Arizona Intelligent Vehicle Research Program - Phase One: 1997 - 2000

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16. Abstract –

This Phase One report documents a three-year research program by the Arizona Transportation Research Center to study possible practical applications of vehicle and infrastructure-based technologies. The project has reviewed, evaluated and demonstrated Intelligent Vehicle and Automated Highway System concepts that may improve the safety and efficiency of Arizona's highway system, particularly in winter maintenance operations.

The key accomplishment of Phase One was to develop a research partnership with the California Department of Transportation (Caltrans) in their Advanced Snowplow (ASP) program. The Caltrans prototype plow, guided by discrete magnetic markers in the roadway, features lane position indication, lane departure warning, and a forward collision warning radar system. The ASP has been tested through two winters, 1998–99 and 1999-2000. Training and evaluations have been conducted at the California test facility on Interstate 80 near Donner Summit, and at a second dedicated test site on US 180 near Flagstaff, Arizona.

This project report is presented in two sections. Section I gives a general history of the program, describing Arizona's interest and involvement in AHS and Intelligent Vehicle technologies through the summer of 2000. Section II of this report focuses in more detail on the Caltrans partnership, the site selection, the development of the magnet infrastructure in Arizona, and the initial two winters of testing and operational evaluation. The ADOT-Caltrans partnership, and the project, are ongoing in 2001 and 2002.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
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ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
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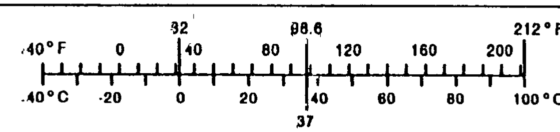

EXECUTIVE SUMMARY

This Phase One report documents the first three years of an ongoing research program by the Arizona Department of Transportation (ADOT) to study possible practical applications of vehicle and infrastructure-based Intelligent Transportation Systems technologies. The ATRC (Arizona Transportation Research Center) has performed this project as an internal research effort. During Phase One of this project, from 1997 to mid-2000, ADOT and the ATRC have reviewed, tested, evaluated and demonstrated Automated Highway System (AHS) and Intelligent Vehicle (IV) concepts. These new resources may improve the efficiency of Arizona's highway system, and in particular, may enhance the safety and efficiency of winter maintenance operations.

This project has focused on a study area that offers significant near-term benefits to transportation agencies. With an extensive rural highway network and only limited resources to keep the roads open in the worst weather conditions, Arizona faces major operational challenges. Snow removal and emergency response operations are among the most critical and hazardous duties for highway maintenance personnel. Safety and efficiency improvements are greatly needed in the winter maintenance field, and real gains can be achieved with ITS and IV concepts.

The key accomplishment of this project in Phase One has been to develop a working partnership between ADOT and the California Department of Transportation (Caltrans), whose Advanced Snowplow partnership offered significant opportunities for both states to benefit. The Caltrans-ADOT snowplow features lane position indication and lane departure warning, as well as a forward collision warning system. A continuous line of discrete magnetic markers embedded in the roadway provides guidance information to the snowplow.

This guidance system, installed on a Caltrans 10-wheel 10-yard plow, has been tested through two winters, 1998–99 and 1999-2000. Training and evaluation activities have been conducted both at the primary California project testbed on Interstate 80 near Donner Summit, and at a second dedicated test site on US Highway 180 near Flagstaff, Arizona.

This project report is organized into two distinct areas of research activity. Section One provides a general overview of the project's inspiration and goals, and it discusses the early IVI efforts in Arizona. It also describes the accomplishments of the program in terms of increasing the agency leadership's awareness of these concepts, and of the potential benefits from future research.

Section Two of this report describes in detail the more focused winter maintenance needs and goals that led to the long-term snowplow evaluation partnership between ADOT and Caltrans. This section discusses the specifics of site selection and construction of the Arizona intelligent infrastructure site. It also details the snowplow testing and evaluation program and the project's Phase One results, conclusions and recommendations for future research.

ACKNOWLEDGEMENTS – CHAMPIONS AND PARTNERS
1997 - 2000

ADOT's I-40 Corridor District Engineers, Maintenance Engineers & Superintendents:

- Flagstaff – Don Dorman, John Harper, Danny Russell
- Holbrook – Jeff Swan, Robert Wilbanks
- Kingman – Debra Brisk, Bill Wang, Larry Thomas

Flagstaff District Team Leaders:

- Joseph Chavez, Tom Durnez, Don Dodge, Tyrone Begishie

Caltrans Advanced Snowplow Project Development:

- Tom West, Greg Larson, Monika Kress, Mike Jenkinson, Kirk Hemstalk: California DOT
- Dr Ty A. Lasky, Dr. Bahram Ravani and the AHMCT project team.
- Dr. Wei-Bin Zhang, Dan Empey and the California PATH project team.

Project 473 Technical Advisory Committee:

During Phase One (1997-2000) the Research Project TAC represented the following ADOT sections and partner agencies; the complete list of TAC members is included as Appendix B.

- ADOT's I-40 Corridor Districts – Flagstaff, Holbrook, Kingman
- Arizona Department of Public Safety – Flagstaff DPS
- ADOT Transportation Technology Group (TTG)
- National Weather Service – Flagstaff -Bellemont
- ADOT Equipment Services
- Federal Highway Administration

The project also received very valuable support in the early activities from the ADOT Phoenix Maintenance and Construction Districts, and Jon Nelson of the VISION Field Office of the TTG.

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PROJECT ACRONYMS AND ABBREVIATIONS

Acronym	Definition
ACMS	Advanced Construction and Maintenance Systems
ADOT	Arizona Department of Transportation
AHMCT	Advanced Highway Maintenance & Construction Technology (Research Center at UC Davis – Prime Contractor for ASP)
APS	Applied Physics Systems
ASP-I	Advanced Snowplow, Phase I (Caltrans)
ASP-II	Advanced Snowplow, Phase II (Caltrans)
ATRC	Arizona Transportation Research Center (at Phoenix)
AVCSS	Advanced Vehicle Control and Safety Systems
AWMT	Advanced Winter Maintenance Testbed (Caltrans I-80 Site)
Caltrans	California State Department of Transportation
CWS	Collision Warning System
DGPS	Differential Global Positioning System
DOT	Department of Transportation
EMI	Electromagnetic Interference
FLD	Front Lateral Displacement
GPS	Global Positioning System
HMI	Human-Machine Interface
HOV	High-Occupancy Vehicle
HUD	Head-Up Display
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
I-40	Interstate 40 (in Northern Arizona)
I-80	Interstate 80 (in Northern California)
ITS	Intelligent Transportation Systems
ITSA	Intelligent Transportation Society of America
IV	Intelligent Vehicle
IVI	Intelligent Vehicle Initiative
LCD	Liquid Crystal Display
LIDAR	Light Detecting and Ranging
MMW	Millimeter Wave
MOE	Measure of Effectiveness
MP	Milepost
MSU	Montana State University (at Bozeman)
NAHSC	National Automated Highway Systems Consortium
NAU	Northern Arizona University (at Flagstaff)
PATH	Partners for Advanced Transit and Highways (at UC – Berkeley)

Acronym	Definition
RF	Radio Frequency
RFI	Radio Frequency Interference
RPM	Raised Pavement Marker
RTOS	Real-Time Operating System
SBC	Single Board Computer
UCB	University of California at Berkeley
UCD	University of California at Davis
US 89	US Highway 89 (NE of Flagstaff AZ)
US 180	US Highway 180 (NW of Flagstaff AZ)
WTI	Western Transportation Institute (at Montana State University)
3M	The 3M Corporation (Minnesota)

SECTION I – AUTOMATED HIGHWAY SYSTEMS FOR ARIZONA

I. INTRODUCTION

The decade of the 1990's saw the development of a strong national and regional interest in the potential of Intelligent Transportation Systems (ITS) technology to improve both safety and efficiency on the highways of the United States. With a general mandate and support from the US Department of Transportation (DOT) and the Federal Highway Administration (FHWA), a number of progressive states and public-private collaborations began to move forward with applications of ITS research for problems of a local or regional nature.

On-board vehicle systems and their complementary infrastructure technology are considered to be the major elements of Automated Highway Systems (AHS), for which coordinated research and development began in the early 1990's. These research efforts culminated in 1997 with a national demonstration of AHS concepts. The Intelligent Vehicle Initiative (IVI) later evolved as a more specific term applied to autonomous vehicle control system research. Today, these concepts offer state and local roadway operators a proven ability to complete their missions in a safer and more effective manner. This advantage applies not only to transportation departments but to public safety agencies and response partners including police, fire, and emergency medical services.

One of the most obvious and practical applications of ITS for state transportation agencies was soon recognized to be the field of advanced vehicle technology. The Arizona Department of Transportation (ADOT) became an early leader in ITS research, especially with studies into the potential of these systems to improve the operational effectiveness of the state's highway system.

Arizona Issues and Intelligent Vehicle Solutions

Why deploy ITS in Arizona? Arizona is the sixth largest state in terms of geographic area, and it has approximately 6,000 miles of highways in the state system. Two-thirds of the five million residents live in the Phoenix and Tucson metropolitan areas, yet ninety percent of Arizona's highway system is in remote rural countryside, where extreme weather and geography are major challenges to keeping the roads open and serviceable. Sixty percent of the state's fatal crashes occur on these rural highways that connect the small cities and towns with the major urban areas.

The entire state offers many potential applications for the proven benefits of ITS technology, including enhancements to capacity, communications, weather information, traveler information, traffic management and public safety response. Significant efforts have been made by this project to demonstrate and evaluate the entire range of benefits from the IVI program. These include autonomous (hands-off driving) vehicles and also site-specific studies on AHS core concepts such as dedicated lanes for high-traffic corridors.

At the long-term research level, this ADOT project has concentrated primarily upon the driver-assistance technology that has been developed in the national arena for winter maintenance and similar applications. The ability to improve ADOT's rural winter operations is particularly promising with many of the IVI / AHS elements of ITS. These include lanekeeping and operator interface systems, as well as automatic vehicle location and collision warning technology.

Focus – The ADOT Snowplow / IVI Research Project

The safety of ADOT's highway operations employees is always a critical concern in the face of intense thunderstorms, fog, blowing dust, and winter storm whiteouts. Also, the safety of the traveling public depends on the efficiency and personal safety of the few key ADOT maintenance workers. Interstate 40 across northern Arizona is frequently the site of chain-reaction pileups in snowstorms or icy road conditions. In such cases, the efficiency of a highway transportation system, measured in delays to travelers and lost time for commercial carriers, depends on the ability of the snowplow operators to keep the highways open and traffic moving.

Arizona's state highways climb from an elevation of 140 feet above sea level at Yuma, on the Colorado River, to 9650 feet on State Route 366 on Mount Graham. Almost every District maintains a fleet of snowplows. Even in the moderate elevations, fierce winter storms can blanket the highways and disrupt the heavy traffic that travels along the main Interstate routes.

Figure 1: Winter Driving Hazards Threaten ADOT Crews and the Public

"Winter maintenance is among the most dangerous but most necessary tasks performed by ADOT crews," states one of this project's sponsors. "Blowing snow creates havoc for drivers trying to clear the road, but warning systems on the snowplow can guide them even if conditions make it impossible to see the road ahead."

Of the intelligent vehicle concepts, the advanced snowplow technologies therefore may offer the earliest potential benefit to Arizona travelers and highway personnel. In this sparsely populated state, with its very limited resources, these IV systems may be the most effective new resource to keep the roads open and vehicles moving. Arizona is a large state in geographic area, with an extensive rural highway network, but with very limited agency resources to keep the roads open in the worst weather conditions.

This Research Project

This report documents the first three years of an ongoing intelligent vehicle research effort by the Arizona Department of Transportation. This project was created to study potentially practical applications of vehicle and infrastructure-based Intelligent Transportation Systems technologies that can improve the efficiency of Arizona's highway system, and can solve some of the worst congestion and safety issues in the state.

From late 1997 to the winter of 1999-2000, Phase One of this ADOT project has performed vehicle-highway research in several ITS areas, and has developed vital working relationships with several key partners. The research has been planned and conducted by the staff of the Arizona Transportation Research Center in Phoenix, with critical support and participation from the three northern ADOT Districts based in Flagstaff, Kingman and Holbrook. The most significant outside partners in this project include the California DOT (Caltrans) and their research agencies in the University of California system.

This Research Project Report

This Phase One research report is divided into two sections:

<u>Section I of this document is basically a summary overview</u> of the evolution of the Automated Highway and Intelligent Vehicle programs, as guided and funded on a national level. It describes the national AHS initiatives, and the efforts of the Arizona Department of Transportation to participate, to learn from, and to build upon this work.

ADOT's early efforts in Arizona to inform the public and the state's leadership are discussed, as is the work to create a stakeholder base for future research and implementation. Section I also details ADOT's ongoing participation in AHS activities on regional and national levels.

<u>Section II of this report is a detailed discussion</u> of Arizona's primary long-term research effort in this intelligent vehicle arena, which is the Advanced Snowplow program. This section provides an in-depth discussion of the need for this research project, and of the evolution of the successful Arizona-California partnership. It further provides details of the development of a roadway infrastructure for the Caltrans system at the Arizona test site. The report then describes the organization of the annual field research program.

Finally, Section II provides the results and conclusions of snowplow testing by the partner states over two winters in Arizona.

II. STATEWIDE NEEDS AND NATIONWIDE SOLUTIONS

The Challenge

Since the early 1990's the Arizona Department of Transportation has shown a strong interest in advanced technology applications for the design and operation of the state's transportation system. The leadership of ADOT, including the State Engineer, Director and many District Engineers, has recognized the potential to apply proven advanced-technology systems to get the job done. In many cases, with limited resources, there are few other practical options available.

This approach is only logical in view of the state's exploding population and demand for highway system development. In the recent years of economic growth and opportunity in Arizona, there have still been many challenges in funding and maintaining the state highway system. Those challenges include low wages, high turnover, and limited funds for basic equipment, personnel and consumables. Staffing reductions, termed "slimming" at the state level, as well as early retirement incentives and experiments in privatization of core tasks were all promoted in order to improve efficiency. All these steps cost the agency heavily in terms of its historical memory, expertise, and depth in human resources.

Other ongoing challenges for the management of the Department and the Districts during the past decade have included public resistance to highway system tax initiatives, legislative indifference, and media manipulation of the issues and public opinion. On an urban basis, Arizona has been far behind most other states in expanding its transportation system and range of modes to accommodate the explosive growth in population and in both private and commercial vehicle traffic in the state.

These challenges are not unusual for a state agency to face, particularly in the rural regions where vast highway systems serve a widely scattered populace. The measure of ADOT's leadership has been their ability to innovate and to focus on solutions that best utilize the resources that are available, or can be persuasively won in skilled negotiations.

National Needs and National Initiatives

For state and local highway managers, the most critical challenge in keeping roadways open is the ability to send maintenance and emergency vehicles to the locations where problems exist, and for them to perform effectively under extreme conditions in the field. Advanced vehicle technology provides a resource to meet this challenge.

The reality of such advanced technologies is that, for fifty diverse states, a national program is needed to provide guidance, funding, and a coordinated sense of mission in these areas of research, evaluation and deployment. This leadership and sponsorship role has been accepted by the US Department of Transportation and the Federal Highway Administration.

A Congressional mandate for development of prototype AHS technologies to enhance the nation's transportation system was established by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. As a result, the National Automated Highway System Consortium (NAHSC) was formed in 1994. This entity was a collaboration of government, industry and academic stakeholders in AHS. The core NAHSC partnership involved the University of California, Carnegie Mellon University, California DOT (Caltrans) and key private partners including General Motors, Delco Electronics, Lockheed Martin, Bechtel, Parsons Brinckerhoff and Hughes Aircraft.

The focal point for the NAHSC program was **<u>Demo '97</u>**, an AHS feasibility demonstration conducted in San Diego in August of 1997. This demonstration was the culmination of a variety of advanced vehicle technology research programs, which were showcased in San Diego in the national spotlight (see next chapter). The seminal work of the federally sponsored and promoted NAHSC generated much of the inspiration for more recent individual state efforts in these areas.

The NAHSC program effort focused on enhancements to safety and reduction of traffic congestion, presenting individual and interrelated solutions for heavy commercial trucks, transit buses, and private vehicles. The three core AHS / IVI solutions developed were:

- Adaptive cruise control
- Collision avoidance
- Lane keeping systems

Even in 1997, these three fundamental technologies were represented by fully developed system prototypes with great potential for improved efficiency and safety. Adaptive cruise control senses vehicles in the lane ahead and adjusts speed accordingly. Collision warning and avoidance systems detect objects in the road ahead and can warn the driver, as well as initiating braking or maneuvering. Lane keeping systems use sensors or cameras to follow markers in the roadway, and can warn the driver or steer the vehicle.

Related fundamental research in support of these three key AHS concepts has involved several approaches to the ideal human-machine interface (HMI) including display screens, warning lights and sensory alarms, and head-up displays. Further research has focused on the roadway infrastructure including coded magnetic embeds, continuous magnetic tape, radio beacons and various coded references for optical systems. Finally, differential GPS (global positioning) satellite systems also offer position-referencing abilities for vehicles at limited levels of accuracy.

Since 1997, the national focus and funding emphasis have shifted away from the pioneering NAHSC program, but these concepts have all been the subjects of continued development and even commercialization. Some are still being refined and tested, while others have fallen from consideration as new constraints are discovered, as the funding emphasis evolves, and as new technology resources develop. The potential benefits of AHS to the country's transportation system, however, continue to grow, and Arizona has been an early leader in recognizing and acting upon this potential.

The Turning Point

While many state DOTs were invited to participate in or to witness the landmark Demo '97 in San Diego, few of the visitors saw the potential of the demonstrations as clearly as did Arizona's key managers on the scene. Their ability to apply these new visions of vehicle and roadway capabilities to real problems and limited resources was soon to be established, and Arizona's ITS research program would soon develop a new focus.

The Demo '97 showcase, as detailed in the following chapter, was a turning point in ADOT's effort to enhance the state's transportation system through vehicle-focused research.

III. THE SAN DIEGO TECHNICAL FEASIBILITY DEMONSTRATION

Much has already been written about Demonstration '97, and it is not necessary to review in detail the accomplishments of the NAHSC partners in reaching that point. It was clearly a complex effort that required tremendous creativity and technical ingenuity to bring the core AHS concepts from the computer screen to the roadway. This report chapter will highlight the relevant achievements of the consortium, and will describe the most significant technology demonstrations that influenced Arizona's decisions to become involved in AHS planning and research.

Demo '97 was promoted by NAHSC as a multi-faceted showcase of AHS technologies, in a public and media event format, to highlight near-term achievable IV vehicle products and ITS technology. According to the NAHSC's presentations, the need for AHS was reflected by the fact that human error contributed to 90 percent of the 6.5 million crashes each year. Further relevant figures in regard to AHS solutions showed that fatigue was the leading factor in heavy truck crashes, that vehicle miles traveled would double by 2022, and that gridlock was costing the United States approximately two billion labor hours lost each year.

The Demonstration '97 activities took place at Miramar College in metropolitan San Diego, California, beginning on August 7. Some of the most prominent intelligent vehicle system showcase activities took place on the nearby reversible HOV lanes of Interstate 15. The four-day event featured an indoor-outdoor Exposition Center with a demonstration area, product display pavilions and static displays of IV vehicles and AHS technologies. The NAHSC also offered demo rides in the various classes of intelligent vehicle prototypes to many of the attendees on the closed HOV lanes.

The showcased AHS demonstration scenarios and concepts, especially those relevant to later progress with Arizona's ITS research program, are briefly described in the following sections.

The California PATH Platooning Scenario

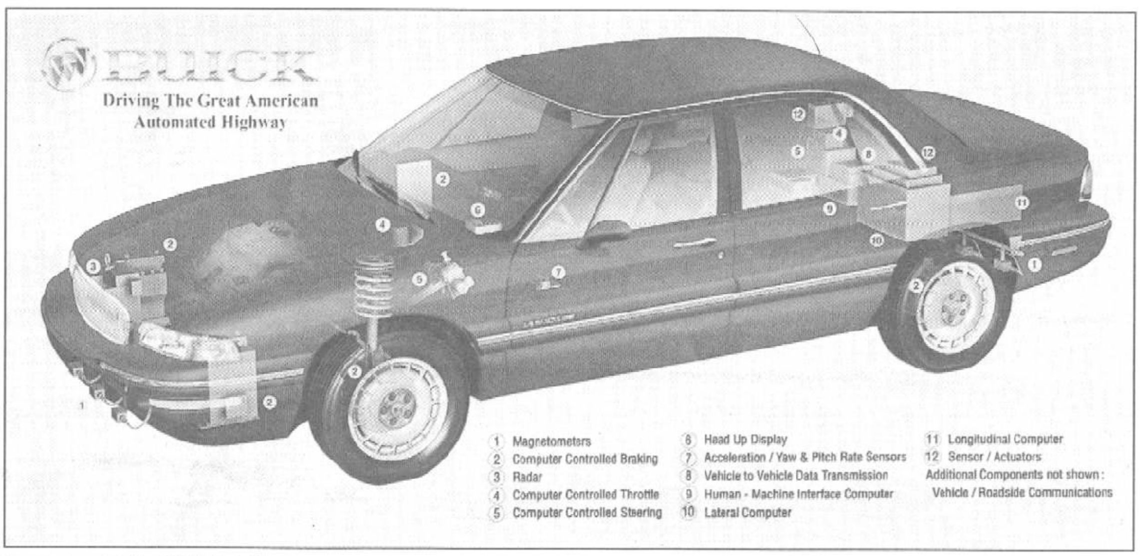
Figure 2: Demo '97 - Platoon Testing near San Diego on I-15 [photo by PATH]

Numerous AHS technologies and completely integrated systems were demonstrated at the Miramar College Exposition Center. Probably the most significant in terms of its potential to improve highway utilization and mitigate congestion was the PATH vehicle platooning concept.

This center-stage demonstration involved a multi-vehicle platoon of completely automated Buick LeSabres, which were loaded with visitors and driven by PATH personnel on the closed I-15 HOV test lanes in a hands-off mode at freeway speeds.

These cars were each controlled by a computer and sensor system, which picked up guidance information from discrete magnetic markers embedded in the center of the test course lanes. An adaptive cruise control radar system allowed the cars to maintain or vary their separation distance. Over a 7.6 mile test lane, the eight AHS Buicks platooned at a fixed separation of only 21 feet at speeds up to 65 mph. They further were programmable to leave the platoon, merge back into it, and change lanes as a group movement. During all this platooning action at freeway speeds, the nominal "driver" calmly kept his hands and feet away from the controls.

This highly sophisticated system was developed by the University of California PATH Program. PATH (Partners for Advanced Transit and Highways) was a core member of NAHSC. The basis of this system is the installation of ceramic magnets every four feet along the lane centerline of the roadway. These magnets are coded to inform the vehicle's computer of its position. The system is programmed with the design geometrics of the roadway segment, so that predictive guidance and automated steering of the moving vehicle is possible. Combined with the head-up display, forward-looking radar and adaptive cruise control, and radio communications among all the vehicle computers, fully automated travel becomes a practical possibility.



Key components in the AHS Buick LeSabre

Figure 3: California PATH Fully-Automated Buick [graphic by NAHSC]

The PATH team, NAHSC and the US DOT presented this practical demonstration as being a key Automated Highway Systems solution to the critical nationwide problems of freeway congestion, safety and air quality. Estimates showed that these tightly spaced platoons of automated cars could double the capacity of a typical urban freeway lane to more than 4,400 vehicles per hour. Compared to new highway lanes, the magnet system costs are minimal. With the greatly reduced separation distance between vehicles at speed, there will also be significant aerodynamic benefits and reductions in fuel consumption and emissions.

Free-Agent, Multi-Platform Scenario

Carnegie Mellon University and the Houston Metro (Harris County) Transit Authority teamed to show other vehicle-based AHS technologies. These systems included full automation, obstacle avoidance and collision warning, based on a machine vision (camera) approach. These integrated concepts were demonstrated with two New Flyer buses, a Pontiac minivan and two cars, each capable of fully-automated operation in non-automated traffic.

Control Transition Scenario

Demonstrations by Honda R&D North America of two "AHS Accords" presented two solutions to the AHS design challenge. These fully automated vehicles operated on both an infrastructure system (roadway magnets) and on a free-agent basis (video system). Honda's concepts demonstrated the ability to provide backup systems for added safety.

Alternative Technology Scenario

The Ohio State University developed an alternative technology concept that also combined and transitioned between two guidance systems. Two Hondas were demonstrated, which were guided both by a video camera system and with radar sensors to follow four miles of 3M Corporation's radar-reflective tape. 3M also showcased their magnetic striping tape for vehicle guidance, which is designed to be embedded or grooved into the roadway surface.

Evolutionary Scenario

Toyota and several partners developed a demonstration of the progression of AHS vehicle automation. Several vehicles were used to showcase multiple systems evolving from diverse warning systems, to lateral control and obstacle avoidance, to fully automated guidance functions. These AHS technologies were all vehicle-based, designed to operate within the existing highway infrastructure.

Commercial Truck Scenario

A commercial tractor-trailer and a test car were equipped by Eaton Vorad to demonstrate AHS building block capabilities. This truck-car team demonstrated EV's adaptive cruise control and collision warning radar systems on the test lanes of the Demo facility. Eaton Vorad also supplied its radar systems to several other core NAHSC program participants.

AHS Maintenance Scenario

Caltrans led the development of the AHS maintenance operations scenario with their core partner, the Advanced Highway Maintenance and Construction Technology Research Center at the University of California-Davis. Two vehicle concepts were demonstrated to support the AHS dedicated lane concept. The first vehicle, the Infrastructure Diagnostic Vehicle (IDV), was designed with support from Lockheed Martin to perform both automated driving and real-time diagnostic monitoring of the intelligent-lane infrastructure (magnets) and communications systems at normal highway speeds. The second support resource, the Obstacle Removal Vehicle, was conceived with a robot pickup arm to safely and non-intrusively remove objects and debris from alongside the AHS lanes.

Demonstration ’97 Summary – the ADOT Perspective

Arizona, as a neighboring state to California, has a clear and realistic vision of its own steadily growing population, traffic volume, congestion, and air quality issues. Meanwhile, new highway construction, maintenance, transportation services and public safety have not been funded adequately to keep pace with this growth. The most recent census figures show that Arizona’s population actually increased by forty percent in the 1990’s. As this growth progressed, the invitation to witness Demonstration ’97 was an excellent opportunity for ADOT officials to learn more about possible practical future transportation concepts.

ADOT senior management, including the State Engineer and key Technology Group staff, traveled to San Diego to participate in the demonstration activities and to develop a better understanding of the potential benefits of AHS for the department and for the state. Some fifteen managers, engineers, planners and maintenance personnel attended the event over several days. Because of the relatively short distance involved, ADOT’s light aircraft was used to shuttle the travelers in an efficient, timely manner to and from a San Diego commuter airfield.

The potential benefits of AHS were seen very clearly by the most senior decision-makers in the Arizona delegation. Most of the ADOT visitors participated in one or more of the Demo ’97 rides in the prototype vehicles. Additionally, there were some crucial discussions with NAHSC, Caltrans and other national-level players with regard to what role a relatively small state such as Arizona could play in the future development of the AHS technologies.

For the Arizona Department of Transportation, the Automated Highway Systems exposition in San Diego was a practical demonstration of integrated technologies and concepts that offer practical solutions to some of the state’s most serious problems. Demo ’97 established the basic technical feasibility of fully automated systems, and it further showed the potential for near-term benefits from semi-automated vehicle and infrastructure technologies.

As stated by an ADOT senior manager of the Technology Group in regard to the Demo ‘97 event, “AHS is a key component of next-generation U.S. surface transportation. Understanding the AHS feasibility and technology will provide ADOT an early opportunity to evaluate this system and its application to the future of Arizona’s congested highways.”

ADOT’s Next Steps

As stated earlier, the San Diego Demo was a turning point in ADOT’s views on technological solutions to transportation problems. After the Demo, discussions of joint research partnerships began, and other AHS demonstration efforts were also suggested to arouse interest and win support in Arizona. With strong support from agency managers, the ADOT Transportation Technology Group began to organize a series of Automated Highway Systems activities. These efforts were intended to attract more attention and funding for these systems, and to earn wider support for future applications in Arizona.

The following chapters discuss several of the most significant AHS efforts.

IV. AUTOMATED HIGHWAY STUDIES IN ARIZONA

The senior management of ADOT saw some tremendous potential in the advanced vehicle and infrastructure concepts that were showcased by NAHSC at Demonstration '97. ADOT had become convinced that there were long-range, and possibly mid-range, possibilities to deal with Arizona's relentless growth and with all of its resulting transportation issues.

A strong need existed to bring back the AHS message and the vision from the San Diego technology showcase to the decision-makers and the public in Arizona. ADOT's Transportation Technology Group (TTG), supported by the ATRC, took the initiative to present the potential benefits of AHS to key agency personnel, to state legislators and executive staff, to Arizona's academia, and to both the media and the public.

A concept study was initiated by the TTG to explore the most beneficial applications of AHS to Arizona's transportation issues, and several significant parallel efforts were begun that focused on public awareness and education. A major goal was to win support and sponsorship for further AHS / IVI research. Funding would be needed from from diverse sources to perform vehicle-related research, and to carry out implementation of these concepts.

The I-10 Tucson-to-Phoenix AHS Corridor Study

Arizona's congestion and air quality problems were a continuing challenge to ADOT's planning and design resources, and several potential applications of AHS / IVI technology were believed to offer opportunities to improve the performance of the state highway system in these areas.

The plan that was developed by senior ADOT management and the Transportation Technology Group was to demonstrate the new concepts to decision-makers and to develop an enhancement program based upon the new AHS technologies. The concept of "intelligent lanes" appeared to be a practical option to deal with the problem of growth in traffic on the Tucson-Phoenix corridor of Interstate 10. This idea had strong potential in an area of great concern for the Department.

Based on ADOT traffic growth modeling, this rural highway corridor would need a third lane in each direction by 2005, and a fourth lane by 2020. Although other studies of options such as light rail had recently been performed, ADOT's planners saw the expansion to four lanes in each direction as almost inevitable. At this point, a new study was clearly needed of the potential for AHS to improve capacity on this corridor and to delay the ultimate buildout.

The TTG turned to an on-call consultant to perform this new study of AHS for the I-10 Corridor. BRW, Inc. of Phoenix was chosen for this effort, and also was tasked to assist with two planned NAHSC Demos that would introduce Arizona's leadership to the concepts being proposed in the new I-10 Intelligent Express Lanes analysis.

At the time of this study, in late 1997, the I-10 Corridor from Tucson to Phoenix carried roughly 30,000 vehicles per day, with 25 percent being commercial trucks. This corridor had recorded some 2,300 crashes in a recent three-year period, with 58 fatalities and over 1,300 injuries.

As national interest in AHS technology grew, Arizona was one of the first states to seriously consider these technologies as a resource to solve real safety and efficiency problems on a rural corridor. The goals of this were to provide a new, practical capacity-enhancement option for a planned Corridor Profile study to support I-10 funding decisions, and also to establish ADOT as a national leader in pursuing such new technological solutions to the major fundamental problems facing all the states.

The Intelligent Highway Concept for I-10

This project's two basic goals, as noted above, were to expand the capacity of Interstate 10 to meet projected demand, and also to stimulate the deployment of intelligent vehicle systems. The concept of automated lanes allowed the planners to accommodate double the current traffic capacity of a given roadway. The challenge for BRW and ADOT was to develop a concept for a phased development of dedicated, controlled-access, protected lanes for AHS vehicles, that would not impact the existing lanes and the flow of non-AHS traffic.

The team developed a basic design that provided a new express lane in each direction with AHS infrastructure elements in the corridor median. These lanes would be separated by barriers from the existing lanes and would have only three termini along the 100-mile rural corridor. Outside of both Phoenix and Tucson, two access-control stations would be built, and the third entry / exit would be at the Interstate 8 highway junction near Casa Grande.

In a phased approach, a protected express lane would be constructed that would meet the capacity requirement for the year 2005, and could support field-operational testing of automated vehicle systems. The roadway design would allow for future conversion to two standard traffic lanes if the AHS / IVI program did not meet expectations in the longer term. This express lane would initially provide HOV capability, with early commercial applications of AHS as a new sub-class of authorized vehicles. The study envisions adaptive cruise control or collision warning radar to be examples of potential semi-automated vehicle systems.

As semi-automated and later fully automated vehicles achieved commercial roll-out status and significant market share, the authorized user classes for the express lane would be adjusted. Ultimately, with sufficient market penetration of fully automated and platooning vehicles, the segregated roadway section could be re-striped for two AHS lanes and would be dedicated solely to their use. It would at that point become the Intelligent Express Lanes that this 1997 ADOT-BRW study proposes.

Conclusions – Intelligent Express Lanes Concept

This study performed detailed analyses of market factors relevant to the market penetration assumptions, which support the phased approach to development of this intelligent highway corridor. The research team also studied the structural design issues for the proposed roadway sections, and the infrastructure issues in supporting AHS / IVI technologies. The results demonstrated that the phased development concept was viable, and that the infrastructure costs were not radically higher than the programmed addition of new lanes in 2005 and 2020.

This AHS corridor study was intended to develop a sound approach at the conceptual level, based on the assumptions, guidance and economic factors developed for Demo '97. It also supported the concurrent AHS vehicle demonstration plans for the Phoenix area, which showcased the feasibility of these concepts. It was expected that as time passed, and as AHS concepts became more clearly defined, further research work would be necessary beyond the conceptual stage.

V. ARIZONA MINI-DEMOS – SMART CARS / SMART HIGHWAYS

One of the most ambitious efforts by Arizona's TTG leadership was to bring the concepts of Demo '97 right to the doorstep of the state's government and the statewide media. Despite the national coverage of the AHS exhibition, and its attendance of some 3,500 stakeholders, much of the country still had only limited exposure to the positive results of the program. What was needed were dynamic "hooks" to connect local transportation problems with the solutions offered by the Demo '97 efforts of the AHS consortium and US DOT.

Fortunately, the NAHSC core partnership was extremely interested in marketing the San Diego concepts to other states and metropolitan regions. ADOT was one of only a few state agencies to immediately explore options to conduct automated highway and intelligent vehicle demonstration activities on their home ground. With support from the consortium members and local on-call consultant resources, ADOT began negotiations to bring some of the most impressive AHS / IVI systems to Arizona.

The intention of the TTG leaders was to organize live demonstrations of the most advanced AHS technologies for the legislators and their transportation staff, for ADOT executive staff, for the media, and for the public. The ADOT Community Relations staff was tasked with developing plans and invitation lists for possible events, and, with the search for possible Demo sites. At the same time, the ATRC was assigned to organize the necessary site selections and infrastructure preparation. The TTG brought in local consulting partner BRW, Inc., as a resource to negotiate, organize and manage the intelligent vehicle commitments with the NAHSC leadership.

As these plans progressed in September 1997, with funding issues nearing resolution, a tentative schedule began to develop. Based on NAHSC partner staff availability and other commitments, the period of December-January became the practical target for live vehicle demonstrations in the Phoenix area. The TTG proceeded with plans to bring two separate intelligent vehicle concepts into the metropolitan Phoenix area.

The first AHS concept demonstration to be finalized was the California PATH system, with its fully automated Buick LeSabres guided by discrete magnetic markers. For this Arizona Demo, a dedicated closed-course test site was required. The PATH date was set for mid-December. The second IVI concept exhibition to be scheduled was the Carnegie-Mellon machine vision guidance system, which could be demonstrated on public roadways. These vehicles were available in mid-January, and plans moved ahead on that basis.

The PATH Mini-Demo Project

By far the greatest effort would be required to organize and carry out the PATH magnet-guidance demonstration. The arrangements for project staff travel and the transport of the vehicles were straightforward – they could be routed to Phoenix from a similar IVI system exposition in Texas. Certainly there were issues that arose, such as the fact that the Buicks were not licensed for public roads and must be trailered to and from their overnight secure storage. Such issues always work out, but not without significant stress and many phone calls.

The more basic challenge was the location and development of the magnet-infrastructure test site. The partners had agreed that the most effective "AZ Demo" plan would be to run the cars on a closed test loop. Because of time and programming limitations, the loop would have to be built precisely as designed for the San Diego event. Caltrans and PATH provided the site design drawings, and the materials specifications and procedures of the earlier testing layout. The

California PATH's mini-demo loop course would be 3000 feet (900 m) in length, requiring some 750 discrete magnetic marker points, and it included eight curves, of which four were spirals. The high-speed loop at the East end of the course had a radius of only 177 feet (54 m).

This condition resulted in an intensive search for a smooth, level, unobstructed and unused surface measuring roughly 1500 feet (450 m) in length and 400 feet (120 m) wide. Other desired features included security and safety fencing, good public access to arterials, extra space for support staff and visitor parking and portable toilets, and all at little or no cost.

Numerous contacts were made and ADOT's Community Relations staff reviewed many sites. In some cases, such as airport runways, the need to drill some 700 holes into the surface was the deciding factor. Ultimately a compromise was reached on a facility where all of the needed conditions could be met – in varying degrees. The site selected was the north overflow parking lot of Sun Devil Stadium, at Arizona State University in Tempe.

Sun Devil Stadium Demo Loop

The VISION Field Office and Phoenix Construction District surveyors coordinated the initial site activities. This demonstration site was ideal in many respects but presented significant problems in others. The parking lot, between the stadium and the dry Salt River bed, was used for student parking as well as many public and athletic events including the ASU and Arizona Cardinals football seasons, the Fiesta Bowl, and their associated tailgate parties. Fortunately this AZ Demo event fell in mid-December, between the major conflicts. Still, needless to say, the first major task was to thoroughly clean the area where the closed loop course would be laid out.

Figure 4: Magnet Layout Activities at ASU Demo Site

The pavement surface varied in depth, smoothness and integrity, consisting of pads for pavilions, asphalt for parking, and soil cement in some areas. Much of the asphalt was only two inches thick or less. It was found that the closed loop design had to be reversed in order to fit within the boundaries of the parking lot. Also, the tail of the loop would not quite fit onto the paved area, due to the geometry and the particularly poor pavement areas. Despite these issues, the entire course design was calculated, surveyed and all 750 magnet points were spotted by the Phoenix District Survey Support team. This layout was about 30 points less than the course design since the start-finish and turnaround zone, being in an unpaved area, was not laid out for magnets.

Once the survey layout was done, volunteer crews from the Phoenix Maintenance District set up with electric drills and a crack-sealer adhesive truck to drill the holes and then set the magnets to complete the test course. This effort began slowly but accelerated as the process was worked out.

The crews additionally had to do some patching of holes in the parking lot's asphalt pavement. At key areas in the high-speed sections of the course, repair work was done to smooth the surface and minimize irregularities. This needed to be repeated during the actual Demo, as the AHS Buicks generated significant dynamic loadings to the pavement in their automated travel mode.

The standard PATH system's "discrete magnetic markers" consist of four cylindrical units, nominally one inch high and 7/8-inch in diameter (see Fig. 10). Each of these magnet assemblies requires a 4.5 inch deep hole of 1.25 inch diameter, and the holes are spaced at 3.94 feet (1.20 m) apart. The accuracy required to drill these holes and to set the magnets is to within plus-or-minus 3/8-inch (10 mm) of the design.   The drilling was done with electric rotary-hammer drills in most cases, and all holes went through the asphalt into the sand beneath. There were some areas of thin, weak pavement, however, where a sledgehammer and steel drift pin was used to punch the hole through.

Once the holes were drilled and cleaned out, the stacked magnets were bedded in silica sand, according to a polarity table provided by California PATH. Each hole was then capped with hot Raised Pavement Marker adhesive, which filled the hole and encapsulated the top magnet.

Figure 5: Placing and Sealing Magnets with Hot Adhesive at ASU Stadium Demo Site

Final preparations for the PATH system demo were straightforward. Barricades, hundreds of traffic cones, and many rolls of yellow warning tape were used to define and protect the test loop. Temporary concrete barriers were placed by ADOT maintenance crews to isolate the course from the site access points and the visitor staging area. The entire site development process required two weeks to complete.

Arizona PATH Demo Events – December 15-17, 1997

hree intelligent Buicks were finally delivered to Tempe, and PATH support staff were on hand to test the magnet installation and commission the systems. Sunday testing was necessary, which resolved a few minor problems and provided the local newspapers with an advance demonstration of the AHS systems before Monday's formal kickoff of the event.

On Monday morning, a large crowd gathered at the Sun Devil Stadium demo site. The PATH, NAHSC and Federal Highways personnel provided their perspectives to those on hand. Senior ADOT staff, including the Director, were on the stage. State Engineer Tom Schmitt welcomed the crowd, and described ADOT's goals and expectations for the benefits of the AHS / IVI technology. Several key legislators and staff also were at the AZ Demo, and State Senator Tom Freestone gave the keynote address. At the conclusion of his remarks on the success of the Demo event, he stated his intention to appropriate funding for a new university research center for study of AHS technology for Arizona highways (see next chapter).

All of the participating decision-makers, as well as many members of the public, were given the opportunity to take a demo ride around the 6/10th mile test loop. Each trip provided three or four passengers with a ride in both directions around the demo course. Since the course was not a full loop, the Buicks were run normally through the course, and then driven in reverse back to the starting point by the PATH technicians. While the 40 mph hands-off first run impressed most of the riders, they were even more excited by the backwards run at the same speed through the cones that defined the serpentine course! One local newspaper, the *Arizona Republic*, described the demonstration as "part serious science and part thrill ride."

Figure 6: PATH Buicks at Arizona Demo – Sun Devil Stadium - December 15, 1997

This AHS / IVI demo was a major event for ADOT and BRW to plan and execute, but the message to the people of Arizona was sent successfully and received favorably. In all, roughly 350 visitors attended the Arizona Demo sessions over two and a half days. A total of about 200 people were given rides in the automated PATH Buicks.

Both ADOT and NAHSC were very interested in evaluating the responses to the demo rides on the ASU test course. The consortium provided a two-page survey form, and 179 of these debriefing surveys were filled out after their rides by participants in this event. The overall results were highly favorable, with over 90 percent reporting that the ride had been a positive experience and that they would like to use these AHS technologies in the future. More than three-fourths of the responses on AHS technology were positive for long trips, and more than half favored the systems for urban freeways and commuting.

Of this group of respondents, the greatest benefit of AHS was felt to be increased safety. Greater efficiency in highway / freeway travel ranked second. As to possible issues, the most common concerns were control in an emergency, and, relying solely on a computer. The evaluation survey and the summary of results are included as Appendix D of this report.

Carnegie Mellon Demo Events – January 21-22

The second AHS Demo that was directly based on the NAHSC program in San Diego was the Arizona demonstration of the Carnegie Mellon University (CMU) fully autonomous cars. The CMU Robotics Institute was a core member of the NAHSC consortium, and their machine vision guidance technology was demonstrated on several of the AHS platforms at Demo '97, including the transit buses and free-agent Oldsmobile and Pontiac cars and vans. The CMU concepts had been already proven in 1995 with a 3,000-mile, no-hands van trip across the United States from Washington, D.C. to San Diego. Only 40 miles were driven under manual control.

This Carnegie Mellon demo event was the second of the AHS Demo functions to be coordinated for the Transportation Technology Group by consultant BRW, who managed the negotiations with the NAHSC. This demo required the transfer of two Pontiac vehicles from Pennsylvania to Phoenix, with their drivers and support technicians.

The free-agent technology demo was scheduled for January 21-22, 1998. The Carnegie Mellon system demonstration was both more and less complex than the PATH fully automated event. These vehicles required no special infrastructure, and instead were capable of operating on the open highway in normal traffic by following the lane markings with a machine vision system. The video camera guidance system, radar sensors, and adaptive cruise control technology combined to showcase full automation, obstacle avoidance and collision warning.

The ADOT role in this Carnegie Mellon demonstration was to provide a suitable test site, and to furnish video of the course so that the machine vision system could be initialized properly. The scenario involved selection of a suitable section of Interstate highway for the demonstration, which would be run in regular traffic. A convenient visitor staging area was also needed.

The selected Demo site was a section of Interstate 10 southeast of Phoenix near the Firebird Lake auto and boat racing facility. The section of I-10 that was driven in the free-agent automation mode was approximately three miles in length. Generally, the passengers would be given a short system briefing and demo on the outbound run. The CMU driver then would exit and rejoin I-10, running fully automated for the return leg of the demo ride.

The CMU demo rides were to be run with only the Interstate portion to be in the automated mode. Because of the small number of vehicles, the time required to make a loop run, and the total time available, this demo was limited to invited guests and the media. Each of these demo rides could accommodate up to three passengers. The greatest concern with this demonstration was the system's safe and predictable performance in the normal traffic stream, rather than the cost and complexity of the infrastructure. The CMU system did perform exactly as expected, although overhead signs did create a few false signals for the adaptive cruise control radar.

This Arizona demonstration of the Carnegie Mellon guidance and control systems was considered to be as successful as the earlier PATH event, from the perspective of both the NAHSC partners and the ADOT Technology Group. Many of the same agency decision-makers, legislators and media were invited to the CMU demonstration, as were a number of ADOT's research partners and stakeholders. As will be described later in this report, both of these NAHSC core concepts would see further application in the AHS / IVI research program being developed in Arizona.

VI. THE ARIZONA VISTA PROJECT

The VISTA research program was one of the earliest positive results of the San Diego Demo, and of the ADOT efforts to arouse interest in AHS intelligent vehicle technologies. This remarkable project was unusual in that the concept and the funding were a direct result of the ADOT Transportation Technology Group's efforts to reach Arizona decision-makers with the message from Demo '97. Although a separate project research report exists, VISTA is critical to this IVI project, and should be addressed in some detail here.

State Senator Tom Freestone championed the VISTA Project as a direct result of the Arizona AHS demonstrations and the I-10 Intelligent Express Lanes study. The State Legislature appropriated funding in June 1998 to establish an intelligent vehicle research center at an Arizona university. This funding was to be administered by ADOT, and proposals were requested from the three state universities. The RFP identified further analysis of the I-10 corridor express lanes as an important element in the new program's workscope.

The VISTA Research Partnership

In November, the Arizona IVI program was initiated with the University of Arizona at Tucson. Under the leadership of Dr. Pitu Mirchandani and Dr. Fei-Yue Wang, the new U of A project was established as the Vehicles with Intelligent Systems for Transport Automation (VISTA) Program.

This new VISTA project would be led by the U of A's Systems and Industrial Engineering Department, and with its partners, the team would perform advanced research of automated highway concepts, including infrastructure and intelligent vehicle control systems. Dr. C.Y. Kuo of the Mechanical and Aerospace Engineering Department at Arizona State University was part of this research team, as was BRW, Inc. who had produced the I-10 study for ADOT in late 1997.

VISTA's fundamental concepts were threefold:

- A hierarchical control structure that, compared to other AHS systems, could operate with reduced communication complexity and reduced real-time computational effort.
- Road design information that could be acquired or calibrated from roadside beacons.
- Cheaper sensor systems combining short and long-range control data acquisition.

The basic mission of VISTA was "…to develop an affordable vehicle that can be deployable within the next 5 – 10 years." A further mandate was to market the AHS program to potential commercial and agency funding partners. The project team was also tasked to review and refine certain aspects of the I-10 corridor express lane study, in light of current AHS developments. The most critical project goal, and most rigorous constraint, was to develop and demonstrate a fully automated Arizona-based vehicle to the state's transportation stakeholders by the Spring of 1999.

The project team faced a major challenge in developing an autonomous vehicle in the roughly six months between November 1998 and early 1999. With the project's ADOT Technical Advisory Committee (TAC), a practical set of goals was developed that could be reached within the allotted time and budget limits. A target was set for March 1999 to demonstrate an operational prototype to the TAC, and therefore April became the milestone for a formal demonstration on the highway.

The VISTA Intelligent Vehicle

The very demanding goals and schedule constraints required a maximum effort by the VISTA project team, and the full support of the TAC was also critical for the project to succeed. The full focus was initially on the vehicle itself.

Based on the University's lab and shop resources, the student labor pool, and the time and funds available, the project team was obligated to use off-the-shelf components for most functions. New custom systems could not be developed with the deadlines facing the team. This would dictate a need for more space under the hood for better access to the controls, to the driveline, and to the braking and steering hardware.

It was clear that an existing vehicle was required that could be readily modified to accept the numerous modifications and additional components needed to fully automate the car. It also quickly became clear that the vehicle was destined to become a "test mule" rather than a sleek, polished "trailer queen" demonstration vehicle. Of the different models considered, the search finally narrowed to a station wagon model with plenty of space for the computers and technicians who would operate, service and trouble-shoot the systems on the fly.

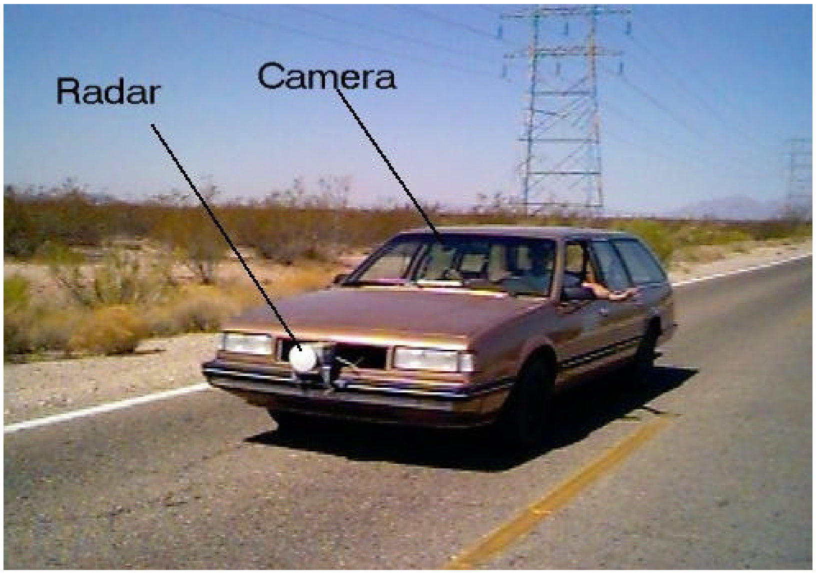


Figure 7: The VISTA Prototype Vehicle

The selected VISTA vehicle was a 1989 Chevrolet Celebrity station wagon from the ADOT fleet. Through the efforts of the Equipment Services section, a lease for the duration of the project was negotiated at a token cost with the University of Arizona. This car already had a significant life history before this special assignment developed, but it provided both the working space and the mechanical simplicity that would enable the VISTA team to perform their modifications, to load up their computer control systems, and to move ahead with the program.

The VISTA car was developed for the initial demonstration deadlines using off-the-shelf systems similar to the free-agent technology of Demo '97. These were primarily a video camera guidance system obtained through Carnegie Mellon University, and a forward-looking radar system to enable the adaptive cruise control function. The goals were to perform platooning and fully automated "hands-off" driving, through the new and refined principles listed above.

Through the first months of 1999, the prototype development went forward at the U of A. By early March, the research team was running successful tests of vision-based lanekeeping and radar-controlled platooning behind a normally driven vehicle. On March 22, 1999, the research staff and the student technicians loaded up their diagnostic instruments, tools and spare parts, and drove the VISTA car to the Phoenix area – an accomplishment in itself. As scheduled in the project workplan, the VISTA team demonstrated the car's capabilities for the TAC at the same Sun Devil Stadium parking lot where the seminal NAHSC demonstrations had been conducted only three months before.

VISTA Demo '99

With the proof of concept established and the program on schedule, work commenced to organize the full-scale demonstration of the VISTA car to the project champions, agency stakeholders, and the media. The stated goal was a public highway demonstration. For practical reasons, ADOT was obligated to provide a closed demo site so that the visitors and support staff could safely park, inspect the prototype, observe the demo runs and line up for the rides. Also, the media needed access to set up for creative coverage of the event.

With vital support from the Phoenix Construction District of ADOT, the ATRC and Community Relations were able to coordinate the VISTA Demo for an unopened new section of State Route 51, the Squaw Peak Freeway, in north Phoenix. The Demo date was set for April 28, 1999.

The ATRC was responsible for laying out the course and defining the staging and support areas. Because some of ADOT's contractors were still active on the roadway, it was decided to use only the southbound lanes for demo runs. This allowed the occasional SR 51 construction traffic to stay on the northbound side, in theory.

The VISTA test course was about two miles in length between the Bell Road staging area and the limits of the closed freeway section. The ATRC borrowed and set barricades and signs to clearly identify the area for the demonstration runs. When the VISTA Car arrived on April 27th, the team began initializing the systems for the new Squaw Peak roadway, which they had only seen before on the design plans.

A problem quickly arose with regard to the SR 51 roadway striping design, upon which the video camera guidance system depended for lateral navigation. The urban freeway was striped along the shoulder, but all of the lanes were defined by white raised pavement markers. This was not a very consistent guidance resource, so a chalk stripe line was soon laid down with a rented striper. This was helpful, but the crosswind tended to scatter the lime and blur the line.

Nonetheless, further tuning of the system and the programs produced consistent test runs and the VISTA Car was pronounced ready for the next day's Demo. Then, at the last minute a major cooling system problem arose. It was only through the late-night emergency overtime efforts of the ADOT Equipment Services shop crew that the car was put back into good running order, in time for the next morning's media events.

Arizona Demo '99 Activities

On April 28, 1999, the University of Arizona's VISTA "smart car" took to the road on the Squaw Peak Freeway before a crowd of ADOT officials, legislative staff and Phoenix-area media. ADOT's State Engineer and other core stakeholders were on hand for the demo rides, and they also offered insights to the media and the crowd during a brief press conference. Several TV stations and local newspapers covered the event, with a very favorable perspective.

Figure 8: Demo of Autonomous Control of VISTA Car on April 28, 1999

As planned, a second manually driven vehicle was used as the lead car for the platooning activity. The southbound test runs were about two miles in length, returning north up the same southbound lanes to the Demo staging area. Both the adaptive cruise control for platooning, and the vision-based lanekeeping systems performed as expected, and the U of A's VISTA demonstration was a significant success. Approximately 25 to 30 people were given rides on the test course.

Achievements of the VISTA Research

Three new and refined technologies were developed and integrated into the prototype Arizona Intelligent Vehicle, the VISTA Car, in addition to the mechanical and electronic achievements of integrating the off-the-shelf components into a functioning system. These key elements of the next-generation VISTA control system are:

- Map-Calibration-based Vehicle Control – instead of guidance-based control, this concept reduces the cost of constructing and maintaining roadside sensors or beacons.
- Trajectory Planning and Optimization – based on the long-range road design data, this will reduce the level of energy consumption and emissions while increasing throughput.
- Distributed Hierarchical Behavior Control – vehicle control functions are decomposed into hierarchically-organized special-purpose task-achieving modules, or behavior programs. Fuzzy logic-based programs from human drivers form the basis for many of the modules.

Next Steps – VISTA Program

This project performed groundbreaking research on a fast-track schedule to accomplish its mandated public demonstration dates on schedule. Once that milestone was passed, the VISTA project principals continued their research activity on a different plane, and pace.

Further work was done to refine and smooth the functions of the control navigational programs, and extensive testing and data collection was performed in the months following the Demo '99. New concepts of communication and roadway data storage have been studied and tested, based on the specific VISTA principles of simplified data requirements and streamlined computation. Vehicle-infrastructure communication remains a topic of continued study.

Further study of the I-10 Intelligent Lanes concept was a secondary mission of this project. With guidance from the research project managers, some graduate-student efforts were focused on validating the assumptions of the 1997 study. In particular, several preliminary studies were performed by the University in regard to the potential of AHS vehicles to improve the capacity of the freeway. These estimates were made for varying percentages of intelligent vehicles in the traffic mix, and also with various sizes of smart-car platoons, and, various traffic stream speeds. Further work was also done on preliminary cost-benefit and market analysis studies.

As the program neared its conclusion, it was determined that significant work remained to be done in this area, although the state funds were no longer sufficient for that effort. However, the ATLAS Center of the University of Arizona maintains an active program of projects that focus on multi-modal transportation logisitcs, control technology and economic issues. With concurrence from the FHWA, the final resolution of the VISTA analytical effort was re-programmed under ATLAS guidelines and the work in these areas was continued. The core of this work was completed in 2000 as ATLAS Project H, *Systems Analysis of Tucson-Phoenix Intelligent Lanes.*

By late 1999, as the vehicle tests continued, the program wound down, and the budget declined, the decision was made that the University would continue its efforts with the VISTA Car. Much more progress was seen to be possible with the control system concepts and the efforts to develop further public and / or private partnerships. The University therefore negotiated with ADOT and was ultimately successful in purchasing the vehicle for continued research.

Further research was performed by the University in regard to control functions, infrastructure requirements and other aspects of autonomous vehicle implementation. Several graduate students on the project team based their Masters' theses on some of the late-program VISTA work in these directions (see web site: *http://tucson.sie.arizona.edu/ATLAS/Research.htm*).

The VISTA Research Report

A project research report was a final task for the University of Arizona. This report was authored by Professors Wang and Mirchandani of the U of A and Professor Kuo of Arizona State. The final report, *VISTA – Vehicles with Intelligent Systems for Transport Automation* is report number AZ-473(b), dated November 2000, and it is available from the ATLAS Center at the University of Arizona, or from the ADOT Transportation Research Center.

VII. ADOT's NATIONAL AND REGIONAL IVI ACTIVITIES

Arizona's involvement in promotion of AHS / IVI concepts, and its efforts to develop its own position as a leader in research and deployment, led to other opportunities in transportation research and policy development. As a direct result of this research project, the ATRC and TTG made a significant effort to become more involved in a number of the national initiatives on intelligent vehicle and infrastructure planning.

This report section covers the several distinct intelligent vehicle research initiatives in which Arizona took part following the AHS Demo activities, from late 1997 until the spring of 2000.

ITSA - Specialty Vehicles (SV) Initiatives

ADOT as an agency is a strong supporter and participant in the activities of ITS America (ITSA). This organization was very active in helping to define and direct ITS strategic planning efforts, with Federal support, and ADOT was involved in some of the core task groups during this time.

The ATRC participated in the Steering and Working Groups of ITSA's IVI Specialty Vehicles Platform. This program was initiated in early 1998 to formalize and address applications for IV systems to improve highway safety by reducing the number and severity of crashes. The ITSA program mission was basically to develop a practical plan giving guidance and direction in detail to the US DOT Intelligent Vehicle Initiative, with regard to this SV platform.

Specialty vehicles fall into four categories, being law enforcement, emergency medical, fire, and highway maintenance and construction. All of these vehicle classes are required to function in extreme weather and demanding driving conditions.

The Specialty Vehicles program was organized and its mission was developed though this ITS America committee process, with Federal funding. Goals, resource and user services definitions, areas of research, a timetable and workplan were developed through the Working Group process, which led to completion of a formal recommendation deliverable to the US DOT. A Request for Information with regard to sponsor interest and commitment was a key part of this plan, as were operational testing recommendations.

ADOT took part in this program with a series of meetings and teleconferences in 1998, and actively supported the draft efforts and final deliverables for the ITSA working / steering groups. Ultimately the program resulted in a Pooled Fund Study being established in late 1998, with California shouldering the role of Lead State to administer the pooled fund for the project. While involved in committee activities, ADOT did not commit funds to join the study as a full partner. Later, in 1999, the US DOT emphasis was changed to some extent to give more emphasis to infrastructure communication factors in crash reduction. The program continues in this form.

ITS America's DEMO '99

Two years after the seminal San Diego IVI Demo, a second national showcase of intelligent vehicle technology advances was conducted in July, 1999. This event was organized by ITS America at the private Transportation Research Center in East Liberty, Ohio. The spectrum of IV platforms was again demonstrated to the media and transportation agency staff at all levels. Of particular interest to ADOT were the demonstrations of two years of progress in competing technologies in the specialty vehicle and commercial vehicle classes. For example, the latest from both the 3M and the California magnetic systems for lane guidance were displayed.

ITS America's RATTS '99

An international rural ITS conference is held in a different region of the United States each year, and it is sponsored by ITS America and their corresponding state chapter. This conference offers an important showcase opportunity for the host state's ITS progress and future plans. In August, 1999, the Rural Advanced Technology and Transportation Systems Conference was presented in Flagstaff, and was hosted by ADOT and ITS Arizona.

Of the many sessions on the agenda for this ITS conference, Winter Maintenance & Intelligent Vehicles was among the most popular. Arizona had recently initiated a snowplow research partnership with Caltrans (see Section Two of this report). RATTS '99 conference presentations included this ASP snowplow project, the Arizona VISTA project, and the Iowa and Minnesota winter research programs. Sessions on ITS technology in rural maintenance, safety and communications also featured presentations related to the Caltrans / ADOT snowplow partnership and to the details of some of its control elements.

Because of the significance of the conference and the proximity to ADOT's new test facility for the Caltrans snowplow system, the ASP snowplow was shipped to Flagstaff for static display in support of the various session presentations. The Caltrans project team sent two of their technical support staff to assist with the display, which attracted a great deal of interest during the sessions.

A related technology from 3M Corporation was also showcased at the RATTS, consisting of magnetized lane striping tape. This magnetic tape was the heart of the 3M Lane Awareness System, which was in use by the Minnesota DOT research program on a variety of platforms. The 3M staff demonstrated this system at the conference, giving rides in the hotel parking area.

Advanced Construction and Maintenance Systems (ACMS) Pooled Fund Research

Another specialty program of great interest to the various state DOTs was the ACM sector of the national IVI program. Many stakeholders saw the Construction and Maintenance field as an area that the US DOT's initial Intelligent Vehicle Initiative did not sufficiently address. The goal of several partner states, led again by California DOT, was to establish ACMS as a significant and separate category for attention in the national plans and architecture standards.

Construction and maintenance vehicles, and their management and efficiency, are crucial to the consistent usability and function of the roadway. As ITS and AHS elements enter the highway infrastructure, efficient construction and maintenance functions become more and more vital. The deployment of new technologies adds to the maintenance challenge. Workzone safety is also a critical issue, with 700 to 800 fatalities annually across the United States. Research in these fields is a critical need.

ACMS Research applies robotics, navigation and computer systems to an area that traditionally has had little technological refinement. The need and benefits are clear. Manual activities can be roboticized. Analysis, decisions and control can be computerized. Sensing and control systems for inspection and vehicle guidance offer great potential. The ability to automate former manual functions and to perform maintenance activity in motion is a core goal of this ACMS research.

The ACMS Pooled Fund Study was another effort for which Caltrans accepted the Lead State role. In this situation, Arizona had a strong interest in the research and its crossover application to several core ADOT disciplines, and it was decided that the state would participate in this new pooled fund project. ATRC initiated this membership with a mid-year request to the Research Council to fund this project from uncommitted SPR monies.

This vote, the first effort at an e-mail ballot for the ADOT Research Council, was approved, and the state's partnership in ACMS was formalized in late 1998. Since that time, Arizona has been an active member in meetings and conferences of the task force. The ATRC, District Engineers and the Traffic Operations Center have all participated at different times. ADOT has provided review and significant comment to the pool group during its development of the National Plan for Advanced Maintenance and Construction Systems.

Transportation Research Board (TRB) Activities

Arizona was invited in 1998 to take part in TRB Task Force A3A53, the Vehicle-Highway Automation study group. This task force was established to champion this research and development field in the TRB program, and to sponsor conference sessions and papers at the Annual Meeting. One key 1999 goal of the V-HA Task Force was to prepare a Millennium Paper for the 2000 session of the Transportation Research Board. The paper focused on likely scenarios for the development and application of vehicle-highway automation in the next 10 to 25 years.

ATRC represented ADOT in several meetings of the V-HA Task Force, including the annual TRB meeting in Washington D.C. and one mid-year ITS America session in Ohio in 1999. The basic mission was to develop and deliver the "vision" for future vehicle-highway research as an element of the larger direction of the TRB. The Millennium Paper deliverable was completed and submitted. This Task Force then evolved into a TRB standing committee, A3A19, in which the ATRC has not remained fully active.

Federal IVI Grant Proposals

The fundamental mission of the US DOT / FHWA Intelligent Vehicle Initiative was to accelerate the market availability of consumer safety systems. To achieve this goal, Field Operational Test (FOT) programs were initiated in several areas. As described above, some ITS America task forces had a role in shaping program goals and enabling FOTs as an evolutionary step to implement IVI in the United States. In December 1998, US DOT / FHWA issued a competitive Request for Applications for IVI field tests in the four Specialty Vehicle classes, with grants totalling $12.7 million being offered.

Caltrans was quick to see the potential of this program in regard to its own research program, and initiated a formal proposal for the FOT. Caltrans based this FOT joint proposal on its Advanced Snowplow program, and Arizona's second independent test site was a strong positive factor in the planning. Based upon its growing research relationship with California, ADOT assumed a key contributing role in preparing a joint proposal for US DOT's Field Operational Test Program. The California Highway Patrol and Freightliner Corporation were among the significant new additions to the current consortium of Caltrans snowplow research partners.

The California Arizona Specialty-vehicle Safety Evaluation (CASSE) Proposal was submitted in March 1999. Despite intensive efforts by the partnership to address all issues and goals, and to present a thorough and complete workplan, the funds were awarded in November to several other specialty vehicle partnerships. This loss of potential funding was a disappointment to the CASSE partners. Nevertheless, the Caltrans team and ADOT were able to continue with their previous long-term research plans and goals using established research funds from their traditional sources.

The Phoenix Project (CVHAS)

Caltrans and its consortium partners established the Phoenix Project in 1998, the year after the San Diego Demo. The FHWA had withdrawn funding from the NAHSC, declaring that its AHS demonstration mission had been accomplished. The Caltrans Phoenix Project is an advanced vehicle-highway system program to promote research, development, testing, demonstration and deployment of technologies leading to an automated highway system in the United States. The emphasis beyond NAHSC was to focus on integration of vehicle and infrastructure systems.

Because the US DOT had shifted its primary focus to specific segments of IVI technology, the Phoenix partnership was slow to gain support. Caltrans carried on with outreach to partners and spoonsors through and beyond 1999. Arizona had a strong interest, and participated in meetings with Caltrans as a snowplow research partner. However, ADOT did not commit any research funds during this 1997-1999 time period.

The Phoenix Project was finally developed successfully by California as the Cooperative Vehicle-Highway Automation Systems (CVHAS) Pooled Fund Study. By July 2000, there were ten states committed to this project. Caltrans continued marketing the program, which was to formally kick off in November. Although it was past the Phase One report period for this ADOT snowplow / AHS project, it should be noted that ADOT did ultimately join the Phoenix-CVHAS pooled fund. This program is continuing.

Nationwide Automated Truck Facility (NATF)

Another related program also was developing during this seminal time period for the AHS / IVI initiatives, and this new project was conceived to a great extent by transportation officials from Arizona. This concept was initially named the Dedicated Commercial Vehicle Lanes on I-10 (DCVLI-10) project. The ADOT State Engineer was a strong champion of the concept, and he developed interest from other states at an AASHTO conference in early 1999.

This dedicated lane concept offered numerous benefits in safety and efficiency for commercial vehicles and for other traffic on the nation’s rural and urban highways. This project proposed to evaluate the feasibility of a dedicated CVO lane for the I-10 Corridor across the southern United States. At least six states showed strong interest in off-line meetings at the AASHTO conference.

Arizona was seen by many to be an ideal “moderate” state to lead this feasibility study, rather than the largest states that anchor the I-10 Corridor. For most stakeholders, the best solution was seen to be having a Federal leadership role for such a program, and correspondence was initiated.

ADOT took an active role in developing this concept into a viable project. ATRC and the Transportation Technology Group met with Caltrans state and regional officials in May 1999 to discuss the potential for the project. Leadership remained the key issue. At about that time, the ADOT State Engineer reached the point of retirement from government service, and without his support, this program began to lose momentum in Arizona.

California, as an anchor state for the corridor, had a strong interest in the concept and Caltrans had identified some of the funding needed to initiate a pooled fund project. The concept offered many potential benefits, and although Arizona stepped back at that time it was ultimately adopted by the California DOT.

More efforts were made by Caltrans to reach a Corridor consensus and seek CVHAS funding. In June 1999, California and seven partner states asked the Federal Highway Administration for support to proceed with the program. Finally, in early 2000, Caltrans was successful in initiating this program with state planning funds from the SP&R program. Arizona has continued to be involved in the program, but participation has been shifted from the ADOT Research Center to the Transportation Planning Division leadership. This program is continuing.

VISION 21 Demonstration – Arizona State Capitol

In the Spring of 2000, an opportunity arose to showcase the most relevant IVI technologies at the highest levels of Arizona state government. The Governor's Transportation Vision 21 Task Force had been created to face the difficult questions of how best to deal with the explosive population and traffic growth in the state. This group included key legislators and business leaders, and their focus was on all modes of transportation that have potential to address the rapidly growing problems of congestion, delays, safety and air quality. Their task was to develop a full suite of transportation enhancements and funding recommendations by early 2001.

The leaders and supporters of the Vision 21 program had reached the point, in early 2000, where more specific recommendations and demonstrations of transportation options were needed. Their studies had explored the scope and detail of Arizona's current issues, and the probable direction and magnitude of the anticipated growth of these problems. Both the public and private sectors were therefore invited to present recommended new concepts to the full membership of the Vision 21 Task Force.

The V21 session was scheduled for June 7, 2000, at the Arizona State Capitol, and was intended to focus on capacity enhancement concepts. The presentations would include advanced vehicle systems, alternate fuel technologies, roadway and signal system refinements, highway safety and travel reduction programs, passenger rail innovations, and any and all relevant ITS concepts to provide safer, more efficient operation of the state highway system.

The advanced vehicle concepts of this Vision 21 Demo agenda included alternate fuel and hybrid vehicles, commercial truck fuel and engine systems, the I-10 automated highway concept, and the ADOT specialty vehicle research program. In particular, current activities in winter maintenance received significant attention. ATRC provided information on the current Arizona snowplow research partnership with California, and 3M also was on hand to give system demonstrations.

ADOT's ATRC and TTG initiated several efforts to set up an IV demonstration for the members of Vision 21, including the PATH and Carnegie-Mellon systems. Ultimately, the best choice became 3M Corporation's lanekeeping guidance system, with their magnetized striping tape as the key infrastructure element of the concept. The 3M team were already discussing their commercial-market system with ADOT for future research, and it was being extensively tested by Minnesota DOT in their snowplow research program.

The 3M Lane Awareness System was ideal for a short-term demonstration, since a fully-equipped research vehicle could be driven to Arizona, and the necessary magnetic striping tape could be laid out on the roadway as needed and removed after the event. The 3M team and ADOT laid out approximately 200 meters of tape in front of the Capitol Building, and little other effort was needed to enable the demonstration rides. A sport-utility vehicle from 3M's partnership with Minnesota and Iowa was used for the Demo. This truck had roadway tape sensor bars and the 3M operator display screen, as well as driver warning systems in the form of peripheral vision lights and seat vibrators.

On June 7, ADOT's TTG and involved consultants gave highlight presentations on the advanced vehicle concepts to the Task Force members in session, and there were gaps in the agenda for the V21 group and guests to visit courtyard and curbside areas for the various vehicle presentations.

Overall, the 3M Lane Awareness demonstration was among the most popular options. Numerous task force members and agency staff, as well as the area's media, experienced the system as it was driven along the tape line on the closed street in front of the State Capitol Building. The comments, as well as the media coverage, were positive, and ADOT's level of interest in the 3M system was also raised by this event.

Conclusions- Arizona's Diverse AHS Activities

ADOT has been involved with, and continues to take part in, many activities on a regional and national scale. ADOT's primary intent is to explore and develop effective technological solutions to transportation problems on the state's highway system. A second goal is to participate in national AHS efforts in order to represent the real long-term interests of the smaller state DOTs.

Many states cannot carry out these complex research programs due to their limited staff, funds and facilities. Arizona does participate as much as possible, and in doing so, it helps to provide a "reality check" for the major state programs to produce valid results that can meet national needs.

The first section of this report has provided a summary of the diverse activities that ADOT has conducted over the three initial years of this intelligent vehicle research program in Arizona.

Section II will describe in detail the history of the Advanced Snowplow research partnership that Arizona has developed with California.

SECTION II - ARIZONA-CALIFORNIA SNOWPLOW RESEARCH

VIII. THE ARIZONA INTELLIGENT VEHICLE RESEARCH PROJECT

The Arizona Transportation Research Program

As a result of the information and perspectives gained by ADOT management from their involvement in the San Diego Demo '97 activities, there was a strong interest in moving forward to determine what benefits could be gained for the state of Arizona. The need to explore the possibilities of AHS technology provided a clear mandate for a new direction in the state transportation research program.

At this time, there were already several Intelligent Transportation System research projects and field deployments under way in Arizona as integral elements of the research and construction programs. The benefits of ITS in freeway management systems and practices, incident management programs, detection device evaluations, remote weather monitoring, and maintenance planning were well established and some early projects were already providing benefits to the Department.

Major research programs to develop corridor and statewide ITS deployment strategic plans, based upon the federal ITS architecture, were well underway during this time. Rural and urban traveler information media were another key focal area for ITS projects being performed for the Arizona Transportation Research Center (ATRC).

Arizona did not have, however, any significant research in the program at this time to deal with automated highways and intelligent vehicle topics. Based on the NAHSC program, and guidance from its core members, ADOT's Transportation Technology Group and the ATRC began to develop a plan to initiate an AHS / IVI research project that would assess and offer new solutions for Arizona's transportation needs.

The ADOT Research Center

Arizona's transportation research program is federally funded, through State Planning and Research budget allotments from FHWA. Research activity is assigned one-fourth of the total of those funds in each program year. Seven technical disciplines, or emphasis areas, must compete annually for the limited funds available. In this situation, the Arizona Transportation Research Center is somewhat limited in its capacities and abilities to do in-house research activities.

In comparison to larger states, the facilities and resources of the ATRC are limited, and they are primarily focused on project management. Consultants and the state universities perform most ongoing research work. There are no laboratory or new product development facilities, and the ADOT Sections that sponsor research topics such as materials studies or product evaluations may also do the lab or field work for these projects.

There are relatively few options, therefore, to initiate a vehicle research program in Arizona. Even the universities have limited resources for the type of vehicle shops that might create prototypes, perform lab and track endurance testing, and deliver presentable products for demonstrations, marketing and sponsorship solicitations. As a result, ADOT's efforts to become involved in AHS research and development required significant planning and creativity to finally provide tangible benefits to the state, to its partners and to the public.

Development Plan for the New AHS Project

Based upon the recent in-depth conversations with NAHSC core partners, and with other research program leaders across the country, a narrowly focused approach was developed by ADOT to become involved in AHS research. The limitations of Arizona's resources were recognized, but the leadership of the AHS initiative had a vital interest in attracting additional states to participate in showcasing the feasibility and the benefits of AHS technology. They were therefore very supportive of ADOT in exploring practical ways to study and demonstrate these concepts.

There were several research areas of interest to ADOT, all focused on different applications of Automated Highway Systems technology. The most urgent concerns dealt literally with automated highways, in light of rapid growth in Arizona's population and traffic volumes. There was also a desire to perform local development and refinement of AHS technologies, particularly in light of the software and systems expertise at the state universities. However, the widest base of support within ADOT was seen to lie with the Districts, where operational efficiency and safety issues such as winter maintenance are the driving forces in any test or evaluation of new technology. This reality, and the research already under way in California and Minnesota, shaped ATRC's approach to earning the support needed to get this new project authorized and funded.

In order to initiate a new research project out of the normal program timeline, the ATRC must present the Problem Statement to the ADOT Research Council for a vote. If a strong case is made, and uncommitted research contingency funds are available, then the new project may be approved by the Council.

As described above, the decision to assign funds for new research is made by a council of senior ADOT managers and section heads. Their judgment of the state's needs determines whether a project wins approval. In this effort to create an Automated Highway Systems research project, it was clear to the sponsors that rural winter snowplowing activity was the specialty maintenance function that could benefit most from deployment of the AHS concepts. Additionally, there were notable programs already underway in which ADOT could consider partnership options.

Therefore, ATRC proposed that the new research would primarily focus on improved snowplow safety and performance, with corollary studies to explore the congestion and freeway safety benefits of AHS (see Problem Statement in Appendix A). In anticipation of the project being approved, a Technical Advisory Committee was formed to guide and monitor the research effort. This TAC group included the northern Arizona ADOT Districts, other key agency sections, and stakeholder partners (see member list in Appendix B).

The project's problem statement was prepared in September by the ATRC and the TAC, with guidance from ADOT's I-40 Corridor District Engineers and the Transportation Technology Group. On this basis, the Research Council approved this project in October 1997, and the FHWA concurred in assigning the requested funds.

Arizona's AHS Program Goals and Partnership Contributions

It was clear that to achieve significant research results, ADOT must develop a partnership with one or more of the major players in the AHS / IVI arena. The issue for Arizona would be how best to ensure the local / regional relevance of any joint research program. Once the project was approved, it was crucial for ATRC to effectively and creatively leverage the limited resources, so that ADOT's core needs were met and all of the stakeholders' key questions were answered.

The ATRC goal was to join a major intelligent vehicle / AHS research program, in order to gain the maximum benefit from the significant funding and the R&D facilities of such an effort. In return, ADOT's primary assets for a partnership were not its limited funds but its unique mix of weather, terrain, and highways, and the strong commitment by the ATRC and the District field staff to support this effort. These factors were to become very significant to the AHS program core partners, and to the success of the research project as it developed.

Both before and after the NAHSC Demo '97, ADOT had contacts with both California and Minnesota in regard to concepts and to possible joint research activity. As a result of the San Diego event, the ADOT senior managers felt that the California PATH system had the most flexibility in developing full-automation capabilities for intelligent-highway use.

Advanced Snowplow Program Coalition

The ATRC received an invitation from Caltrans, and a verbal commitment to become involved as much as possible in their Advanced Snowplow Project. The California DOT and its partner organizations were committed to the PATH concept of discrete magnetic markers in the lane centerline of the roadway. The polarity coding and the route geometry provided the PATH-equipped vehicles with predictive abilities that resulted in full automation of the steering / lane-keeping function. This magnet system was felt to be the most robust and flexible of the roadway infrastructure options available for deployment.

Caltrans was well along in this project in the months following the Demonstration '97, and ATRC was invited to an impromptu scoping meeting with the intent of forming a regional coalition for testing of the Caltrans advanced snowplow technologies. Two ADOT snowplow operators also attended, to offer their field perspective on the design criteria for the Caltrans prototype system. The Montana DOT, PATH, and Western Transportation Institute (Montana) also took part in the meeting at the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center of the University of California at Davis. This meeting was in September 1997, before ADOT's Research Council had met to vote on the need to fund the new mid-year project.

With a new 10-wheel International snowplow truck committed to the Caltrans research, the UC-Davis / AHMCT was tasked to carry out the snowplow modifications, to accommodate the PATH sensors and hardware, and to determine the best operator display system options. Caltrans stated in the meeting that their vision for the system was to deploy the infrastructure magnets only in the specific locations or "hot spots" where safety and operational problems were greatest. A further key decision by Caltrans was to concentrate the work not on full automation, but on practical "driver assistance" technology. This approach offered a smoother learning curve and transition to acceptance of AHS concepts at the critical field-operational level of each agency.

Montana and Arizona both expressed strong interest. However, Montana also stated an interest in magnetic striping tape options, and ADOT noted that differential GPS control concepts were also of interest to Arizona's leadership. Both states were formally invited by PATH and Caltrans to form a coalition, and it was agreed to pursue a regional field test plan if funds could be arranged. The group visualized possible coalition responsibilities as follows:

- AHMCT Research Center / UC-Davis - Technology Integrator
- PATH, 3M, other core team - Technology Development
- Western Transportation Institute - Demonstration Coordinator
- State DOTs (CA, MT, AZ, MN) - Facility Improvements

Each potential partner agreed to explore its goals and time constraints, and if practical to commit its resources to the program. Ultimately, Arizona did commit project funding in late 1997, while Montana deferred on active support at that time. Therefore, plans were set in motion to create a regional Advanced Snowplow research program, with Caltrans as the lead state agency and ADOT as a core partner. The other partners in the ASP program were the AHMCT Research Center, and its subcontractors, California PATH and the Western Transportation Institute (WTI).

ASP – Arizona's Role in the Caltrans Program

Arizona's commitment to this program, with the limited funding available, was agreed to be the development of a second, completely independent test site infrastructure. ADOT would identify an optimal route and site, and would install several miles of PATH magnets for cooperative tests of the Caltrans prototype snowplow.

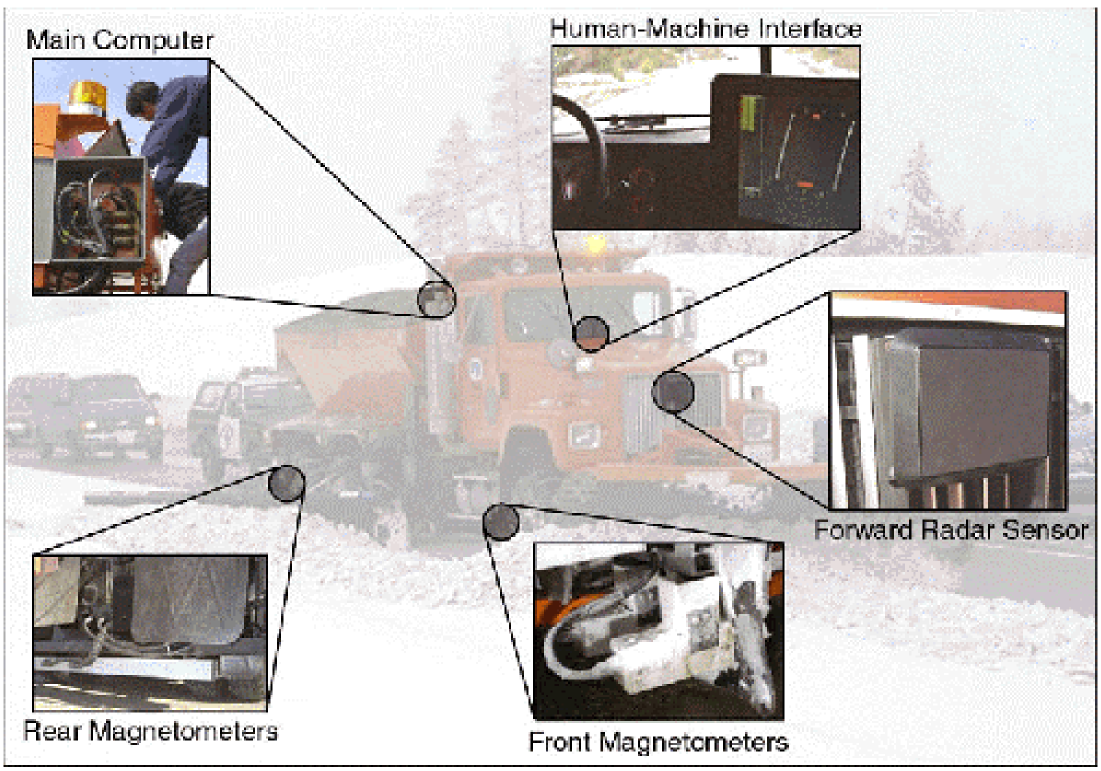


Figure 9: Caltrans ASP-I Prototype Snowplow with Subsystems
[courtesy of AHMCT]

This single most critical ADOT contribution to the ASP program would provide California with a unique second test area with its own terrain, weather, and roadway conditions. It would be different in every way from the Caltrans test lane on Interstate 80 at Donner Summit. It would further provide a second independent pool of snowplow operators and winter maintenance practices to test and evaluate the AHMCT / PATH systems.

Arizona further agreed to fund the transport of the snowplow between the two states, and the costs of commissioning and technical support during the Arizona tests. At least one month of training, testing and evaluation each winter was planned for the Arizona site.

Both California and Arizona determined that under the circumstances, the formal agreement for this collaboration should be in the form of an intergovernmental Joint Project Agreement (JPA). Over several months, this agreement was worked out and ultimately formalized in 1998. The joint project document appears in Appendix C.

With this understanding and commitment, internal planning and basic research was begun to identify the Arizona magnet system-testing site.

Arizona's Critical Contribution

Arizona recognized that its ability to develop a second test site offered the greatest benefit to the Caltrans program, due to the region's unique terrain and climate characteristics. The Project TAC nominated several locations across Northern Arizona to be considered for the PATH magnet testing, and in each case the goal was to define the site's unique conditions for the future system evaluation process. In comparison to the Caltrans Advanced Winter Maintenance Testbed site at Donner Summit, every significant characteristic of the Arizona selection should be distinctly different.

As tabulated below, the final site selection on US 180 near Flagstaff did meet this standard, and offered unique testing conditions for further vehicle system development. In addition, it is in a completely different winter storm track and weather pattern than are the California Sierras.

Table 1: Test Site Diversity Guidelines

Test Site Criteria	Arizona Site	California Site
Name / Route	Kendrick Park on US-180	Donner Summit on I-80
Pavement Type	Asphalt	Concrete
Roadway Design	Two-Lane Rural	Three–Lane Interstate
Traffic Stream	Oncoming – Two-way	One Way
Roadway Shoulders	None	Interstate Standards
Roadway Geometry	Min Curve Radius 946 Ft	Interstate Standards
Roadway Grades	To 8 Percent	To 6 Percent
Elevation	7,000 to 8,000 Ft	6,400 to 7,200 Ft
Traffic Volume ADT	2,500 – 3,000	27,000
Snowfall – Annual	90 to 100 Inches	400+ Inches
Operating Procedures, Labor Force, & Vehicle / Plow Designs	ADOT	Caltrans

This report will discuss the site selection decision in more detail later. However, ADOT and the ATRC were faced with another issue that required prompt resolution – the decision on exactly how, and if, the PATH magnets should be installed in Arizona's roadway pavement. In January of 1998, ADOT moved into the active phase of this research project partnership with California.

IX. THE ADOT MAGNET-TESTING INITIATIVE

The decision for Arizona to partner with California on the basis of PATH's magnetic nail concept was a significant issue for all of the ADOT stakeholders. For various reasons, many concerns and questions had to be resolved. Perhaps the most basic issue was what effect would the thousands of magnets have on the roadway surface itself? Should ADOT proceed with the plan to drill these holes in its highway surfaces? The project team was given a mandate to resolve any issues before continuing with the site selection and the planned installation on the roadway.

This issue left the TAC and the ATRC with a range of basic questions, not limited to:

- How to drill or punch the holes?
- What tools would perform best?
- How to achieve the needed drilling accuracy?
- How to place the magnets?
- How to seal the magnets?
- What sealant would perform best?
- How to avoid losing the caps or seals?
- How efficiently could the installation be done?
- What resources were required to install magnets?
- What would this activity cost?
- Would the roadway crack along the line of holes?
- Would the pavement surface fail at the holes?
- Would the magnets come out?
- Would cinders and chemicals affect the sealant?
- Would freeze-thaw affect the sealant?
- Would summer heat affect the sealant?

ADOT had already installed PATH magnets at Sun Devil Stadium in Tempe for the December '97 Demo of the AHS vehicles. The surveying, drilling and magnet-setting tolerances were known, and they are summarized below. The challenge would be to find the best equipment, materials and processes to install the thousands of magnets efficiently and accurately.

Figure 10: California PATH Discrete Magnetic Markers

Roadway Magnet Parameters

The requirements of this unique communicative highway infrastructure are extremely precise, but the fundamental basis for the PATH vehicle control system is a simple ceramic magnet. Each magnet is a dense gray-black cylinder 1.00 inch tall and 0.875 inch in diameter. Installed in stacks of four, the magnets are placed in the roadway in a continuous line with the positive polarity upwards. The infrastructure details such as roadway curves, grades and obstacles are coded into this magnet line by reversing the polarity in a unique binary code for each section of the highway. The specifications provided to ADOT defined each typical highway control segment to be 170 magnets in extent, beginning with 16 magnets coded and then 154 standard.

The PATH magnets were specified to be installed at 1.2 meter intervals on the lane centerline. The length of the control sections therefore was 204 meters (670 feet). Based upon the planned four lane-miles to be installed in Arizona, this would require 32 sections to be programmed, each with its unique set of codes, and with approximately 5400 sets of four magnets to be installed.

PATH and Caltrans had developed specifications for accuracy that challenged the surveyors and installers (Figure 11). The magnet holes, of 1.25 inch diameter, were to be laid out on a 1.2 meter (47 1/4 inch) spacing, drilled 4.5 inches deep, and with a lateral accuracy of +/- 3/8 inch (10 mm) and a longitudinal accuracy of 2 inches. Individual magnet spacing could be shifted up to 20 cm (8 inches) along the line to avoid pavement joints or defects, but the lateral tolerance was critical. The most critical step was to drill the holes on the mark, because the magnets would have only 3/16 inch of annulus if centered perfectly. They were to be set at least one-half inch below grade, perpendicular to the surface, and sealed flush with the pavement.

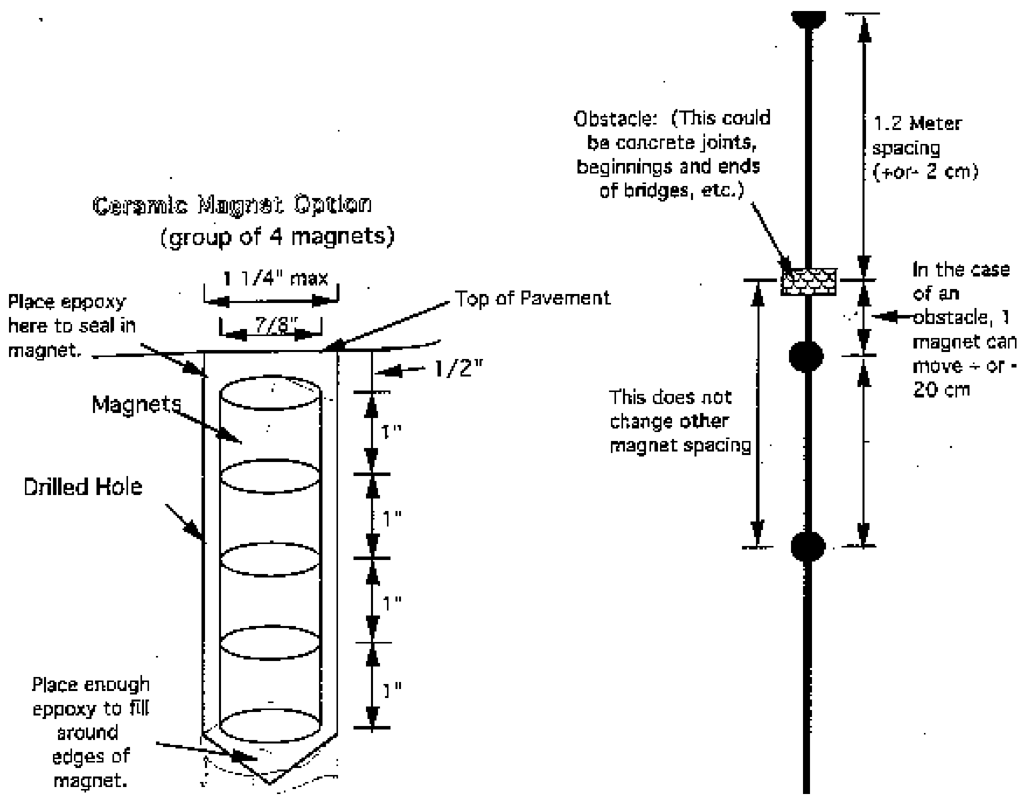


Figure 11: Magnetic Marker Installation Requirements [graphic courtesy of Caltrans]

Magnet Test Sites Planning

Initially, the TAC and ATRC focused on the range of materials and methods that might serve the installation and materials testing requirement. Although the magnets themselves were a given, their field installation had many variables. In order to assess the real-world performance of all elements in the program, the project team decided to install six test sites where a short sample section of magnets would be installed on the centerline of the highway.

In January 1998, the time window for action was very short, since winter and summer conditions both needed to be evaluated before a decision could be made for installation in the fall. The best site also should be subject to heavy traffic, to more quickly determine the stability of the magnet installations. Because of the urgency to make procurement decisions, it was decided to proceed immediately, and six magnet test sites were selected along Interstate 40 across northern Arizona.

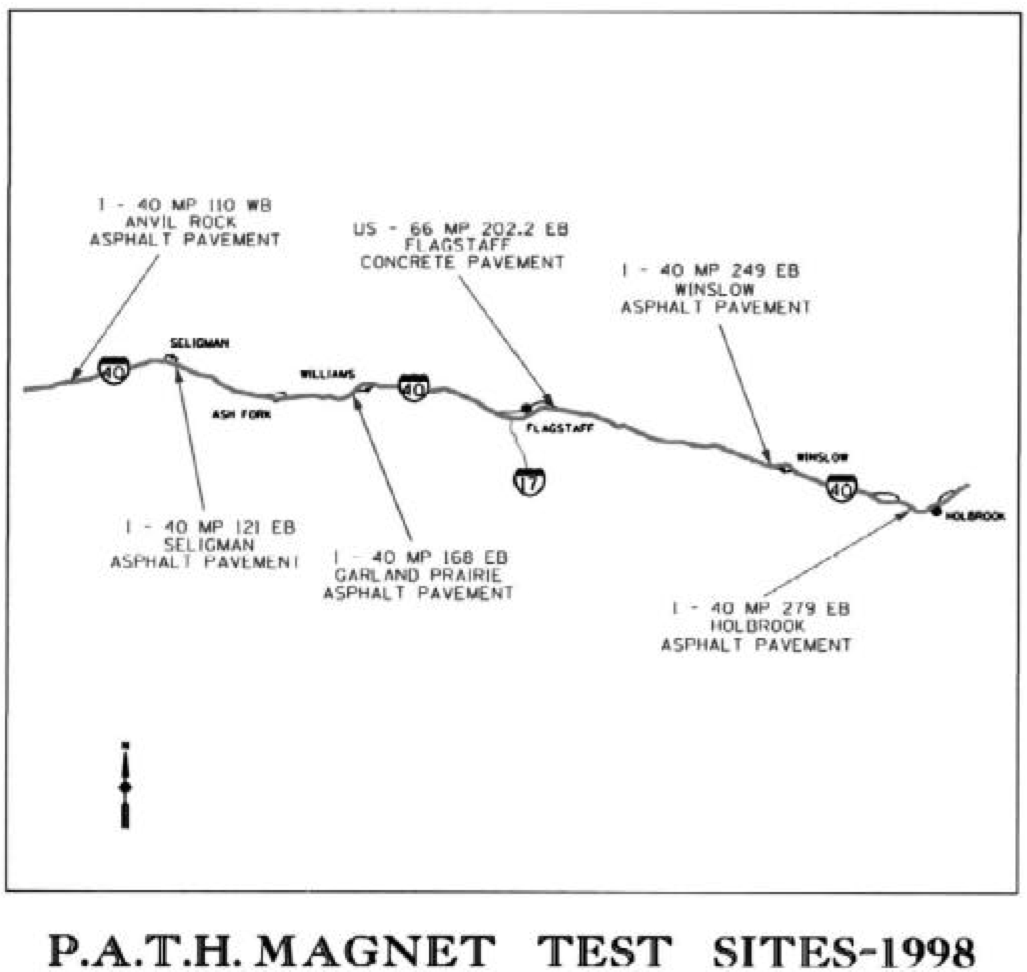


Figure 12 [graphic by Flagstaff District]

This magnet test project mandate required the ATRC to consult further with Caltrans and their partners, however, very valuable experience had already been gained only two months before. The Phoenix maintenance and construction sections of ADOT had provided the equipment, supplies and manpower to set up the PATH Demo course at the ASU Stadium site in December. Some of the tools and supplies such as electric drills and bits were still on hand, and there were sufficient magnets left to install 16 points at each of six locations. This would result in magnet materials and installation test sections that were at least 50 feet in length. It was agreed to test three different recommended sealant types at each of the six sites.

Magnet Product Test Installations

Although it was unusual for ADOT to send local maintenance and construction forces out on the road, that was the solution that this project developed in order to most quickly and effectively get the six magnet test sites established. The VISION Field Office offered the services of their ASU Demo supervisor, and Mesa Maintenance volunteered two of their installation team to go north to the I-40 Corridor to lead this test installation work in late January.

This approach was very successful since the Phoenix-area crew's knowledge ensured a smooth installation process. Each of the local field offices involved provided their best planning and traffic control resources to the effort. They also gained both experience and perspective about the PATH magnets and the vehicle systems, with which they would soon become more involved.

Figure 13: Test Magnet Installation at Seligman (I-40 MP 121.0)

The installation of the magnets would follow the precedents of the Tempe / ASU demo course. The holes would be drilled 4.5 inches deep at 1.25 inch diameter, using generator-powered electric rotary-hammer drills. Two rock bit designs, two-edged and four-edged, were tested.

A portable air compressor was used to clean the holes, and the magnets were set and bedded with masonry sand. Although magnet alignment was not critical in this case, efforts were made to mark and drill the holes precisely, to verify the ability to get all of the holes on line in the mainline pavement. This approach was also valuable to inform the field crews about the entire process and its requirements for precision.

The magnet sealant was the biggest single issue and question. The first material evaluated was ADOT's standard raised-pavement-marker (RPM) hot adhesive, which was used at the Tempe demo site. This material, normally used with a truck-mounted gas-fired unit, was heated and placed by hand. Despite the cold weather, this system did not present any placement problems.

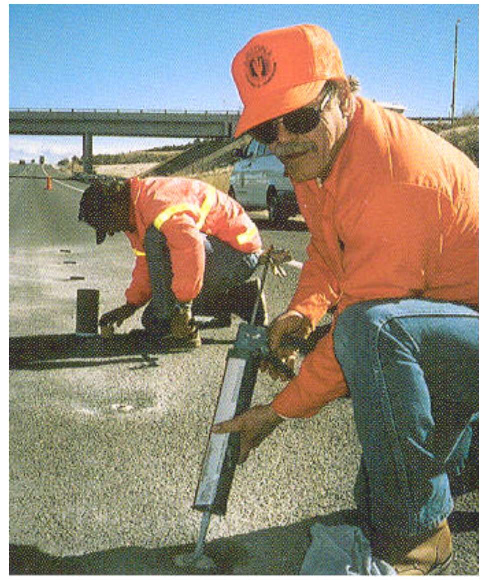


Figure 14: Installing and Sealing Test Magnets on I-40

The other cold sealants tested were provided in cartridge form and needed a caulking gun for placement. These were first, a standard 3M black sealant for traffic loop detector installation, and second, a typical commercial silicone sealant obtained from a Phoenix-area maintenance shop. Both these cartridge-packaged products needed special handling on the cold January mornings. They were kept near the heater vents in the trucks, but the silicone was so stiff that a propane torch was needed to get it to flow into the holes. Road surface temperatures varied from roughly 40 to 60 degrees (F) during the placement phase of the six test site installations.

The initial results of the ADOT magnet test program were fairly clear. The installation team made recommendations based on the ease or difficulty of the different steps in the process, repeated on six setups in January weather across 170 miles of northern Arizona. The first key lesson was that the 4-edged cross or star bit with the hammer drill gave the best hole quality. Later in the planning process, however, it was decided that to meet the accuracy standards would probably require a different method, such as a non-percussive core-type drill.

Also, it was noted over several cold days that the hot RPM adhesive cured hard in a short time, but the detector loop sealant and the silicone would skin but not cure for 24 to 48 hours. These observations were the first clear data obtained from the process, however, it was necessary to monitor material behavior over time before making final decisions.

The project took four days of travel and installation work to complete the six magnet test sites along the I-40 Corridor. The work was finished on January 23, 1998. After initial inspections and documentation by ATRC, the field crews were asked to check the sites periodically, and in particular after winter storms with significant plowing activity on the Interstate. Otherwise, the weather and the seasons were allowed to do their worst, until nearly six months had passed and the weather was some sixty degrees warmer.

Magnet Test Site Inspections

The first and most critical formal inspection of the six I-40 magnet test sites by the ATRC was scheduled for July 14, 1998. By that time it was necessary to carefully evaluate the results of the long-term testing, in order to make the key decisions for the next stage of the project. ATRC arranged with the Districts and with the five involved field maintenance yards to have traffic control ready for a lane closure at each of the test sections of the highway.

At each site, all holes were inspected and each was numbered with chalk. Photographs were then taken of every hole with a macro lens. The whole 50-foot lane section was inspected by the field crew to identify any problems related to the line of holes. In all cases, no chipping, spalling, cracking or any other damage was found to the pavement surface at or near any of the 90 magnet holes in the I-40 roadway. Also, all of the magnets were still securely in their holes after six months of heavy traffic, with frequent snowplowing activity.

Figure 15: The 6 Month and 18 Month Test Results with 3M Loop Sealant

The results of the sealant testing varied significantly. This inspection was performed in mid-July, and the air temperatures rose above 90 degrees (F) in the eastern section of the corridor. Some conclusions made in January were less certain by mid-summer, but the final recommendation was fairly clear based on these observations. The hot RPM sealant had set quickly in winter but was too soft and tacky in hot weather. The tan silicone was not used at all six sites; it seemed good in asphalt but it failed in concrete. Finally, the 3M loop detector sealant was still intact and solid at all sites, unaffected by the heat. This material was therefore selected for the ADOT Test Site as the best compromise on cost, ease of application, and four-season durability.

The details and results of the inspection are summarized in Appendix E, in a follow-up report memo by ATRC that was sent to the project TAC and the supporting crews. The entire inspection across 170 miles of I-40 was completed between 7:00 AM and 2:00 PM. This successful, safe and efficient process was a great credit to the ADOT maintenance crews from Seligman, Williams, Flagstaff, Winslow and Holbrook.

Although this inspection justified the procurement of materials and tools for over four miles of roadway magnet installations, it was not the final step. One year later, another inspection was scheduled by ATRC of the sites, and was conducted on June 21, 1999, in the same way as before. This second inspection after 18 months verified that the materials being used had sufficient durability for a period of years in the roadway, without visible degradation and without any negative effect on the host pavement surface. The results further justified the use of these products and methods for the ADOT snowplow test lane near Flagstaff.

X. TEST SITE REVIEW AND SELECTION – THE US 180 PROGRAM

In the earliest stages of the partnership with Caltrans, ADOT made an effort to provide the greatest potential benefit to the project in its selection of a snowplow test lane site. In the very first TAC meeting in September 1997, this issue was discussed and at least twelve sites or sectors were suggested across the three northern Districts of Arizona. At that time, weather and visibility conditions along with accident histories were the first criteria, as well as known problems for ADOT in keeping those roads open.

Test Lane Criteria

As time passed, and the project TAC reviewed the sites and the winter weather records, more parameters began to develop. Many factors, as tabulated earlier, have a bearing on the unique value of the Arizona test data. As noted previously, road geometry, grades and elevations, pavement type, terrain, extent of forest cover, wind and snowfall are all factors affecting the system evaluations. Other key data will include weather history and activity patterns, traffic volumes, accident records in general and for snowplowing, and, both winter maintenance and claims cost records. As noted before, each state's winter maintenance practices, equipment types, communications systems, deployments of ITS technology, makeup of the operator pool, turnover rates and even pay scales are also unique factors in effective operations.

With all of this to consider, the goal of providing Caltrans with the opposite of their own Donner Summit testing conditions helped the TAC to advance the site selection process. The group developed a short list of four possible sites. Two sites, near Flagstaff and near Seligman, were on the traffic-choked I-40 Corridor. Another was near Clints Well on SR 87 on the Mogollon Rim, and the fourth was on US 180 west of Flagstaff at Kendrick Park. All sites offered heavy snow, high wind and whiteout conditions. It was decided that the Interstate highway segments were not truly unique and would have traffic problems during construction and vehicle testing. The Rim segment was felt to be too isolated with regard to suppliers and shop facilities, as well as for easy access for technical support from Flagstaff or Phoenix.

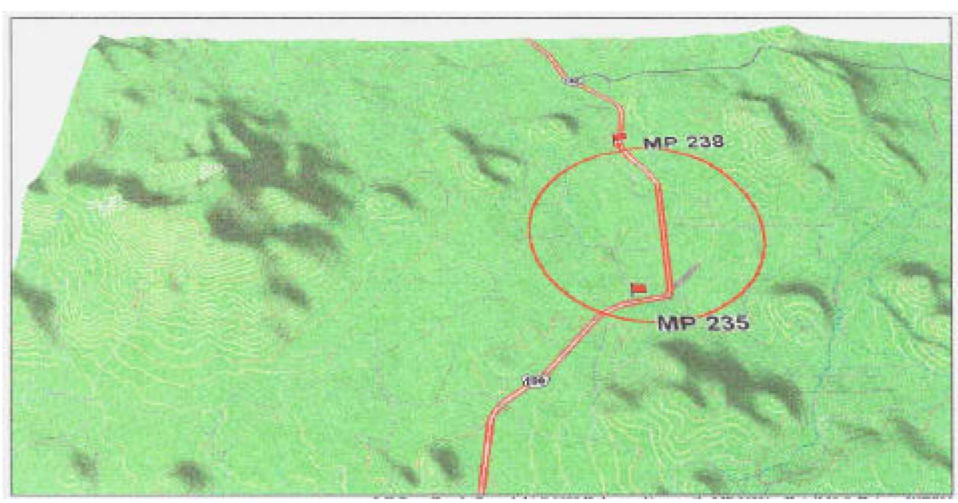


Figure 16: Map View to North - US 180 Across Kendrick Park [graphic by ATRC]

As a result, the US 180 segment passing through Kendrick Park was selected on the basis of its weather conditions, accessibility, traffic counts, and strategic visibility. This sector is part of the main route for most tourists driving to the Grand Canyon, regardless of the weather or season.

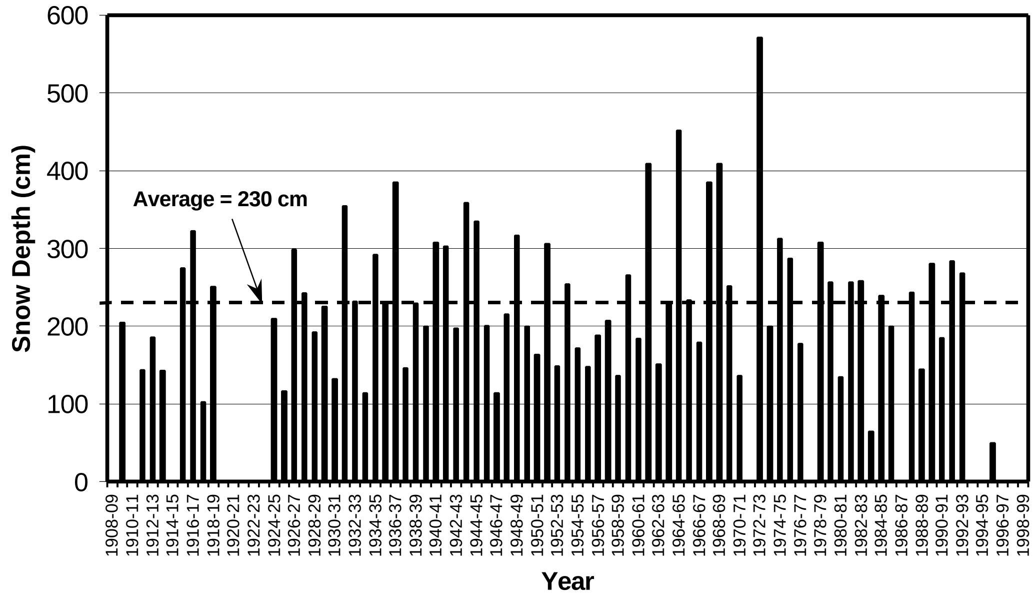


Figure 17: Total Snowfall in the Kendrick Park Region: 1909 – 1996
[Graphic by WTI – MSU]

Snowfall data for the US 180 corridor is collected from the closest recording station in the Fort Valley area, roughly 10 miles south of the test site. Kendrick Park is at an 8000 foot elevation, and the estimated snowfall there would be higher by three to five percent than the 2.31 meters or 91 inches at Fort Valley. The level, open terrain of the park is also subject to nearly constant winds that create major snowdrifts. Kendrick Park is one of only a few places in Arizona where a rotary snowplow is sometimes required to keep the highway open.

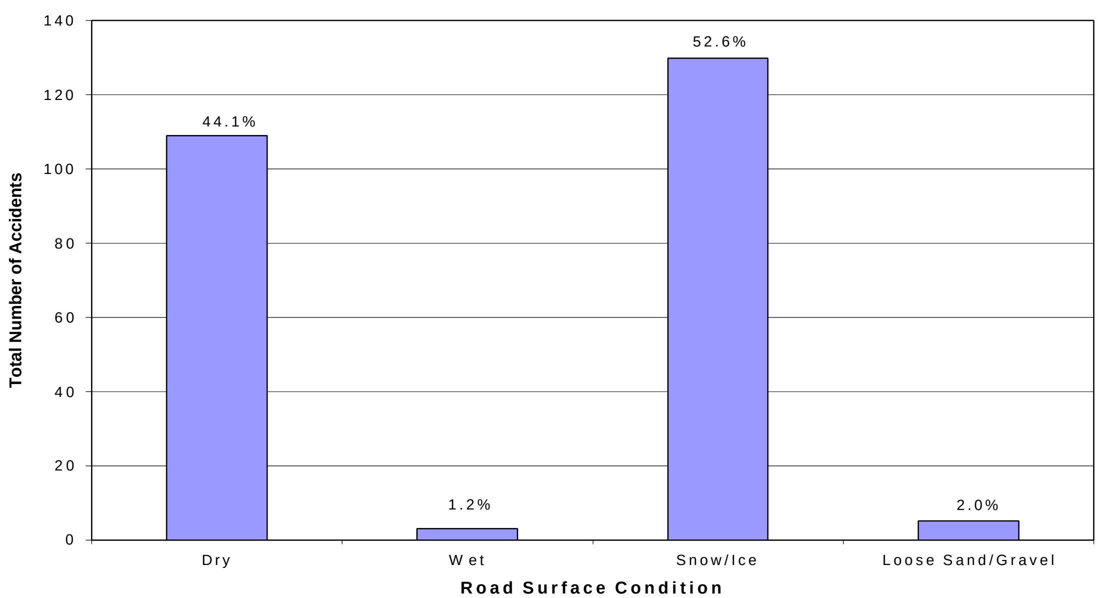


Figure 18: Accident Distribution by Conditions on US 180 - Kendrick Park Plow Route: Five Winters - October 1994 to May 1999
[Graphic by WTI – MSU]

Although the Average Daily Traffic records for the test site show only about 2500 to 3000 vehicles per day, the project TAC noted that a high percentage of the drivers are tourists, and many are foreigners. They are unfamiliar with this road and with high country driving in general.

The situation in winter is naturally worse. The number of heavy trucks is small, but a large part of the traffic stream is RVs and tour buses. The highway is an old design, meant for light rural traffic, but it has unusually heavy and high-speed use for the above reasons. New systems and methods are needed to keep this road open in winter, especially in the Kendrick Park segment.

The section of US 180 maintained by the Flagstaff Maintenance Yard extends from Milepost 214.5 to MP 250. Roughly half of all accidents in the last five years were snow-related.

The Kendrick Park Test Site

The project TAC made the decision that Kendrick Park faces a microcosm of all the problems and challenges of rural winter maintenance. The critical part of the test lane is defined as the highway section that crosses the open grassy plain of Kendrick Park. However, in one three-mile segment this highway offers a mix of dense forest and meadow, the long straight open Park known for its wind, winter whiteouts, and drifting, plus, its grades and canyon terrain. At the north end, nearly a mile of winding roadway climbs and drops at an 8 percent grade. There are also, for testing use, several convenient pullouts and turnarounds along and beyond this section of highway. ADOT and Caltrans agreed that overall, this location offered many unique benefits to the program. The section from Milepost 235.0 to 238.0 was selected for the PATH magnet test site.

The US 180 site, at over 8,000 feet in elevation, also offered numerous challenges to the project. As noted before, its winter weather, extreme winds, drifting, and whiteout storm conditions are major challenges to ADOT's equipment operators. Snowplows coming from Flagstaff often must plow the upwind (oncoming) lane first, before their own. As noted above, ADOT may also use a rotary snowblower as well as plows in this sector. Another problem is communications, as the San Francisco Peaks between this area and Flagstaff often create dead spots for ADOT radios.

Figure 19: View South to San Francisco Peaks at Milepost 237

With this decision made, planning proceeded to organize the magnet installation effort on a grand scale. After much review and discussion with Caltrans and within the core TAC sections of ADOT, several key decisions were made. First of all, the three northern District Engineers from Holbrook, Flagstaff and Kingman confirmed their strong interest and continuing support for the research. Each district committed to provide both men and equipment to form an installation team for the Kendrick Park test site. This support was vital considering that the project was not funded adequately to involve contractor forces on the scale needed to complete this work.

The ATRC was obligated to plan, organize and direct the installation work. Based upon cost information from Caltrans and on the promise of District labor and other resources, it was estimated that ADOT had the budget to procure and install a total of four lane-miles of magnets. This was calculated to be roughly 5,400 discrete magnet points, calling for 22,000 of the ceramic magnets as specified, and all of the related materials and supplies in suitable quantities as well.

Figure 20: ADOT Snowplow on 8 Percent Grade at US 180 Milepost 238

The ATRC and the TAC determined that the most practical utilization of this quantity of control magnets would be to create a three-mile instrumented lane northbound, and then to also install one mile of the reverse lane southbound. This layout was first met with some concern from the partners, but agreement was soon achieved. This configuration provides the longest practical continuous run through the several distinct terrain, forest, and geometric sections of the roadway. Both ends are well beyond the whiteout-visibility section of US 180 as it crosses more than a mile of Kendrick Park. This also provides for magnet guidance in both directions on the north end of the course, with its multiple tight-radius curves on an 8 percent grade. Some of those involved felt that this steep winding section would challenge the guidance systems more than the whiteout zone across the open park.

There were also two turnaround locations on US Forest Service roads within a half-mile of either end of the course, as well as two convenient parking and staging areas within the limits of the site. These features offered greater safety for all concerned in training and evaluation activities.

In summary, the selected US 180 highway segment at Kendrick Park was to become the first Arizona / PATH magnet guidance test site. This section begins at Milepost 235.0 westbound, near the Hart Prairie Road turnoff to the east. After crossing the grassy open plain, it climbs slightly onto a ridge and then drops steeply along a hillside to end at MP 238.0. There is a turnout just a few hundred yards further north. On the reverse run, the magnet line climbs from MP 238.0 up and over the ridge, and down into Kendrick Park eastbound, ending at MP 237.0 in the open park. The asphalt-paved roadway consists of two lanes striped 13 feet in width, with two areas that have center turn lanes to US Forest Service trailhead and recreation parking areas. The curve radius in this area was relatively tight, in some cases between 950 and 1000 feet.

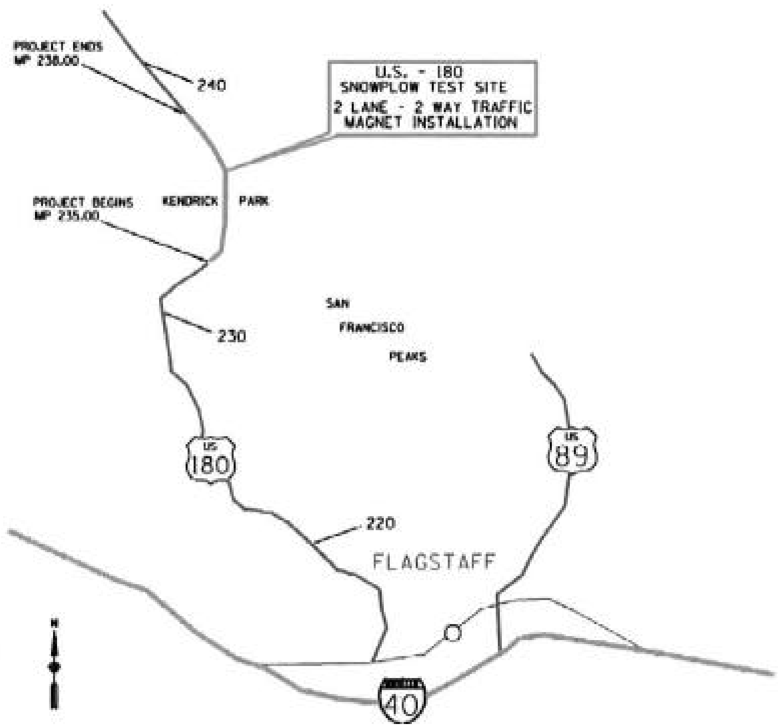


Figure 21: Advanced Snowplow Test Site Map – US 180
[graphic by Flagstaff District]

The roadway design information was sent to the Caltrans partners for planning and programming of the guidance systems, and to provide ADOT with the necessary coding for magnet installation. Generally this data was in the form of as-built plans, and recent plans for pavement preservation projects. Most were dated in the early 1990's. Overall, the road surface was in good condition – another factor in the site selection. There were, however, some areas where cracking and crack repairs would soon be found to conflict with the hole layout.

XI. US 180 TEST LANE MAGNET INSTALLATION

With the site selection issues resolved and the procurement of magnets and sealant materials well under way, the only remaining obstacle to the magnet installation on US 180 was its planning. Fundamentally, these efforts went very well with full support from the host Flagstaff District as well as Holbrook and Kingman.

The TAC determined that the four miles of magnets should be installed during the “shoulder season.” This would be when summer rains had ended, road repairs were wrapping up, schools were in session and tourist traffic had ebbed, but before the onset of fall with its freezes and early snowstorms. This season was a narrow window of time under the best conditions. The TAC decided in late July that the fewest work conflicts would exist, and the most resources would be available, during mid-September.

Each District agreed to provide a total of three men plus one alternate from their maintenance camps. It was decided that the magnet crew would work four ten-hour days, to reduce the problems of setup and teardown. The date to start the work was set to be September 14, 1998. This period was selected because it was after the summer rains, Labor Day and the start of the school session, but before deer season and the typical early-winter snow flurries. Reduced tourist traffic and fair, mild weather were expected for this time period.

It was estimated initially that the work would take about three weeks. Critical surveying would have to be done before that time; and Flagstaff District further offered to provide the field survey support for the ongoing magnet point layout task.

A kickoff meeting for the volunteer installation crew was planned for September 1, in Flagstaff. The ATRC invited key suppliers to the meeting, also, to be sure that the deadlines and support needs were agreed upon by everyone. The VISION field supervisor from Phoenix, who had led the test installations with some of the district crews, was asked to participate in the planning and training at that meeting. He later was also asked to help follow up with initial work at the site.

This first session went very well, and the districts confirmed their manpower commitments and also the items of ADOT equipment that they could provide to the project. These items included generators, welders, a compressor, water tanks, and trucks. Also at this meeting, a rental electric core drill was brought in, and numerous holes were test-drilled and magnets set in the shop’s parking lot. Work proceeded on this basis towards meeting the key date of September 14^{th}.

Surveying Activities

At the end of August one significant issue did come to light. The Flagstaff Construction District had been very supportive in checking as-built and related highway geometry information, but their heavy workload around the region became a problem before much progress could be made on the US 180 test site. Because of the rigorous horizontal control tolerances for setting the PATH magnets, it was necessary to turn to other resources to tie in the site control and to set the key points from which the individual drilled hole layout work could be done.

ATRC also conferred with the Phoenix District survey staff on tolerances, methods and options to establish control and to tie in the lanes. There were some additional concerns about the fact that on an older remote rural highway such as US 180, the survey design centerline might not be the center of either the various pavement overlays or of the striping pattern. This issue arose again more than once, as both the survey and the drilling work progressed.

Because the survey manpower issue surfaced just a few days before the hole layout and drilling were to begin, an urgent compromise was sought with help from ADOT's Engineering Survey Section. The ESS was fortunately able to identify a third-party consultant, Entranco, which had the resources to step in on short notice.

With this new partner, Entranco, on the project team, a plan was developed to verify the basic survey control for this test section of US 180. In addition, they would pick up additional survey data needed in general by ADOT as regards this area, and they would leave all needed control points for the layout of the individual holes on the roadway. The precise control survey eventually became a major effort as issues arose and were resolved with regard to the as-built conditions on this remote rural highway.

Ultimately this contingency plan came to a successful conclusion. ADOT's ESS group not only provided the critical survey resource but also settled the increased costs through their project support budgets. This was crucial because the internally manned project had no budget for the third-party survey costs of establishing the four lane-miles of this PATH magnet test course.

Once the area survey control was verified and marked out by the contractor, the Flagstaff construction survey team was able to devote enough time to this project to keep the hole layout work ahead of the drilling for the balance of the installation. The Flagstaff District surveyors were enthusiastic and innovative in their methods. They were able to complete extensive layout runs and magnet stationing in a short period of time with a variety of tapes, stringlines and painting templates. However, it was a process requiring multiple steps of layout, marking, and referencing each point, and it still was a major effort.

Figure 22: ADOT Survey Team at MP 237

Equipment Decisions

After the kickoff meeting for the volunteer crews on September 1, there were still questions about the best methods and supplies to drill and install the magnets. Much of the debate centered upon the best way to drill accurate holes in the roadway. On September 9, after the kickoff but before the site work began, the ATRC and VISION project staff made a brief trip to California to inspect the ongoing Caltrans installation on I-80 at Donner Summit.

The units used by the Caltrans crew were pneumatic sinking hammers mounted on large, heavy, wheeled jumbos. A large air compressor powered two such drill rigs. These drills were observed to be fairly fast and fairly accurate. They obviously met the Caltrans needs and tolerances. However, this equipment had some drawbacks for Arizona.

First and foremost, the pneumatic drills were working well in a white concrete (PCCP) roadway. The weight of drill and frame helped ensure that the chisel-style drill bit penetrated cleanly into the concrete on the survey mark. However, the ADOT visitors were very concerned that such drills, depending on mass and impact, would bounce around excessively on the flexible asphalt surface of US 180.

Because accuracy was paramount in order for the magnets to be set within tolerance, another approach was required. ADOT had already installed magnets at ASU and on I-40 with an electric rotary hammer drill, but these units were somewhat light and required a lot of brawn to advance a hole into the asphalt pavement that would be both true and plumb. The project team determined that cutting a hole, rather than smashing through, was the best approach for the required accuracy. Therefore, a core drill was considered to offer the best performance and accuracy in this situation. With help from Flagstaff Maintenance, the locally-available options were reviewed.

Selection of Core Drills

ADOT had investigated its own pavement core drills, but their size was a negative factor. The answer in the near term appeared to be to use concrete coring equipment – a type of rental drill that was readily available in the Flagstaff area. Supported by the local vendor, Prime Equipment, the project rented four electric concrete-coring drills mounted on wheeled dollies. The units were light and manageable, especially with their vacuum base pads removed. These drills were water-cooled, so each team of drillers would need a water hose as well as electric power. Fortunately the districts were able to provide all of the support systems that were needed to keep four of these core drills operating.

Figure 23: Caltrans Pneumatic Percussion Drill (L) and ADOT Electric Core Drill

The real success of these coredrilling efforts hinged upon the drill bits themselves. Based on the size of the project, nearly 5,500 holes over four miles of highway, the supplier placed an urgent factory order for custom core bits that were designed to perform efficiently in asphalt pavement. Target Saw and Diamond Boart were able to provide the first consignment of the improved core bits by Week One of the installation.

Because there are always surprises, there were still problems, especially when the drill crews reached some areas where an inch of rubberized asphalt (AR) had been placed as a new friction course. This required heating the bits to dig out the swollen core of asphalt-rubber mix. While a bit was being unplugged, a second bit was used to drill the next hole in line. The plugging cores were an ongoing problem whenever water circulation was lost and the bits got very hot.

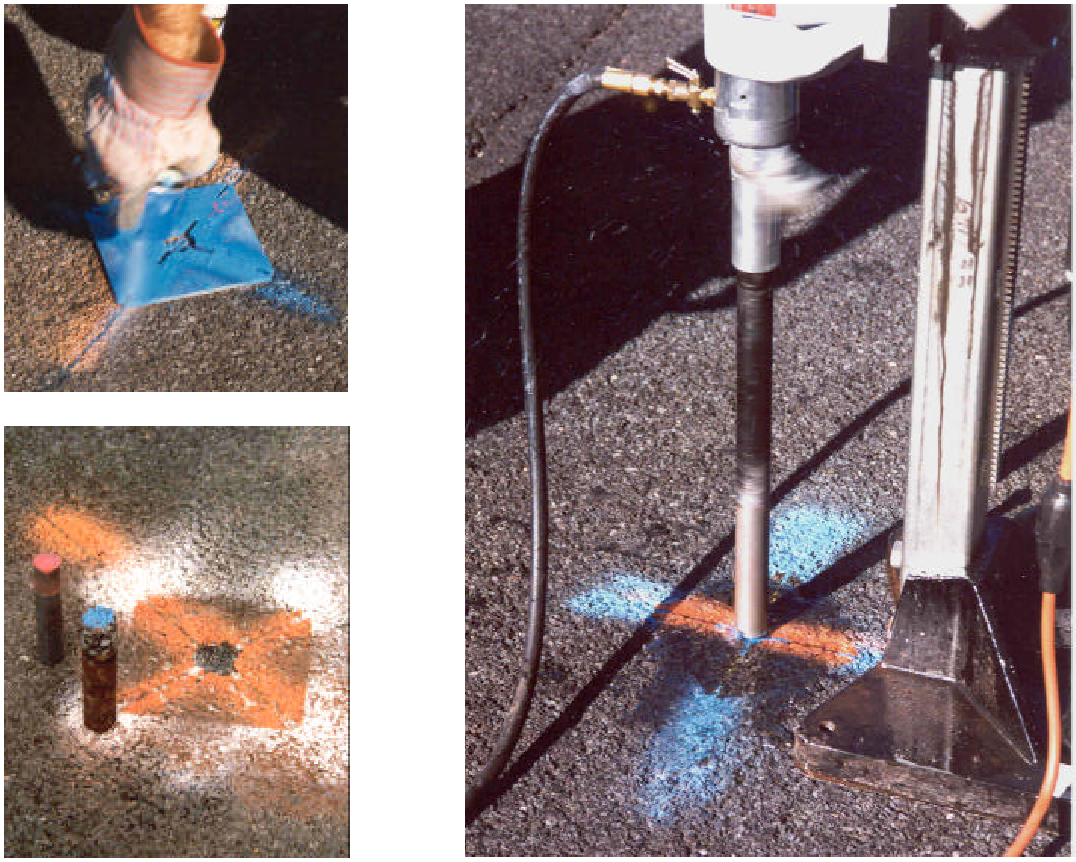


Figure 24: The Core Hole Layout Template and Drilling Process

The pavement's history, as well as its surface, was very variable. Most of the holes were drilled right through the four inch pavement into the subgrade, adding to bit wear and cleanup woes. However, in some areas the roadway was six inches thick. A related issue was that by drilling wet, the holes needed to be blown dry with compressed air before magnets could be set. Naturally this was a problem when blowing out a hole that went into the subgrade material.

Overall, records show that the crews logged roughly 45 drill-days, and 5,420 holes were drilled. The daily average was 123 holes per drill overall in 500 feet of highway. On the best day, each drill averaged 155 holes. The asphalt bits performed well, drilling over one hundred holes each in most cases. However, too much down-force and not enough water would quickly result in a burned bit that was a total loss. Early in the project, this happened several times.

The overall average drill bit life was 142 holes per bit, since 38 of the 50 core bits were totally or partly consumed in drilling the 5,420 holes. That average useful life is about 700 inches or 60 feet of asphalt core. However, the absolute figure is somewhat higher since 16 bits were still being used, with varying degrees of wear, at the end of the installation.

The only other unplanned issue with these drills was that more dedicated drillers were needed to keep all four units running (see project summary memo in Appendix F).

Magnet Installation

The final tasks were to set the magnets and to seal them within the holes. The magnet placement in the drilled holes was tedious and back-straining work, performed while kneeling, sitting or lying on the pavement. This task required placing the magnet, bedding it with masonry sand, edging it into alignment, setting the grade, and blowing out the excess sand. The last task was capping the hole with 3M loop detector sealant, then wiping the surface flush to avoid a bubble or dome of material. This sealing was done with a standard caulking gun.

Frequently an error in setting the magnet meant digging the hole out and starting over. Some installers tried different carts or dollies to more easily work and move from hole to hole. Several times a skateboard was used successfully.

The necessary materials included more than 22,000 magnets which, based on the Caltrans-PATH specifications, were obtained through All-Magnetics in Placentia, California. Also required were an estimated 48 tubes (of 29 ounces) per mile of 3M Detector Loop Sealant from John Henberger in San Diego. This project application actually required 40 tubes per mile, averaging 34 holes or one ounce per cartridge. Consumption was high due to normal waste factors, to the difficulty in placing very small quantities, and to water or other physical damage to some of the tubes.

Manpower Issues

The project planning turned out well for these four miles of magnets along US 180. Manpower was always an issue from the first survey activities, but the Districts were very supportive in scheduling the volunteers and sending alternates when necessary. The crew size was nominally twelve men, being the three plus alternate from each District. On average, however, thirteen men were active on the project for most days.

Figure 25: Four Two-man Crews on the Drill Line

As noted above, at least eight men were needed just to keep the four drills going, and others were immersed in survey layout, magnet marking and sorting, blowing drilled holes, the bedding and alignment of magnets, sealing of holes, and of course traffic control.

The biggest manpower concern seemed to be traffic control – it is a task that seems to polarize highway maintenance and construction workers, especially equipment operators. During this project, efforts were made to rotate this duty, but most preferred to work on the magnet assembly line along the roadway.

Traffic control and safety are always major issues for work on rural highways. This project was perhaps more exposed to risk in that the installers were intently focused on their precision work. Better planning and constant monitoring of the situation were therefore required for safety. Overall, it was found that the safest approach was to stop all traffic and to run a pilot vehicle to escort the queues at a safe speed through the work zone. Despite signing and cones, intruding vehicles from side roads were an issue and constant observation and radio contacts were required.

Figure 26: Setting and Sealing the PATH Magnets

For part of the time, third party flaggers were used who had originally supported the contract survey crew. They were effective because it was their role in the project. However, they added to the unbudgeted side of the project ledger. Generally, the drill crews took turns at flagging, and at other times it was necessary for ADOT to run its own pilot car operation to restrain traffic and to ensure safety for the several installer teams working along the closed lane of the roadway.

Results – 1998 Installation Project

This initial magnet installation project was very successful in many ways. The ATRC and the three Districts collaborated to complete a precision installation of nearly 5,500 magnet points in the US 180 roadway. This effort also initiated a very productive mutual research effort between ADOT and Caltrans. Just as importantly, ADOT's maintenance volunteers from three Districts worked as a team together, often for the first time, and set production records despite many setbacks. They also became involved in many aspects of ITS research. These magnet installers were almost all snowplow operators from around northern Arizona, who were also in line for training on the Caltrans snowplow.

The primary result of this installation of the four-mile US 180 test lane is that despite problems, the work was completed as required on schedule and generally within the budget. The survey consultant effort was unplanned, but was paid through ADOT's ESS, not the research budget.

The basic result of this effort is that 5,420 magnets were installed in roughly 13 ten-hour days of activity at the site. There were startup and rain days, but basically the magnets were installed at the rate of one mile per four-day workweek (see appendix F). The activity required 2250 man-hours, according to the timesheets, but more than ten percent of this was long-distance travel and other overtime based on the workplan arrangements.

This project installation phase developed costs in the range of $17,500 per lane-mile using ADOT forces and support equipment. This final cost is a difficult number to pin down because of the shared cost categories within ADOT and the subcontracts such as traffic control. Further, state DOT accounting may not reflect the same basis as a large-scale installation contract. The average state labor rate charged for this magnet project, with burdens, is roughly $12.00 per man-hour.

This magnet project cost does not include the third-party surveying. It was felt after the fact that much of the precision for the control survey was beyond the needs and basis for the survey to establish the lane centerline. In fact, much simpler processes were used in the hole-by-hole layout, and on a later similar project that was completed satisfactorily.

Initial Lessons

The installation of four miles of PATH magnets on US180 in northern Arizona provided very valuable experience and several clear lessons for ADOT and other stakeholders in this system. These lessons were applied a year later when the test site was expanded in 1999.

The installation certainly was labor-intensive. Arizona did not have a variety of drills available and the use of electric core drills seemed most practical to achieve the accuracy required. Of course each drill required two men to keep drilling and moving. Although the core bits drilled well, in several areas the one-inch asphalt-rubber overlay material frequently would overheat and plug the barrel so that the drilling water would not circulate. Crews then had to heat the bits to drive out the cores. Generally they resorted to changing bits for each hole rather than pounding on the bit in hopes of freeing the plugs.

When all went well, crews took pride in drilling over 150 holes in a shift. The best day was 618 holes but in the asphalt rubber, the number fell below 300. The available percussion drills, air or electric, may have been faster but would have been less precise.

In retrospect, the surveying accuracy issue was found to be overstated in that a control survey provided precision on an imprecise roadway. It was obvious that neither the pavement nor the striping followed the geometric design exactly. Because the oncoming traffic follows the painted stripes, it was immediately obvious that for safe operation of the plow, the magnet line would need to be centered in the actual lane.

As a result, the tangents and curves had to be adjusted to smoothly follow the curvature of the traffic lanes themselves. This approach proved successful and was vindicated during the testing of the Caltrans snowplow at operating speeds.

Second Phase Magnets - 1999

From the beginning of this magnet installation project, it was recognized that the four miles of infrastructure would compromise testing because the critical section of roadway was not fully magnetized. That is, only one mile of magnets were embedded in the eastbound return roadway. After the first winter of successful joint ADOT-Caltrans snowplow training and testing, ATRC requested that additional funds be budgeted to continue the project and the research partnership. Part of the new budget was allocated to completing the advanced snowplow test course loop.

The gap to be filled in the eastbound test lane was from MP 237.0 at the north side of Kendrick Park down to the start of the original course at MP 235.0. This final point is across the park and a half-mile around a long curve into the forest. When completed, the additional magnets would provide a six-mile testing loop of three lane-miles in each direction across one of ADOT's most challenging winter maintenance areas. Approximately 2,640 additional magnets were required.

This new effort was organized very much as the first installation. Once again, the three Districts offered volunteer support from the various maintenance camps, including such equipment as generators, compressors and water tanks. Four core drills were again rented locally, and some additional asphalt bits were ordered to supplement those remaining from the first installation.

More magnets and 3M detector loop sealant also were required. The sealant was provided in a new package this year; the old caulking-gun cartridges were replaced with a plastic-foil sausage package meant to fit into a special dispenser gun roughly three feet long. ADOT field-tested both a pneumatic and a manual version of this 3M applicator tool, and found the manual unit to work best for the very small amounts of sealant needed to cap the 1.25 inch holes with minimal waste.

Figure 27: Pneumatic Sealant Gun

Basically there were no changes in the methods for drilling holes, and for setting and sealing the magnets. Based on the first year's lessons, however, traffic control was handled by the ADOT crew and for safety, nearly all of the work was done with a pilot car to lead traffic through the workzone. No subcontractor was needed for this aspect of the work.

As to the layout of the magnet holes, the Flagstaff District construction survey team again used a combination of instruments, tapes, strings and templates to spot and mark the reference points and the actual individual holes in the roadway. Arcs and chord offsets were effectively laid out and the 1.200-meter intervals were marked accurately in this manner.

The Second Installation

The 1999 magnet installation project was scheduled once again to begin in mid-September. There was also time scheduled for surveying prior to the kickoff of drilling work. All of this work went smoothly except for weather delays. Overall, the two miles of new test lane, required a final count of 2617 new magnetic markers. The project required three days of survey work and nine days of crew activity. That time included significant parts of three days lost to rain.

In general this second effort was very successful. Again, the magnet installation rate was about one lane-mile of roadway per four-day workweek. Due to the prior year's planning experience and the return of many of the installation volunteers, this was a very efficient and safe operation.

In all, a total of 1568 man-hours were logged to complete the two miles of magnet infrastructure, during the 12 crew-days spent on the roadway. This includes travel overtime for some of the crew. During this second phase, there were no reductions to the crew size or the equipment array. In fact, with the need to address traffic control and give survey layout assistance, the ADOT crew size averaged about one man more than for the first year.

As before, there were cost issues relative to charges among the numerous partners in the work. The ATRC determined that this project phase cost approximately $35,000 for two miles. As in the first phase of the project, these figures are based upon ADOT wage rates, burdens, and equipment accounting practices and include some travel overtime for part of the crew.

Final Results and Lessons – Magnet Infrastructure

The most fundamental lesson was that the ADOT maintenance crews from the three Districts worked extremely well together, had a strong interest in the special nature of the work and of the project, and did an excellent job on the precise and repetitive tasks to install the PATH magnets. Volunteer crews from the following maintenance camps took part in the project:

- Flagstaff District: Green River (Flagstaff East), Williams, Gray Mountain, Little Antelope
- Holbrook District: Holbrook, Winslow
- Kingman District: Kingman, Seligman, Wikieup

The basic result is that ADOT forces installed six miles of PATH-Caltrans magnets on the lane centerline of US 180, a rural two-lane asphalt roadway. This intelligent vehicle infrastructure consists of 8,037 discrete magnetic markers, each composed of four embedded ceramic magnets. The actual magnet installation activity was done in approximately 21 workdays of 10-hour shifts. This is about 3.5 days per lane-mile with a crew averaging about 14 men. The completion rate averaged 382 magnet points per day, using electric core drills.

The overall cost of these six miles, based on burdened ADOT wages of roughly $12.00 per hour, are approximately $105,000. This equates to a total of $17,500 per lane-mile of infrastructure. Labor costs averaged $9,000 per lane-mile. Materials cost for magnets and sealant was only about $2,150 per lane mile of the above total. Core drill equipment, bits and supplies cost about another $2,000 per mile on average over the two years. The balance of the costs went to ADOT equipment charges, traffic control contractors, crew per diems, etc.

As noted before, the true costs are difficult to define when an agency performs such work internally. For example, these figures exclude the precise control survey in 1998, as discussed earlier. Finally, contractors might well install magnets more effectively with newer, larger, more powerful specialized tools, but their labor rates, margins and overheads would differ from those of the Arizona DOT. The results that have been reported for the Caltrans installations, using contractor forces, should be considered.

Figure 28: Installing Magnets

Generally, the key conclusion from Arizona's two years of PATH magnetic marker installation on the US 180 roadway is that a better way is needed to develop this infrastructure if it is to be deployed extensively. The two installations went very well on a research basis, but with the limited resources of Arizona's rural districts, it will be a challenge to deploy this infrastructure on any large section of roadway.

The Kendrick Park test site is in a remote rural location, with a relatively low volume and speed of traffic. For ADOT to follow these same installation procedures on I-40 or I-17 would not be very successful, nor would it be very safe for the crews. More efficient methods are needed to make the installation of large quantities of the magnets practical.

Based on ADOT's experiences, there are a number of ways that could be considered to reduce the costs of this work and enhance the system's practicality:

- Automate the survey and hole layout process.
- Review the lateral tolerances for installation based on vehicle sensor abilities.
- Program the system to accept greater lateral variations in magnets.
- Automate the slow and labor-intensive magnet drilling process.
- Automate the very slow, labor-intensive, backbreaking magnet installation process.
- Review the magnet specifications and resulting materials costs.
- Program the system for fewer magnetic markers, and fewer holes, spaced further apart.

XII. CALTRANS – ADOT ADVANCED SNOWPLOW OPERATIONS IN ARIZONA

Goals and Partnership Basis

The basic ADOT goal of this research project, since its initiation in late 1997, has been to learn as much as possible about automated highway systems, and specifically about the practical benefits of the Advanced Snowplow (ASP) technology for Arizona's conditions. ADOT has recognized that to gain the desired experience and knowledge, the state must participate actively and fully in the larger research program of its senior research project partner, the California Department of Transportation. The activities described in this report are testimony to ADOT's commitment to a major role in the testing and development of the Caltrans Advanced Snowplow program.

California has welcomed the ADOT partnership in order to test, to develop, and to market the PATH magnetic marker system outside the borders of their own state. Caltrans and their partners have dedicated extensive staff, laboratory, and financial resources to this project. The project team includes the Caltrans prime contractor AHMCT Research Center, with support from the California PATH program and the Western Transportation Institute at Montana State University.

This partnership also includes the Caltrans commitment of Snowplow 7005, the testbed for all of the driver assistance, lane guidance, collision warning, vehicle tracking, and communication systems that may enhance winter maintenance operations in the future (Figure 29). This ASP system technology has been integrated onto a Caltrans nose / wing snowplow truck, on an International Paystar 5000 platform.

Arizona made the critical contribution to this project of a unique, standalone, fully instrumented test lane for the Caltrans-PATH magnetic guidance technology in northern Arizona. ADOT then went further and completed an extension of the test course by 50 percent to its present length of six lane-miles. In return, California has released its one-of-a-kind research snowplow to Arizona, along with a covey of technicians, to carry out both states' mutual research activities and also for ADOT to pursue its further internal goals. This exchange has taken place for approximately one month each winter, in March 1999 and in February 2000.

Arizona covers the snowplow's transfer and technical support costs, and also makes one more key contribution to the project – its pool of skilled snowplow operators. ADOT's winter conditions, snowplow equipment, operator training, and winter maintenance practices are all quite different from those of California. The Arizona operator pool is a key asset for the California program. ADOT drivers provide a vital third-party view, or reality check, on the strengths and weaknesses of the ASP system at each stage of its development.

This ADOT Project Report – Focus and Limitations

This Phase One research report is a summary of the goals, activities and observed results of Arizona's efforts in the AHS and Advanced Vehicle Control and Safety Systems areas between late 1997 and mid-2000. Because so much of the technical research activity and evaluation processes and results have been reported formally by the Caltrans partnership, this ADOT research report will not attempt to duplicate that extensive body of information (see next page).

Instead, ATRC will refer to and quote from the California project reports, as needed to support the discussion of and conclusions on the Arizona activities and the results achieved as they pertain to this project's goals. The most pertinent key figures and tables also will be used here.

The remainder of this report will describe Arizona's perspective on the winter testing activities during the first two years of the ADOT partnership with the Caltrans team. This period extended into the summer of 2000, when both states renewed the Joint Project Agreement for their vital partnership, while also expanding their AHS research programs in other, new directions.

The results of the Arizona research project needed to be complete, detailed and accurate, to support ADOT's deployment decisions with regard to roadway magnets or other comparable systems. This evaluation has focused on operator comments and suggestions, on measurable efficiencies and safety benefits, and generally on costs, durability and reliability for the system. There was a clear need to explore ADOT-focused topics, and to make specific conclusions based on the goals and on perceived cost and benefit results.

Related Reports – Caltrans Research Activity

The California Advanced Snowplow Development and Demonstration Program was initiated after the San Diego Demo in 1997. Caltrans, AHMCT and its partners were funded, supported and organized to carry out the initial stages of the benchmark Intelligent Vehicle project, which was able to field the Advanced Snowplow on I-80 in the Sierras in less than six months.

The Caltrans partners have extensively documented the Advanced Snowplow research over the past several years. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center of the University of California-Davis is the lead agency for this ASP research collaboration. The initial report on this Caltrans-ADOT partnership is listed as:

FHWA Report No.	FHWA/CA/NT-99-17
AHMCT Report No.	UCD-ARR-99-06-30-03
Title:	**Advanced Snowplow Development and Demonstration: Phase I: Driver Assistance – Final Report**
Period of:	**March 1998 – June 1999**
Principal Investigator:	Bahram Ravani

This Phase I report covers the details of the California project's initiation, the various advanced snowplow systems, and the early research activities through the first winter of 1998-1999. It will be referenced here as the Caltrans ASP-I Report, and certain quotes, excerpts or graphics will be incorporated with permission in this ATRC report section.

The AHMCT / UC Davis report, covering the second year of ASP activities, is:

FHWA Report No.	SPR-3(063)
AHMCT Report No.	UCD-ARR-00-06-30-02
Title:	**Development of an Advanced Snowplow Driver Assistance System (ASP-II) – Final Report**
Period of:	**July 1999 – June 2000**
Principal Investigator:	Bahram Ravani

Information from the ASP-II Report will also be included with permission, in this ATRC report.

These Caltrans ASP reports discuss in depth the basic snowplow research issues, and describe in detail the evolution of the system hardware and software, the displays, the magnet sensor system, and the collision warning radar. These two reports also detail each phase of the evaluation program and its results, and finally they offer recommendations for future phases of the project.

XIII. ARIZONA ASP-I RESEARCH ACTIVITY – MARCH 1999

The ASP-I Snowplow

California's Advanced Snowplow concept focuses primarily on driver-assistance technologies. While the systems offer the potential for integration into fully automated operation, the mission was to support, not replace, the plow operator. The ASP-I prototype vehicle (see figures below) was equipped with an integrated driver-assistance system that deploys technologies for lane position indication, lane departure warning, and forward collision warning.

The AHMCT research reports, listed in the preceding chapter, provide very detailed descriptions of these systems. The general concepts for the Advanced Snowplow are briefly described here for reference, in presenting the progress and key details of the Arizona testing program.

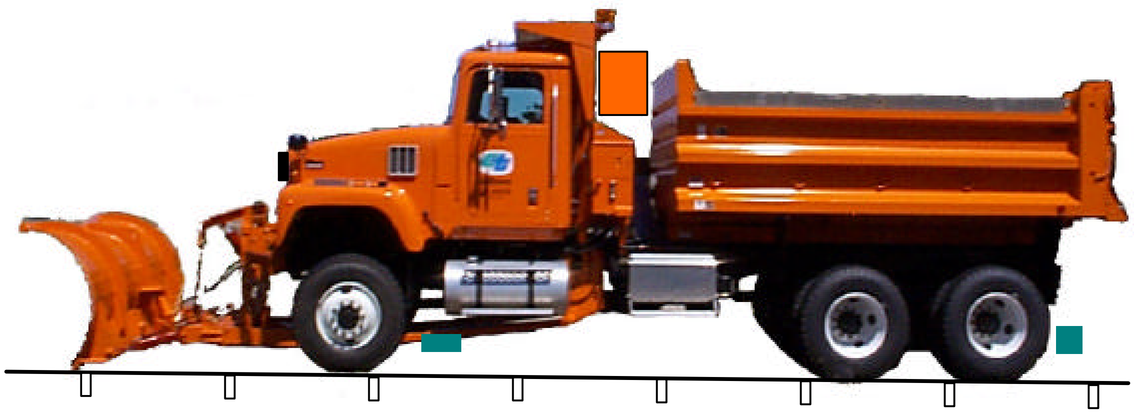


Figure 29: Caltrans Advanced Snowplow ASP-I [courtesy of AHMCT]
(Note magnetometers behind wheels)

The magnet infrastructure has been described earlier. It provides a magnetic field as a line of points located at a 1.2 meter spacing. The basic roadway design information is programmed into the vehicle's computer, and the magnets are installed with a specific polarity coding that when read by the sensors can communicate where the snowplow is along the test lane at any given time.

To locate its position in the highway lane, the ASP-I snowplow computer had to read the coded magnet line using two sets of lateral sensors mounted underneath the truck chassis. Two sensor bars, fore and aft, gave redundant position data to the vehicle computer. This redundancy was necessary to improve the confidence level for the positional computations, and it also allowed for possible equipment failures or physical damage to the exposed sensors in the extreme operating conditions of winter maintenance. Each ASP-I sensor bar carried seven magnetometers at a one-foot lateral spacing.

The sensor bars on the ASP-I vehicle were mounted behind the front wheels, and also behind the tandem rear axles. The front sensor array had to be made in three sections to fit around the truck frame, snowplow push bars and front driveshaft. The sensor bars were protected to some extent by mud flaps and were supported on steel framing members. However, to achieve an acceptable signal-to-noise ratio, they were mounted only eight inches above the road surface. This design was vulnerable to possible damage while turning around off the test lane, and also while loading and unloading the snowplow for transport on a low-deck trailer.

The second key subsystem is the collision warning radar (CWS), which scanned the lane directly ahead of the plow truck for moving or stationary obstacles. This system utilized a commercial radar antenna from Eaton Vorad with a horizontal detection range of over 300 feet. The return signal was processed with programs developed by the Caltrans project team that offered more detailed warning display information than the commercial system. The CWS radar antenna was mounted on the radiator of the truck at a height that allowed it to “see” over the snowplow blade.

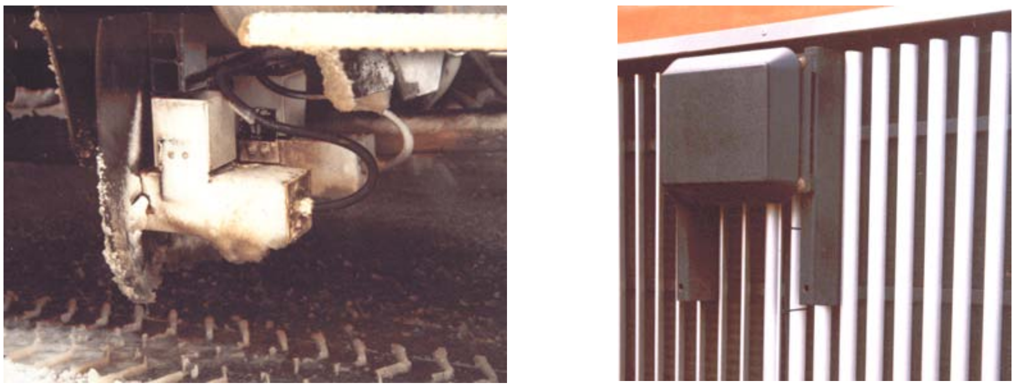


Figure 30: ASP-I - Magnetometers (L) and CWS Radar Antenna

The third key element of the Advanced Snowplow is the Human-Machine Interface (HMI), or operator display system. For the ASP-I program, a display was developed that integrated all of the information into one screen mounted on the dashboard near the driver’s normal sight lines. The integrated display shows the truck’s lateral position in the lane, based on the magnet sensor position, and it shows the predicted future position of the vehicle based on the steering column inputs, travel speed, and roadway geometry.

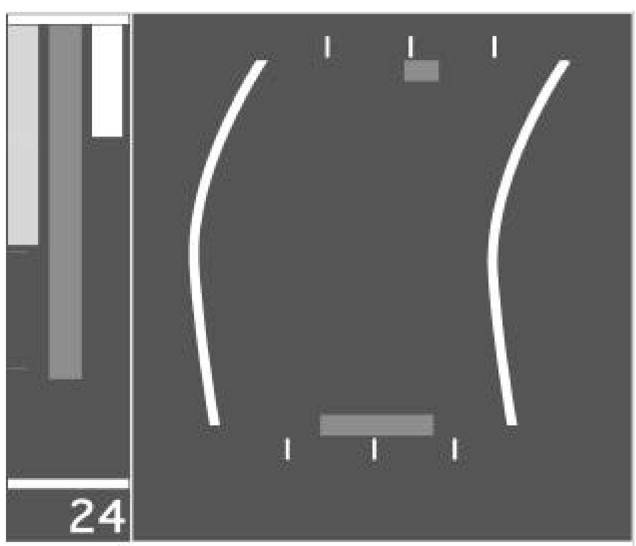


Figure 31: The HMI Display – ASP-I Program
[Graphic by AHMCT]

The HMI also shows the enhanced results from the CWS radar system. It displays vertical bars at the side of the screen, each of which changes color and length as the distance is reduced between the ASP-I snowplow and the nearest detected obstacle(s). This system will show up to three such bars for three detected obstacles ahead of the snowplow.

Project Workplan - Arizona

As described in earlier sections, ADOT, the project TAC, and ATRC committed their resources not only for the magnet installation but for the testing program as well. The project goals were to learn as much as possible, to disseminate the resulting information both within and outside of ADOT, and to evaluate the true potential of the new systems to improve safety and efficiency in Arizona's winter conditions. This set of goals could be achieved through a two-phase plan.

When the Caltrans ASP snowplow was delivered to Arizona for the first time in early March, 1999, very few ADOT personnel had had any exposure to such systems before. During the time that the truck was in Arizona, it was important to expose as many people as possible in a short time to its concepts and abilities. It was also very important for ADOT to employ and evaluate the advanced snowplow over the long term, in normal winter storm operations. The project workplan therefore focused equally on both of these phases of research activity.

Figure 32: ASP-I Operational Evaluation - North End of US-180 Test Area

The project's Technical Advisory Committee had an important role in developing the concepts, and in later reviews of the Caltrans snowplow testing workplan. However, the real responsibility to make things happen rested with the maintenance staff of ADOT's Flagstaff District. The local maintenance forces and equipment shop crew assisted with many details such as test site traffic control, fueling and servicing concerns, mechanical and electrical troubleshooting, standby plans for magnet repairs, and the scheduling of local trainees as well as those coming from the more distant Kingman and Holbrook Districts.

California's prototype research snowplow, number 7005, was dedicated to the Caltrans research program by the regional district that maintains Interstate 80 in the Sierra Nevadas. While the plow is assigned to support research work, the agreement still calls for it to be stationed, as much as is practical, in the parent district for winter evaluations. It is part of the operational fleet and is used full time during major storms, while collecting research data is secondary. This makes the Arizona transfer much more complex, since the long-term winter weather cycles in the Sierras and in the Four Corners region must both be balanced with the training and evaluation schedules.

Figure 33: Caltrans ASP-I at the Kendrick Park Staging Area

The Caltrans plow was assigned to the Arizona research operation for a period of three weeks, beginning on March 8, 1999. The technical support team requested that several days be allowed for orientation, systems tests, roadway and magnet inspections, troubleshooting and initial work with the ADOT plow drivers. Once the system was fully operational, the driver training and evaluation of the systems were in ADOT's hands.

The overall schedule called for a week of startup and at least a second week of operator training. This left the third and final week for operational plowing of US 180, including Kendrick Park, on an as-needed basis in order to assess the system's effectiveness during nighttime and snowstorms.

Training Concepts

ADOT intended to involve as many veteran snowplow operators as possible in the evaluation program, and some of its novice drivers as well. The plan was to invite basically the same personnel from the nine different maintenance camps across northern Arizona who had performed the installation of the magnets on US 180 at Kendrick Park. Of those who completed that project, almost all were regular snowplow operators, they had worked well together on the magnets, and they had shown intense interest in the project and its possible benefits to their work. These men were ideal candidates for training on the Advanced Snowplow, and could quantify its potential, if proven, into benefits for their own plow routes across the three Districts.

The first goal of the training program was to establish familiarity and a basic comfort level on the Caltrans system for ADOT operators at a variety of experience levels. For an effective sampling of opinions and reactions, a target of 21 participants was established by the project TAC. It was agreed that training of three drivers per day, each with at least five or six test runs, would offer a significant learning experience. This would be sufficient to show any measurable improvements and increased confidence in the systems. Each operator would also fill out a brief survey on his training experience, and could offer comments or suggestions on these first-generation systems. The Caltrans team, in particular Western Transportation Institute-MSU and PATH, provided the training materials and baseline evaluation surveys for this phase of the activity.

The second project goal was to perform operational evaluations during winter storms while the plow was in Arizona's care. This plan was dependent on the relatively dry regional weather patterns of March 1999. The general intent, depending on the local and regional weather activity, was to use the Caltrans plow in place of the ADOT snowplow that was normally assigned to the 35 mile US 180 Kendrick Park route. Because of the dry forecasts, the TAC recommended that some of the training and operational testing be done at night, in reduced visibility.

A third project goal, as priorities and conditions permitted, was to provide technology transfer information to partner agencies. The project's TAC decided that it was not practical to send the California snowplow to other areas of the state for display, in the short time window available. However, a project open house and local demonstration was scheduled at the US 180 test site midway through the program. The Flagstaff District was responsible for inviting their local and regional transportation partners to this Mini-Demo event.

The project workplan involved support from many people in the Flagstaff District. There was a myriad of details to resolve, including standby equipment and tools, communications plans, trainee lodging, and placement of "truck turning" warning signs in the Kendrick Park area. A key concern was to identify turnaround areas at each end of the US 180 test lane, with clear sightlines and without rough terrain that could damage the truck's low-hanging sensors. Another issue was to find the best route through Flagstaff's tight streets and congested traffic for the snowplow to travel between the maintenance yard and the test site.

Team Leaders

Although the goal was to develop a large pool of trained ADOT snowplow operators to use and evaluate the Caltrans system, it was obvious that the Caltrans technical support team would not be able to provide complete training to all of ADOT's operators. Another link would be required in the trainee / trainer chain to provide effective instruction to the entire group, and so to achieve a valid Caltrans system evaluation in Arizona.

The ATRC, the TAC and the Districts determined that the best approach to achieve the goals of operator pool training and evaluation was to develop a core group of Team Leaders (TLs). These operators would become the key interface between the snowplow itself, the Caltrans technicians, and the operator trainees from across northern Arizona.

Because of travel distances, available operator personnel, and the issues of process ownership, it was clear that the Team Leaders must come from the Flagstaff District. An effective snowplow Team Leader must be an experienced operator with a history of winter storm operations. To be an effective instructor and coordinator for the training, he needed above-average communication and leadership skills. To operate the Caltrans plow safely and effectively on US 180 in winter weather, he needed familiarity with the highway, and with the entire 35-mile plow route that includes the Kendrick Park test site.

The Flagstaff Maintenance staff assigned three experienced snowplow operators to the Team Leader role. All three had been involved in the Kendrick Park magnet installation and two of them were normally assigned to the day and night shifts on the US 180 plow route. They also had extensive experience plowing other challenging routes in the Flagstaff area including I-40 with its heavy, high-speed traffic as well as the city-street portions of US 180 and US 66.

The three Team Leaders would rotate the instructional duties at Kendrick Park during the time window allocated to train the operator pool on the Caltrans driver assistance systems. They would be responsible for scheduling the students, and for explaining, demonstrating and training them on the systems. They also had to ensure that the post-training surveys were filled out and collected, in addition to their own reports on use of the Caltrans plow. The Team Leaders were also responsible for preparing, fueling and checking the vehicle, doing start-up systems tests, and coordinating with Caltrans team members on trouble-shooting. Finally, they were encouraged, but not required, to use and evaluate the Caltrans snowplow during any opportune winter storms.

Caltrans Team Support

The first year of the snowplow evaluation program in Arizona got underway on Monday, March 8, 1999, when the flatbed hauler arrived at the Flagstaff yard with his cargo. The ADOT crews unloaded the truck and went to work on mounting the plow blade, the rotating beacon, and other minor items that had been secured for the third-party transportation to Flagstaff.

Also arriving that day in Arizona, along with Caltrans Advanced Snowplow Number 7005, was a team of technicians and project personnel. ADOT was contractually responsible for arranging for the shipment of the truck, and for the travel and support of the technical team. The partners were on hand for as long as was needed to equip and commission the snowplow and to initialize and troubleshoot the systems. For this first trip of the plow into its new testing situation, staff from Caltrans, AHMCT / UC Davis, PATH / UC Berkeley, and WTI / Montana State University were all on site to fulfill their respective roles in the project startup.

Generally the initialization of the systems went very smoothly. There were no major problems with the hardware or software, although at mid-week some software issues had to be resolved. Several team members had to stay one or two days longer than initially planned but this was not unusual for their first out-of-state effort to commission the Caltrans snowplow at a remote site.

Repeated test runs with the guidance system allowed an on-the-fly inspection of the four miles of magnets installed on US 180, and no magnets were found that needed to be repaired or replaced. Generally the Caltrans partners were completely satisfied with the test site conditions, and with the operational and training plans that ADOT had established for this field evaluation.

Operator Training and Evaluation

As noted above, there were nine maintenance yards, or Orgs, involved in the four-mile magnet installation on US 180 during September 1998. These included four Orgs from Flagstaff District, two from Holbrook District, and three from Kingman District. Nearly all of the personnel who worked on that initial magnet project did return for the ASP-I systems training in March 1999. In all, the project trained 17 snowplow operators on the Caltrans driver-assist systems. There were 14 stakeholder trainees from all across northern Arizona, in addition to the three Team Leaders from the Flagstaff Green River maintenance yard.

The Team Leader training deservedly received a lot of attention form the Caltrans partners. After the TL's reached a certain level of proficiency, they were asked to return the favor by performing complete training cycles for the Caltrans team. This hands-on reverse training was very helpful in building confidence and in confirming understanding of the various elements of the systems.

The 14 student operators basically completed the planned training program successfully. There were fewer students than originally planned but this was partly due to scheduling conflicts, minor snow storms, and limited local resources to release some trainees for travel.

All of the operators did fill out their post-training survey forms for the Caltrans program. There were also a number of follow-up interviews with several of them, conducted primarily by a WTI staff member on hand at the test site. This independent group of Arizona snowplow operators gave Caltrans some valuable comments and criticisms, in addition to the numerical rankings of the different system components and of the improvement, if any, to their level of confidence in plowing the highway under low-visibility conditions.

During the 1999 Arizona training period, as noted earlier, a local-area open house was organized at a Flagstaff hotel and at the Kendrick Park test site. Flagstaff District publicized the half-day display opportunity within ADOT, to local snow control and emergency response partners, and to the local media. Approximately 20 visitors went out to the staging area, and about half of those took a demo ride in the Caltrans snowplow. Agencies on hand included the City of Flagstaff, Coconino County, the Arizona Department of Public Safety, Federal Highway Administration, private consultants, key project vendors, and ADOT staff from the District and from Phoenix. In addition, the snowplow research project was featured in the local TV and print media, as well as by a Phoenix TV news outlet.

Operational Evaluation

As described above, the Flagstaff District was willing to assign the Caltrans 7005 snowplow to the US 180 route in order to assess its performance under local winter storm conditions. The initial plan was for the Caltrans plow to be accompanied by an ADOT unit. In this way, the two Team Leader or trainee drivers could switch off and cover the route effectively while still making limited test runs through the Kendrick Park area. Later, once the system was clearly functioning effectively, one Team Leader could maintain this route with the California snowplow.

As the project progressed through the three-week testing period, there were a number of small storm events including the first week of commissioning and training. The plow was run on the test section at night and during light snow, to a limited extent. However, despite the system's apparently normal operation in this time period, some concerns came to light that limited the ability to stay with the original plan.

One problem that could not be solved at this time was radio communications with the Flagstaff dispatchers. The 7005 snowplow carried a standard Caltrans radio, which had a different range of frequencies than the Arizona communications system. ADOT tried hand-held radios for the evaluation, but they were not consistently able to reach Flagstaff from the test site northwest of the San Francisco Peaks. This did limit the ability to operate unassisted on US 180, but in the mild March of 1999, with no significant storms, it was not a serious problem.

One other area for which the level of driver confidence did not rise particularly high was the collision warning radar. This system on ASP-I used a single radar antenna facing straight ahead from the truck's radiator grille, with a range of roughly 325 feet and a 5-degree field of view.

In general, the radar performed as designed and programmed, however for ASP-I, that design was focused mainly on the parallel lanes of I-80 on Donner Pass. In Arizona, the Caltrans snowplow had to face oncoming traffic in the next lane, as well as trees, markers and guardrails within 20 feet or less of the edge of the lane. Additionally, the winding roadway geometry at the north end of the course had several curves of less than 1000 foot radius, which had the radar signal fanning rapidly across the roadside obstacles like a searchlight beam.

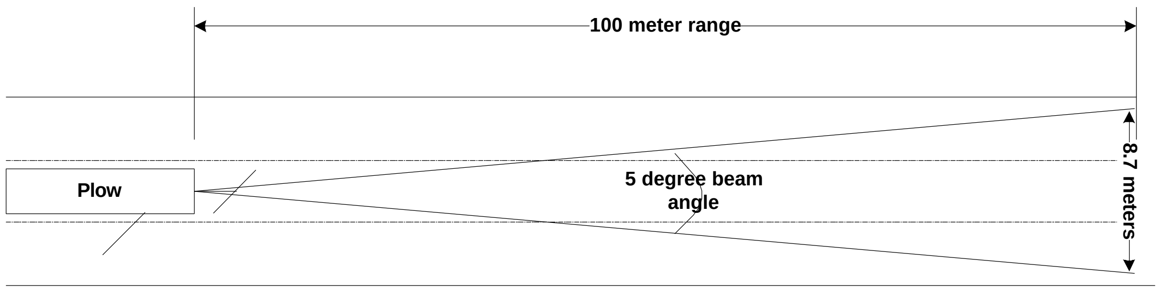


Figure 34:   Diagram of Single-Antenna CWS Radar Coverage on ASP-I
[Graphic courtesy of AHMCT]

While this did not create a dangerous situation in the training phase of the testing, it was less desirable in operational conditions. The US 180 roadway geometry was simply outside of the initial design parameters for the collision warning radar on the ASP-I, and the main drawback for Arizona's training effort was that the system gave frequent false warnings and was obviously not dependable in that situation.

Finally, there were, and always will be, truck mechanical problems. While nothing really major failed on this brand new snowplow, there were some adjustments and leaks that, over time, cut into the training and operations schedule. The three-week time window for Caltrans snowplow 7005 in Arizona, with setup, commissioning and troubleshooting, was really only about 10 days.

In summary, the initial year's training and evaluation program, with full cooperation and support from Caltrans, was very successful in meeting the Arizona research project's needs and goals. Although it was too brief, this phase of the project made major strides in educating ADOT field personnel and supervision as to the potential of ITS concepts to improve performance, and to increase safety.

ASP-I testing in Arizona also provided the California partnership with valuable experience and commentary on their system from a new perspective. In summary, both sides of the partnership did achieve their basic goals for the first winter of the research program.

XIV. ASP-I RESULTS: WINTER 1998-1999

Caltrans Performance Analysis

As noted elsewhere, Caltrans / AHMCT has published a detailed report that presents program goals, measures of effectiveness, and operator training results for both states, and the reader is referred to that document for more information. Only the most relevant background data and the key conclusions of that process will be presented in this report, as they relate directly to ADOT goals and concerns.

The Caltrans ASP-I project report offers valuable background data on the Advanced Snowplow program, which forms the basis for this and future years of reporting and data evaluation for both of the partner state DOTs.

The California program evaluation was performed primarily by Western Transportation Institute, for the Caltrans partnership. For both states, operator surveys were the first resource, along with on-site interviews and ride-alongs in the ASP-I Advanced Snowplow. Later, follow-up telephone interviews were conducted by WTI with the ADOT Team Leaders to gather more details and clarifications. For each state, the WTI evaluation interviews concentrated on three Team Leaders or primary operators for the Caltrans 7005 snowplow.

It should be noted that in this first program year, the California project team had less exposure to Caltrans training and operational plowing activities and less opportunity to record data. For example, driver surveys were collected from the large pool of ADOT operators but only from the Caltrans core operators. Also, driver performance data was collected by the ASP-I computer system for a few Arizona drivers during the test program, but not during California operations. As a result, the normal and system-assisted driver response measurements (see Figure 34 below) in the Caltrans / AHMCT ASP-I research report reflect recorded Arizona data only, since for that winter no similar Caltrans data had been collected.

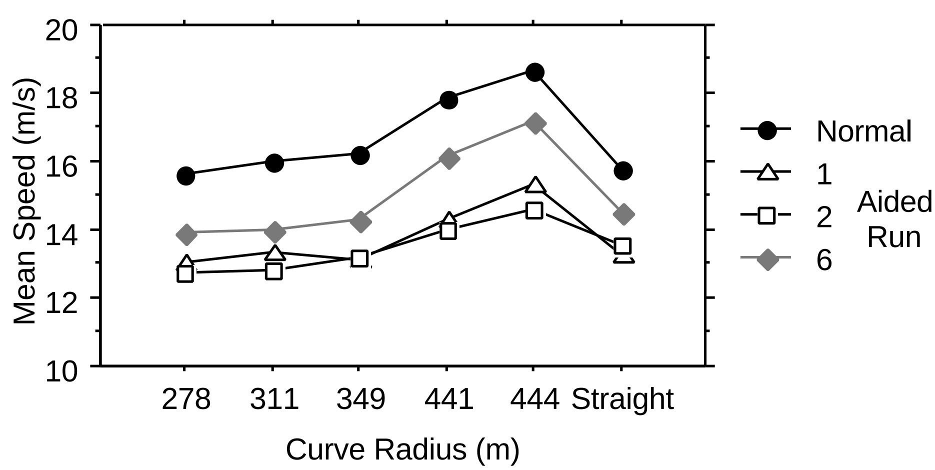


Figure 35: Mean Speed as a Function of Curve Radius [by WTI – MSU]

This illustration of mean speed is based on repeated training and test runs with one ADOT Team Leader during fair weather in daylight. It shows the increase in average speed through the three-mile test section of US 180 while using the system as the primary guidance resource. The result after six runs is that assisted mean speeds approached the driver's "normal" speed for this section.

The evaluation approach that was developed by the California project team considered each of the primary Caltrans research goals. These were to improve highway safety, to improve operating efficiency and traveler mobility, and to demonstrate the benefits of advanced vehicle control and safety systems (AVCSS).

From these project goals and more detailed objectives, key Measures of Effectiveness (MOE) were agreed on, as tabulated below. The MOEs in turn defined specific data sources for the project team, and for the Western Transportation Institute (WTI - MSU) in particular.

Table 2: Evaluation Goals, Objectives, Measures of Effectiveness and Potential Data Sources

Goals	Objectives	Measures of Effectiveness	Data Sources
Improve Safety	• Reduce snowplow accidents • Reduce damage to snowplow, other vehicles and infrastructure • Reduce injuries to snowplow operators, or other vehicle occupants	• Snowplow accident frequencies • Repair/replacement costs for snowplows, infrastructure	• Traffic accident reports • Maintenance work reports
Improve Operational Efficiency & Traveler Mobility	• Increase speed of snow removal • Reduce erratic snowplow movements • Reduce road closures/travel delays • Reduce run-off-road incidents, lane departures	• Number of roadway miles cleared per hour • Frequency and duration of road closures and chain requirements • Frequency of snow/ice related incidents, lane departures	• Maintenance work reports • Road closure logs • Chain requirement logs • Operator interviews • Ride-alongs
Demonstrate Benefits of AVCSS Technologies	• Evaluate system performance • Assess operator's acceptance of the system • Assess system's ease of operation • Assess perceived benefits of the system • Assess operator's level of confidence	• Frequency and severity of component malfunctions • Perceived benefits or problems with system • Frequency and severity of human error associated with system • Operator's assessment of system accuracy and reliability	• Operator interviews • Technology failure reports

[courtesy of WTI / AHMCT]

Western Transportation Institute, as noted earlier, was under contract as the evaluation partner for the ASP-I program. Their responsibility to the project involved collection and analysis of extensive background data on the two test sites, including weather history, roadway design, traffic volumes, and accident and repair cost records. The basic goals of the training and operational evaluations were to collect both quantitative and qualitative data on the performance of the ASP systems, and to capture the comments, concerns, suggestions and levels of confidence of the Team Leaders and core plow operators, and the trainees in each state.

As indicated in the Table above, many potential data sources existed that could provide valid information for the project. WTI found, however, that many records were incomplete or not currently and consistently maintained by the various agency sections and partners. Also, operating practices, training, pay and equipment varied between the two states. They further found that California and Arizona did not keep identical records, nor did they collect all the same data or level of detail. Agency internal-cost figures are particularly difficult to compare.

The short timeline of the evaluation effort did limit the amount of valid data that was collected. Equipment scheduling and data collection methods and staffing were other limiting factors. Still, significant information from both test sites was collected and interpreted in quite meaningful ways, and one of the most reliable and consistent data sources turned out to be the operator interviews and questionnaires (see Appendix H).

Table 3: Summary of Snowplow Operator Responses to Interviews

State	Driver	General						Lane Positioning			Collision Warning			Human-Machine Interface		
		Operator experience (yr)	ASP experience (hr)	Training	Safety	Efficiency	Ease-of-use	Safety	Efficiency	Ease-of-use	Safety	Efficiency	Ease-of-use	Ease-of-use	Timeliness	Quantity of info
CA	1	4	70	+	7	8	9	+	+	+	-	+	+	+	+	+
	2	6	80	+	10	10	9	+	+	+	0	+	+	+	+	+
	3	14	150	+	8.5	7	6	+	0	+	0	0	0	+	0	+
AZ	1	7	40	+	9	10	7	+	+	+	-	-	-	+	-	-
	2	9	32	+	10	10	7	+	0	+	+	+	+	+	+	+
	3	11.5	8	+	8	10	9	+	+	+	0	+	0	+	+	0

[courtesy of WTI / AHMCT]

Reactions by the drivers in both states were generally very positive. It should be noted that WTI and the California partnership gave their primary attention to experienced ASP-I drivers of both states, the ADOT team leaders and the Caltrans key operators. WTI developed their conclusions based primarily on in-depth interviews with six primary operators and team leaders (see Table 3 above), and supported by the larger pool of training surveys

The ASP-I driver surveys showed that ADOT's group of plow operators, including the Team Leaders, averaged 5.8 years of experience, and they averaged 4.9 hours on the ASP-I snowplow. The ASP-I report shows that, according to WTI's survey results, core operators rated improved safety as 8.75, improved efficiency as 9.17, and ease of use as 7.83 on a scale of 1 to 10.

The ASP-I report reaches mostly positive conclusions on the testing program, and it provides many recommendations for the second year (ASP-II) and future phases of research. These suggestions as they relate to the ADOT program include more consistent sharing of the plow between the partner states, and providing systems for consistent automatic data collection. As expected, the subsequent Caltrans ASP-II project would address most of the results of this WTI evaluation program.

The AHMCT Phase I Research Report contains the full details and conclusions from the first year of the program, with regard to the entire Caltrans Advanced Snowplow partnership.

ADOT Evaluation Results

ADOT and ATRC were basically dependent on WTI and the diverse Caltrans project team to collect, process and report the detailed information on the ASP-I activities, and to develop valid conclusions for the program with regard to both of the partner states. However, as noted above, the Caltrans evaluation program focused on their core ASP-I operators with the greatest level of experience on the Advanced Snowplow at Donner Summit. ADOT, on the other hand, focused on a broad cross section of the state's snowplow operators who must perform in a variety of terrain and weather conditions. Caltrans did not train a large pool of stakeholder operators, as Arizona chose to do with the three northern maintenance districts.

The ATRC also developed an ADOT training survey format that provided additional information on the usefulness of the system and its limitations (Appendix H: Caltrans and ADOT forms).

The ADOT surveys were given to each student driver after his roughly two-hour training block. They covered training site conditions and operator levels of confidence for each subsystem. Most of the operators scored the systems highly for their potential to improve safety and plowing efficiency, as noted by WTI in their report. They also noted any performance problems that reduced confidence, such as intermittent failures. Many of the drivers were very positive about the training and the potential of the ASP systems, and several offered some detailed and very perceptive suggestions to the Caltrans team for improvements.

ADOT operator comments and requests included changes to the screen mounting, display format, perspective, and symbology, and to the types of data displayed. The basic screen (Figure 31) shows the ASP-I vehicle position in the lane and the curvature of the roadway ahead, as well as the radar warning symbols.

Several drivers asked for better, more advanced lane prediction, and many had suggestions or requests for simpler radar displays. The ADOT operators also asked for the display to show additional useful data such as the area of the roadway or snowplow location by mileposts, as well as operating information such as truck speed and engine RPM.

Conclusions – Year One

The new concepts were viewed with real enthusiasm by most of the first-season operators. This is apparent from the detailed comments, sketches and suggestions that were submitted to the Caltrans / WTI team for evaluation along with the basic 1-to-10 "level of satisfaction" surveys.

In concluding the first year of the research partnership, ATRC would comment that the California ASP-I system was very impressive. It displayed a great potential, as well as presenting some problems in the first year. The strong positive operator response in this initial research year may be at least partly due to several factors, some perhaps more relevant than others:

- The sophisticated systems, despite some problems, offer real safety improvements in the nerve-wracking process of plowing snow in severe storms on remote rural highways. There are few other such breakthroughs in driver assistance on the Arizona winter maintenance horizon.

- The Caltrans all-wheel-drive snowplow was newer, better equipped, and more powerful than most of the ADOT plow trucks, at least during the 1998-1999 period of ASP-I.

- The ADOT plow operator trainees had installed the roadway magnets as a multi-district work team, an unusual opportunity for most of them, and they had a strong feeling of ownership in the concept.

Reactions at other levels of ADOT were also positive, tempered by cost and reliability concerns. The outreach that was done with stakeholders in the Flagstaff area also received some positive comments, with regard to the State's willingness to make a commitment to explore new advanced solutions for ongoing winter maintenance challenges.

Overall, the initial year of this Advanced Snowplow research program produced very positive reactions from Arizona's plow operators, Team Leaders and supervisors. There were some systems shortfalls, primarily in the radar on two-lane highway US 180. There were operational issues due to radio incompatibility, but that was an agency coordination problem to be solved as the project moved ahead.

In the project TAC meeting following the conclusion of the testing cycle, the committee members reviewed the progress made in the first year. At this time, support was expressed for equipping an ADOT snowplow with the system, as costs and developmental progress would permit. This suggestion would be made over and over in the next year, as the joint research project developed.

The following section discusses ASP-II, and the second year of the ADOT – Caltrans partnership.

XV. ARIZONA ASP-II RESEARCH ACTIVITY – FEBRUARY 2000

The ASP-II Snowplow

Both California and Arizona made separate significant contributions to the Advanced Snowplow partnership as a result of the success of the first year of this joint research program. As described earlier, ADOT, the project TAC and the ATRC all agreed that the two-mile eastbound gap in the line of magnets at the Kendrick Park test lane should be completed. This new construction was done in September 1999.

By providing a full six-mile test loop, ADOT eliminated the loss of training time and data collection while traversing that section of the route. More importantly, the completion of three miles in both directions also greatly improved the ability and flexibility to operate the ASP-II continuously in that area of US 180 during winter storms and whiteouts.

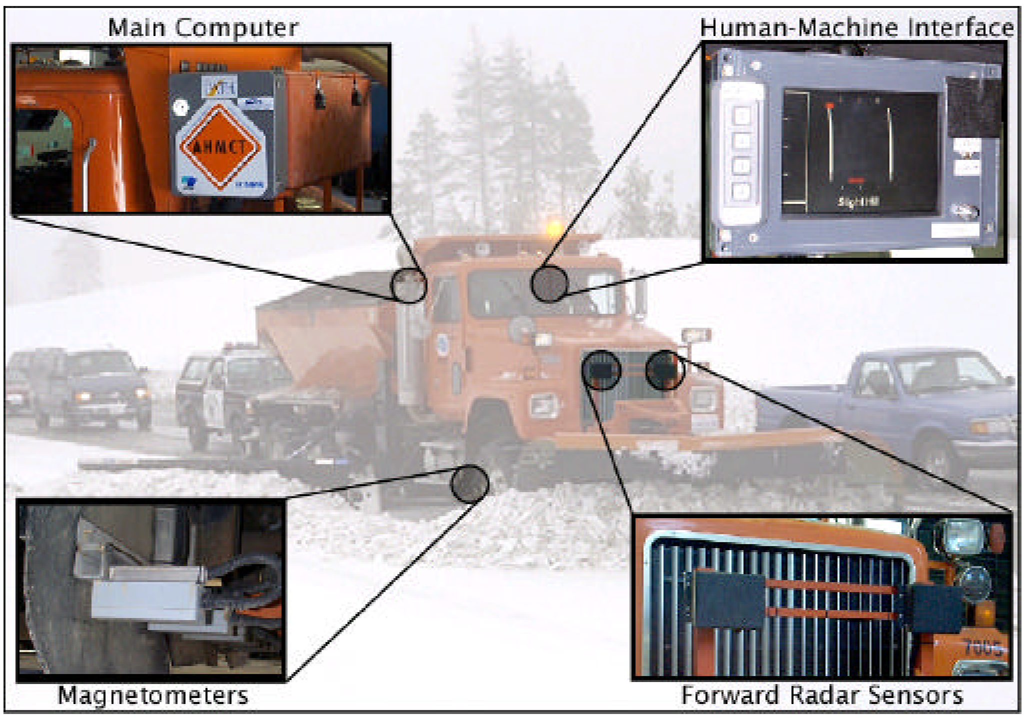


Figure 36: Key Subsystems – Second Winter - the Caltrans ASP-II Snowplow
[courtesy of AHMCT]

The Caltrans partners had also completed a number of important advances with the prototype Advanced Snowplow since the first winter of the program. The first objective of the ASP-II program was to further develop the snowplow guidance system to provide a more rugged and functional package. Additional goals were to refine the Human-Machine Interface (HMI) display and its functions, and to refine the original quantitative Measures of Effectiveness (MOE) for the evaluation program. Numerous refinements to the snowplow were made after the first winter:

- One key enhancement of the Caltrans ASP-II snowplow was the integration of two new radar antennae. Dual Eaton-VORAD 300-series units were mounted side by side on the truck's grille to provide a binocular signal for processing, and to compute azimuth angles to multiple targets (Figure 38). The new antennas are designed to cover three full lanes of Interstate 80.

- The redundant rear magnetometer bar was deleted, and the front system was strengthened and redesigned for better moisture sealing and durability.

- Another major change was the replacement of the ASP-I's HMI screen with a smaller but brighter driver-adjustable LCD display. To facilitate diagnostics and training, a second smaller LCD display screen was also added on the passenger side of the truck cab.

- A video camera and recorder were added to support the Measures of Effectiveness study. This system allows HMI display images to be integrated with views of the road ahead and of the driver's actions, for example, his frequency of referring to the display.

- A simulation switch was added to the system for driver training.

- The steering angle encoder on the steering shaft was altered to adjust its sensitivity and response rate.

As in the previous year, the ASP-II was deployed operationally in the Caltrans fleet as soon as it was modified, in December 1999. Based on ADOT requests and on long-term predictions of precipitation and temperature for both test sites, it was decided that the Caltrans ASP-II would be sent to Arizona for four weeks during the month of February – one of the historically wet months for the northern Arizona high country. The ASP-II snowplow was delivered to Flagstaff on January 31, 2000. One important issue that had not been solved in advance was the problem of radio communication for ADOT operations.

Training Concepts

From the perspective of ADOT, the TAC and ATRC, there was no need to make significant changes to the training and evaluation methods that were successful for ASP-I in 1999. It was agreed that the Team Leaders and the student operator program would be organized as before. There were differences, such as personnel turnover, and there were a number of new operators on the training roster, as well as several who had been exposed to the ASP-I in the preceding year. Also, most of the ADOT operator pool had once again worked recently on extending the test lane from four miles to six miles during September. They had developed a team spirit during that work, as well as a positive attitude towards evaluating the new Caltrans systems.

For this second year of the ASP program, Caltrans and ATRC agreed that there was not a strong need for multiple operator surveys. Therefore the Caltrans team added some suggested detail to their basic operator survey, and this became the basic post-training report for the student drivers to fill out. Interviews with the ADOT Team Leaders were a second, more detailed source of feedback. California PATH performed the evaluation tasks for ASP-II, rather than WTI this year, and ADOT / ATRC provided the completed surveys to PATH at the end of the project.

The Caltrans perspective on program evaluation differed markedly from Arizona's project goals. For ADOT, the need was to widely disseminate the benefits of the new technology, and to collect a broad range of operator evaluation ratings and comments. Caltrans, however, had no need to market the concept within their agency at this program stage. They continued to emphasize the operational deployment evaluation of the snowplow with the truck's assigned operators at Donner Summit, rather than training a wider range of snowplow operators.

Efforts were made in this second year to provide a better training environment in the ASP system. The ASP-II was provided with a training simulator switch that was used in the field at Donner Summit to provide an overview of system function for new Caltrans plow operators. It also was demonstrated in Arizona.

As noted in the ASP-II program report by AHMCT, the Caltrans team concentrated their program evaluation on only five plow operators on I-80 during significant storm events at Donner Summit. They also relied primarily on ride-along training and interviews with electronic data collection during these winter storms. However, this was not done in Arizona for several reasons, including availability issues and the standby cost for the Caltrans team to be on hand, as well as Flagstaff's relatively dry weather in February 2000.

Project Workplan - Arizona

The workplan for the second year of ASP-II activity in Arizona was more detailed than the first, but it was also simpler to initiate. In general, everyone knew their roles and their expectations. Many of the unknown factors and their contingencies were no longer of any concern. Shipping and travel arrangements, and documents such as contact lists, cost coding, and progress reports were all simply updated rather than built from scratch.

Figure 37: ADOT Team Leaders Being Briefed on the New CWS Radar Equipment

The ASP-II snowplow was to be in Arizona for four weeks during February. As with the first winter's evaluation program, the project TAC intended to allow for three to four days of system tests, commissioning and Team Leader training during the first week. Then, the balance of the first two weeks would be scheduled as training days for the stakeholder operators from the three northern Districts. The Flagstaff supervisors would coordinate the training schedule with the other Orgs (camps) in the District, and with those from Holbrook and Kingman Districts.

During the last two weeks of the month, the Team Leaders would run the snowplow operationally on US 180 during any storm event. This would again provide the perspective of experienced operators who were completely familiar with the US 180 plowing route that included the Kendrick Park magnet test site.

The Caltrans team would assign six of their staff for varying time periods to commission the ASP-II plow and its systems, to verify the conditions of the magnets at the newly expanded test site, and to provide systems training to the ADOT Team Leaders for US 180.

ADOT's Team Leaders were not all the same as for ASP-I, due to changing assignments and personnel turnover. This meant that the Caltrans team needed to provide refresher training and some basic training simultaneously to this year's cadre of three snowplow operators.

Caltrans Team Support

Caltrans and its project partners supported the 2000 testing and training in the same manner as during the first season of the joint project. Once again, six team personnel were on hand to commission and hand over their 7005 snowplow to ADOT. There were, however, a number of minor problems that delayed the start of training.

The Caltrans team, as before, focused on inspecting the US 180 test lane including the two miles of new magnets. Once again, the ADOT installation was found in repeated test runs to have no detectable problems with regard to magnet spacing, lateral tolerances, or polarity and coding.

As the second year of project operations began on Arizona soil, or snow, there were a variety of challenges to be met in the commissioning process. The plow needed more support during the second winter in Arizona, and a greater unplanned effort was required. As events developed, there were problems ranging from minor to major that required most of the Caltrans team to stay for the entire first week of the training program.

The failure of the truck's alternator was a major problem in the first week, in particular because ADOT did not use or stock parts for the International Paystar heavy truck series. Fortunately, a team from ADOT Equipment Services was able to assist the Caltrans staff to replace the unit at the Kendrick Park staging area. That problem took time but was finally solved by the joint procurement and servicing efforts of the two DOT equipment services representatives.

Extensive tuning of the Collision Warning System radar was required to work out "bugs" related to the winding road with its narrow shoulders and limited clear zones. Guardrails, signs and trees generated many false radar warnings, due to the new dual antenna deign. The system, while much more advanced than with ASP-I, presented more challenges in tuning for the two-way traffic and in suppressing false signals from the roadside.

The radar problems required intensive troubleshooting and tuning efforts until Friday of Week One. Solving the CWS radar problem, and related electrical problems, delayed the training schedule by about two days.

All problems were finally resolved so that the plow was turned over to ADOT on the fifth day.

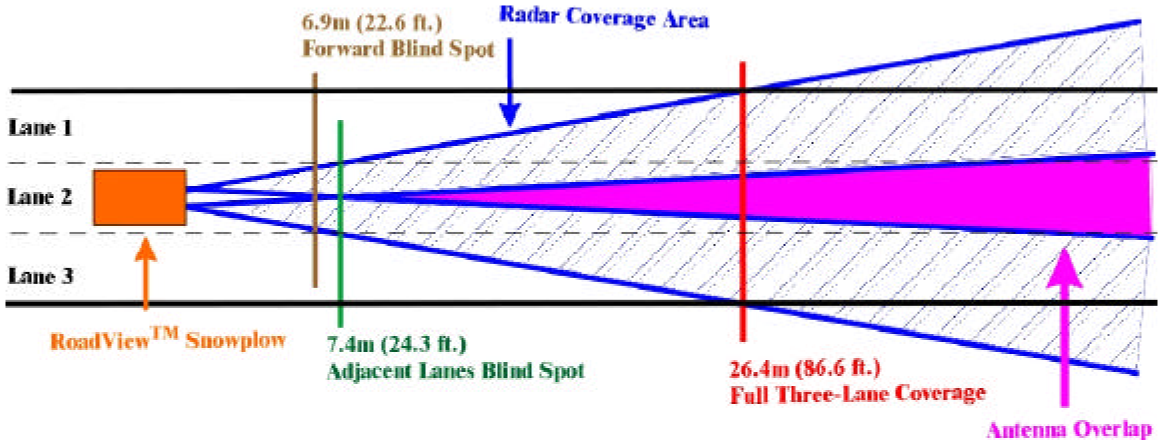


Figure 38: Area of Coverage with Dual Radar Antennas
[Courtesy of AHMCT]

A second problem that was never fully resolved in this test cycle was communications. Because ADOT and California operate in different frequency ranges, different radios were required for operations in the two states. As noted previously, ADOT needed reliable radio communications on the US 180 corridor in order to operate the snowplow safely at night and during major storms. If an accident occurred and the operator could not reach the Flagstaff District Snow Desk or the highway patrol, then both public safety and operator safety were compromised.

ADOT provided the radio channels to Caltrans in advance, but no suitable radio was found before the snowplow was shipped to Flagstaff. Likewise, no Arizona radio was available because the DPS is responsible for the state communications network, and surplus or obsolete units are exchanged rather than set aside for other crises or opportunities. Therefore, the snowplow would be limited for a second year to operating with hand-held ADOT radios, when another unit was nearby to relay the call, or with cellular phones.

For the four-week training schedule in Arizona, the marginal solution appeared to be cellular service. This was partly by coincidence, since Caltrans shipped the snowplow to Arizona with a spare Logistixx-Greylink AVL system and demo diskette for vehicle tracking.

The ATRC and the district welcomed this chance to evaluate the system, and by purchasing a mobile phone with a local Flagstaff number, the team was able to monitor the snowplow when cellular conditions were favorable. More importantly, the cell phone allowed for voice communications with the District office, and also with the Caltrans partners when trouble-shooting was required during both training and snow plowing. However, it was not a reliable means of basic communications along the entire US 180 route.

As noted earlier, the radar and electrical system problems had an impact on the training schedule for ADOT’s operator pool from the three northern Districts. However, the weather during this period was mild, and there were no major impacts from the delay.

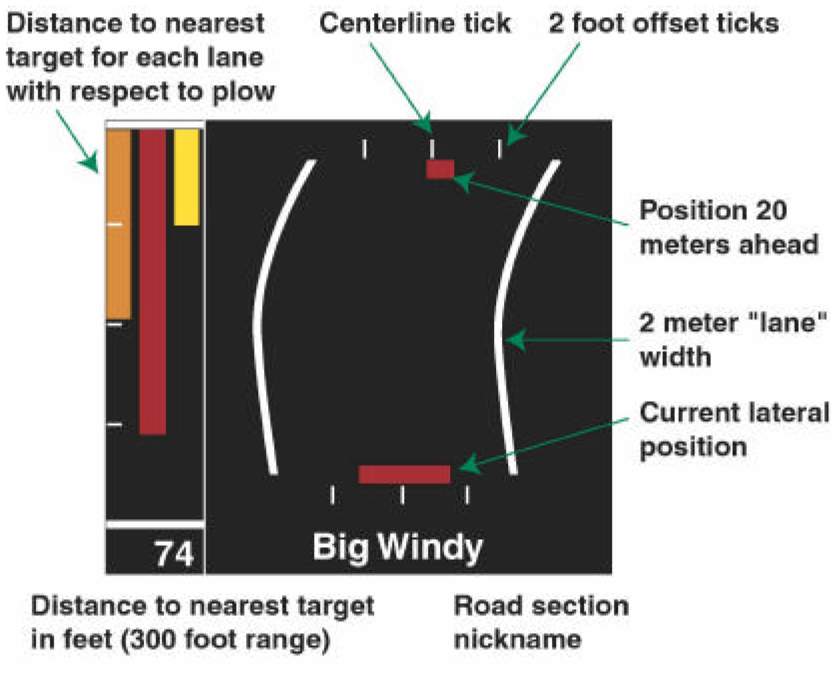


Figure 39: Revised HMI Screen Display for ASP-II

During February 2000, there were three Team Leaders with varying amounts of time dedicated to the training. One was from Gray Mountain, and two were Flagstaff primary operators who used the plow during the operational phase. There were a total of 15 trainee evaluations turned in, of which eleven were new to the ASP program this year. As in the previous winter, the student operator pool involved all three northern ADOT Districts – Kingman, Holbrook and Flagstaff. The 15 drivers who came to Kendrick Park for ASP training represented eight maintenance yards.

The trainees were asked to fill out a Caltrans program questionnaire that was very similar to that used in ASP-I (Appendix H). The two-page survey allowed for numerical rankings of system elements, and also asked for comments and suggestions. Some of the comments received were quite detailed and gave valuable third-party insights on operator needs to the Caltrans team. Several drivers also offered sketches of HMI displays that would improve their performance during plowing operations (Figure 40). As before, the CWS radar performance was not rated as well as the guidance system by the ADOT snowplow operators.

Apart from the operator surveys, there was no data collection from the on-board computer this season, since there was no significant winter storm activity while the Caltrans partnership staff were at the Arizona test area. Most of the performance data in the ASP-II project report from AHMCT for the winter of 2000 was collected from Donner Pass evaluation program.

In general the training and operator-input elements of the program were conducted just as in the first winter, with refinements dictated by the earlier results. There were few changes needed in the ADOT workplan for this aspect of the program (refer to the 1999 section of this report for more details on the training concepts).

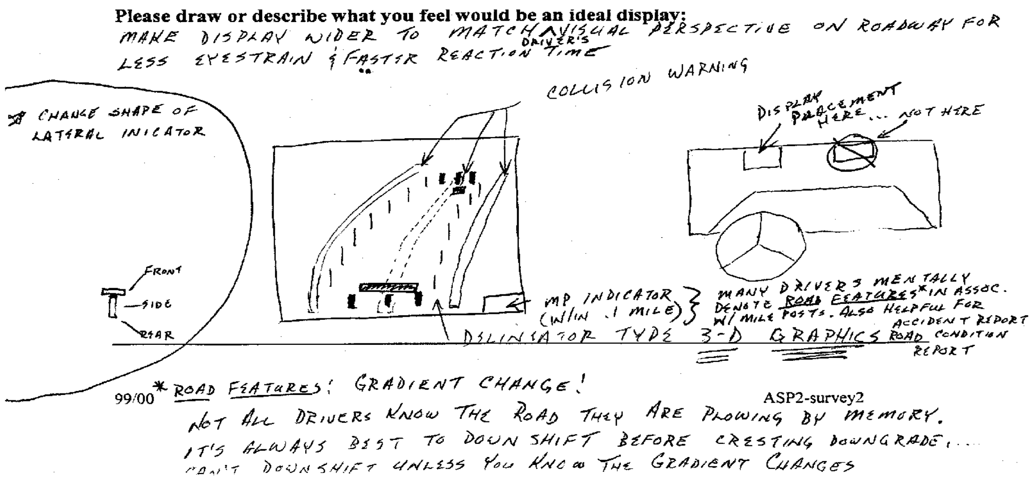


Figure 40: Sample of ADOT Operator Suggestions for ASP-II

During the second year of the program, the TAC did not feel it was necessary to repeat the successful media and regional agency open house from March 1999. However, the 2000 testing did attract interest both locally and statewide. A number of staff did visit from local agencies, from ADOT in Phoenix, and from other non-participating ADOT districts. Also, on the final day of the operational evaluation, the project TAC met in Flagstaff, and the various systems were demonstrated to the group.

Operational Evaluation

Overall, the Kendrick Park weather during the training phase was mild and dry for a second year. However, during the final two weeks of the testing, there were three storm events that provided an opportunity to evaluate the systems in the operational mode. Two of the ADOT Team Leaders ran the 7005 plow on the entire US 180 plow route, a distance of 35 miles between Flagstaff and the limit of their work zone. During the two weeks of field evaluations, the Caltrans snowplow logged 866 miles of plowing snow in full operational conditions.

The first storm came through on the weekend that training ended, and dropped four to six inches of snow in the region. Both Flagstaff Team Leader-operators used the Caltrans snowplow on both day and night shifts, and they reported that the systems were fully functional and were providing a significant benefit to maintaining the plow route.

Unfortunately, the radio communications issue came to the fore at this time. An accident on the US 180 plow route occurred that the ADOT operator could not call in by cell phone to Flagstaff, due to the erratic cellular coverage to the northwest of the San Francisco Peaks. The hand-held ADOT radios did not have the range to call from this area. Another state vehicle was able to radio the call in, but this incident led the operators and supervisors to leave the Caltrans plow parked in the Flagstaff yard during some later storm events.

Unable to depend on the cell-phone link, and with no spare personnel to support them on this remote plow route, the operators declined to run US 180 at night. Basically, from that point on, the plow was used only during weekdays, when other ADOT personnel were close enough to support radio communications.

Overall, there were at least four shifts in three storms between February 11 and 24 when the snowplow could be used operationally by the Flagstaff crews, and operator reactions were always positive to the system's overall performance. During most of this time, the guidance system functioned effectively in the Kendrick Park test area, and the CWS and AVL systems also were in use over the entire route. The radar system provided useful warnings, but the operator had to always depend on his visual information to verify the CWS display, and so to effectively interpret the positive and the false obstacle warnings. As to the GPS system, the cell phone was its weak link, since in several areas it could not be called for real-time tracking data.

As implied above, there were some problems that developed with the snowplow's lane awareness system in the last few days of the Arizona project activity. The operator's primary HMI display screen for the guidance system failed, and despite much long distance traffic on the truck's in-cab cellular phone, the Caltrans team could not resolve the hardware problem. The AHMCT support team provided a new LCD display screen by courier on the final workday, but it was not entirely compatible with the unit on the truck and did not solve the problem.

Figure 41: Passenger –Side Secondary LCD Diagnostic Screen
[courtesy of AHMCT]

Finally, as noted above, there was no data collection during storm events in Arizona for several reasons. While the Caltrans team was on hand, the weather was fairly mild, and of course all of their efforts were focused on repairs to the snowplow and its systems. When the operational evaluation began, the weather became more favorable. However, the radio problems reduced the number of times that the plow was in use, and the situation became too unpredictable for the technicians to return to Flagstaff on a standby basis.

The Arizona system performance data for February 2000, therefore, was primarily that which was derived from the operator and Team Leader surveys and from later long-distance interviews.

XVI. ASP-II RESULTS: WINTER 1999-2000

ASP-II Results - Performance Analysis

As was done earlier for ASP-I, the AHMCT Research Center has published a detailed Caltrans ASP-II project report covering the second-year research program's background, goals, measures of effectiveness, operator training results for both states, and achievements. Only the most relevant background data and the key conclusions will be presented in this ATRC report, as they relate directly to ADOT goals and concerns.

The Caltrans program evaluation during the second ASP year was done primarily by the PATH program from UC-Berkeley, for the partnership. For data from Arizona, operator surveys were the first resource, along with interviews. As noted above, there was no opportunity this winter for Caltrans ride-alongs during storm activity in Arizona. Also, the Caltrans ASP-II operator survey was refined from the prior year. ADOT therefore did not need to develop its own driver survey for ASP-II, because in the first year, the two state's formats had overlapped to a great extent.

For California, the project team was able to spend more time to observe Caltrans training and operational plowing activities at Donner Summit. Their main information sources were on-board data collection and ride-alongs in the ASP-II Advanced Snowplow. For both states, the PATH evaluations concentrated on the Team Leaders and primary operators for the Caltrans snowplow.

During the 1999-2000 winter, the Caltrans evaluation team collected data at Donner Summit for five plow drivers over six days of storm activity. During this period, all plowing was performed at night. The data was recorded, and observed, during ride-along activities by the team members. Caltrans planned to record truck movements and driver control inputs, as well as visual images of the screen, the road and the driver. According to the ASP-II report, the truck's video recording system did not function but some success was achieved with a hand-held camera.

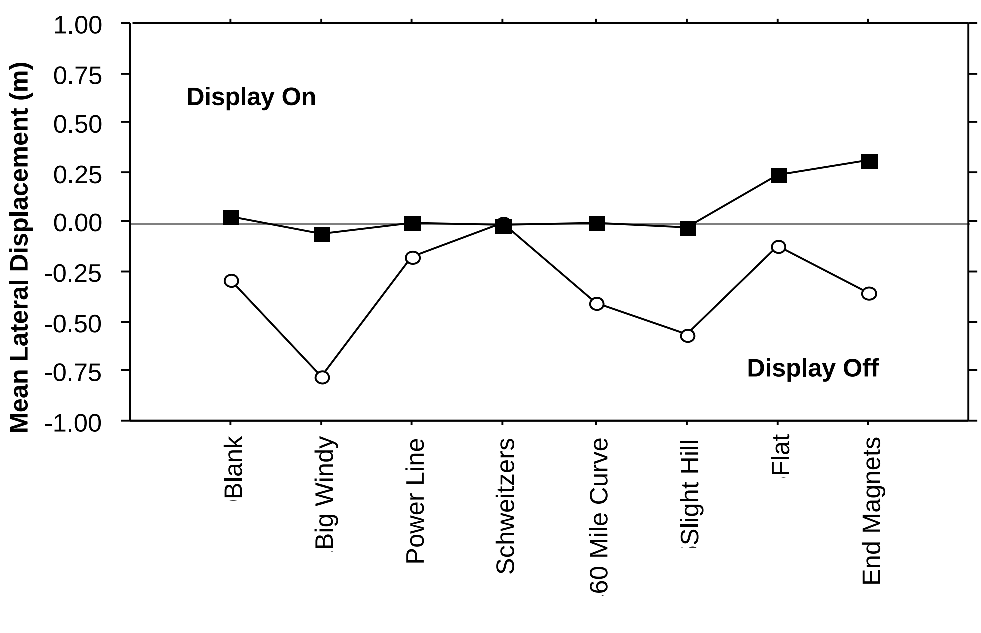


Figure 42: Lateral Displacement by Road Segment – ASP-II on I-80 at Donner Summit
[Courtesy of AHMCT]

The Caltrans recorded data included 29 runs at Donner Summit, including ASP operations and also baseline data runs. The key measurements and averages included the 7005 snowplow's speed, the lateral deviation from the magnet line, and the vehicle-to-road angle. Similar data had been recorded the year before in Arizona for the ASP-I program, on a very limited basis.

During snow removal activity at Donner Summit, the systems recorded a significant average reduction in lateral deviation with the guidance system in use (Figure 42). The results also show very minor reductions in plowing speed, and minor increases in steering wheel movement. This may be attributed to the lateral shift of visual focus from the road to the screen, as conditions required. Without the ability to record driver eye movements, however, this interpretation of the very limited data is unclear.

Another part of the California evaluation involved new driver training. Results are recorded in the AHMCT's ASP-II report for the experience of one new driver. The data show that after only one run over Donner Summit with the driver-assist system in use, the Caltrans trainee's plowing speed and lateral deviation improved to the point of matching the baseline performance of an experienced operator from the preceding shift.

The ASP-II report states that for all of the situations being analyzed, more data is needed, especially from test runs during whiteout visibility conditions.

ADOT Evaluation Results

Once again the ADOT evaluation concept was intended to provide exposure to the advanced snowplow for a representative group of plow operators with a range of experience and working conditions. This provided a substantial number of comments and suggestions for both ADOT and Caltrans. In addition, the Arizona Team Leaders gave Caltrans the in-depth analysis and growing base of experience that they needed to balance the evaluations of their own plow operators.

The Caltrans team recorded survey results for 15 ADOT snowplow operators during the second winter of the project. Of these 15 responses, only four noted experience with Caltrans plow 7005 from the previous winter. In the ASP-II report on these surveys, the ADOT operator pool showed a mean experience level of 6.43 years.

As with the first year, the responses were more positive for the lane-keeping system than for the collision warning radar. The four drivers who had experience with ASP-I overwhelmingly indicated that the overall system had been improved during the redesign to ASP-II. The CWS concerns were mainly for false signals and for extraneous readings from the roadside, and to some extent they reflected the delays in commissioning the radar system for Arizona testing.

The ADOT operator pool also showed a significant improvement in their view on the time it would take to learn the system and achieve a high comfort level in its use. For ASP-I, less than 50 percent of the operators felt that a week was sufficient time for learning to use the systems. For ASP-II nearly 70 percent, or three-quarters of the group, felt that less than one week was adequate to achieve proficiency. However, this group did include four snowplow drivers with prior experience in ASP-I.

Conclusions – ASP Year Two: 1999-2000

The results from both states showed that the Advanced Snowplow systems had been significantly improved for the second winter of testing and evaluation. Even with limited instruction, the HMI display and related features provided an interface that was intuitive and easy to learn. Most drivers, especially on instrumented training runs, were observed to reach a stable level of performance after only one run. This was borne out in Arizona by the Team Leader observations during their training of the individual operators from around the state.

This validation of the program's direction was very important for Caltrans and their partners. The positive reactions and the recorded improvements in performance bore out the basic principles upon which the program had been built. In particular, the Caltrans ASP-II report stated that the success of the relatively simple low-fidelity HMI display proved that advanced graphics and display optics were not fundamental to a successful system. This finding was very important for future development and possible commercialization of the concepts.

From the perspective of Arizona, the second year's successful test program and the positive reactions of the operators was also a strong validation of the research program. The results further justified the decision to partner with California, and it led the TAC to once again discuss the conversion of an ADOT snowplow for long-term tests of the system.

XVII. PHASE ONE RESEARCH SUMMARY – THE FIRST TWO YEARS

The Advanced Snowplow Project: 1998 - 2000

The achievements of the Caltrans ASP program, and of the partnership with Arizona in the first two years of this project, have been remarkable. A prototype snowplow system was conceived and constructed by the AHMCT team in less than six months, and it was tested exhaustively in harsh winter conditions for two winters. Major advances were made in system performance, capacity and reliability between the first and second years.

In addition to this one-of-a-kind snowplow, two complete test site infrastructures were developed in California and in Arizona. In each case five to six lane-miles of PATH guidance magnets were installed in the highway surface, in areas of severe winter weather and harsh operating conditions.

Overall, the ASP systems were effective and the advantages of their further development and deployment have been clearly shown. From the perspective of Caltrans and its research partners, the ASP systems are ready for the transition to commercialization, through further research done in a cooperative program with potential vendors.

There is no question that the ADOT snowplow operators have become converts to such systems, as is shown by their performance ratings and by comments and sketches of suggestions to further improve the real-world functionality of the equipment. Local and regional DOT management has also recognized the benefits of the systems, although the costs of deploying the concept will be a major issue in any expansion of this program.

With a vision of statewide deployment of advanced snowplows across Arizona, the Phase One research project conclusions will provide the justification for both further research and possible deployment of these technologies in the future. Each partner state, California and Arizona, has gained a great deal of specific knowledge and perspective on the intelligent vehicle systems and their ability to improve winter maintenance operations, as described in the following pages.

Project Results for California - First Two Years

From the Caltrans partnership perspective, the results of ASP-I and ASP-II are quite positive. The key achievement of this project to date, as described in the Caltrans / AHMCT reports, is the development of an integrated driver-assistance system that deploys technologies for lane position indication, lane departure warning, and forward collision warning.

During the first year, the prototype snowplow was put into the field, where the Caltrans research team immediately gained a new perspective of the true nature of the harsh environmental conditions that the snowplow systems must overcome. They also gained valuable knowledge of the entire winter maintenance mission and snow removal operation. Thirdly, the Caltrans team gained a realistic perspective of how to work effectively with the department's field forces in the remote mountain areas where the ASP system has the greatest potential to improve performance and safety. All of this experience and data led to the much more robust and reliable systems of the ASP-II prototype snowplow.

The results of the ASP program, as expressed in the AHMCT reports, clearly demonstrate the safety and efficiency that can result from use of Intelligent Vehicle technologies for maintenance vehicles in an extreme and hazardous operating environment. The system is simple to learn and to use; it eases the workload of the snowplow operator, while simultaneously enhancing the safety and efficiency of the plowing operation.

The concept of driver assistance for snowplow operators has been proven to be both effective in terms of enhanced safety, and desirable from the driver's point of view. The results show a quick learning curve and a high degree of confidence for the guidance system. The ASP technology has been shown to be field-ready through two winters' testing in severe winter storm environments.

The research team states in the AHMCT / Caltrans report that after two years of development, "the system concept as embodied in the ASP-II research prototype is a viable launching point for future commercialization." The Caltrans partners see these concepts and systems as having potential for use on other classes of vehicles as well, including emergency, commercial and transit types. The report also states that the project team plans to work with commercial vendors "to ensure that this valuable addition to the winter maintenance arsenal is transitioned smoothly from a research project to a commercially available system."

Future Directions of the Caltrans ASP Program

As a result of ASP-I and II, Caltrans and their partners stated their intention to seek commercial support to refine the products. However, further research efforts to refine and enhance the ASP systems in those areas have also been funded with research monies and will proceed regardless. As of mid-2000, the Caltrans project partners were proposing to initiate "A Rural Field Test of the RoadView System," which will develop and field two new snowplows for longer-term operational tests in California and in Arizona. The new RoadView project will also refine the Measures of Effectiveness to ensure that the goals of the US DOT's IVI program are met.

This RoadView program is to be a regional pooled fund study, led by Caltrans and with support anticipated from Arizona and other states. It involves the same agency / university team that performed the ASP-I research program. Additional magnet test lanes are envisioned, both on I-80 at Donner Summit and on two-lane rural highways near Redding and South Lake Tahoe. Other states are also being approached by Caltrans as possible partners, including the Alaska DOT.

Another related project that would impact the future of the ASP / RoadView program involves further research to automate the magnet installation. As noted earlier, AHMCT is performing work in this area. In ADOT's view, any progress that would speed the installation, reduce manpower, and reduce cost without sacrificing accuracy, will certainly improve the prospects for wider deployment of the PATH magnet-based systems.

One other related Caltrans research project is the Advanced Rotary Plow program. This new project is related to the ASP technologies, in particular the magnet-based intelligent roadway infrastructure and the collision warning system. Some areas of California's mountains average as much as 35 feet of snowfall in a winter. Rotary snowblowers operate in very deep snow at very low speeds, to clear massive snowdrifts that may have completely closed the highway.

The requirement for precision control of rotaries is even greater than for the high-speed ASP and RoadView snowplows on open highways. This is due to the steep terrain, cliffs and highwalls, and to roadway obstacles such as guardrails, which the rotary plows must clear within a few inches. In current practice the snowblower operators often must "plow by feel" along the guardrails, which results in frequent damage to both plow and guardrail.

This Advanced Rotary Plow research offers a practical testbed for semi- or full automation of the plowing operation in such areas as described above. The installation of the magnets or a similar guidance concept may allow an automated rotary blower to plow more precisely in critical areas than its operator can do even with the current driver-assist systems of the ASP program.

California envisions further expansion of their program through partnerships with other states. The ASP-II project has produced refined guidance system Measures of Effectiveness (MOEs) based on a collaborative effort with Minnesota. The Draft cooperative measures of effectiveness are included in Appendix I of this report, courtesy of AHMCT's ASP-II report.

Project Results for Arizona - First Two Years

For Arizona, the basic goal from the beginning of the 1997-2000 Phase One snowplow research program has been to evaluate the potential of the Caltrans system for Arizona's conditions and maintenance practices. The core of the snowplow partnership was the development of a second rural test site that provided unique conditions for the Caltrans team to conduct real-world testing and validation of their systems.

The training, testing, and evaluation program drew from and built upon the Caltrans Partnership approach. In the ongoing partnership over two winters, ADOT snowplow operators continued to train with Caltrans technicians and ADOT Team Leaders. The Arizona stakeholder input to the research program included comments and suggestions on HMI screen mounting, display characteristics and features, and types of relevant data to be displayed. This feedback gave the Caltrans ASP partnership a much better perspective on making their system marketable to other snowplow fleet operators across the United States.

The quantitative results for ADOT in Phase One of this project are limited, but the qualitative conclusions are significant. Approximately 30 ADOT snowplow operators gained experience on the state-of-the-art lane guidance technology. As the Caltrans reports show, in almost every case the training in Arizona produced high overall rankings for the ASP system's ease of use, comfort levels, and perceptions of improved driver safety and operating efficiency. It was unfortunate that the two years of testing in Arizona were relatively mild and dry, so that ADOT could not conduct more winter training and operational testing. However, there was significant plowing activity on US 180 in both winters during several moderate storms, and good system results were reported in every case by the Team Leader operators.

The ratings on the lane-awareness system were very high among the Arizona operators. This reflects the difficult Arizona winter operating conditions on remote rural highways and also the frustration with the visibility problems of typical snowplows during storms. The ADOT plow operators also ranked the HMI screen and display highly, although they had numerous suggestions on how to improve these features.

Overall, the driver satisfaction ratings of the collision warning radar system were relatively low, despite the enhancements for the second year. This issue was basically due to the ASP program being focused on a specific site and conditions, on I-80 at Donner Summit. As noted previously, ADOT drivers and ATRC project staff provided a great deal of feedback to the Caltrans team on the market reality of making their system fully reliable for rural two-lane highways, with oncoming traffic and less-than-interstate design standards. The ASP Team is continuing their efforts to refine the collision warning system for the RoadView program, based on Arizona's operator comments.

Vehicle System Cost Results

After two years of research and operational development of the system, reliable cost figures for the ASP package are becoming clearer. As stated in the ASP-II report by AHMCT and Caltrans, the unit cost for equipment and labor to duplicate the vehicle system is estimated in mid-2000 at approximately $60,000 (reported as $75,000 in ASP-I). Based on foreseen revisions in hardware and installation approaches, the Year 2000 estimate for a volume production unit is in the range of $25,000 to $30,000. However, this was estimated at or below $20,000 in the ASP-I report.

These costs are very significant for a fleet of $140,000 snowplow trucks such as those in wide use by ADOT and other states, and further improvements are forecast by the Caltrans partnership.

A peripheral finding of the integrated ASP systems research, at this point, is that stand-alone collision warning and vehicle tracking systems are options which, at relatively low cost, could improve the safety and efficiency of any fleet vehicle on any highway, without any additional infrastructure investment.

Roadway Infrastructure Cost Results

Both ASP-I and ASP-II document the cost of infrastructure installation for the Caltrans test sites to be approximately $25,000 per mile in concrete, including surveying, installation, and magnets. The cost is evenly divided between surveying and mechanical installation of the magnets. For future installations, the Caltrans team estimates contractor cost to be near $18,000 per lane mile.

ADOT developed cost figures that were effectively repeated from the first to the second years. As noted earlier, the installation of six lane-miles of magnets by ADOT forces was carried out at a cost of approximately $17,500 per lane mile of asphalt highway in 1998 and in 1999.

However, this figure is based on ADOT internal maintenance labor costs with burdens averaging $12.00 per hour, and on shared internal or overhead account billing of needed equipment such as pickup trucks, generators, and compressors as well as services such as traffic control, flagging and layout surveying. Materials alone for six miles cost $12,800 total, or $2,150 per lane mile.

The ADOT installation cost total is based on a slow but precise core-drilling method; it is realistic for future magnet installations under the same conditions. ADOT recognizes that the cost for a contractor to perform magnet installation, even on a large scale, would approximate the Caltrans figure until a breakthrough in design, methods or materials can be achieved.

The California ASP partners hope to reduce the costs over time, based on possible refinements in the installation procedure. This depends on many factors that include methods, equipment, experience, efficiency, installation tolerances, material specifications, profit margins and labor burdens, roadway design, traffic issues, and others. In particular, the AHMCT Research Center is conducting a technical feasibility study of automation of the mechanical installation process for the magnetic markers. In addition, recent advances in the use of GPS for surveying may help to reduce that portion of the installation cost.

Magnet installation costs also must be balanced with the anticipated lifespan of the roadway, which may vary depending on its design from 7 to 15 years or more. While pavement overlays can extend the life of the highway for many years, at some point it will probably have to be rebuilt, and any embedded system will have to be replaced.

ADOT Phase One Conclusions - Vision

Arizona's more subjective results are also clear. In return for the commitment of the test site and the active participation in testing, ADOT was able to gain its own perspective on the suitability of these concepts for wider use in Arizona. The loan of the only existing ASP snowplow prototype to Arizona, for up to a month during each winter, provided a priceless opportunity to educate ADOT management and maintenance personnel on new technology at every level of the agency.

One key conclusion from the Phase One years of ADOT's advanced snowplow research is that these systems offer real advantages to the plow operators and to the traveling public, but that the costs will always be a major constraint to deployment. Therefore, for a rural state such as Arizona, the roadway infrastructure and the vehicle systems will only be practical in limited but critical locations around the state.

Arizona has over 6,000 miles of highways to maintain, and a fleet of some 240 snowplows. Much of the state's terrain is on a high plateau, north and east of the 7,000-foot Mogollon Rim, and many highways run for hundreds of miles at high altitude. Arizona has few of the classic high mountain passes that are transportation system bottlenecks in winter for other Western states. Instead, there are many wide areas of low visibility where the incessant winds create whiteout conditions. However, there are also many areas of highway where cliffs, deep canyons and long steep grades challenge the ADOT snowplows and their operators. These specific areas, selected on a district-by-district basis, may be practical sites for effective limited deployments of the snowplow guidance systems and their infrastructure.

The project's Technical Advisory Committee included all three northern Arizona Districts, as well as the state and regional sections of Equipment Services and the Technology Group. This involvement of the department's core staff was vital in setting realistic goals and objectives for the research, and in carrying out the complex efforts for both the installation and the testing phases of the project. Without the strong and substantial support of these partners, none of the accomplishments of these two years of field research could have been achieved.

ADOT's Future Advanced Snowplow Program – Phase Two

At the conclusion of Phase One of the project, in mid-2000, there is strong support within ADOT to continue with California in joint project activities to refine the ASP systems. The goal of this research is practical commercialization at a reasonable cost. There is also a very strong interest among the project TAC members in <u>equipping an ADOT fleet snowplow</u> with advanced guidance equipment, if that is feasible. This desire will drive ATRC to negotiate with the Caltrans partnership and also with other possible sources of these technologies, be they commercial or other research programs. This wider range of advanced snowplow activity and related research topics will become Phase Two of ADOT's IVI research program.

One possible option for expansion of the ADOT 2000-2001 snowplow research program would be to conduct research on the 3M Lane Awareness System. As referenced earlier, 3M has shown great interest in working with Arizona and other mountain states to carry out regional research programs outside of their core market in the upper Midwest. Their magnetic tape-based system was demonstrated twice in Arizona, at the August 1999 Rural ITS conference in Flagstaff and at the June 2000 Vision 21 showcase in Phoenix. In early 2000, 3M also gave presentations and conducted a market analysis with ADOT management and district maintenance supervisors. As a result, they offered several proposals to ATRC to share costs on an Arizona evaluation of the 3M tape and guidance system.

Assessment of this project's progress and results is an issue, since ATRC is performing all of the detailed research planning and management in-house. The ADOT project's Technical Advisory Committee have recognized that as the ATRC research program expands beyond Phase One, there will be a need for a more formal Snowplow Testing Evaluation Program. This study would be particularly important if future tests are done of other concepts and systems that may compete with the Caltrans ASP partnership. For this reason, ATRC and the TAC are discussing the option of a third-party evaluation program of the snowplow research activities.

One logical possibility is to develop a contract with Northern Arizona University as a neutral evaluation consultant. The University is located in Flagstaff, where all snowplow testing has so far been centered, and their engineering faculty has a successful history of involvement in other research with ADOT. As a result, ATRC will review the program direction and budget with the TAC, and will develop a tentative evaluation workscope based on planned snowplow research activities in 2000-2001.

These new directions for the Arizona advanced snowplow research program, and other intelligent vehicle opportunities as well, will be pursued in the coming years of this project. Progress will be documented by ATRC and its partners in future Phase Two research reports.

APPENDICES

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B - TECHNICAL ADVISORY COMMITTEE – SPR 473

C - JOINT PROJECT AGREEMENT JPA 98-222

D - NAHSC - PATH - ADOT PUBLIC AHS DEMO – TEMPE ARIZONA – DEC 1997

E - SUMMARY REPORT - SIX MAGNET TEST SITES – JULY 1998

F - SUMMARY REPORT – US 180 MAGNET INSTALLATION – SEPT 1998

G - OPERATOR INSTRUCTION SHEET - ASP-II - FEBRUARY 2000

H - OPERATOR EVALUATION FORMS – ASP-I / ASP-II

I - DRAFT MEASURES OF EFFECTIVENESS FOR GUIDANCE SYSTEMS

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APPENDIX A

ORIGINAL RESEARCH PROBLEM STATEMENT

*   *   *   *

SUBMITTAL FOR FUNDING APPROVAL TO

ADOT RESEARCH COUNCIL

Research Project Statement
Project 46X
Snowplow Guidance Technology – Field Test

TRACS NO.	**R046X10P**	**PROGRAM DATE:**	**10/01/97**
BUDGET:	**$XX,000**	**COMPLETION:**	**06/30/98**

Title

Field operational testing of on-board systems and infrastructure using Automated Highway smart-vehicle navigation technology (AHS) for guidance of snowplows in zero visibility conditions.

Problem Statement

Snow and ice removal in Arizona's mountainous areas may be the most hazardous duty faced by ADOT maintenance crews on a regular seasonal basis. This work frequently requires long working hours, often at night during extreme weather conditions with literally zero visibility. Visibility is impaired during snow plowing operations by a combination of factors including reflected headlight glare, obscured windows, and blowing snow. These factors are often influenced by the design of the plow, the vehicle, and its lighting systems. Airborne powder snow reflects light scatter to create the effect of a white cloud around the blade and the truck cab.

A further problem may occur when drifting snow can completely obscure the lane markings, details of the roadway shoulder, and even guardrails. These hazards are often increased due to steep roadway grades and shoulder dropoffs. Poor visibility reduces operational safety and contributes significantly to the hazards faced by both the operator and the travelling public.

Importance

This project is viewed as very important, having the potential to provide significant safety benefits to both ADOT maintenance personnel and to the travelling public. The results of the research should result in both safer, more consistent plowing of the roadway and also in a reduction of accidents involving both the snowplows and other vehicles.

Urgency

This project is considered very urgent, as it will address a current need for safety enhancements in this recurring problem area.

Literature Summary

Only limited specific information is yet available on ITS smart-vehicle technology research with regard to the problems of obscured roadway and visibility issues.

Are research results already available? If so, how can ADOT implement these results?

This problem is not unique to ADOT, but the recent developments and demonstrations of new AHS technologies may provide an opportunity for a breakthrough in this problem area. The research program will involve communication and cooperation with other DOTs that have a shared interest in the problem.

Research Objective

Identify, evaluate and field-test vehicle guidance technology that will enhance the safe operation of ADOT snowplows, both in "whiteout" storm conditions and in areas of heavy drifting where the roadway lanes and shoulders are completely obscured. The accuracy and reliability of "real-time" vehicle guidance at the normal snowplowing speeds will be a paramount concern.

Research Tasks

At a minimum, the following tasks are to be completed:

1. A Technical Advisory Committee will meet to review the scope of work, define the program requirements, and confirm the proposed work plan. The TAC and the various ADOT District staffs will identify the best locations for field testing and will confirm the site's test parameters.

2. A contact program will be initiated with other DOTs and research groups to confirm the extent and direction of existing research and implementation. The TAC will review commercial and prototype vehicle guidance systems now in use or in development by various Automated Highway System suppliers. *Discussions have begun with CalTrans, University of Minnesota and Montana DOT.*

3. The TAC will recommend guidance systems for field evaluation in ADOT's expected winter conditions. Options may include:

    - Differential GPS (global positioning satellite) navigation with screen or heads-up display.
    - Vehicle sensors with roadway-embedded markers.
    - Vehicle sensors with roadway-embedded tapes.
    - Vehicle sensors for objects in the roadway.
    - Other identified candidate technologies.

4. The selected sources or suppliers will implement the field testing with District staff, deploying the test system(s) on a snowplow for an evaluation period of one winter.

5. Evaluation of the program's effectiveness will be monitored and carried out by the TAC, possibly assisted by a university research staff, who will prepare a final report that fully documents all project activities and recommendations.

Expected Implementation

The execution of this project will be a key step toward the implementation of AHS devices in the ADOT snow removal vehicle fleet. This technology also has the potential to carry over to other agency fleet vehicles in other limited visibility scenarios statewide.

Duration

8 to 10 months

ADOT Involvement

The ADOT Districts will provide recommended roadway locations for field testing, and snowplow vehicles with operators for the initial winter testing activities. ADOT also will provide for any needed surveying and placement of guide marker devices, possibly as part of a planned construction or maintenance project.

Technical Advisory Committee

- ADOT Transportation Technology Group
- ADOT I-40 Corridor Districts – Flagstaff, Holbrook, Kingman
- Arizona Department of Public Safety – Flagstaff DPS
- National Weather Service – Flagstaff / Bellemont
- ADOT Equipment Services
- Federal Highway Administration
- ATRC

APPENDIX B

TECHNICAL ADVISORY COMMITTEE

ATRC PROJECT SPR 473

ATRC PROJECT TAC
TECHNICAL ADVISORY COMMITTEE
473

PROJECT: Intelligent Vehicle Initiative (IVI) & Snowplow Guidance Research
TRACS No.: R0473 08P

CURRENT PROJECT TEAM:
1. TECHNICAL ADVISORY COMMITTEE

NAME	AGENCY / FIRM	AREA CODE	PHONE	FAX	MAIL DROP
Debra Brisk (Bill Wang) Larry Thomas	ADOT – Kingman Dist Engr				K600
Bruce Mejia	ADOT – Seligman Maint				K651
Don Dorman	ADOT – Flagstaff Dist Engr				F500
John Harper Danny Russell Jack Gray	ADOT – Flagstaff Maint Engr				F520
Ernie Sanchez	ADOT – Gray Mountain				F552
(Kent Link)	ADOT – Flagstaff Constr. B				F533
Jeff Swan	ADOT – Holbrook Dist Engr				H700
Robert Wilbanks	ADOT – Holbrook Maint				H769
Lt. Dan Wells	DPS District Two – Flagstaff				
Mike Campbell	National Weather Service				
Dennis Halachoff Mike Signa Dean Murgiuc	ADOT Equipment Services				071R
Larry Presnall	ADOT Eqpt Serv – Prescott				P700
Carl Eyrich	ADOT Eqpt Serv – Flagstaff				F700
Steve Owen	ADOT – ITS				PM02
Manny Agah	TTG / TOC / ENTERPRISE				PM02
Alan Hansen / Jennifer Brown	FHWA				005R

2. PRINCIPAL INVESTIGATOR(S):

   ATRC

3. ADOT – ATRC PROJECT MANAGER - ITS
   Steve Owen
   Arizona Transportation Research Center (ATRC)
   2739 E. Washington Street / MD 075R
   Phoenix, AZ 85034

4. ADOT ASSISTANT STATE ENGINEER - ITS
   Tim Wolfe
   ADOT Traffic Operations Center (TTG)
   2302 W. Durango / MD PM02
   Phoenix, AZ 85009

APPENDIX C

JOINT PROJECT AGREEMENT JPA 98-222

ARIZONA DOT – CALIFORNIA DOT

AG Contract No. KR98 2752TRN
ADOT ECS File No. JPA 98-222
Funds: ORG P/O's
Project: Advanced Snowplow Testing

INTERGOVERMENTAL AGREEMENT
BETWEEN
THE STATE OF CALIFORNIA
AND
THE STATE OF ARIZONA

THIS AGREEMENT is entered into 16 AUGUST, 1999, between the STATE OF ARIZONA, acting by and through its DEPARTMENT OF TRANSPORTATION (the "Arizona") and the STATE OF CALIFORNIA, acting by and through its DEPARTMENT OF TRANSPORTATION (the "California").

I. RECITALS

1. Arizona is empowered by Arizona Revised Statutes Section 28-401 to enter into this agreement and has by resolution, a copy of which is attached hereto and made a part hereof, resolved to enter into this agreement and has delegated to the undersigned the authority to execute this agreement on behalf of Arizona.

2. California is empowered by Government Code 6500 to enter into this agreement and has authorized the undersigned to execute this agreement on behalf of the State of California.

3. California and Arizona have agreed to work in cooperation on the testing of California's Advanced Snowplow on Arizona State Highway US-180, all at Arizona expense, in a total amount not to exceed $50,000.00 for the program.

==

NO. 23472
Filed with the Secretary of State
Date Filed: 08/16/99
Betsey Bayless
Secretary of State
By: Vicky V. Groenewold

Contract No. 65a0044

THEREFORE, in consideration of the mutual agreements expressed herein, in its agreed as follows:

Article II Scope of Work:

1. California will:

   a. Transport the Advanced Snowplow from California to the Arizona Maintenance Yard located at 5701 E. Railroad Avenue, Flagstaff Arizona and from said location back to California.

   b. Deliver the Advanced Snowplow to the Arizona Maintenance Yard located at 5701 E. Railroad Avenue, Flagstaff, Arizona, on a mutually agreeable date and for a mutually agreeable period of time between California and Arizona.

   c. Provide driver training on the operation of the Advanced Snowplow to a selected number of Arizona snowplow drivers.

   d. Provide a technical representative for discussions on the Advanced Snowplow technology.

   e. Invoice Arizona upon return of the Advanced Snowplow to California for all costs associated with transportation of the snowplow and California Advanced Snowplow training staff to and from Arizona.

2. Arizona will:

   a. Reimburse California for all of the costs associated with the transportation of the Advanced Snowplow and California Staff to and from Arizona pursuant to this Agreement, within 30 days after receipt and approval of invoice. **Such reimbursement shall be made via Arizona State purchase orders issued by the Arizona ADOT organization receiving the training.**

   b. Arizona will ensure the Advanced Snowplow will only be operated by authorized and trained Arizona State employees.

   c. Arizona will assume all liability for any and all loss, injury or damages associated with the operation of the Advanced Snowplow while being driven by an Arizona operator.

   d. Arizona will provide California with a written evaluation and recommendation relative to the Advanced Snowplow.

Article III Miscellaneous Provisions:

1. This Agreement is subject to the appropriation and availability of funds of the respective parties hereto, however, that this Agreement may be canceled at any time by either party upon thirty (30) days written notice to the other party, with each party responsible for its share that has been accomplished to date.

2. This Agreement shall become effective upon execution by both parties and filing withthe Secretary of the State of Arizona. This Agreement may be canceled in accordance with A.R. S. 38-511, as regards conflicts of interest on behalf of Arizona State employees. The provisions of A.R.S. 35-214, pertaining to 5-year record retention for audit purposes, are applicable to this Agreement.

3. The parties agree that the employees assigned to perform any service under the terms of this Agreement shall remain solely the employees of their respective agencies and entities and will not be entitled to any additional compensation or benefits by reason of this Agreement.

4. That the illegality or invalidity of any provision or portions of this Agreement shall not affect the validity of the remainder of this Agreement

5. This Agreement constitutes the entire contract between the parties and shall not be modified unless in writing and signed by the parties.

6. Arizona and California shall select a process, agreeable to Arizona and California, for the resolution of claims or disputes. Such process shall include a provision for arbitration.

7. All notices or demands upon any party to this Agreement shall be in writing and shall be delivered in person or sent by mail addressed as follows:

California Department of Transportation
Attn.: Mike Jenkinson
New Technology and Research Program, MS# 83
P.O. Box 942873
Sacramento, Ca 94273-0001

Arizona Department of Transportation
Joints Projects Administration
205 S. 17th Avenue MD 616E
Phoenix, AZ 85007

Steve Owen, Project Manager
Transportation Research Center
1130 N. 22nd Avenue
Phoenix, AZ 85009

8. This **Agreement shall terminate on December 31, 1999.**

IN WITNESS WHEREOF, the parties have executed this Agreement the day and year first above written:

STATE OF CALIFORNIA
Department of Transportation

By ____________________
Tom Sanborn
Contracts Officer

Date: 5/5/99

Approved as to form and procedure by California Attorney

By ____________________

STATE OF ARIZONA
Department of Transportation

By ____________________
Tim Wolfe
Assistant State Engineer

Date: 4/7/99

APPENDIX D

NAHSC - PATH - ADOT PUBLIC AHS DEMO

TEMPE, ARIZONA

*   *   *   *

SURVEY AND RESULTS

DECEMBER 15-17, 1997

DATE: 12/__/97 **NAHSC/PHOENIX DEMO SURVEY**

NAHSC is interested in conducting a survey among people who have taken part in the automated vehicle and highway technologies demonstration. Your participation would be appreciated. At the end of the demonstration, your survey will be collected. All your responses will be kept strictly confidential.

1. What is your initial impression of the automated vehicle and highway technologies that you experienced on this demo ride?

____
___________________________________(13-14)
____
___________________________________(15-16)

2. What did you like or dislike most about the demo ride:

LIKE: ____________________________________
___________________________________(17-18)
DISLIKE: _________________________________
___________________________________(19-20)

3. How would you rate the experience you just had riding the demo vehicle in terms of the following attributes? **(Please circle a number below using a 1 to 5 scale, where 1 means you "completely disagree" with the statement and 5 means you "completely agree" with the statement.)**

		COMPLETELY DISAGREE				COMPLETELY AGREE	
a)	The ride felt smooth	1	2	3	4	5	(21)
b)	The ride felt safe..	1	2	3	4	5	(22)
c)	The ride was noisy...	1	2	3	4	5	(23)
d)	The ride was enjoyable......................................	1	2	3	4	5	(24)
e)	Acceleration was too sudden.............................	1	2	3	4	5	(25)
f)	Deceleration was too sudden.............................	1	2	3	4	5	(26)
g)	The display looked like it would be easy to use.	1	2	3	4	5	(27)
h)	The display was well designed so that the.......... information could be easily understood	1	2	3	4	5	(28)
i)	The audio was pleasant and reassuring..............	1	2	3	4	5	(29)

4. Did the car go too slow, too fast, or about the right speed?
❐-1 Too slow ❐-2 Too fast ❐-3 About right (30)

5. After taking the demo ride, do you think you would like to use automated vehicle and highway technologies?
❐-1 Yes ❐-2 No (31)

6. For what kind of driving or in what situations would you use it? **(Please check as many as apply.)**
- ❐ Urban freeways during peak hours (32)
- ❐ Rural freeways (33)
- ❐ Long trips (34)
- ❐ Commute trips (35)
- ❐ Driving on surface streets (36)
- ❐ Driving at night or in the fog (37)
- ❐ Other: specify____________________ (38)

7. What do you see as the THREE MOST IMPORTANT benefits of vehicle automation for driving on a highway? **(Please rank in descending order of importance, using numbers 1, 2, and 3. <u>Do not give the same number to more than one item</u>.)**
- ❐ Increased privacy (39)
- ❐ Reduced stress (40)
- ❐ Reduced travel time (41)
- ❐ Makes the driving task easier (42)
- ❐ Being able to do other things while traveling (43)
- ❐ Other: specify____________________ (44)

8. What do you see as the THREE MOST IMPORTANT benefits of vehicle automation for driving on a highway? **Please check only THREE boxes.)**
- ❐ Increased safety (45)
- ❐ Reduced pollution (46)
- ❐ Reduced noise (47)
- ❐ More vehicles can travel on an automated lane (48)
- ❐ Fewer new highways will be needed (49)
- ❐ Other: specify____________________ (50)

9. After riding in the demo vehicle, what concerns you personally about vehicle automation technology? **(Please rank in descending order of concern, starting with the number "1" to indicate your greatest concern. Do not give the same number to more than one item. If an item is not of concern to you, leave it blank.)**

_____ Control of vehicles in emergency situations, e.g., debris on the road, tire failure, earthquake, etc. (51)
_____ Automated control hardware breaking down (52)
_____ Trusting computer technology to make the right decision (53)
_____ Other, specify: ______________________ (54)

10. What concerns you personally about vehicle automation usage in general? **(Please rank in descending order of concern, starting with the number "1" to indicate your greatest concern. Do not give the same number to more than one item. If an item is not of concern to you, leave it blank.)**

_____ More air pollution will result (55)
_____ It encourages greater use of personal vehicles (56)
_____ Giving up control of the vehicle to a computer (57)
_____ Possible government invasion of privacy (58)
_____ Other, specify: ______________________ (59)

11. Would you be willing to pay a toll charge to use an Automated Highway System?

❒-1 Yes ❒-2 No (60)

12. What toll charge would you expect to pay for a trip of approximately the same length as the demo ride?

________ DOLLARS ________ CENTS
(61-62) (63-64)

13. Which functions and features that you experienced today would you like to have on your own vehicle?

______________________________ (65-66)
______________________________ (67-68)
______________________________ (69-70)

14. As a result of the demo ride, how has your perception of automated vehicle and highway technologies changed? Has it become more positive, more negative, or has there been no change?

❒ Positive ❒ Negative ❒ No Change (71)

15. What percent of all your driving is on freeways **(Cannot be more than 100%)**

PERCENT: ______________________ (71-72-73)

16. What is your gender, please:

❒-1 Male ❒-2 Female (74)

17. And what is your age? ________________ (75)

18. Are you employed or are you retired?

❒-1 Employed ❒-2 Retired ❒-3 Neither (76)

19. Which type of organization do you work for (or did you work for before retirement)? **(Please check only one.)**

❒-1 Transportation industry
❒-2 Electronics industry
❒-3 Telecommunications industry
❒-4 Public sector, local or regional, state, or federal
❒-7 College/university or research company
❒-97 Other: specify______________________ (77)

20. As part of this study, we would like to conduct follow-up surveys. Please provide us with your name and home/work phone number.

Name (last name optional) ____________________
Work telephone number ____________________
Home telephone number ____________________
Fax number ____________________
E-mail address ____________________
Best time to call ____________________
Do you have any additional comments? ____________________
____
____

AHS DEMO – TEMPE ARIZONA
SURVEY RESULTS

- Demo was on a ½ mile test course at Arizona State University
- Magnets were installed in the pavement by ADOT personnel
- Three Buick LeSabres were shipped from California for the demonstration
- Preparation took three months
- Course layout and magnet installation took one week
- Trial runs and advance testing took one week.
- Over 200 people attended the two and-a-half day demo
- Cost of demonstration was roughly $20,000

- At the end of the ride each participant was asked to complete a 10 minute survey
- 179 surveys returned

- 96% of the respondents concurred that the ride felt safe
- Less than 5% felt the ride was not smooth, acceleration was too sudden, deceleration was too sudden, the display was difficult to use, or the audio was not pleasant.
- After taking the demo ride, 93% said they would like to use automated vehicle and highway technologies.

When asked what driving situation would they use if for:

86% long trips
71% rural freeways
65% urban freeways
58% driving at night or in fog
55% commute trips
6% driving on surface streets

When asked the most important benefits:

75% reduced stress
69% reduced travel time
69% makes the driving task easier
56% do other things wile traveling
7% increased privacy

When asked the three most important benefits:

94% selected Increased safety
80% selected more vehicles per lane
51% selected reduced pollution
47% selected fewer new highways will need to be built
6% selected reduced noise

Slightly more people were worried about control of vehicles in an emergency than about hardware breaking down or about trusting technology to make the right decision.

When asked what concerns people personally:

- 62% included giving up control of the vehicle to a computer
- 50% included that it encourages greater use of personal vehicles
- 44% included possible government invasion of privacy
- 37% included more air pollution

When asked if they were willing to pay a toll charge to use an automated highway, 70% said they would.

As a result of the demo ride, 82% of respondents said their perception of automated vehicle and highway technologies had become more positive. 17% was unchanged, and only 1 person was more negative.

Gender of respondents

- 79% male
- 21% female

90% of respondents were currently employed

Type of organization

- 39% public sector, local or regional, state, or federal
- 37% transportation industry
- 18% college/university
- 4% electronics industry
- 1% telecommunications industry

APPENDIX E

SUMMARY REPORT OF

SIX MAGNET TEST SITE INSPECTIONS

*   *   *   *

SIX MONTHS AFTER INSTALLATION

JULY 1998

IVI / SNOWPLOW GUIDANCE
RESEARCH PROJECT No. 473

MEMORANDUM

DATE: July 28, 1998
TO: File
FROM: Steve Owen
SUBJECT: **MAGNET TEST SITE INSPECTIONS**

With the help of the Kingman, Flagstaff and Holbrook Districts, the ATRC carried out a formal inspection on July 14th of the six magnet test sites along the I-40 Corridor.

The inspections were initiated at 7 AM west of Seligman, and were completed at Holbrook by 2 PM. Weather was clear, and temperatures ranged from 60 degrees at 7 AM to 90-plus degrees by 2 PM.

Test Site Location	**Milepost**	**Direction**	**Pavement**	**Hot RPM Adhesive (Black)**	**3m Loop Sealant (Gray)**	**Silicone Sealant (Tan)**
Anvil Rock	110 - I-40	WB	Asphalt	7	7	N/A
Seligman	121 - I-40	EB	Asphalt	8	8	N/A
Garland Prairie	168 - I-40	EB	Asphalt	N/A	9	7
Flagstaff	202.2 – US 66	EB	Concrete	4	5	3
Winslow	249 - I-40	EB	Asphalt	8	8	N/A
Holbrook	279 - I-40	EB	Asphalt	8	8	N/A
Totals				35	43	10

<u>General Results -</u>

In all cases the magnets were still in place in the drilled holes. The condition of the sealant varied with the location and with the pavement temperature, as described below.

In all cases, after six months there was no significant chipping, spalling or cracking visible in the pavement where the drilling had been done.

<u>Results By Site -</u>

- MP 110 WB – All of the RPM sealant was intact, but somewhat soft and spongy. Some RPM seals showed a quantity of silica sand on and in the seal material. Most of the gray 3M loop sealant was firm to the touch, but two holes were somewhat spongy.
- MP 121 EB - All of the RPM sealant was intact, but soft. The 3M sealant was intact, and all but one was firm to the touch.
- MP 168 EB - All of the gray 3M sealant was intact, and solid. All of the tan silicone sealant was also intact and solid.

- MP 202.2 - All of the 3M loop sealant was intact and solid. All of the RPM adhesive was very soft, and some tearing was evident on two of the holes. The silicone sealant had been previously observed to have formed a skin rather than a seal; those skins had failed and had filled with cinders.

- MP 249 EB - All of the 3M loop sealant was intact and solid. All of the RPM sealant was intact, but very soft and sticky from the heat.

- MP 279 EB - All of the 3M loop sealant was intact and solid. All of the RPM sealant was intact, but very soft and sticky from the heat.

Conclusions & Recommendations -

- **Hot RPM Adhesive** - This material when heated flows well around the magnets to seal them in place. It was quick to cure firmly in cold weather, but in hot weather it has become very soft and sticky. This could lead to traffic damage. It also requires a dedicated truck to properly place the material, and needs special care and precision to avoid over-filling the small magnet holes. It therefore is suitable but will have long-term stability concerns.

- **3M Loop Sealant** - This material was slow to cure in cold weather but it did cure solid eventually. The sealant forms a firm cap over the magnet even in hot weather. The installers say it does flow well and seals the magnets effectively, and it is easy to apply small quantities with a caulking gun. This material should have less waste during installation. It may be somewhat more expensive than the hot sealant, but the labor and equipment needed are less. Based on the inspections, this material appears to be the most suitable and the most efficient.

- **Silicone Sealant** - This material was not available in sufficient quantities for valid testing. It performed well on I-40 at Garland Prairie, but it failed at the only other site tested, on Old US 66 in concrete. It may be that existing fine cracking in the concrete allowed the material to bleed out. The characteristics of the concrete, poor cleaning of the holes, and expired product life also may have degraded the seals. It appears that not enough was learned about this material to support its use in large-scale installations.

This testing program for magnets and installation materials has, after six months, produced fairly clear results. There are some problems at individual sites that may be due to weather conditions during the installation, as well as to the crew's learning curve for the installation process. Also, the installers noted difficulties with some of the materials including expired shelf life dates and related workability problems.

Effective training can minimize these problems, as well as using fresh material, and installing in better weather. Overall, the magnets are all intact and the pavement remains sound after six months. There should be no physical result of these tests that would prevent ADOT from proceeding to the full-scale installation at the US 180 test site.

Acknowledgements -

All of the lane closures were set by the local maintenance forces without any problems or delays, in a very professional manner, and the coordination between the supervisors and their teams worked out very well. This includes Bruce Mejia, Kenny Brooks, Jack Gray, Frances McCauley and their crews, and also the three District Engineers who committed their support to complete this activity.

The desired information was obtained safely and efficiently. The ATRC is very grateful to all those who took part in this inspection program.

APPENDIX F

SUMMARY REPORT

US 180 MAGNET INSTALLATION

SEPTEMBER 1998

SPR – 473
MAGNET INSTALLATION PROJECT
US 180 – KENDRICK PARK
MP 235 – 238

FINAL RESULTS: 8 OCTOBER 1998

Progress Rates - The work was carried out by a nominal twelve-man crew over 15 days on a 10-hour shift basis (6 AM to 4:30 PM). Work started on September 14 and ended on October 7. The work was originally planned to take three weeks. One day was spent in setting up the equipment and testing the drills, other equipment, and methods. Only one day was actually rained out. Effective work days in the field, therefore, were roughly 13 work days.

Effective crew size was variable due to manning of traffic control, absences, equipment breakdowns, and catching up of the magnet installations. Each day, either 3 or 4 drills were kept running continually, and notes indicate roughly 45 drill-days were required to complete the work. On that basis, the daily average per drill was 123 holes. The best full day, however, was Monday, October 5th, with an average of 155 holes per drill.

Results were extremely variable from day to day and from drill to drill. On the last day, crews drilled an average of 85 holes in only 5 hours, and earlier some crews had reported 200 holes in a day. However, on September 27 the average for four drills was only 70 holes in one area of thick pavement with asphalt-rubber layered in it.

Equipment - The drills were the key to the progress of this project. The decision to use electric, water-cooled coredrills was made to achieve the best accuracy and hole consistency, based on tolerances and standards for installation of the magnets. Other alternatives were light electric hammer-drills or pneumatic rock drills such as used in blasting or mining applications. Problems of accuracy and availability ruled these out. As it was, the drill vendor (Prime Equipment of Flagstaff) was very cooperative in sourcing and servicing these drills during the project. They also assisted in ordering special adapters and custom coring bits (from Target Saw) for asphalt pavement. When the asphalt rubber problem arose, those two companies provided field service to the project.

Safety - The 3 mile long work zone for this project required two separate lane closures for part of the work. There were also side roads, businesses and picnic areas within the project limits. It was not effective to use ADOT magnet team members for flagging, and most of the work had to be conducted using outside traffic control personnel. In the northwest end of the site where 8 percent grades exist, it was necessary to use a pilot car to ensure safe conditions for the survey, drilling and magnet activites.

Methods - This was a very labor intensive operation. There are numerous steps of surveying, laying out and painting the individual holes, of the slow drilling and cleanout process, and in the laborious on-the-pavement work of aligning, bedding and sealing the magnets. It is clear to all team members that creative methods will be needed in the future to make this a practical technology for rural highways. In fact, there was a lot of creativity developed during this project, including -

- Heating of drill bits in generator exhaust pipes to release the jammed asphalt cores -
- Use of soda straws to blow out excess silica sand used to bed the magnets on line and grade -
- Use of a wheeled work platform for moving down the line of holes to set and seal magnets (possibly perceived by passing motorists to resemble a skateboard)

Costs - The expenditures committed for this project are not yet all reported. Materials and equipment expenditures are fairly well defined; the subsistence and travel costs for the volunteer installers are still being determined. Most of the installation labor was carried as district maintenance activity, as determined by the three District Engineers who are the core TAC members for the project. Some supporting labor is charged to the project including some supervision, traffic control (sub) and district surveying. More critically, the northern districts did not have resources at this time to carry out the control survey, which had to be done by on-call Entranco forces. As with California's experiences, surveying and layout are major cost elements for this concept.

Conclusions - This activity as performed may be seen as less than efficient, casting some doubts on the practicality of this technology for rural highways. However, the project as planned was very successful. The spirit of research lies in starting from a given level of feasibility and then making progress from there. The goals of this intelligent vehicle research are to develop practical, durable systems and to refine them in order to slash their costs. The testing to be done on this type of infrastructure project will enable future systems to be developed with fewer magnets at greater spacing, and with fully redundant technologies such as GPS. As a result, the in-the-road component of the system may be drastically reduced.

Credits - The magnet installation phase of this project was a very complex activity that required a major effort from the Flagstaff, Kingman and Holbrook Districts as well as the ATRC and ADOT Procurement. The maintenance engineers and supervisors, and their staffs carried the load of organizing the volunteers and alternates as well as vehicles and other equipment. Flagstaff also provided additional core support in such areas as lining up the drills, traffic control and install materials, and in coordinating local lodging and travel details for some of the install team. All of the Orgs that participated deserve credit for providing the volunteer installers, and also for covering their tasks during the four week project.

Finally, the volunteers on the magnet installation team deserve a great deal of credit. All of the tasks - surveying, layout, drilling and setting of magnets - became both tedious and backbreaking long before the 5,420th repetition. Altohugh there were differences of opinion on details, the crew from three Districts and at least ten Orgs worked very well together. It was a good opportunity for a special project to cross district boundaries, and I was impressed by the positive attitudes and teamwork throughout the operation.

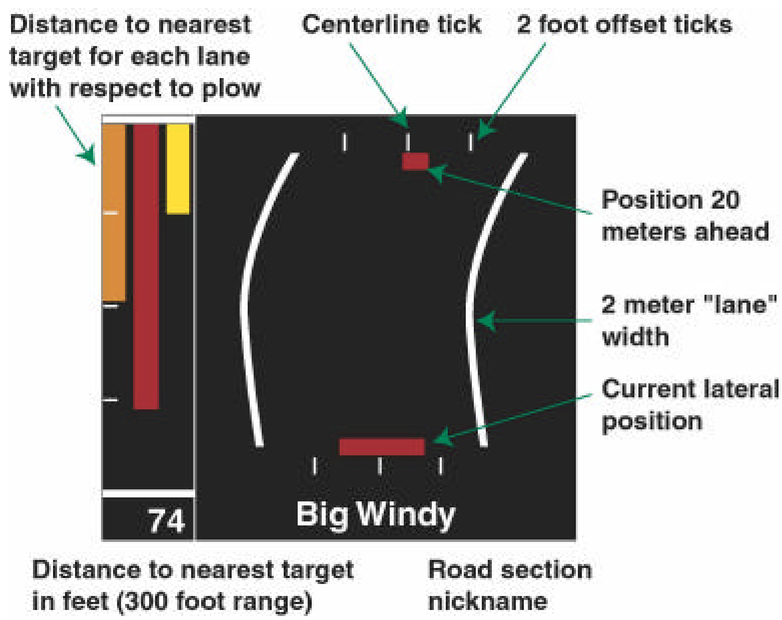
APPENDIX G

OPERATOR INSTRUCTION SHEET

ASP-II - FEBRUARY 2000

ASP Driver Instructions for HMI

Winter 1999-2000



In all cases, driving normally is preferred to driving from the display.

Only use the system for the following two scenarios:
1) As a driving aid during low visibility, low-speed conditions
2) As a reference tool for lane positioning

Lateral component (right hand part of the display)
- Make corrections using prediction marker (top rectangle). When you drive normally you look out in front of your vehicle, not down through the floorboards.
- Move the predictor to your desired lane position and keep it there, the current position marker will move over slowly.
- With experience you should only need to glance at the display. Try not to stare too long at the display.
- When driving in a low visibility condition, reduce speed considerably (preferably below 15 mph).

Color coding for lateral component only:
- Red & White = high trust for lane position
- Yellow = reference with caution
- Gray = not reading magnets (recent), points to magnet lane
- No road display = not reading magnets

Forward collision component (left hand part of the display)
- The radar sensors do not detect everything and will usually not detect people or animals.
- Look out your window whenever possible.
- Independent of lateral component and will work when you are not over the magnets.
- Each bar shows the closest target in the left, center, and right lanes with respect to the plow.
- The range of this display is 300 feet.
- Bar colors will change as target gets closer.
- The distance of the closest of the three targets is shown in numbers at the bottom (in feet).
- There are blind spots to the left and right of the plow.

APPENDIX H

OPERATOR EVALUATION FORMS

ASP-I / ASP-II

Advanced Snowplow Evaluation Questionnaire
ASP2 - 1999/2000

We would like to ask you some questions regarding your opinion of the driver assist system. We will not be recording your identity and this information will not associated with you or be used as a means of evaluating your performance. We are only interested in evaluating the system. We may share this with Caltrans/Arizona DOT.

Your participation is voluntary. You are free to refuse to take part. You may refuse to answer any question and may stop taking part in the study at any time. Whether or not you participate in this research will haveno bearing on your standing in your job.

How long have you been driving snowplows? ______________

How much time have you logged on the Advanced Snowplow? ______________

Did you experience this system last winter? Yes No (If "No" skip to Question 2)

For the following questions, please circle the number of your choice:

1) Is the system better than last year?

(Not at all) 1 2 3 4 5 (A lot)

2) How easy is the system to use overall?

(Not easy at all) 1 2 3 4 5 (Very easy)

3) How much do you like the system overall?

(Not at all) 1 2 3 4 5 (A lot)

4) If you had more time to practice with the system, would you like it more?

(No) 1 2 3 4 5 (Yes)

5) Please rate the potential of the system to improve your safety:

(Not at all) 1 2 3 4 5 (A lot)

6) Please rate the potential of the system to improve your efficiency:

(Not at all) 1 2 3 4 5 (A lot)

Please answer the questions on the back/next page.

For each *component* (Collision Warning, Lane Keeping):

Collision Warning
How easy is this component to use?

(Not easy at all) 1 2 3 4 5 (Very easy) (Not easy at all) 1 2 3 4 5 (Easy)

How much do you like this component?

(Not at all) 1 2 3 4 5 (A lot)

Comments:

Lane Keeping
How easy is this component to use?

How much do you like this component?

(Not at all) 1 2 3 4 5 (A lot)

Comments:

How long do you think you would need to become comfortable with this system?

Please draw or describe what you feel would be an ideal display:

US 180 SNOWPLOW TESTING RECORD / OPERATOR EVALUATION

Site: US 180 – MP 235.0 -→ 238.0 (Kendrick Park Test Lane)

Date: _______________**Time Start:**_____________ **Time End:**________________

Name: _____________ **Org No:**________________ **Org Name:**________________

* * *SITE CONDITIONS DURING TESTING* * *

	235.0 – 235.5 NB	235.5 – 237.0 NB	237.0 – 238.0 NB	238.0 – 237.0 SB - Return
CONDITIONS (check all that apply)	Hart Prairie	Kendrick Park	Steep Downgrade	Steep Upgrade
Wind (Speeds?)				
Snow Falling				
Sunny				
Cloudy				
Dark				
VISIBILITY				
Zero				
50 feet				
100				
200				
300				
Over 300 feet				
ROAD COVER				
Snowpack / Ice				
Slush				
Clear				
ACTIVITY				
Plowing				
Sanding				
Dry Test Run				

Operator's Background:
Years of Snowplow Experience: _________Hours on the Test Plow: _____________

Satisfaction with Caltrans Driver-Assistance Systems (10 – best, 1- worst):
1 to 10 Scale - Ease of Use of Automated Systems: ___________________
1 to 10 Scale - Potential to Improve YOUR Safety: ___________________
1 to 10 Scale - Potential to Improve Your Efficiency: ___________________
Lane Position Indicator:
Did this feature Increase your level of safety ?? ___________________
How often did you look at the display screen? ___________________
Lane Departure Warning:
Did this feature Increase your level of safety ?? ___________________
Collision Warning System:
Did this feature Increase your level of safety ?? ___________________
Displays / Warnings:
Were these features clear and easy to understand? ___________________
Did the system provide enough information to be useful?___________________
Was the system response fast enough to be useful? ___________________
*Comments and Recommendations (please use back of page):

1. Were there any system problems when you were operating the vehicle? (Describe):
2. Did the system ever lead you to make a wrong maneuver or error in judgment?
3. What suggestions would you make to improve any feature's usefulness to you?

APPENDIX I

DRAFT COOPERATIVE MEASURES OF EFFECTIVENESS

FOR GUIDANCE SYSTEMS

*   *   *   *

A CALIFORNIA / MINNESOTA JOINT EFFORT

DRAFT COOPERATIVE MEASURES OF EFFECTIVENESS

This Draft Cooperative Measures Of Effectiveness (MOE) document is a living document, and will evolve over time through further cooperative efforts between the California and Minnesota research teams.

Measure of Effectiveness (MOE)

1. Safety

The snowplow guidance system is intended to improve safety and operational efficiency. The snowplow guidance system must not compromise safe operation of the plow, nor should unavailability of the system compromise safety.

Failure or fault in the snowplow guidance system should not induce any instructed unsafe operation of the snowplow. ***Failure*** in the snowplow guidance system can include intermittent or permanent failures of sensing, processing, information transmission between components, or information/warning displays. System ***faults*** during the snowplow operation can include those that are induced by failures in the system or components, or environment interference such as weather, roadside, and road surface conditions.

An ***instructed unsafe operation*** for the snowplow guidance system refers to maneuvers that are instructed by the guidance system but are incorrect and/or hazardous. Missing detection of forward obstacles is a special case of fault and deserves special attention.

Safety of the system needs to be verified or validated through safety analysis. At a minimum, a Fault Tree Analysis (FTA) needs to be performed to investigate all possible failures and faults and the consequences.

2. Operator Performance

System effectiveness is related to the ability of the operator to take advantage of the system *features*, some of which can provide help beyond simple guidance. Proper accounting of such elements is necessary, especially for those that have direct impact on other measures.

There are a variety of human factors related metrics that can be valuable as measures of effectiveness. Substantial care should be taken to eliminate biases due to road geometry, weather, and speed, as these all can have significant impacts on system performance. However, it will be important to record how the chosen metrics are affected by such environmental conditions.

Perhaps the simplest measure of operator performance is *Unintended Lane Excursions per Unit Distance.* The main goal of these systems is to keep the snowplow safely within the target lateral range. Thus, it is necessary to measure excursions from this range. Intentional excursions are usually characterized by slow, consistent steering wheel motions; corrections for unintended excursions usually occur quickly after the excursion. Measuring departures from the range can be filtered by a standard description of steering wheel behavior to discriminate between intentional and unintentional excursions.

The system should be easy to use. Thus, metrics of *mental workload* are valuable. For example, high steering variability implies that the system requires higher levels of mental workload and, therefore, is harder to use. For systems that use strictly visual displays, measuring visual demand is another technique. Using shutter glasses or some analogous method, it is possible to determine the visual attention required to use the system. Lower amounts of visual demand signify an easier to use system with more free visual capacity to check for improved visibility, potential obstacles, and dashboard information.

The system should permit easy and quick *Acquisition of the Target Range* when a plow enters the target area. For example, if a plow departed the instrumented target area for an amount of time beyond a minor excursion and then regained the instrumented area, what was length of the period that the driver spent aligning to the desired path from the point where the plow entered the target range?

3. Availability

The snowplow guidance system will improve the availability of the snowplow for severe operating condition. Therefore, it should work on all roads for which snowplows are designed, including flat or mountainous, as well as straight or winding roads, with asphalt or concrete surface. The effectiveness of the snowplow guidance system will also be measured based on its availability under a variety of weather, road surface, and visibility conditions.

To verify the availability of a snowplow guidance system, analysis and, if necessary, field tests must be conducted to gain knowledge about its availability under relevant operating conditions and environments.

4. Reliability

The reliability of snowplow guidance system is measured by ***Mean Time Between Failures (MTBF)***. Failures here refer to both physical breakdown of the system or components and faults due to environmental interference.

Failures and fault should be recorded separately for vehicle and infrastructure elements in order to assess the reliability of the system. For vehicle element damage, care should be taken to describe how non-system induced failures occur. An example would be system hardware damaged by broken vehicle components or impact forces (e.g., from plow blades striking road surface imperfections).

5. Maintainability

The maintainability of snowplow guidance system should be measured by the ***frequency*** of and ***time*** required for regular maintenance that is needed in order to support normal operation, and ***Mean Time To Restore (MTTR)***.

The maintenance of both vehicle and infrastructure elements should be documented.

6. Cost

The cost of the snowplow guidance system needs to include the following cost elements:

a. On-vehicle instrumentation, including cost of components and labor for installation.

b. Roadway instrumentation, including initial cost and replacement cost. This would include roadway infrastructure additions, roadside components, and vehicle-to-roadside communications links.

c. Maintenance, including cost of labor and parts and time required for lane closures due to maintenance.

7. Potential for extended applications

Shared applications of the infrastructure or vehicle components can improve the cost effectiveness of the system.