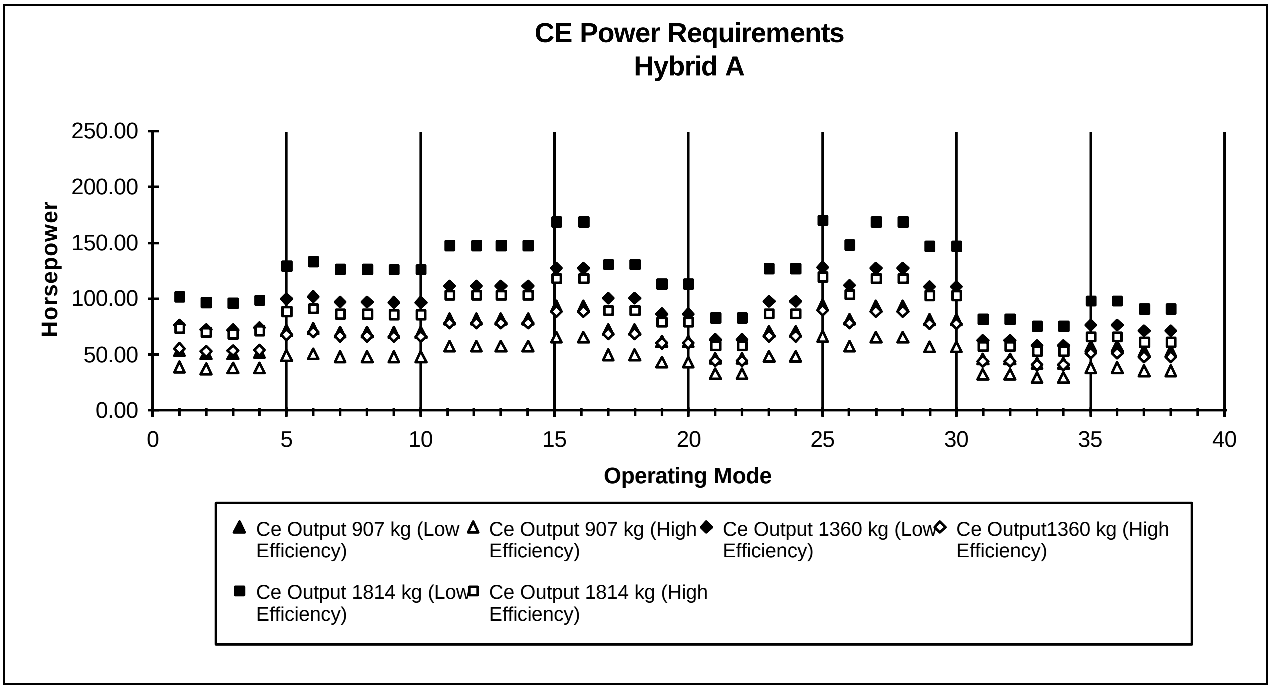

Figure 4.3.4-2. Combustion Engine Power Requirements for Hybrid A

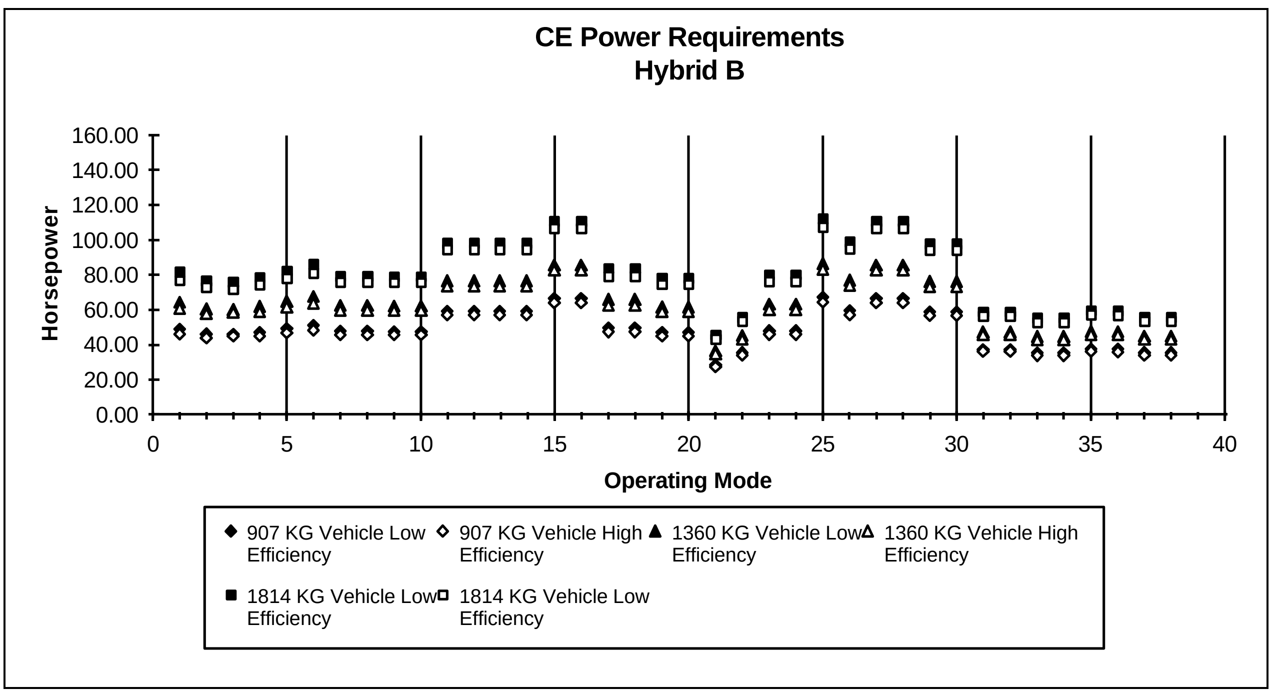

Figure 4.3.4-3. Combustion Engine Power Requirements for Hybrid B

4.3.5 Roadway Powered Vehicle Performance

The roadway powered electric vehicle (RPEV) is actually an EV with a guideway pickup.[12] Off the guideway, the vehicle operation is identical to that of a battery powered EV, having the same power and energy requirements and performance envelope as the EV. A close parallel may be drawn between Hybrid A and the RPEV operating on the guideway, in that the ICE/generator combination in the hybrid serves the same function as the guideway for the RPEV. This is a significant comparison when estimating the power requirements for the RPEV, since the CE/generator combination for the hybrid must provide the same power to the hybrid on-board power control unit that guideway must provide to the RPEV.

However, when operating on the guideway, the RPEV road horsepower capacity is only limited by the amount of power provided by the guideway, the guideway to vehicle transmission efficiencies, vehicle power transmission efficiencies and the power rating of the vehicle electric motor. These factors will determine the vehicle maximum speed for a given roadway condition. The energy available to the vehicle is not a limiting factor for powered guideway operation, assuming roadway power is available for the total driving mission.

In order meet the most stringent AHS operational scenarios, the roadway must be able to meet the power requirements for all classes of RPEVs allowed on the roadway. The power demand of the vehicle will depend on the driving mission (vehicle speed, grade, platooning) and the weight and internal efficiencies of the RPEV.

<u>Power estimates for electrified guideways</u>. The numerical results of the study indicate that an electrified guideway would require 3-5 Megawatts of power to be delivered by the roadway per kilometer per lane for a modest vehicle scenario - (40 to 50 vehicles per kilometer) and no more than a 3% grade at a nominal driving speed of 100 kph. For electromagnetic coupling, i.e., induction between the road and the vehicle, gap losses may be as high as 50% depending on the precision of gap control.

<u>The RPEV performance on the guideway is limited, primarily, by the power that the vehicle electric motor can deliver to the roadway</u>. This factor could influence the design of EV/RPEVs in that smaller vehicles with insufficient battery power and energy for high performance and long hauls, could be designed with oversized electric motors to take advantage of the higher power and energy of electrified guideways.

<u>The electrified guideway can extend the off-guideway range of EVs</u>. The electrified guideway could simultaneously provide charging power to RPEV batteries, as well as driving power to the RPEV power train.

[12] The guideway powered vehicle model described in section 4.2 does not consider energy transfer efficiencies between the guideway and the vehicle.

5.0 APS IMPACTS

5.1 Population Projections for APS-Powered Vehicles

Proposed AHS concepts are influenced by the performance, design and population mix of contemporary vehicles, all powered by combustion engines, and in particular the spark ignition, gasoline fueled internal combustion engine. It is our belief that AHS concepts which may evolve over the next several decades will also be influenced by conventional vehicles existent in the time frame. A primary driver to that belief is the number of internal combustion engine vehicles in existence today, and postulates of slowly a major change to vehicle power could be introduced and thus influence AHS concepts.

We also believe that only electrically powered vehicles will have performance levels below that of contemporary vehicles. Alternatively fueled vehicles using gaseous - natural gas, petroleum-derived gas - or liquid fuels such as ethanol or methanol, will have similar performance capabilities to present vehicles and thus cannot be expected to influence AHS development to any measurable degree.

Therefore estimates of only electric vehicle sales and population were made for a twenty-five year period in order to gain insight into the potential market penetration of EVs during that same time frame.

Vehicle population projections were made using U.S. Department of Transportation and the Federal Highway Administration 1991 figures[13] for registered vehicles per capita and high, low and expected population projections provided by the Bureau of the Census[14]. The vehicle per capita value is assumed to be constant over the period of interest and is multiplied by the high, low and expected population projections through the year 2015 to yield an approximation high, low and expected vehicle populations. Assuming a constant vehicle/person figure to compute vehicle population projections is a more realistic approach than integrating vehicle sales over time, since the former allows for vehicle retirement.

[13]1994 World Almanac
[14]1990 Census

The results are illustrated in Figure 5.1-1, which suggests that there will be at least 200 million registered vehicles in the USA by 2015.

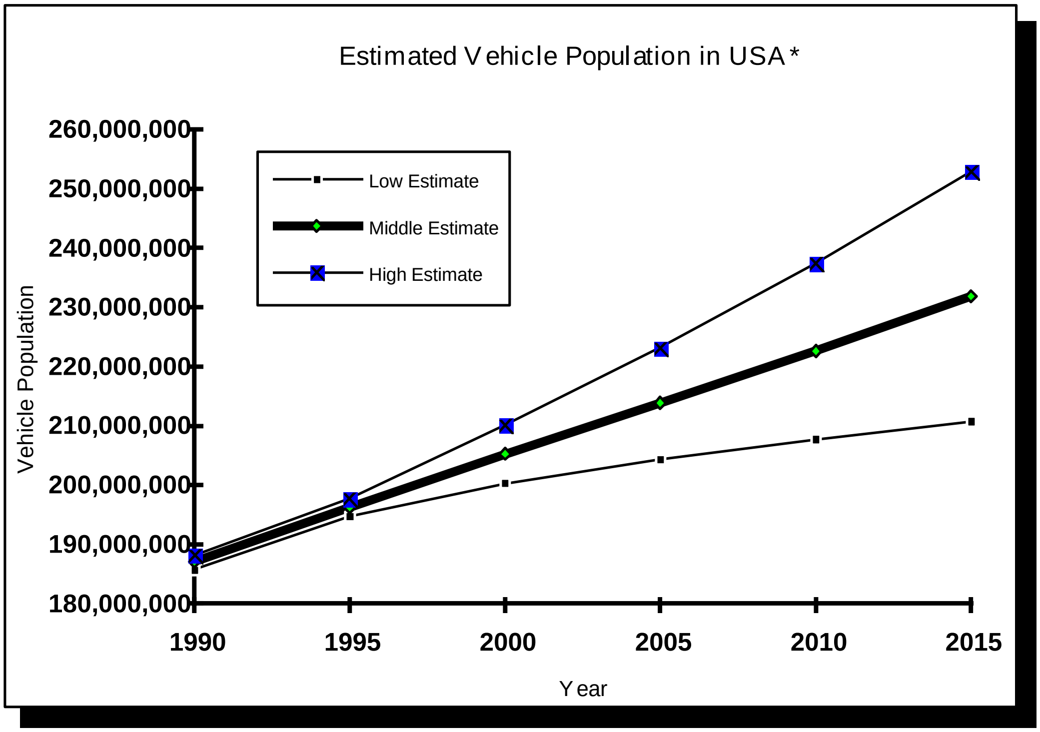

Figure 5.1-1. Vehicle Population Projections for the U.S.A.

Estimates for the annual EV sales were made using the percentages of zero pollution vehicles to be sold in California starting in 1998. Similar mandatory sales requirements are being considered for the northeast states. We applied these sales requirements on a national scale for high, low and median population growth. Figure 5.1-2 shows the results of this analysis.

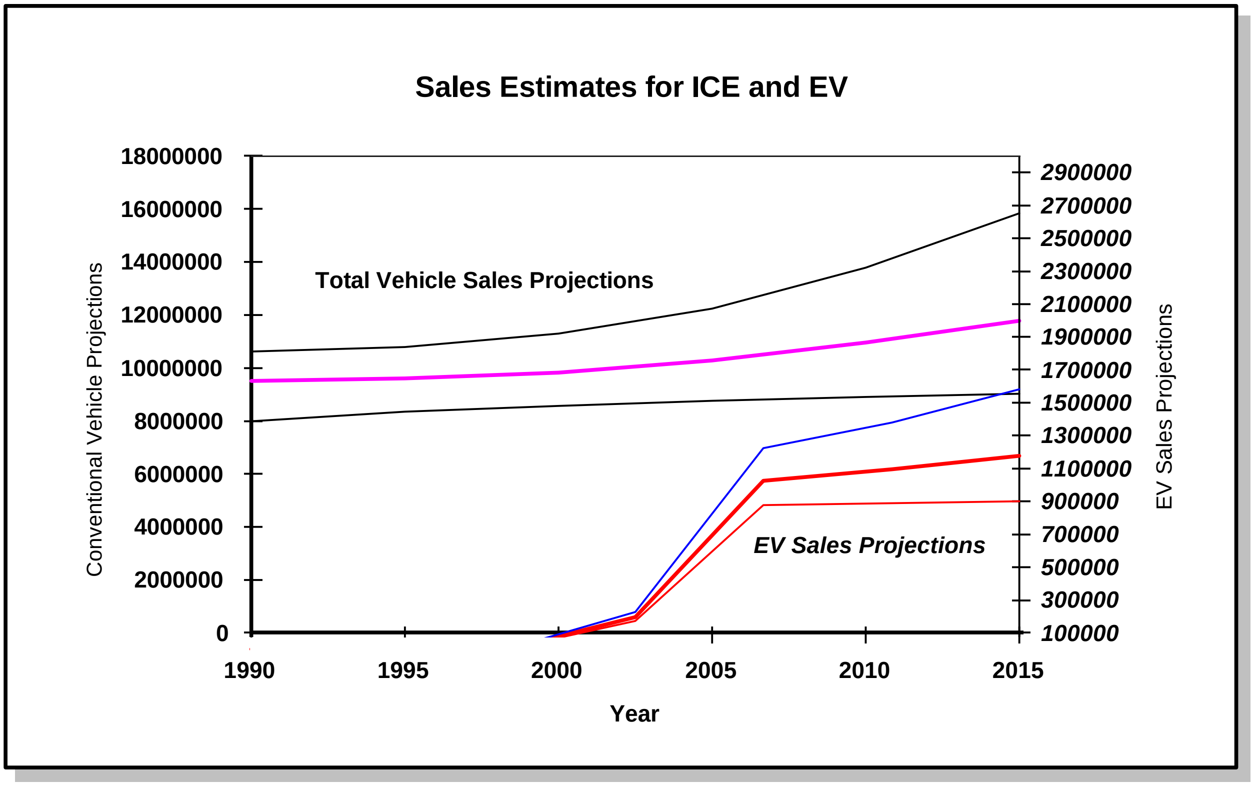

Figure 5.1-2. Estimated Sales Projections for ICE and EVs in the U.S.A.

The number of vehicles sold each year is not expected to vary much from 10 million vehicles per year. This number implies that non-ICE vehicles of any type could require at least 20 years to replace those vehicles that are on the road today. The figures also imply that EVs will continue to be in the minority beyond 2015, with less than 15 million EVs on the road, representing at most less than 7% of the total vehicle population.

If the EV population growth is close to the projections shown in the chart, the figures would suggest that, in general, there will be little market stimulus for utilities to invest in increased production capacity.

This analysis suggests that little can be done to shift the balance of influence away from the ICE and toward some LEV or ZEV concept, short of; (a) a very stringent, but probably unacceptable Federal mandate, or (b) major technological and cost breakthroughs in LEV/ZEV technology which would make those vehicles attractive.

5.2 Impacts of APS Vehicles

We have segmented potential impacts of APS vehicles into five categories: environmental impacts, impacts on the transportation energy market, particularly the electric utility market, vehicle design impacts, cross impacts between APS and AHS concepts, and administrative impacts.

5.2.1 Environmental Impacts

APS vehicles environmental impacts are twofold: impacts on vehicle and/or tailpipe emissions, and impacts on transportation energy sources.

Emission shifts. Widespread acceptance of AFVs and EVs will result in shifts in the type and level of emissions from vehicles. For example, it has been readily demonstrated that gaseous hydrocarbon fuels exhibit lower levels of carbon monoxide and total unburned hydrocarbons than gasoline fueled vehicles. Substitute liquid fuels may reduce the levels of carbon monoxide, but also may, under some circumstances introduce additional photochemically reactive pollutants. At best, given the small market share of AFVs in the next decades, we can expect very modest improvements in air quality. With an increasing number of combustion powered vehicles on the road, the ultimate question may lie in longer range issues of possible effects of carbon dioxide, i.e. green house effects.

A shift from on board stored energy to on board electric energy suggests a complete elimination of tailpipe emissions with a growth in emissions from central generating plants. The net effect on national air quality depends on a complex set of future scenarios which include air, water, thermal, and solid hazardous and radioactive wastes from generating plants, generating mixes - percentage of generation from coal, oil, nuclear, etc., generating plant geographical distributions, and time of day, week, and season of generating capacity devoted to vehicle propulsion.

Hazardous wastes and emissions from EVs. On board electrical energy storage suggests new forms of hazardous wastes may occur from non-complete recycling of spent batteries, hazardous chemical releases from road accidents and normal handling and operations. Electric propulsion will generate electromagnetic radiation which, if not properly controlled, can interfere with surrounding electronic systems.The net result of APS vehicles on a national basis is still a matter of considerable speculation: however within the time horizon of this study, and given the expected relatively low level of APS vehicle introduction in the market, the near term environmental impacts should be small.

EV batteries create materials demands. The large scale production of alternative liquid and gaseous fuels and their storage facilities will create a demand for raw materials such as lead, sulfur, chlorine, lithium and specialized steels. Such demand could have an adverse affect on the availability of those materials.

5.2.2 Utility Impacts

A shift to electrically powered vehicles will influence electrical utility generation in several ways.

First, the demand for electric propulsion power will tend to coincide with the beginning and end of normal work day industrial and commercial electric loads. If the transportation component had to be supplied on demand, it would add to problems of load matching and result in added peak capacity. For example, neglecting electric distribution losses and roadway to vehicle transmission losses, an electrified guideway would require 3-5 Megawatts of power to be delivered by the roadway to the vehicle per kilometer per lane for a modest vehicle scenario such as Operating Mode 3. Utilities would prefer that batteries be charged during of peak, night time periods and level their generating loads for more efficient baseload utilization.

Weather can affect the availability of electric power for battery charging and for guideway power. This issue is of particular concern in severe climates where extreme temperatures can require that central station electric power to be diverted for heating and cooling, or where weather can disrupt power service. Power generation, distribution, storage and backup power requirements will need to be addressed in the design and support of EVs and powered guideways.

During extreme weather conditions electric utilities may have to prioritize their services, and trade off among serving residential, industrial/commercial, and transportation segments.

5.2.3 AHS Cross Impacts

<u>Drafting affects in platoons reduce power requirements for following vehicles</u>. Following vehicles in platoons can benefit from the drafting affect of the lead vehicle and can result in as much as a 50% reduction in the aerodynamic component of drag. This translates into an energy savings of up to 20% for the high speed, long haul AHS scenarios. The lead vehicle may gain as much as 25% reduction in aerodynamic drag.

<u>Roadway controlled power scheduling</u>. All APS vehicles having more than one power source, i.e. hybrids, could greatly benefit from roadway controlled power scheduling. This feature would be essential for scenarios in which hybrid vehicles are operating in platoons. For conventional vehicles, on-board fuel supply and vehicle destination can be passed to roadside equipment during check-in, allowing the AHS to determine if the vehicle has sufficient fuel and power to reach a specified destination while operating in a high-speed, short headway AHS mode.

However, this is not sufficient information when considering certain hybrid vehicle designs, where the secondary power source is needed for acceleration and hill climb boosts. For such vehicles to operate in high-speed, short headway modes, the roadway must be more sophisticated and would require additional information and intelligence in order to ascertain the ability of the vehicle to reach its destination under particular AHS operating mode conditions. Other parameters required by the roadway might include: the vehicle destination, knowledge of terrain en-route to the vehicle destination, the vehicle primary power source capability, fuel on-board, the power boost capability of the secondary power source and the current energy state of the secondary power source.

Check-In Requirements. An AHS would need to have the ability, at check-in, to determine the overall capacity of an electric vehicle to meet the distance and peak power requirements of the proposed trip. This would include the ability to determine whether the vehicle had sufficient time and capacity to charge battery enroute, prior to any peak power battery load required by the road terrain.

AFV and EV refueling needs. An infrastructure to service APSs and EVs will need to grow and keep pace with the acceptance of those vehicles. At-home charging systems may require extensive electrical system distribution modifications. It is essential that industry-accepted, common charging/fueling system interfaces be developed.

Guideway power. Extensive and costly capital modifications will be required to roadways and power distribution systems to handle guideway propulsion power.

5.2.4 Vehicle Design Impacts

Passenger comfort requirements impacts. The ambient temperature determines passenger heating and cooling requirements both of which must be served by energy stored in EV batteries. The power requirements for typical on-board accessories may be as high as 9.4 Kw. Our study suggests that accessories consuming such high power levels would be incompatible with the limited battery capacity of many of the vehicles.

Braking regeneration capability for EVs. The benefits of regenerative braking for increasing vehicle range is marginal for AHS operation. Regenerative and dynamic braking can, however, reduce brake wear and braking effort, and provide independent wheel braking.

Temperature versus performance of EV Batteries. Special consideration will have to be given if EVs are to operate in particularly cold weather. Decreasing the ambient temperature generally reduces the stored energy effectiveness in conventional batteries, resulting in the loss of power and vehicle range.

Increased gross vehicle weight decreases range of EVs. Electric vehicles, because of their low power and energy, are very sensitive to vehicle gross weight. An increase of ten percent in gross vehicle weight can impose as much as a 6% penalty in vehicle energy, decreasing range accordingly. Interestingly our studies showed that given the allocation rules for contemporary vehicles, larger vehicles may be allocated a proportionally higher percentage to batteries and thus might compensate for the diminished range penalty.

Battery crash worthiness. Battery crash hazards are a concern for conventional batteries and an even greater concern for some of the more exotic battery concepts being evaluated today.

This is an added design concern for vehicle designers where the release of reactive agents or super heated materials could pose a greater danger than the initiating crash. Current preventive measures may add undesirable weight and volume that may compromise some of the advanced battery benefits.

Driving mission dependencies. AFVs and hybrid vehicles are inherently better suited for cruising and long haul scenarios than EVs, due primarily to inherently greater energy storage capacity of former. Even with promising battery technologies the EV is expected to be relegated to the urban driving mission. The availability of charging stations and the time required to charge are further limits to range and endurance.

Vehicle Handling and Feel. Since APS vehicles will have their propulsion subsystem weights and locations allocated differently than contemporary vehicles, designer must account for the change vehicle handling and feel due to changes in weight distributions. Further, electrically powered vehicles may have brake and throttle “feels” that are substantially different from contemporary vehicles. Both of these design impacts will require extensive engineering design effort to mitigate.

5.2.5 Administrative Impacts

Emergency response to AFV and EV incidents. This is a safety concern affecting the viability and public acceptance of AFVs and EVs. The existing police and fires services must be trained to respond to accidents involving these vehicles. Emergency road services must augmented with training and equipment to handle AFV- and EV-specific breakdowns. Hazardous material response teams must be created and trained for such incidences. This added level of infrastructure and service will need to be integrated into existing and planned traffic management centers.

Public education and training The public must be made aware, trained and qualified in the hazards presented by AFVs and EVs after an accident., as well as during normal operation and maintenance. Safety of home charging systems must be considered.

Maintenance and upkeep of AFVs and EVs. Training of technicians and mechanics will be required. Maintenance support systems will be required to cope with the problems associated with gaseous fuels, reactive materials, high voltages, and power electronics.

Road taxes. AFVs and EVs will not provide gasoline fuel taxes. This will cause a proportionate drop in tax revenues from gasoline taxes and the public and/or commercial operations shift to alternative propulsion systems. There will need to be a means established for including these vehicles in the road tax revenue structure.

REFERENCES AND BIBLIOGRAPHY FOR APS RESEARCH

Adlhart, O., "Fuel Cells, in Douglas M. Considine(ed.)," Energy Technology Handbook,McGraw-Hill Book Company, 1977, pgs. 4-59 to 4-74.

EVAA, EVolution, "Alternative Paradigm for EV Marketing", Vol. 1 Issue II, July 1993, pgs 3-4.

American Methanol Institute, "Nationwide Methanol Refueling Infrastructure Announced - 2500 New Pumps Planned Across U.S.," The Big M, Fall 1993.

American Flywheel Systems, "AFS20 compared to GM Impact and Chrysler LHS", January, 1994.

Automotive Engineering, "Fuel Cells: an overview," April, 1992, Vol. 100, No. 4, pgs 13-16.

Automotive Engineering, "Methanol/gasoline blends and emissions: part 1," April 1992, Vol. 100 No. 4, pgs 19-21.

Automotive Engineering, "Methanol/gasoline blends and emissions: part 2," April 1992, Vol. 100 No. 5, pgs.17-19.

Automotive News, May 26, 1993, 1993 Market Data Book, pgs 3-36.

Bender, J.G., "An Overview of Systems Studies of Automated Highway Systems," IEE Transactions on Vehicle Technology, Vol. VT-40, No. 1, Feb. 1991.

Bornhop, Andrew: "1994 BMW 540i," Road & Track, Vol. 45, No. 3, Nov. 1993, pgs. 95-98.

California Energy Commision, "Methanol Fueling Locations in California," July 1993.

Chalsma Jennifer K., "Filling Up on Alternative Fuels," Machine Design, 1993, pgd 63-80.

Chan, C. C.: "An Overview of Electric Vehicle Technology",Proceedings of the IEEE, Vol 81, No. 9, September 1993.

Columbia Gas Co., "An Informational Guide to Natural Gas Vehicles", 1994, Volume 1, Issue 1, January 1994.

Cooper, Barry, "The future of catalytic systems, Automotive Engineering," April, 1992, Vol. 100 No. 4, pgs. 9-12.

Dauvergene, J.:Electric vehicle climate control, Automotive Engineering, April, 1994
Vol. 102, No. 4, pgs. 55-57
NASA: Mission Accomplished, March, 1994, NASA Tech Briefs, Vol. 18, No. 3, pgs.15-16

Delaney, Tom: Science Advances Herald Polutant-Free Automobile, National Defense, March, 1994, pgs 26-27.

Electric Power Research Institute, "Battery Development for Electric Vehicles", December 1990, CU.3034.12.90.

EPRI, 1992, "Electric Vehicles and the Environment," BR-100553.
Erskine, Chris: The Car of the Future, LA Times, March 1, 1994

Fenton, R.E., Mayhan, R.J., "Automated Highway Studies at the Ohio State University - An Overview, " IEEE Transportation Vehicle Technology, Vol. VT-40, No. 1, Feb. 1991.

Flywheel Batteries for Electric Vehicles, An Introduction, EVolution, EVAA, Vol. 1, Issue I, June 1993, pgs. 3-4.

Ford Motor Company -- Working Towards a Cleaner Future, EVolution, EVAA, Vol. 1, Issue II, July 1993, pgs. 1-2.

Fortune, March 8, 1993, Coming of Age of the Electric Vehicle, A Special Advertising Section.

Foss, Christopher F., Gander, Terry J.(ed.): Jane's Military Logistics, Eleventh Edition, 1990-1991,Jane's Information Group, Coulsdon, Surrey,UK,1990, pgs. 385,570-572.

Gelb, George H., Richardson, Neal A., Wang, T.C., Dewolf, Robert S., "Design and Performance Characteristics of a Hybrid Vehicle Power Train," SAE Internation Automotive Engineering Congress, January, 1969.

Gelb, G. H., Berman, B., E. Koutsoukos, "Cost and Emission Studies of a Heat Engine/Hybrid Family Car," EPA Contract No. 68-04-0058, April, 1972.

Gelb, G. H., Wang, T. C. "Hybrid Vehicle Study Program Six Month Progress Report," TRW, June 1968.

Gelb, G. H., "The Case for Constant Speed Accessory Drives," TRW Automotive Worldwide, January 1975.

GM: 1994 Chevy Trucks, July, 1993.

GM Electric Vehicles, "Impact 3 Specifications," 1993.

GM, "Natural Gas Vehicle Program Vehicle Specifications," P&P 7309 12/94.

GM Transportation Systems Center et al, "Systems Studies of Automated Highway Systems," report EP-81041A, July 1982.

Heitner, K., Skartvedt, P., "Battery Technology -- An Assessment of the State of the Art," DOE, Contract No. EX-76-C-10-3885, Task Order No. 23.

HBTI: Manufacturing the Horizon Battery, 1994

HBTI: Horizon Battery, Technical Summary, 1994

HBTI: The Horizon Battery, 1994

Ioannou, P., "AHS Evolution," Raytheon/USC Team, January 1994.

Jerry, W.D., "A Hypothesized Evolution of an AHS," Rockwell International Team, January 1994.

Kumakura, H., Sasaki, M., Suzuki D., "Low NOx Combustor for Automotive Ceramic Gas Turbine--Reliability Assurance,Journal of Engineering for Gas Turbines and Power," Transactions of the ASME, July 1993, Vol. 115, pgs. 547-553.

Los Angeles DWP, "Electric Vehicles... Plugging into a Clean-Air Future," 8M 4/93, April, 1993.

Mayersohn, Norman S.: The Outlook for Hydorgen, Popular Science, October, 1993, pgs. 66-77, 111.

Metro Magazine, Buses Bear Brunt of Cleaning Nation’s Air, Vol. 88, No. 2, March/ April 1992, pgs. 24-32.

Miller et al, "Highway Automation: Regional Mobility Impacts Assessment," Session 94A on IVHS System Evaluation, Transportation Research Board, Washington D.C., 1993.

Moore, Taylor, "The Push for Advanced Batteries," EPRI Journal, April/May 1991, pgs. 17-19.

Nauss, Donald W." Battery Technology Fuels the Electric Vehicle Debate", LA Times, May 11, 1994.

Nemecek, Sasha, "Bettering Batteries", Scientific American, November 1994, Vol. 271, No. 5, Page 106.

O’Connor, Leo, "Energizing the Batteries for Electric Cars, Mechanical Engineering", Vol. 115, No. 7, July 1993.

Pasternak, Alan, "Methyl Alcohol-A Potential Fuel for Transportation, in Douglas M. Considine(ed.)," Energy Technology Handbook, McGraw-Hill Book Company, 1977, pgs. 4-44 to 4-49.

Proceedings of the 1992 IVHS America Annual Meeting, "Advanced Vehicle Control Systems" section.

Purcell, Gary, "Electric Vehicle Infrastructure The Key to Successful Introduction," EPRI,TR-102504, Research Project 3272, May 1993.

Reed, Robert M., "Hydrogen, in Douglas M. Considine(ed.)," Energy Technology Handbook, McGraw-Hill Book Company, 1977, pgs. 4-26 to 4-43.

Reynolds, Kim, "1994 Integra GS-R," Road & Track, Vol. 45, No. 3, Nov. 1993, pgs. 80-84.

Riezenman, Michael J., "Electric Vehicles," IEEE Spectrum, November 1992, pgs. 18-21.

Riezenman, Michael J., "Pursuing efficiency", IEEE Spectrum, Novenber 1992, pgs.22-24,93.

Riezenman, Michael J., "Architecting the system," IEEE Spectrum, November 1992, pgs.94-96.

Riezenman, Michael J., "The great battery barrrier," IEEE Spectrum, November 1992, pgs. 97-101.

Road & Track, "AC Propulsion CRX," Vol. 44, No. 2, Oct. 1992, pg. 129.

RTD, "Leading the Way to Cleaner Air for the Nation's Buses," 4840/10M/390.

Rusz, Joe, "1994 Chrysler LHS, Road & Track," Vol. 45, No. 3, Nov. 1993, pgs. 88-92.

Saturn Corporation: 1994 Saturn,SO2-94-025, August 1993.

Shladover, S.E. et al, "Automatic Vehicle Control Developments in the PATH Program," IEEE Transactions on Vehicle Technology, Vol. VT-40, No. 1, Feb. 1991.

Simanaitis, Dennis. "Volvo ECC, Road & Track," Vol. 44, No. 10, June 1993, pgs 120-123.

Simanaitis, Dennis, "Hydrogen is abundant and clean, but is it tomorrow's motor fuel?," Road & Track, Vol. 44, No. 12, Aug. 1993, pgs. 118-123.

Southern California Edison, "Preparing for Tomorrow, Today," EVolution, EVAA, Vol. 1, Issue I, June 1993, pgs. 1-2.

Southern California Gas Co., "Southern California Gas Co. Natural Gas Program," Sept. 1993.

Southern California Gas Co., "Southern California Gas Co. Pushes Natural gas Vehicle Market Ahead with plans to build, market and fuel vehicles," News Release,94-004,Jan.6, 1994.

Stevens, W.B., "The Automated Highway Systems (AHS) Concepts Analysis, "MTR 93W0000123, MITRE, McLean VA, August 1993.

Sullivan, E., et al, "Vehicle Speeds and Accelerations Along On-Ramps: Inputs to Determine the Emissions Effects of Ramp Metering," Final Report, ARDFA, Cal Poly, October 1993.

Unique Mobility, "Technology for Today's Electric Vehicles," EVolution, EVAA, Volume 1, Issue III, August 1993, pgs 1-2.

U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, "Statistical Abstract of the United States, 1991, The National Data Book", 111th Edition, page 608.

Voight, Keith, "Fast Lane to Practicality Electric Vehicles," Electric Perspectives, May-June 1992.

Westinghouse, Electic Power Train, Ds-070-CAD-1293

World Almanac, 1994, pgs. 189, 191, 361, 363.