

UC Berkeley

Research Reports

Title

Highway Electrification And Automation

Permalink

<https://escholarship.org/uc/item/8kk9d7f7>

Author

Shladover, Steven E.

Publication Date

1992

This paper has been mechanically scanned. Some errors may have been inadvertently introduced.

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Highway Electrification and Automation

Steven E. Shladover

UCB-ITS-PRR-92-17

This report has been prepared for the Secretary of Transportation under the provisions of Section 164 of the Surface Transportation and Uniform Relocation Assistance Act (STURAA) of 1987. That Section allocated \$2.91 million to the California Department of Transportation “for the purpose of determining the feasibility and applicability of utilizing a highway electrification system as a source of energy for highway vehicles. ” The Conference Committee report on Section 164 expressed “the Committee’s intent **that** the activities funded under this section extend from highway electrification to the related technology of highway automation,” as well as its belief that the funding authorized “will serve as a nucleus of funding for a larger, overall program attracting contributions from other public agencies and the private sector.” This report will demonstrate how effectively the intent of the 1987 Act has been realized.

DECEMBER 1992

ISSN 1055-1425

CONTENTS

Executive Summary	1
I. Introduction	3
II. Caltrans New Technology Program and the California PATH Program	5
III. Roadway Electrification Experimental Results	8
IV. Deployment Considerations for Roadway Electrification Systems	15
V. Roadway Electrification Deployment Impact Study for Los Angeles	18
VI. Highway Automation Development Work	20
VII. Vehicle Control Experimental Results	24
VIII. Highway Automation Deployment Impact Study for Los Angeles	27
IX. Conclusions	29
References	32

HIGHWAY ELECTRIFICATION AND AUTOMATION

Report under Section 164 of 1987 STURAA

EXECUTIVE SUMMARY

Section 164 of the 1987 Surface Transportation and Uniform Relocation Assistance Act (STURAA) allocated \$2.91 million to the California Department of Transportation for the purpose of determining the feasibility and applicability of highway electrification and automation technologies. These funds were intended to serve as a nucleus of funding for a larger program attracting other sources of public and private support. This report documents the accomplishments that have resulted from the investment of these federal funds, combined with substantially larger state resources and some private resources as well.

The California Department of Transportation (Caltrans) used this initial research grant as leverage to obtain matching state funding and to initiate a comprehensive partnership with the major research universities in California and industry to address future highway and transit needs. Caltrans reorganized to place more resources and emphasis on “New Technology and Research” and solicited the University of California at Berkeley to organize and manage the research portion of this new effort, now called the Partners for Advanced Transit and Highways (PATH). Today California has the largest IVHS R&D program in the country, with funding of about \$8 million per year, involving 25 full-time staff members, 30 faculty members, and 60 graduate students.

The highway electrification technology has been tested on full-scale vehicles, using a test facility especially developed for this purpose. This has demonstrated the capability of inductively transferring energy across an air gap to a moving vehicle at an efficiency comparable to that of conventional battery charging systems. The experiments have demonstrated the ability of the energy transfer system to extend the operating range of an electric vehicle by a factor of ten. The system has been shown to be capable of operating within reasonable limitations on acoustic noise and electromagnetic field emissions. The principal remaining uncertainties are associated with the methods for installing roadway inductors, the power distribution system design, capital costs and the means for achieving the needed vehicle steering accuracy.

A planning study has shown that highway electrification could save gasoline in proportion to the fraction of regional vehicle miles traveled (VMT) driven by the electrified vehicles, with somewhat lesser reductions in pollutant emissions. With overnight battery recharging, the highway electrification concept, surprisingly, should have only a minor impact on the power generating capacity needs of Southern California.

The highway automation technologies of automatic lateral (steering) and longitudinal (speed and spacing) control have been tested on full-scale vehicles. In both cases, it was demonstrated that use of largely off-the-shelf components could produce accurate vehicle response together with good ride comfort. This provides encouragement that an automated highway system (AHS) can be developed to provide increased capacity and safety by making use of a judicious mixture of

technology applied in the vehicles and the roadway. Design studies indicate the possibility that an AHS could triple the capacity of existing freeway lanes.

A planning study for the Los Angeles region has indicated that application of an AHS on a portion of the existing freeway network could produce dramatic improvements in travel speeds and delay throughout the entire roadway network, including arterials and non-automated freeways.

The research reported here can serve as the foundation upon which to build the test track demonstration of an AHS prototype as mandated in the 1991 **ISTEA**.

I. INTRODUCTION — IDENTIFICATION OF PROBLEMS

Our surface transportation systems are over-stressed. Worse, the problems have not responded to conventional solutions. These problems include:

- limited capacity and productivity of infrastructure
 - traffic congestion
 - accidents producing injuries, fatalities and property damage
 - limited mobility, especially for the disadvantaged
 - stressful travel conditions

- air pollution
 - noise pollution
 - excessive energy consumption (especially petroleum)

- high capital and operating costs.

The first group of five problems can be addressed primarily by the emerging family of technologies of intelligent vehicle/highway systems (IVHS), and particularly by the most advanced of these, the highway automation technologies. The second group of three problems can be addressed by electric vehicle technologies, if the inherent limitations of their electrical energy storage systems can be overcome, for example by use of highway electrification technology. Ultimately, the cost problems cut directly across everything else, in terms of both problems and potential solutions.

There is a danger in segregating the transportation problems and potential solutions as above, because they are all in reality closely coupled with each other. Improvements in the operational area from IVHS measures such as highway automation can also have significant benefits in the energy and environmental areas, for example. It is also important that the problems be addressed together as a complete set, so that none of them is overlooked when considering a solution to one that may have an adverse effect on another.

The technologies of highway electrification and automation that are considered in this report have the potential to make significant contributions toward solving the problems that were identified above. They should not be viewed as complete solutions to the problems, but as elements in the “toolkit” of solutions that planners and policymakers can have available to use where they are most appropriate.

This report addresses how Caltrans and the California PATH Program have applied the resources allocated in Section 164 of the 1987 STURAA, together with much larger matching state and private resources, to evaluate the feasibility and applicability of highway electrification and automation technologies. Chapter II describes how the work was conducted. Chapters III to V describe the findings on highway electrification, with experimental results, design study results, and a region-wide application impacts study for Los Angeles. Chapters VI to VIII

describe the highway automation findings, beginning with the concept definition and analysis work, followed by the experimental results and the region-wide application impacts study results for Los Angeles. The overall conclusions are summarized in Chapter IX.

H. CALTRANS NEW TECHNOLOGY PROGRAM AND THE CALIFORNIA PATH PROGRAM

The \$2.91 million of federal funding augmented state funding for the Caltrans New Technology Program and became the cornerstone of the California PATH Program at the Institute of Transportation Studies of the University of California, Berkeley. It served to ignite national interest in what subsequently became known as Intelligent Vehicle/Highway Systems (IVHS). PATH emissaries visited key institutions in the public, private and academic sectors around the country and hosted workshops and demonstrations to develop an awareness of the potential of advanced technologies for improving transportation operations, leading to the formation of the ad hoc working group that eventually named itself Mobility 2000. This, in turn, led to the founding of IVHS America as a utilized advisory committee to the Department of Transportation.

Since its founding in 1986, the California PATH Program has received a mixture of direct federal and state funding, together with indirect matching cost contributions from various private sector organizations. The public funding totals, incorporating cumulative obligations through October 1992, are:

FHWA (Section 164, 1987 STURAA)	\$	2.91 million
UMTA (Section 333, 1987 STURAA)		SO
FHWA (FY 89 appropriations)		.02
FHWA (FY 91 appropriations)		SO
FHWA (FY 92 appropriations)		1.30
NHTSA (FY 90 appropriations)		.30
Caltrans (HP&R funds)		.21
Caltrans (state highway account funds)		23.08
California Department of Commerce (CompTech funds)		.10
Total	\$	28.92 million

A variety of organizations have participated in cooperative projects with the PATH Program, investing their own resources to provide further leveraging of the public funds. In the area of highway electrification technology in particular, the Southern California Edison Company and City of Los Angeles, Department of Water and Power have invested about \$1.7 million in extending the publicly-funded PATH research to new design conditions of particular interest for possible application in a large scale mixed-use real estate development at Playa Vista. The Southern California Association of Governments (SCAG) has matched the \$450 thousand of Section 164 funding allocated for its regional impacts studies with an additional amount of approximately \$340 thousand from other sources. The value of the in-kind contributions of the various cooperating private companies cannot be determined precisely, but it is likely to represent additional millions of dollars.

Clearly, the expectation in the Committee Report that the Section 164 funding “will serve as a nucleus of funding for a larger, overall program attracting contributions from other public agencies and the private sector” has been more than met.

The research and development program that has resulted is very broad and ambitious in its scope, and continues to grow substantially beyond the level that was envisioned at the start. It currently employs about 25 full-time staff people, plus about 30 university faculty members and about 60 graduate student researchers on a part-time basis. These researchers are conducting about 50 currently active projects, while the total number of projects since the program’s inception is approaching 100.

The distributions of funding and projects by topic area are summarized in Table 1.

Although the Caltrans New Technology Program and the California PATH Program began with a dual focus on highway electrification and automation, Table 1 indicates how much more broadly the efforts are distributed now. This reflects evolution in the thinking within California as well as the influence of the national program in IVHS. IVHS includes many technologies and services that can be made available for use in the nearer term, providing an evolutionary progression toward the eventual full-scale Automated Highway System (AHS). These range from systems for driver safety warning and control assistance to more intelligent traffic signal control, real-time traffic information, in-vehicle navigation and route guidance, transit and rideshare information, integrated areawide arterial and freeway traffic operations, enhanced incident response and electronic toll collection integrated with transit fare collection and parking payment. While none of these is likely to have as large an impact as highway automation, they are nevertheless important elements in the early implementation of advanced technologies to improve the operation of the surface transportation system.

Table 1: Distribution of PATH Funding and Projects by Topic

Topic Area	Cumulative Funding Obligations 86-92	Current Projects
Clean Propulsion Technology (Roadway Electrification and Hybrid Vehicles)	\$ 2.6 million	1
Advanced Transportation Management and Information Systems (ATMIS)	\$ 3.2 million	14
Advanced Vehicle Control Systems (AVCS), including Highway Automation	\$ 8.5 million	15
Human Factors and Safety	\$ 1.3 million	5
Commercial Vehicle Operations (CVO)	\$ 0.2 million	
Advanced Public Transportation Systems (APTS)	\$ 0.2 million	3
Impacts and Applications Studies	\$ 1.5 million	2
Policy and Planning Studies	\$ 1.5 million	6
Enabling Technologies Research	\$ 2.4 million	7
Systems Engineering	\$ 1.0 million	1
Electronic Toll Collection	\$ 0.2 million	--

III. ROADWAY ELECTRIFICATION EXPERIMENTAL RESULTS

Roadway electrification is the non-contact transfer of energy to an electric vehicle while it is stationary or moving. This energy transfer permits the vehicle's operating range to be extended beyond the range limitation imposed by the capacity of the vehicle's **onboard** energy storage device (battery). The energy collected by the vehicle can be provided directly to its powertrain (motor controller and motor) while it is driving, and can also be used to recharge its battery. The vehicle can operate on powered roadways or conventional existing roadways (where it draws energy from its battery).

Use of electromagnetic induction from a source beneath the road surface for the energy transfer permits use of the technology by all road vehicles and avoids possible electric shock hazards. The elements of the inductive energy transfer system typically include a roadside AC power supply and distribution system, a roadway inductor installed immediately below the road surface, a pickup inductor mounted to the underside of the vehicle, and **onboard** power control, rectification and filtering circuitry.

Prior to 1987, considerable research had already been conducted on roadway electrification, using the inductive transfer of energy from roadway to vehicle. The results of that research were documented in some early reports on a first-generation system from the Lawrence Berkeley Laboratory [1,2] and Lawrence Livermore National Laboratory [3], followed by a series of reports on a second-generation system for the Santa Barbara Electric Bus Project [4-7]. Those reports described the analysis and design of the inductive energy transfer system, as well as extensive laboratory testing of a full-scale mockup of the system at the Caltrans Transportation Laboratory in Sacramento. They also covered the design and specifications for the on-vehicle equipment installed in a specially constructed 35-passenger midsize bus, which was tested under battery-only power along its intended route in downtown Santa Barbara, CA.

Research since 1987 has brought the roadway electrification technology much closer to deployability, proceeding through third and fourth generations of design. Principal attention and resources have been devoted to:

- design and construction of a 400-foot electrified roadway test track at the Richmond Field Station of the University of California, Berkeley on which dynamic tests were conducted;
- dynamic tests of roadway power transfer to an electric bus, representing operation analogous to downtown Santa Barbara bus circulation service;
- effectiveness testing of design enhancements to reduce acoustic noise and electromagnetic field effects;

- design enhancements of in-vehicle power control circuit for compact installation in the vehicle and smooth control of power transfer level;
- evaluation of power transfer efficiency and expected operating range of roadway-powered electric bus;
- design and testing of fourth-generation inductive power transfer system for electric G-van, employing different operating characteristics.

Detailed descriptions of these activities can be found in the comprehensive report describing the roadway electrification research work [8]. Attention here will focus on the significance of the results of that work for determining the feasibility and applicability of the technology.

Power Transfer Effectiveness

The third-generation system has demonstrated the capability to transfer up to 60 kw from the roadway to the electric bus while the bus was traveling along the powered roadway. The maximum power transfer rate is reduced when the power pickup is not centered over the roadway inductor or if the pickup rides at a larger than nominal air gap height above the roadway. The larger air gap height does not normally arise in practice (except if the vehicle body bounces on its suspension when it hits a bump, or if there is an accumulated layer of snow on which the vehicle is driving). Because drivers cannot normally follow the lane center with high precision, the test bus is equipped with meters to tell the driver how close he is to the lane center. If the vehicle is displaced from the lane center by four inches, the power coupling is reduced by half, and if it is as far as 7 inches from lane center, effective power coupling is lost. This indicates the desirability of coupling the roadway electrification technology with lateral guidance or steering assistance systems to help the driver remain as close as possible to lane center.

Power Transfer Control

It is important to be able to control the amount of power transferred from the roadway to the vehicle so that the power supply can be matched to the power demand. This helps avoid overcharging the battery or wasting energy when, for example, regenerative braking energy is available from the motor control system (during decelerations or operations on down grades). The inductive power transfer system can be designed to ensure that it transfers the power needed by the vehicle on the average. In order to do this, the power available when the vehicle is centered in its lane is higher than the average needed and the control system is used to electrically detune the system so that only the needed power is drawn.

The **onboard** control system was completely redesigned and rebuilt during the current phase of the project in order to make it more compact, lighter in weight, and smoother and quieter in

operation. All of these objectives were achieved and verified in the testing program. The acoustic noise from the onboard controller in the test bus was low enough that it was not perceptibly distinct from the noise from the power pickup unit (which was reduced to an acceptable level, as explained subsequently). The operation was smooth enough to enable the system to match the actual transferred power to the desired power with reasonable accuracy.

Acoustic Noise

The principal objection to the earlier generations of inductive power transfer system was their very noticeable acoustic noise, which is produced by magnetostrictive forces induced in ferromagnetic materials by the magnetic field that transfers the power. The third-generation system for the test track and electric bus was designed to take advantage of every opportunity to reduce acoustic noise generation. The inductor core design was optimized for noise reduction potential, and significant care was taken with assembly and installation of parts to minimize noise. The result was that the open roadway produced virtually no perceptible noise when it was powered up.

When coupling power to the vehicle, perceptible noise is created in the power pickup, at a dominant frequency twice the frequency of the electrical excitation (800 Hz for the 400 Hz system). Because this noise has a strong fundamental component (not really a pure tone, but certainly a distinct pitch), it is perceptible even against a higher ambient level of background noise. Within the bus, this noise was measured to be in the range of 40-45 dBA, and alongside the bus it was not directly measurable because it was dominated by the sound of the moving vehicle itself (56-66 DBA at 20 mph regardless of whether power was being transferred or not). The bus motor and rear axle were clearly noisier than the inductive coupling system, but even still this powertrain is 15-20 dBA quieter than a diesel bus of the same size and weight.

The remaining acoustical problem was the generation of noise in conventional (non-electrified) vehicles located above the powered roadway. The magnetic field caused the bodies of these vehicles to hum loudly enough to be disturbing to their occupants. This problem was overcome in the fourth-generation design of the inductive power transfer system that was developed for the electric G-van. This was accomplished by increasing the operating frequency significantly, which permitted a reduction in the roadway current, and by installing additional cable windings along the outer edges of the roadway inductor to help cancel the magnetic fields.

Electromagnetic Fields

Since the inception of work on inductive power transfer to road vehicles, questions have been raised about the effects of human exposure to the magnetic field that is produced. These concerns have become stronger during the course of the development work because of the publication of books and articles in the popular press, which have raised public consciousness of the issue. The available scientific data are at this point so limited that it is not possible to

define a standard for human exposure to low-level low frequency magnetic fields that will be generally accepted. Since no such standard is available, the significance of the fields produced by the electrified roadway can be illustrated by comparing them with other electromagnetic fields we all encounter in our everyday environment.

The baseline 400 Hz inductive power transfer system for the main test track and electric bus (third generation) produces an electromagnetic flux density of about 100 milligauss for passengers inside the bus, and 30 to 60 milligauss at chest height for passengers in conventional cars located above the powered roadway. Pedestrians who walk across the powered roadway inductor are exposed to 10,000 milligauss at a height of 1 ft and about 1,000 milligauss at a height of 4 ft above the center of the inductor's conductor slot. For a pedestrian walking along a sidewalk parallel to the powered roadway, at a distance of 15 feet from the center of the powered lane, the flux density is in the range of 50 milligauss. These levels compare with everyday exposure levels of 1,000 to 10,000 milligauss while using an electric shaver, 100 to 200 milligauss for an electric blanket or electric toaster user, and 1 to 10 milligauss for sitting in the center of a typical living room. The durations of these exposures can vary significantly, as can the durations of exposures to the roadway inductor. For example, the pedestrians walking across the powered roadway are likely to be exposed for only a couple of seconds, substantially shorter than an electric shave, and pedestrians along the sidewalk or waiting at a bus stop will be exposed for much shorter times than people who sleep under electric blankets.

It is also useful to note for comparison that the Florida state regulatory standard for magnetic flux density at the periphery of an electric utility transmission line right of way ranges from 150 to 250 milligauss. The utility industry would be unwilling to apply the roadway electrification technology unless its human EMF exposure levels were below this standard level.

The electromagnetic field effects of the fourth-generation design were reduced by the same measures that were used to reduce acoustic noise: higher operating frequency, lower roadway current and field cancellation windings along the outer edges of the roadway inductor. These led to reductions of the magnetic flux density to about 1000 milligauss at a height of 1 ft and about 100 milligauss at a height of 4 ft above the center of the conductor slot, with similar reductions by about one order of magnitude for the flux densities at locations near the roadway inductor and two orders of magnitude at larger distances to the side (10 ft or more). These changes bring the magnetic fields down to much lower levels than those commonly encountered in use of the everyday electric appliances referred to earlier.

In the earlier stages of the project, concerns were raised about the possibility that the electromagnetic field of the roadway inductor could interfere with the operation of heart pacemakers. However, even at the measured levels of the third-generation design it appears that there is no appreciable chance of producing a health hazard by this mechanism.

There was some limited experimental evidence that the third-generation system could produce interference with automotive electronic systems. It appears that the magnetic field from the roadway inductor can cause speed sensors that are based on magnetic pulse counting to give false

readings, thereby confusing some electronic engine control systems and anti-lock braking systems. Limited experimental work with the lower roadway currents and higher operating frequency of the fourth-generation system indicates the likelihood of a significant reduction of these effects as compared to the third generation system.

Power Transfer Efficiency

Since the primary motivations for use of electric vehicles and the roadway electrification technology are associated with environmental protection and energy consumption, it is important that the system be reasonably efficient. There is a design trade-off between efficiency and economy for this technology, because electrified roadway system capital costs increase much more quickly with increases in efficiency than the operating costs decrease. The **400-foot** test track of the third generation design provided the first opportunity to measure operating efficiency of the inductive power transfer system, because losses were not measurable at the laboratory facility where the earlier generation designs were tested.

The principal loss components in the operation of the system are fixed, and therefore do not depend on the amount of power being transferred. This means that the efficiency is inversely related to the amount of power transferred (i.e., if less power is transferred and the losses remain unchanged, the efficiency decreases). For the conditions represented by the full-scale test track and electric bus, the measured power transfer efficiency from utility source to battery terminals on the vehicle was a maximum of about 60% (when transferring the maximum power of 60 kw). This decreased at lower levels of power transfer (50% at about 27 kw, for example). While these efficiency levels are lower than one would expect for a conventional battery charger, the comparison between the two becomes more nearly equal when one considers the efficiency on a complete system basis. This is because much of the energy transferred to the moving vehicle by the inductive power transfer system (about half in the test cases, and as much as 80 to 90% in operational scenarios) goes directly to the motor controller and is therefore not subject to battery charging and discharging losses.

The fourth-generation design for the electric G-van incorporates some changes to increase its efficiency relative to the third-generation design. Based on the initial test results on a short segment of inductor, it appears that its efficiency is in the range of 65%. It should be possible to increase this by some modifications to the roadway core fabrication process and by a reduction in the operating frequency from 8500 Hz to perhaps half that.

Vehicle Operating Range

The highway electrification technology overcomes the primary problem of conventional electric vehicles-their very limited operating range. It does this by providing charging of the battery while the vehicle is traveling, so that it can travel much further in a day than the range associated with a single recharge of its battery. The test facility developed under this project

was designed to approximate one block of downtown Santa Barbara so that the Santa Barbara downtown circulation duty cycle could be represented in the testing.

The electric bus was tested on the actual downtown Santa Barbara route during an earlier phase of the project using battery power only. It was able to operate for about 2.5 hours, covering a distance of about 18 miles, before the battery was too deeply discharged to provide adequate performance. With use of the roadway power on the test track, the vehicle was driven about 50 miles in 7 hours of operation, and had still only discharged 83 amp-hours of battery capacity (about one-seventh of its usable capacity). It was not possible to continue the test long enough to determine the ultimate range of the vehicle, but several estimates of that range have been made based on the test results. These estimates are in excess of 250 miles, which is more than ten times the range achievable on battery power alone.

Component Sizes, Weights and Costs

In order for the roadway electrification technology to be practicable, that its equipment must be of sufficiently modest size, weight and cost that it can be accommodated within the vehicles that need it, as well as the roadways. The technology has been installed on two different test vehicles, a mid-size electric bus and an electric G-van. The weights of the on-vehicle equipment are tabulated below:

	Bus 3rd generation	G-van 4th generation
Battery	6000	1700
Inductive pickup	1200	600
Onboard controller	700	<u>150</u>
Subtotal	7900	2450
Gross vehicle weight	31,200	8600
Percentage for RPEV equipment	25.3%	28.5%

The inductive pickup fits beneath the floor of the bus, while the **onboard** control equipment is installed between the front wheel wells, where it is easily covered and concealed from the passengers. On the G-van, the battery tray that is normally used for the electric version of this vehicle is replaced with a modified tray that incorporates a new, lower-capacity battery, together with the inductive pickup, without exceeding the weight of the original battery tray. The **onboard** controller has been developed in breadboard form for this vehicle, but has not yet been packaged compactly. The smaller battery provides a reduced autonomous range for the vehicle, but its effective operating range is increased by receiving energy from the roadway inductor.

The roadway inductor for the third-generation design is about 4 inches deep and 40 inches wide, and is intended to be installed in the center of the traffic lane. The fourth-generation design features a roadway inductor cast into a concrete module 7.5 inches deep and 50 inches wide, which can serve as an element of the roadway structure.

The costs of the roadway electrification equipment are extremely difficult to estimate at such an early stage in their development, when they have only been produced in hand-built quantities of one or a few. It appears that the roadway costs could be in the range of \$2.5 million per lane mile installed, while the on-vehicle equipment costs will depend on the size and power level of the vehicle. These might be of the order of \$1500 to \$2500 per light-duty vehicle or \$3600 per bus, as very crude initial estimates. At these cost levels, the roadway electrification equipment plus battery costs would be comparable to or less than the costs of the (larger) battery alone that would be needed for a pure battery electric vehicle. These capital costs remain higher than the costs of comparable conventionally-powered (diesel) buses, for example.

IV. DEPLOYMENT CONSIDERATIONS FOR ROADWAY ELECTRIFICATION SYSTEMS

The experimental work involved detailed explorations into two different designs for roadway electrification systems, for two different vehicles and applications. However, because of the nonlinear relationships that govern the design and performance of the roadway electrification technology, ‘it is not possible to directly project the characteristics of these two designs to other design cases. It has been necessary to perform a series of parametric design studies to develop an understanding of the relationships among the different variables that affect system performance. These are conducted using computer analyses and simulations in place of experimental hardware in order to save both time and money.

These parametric design studies have provided some indications of how a full-scale system should be designed to accommodate a range of vehicles, including private automobiles. These have also shed light on the principal design trade-offs that must be considered among the dozen different variables that interact with each other in complicated ways to determine system performance.

The experimental work and design studies have addressed many of the questions that need to be answered before the roadway electrification technology can proceed into deployment in public service. However, there are still several issues that are not fully resolved and will need some additional attention. The remainder of this section indicates the principal remaining technical uncertainties surrounding the roadway electrification technology. These appear to be considerably simpler than the issues that have already been addressed in the experimental and analytical work of the past five years, but they will require careful attention and the investment of some resources.

Capital and Operating Costs

As mentioned in Section III of this report, the current estimates of costs are extremely crude and subject to great uncertainty. This is unavoidable at this early a stage in the development of such a new technology. As more vehicles and test facilities are developed, it should be possible to gain more experience in the design and fabrication of the equipment for minimum cost. The maintenance costs for both vehicle and roadway equipment will be virtually impossible to predict with much certainty prior to engaging in a real operational test.

Electromagnetic Exposure Considerations

There is no generally accepted standard for human exposure to low frequency magnetic fields, which makes it impossible to design a roadway electrification system that can be certified to meet such a standard. The environmental impact review process for the first public deployment

of the technology is likely, to be complicated by the absence of standards. It will therefore be necessary to show the comparison between the fields produced by the electrified roadway and the fields associated with technologies that are already in everyday use. More research is needed on the potential interference with automotive electronic systems, to establish how that interference can be avoided. Since there is great diversity in the electronic systems installed on different cars, it may be necessary to conduct experiments on large numbers of vehicles or to collect information about the sensors installed on virtually all currently available vehicles in order to ensure no interference.

Battery Performance

Although the roadway electrification technology overcomes the energy storage limitations of the available storage batteries, it is not immune to other limitations in battery performance because it still depends on use of a battery for **onboard** energy storage. In particular, the duty cycle imposed on the battery by the roadway electrification system is very different from that for which vehicular propulsion batteries are normally designed. This duty cycle requires high charging and discharging currents, in rapid alternation, but without the typical daily deep discharge cycle. In the course of a day of use, the battery could receive charging currents corresponding to several times its storage capacity and could be asked to deliver comparable discharge currents. This may impose thermal stresses on the batteries beyond what they are normally able to accommodate and may shorten battery life. However, in the absence of substantial experimental data it is not possible to determine whether or not this should be a serious concern. Therefore, systematic and extensive battery duty cycle testing should be conducted to address this issue.

Power Distribution System Design

The experimental work on roadway electrification has all been conducted on a 400-foot-long section of powered roadway containing two segments that can be powered separately or together. This relatively simple installation does not represent all of the complexities that could be expected in a large-scale operational deployment, with potentially many power supplies and many powered segments. Substantial engineering work will be needed to define the most **cost-effective** way of scaling the powered roadway operations up to a fully developed network with its own power distribution network.

Roadway Inductor Installation and Durability

The highway engineering community is not yet comfortable with the idea of installing a roadway inductor of substantial dimensions (such as the 4 inch deep by 40 inch wide third-generation design) in a roadway surface. Issues of structural design, compatibility with existing roadway structures, maintenance of the electrified roadway, and long-term durability have not yet been

addressed. These issues are likely to assume different importance for installations in new roadways compared to retrofitting into existing pavements, and are also likely to differ from Portland cement concrete to asphalt concrete roadways. These need to be studied by experts in construction technology so that the uncertainties about installation approaches, costs, and durability can be resolved.

V. ROADWAY ELECTRIFICATION DEPLOYMENT IMPACT STUDY FOR LOS ANGELES

In response to the intent expressed by the Conference Committee in their report, a study was conducted by the Southern California Association of Governments (SCAG) of the long-term impacts of the roadway electrification technology on the Los Angeles region. The technical characteristics of the technology were identified on the basis of the analysis, design and experimental work described above in Sections III and IV of this report. The impacts of the technology were predicted for the year 2025, using the SCAG regional transportation modeling system and auxiliary models to predict air quality, costs and economic impacts. This study is fully documented in [9].

None of the available models is able to predict the market penetration for the roadway electrification technology, so this had to be selected exogenously by the research team. The transportation network used for the study included the existing highway network, currently funded new highway construction and reconstruction specified in SCAG's Regional Mobility Plan for 2010 and long-range corridors that have been identified to serve future needs. The 2025 population and employment projection updated the socioeconomic component of the regional transportation model. Policy-driven transportation demand management measures were incorporated for all studies, including the baseline case with no new technology as well as the roadway electrification case study.

The roadway electrification impact study assumed that the market penetration for roadway-powered electric vehicles would consist of the vehicles that travel 15 % of the regional vehicle miles traveled (VMT) during the AM peak period, with a bias toward vehicles that make longer than average trips on the freeway part of the network. In order to adequately serve this vehicle population, it was necessary to electrify 1035 lane miles of freeway (9.6% of the total freeway lane miles in the region), along 300 centerline freeway miles. The impacts of this level of roadway electrification included:

- 15% reduction in gasoline used for transportation (2.2 million gallons per day saved)
- 60% increase in use of natural gas for transportation. This is because current use of natural gas for transportation is extremely low (as an intermediate fuel in production of gasoline) and natural gas is expected to account for the majority of energy for electricity generation. This is not expected to be a problem because supplies are expected to be plentiful, it is a clean burning fuel, and the generating stations are primarily outside the seriously polluted air basin. The increase in region-wide use of natural gas would be about 7.2 % .

- 1% increase in peak-hour utility demand for electricity, potentially requiring a small increase in generating capacity (but insignificant compared to the 93% growth projected from today to 2025)
- 2.1% increase in daily electricity demand. Of this, more than half would be attributable to the overnight recharging needed to bring the vehicles' batteries up to full charge, rather than to daytime use of power drawn from the roadway.
- air quality improvements via diverse reductions in the production of pollutants:

Reactive Organic Gases (ROG)	- 7.2%
Carbon monoxide (CO)	- 8.1%
Nitrogen oxides (NOX)	-10.3 %
Sulfur oxides (SOX)	-14.7%
Particulate matter (PM)	-13.2%

These tend to be reduced by less than the amount of the VMT attributed to the electric vehicles because of pollution associated with number of trips (cold starts, etc.) rather than VMT and because of the pollution associated with electricity generation.

The analysis accounts only for vehicles that draw power from the electrified roadway during the AM peak, but not for equipped vehicles that make shorter trips using battery power alone. This introduces a potentially significant conservative bias into the analysis, since the availability of roadway power for larger trips within the region could substantially increase market penetration for electric vehicles that are used predominantly for short trips that do not need recharging en-route. The magnitude of this effect cannot be estimated until further research is conducted on the process by which consumers decide whether to purchase electric vehicles.

The costs of the electrified roadway system were estimated, based on the assumption that all costs associated with the installation and use of the roadway inductor would be passed on to the users in the form of increased charges for the energy they draw from the roadway. This would require that the energy cost be 29.4 cents per kilowatt hour retail (compared to 7 cents wholesale cost for the energy alone). When these costs are factored together with the rest of the vehicle operating costs, the overall automobile operating costs would be 29.03 cents per mile, compared to 24.88 cents per mile for conventional gasoline powered vehicles. This somewhat higher cost does not account for any of the pollution-related externalities associated with use of the **gasoline-**powered vehicles.

VI. HIGHWAY AUTOMATION DEVELOPMENT WORK

Highway automation provides road vehicles with the ability to drive themselves, making use of technology installed on the vehicles and in the roadways. This would enable vehicles to control their own steering, speed and spacing from each other, as well as maneuvers such as lane changing or merging, without human intervention.

Like highway electrification, highway automation is a new technology that requires close coordination of design and operation between elements in the public roadway infrastructure and elements **onboard** private vehicles. There are potential synergisms between the two technologies, particularly when one considers the opportunity to implement them together as a single construction project. Automatic steering control could enable vehicles to steer themselves more accurately, which would enhance the effectiveness of the inductive energy transfer system. The powertrains of electric vehicles could be more suitable for implementing high-accuracy control of the longitudinal spacings between vehicles.

The automatic control of vehicle steering, speed and spacing that are embodied in highway automation offer great potential for improving the productivity, capacity, safety and efficiency of highway transportation. California's transportation problems are of such a scale and are growing at such a rate that it is very important to the state's economy that the potential of highway automation be evaluated thoroughly. The Automated Highway System (AHS) could be the next generation equivalent of the Interstate Highway System of the 1950s and 1960s, with impacts of comparable magnitude. Careful planning and design in the early stages can maximize the favorable impacts and minimize the unfavorable ones. Travel needs for a growing population and economy should be met while safety is improved and environmental and energy impacts are reduced by the AHS. This combination of benefits does not appear to be achievable by any other means.

The concept of highway automation has existed for a long time, certainly as far back as the Futurama exhibit of General Motors at the 1939 New York World's Fair. During the 1950s and early 1960s, GM and RCA conducted test track experiments on highway automation under the rubric of "The Electronic Highway." The Bureau of Public Roads (later the Federal Highway Administration) sponsored research on highway automation at the Ohio State University from the middle 1960s through the late 1970s, and much analogous technology development research was conducted under the sponsorship of UMTA for Personal Rapid Transit and Automated **Guideway** Transit applications throughout much of the 1970s.

Highway automation received virtually no attention in the 1980s until the California PATH Program began its work in 1986, based on a combination of state resources with the Section 164 funding. PATH built on the foundations established by the earlier decades of work, but with the addition of the new technologies and capabilities that have become available more recently. The PATH orientation toward highway automation was also the genesis of the national interest

in IVHS, which has since combined automation with a wide variety of nearer-term applications of high technology to improving road transportation operations.

The PATH work on highway automation has included diverse activities:

- research on policy and planning constraints
- identification of applicable concepts
- system analysis and evaluation
- studies of system designs for safety
- development and evaluation of enabling technologies (sensors, communications)
- design and simulation of vehicle communication and maneuvering protocols
- design and experimental evaluation of vehicle control systems in “proof of concept” tests
- evaluation of regional impacts for Los Angeles area.

The last two of these activities are of such special significance in themselves that they will each be the subject of a separate section of this report (Sections VII and VIII).

The PATH work is aimed at developing a basic understanding of the potential benefits that could be gained from highway automation and of the potential costs and impediments to deployment. This represents research of a variety of types, but stops short of product development, which is the province of private industry rather than publicly-funded academic research. However, some of the significant research projects have been conducted in cooperation with private companies that are developing products, providing mutual leveraging of public and private sector resources and talents.

PATH research is primarily conducted by faculty members and graduate student researchers on the campuses of the universities that are partners in the program, together with the full-time research staff at the PATH Program office. Since the inception of the program, about 100 projects have been initiated, of which 30 have been on highway automation (15 of which remain currently active). There have been another 10 projects somewhat related to highway automation, of which 8 are currently active. These latter projects typically address general enabling technologies such as sensors or cross-cutting issues such as safety and human factors, which are important across all of IVHS but have the most acute significance for highway automation.

The PATH research on vehicle-highway automation is directed at development of systems that can make significant contributions toward solving transportation problems within a reasonable time frame (deployments starting within ten to twenty years). This means that the PATH efforts have not been concentrated on developing the ultimate fully autonomous automated vehicle that can deal with every possible driving condition. Rather, PATH has emphasized approaches that are less technologically challenging, while offering the potential for significant benefits to transportation operations.

Specifically, PATH research is targeting the automation of freeway driving in special-purpose lanes segregated from conventional (manually driven) vehicles. The freeway system carries much heavier traffic than other parts of the road system, offering the greatest potential impact for any given level of investment in deployment. Furthermore, because it represents such a well structured environment it also poses the least daunting technical challenges. Freeways are simpler to automate than any other kinds of roads because they have relatively uniform and benign geometric characteristics (lane width, vertical and horizontal curvature, pavement surface) and can have well controlled access (no pedestrians, driveways, cross traffic, traffic lights, animals, bicycles, etc.). This simplicity means that the sensing and control systems on the automated vehicles do not need to respond to nearly as wide a range of inputs as they would in general traffic.

In developing an automated vehicle-highway system, it is important to consider the responsibilities placed not only on the vehicles but also on the highway. In development of a truly system-level design, it is necessary to allow for different distributions of intelligence and authority between the private vehicles and the public infrastructure. Considerable research will be needed to develop firm recommendations regarding the optimal allocations. Initial consideration of this issue indicates only that it is better to have an intermediate solution than an extreme one (i.e., neither a fully centralized control system with “dumb” vehicles nor a fully autonomous vehicle system with a “dumb” roadway). [10]

Much of the uncertainty about highway automation concerns its realizable potential for conferring benefits in two critical areas — improved safety and increased capacity. The safety improvements are possible because well in excess of 90% of the accidents that occur today are attributable to driver errors, and under automated highway operations the drivers would no longer have the opportunities to make those errors. On the other hand, failures in the automated systems could introduce new accidents that do not occur today. [1 1] Much of the research attention is directed at maximizing the reliability and fail-soft capabilities of automated systems in order to minimize the new accidents. [12,13] However, it will not be possible to provide definitive resolution of this uncertainty until there is a reasonable scale operational test to prove how safe the automated systems can be.

The capacity increases are somewhat easier to address in the current research program, using both analytical and experimental approaches. The potential capacity increases depend on several different factors:

- how close the longitudinal spacings between successive vehicles can be made while they are operating at full cruising speed
- how much the highway lane widths can be reduced because of the increased accuracy of automatic lateral control
- how much extra space must be provided to allow for maneuvering, including lane changes, merges, and exit maneuvers

- what level of risk aversion must be built into system designs to allow for the likelihoods of various failures.

The longitudinal spacing and lateral accuracy issues are being addressed directly in the vehicle control experiments that will be described in the next section. The longitudinal spacings will also depend on human factors considerations that will be studied in future simulation experiments, as well as on some details of sensor technologies. The maneuvering issues are being considered in detailed computer simulations, which are much more economical and safer to conduct than full-scale vehicle experiments. [14] The risk aversion factors are being studied in several current projects that aim to define the trade-offs between capacity and safety and to determine how to design a system operating concept to a desired level of safety.

While all of this research continues in the attempt to reduce the uncertainties about automated highway system safety and capacity, it remains necessary to make some assumptions about what can be achieved for planning purposes and to design the “proof of concept” experiments. The current working assumptions are that the safety can be increased beyond that of today’s highway system (i.e., reduced injuries and fatalities) and that the capacity can in effect be tripled from today’s capacity (from 2000 vehicles per lane per hour to 6000). These assumptions are based on the operation of automated vehicles on their own reserved lanes, separated from conventional traffic, and clustered together in close-formation platoons. The platoons would be separated by large enough spacings that an accident would be exceedingly unlikely to involve more than one platoon, while the spacings between vehicles within platoons would be small enough that mild “fender-bender” collisions could occur, but not the kind of high-relative-speed collisions that would produce serious injuries or fatalities.

VII. VEHICLE CONTROL EXPERIMENTAL RESULTS

Since this is a feasibility report about what could become the next generation of surface transportation, California wanted to make sure that any prognosis was based upon results from full-scale vehicle testing and that projections were based upon conservative assumptions. Thus the first series of PATH tests was based in large part on use of existing and emerging technologies.

Substantial effort has been devoted within the PATH Program to the performance of some initial “proof of concept” tests that are critical to developing assurance that highway automation concepts are valid. These tests were designed to answer the first set of critical questions about automatic control of vehicle motions. Initially, the testing activities were subdivided into lateral and longitudinal control of vehicle motions, although in the near future attention will shift to the integration of both lateral and longitudinal control on the same vehicle.

Lateral Control Experiments [15]

The lateral control experiments were designed to determine how a lateral (steering) control system can be made to combine high accuracy of lane following with good passenger ride quality. The lane following accuracy is needed in order to be able to reduce the widths of automated lanes, while the ride quality will be essential to user comfort and acceptance. Normally, these two measures are in conflict and need to be traded off against each other. The potential problems are made that much more difficult when one tries to accomplish the lateral control using discrete markers as the lane center references. The PATH experiments were conducted using very simple ceramic permanent magnets, installed at one-meter longitudinal spacings, as the reference markers. [16] These were chosen because they are cheap, passive, immune to weather effects and require no maintenance. However, they do not provide a continuous position reference for the vehicle, so that it does not always know how far it is from the lane center. On the other hand, they do provide a means for binary coding of preview information (one bit per magnet) about upcoming road geometry changes (curves) so that steering corrections can be made in anticipation.

The lateral control experiments were conducted on a specially constructed test track at the Richmond Field Station of the University of California, Berkeley, using a test vehicle provided by IMRA America, Inc. The PATH researchers developed the test track with its magnetic marker references, the magnetic sensors to go on the vehicle, and the control computer and its software. The IMRA researchers provided the Toyota Celica test vehicle and a steering actuation system that turns the front wheels in response to commands issued by the control computer. Tests were conducted on two sections of test track, one incorporating a 90-degree curve of small radius and the other incorporating several milder reverse curves. In each case, reference markers were installed at spacings of one or two meters.

The results of the experiments were extremely encouraging. When the vehicle traveled around the 90-degree curve at the maximum allowable speed, corresponding to a lateral acceleration of 0.27 g, it remained within two inches of the lane center under normal conditions. Even with abnormal conditions (partially deflated tires, extra vehicle loads, wet and slippery road surfaces, imprecisely placed markers) the tracking remained within a range of six inches of the center, which is considerably better than the human driver can do under comparable conditions. The preview information about upcoming road geometry changes is very important for achieving this accuracy. ‘The ride quality as perceived by the driver and passengers remained smooth throughout the steering maneuvers, an observation which was confirmed by analyses of the test data.

The experiments conducted thus far were all at low speeds, based on the limited length of test track available. The 90-degree curve tests were at speeds up to about 30 mph, while the tests on the reverse curves were in the 40 mph range. Additional test facilities will be needed to conduct higher speed tests. Further tests will also investigate the effects of external force loads (such as wind gusts) on the response of the test vehicle. Although these tests have not yet been conducted, the tests that have already been completed have gone a long way toward demonstrating proof of the validity of the concept of automatic lateral control using discrete reference markers. In particular, the tests have proved that highly accurate lane following can be achieved together with good ride quality, but without need to resort to exotic or inherently costly technologies.

Longitudinal Control Experiments [17]

The longitudinal control experiments were also designed to establish the feasibility of achieving a combination of high tracking accuracy and good ride quality, although in this case the accuracy refers to maintaining the longitudinal spacing relative to a preceding vehicle. The high accuracy is necessary in order to operate vehicles at very short spacings without collisions. High accuracy is also important in order to convey to the occupants of the vehicles the sensation that they are firmly coupled to the other vehicles, so that they do not have the sensation of “slop” in the system, which could decrease their confidence in its safety.

The longitudinal control experiments were conducted primarily on the 8-mile-long “commuter lane” high-occupancy-vehicle facility in the median of I-15 to the north of San Diego. This facility, which contains two full-width lanes plus shoulders, is physically separated from the main I-15 freeway for its entire length and is closed to the general public during the non-commute hours, when it is available for testing. The vehicle-follower longitudinal control scheme developed by the PATH researchers was tested on a fleet of four automobiles supplied by Ford, using radar sensors and throttle control actuators developed by VORAD Safety Systems of San Diego. The measurements of vehicle-to-vehicle range and range rate supplied by the VORAD sensors were combined with radio communication of the acceleration and speed of each vehicle and of the leader of the platoon to each following vehicle.

The sensor systems that would be needed for very short spacings (3 feet or so) are still under laboratory development, so the testing on the vehicles made use of the available sensors at spacings of about 25 to 30 feet, and operating at normal highway speeds of 55 to 75 mph. These combinations of spacings and speeds represent **headways** in the range of a half second, which translate into maximum lane capacities of around 7000 vehicles per lane per hour. However, there is considerable doubt whether it would be desirable to operate an automated highway system in this fashion because of concerns about how to accommodate a failed vehicle without producing a high-speed collision.

The test conditions included constant-speed cruising as well as accelerate-cruise-decelerate cycles and operations on grades of up to 3% (both positive and negative). The vehicles typically maintained the desired (constant) spacings within a tolerance of a few feet, while maintaining good ride quality. These experiments provided the first available proof that it is possible to control internal combustion engine vehicles with this degree of accuracy, which is an extremely significant finding. Prior to this work, there was some concern that these accuracies could only be achievable with an electric powertrain, which would have severely limited the population of vehicles suitable for use on the automated highway.

Further longitudinal control experiments are needed to incorporate braking as well as throttle control, to employ short-range sensors and vehicle-to-vehicle communication systems suitable for use in very close formation platoons, and to demonstrate successful operations on more demanding roadway geometries. Some imperfections in the performance measured in the tests conducted thus far appear to be consequences of well understood causes, and should be readily overcome in the next phase of testing. Evaluations of the human factors responses to different modes of operation of automatic longitudinal control, particularly including operations at very short **headways** and transitions in and out of platoons, will be needed as soon as it is possible to implement the experimental conditions realistically in either a driving simulator or test vehicles.

VII. HIGHWAY AUTOMATION DEPLOYMENT IMPACT STUDY FOR LOS ANGELES

In combination with the roadway electrification deployment impact study described in Section V, an analogous study was conducted by SCAG for highway automation. The base study year of 2025 was the same, as were all the socio-economic variables and the baseline case for use of no new technology. [9]

This highway automation impact study assumed that the market penetration for vehicles equipped to use the automated highway would consist of the vehicles that travel 45 % of the regional VMT during the AM peak period, with a bias toward vehicles that make longer than average trips on the freeway. In order to adequately serve this vehicle population, it would be necessary to automate 2165 lane miles of freeway (20 % of the total freeway lane miles in the region), along 646 centerline freeway miles. It was assumed that these automated lanes would share the existing freeway right of way with conventional non-automated lanes, and that additional freeway width would not be permitted. This means that in parts of the network where one automated lane per direction is recommended, the number of conventional freeway lanes is reduced by one. Since automatic lateral control should enable automated lanes used by light-duty vehicles to be narrower than standard lanes, three automated lanes can be accommodated where needed by eliminating only two standard lanes. Additional on and off ramps were found to be needed at high-demand entry and exit locations in order to avoid creating bottlenecks at these interfaces between the automated and manual networks. The automated lanes are assumed to operate at a constant 55 mph, accommodating 6,000 vehicles per lane per hour.

The impacts of this level of freeway automation, relative to the baseline case without any automation, included:

- Reduced vehicle hours of delay
 - 62% on conventional (non-automated) freeway lanes
 - 24% on major arterials
 - 28% on minor arterials
 - 40% regionwide (about 430,000 hours saved per daily AM peak period)
- Increased average speeds
 - 23% on conventional (non-automated) freeway lanes (from 28.9 to 35.5 mph)
 - 1% on major arterials (from 18.2 to 18.3 mph)
 - 10% on minor arterials (from 13.0 to 14.3 mph)
 - 26% regionwide (from 22.0 to 27.7 mph)

Both the baseline and automation cases include substantial policy-driven demand management assumptions.

It is important to recognize that these impacts are extremely large, and dwarf the impacts that could be expected from virtually any other congestion reduction strategy short of drastic travel-

reduction measures that would impose severe economic penalties on the region. It is also extremely important that the favorable impacts are distributed to all travelers, not only those who choose to (and can afford to) equip their vehicles for automated freeway operation. This means that concerns about adverse distributional equity implications of highway automation should be greatly reduced. In effect, by providing substantially increased capacity, the automated freeway attracts traffic away from the conventional freeways and arterials, reducing the congestion on those roads. The users of the automated freeway would still enjoy a speed advantage over the other travelers, because they would operate at a constant 55 mph speed, as compared to the 35.5 mph average for non-automated freeway drivers.

To place these delay and speed estimates in context, it is useful to refer back to 1984 baseline conditions in the Los Angeles region that is the subject of this study:

Total vehicle hours of delay, AM peak: 152,000

Average speeds during AM peak:

Freeways	40 mph
Major arterials	27 mph
Minor arterials	26 mph
Total	31 mph

Obviously, the speeds and delays in 2025 are expected to be worse than they were in 1984 whether or not highway automation is adopted. However, they will be much worse on the freeways if automation is not adopted.

It is worth noting two important limitations of this application study. The market penetration level for automated vehicles had to be assumed exogenously to be 45% of AM peak VMT, because there is no data or model available to predict what that level would be for a “mode” as unconventional as the automated highway system. If different market penetration levels are assumed, the impacts will of course scale accordingly. It was also not possible to evaluate the possible effect that the freeway automation would have on latent or induced demand. The trip tables for the baseline case and the freeway automation case were virtually the same, which means that if there are in fact significant latent or induced demand effects the benefits of the automation would be overstated in the results reported here. Until a validated, generally accepted model of transportation-land use interactions is available, it will not be possible to evaluate the significance of the latent or induced demand in any meaningful way.

IX. CONCLUSIONS

The studies conducted under the funding allocated in Section 164 of the STURAA of 1987 and with substantially more state and other funding have made major contributions to the understanding of the feasibility and applicability of the technologies of highway electrification and automation. Design, analysis and experimental work on both technologies have resolved major uncertainties that had previously clouded the prospects for both. The application impact studies for the Los Angeles region have shed considerable light on the applicability of the technologies in a major urban area, and in particular on the benefits that could be gained from their deployment. Principal findings from these studies include the following:

Highway Electrification

- (a) The inductive power transfer technology can successfully transfer 60 kw to an electric bus in motion, and the technology can be scaled to transfer lesser amounts of power to lighter duty vehicles. It may be necessary to use lateral guidance or control assistance systems to provide accurate enough positioning of the vehicle over the lane center to achieve effective power transfer.**
- (b) With use of the inductive power transfer technology, the effective operating range of a battery electric vehicle can be dramatically increased. The extent of the increase depends very heavily on the driving duty cycle and the design of the roadway electrification system.**
- (c) The inductive power transfer system can function within reasonable limitations on acoustic noise and electromagnetic field emissions.**
- (d) The inductive power transfer system can be designed and built to operate at overall system efficiencies that approach those of conventional plug-in battery chargers.**
- (e) The roadway inductor can be installed for costs of a few million dollars per lane mile, but the unit costs of the in-vehicle equipment remain considerably more uncertain at this time.**
- (f) Regionwide deployment of the roadway electrification system can save gasoline in proportion with the fraction of the regional VMT driven by the electrified vehicles. Pollution savings are somewhat less (in the range of half to three quarters of the VMT fraction for the Los Angeles area) because some of the pollutant generation does not depend on VMT, but on the number of trips or cold starts. Both of these effects could be strengthened considerably if the availability of the electrified roadway encourages more people to use electric vehicles for short trips that do not need the roadway power for battery recharging.**

- (g) Utilization of the roadway electrification on vehicles that travel 15% of the AM peak period VMT in the Los Angeles region would require only a 1% increase in the region's electrical generating capacity.**

The research conducted within the past decade has resolved most of the technological uncertainties about the highway electrification technology. The electromagnetic and power transfer system design issues are now quite well understood, with the exception of the power distribution system design optimization. The remaining uncertainties involve the civil engineering issues associated with installing the roadway inductor, the costs for the inductors and onboard electronics, the effects of the electromagnetic fields surrounding the inductors, and the basic consumer acceptance issues common to all electric vehicles.

Highway Automation

Highway automation is considerably more complicated and is currently less mature technologically than highway electrification. Intensive research and development activity in this area has only begun within the past few years, and numerous additional years of such activity will be needed before full-scale deployment can be attained. While this R&D activity is proceeding, many intermediate level spin-off products are likely to be developed and deployed, contributing to improved highway safety. These could include autonomous intelligent (or adaptive) cruise control, near obstacle detection, collision warning or lane departure warning systems.

There is at present no regulatory incentive forcing the advancement of the AHS technology. In addition, there are no safety regulations in this area and thus there are concerns about the liability and safety implications of vehicle control technologies. These must be addressed as part of the federally funded program in order to overcome private sector reluctance to invest their resources in a subject that still offers the appearance of significant risk. The availability of federal R&D funding to satisfy the provision in the 1991 ISTEA requiring demonstration of an AHS prototype by 1997 will help stimulate progress in this area.

Given these factors, it should not be surprising that the findings from the PATH work on highway automation are not yet as advanced as the findings on highway electrification. However, it must be remembered that in the long term the implications here are likely to be significantly more dramatic.

- (a) Highway automation offers the potential for very significant increases in highway safety and productivity or capacity. However, it will take considerable research, development and testing work to quantify these potential benefits, especially in the safety area.**

- (b) Preliminary analyses and conceptual studies indicate the potential for highway automation to as much as triple the capacity of a freeway lane, depending on the assumptions that are made about safety, level of risk aversion to embed in the design, and capabilities of the technologies to be used.**
- (c) An automatic steering control system can be made to follow the center of a lane with high accuracy and good ride comfort by making use of discrete markers in the pavement as the lane center reference. The accuracy is high enough under a range of test conditions to support the technical feasibility of making automated lanes significantly narrower than existing highway lanes.**
- (d) Vehicle-follower longitudinal control can be achieved with high accuracy and good ride comfort in an internal combustion engine vehicle. The accuracy is high enough in the initial tests to support the technical feasibility of short-headway vehicle-follower operation in platoons.**
- (e) Regionwide deployment of highway automation on a portion of the existing and planned freeway infrastructure for the Los Angeles area could produce very dramatic reductions in vehicle hours of delay and significant increases in average travel speeds. The precise extent of these improvements will depend on the degree of market penetration that is actually achieved, as well as the capacity of the automated facility.**
- (f) Regionwide deployment of highway automation would confer substantial delay and speed benefits to travelers throughout the region, including in particular those who continue to drive on the existing freeway and arterial system rather than on the automated portion of the network.**

A great deal more research, development and testing work will be needed to bring the highway automation technology to maturity and eventual deployability. This work will also be needed to resolve the many uncertainties that remain about both technical and non-technical aspects of highway automation, including levels of achievable performance and safety, human interfaces and acceptability, vehicle and infrastructure costs, and congestion reduction potential.

The provision in the 1991 ISTEA requiring demonstration of an automated highway prototype on a test track by 1997 will serve as a vital stimulus to direct attention toward resolving the remaining uncertainties about highway automation. The Conference Committee report on Section 164 of the 1987 STURAA planted the first seed of an idea about exploring the potential of this technology, which sprouted in the 1991 ISTEA language. That sprout should lead to a substantial harvest of operational testing and eventual deployment associated with the 1997 successor legislation to ISTEA.

REFERENCES

1. Bolger, J.G., and F. A. Kirsten, "Investigation of the Feasibility of a Dual Mode Electric Transportation System," Lawrence Berkeley Laboratory Report LBL-6301/UC 96, May 1977.
2. Bolger, J.G., M.I. Green, L.S. Ng, and R.I. Wallace, "Tests of the Performance and Characteristics of a Prototype Inductive Power Coupling for Electric Highway Systems," Lawrence Berkeley Laboratory Report LBL-7522/UC 96, July 1978.
3. Walter, C.E., and J. Salisbury, "Roadway Powered Electric Vehicle Project Final Report," Lawrence Livermore Laboratory Report UCID-19576, September 1982.
4. Systems Control Technology, Inc., "Santa Barbara Electric Bus Project, Phase 3A—Final Report," Palo Alto, CA, September 1983.
5. Systems Control Technology, Inc., "Santa Barbara Electric Bus Project, Prototype Development and Testing Program, Phase 3B—Final Report," Palo Alto, CA, September 1984.
6. Systems Control Technology, Inc., "Santa Barbara Electric Bus Project, Prototype Development and Testing Program, Phase 3C—Final Report," Palo Alto, CA, May 1986.
7. Systems Control Technology, Inc., "Santa Barbara Electric Bus Project, Test Facilities Development and Testing Program-Static Test Report," Palo Alto, CA, June 1985.
8. Systems Control Technology, Inc., "Analysis, Development and Testing of Roadway Powered Electric Vehicle Technology," Palo Alto, CA, 1992.
9. Southern California Association of Governments, "Highway Electrification and Automation Technologies - Regional Impacts Analysis Project," Phase I, II, and III, and Executive Summary, Los Angeles, CA, 1990-1992.
10. Varaiya, P., and S.E. Shladover, "Sketch of an IVHS Systems Architecture," PATH Research Report UCB-ITS-PRR-91-3, Institute of Transportation Studies, University of California, Berkeley, CA, 1991.
11. Hitchcock, A., "Fault Tree Analysis of a First Example Automated Freeway," PATH Research Report UCB-ITS-PRR-91-14, Institute of Transportation Studies, University of California, Berkeley, CA, 1991.
12. Hitchcock, A., "A First Example Specification of an Automated Freeway," PATH Research Report UCB-ITS-PRR-91-13, Institute of Transportation Studies, University of California, Berkeley, CA, 1991.

13. Hitchcock, A., "A Specification of an Automated Freeway with Vehicle Borne Intelligence," PATH Research Report, Institute of Transportation Studies, University of California, Berkeley, CA (in press).
14. Hsu, A., F. Eskafi, S. Sachs, and P. Varaiya, "The Design of Platoon Maneuver Protocols for IVHS," PATH Research Report UCB-ITS-PRR-91-3, Institute of Transportation Studies, University of California, Berkeley, CA, 1991.
15. Peng, H., W-B. Zhang, A. Arai, Y. Lin, T. Hessburg, P. Devlin, M. Tomizuka, and S. Shladover, "Experimental Automatic Lateral Control System for an Automobile," PATH Research Report, Institute of Transportation Studies, University of California, Berkeley, CA (in press).
16. Zhang, W-B., R. Parsons, and T. West, "An Intelligent Roadway Reference System for Vehicle Lateral Guidance/Control," Proceedings, 1990 American Control Conference, San Diego, CA, 1990, pp. 281-286.
17. Chang, K.S., "Final Report, Longitudinal Control, Phase I," PATH Research Report, Institute of Transportation Studies, University of California, Berkeley, CA (in press).