Arizona Intelligent Vehicle Research Program - Phase Two(b): 2001 - 2002

Final Report 473(3)

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16. Abstract –
This report covers Phase Two(b) of a long-term in-house advanced vehicle research program of the Arizona Department of Transportation (ADOT) and its Arizona Transportation Research Center (ATRC). The focus of the research evolved early to winter maintenance topics. Phase Two(b), this fourth year of the program, addresses the 2001-02 winter season.

ADOT's Phase One snowplow research (1997-2000) was a joint effort with California to field test the Caltrans advanced snowplow (ASP) in Arizona conditions. ADOT crews evaluated the Caltrans ASP lane-guidance system in four-week test cycles for two consecutive winters at a six-mile test loop of embedded roadway magnets near Flagstaff.

ADOT's key goal In Phase Two (2000-01) was to acquire and test its own snowplow driver-assistance system. ADOT procured a 3M Lane Awareness System, with 5 miles of 3M magnetic striping tape to develop a second field site. Testing also continued with Caltrans to compare both lane guidance systems in similar conditions, however, system problems with both concept snowplows severely reduced the ability of ADOT and its partners to effectively evaluate either concept.

In this current Phase Two(b), the 2001-02 winter, ADOT's testing and evaluation could proceed as the system problems of the previous winter had been resolved. The goals were based on same-day training for ADOT drivers with both advanced snowplow systems. However, the side-by-side operational testing of the Caltrans and 3M systems was limited by a total lack of snowfall in the Flagstaff area during the five weeks that the Caltrans RoadView™ plow was in Arizona. The Caltrans RoadView team did conduct night testing with ADOT drivers so that their performance could be monitored and evaluated

ADOT's own evaluation effort experienced only a few major storms all winter; and the ADOT-3M plow operated effectively in these storms. Overall, both systems showed their effectiveness and reliability in 2001-02, but the weather provided few opportunities to document the key advantages for either system. By this point in the program, after four winters of field tests, it had also become clear to the project sponsors that the current cost of either system was prohibitive for Arizona. As a result, it was decided to shift the future research focus in 2002-03 (Phase Three) from roadway-based guidance systems to commercial on-board driver-warning systems.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: Volumes greater than 1000L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000lb)	0.907	megagrams (or "metric ton")	mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE AND PRESSURE OR STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (or "metric ton")	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS		
N	Newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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TERMS, ACRONYMS AND ABBREVIATIONS

TERM	DEFINITION
3M	The 3M Company (originally Minnesota Mining & Manufacturing)
ADOT	Arizona Department of Transportation
AHMCT	Advanced Highway Maintenance & Construction Technology (AHMCT Research Center at UC Davis – Core Contractor for RoadView ASP)
AHS	Automated Highway Systems
ASP	Generic term for advanced snowplow (since Caltrans evolved to RoadView ASP)
ASP-I	Advanced Snowplow, Phase I (Caltrans 1998-99)
ASP-II	Advanced Snowplow, Phase II (Caltrans 1999-2000)
ATRC	Arizona Transportation Research Center – ADOT (at Phoenix)
AVL	Automatic Vehicle Location
Caltrans	California Department of Transportation
CWS	Collision Warning System
DGPS	Differential Global Positioning System
District	ADOT Maintenance & Construction Districts
DOT	Department of Transportation
DPS	Department of Public Safety (Arizona Highway Patrol)
DVI	Driver-Vehicle Interface
GPS	Global Positioning System
HMI	Human-Machine Interface
HUD	Head-Up Display
I-17	Interstate 17 (in north-central Arizona)
I-40	Interstate 40 (in northern Arizona)
I-80	Interstate 80 (in northern California)
ITS	Intelligent Transportation Systems
IV / IVI	Intelligent Vehicle / Intelligent Vehicle Initiative
LAS	Lane Awareness System (3M)
LCD	Liquid Crystal Display
MP	Milepost
NAHSC	National Automated Highway Systems Consortium
NAU	Northern Arizona University (at Flagstaff)
ORG	ADOT Sub-District Level Maintenance Camp / Yard / Organization
PATH	Partners for Advanced Transit and Highways (Core Contractor for Caltrans RoadView ASP - at UC Berkeley)
RF	Radio Frequency
RoadView™	2000-2002 Evolution of the Caltrans Advanced Snowplow (ASP)
SR 87	Arizona State Route 87 (southwest of Winslow)
UCB	University of California at Berkeley
UCD	University of California at Davis
U of I	University of Iowa (at Iowa City)
US 89	US Highway 89 (northeast of Flagstaff)
US 180	US Highway 180 (northwest of Flagstaff)

I. EXECUTIVE SUMMARY

Figure 1: Winter Storms Close the Interstate 40 Corridor

INTRODUCTION

This report summarizes Phase Two(b) of a long-term Intelligent Transportation Systems (ITS) research program by the Arizona Department of Transportation (ADOT) to study cooperative infrastructure-based guidance technologies and vehicle systems. The Arizona Transportation Research Center (ATRC) in Phoenix is conducting this research as an ADOT in-house effort.

The current Phase Two(b) of Arizona's advanced-vehicle research is Year Four of this program, the 2001-02 winter. During this phase of the project, the ADOT research team conducted side-by-side evaluations of two infrastructure-based vehicle lane guidance systems. 3M Company had already developed one of these systems commercially, and the other was under development through a program sponsored and led by Caltrans, the California Department of Transportation.

BACKGROUND TO PHASE TWO(B)

Phase One of the ADOT Intelligent Vehicle Research Program (1997-2000) began with Arizona demonstrations of Intelligent Vehicle (IV) and Automated Highway System (AHS) concepts. It soon became clear to ADOT that the most practical near-term application of IV technology for a state highway agency would be in the challenging field of winter maintenance operations, and this project evolved toward the "specialty vehicles" research arena.

Phase One was a joint partnership with Caltrans to field test its prototype Advanced Snowplow (ASP-I and ASP-II) in Arizona. Relieved from developing an advanced research snowplow on their own, the ATRC's research team instead constructed a six-mile magnet test loop at Kendrick Park on US 180 northwest of Flagstaff. This Arizona test site enabled Caltrans to diversify its research experience under different conditions and with a second discrete pool of plow operators.

During the two winters of the Phase One research program, the ADOT snowplow crews trained on and evaluated the prototype Caltrans lane-guidance system in month-long test cycles.

In Phase Two (2000-01) of the project, the ADOT project team set a new key goal. The Caltrans ASP, now evolved into the RoadView^{TM} advanced snowplow, was available to Arizona for only a few weeks each winter. This was not sufficient for a thorough evaluation of the ASP system or its secondary components. The key 2000-01 project goal was to equip an ADOT snowplow with a roadway-based driver-assistance system for long-term testing in Arizona.

At that point, the Caltrans program did not have the staff resources to assemble another ASP system, or to provide support for operations outside of California. Also, the Caltrans RoadView plow was very much a developmental prototype and many key components were not packaged systems, but were unique or even hand-built.

Other options were needed, and in late 2000, ATRC and ADOT's Flagstaff District procured a 3M Lane Awareness System (LAS) with five miles of magnetic striping tape. This 3M tape was installed between layers of asphalt pavement in a reconstruction project on US 89 northeast of Flagstaff at Sunset Crater, as a test site for the new ADOT-3M advanced snowplow. This new ASP was also equipped with a collision warning radar system, for comparison with RoadView.

ADOT continued its long-term evaluation program with Caltrans in Phase Two, with a new goal of comparing both guidance systems in similar weather and road conditions. Both the Caltrans and the 3M concepts were developed as low-visibility, low-speed driver-assistance systems. Northern Arizona University joined ATRC's project team in 2000 to provide neutral Phase Two evaluations, while 3M funded a separate study in Arizona by the University of Iowa (U of I).

WINTER 2001-02: PHASE TWO(B) RESEARCH

This Phase Two(b) project report addresses 2001-02, the second and final winter season of the ADOT side-by-side evaluation program for snowplow lane guidance systems. Testing during the previous winter had been seriously compromised by a combination of technical issues for both of the advanced snowplow systems, so that only limited results were achieved.

The research efforts for this fourth year of ADOT's IV research program were focused on a more thorough and complete evaluation of the two roadway-based, near-zero-visibility ASP systems. The ATRC's fundamental goal was to determine with confidence the key factors for successful implementation of these two ASP lane guidance systems for rural states such as Arizona, and to determine the state of development, effectiveness, flexibility, and reliability of each.

Winter 2001-02: Research Plan

With two test sites on either side of the San Francisco Peaks, and all systems fully functional, the project's ambitious back-to-back ASP evaluation plan could at last be implemented for 2001-02. ATRC prepared a workplan to test the Caltrans and 3M systems side-by-side for a second season.

The Arizona plan was patterned on the Caltrans evaluation program, as carried out each winter by their site team of technical and human factors specialists. Caltrans used driver surveys and interviews to assess perceptions of the system and its components, after limited instruction and test runs at the roadway magnet site. The Caltrans evaluation team also planned to use on-board data recording, as well as project staff ride-alongs during any major winter storm operations.

The Arizona evaluation emphasis differed from the RoadView test program in California, which focused on a few key drivers assigned to the ASP on I-80's Donner Summit. The ATRC's goal was to provide information on advanced snowplow concepts to the regional maintenance forces. ADOT Team Leader drivers were assigned to both project snowplows each winter, to conduct introductory training for other operators from the northern Arizona districts. This plan produced a large number of evaluations from a diverse pool of ADOT drivers, but only the designated Team Leader operators gained extensive experience with either ASP snowplow.

The most challenging aspect of ADOT's operator training and evaluation plan was the back-to-back approach to bring in drivers from distant maintenance yards for training on both snowplows in a single day. This plan was feasible because the Caltrans magnet site and the 3M tape site were only about 30 miles apart, roughly a 45-minute drive through Flagstaff.

Winter 2001-02: Training & Evaluation Activities

The two advanced snowplows were both fully functional for the 2001-02 winter season, as the previous year's problems were resolved. As a result, the training program was a success. For the Caltrans plow, with their full project team on hand, a total of 27 ADOT snowplow operators were introduced to the RoadView ASP system. In comparison, 18 of these operators were also trained on the 3M LAS system at the US 89 test site, in most cases on the same day.

Local operational constraints were a factor in training on the ADOT-3M snowplow. Caltrans had staff at the site to support ADOT's Team Leader drivers, and the RoadView ASP initially was dedicated to training. On the ADOT-3M side, the only trainers available were the local Team Leaders, by turns. Also, this plow was sometimes called out for maintenance activities on the highway. Due to these conflicts, a few drivers were trained on this ASP at other times.

The focus was a side-by-side evaluation of two different ASP systems with similar concepts and goals. Driver training on one system in the morning and on another the same afternoon produced informed preference rankings and comparative comments in debriefing surveys and interviews. This approach was valid, although many operators had only brief exposure to each system.

After an initial briefing, drivers made one or two runs in 30 to 45 minutes at each test site with an ADOT Team Leader or with Caltrans project staff. This was sufficient time for the experienced ADOT drivers to develop their responses to the "preference" questions on the survey, and to also provide numerous comments and suggestions for improvements to both systems.

Another key activity was the RoadView impaired-vision test. As it became apparent that no major storms would occur during the Arizona site activities, the Caltrans team developed a "no-snow" ride-along evaluation plan for night performance testing on US 180. The late evening and nighttime effort, during the last three days of the evaluation, developed significant data on driver adaptation to the guidance system. The data included radar performance, progression of steering and tracking accuracy, and mean speed for multiple runs over the test course with three ADOT drivers of different experience levels.

Winter 2001-02: Operational Activities

The project's Phase Two(b) winter was a disappointment with regard to operations. The two project snowplows were fully operational, but it was an unusually mild and dry winter, with less than half the normal snowfall for Flagstaff. In fact, no measurable snow fell during the entire five weeks that the Caltrans ASP was in Arizona. The ADOT-3M plow was used in a series of moderate storms early in the season, when it was operated successfully on at least eleven dates between November and March when snow fell in recordable quantities.

WINTER 2001-02: RESULTS

The Phase Two(b) winter was the second full season of operations and training for the dedicated ADOT-3M snowplow, fulfilling the fundamental mandate for the research project. This was also the fourth winter of the Caltrans RoadView snowplow partnership activities, demonstrating the long-term potential for the concept as it became more reliable and robust for each winter season.

For Caltrans, the training results were positive, with significant data developed from both the on-board instrumentation and from the operator feedback of the surveys, interviews and ride-alongs. However, operational deployment in storms was impossible, due to the mild weather during the limited Arizona test period.

For the ADOT-3M snowplow, testing and operations with the tape-based guidance system were spread over the full winter. Operational results were positive despite the limited number of storms that occurred. Drivers had no significant problems with the on-board components through the winter. Their level of confidence was good for both the guidance and warning radar systems.

ADOT ASP PROJECT RESULTS: 1997-2002

The most basic result of four winters of ADOT's snowplow research is the confirmation that both Caltrans and 3M have successfully developed effective and reliable advanced snowplow lane guidance systems that, if deployed, would provide significant benefits in Arizona for winter maintenance operations in extreme storm conditions.

For this research program to date, however, the variable weather and the equipment and roadway problems have repeatedly constrained a clear identification of potential benefits. At the present time, commercial ASP system sourcing and cost issues preclude any clear determination of the relative value of each of these infrastructure-based guidance systems for a wider deployment.

FUTURE PROGRAM DIRECTION

After four winters it was clear to the project sponsors that the cost of either lane guidance system was prohibitive for ADOT. In early 2002, the project objectives were further revised. The new focus for 2002-03 will be on driver warning systems to plow more safely when blowing snow impairs vision, rather than to forge ahead in near-zero-visibility, white-out storm conditions.

The Year Five research will evaluate commercial on-board warning systems in limited-visibility storm conditions. Collision warning radar systems (CWS) and passive-infrared (IR) night vision cameras have been selected for field testing. The number of on-board units and test areas across northern Arizona will also be increased, allowing ADOT's Holbrook and Kingman Districts to participate in the research program on an equal basis with the Flagstaff District for the first time.

II. PROJECT BACKGROUND

For travelers crossing Arizona in winter, long-held images of arid desert terrain, cacti and climate can be quickly shattered as major snowstorms often blanket the high country from early October into April. Today, long-haul transport market conditions, economic factors, and driver mobility expectations all constantly raise the bar for those who struggle to keep the state's highway routes open through the long winter storm season. As described in later sections, the cost impacts of winter storm-related crashes in Arizona are very high.

Figure 2. Arizona's Interstate Routes are Critical to Commerce and Travel

Across the state, the Arizona Department of Transportation (ADOT) maintains a fleet of more than 240 snowplows to patrol and clear nearly 4,000 miles of designated plow route corridors in the 6,200-plus miles of the state's highway system. In the past several years, this Intelligent Vehicle Research Project, conducted by the Arizona Transportation Research Center (ATRC), has demonstrated and evaluated new concepts with significant potential benefits for snowplow operators and highway agencies in many rural states such as Arizona.

PRIOR RESEARCH PHASES

Phase One of this ADOT research project, from 1997 to 2000, grew from Federally-sponsored efforts to demonstrate advanced vehicle control concepts and to stimulate further development. A variety of Phase One research efforts by ADOT included local demonstrations of Advanced Highway Systems (AHS) and Intelligent Vehicle (IV) concepts as potential solutions for urban and rural highway congestion and air quality problems in Arizona.

In the near term, impaired visibility problems in winter storms soon led ADOT to focus this IV research on improved safety for both snowplow operators and the public. A partnership with California was begun in 1998 to test the Caltrans magnet-guided Advanced Snowplow (ASP) in

Arizona. This also leveraged the limited ATRC research budget for meaningful ASP evaluations on ADOT's highways. This project installed six miles of magnetic roadway infrastructure near Flagstaff in Phase One, and conducted ASP testing over two winter seasons.

ADOT's partnership with Caltrans was quite successful, but was limited by the developmental status of the ASP system and by erratic winter weather. The Caltrans ASP, which had evolved into the RoadView™ advanced snowplow by mid-2000, was available to Arizona for only a few weeks each winter. This restriction allowed only limited testing, with limited results.

For Phase Two (2000-01), ADOT expanded the project to gain more hands-on experience than the Caltrans partnership could provide. It was decided to add a lane guidance system to an existing ADOT snowplow for expanded winter testing in Arizona. However, the RoadView program was not able to support a new ASP outside of California. ADOT then acquired and evaluated the 3M Company's magnetic tape-based Lane Awareness System (LAS) alongside the Caltrans ASP, but technical issues with both systems hampered this program in 2000-01.

PHASE TWO(B) RESEARCH REPORT OUTLINE

This project report describes the recently concluded Phase Two(b) of Arizona's Intelligent Vehicle research program, which continued and evolved from the two previous project phases. Phase Two(b) was Year Four (2001-02) of the ATRC's long-term project to evaluate and compare state-of-the-art advanced snowplow systems in Arizona.

Early chapters of this report provide a background on the two earlier phases of the research. Then the report describes the site magnetic infrastructure, the on-board system components, the ADOT research plan, and the results and conclusions for each low-visibility guidance concept. The final chapters of the report review the goals and challenges of the Phase Two(b) research program for the 2001-2002 winter, the project's results and conclusions, and the project team's recommendations for further snowplow system research and implementation in Arizona.

PROJECT DIRECTION & PARTICIPATION

The project stakeholders bear much of the responsibility to enable a successful research project, by giving clear direction and leadership for the work, and providing generous resource support. The Intelligent Vehicle Project's TAC members, by their participation and their positive attitude, have been vital to the development of the unique Arizona test sites, and to the ATRC's ability to capture valid and relevant results from the ongoing field activities.

Many individuals have key roles in the testing, training and evaluation of Advanced Snowplow systems in Arizona, including service on the Technical Advisory Committee (TAC). Many of those named below have been actively involved in this research since 1997 (**asterisks indicate TAC membership during Year Four*):

ADOT Field Personnel (1997-2002):

ADOT Interstate 40 Corridor District Engineers, Maintenance Engineers & Superintendents:
- Flagstaff – *John Harper, *Kent Link, *Danny Russell, *Don Dorman
- Holbrook – *Jeff Swan, *Robert Wilbanks
- Kingman – *Sam Elters, *Rance Spurlock, *Debra Brisk, *Bill Wang

ADOT Maintenance and Equipment Supervisors:

- *Carl Eyrich (Flagstaff Equipment Shop)
- *Tim Bighorse (Gray Mountain)
- *Mike Gutzwiller (Little Antelope)
- *Ernie Sanchez (East Flagstaff)
- *Bruce Mejia (Seligman)

Project 473 Technical Advisory Committee:

During Phase Two(b) in 2001–02, the Project TAC included personnel both from key ADOT sections and from partner agencies. In addition to those ADOT field personnel denoted in the preceding sections, the project's other TAC partners were:

- Dennis Halachoff, Larry Presnall, Dean Murgiuc, Mike O'Malley, Mike Signa (ADOT Equipment Services)
- Tim Wolfe, Manny Agah (ADOT Transportation Technology Group)
- Doug Nintzel (ADOT Community Relations Office)
- Lt. Dan Wells (Arizona Department of Public Safety: Flagstaff District)
- George Howard, Mike Campbell (National Weather Service: Flagstaff-Bellemont)
- Alan Hansen, Jennifer Brown (Federal Highway Administration)

ADOT Project Snowplow Operators (2001-02 season):

- Robin Nelson, Francis Martin, Paul Huskie (ADOT-3M ASP: Gray Mountain)
- Joseph Chavez, Tom Durnez, Manuel Santana (Caltrans RoadView ASP: Flagstaff)

Project Partner & Vendor Support (2001-02):

Caltrans Advanced Snowplow Project Development:

- Bob Battersby, Kirk Hemstalk, Mike Jenkinson, Greg Larson (Caltrans)
- Dr. Ty Lasky, Dr. Bahram Ravani, Kin Yen and the UC-Davis AHMCT project team
- Dr. Han-Shue Tan and the California PATH project team at UC-Berkeley

3M Lane Awareness System Project Development:

- Heinrich Bantli, Gary Nourse, Chin-Yee Ng

Eaton VORAD System Technical Support:

- Jeff Hall, Tom Mattox

Bendix XVision System Sales and Technical Support (*pending for 2002-03*):

- Craig Stark

III. ADVANCED SNOWPLOW RESEARCH IN ARIZONA

Winter travel in rural Arizona can be a true challenge to drivers for a number of unique reasons. The terrain in northern Arizona rises from just 500 feet above sea level at the Colorado River, to 7300 feet on Interstate 40 near Flagstaff. Over 250 miles of I-40 across Arizona are at elevations above 5000 feet. Many other routes in the northern, eastern and central mountains rise above 8000 feet and even as high as 9500 feet above sea level. Keeping Arizona's highways open and operating smoothly for commercial and tourist traffic in winter is a tremendous challenge. In this new millennium, each state must do more with less.

Figure 3: ADOT Snowplow Evaluation Program – Early Phase (1933)

[Photo courtesy of ADOT's Norm Wallace Collection]

For ADOT's highway maintenance crews, advanced technology offers new abilities to cope with winter operational problems that include reduced budgets, high crew turnover, growing truck and passenger car volumes, increasing traffic speeds, and motorists with suspect driving skills.

The Arizona Transportation Research Center began this project in 1997 as an in-house research effort for the Arizona Department of Transportation. The project's mission was to study the possible practical applications in Arizona for vehicle-based and infrastructure-based Intelligent Transportation Systems (ITS) technologies, to enhance both efficiency and safety.

This project report covers Phase Two(b) of the Intelligent Vehicle (IV) research program, which began in the spring of 2001. It focuses on northern Arizona's 2001-02 winter season, and it also describes the project transition in testing and research that was decided at the end of the winter.

PROJECT NEED – THE COSTS OF WINTER TRAVEL

With regard to winter highway safety, crash statistics from the ADOT Traffic Records Section show that snowy or icy road surface conditions were cited in 2,073 crashes that took 14 lives and caused 818 injuries across Arizona in calendar year 2001, an above-average snow season. With the Flagstaff region as a baseline, the year 2002 had less than 30 percent of average snowfall. In that winter, a much smaller number of crashes (1,243) still took 14 lives and caused 539 injuries.

Weather records show that Flagstaff had 27 days of significant snowfall in calendar year 2001 (one inch or more), but only eight such days in 2002. An average season has roughly 20 such storm events. Table 1 presents the key crash statistics for the past two calendar years.

Table 1: "Snow-and-Ice" Crash Statistics: 2001 and 2002

Description	2001	2002
Total Crashes – Snowy or Icy Conditions	2,073	1,243
Fatal Crashes - Snowy or Icy Conditions	14	12
Fatalities – Snowy or Icy Conditions	14	14
Injuries – Snowy or Icy Conditions	818	539
Property Damage Only – Snowy or Icy Conditions	1,541	909
Flagstaff Snowfall Days / Total Inches for Calendar Year: *Source: National Weather Service – Bellemont*	*27 days / 131"*	*8 days / 30"*
Total Estimated Economic Loss – Snowy or Icy: *Source: National Safety Council Estimating Criteria*	$37,842,006	$29,944,532

Source: "Motor Vehicle Crash Facts" Annual Reports, ADOT Traffic Records Section [3,4]

These economic loss figures include estimates of lost personal earnings, medical costs, and property losses from crashes, but do not assess the fiscal impacts to a time-sensitive economy of accident-related travel delays for the public and commercial carriers. These motor vehicle crash cost figures are separate from any estimates of regional storm-related travel delays, and they do not include any snowplow crash repairs or operational costs to ADOT. Note also that the crash and weather statistics above are tabulated on a calendar year basis, not by the winter season.

The ADOT snowplow fleet is subject to serious attrition during major storms, when all available trucks and manpower are deployed on the state's highways. Even for the relatively mild winter of Year Four, between November 2001 and March 2002, a total of 22 snowplow vehicle damage incidents were posted to ADOT's internal repair cost system. These events amassed a total plow equipment repair cost of $49,900, as shown in Table 2 below. This cost does not include such property damage as guardrail and signs, or third party damages. It also does not include various internal costs for maintenance or repair work described as ordinary snowplowing wear and tear.

Table 2: Two Winter Seasons: Snowplow Equipment Repair Cost Summary

Description	Phase Two 2000-01	Phase Two(b) 2001-02
Snowfall Total by Winter Season at Flagstaff	*125"*	*39"*
Total Repair Cost for Snowplows - Statewide	$66,714	$49,852
Total Incidents of Snowplow Damage	19	22
Damaged During Snowplowing Activity	15	8
Struck or Struck By Other Vehicle	9	9
Struck Fixed Object	6	6
Other Incidents – Loading, Rigging, Transit	4	7

Source: ADOT Equipment Services Group

In both the Phase Two and Phase Two(b) winters, many if not most of the damage reports were during roadway snowplowing activity, as opposed to loading de-icing materials, rigging plow equipment, training or other causes. For each winter, nine of the incidents involved collisions with other vehicles, and six involved plows striking fixed objects. It is assumed that roadway visibility in snowplowing operations would be a factor to some extent in these crashes.

PROJECT EVOLUTION

ADOT first became involved in IV research activities shortly after key managers attended the landmark National Automated Highway Systems Consortium (NAHSC) Demo ’97 exhibition in San Diego, California. This national forum and showcase for vehicle control concepts and fully automated highway systems (AHS) was a turning point for the senior management of ADOT.

Initially, several “smart car” tests and demonstrations were organized by ADOT for state leaders and the media in late 1997 and 1998, such as a public magnet-guided “hands-off” driving display at Arizona State University (Figure 4). These AHS and IV “concept demos” had a primary emphasis on the potential of ITS technologies to reduce freeway congestion and to improve air quality. However, benefits to heavy vehicle operations were also being emphasized at this time.

Figure 4: Demonstrating California-PATH Concepts: ASU Sun Devil Stadium (1997)

The key Phoenix-area AHS demonstrations included several prototype passenger cars employing both machine-vision and roadway-based guidance systems. The latter category included both the magnetic-tape lane awareness system developed commercially by the 3M Company, and the embedded magnet concept of the Partners for Advanced Transit and Highways (PATH) Program of the University of California at Berkeley.

Despite the success of the Arizona demonstrations, ADOT soon realized that the infrastructure costs for AHS technology in the urban areas could not be balanced by congestion or air quality savings, nor was there any indication of near-term initiatives by the major vehicle manufacturers. In this time period, the emphasis shifted generally to practical gains in safety and efficiency, and this approach pointed towards specialty vehicles. The public safety and roadway maintenance fleets became the focus for ongoing research and development of the IV concepts.

The fully-automated California PATH infrastructure-based lane guidance system had been a key element of the NAHSC Demo ’97 in San Diego. It would be further refined in the Caltrans-led ASP snowplow research program. After Demo ’97, ADOT was invited by Caltrans to participate in the ASP research effort, as discussed further below.

With strong interest and sponsorship among ADOT senior management, this research project was initiated in late 1997. Over the past four winters, two research project reports have already been completed by the Arizona Transportation Research Center (ATRC), which conducts this program as an in-house effort. This report describes Phase Two(b) of the project, which has effectively resolved ADOT’s questions about infrastructure-based guidance technologies for snowplowing.

PRIOR RESEARCH

Phase One: 1997-2000

During Phase One of this project, from 1997 to early 2000, ADOT and the ATRC reviewed, tested, evaluated and demonstrated a variety of promising Automated Highway System and Intelligent Vehicle concepts. These new resources were evaluated with regard to their potential to improve the safety and efficiency of Arizona’s highway system. Key project goals were to improve safety for both travelers and ADOT personnel, to defer more highway lane construction, and to improve regional air quality in Arizona.

As indicated above, the original Phase One research goal was to explore potential solutions for urban and rural highway congestion problems, but ADOT senior management ultimately decided that the best near-term potential use of the new technologies was to improve the safety and efficiency of winter storm operations. This initial broadly-scoped research project is detailed in the ATRC’s Final Report No. 473(1), “The Arizona Intelligent Vehicle Research Program – Phase One: 1997-2000.” [1]

ATRC immediately established a winter maintenance research partnership with the Caltrans ASP program, at their invitation. The ASP guidance system, developed for a 10-wheel Caltrans plow truck, was tested in Arizona during the winters of 1998–99 and 1999-2000. The ASP, developed by the Advanced Highway Maintenance & Construction Research Center (AHMCT) of the University of California at Davis, was an operational fleet snowplow. Therefore the ADOT field-testing transfer period was limited to approximately a four-week time window, and occasional ASP technical issues further reduced the time spent out on the highway.

The ADOT project team and its sponsors soon recognized a clear need to obtain driver-assistance systems for full-winter, long-term testing in the Arizona snowplow fleet. On that basis, a new phase of the research program was initiated.

Phase Two: 2000-01

The Caltrans advanced snowplow prototype was designated ASP-I and ASP-II during the first two winters of the partnership with ADOT. From that point, the technology was further refined and was reintroduced in the third program winter as the RoadView™ advanced snowplow.

The Phase Two research project is described in ATRC Report No. 473(2), “Arizona Intelligent Vehicle Research Program – Phase Two: 2000-2001.” [2] The key task was to locate a snowplow lane guidance system that ADOT could purchase on its own for long-term evaluation. The current Caltrans RoadView ASP system was not sufficiently developed to be able to be deployed and supported outside of California at that time. Ultimately, the ATRC and the ADOT Flagstaff District agreed to purchase the 3M Lane Awareness System package, as well as five miles of the 3M magnetic tape to guide the snowplow vehicle.

A second new factor in the Phase Two research was the need for a formal, unbiased analysis of the Arizona training and evaluations for both the 3M and Caltrans ASP concepts. Northern Arizona University (NAU) was assigned to document ADOT's training and testing, to develop evaluation results, and to make recommendations for the future. The ATRC-NAU evaluation effort was also supported by the University of Iowa (U of I), as part of an ongoing evaluation program for 3M.

This project's second phase encountered a number of unexpected setbacks in the mild winter of 2000-01, but the equipment tests and training program for both systems proceeded as planned at the two regional test sites near Flagstaff. One or both of the advanced snowplows were deployed in plowing operations, as available, through nearly the entire winter season.

As planned and executed, the Phase Two effort was very productive, and the results are detailed in that project's report. The key achievement was that in 2000, Arizona had established the first advanced snowplow operational evaluation program in the West, with real-world high-altitude test sites for both the Caltrans ASP and 3M's commercial LAS system, just 30 miles apart.

Phase Two(b) Research: 2001-02

In this recently–ended Year Four of the program, guidance system evaluations continued with the side-by-side field testing of the ADOT-3M magnetic tape and the Caltrans roadway magnet concepts. The same-day training program, field testing, and operator evaluations of these two low-visibility, low-speed guidance systems were quite successful, as described in more detail below. However, unfortunately no snow at all fell in February, during the fourth and last annual visit of the Caltrans RoadView research snowplow to Arizona.

This Phase Two(b) report reviews in detail the various systems and subsystems under test by ADOT over the past four winter seasons, and the various research activities carried out during the recently-concluded winter of 2001-02.

The next five chapters include a brief review of the concepts, costs, and magnetic infrastructure details for each of the two roadway-based systems tested by ADOT and ATRC on the highways around Flagstaff. For each of these systems, a separate chapter also reviews the evaluation plan, training and operational activities, and the season's results.

The concluding chapters relate the key findings, conclusions and program recommendations that have been developed from Phase Two(b), the 2001-02 winter, and from four years of joint testing of roadway-based guidance systems. This discussion explains the resulting TAC decision to modify the basic research concept, and it describes the ATRC's program to prepare in a timely manner for the crucial fifth and final year of the project.

IV. TWO SYSTEMS, TWO SITES: PARALLEL EVALUATIONS

In Year Four of the project, the winter of 2001-02, ADOT and the ATRC continued with the core concept of side-by-side comparative evaluations of the commercial 3M Lane Awareness System and the Caltrans developmental prototype RoadView advanced snowplow system. While not in direct commercial competition at the present time, both of these low-visibility, low-speed vehicle guidance concepts could potentially be viable options for other states in the foreseeable future.

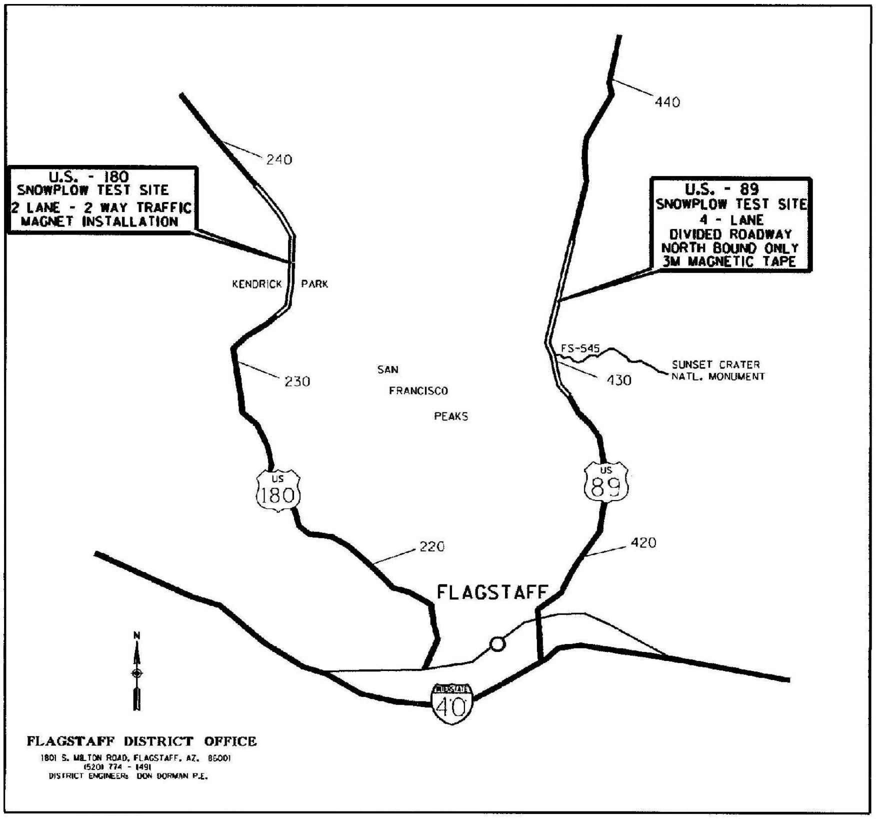

Figure 5: ADOT Snowplow Test Sites Map – Flagstaff District

Despite above-average snowfall (125 inches at Flagstaff) in the preceding third winter of the project, numerous technical, roadway, and weather issues had constrained ADOT's driver training and operational testing. As a result, the 2001-02 winter would be the crucial year to effectively and fairly evaluate the two IV concepts at the two adjacent test sites.

EVALUATION PLAN: SIDE-BY-SIDE SYSTEMS

ADOT's Year Four evaluation goal was, at long last, to thoroughly analyze and compare the two advanced guidance systems, in support of future deployment recommendations. A secondary goal was to evaluate commercial warning radar (CWS) and automatic vehicle location (AVL) technologies that might be practical as stand-alone on-board tools to improve winter maintenance operations in Arizona. As in the previous winter of the project, the 2001-02 program involved evaluation consultant teams working in support of both ADOT and Caltrans, but the primary ADOT operations and training documentation for the project was developed by the ATRC.

Both the Caltrans team and ATRC collected field data and solicited driver feedback to determine the relative performance and suitability of their own systems. For ADOT to develop a valid side-by-side comparison of the 3M and Caltrans concepts, a neutral third party was needed to analyze, interpret, and judge the merits and relevance of the information. As in the previous winter, the Year Four comparative evaluation of the two advanced snowplow concepts was assigned by the ATRC to Northern Arizona University (NAU).

The overall evaluation program was based on two concepts: same-day training at two sites, and field operations. The side-by-side comparison of the two discrete lane guidance systems was intended to allow snowplow operators from across northern Arizona to visit one test site in the morning, and to travel through Flagstaff to the other test site in the afternoon.

At each location, the research project team and the ADOT Team Leader operators would provide introductory rides and brief hands-on training. Afterward, each trainee was asked first to fill out an evaluation survey on the lane guidance system (see Appendix F), and then to proceed around the mountain to ADOT's other advanced snowplow test site.

The second element of this evaluation of the guidance and secondary systems was operational usage on the truck's normal snowplow route. Because of system issues and communications problems, and above all the dry winter weather, the extent of plowing operations was very limited, and relatively little ASP performance data could be documented.

Despite these constraints, the NAU evaluation team studied each system's functionality and performance in varying weather and lighting conditions. They interviewed the ATRC-Caltrans project team and the ADOT trainees, and reviewed their post-training surveys. The NAU team was able to observe, learn and document ADOT's winter maintenance practices in northern Arizona so that the results of both systems, and the user and stakeholder perspectives, could be properly applied to validate the overall effectiveness and potential utility of each ASP.

YEAR FOUR – EVALUATION PLAN CONSTRAINTS

Arizona had been successful in Year Three with the ambitious goal of creating two independent ASP test lanes near Flagstaff to directly compare the ADOT-3M LAS concept with the Caltrans RoadView system. An ADOT advanced snowplow had been developed and fully equipped with commercial IV technologies. However, despite the above-average snowfall, the 2000-01 winter testing had been limited by many program setbacks and technical constraints.

As Phase Two(b) of the program began, there were indications that 2001-02 would be a warmer and dryer winter for northern Arizona. In the end, the regional snowfall for this fourth winter was far below expectations, with only 39 inches recorded at Flagstaff - barely one-third of the 30-year historical average of 111 inches.

Year Four was actually among the driest winters on record across northern Arizona, which put the ADOT-Caltrans training and evaluation program at a severe disadvantage. But despite the disappointing winter weather, the project's training and evaluation plan was pursued aggressively by all involved, and this season is considered to have been a success overall.

V. CALTRANS ROADVIEW SNOWPLOW: FOUR YEARS IN ARIZONA

At a very early stage, the ADOT intelligent vehicle research program came to focus specifically on winter maintenance concepts. Phase One (1997-2000) developed a strong partnership with Caltrans, whose prototype advanced snowplow offered significant benefits to both states.

The Caltrans ASP features a predictive lane position display and lane-departure warning, as well as an integrated forward collision warning. The heart of the Caltrans ASP concept is a line of PATH discrete magnetic markers embedded in the roadway, with a unique polarity coding to provide position and guidance information to the snowplow's magnetometer array. The primary vehicle components of the Caltrans RoadView ASP are shown in Figure 6.

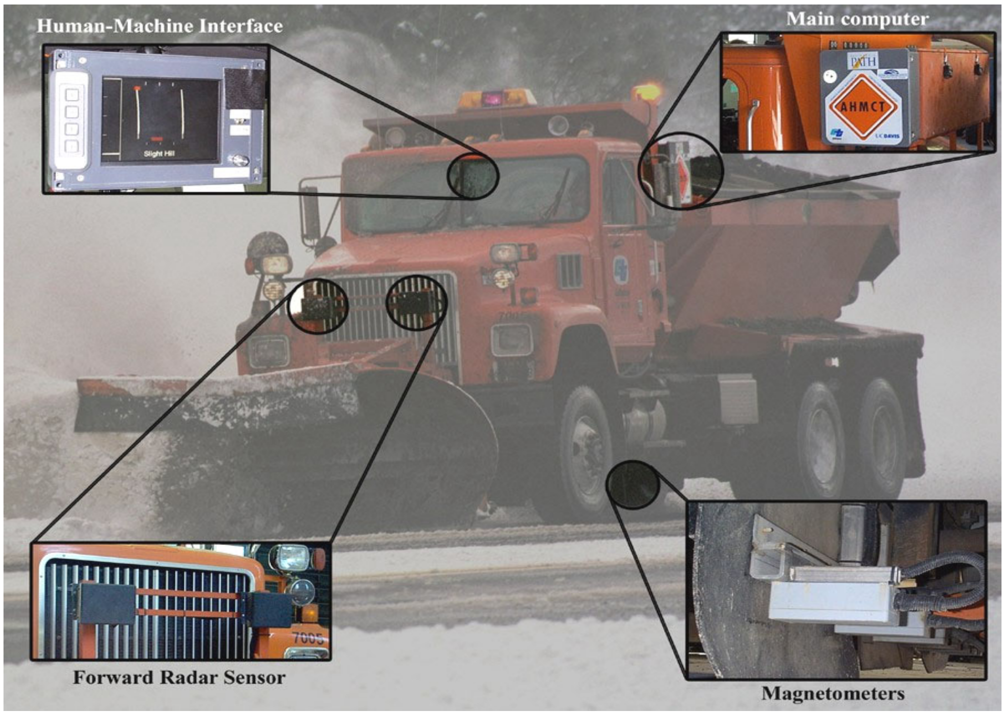

Figure 6: The RoadView Advanced Snowplow

[Graphic Courtesy of AHMCT]

The Caltrans ASP system, installed on a ten-yard all-wheel-drive plow truck, was successfully tested in Arizona during ADOT's Phase One research in 1999 (ASP-I) and again for Phase Two in 2000 (ASP-II). The Caltrans ASP was shipped to Flagstaff for four weeks each winter, as the focal point of the Arizona field research program. The Caltrans project team collected training and evaluation data both at their primary California test lane on Interstate 80 near Donner Summit, and at ADOT's new Kendrick Park test site on US Highway 180 northwest of Flagstaff.

This collaboration grew in Phase Two of the project (Year Three, 2000-01). At that point ADOT had developed its own research snowplow utilizing the 3M magnetic tape system, and Caltrans had refined its early ASP designs into a new generation RoadView™ snowplow (at which point "ASP" reverted to a generic term for any advanced snowplow concept). The new project goal for 2000-01 was to directly compare the performance of the RoadView and the ADOT-3M concepts.

This section of the report describes 2001-02, Year Four of the ADOT-Caltrans project, and of the successful research partnership with the California program. This would prove to be the final winter of direct comparative testing of the two competing roadway-based guidance concepts, and it was also the last year of intensive Caltrans ASP training and testing in Arizona. This section of the report will review the concepts and elements of the Caltrans RoadView guidance system, and the development of a suitable Arizona test facility, so that the casual reader need not search through the ATRC's two more detailed prior reports for this information.

THE US 180 CALTRANS MAGNET TEST SITE

The Kendrick Park test site on US 180, about 20 miles northwest of Flagstaff, was selected as the functional opposite of the I-80 test area at Donner Summit in California. As Table 3 indicates, in comparison to the Caltrans facility, every key characteristic of the ADOT site was distinctly different. Arizona offers unique conditions for vehicle system testing and development, and lies along a completely different winter storm track and weather pattern than the California Sierras.

Historically, the US 180 highway corridor is a severe winter maintenance challenge for ADOT. One critical mile of the test lane, across windswept Kendrick Park, is subject to whiteouts and drifting snow in heavy storms. This site is at an 8,000-foot elevation and receives on average about 110 inches of snow each winter. Severe drifting, more than 10 feet deep in some winters, makes this one of the few ADOT highways where a rotary snowblower may sometimes be used to reopen the roadway after major storms.

The narrow, steep, winding asphalt roadway of US 180 has an annual average traffic count of less than 3,000 vehicles per day, but as the shortest route from Flagstaff to the Grand Canyon, it is a vital link in the highway system and for the regional economy.

Table 3: Test Site Diversity Criteria

Site Criteria	Arizona Test Site	California Test 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 (Average Daily Traffic)	2,500 – 3,000	27,000
Snowfall – Annual	90 to 100 Inches	400+ Inches

Needless to say, the operating procedures, labor force considerations, and truck and snowplow blade designs also varied between the California and Arizona programs. A unique second test site, and a second operator pool, provided Caltrans with independent validation of the concepts, as well as a reality check for possible future efforts to commercialize the system.

THE CALIFORNIA ASP PROGRAM

The Caltrans ASP research effort evolved by mid-2000 into the RoadView advanced snowplow program, with two more operational plow units to be deployed at key maintenance facilities at Kingvale and Burney in northern California. As part of the RoadView development, the earlier ASP technology was extensively updated based on the latest component designs.

The California research program involves three primary research and development organizations, each with distinct responsibilities. The RoadView ASP program manager and guiding force is the Caltrans Division of Research and Innovation, based in Sacramento. The project's two core technology-support agencies that perform the critical research and developmental tasks are the AHMCT (Advanced Highway Maintenance & Construction Technology) Research Center at the University of California at Davis, and PATH (Partners for Advanced Transit and Highways) at the University of California at Berkeley:

AHMCT is responsible for:

- System architecture and design.
- Hardware installation and support.
- Radar warning system development.

PATH is responsible for:

- Steering guidance system development.
- Software architecture design.
- Human factors analysis.

The Caltrans ASP design is based on the cooperative infrastructure concepts developed by the California PATH program, with detailed system design and implementation by the AHMCT Research Center. The lateral and predictive guidance concepts are derived from the Automated Highway Systems technology that was originally developed by PATH for the fully- automated Demo '97 concept vehicles.

The high level of sophistication of the current RoadView ASP is exemplified by the system's ability to integrate the lane-position and lane-prediction reference information with the warnings from the independent forward-looking collision warning radar. The communication of all this information to the snowplow operator is the greatest human factors challenge for the system.

DRIVER VEHICLE INTERFACE (DVI)

The Caltrans advanced snowplow Driver Vehicle Interface has developed in an evolutionary design process, beginning with ASP-I, then ASP-II, through RoadView. The design goals of the DVI are to allow drivers to acquire vehicle lateral information at a glance, as described below, and to quickly and easily switch between normal and guidance-assisted driving.

The Caltrans RoadView advanced snowplow uses numerous technologies to improve the safety and efficiency of snow removal:

- A sensing system that detects the current vehicle location.
- A prediction system that predicts the future vehicle location.
- A collision warning system that detects obstacles and potential hazards.
- A driver vehicle interface that integrates all information into a driver display screen.

In an intuitive format that is easy to scan, the DVI display provides:

- Collision warning.
- Current lane position.
- Predicted future lane position.
- Steering prediction target marker.
- Upcoming roadway curvature.
- Landmark and milepost information.
- System status.

A key Caltrans goal of the Year Four (2001-02) RoadView testing program in Arizona was to further evaluate the current DVI, and to develop suggestions for future refinements. The prior versions had been tested and improved through analysis of both driver feedback and plowing performance. This winter's evaluations in both states were critical to identify and to justify any further DVI development, as RoadView was entering the deployment phase in California.

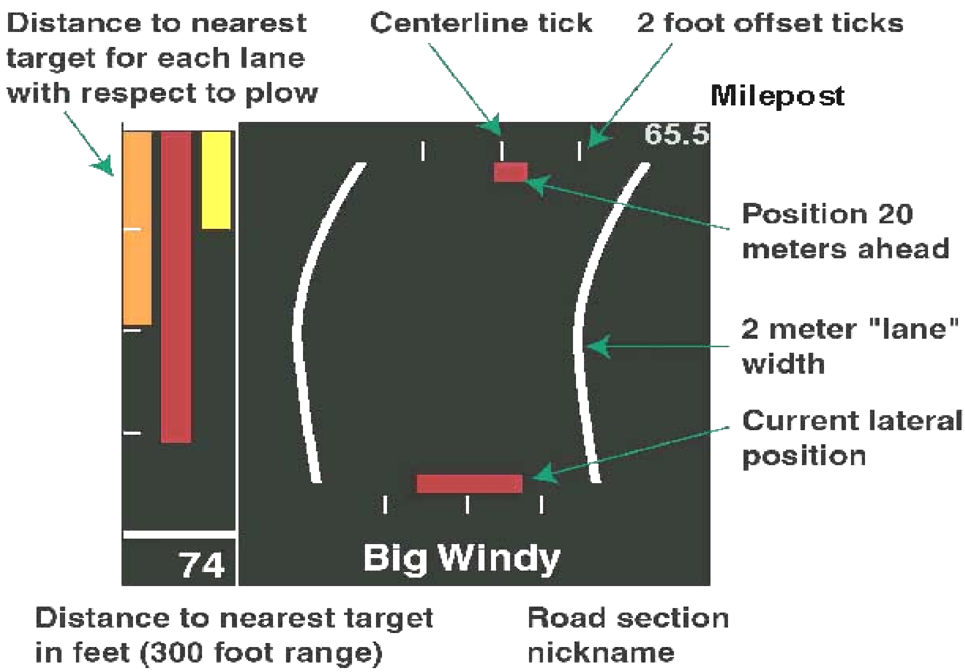

Figure 7: The RoadView Driver Vehicle Interface (DVI) Display

[graphic and descriptive text courtesy of California PATH]

As shown in figure 7, the DVI display has two major components, a forward collision warning system (CWS) and a lane-keeping system. The left-hand section of the display contains CWS information that is integrated from twin radar antenna data streams. Downward-moving tapes, or bars, indicate the distance to each detected forward target. Distance rather than time was chosen as the best warning metric, based on operator comments that distance is a more valuable decision factor at low speeds. Moving bars or tapes mimic the forward approach of obstacles. The tapes change from yellow, to orange, and then to red as a target approaches. The three tapes place targets in their proper lateral position (left, center, or right) with respect to the plow, simplifying driver interpretation. The DVI also displays the distance to the closest radar target.

To distinguish the long-range collision warning display from the short-range lateral guidance display, a white line separates the sections. A key component of the lateral guidance display is the prediction feature. The marker shows the future lateral position, 20 meters (66 ft) ahead, for the current angular deflection and direction of the steering wheel. When the steering wheel is turned left, the prediction marker moves left. The current lateral lane position of the truck is shown at the bottom of the display. The graphics represent a displayed longitudinal distance of 20 meters, with a two-meter width between the “curb” or lane lines. The lane lines are computed from an internal map database of roadway curvature and heading angle, based on position coding of the roadway magnets. The driver can steer within the lane by positioning the predictor at the desired “future” location, 20 meters ahead.

The center tick marks indicate the center of the lane, while the exterior tick marks indicate 0.6 m (2 ft) offsets. Offsets are used during certain plowing formations and are often used intentionally by snowplow operators in many areas. Under normal conditions the lateral assistance lines are displayed in white, and the current and prediction markers are red. If the computer is uncertain of its current longitudinal position on the track, but is detecting position markers (magnets), the whole lateral display turns yellow and the display depicts a straight road. This signals to the driver that the display should not be completely trusted.

If the plow moves off the line of embedded magnets, the road display changes to gray and freezes with a yellow arrow pointing back towards the lane center. This arrow appears over the lane boundary that has been crossed. After a short time off the magnets, the lateral display blanks out. Besides color changes and the yellow arrow, no other lane departure warning is given.

Road segment names are displayed below the lateral position imagery. These names correspond to the local names used by the drivers for specific curves and stretches of road. The names were linked through the software to specific sections of the roadway magnet internal map. In addition, milepost numbers are provided in the top right portion of the display.

CALTRANS MAGNET INFRASTRUCTURE AT KENDRICK PARK

The RoadView ASP vehicle has one transverse row of seven suspended magnetometers to track a continuous line of embedded magnets in the roadway. The magnets are installed with a unique binary polarity coding for each 204-meter (670 ft) control section of the test site roadway. For each section of 170 magnet points at 1.2 meter (3.95 ft) spacing, the first 16 magnets are installed with a plus-minus orientation as specified by the California PATH team. This coding identifies each roadway segment and tells the on-board ASP system its exact location on the roadway. More importantly, it identifies the geometrics and reference points in the next 204 meters ahead. The RoadView system DVI screen, as described above, gives the driver a predictive display of the lane ahead, to enable the snowplow to keep moving in situations of nearly zero visibility.

In Phase One, ADOT maintenance crews installed four miles of the PATH magnets to establish the US 180 test site in 1998, for the first winter of joint activity with Caltrans. Two more miles of magnets were added in mid-1999 for the second winter, completing a two-way test lane across Kendrick Park, three miles in each direction, with more than 8,000 embedded magnet points.

The ADOT-Caltrans test area begins at northbound Milepost (MP) 235, in a forested section near Hart Prairie Road, and then runs for one critical mile across open, windswept Kendrick Park, the worst area for drifting and for zero-visibility plowing conditions in severe storms. Continuing north, the test lane climbs a ridge and then it S-curves down an 8 percent grade to MP 238, where the snowplow turns around for its southbound run.

Prior to the decision to install magnets at Kendrick Park on US 180, there were concerns that the drilling for the magnet points could damage the roadway surface or the subgrade. ATRC initially conducted long-term testing along the I-40 Corridor, where groups of 12 to 16 magnets were installed into the lane centerline at six locations between Seligman and Holbrook. These tests identified the most practical methods, materials and equipment for the larger program of creating a dedicated test lane.

Figure 8: Magnet Installation on US 180: 1998-99

Based on this initial I-40 process evaluation, the first four miles of magnets on US 180 were installed at Kendrick Park in September 1998. ADOT's three northern maintenance districts provided volunteer crews to establish survey control, to man the four electric core drills, to set and seal the magnets, and to do traffic control. This effort was repeated for two more miles in late 1999, with a similar joint district effort to complete a three-mile closed-loop test course.

Each of the individual Caltrans ceramic magnets is 7/8-inch in diameter and one inch in height. As shown in Figure 9, these magnets must be installed in stacks of four, in holes drilled into the pavement at exactly 47-1/4-inch intervals (1.20 meters). To ensure constant signal strength, the magnets had to be placed on the centerline of the lane with very demanding lateral (3/8-inch) and vertical (1/4-inch) tolerances. Based on these rigid PATH specifications given to ADOT, precise survey control was a critical requirement for the project to be successful.

Electric core drills were selected by ADOT for the drilling operation, in order to improve the accuracy and to maintain hole integrity in the pavement. It is worth noting that while the US 180 pavement is actually less thick in most areas than the drilled holes are deep, there were very few observed problems with the asphalt material during installation. Some holes as surveyed fell in existing areas of significant cracking, but the use of rotary core drills reduced pavement stresses and did not create any new cracking or spalling of the holes. Many of the 4-1/2-inch-deep holes actually were drilled clear through the pavement into the subgrade, so the long-term durability will be a concern to be monitored regularly on this lightly traveled section of roadway.

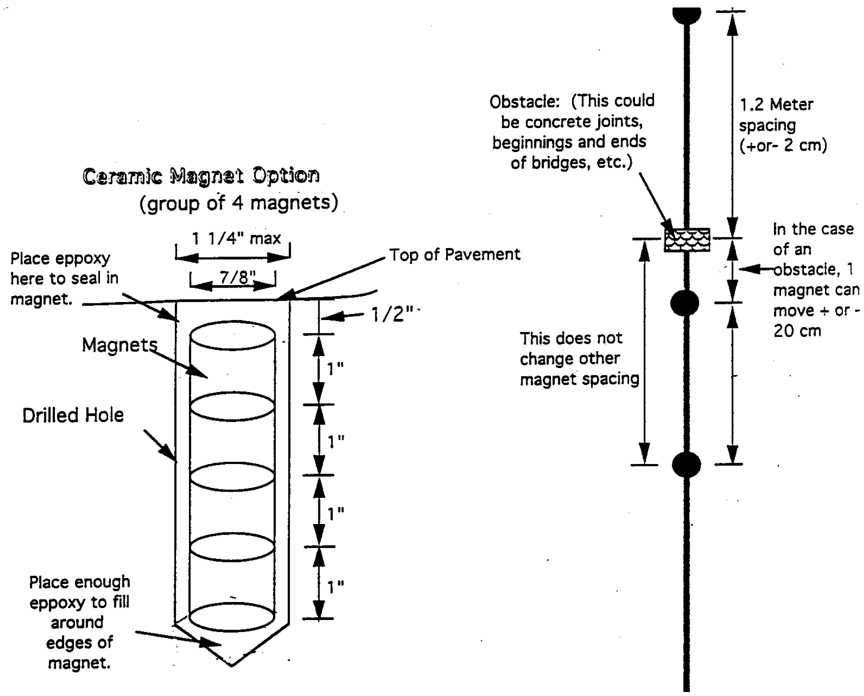

Figure 9: Magnet Installation Requirements

[graphic courtesy of Caltrans]

The project selected 3M Loop Detector Sealant to permanently seal the magnets in place once they were set on line and grade, and had been immobilized with a layer of fine sand (Figure 8). This was a tedious task that required enduring patience from the volunteer installation crews who worked day after day to set the magnets to the necessary tolerances.

Overall, the project's Caltrans magnets have proven to be stable and inert in the roadway through the four winters of the RoadView joint research project. Inspections each fall found between 10 and 30 magnet points that needed to be reset and resealed before the Caltrans RoadView testing cycle could begin. While the sealant caps sometimes came out, only a few holes ever lost one or more of their embedded magnets. After four winters, in late 2002, some crack propagation was observed in a few localized areas, and ADOT crews continue to inspect the site periodically.

MAGNET INSTALLATION COSTS

The ADOT magnet installation effort was reported in detail in this project's Phase One report, and the cost findings are repeated here for reference, in this concluding report on Arizona's four-year research partnership with California.

Volunteer crews from ten maintenance camps in three ADOT Districts worked on the ATRC-led magnet installation projects in 1998 and 1999. Overall the two projects installed 8,037 magnets by hand at an overall average rate of 382 per day, in a total of 21 ten-hour work shifts.

The magnet installation utilized four electric drills and required a 14-man crew. The overall cost per traffic lane was roughly $17,500 per lane-mile, at ADOT's burdened average labor rate of $12.00 per hour. Labor costs were found to be 52 percent of the total installation budget.

The actual costs of the magnet materials and installation supplies were only about $2,150 per mile, or about ten percent of the total, while the drilling-related cost ran $2,000 per mile. The third-party control surveying was expensive, and was later determined to have been unnecessary (see "Lessons" below), so that cost is not included in the overall total.

These installation costs are difficult to capture, as many accounting factors were internal or unique to ADOT. The key economic factors in the Caltrans magnet program were the material cost, the methodology, the total lane-mile cost, and the number of working shifts required. The magnet installation effort averaged about 50 man-shifts, or 3.5 crew-shifts, per completed lane-mile, with 1,340 magnet points required per mile for the Caltrans ASP roadway infrastructure.

As noted elsewhere, ADOT was unable to procure its own prototype Caltrans system due to cost and support concerns during ongoing development. While the Caltrans team had projected a target market cost of $20,000 to $30,000, the figures discussed with Arizona for a research-level prototype were notably higher.

LESSONS – THE CALTRANS MAGNET EVALUATION PROGRAM

A key lesson from this project was that precise surveys of the theoretical lane centerline were not practical nor critical, since the efforts of the roadway striping crews did not precisely match with the survey lines. On US 180, in several tight reverse curves, the magnet line clearly had to relate to the actual lane striping, which defines the travel paths of both the ASP and oncoming vehicles. These factors prevented the crew from setting the magnets precisely on the survey centerline, since for daylight ASP training and for later operations, the RoadView plow had to stay within its own lane striping.

Another key lesson was that work-zone traffic control was critical, and that setting roadway magnets precisely required lane closures and a high degree of protection for the crews. The best solution on this two-way highway was to use a pilot vehicle to control the speed of work zone traffic, but on a high-volume roadway, physical barriers will be required. Side road traffic was also a continual problem at some points along this roadway, and required constant vigilance.

These lessons from the magnet installation phase are relevant to the 3M magnetic tape option. The 3M tape was installed during construction, and the factors and the issues noted above were rigidly controlled and mechanized. On the other hand, third party contractors installed the 3M tape, with no direct ADOT maintenance crew involvement as in the magnet program.

A significant factor for the Caltrans magnet evaluation was that the ADOT maintenance crews who manually set the embedded magnet points, one by one, were the same snowplow operators who would be trained to use the RoadView ASP in winter storm operations. This personal buy-in, for plow operators from across the entire region, would be very significant later in terms of their enthusiasm, training and scheduling, and overall commitment.

VI. CALTRANS ROADVIEW TRAINING & OPERATIONS ON US 180

In the previous Phase Two, the third year of ADOT's snowplow research project, two competing roadway-based driver-assistance systems were evaluated for the first time at two adjacent field test sites. However, as described in that project's report, a number of problems arose in 2000-01 that reduced the effectiveness of the testing program both for ADOT and for Caltrans.

On the US 180 test site at Kendrick Park, the Caltrans ASP system was out of service for almost two weeks out of four, which severely limited training and operational use. The new ADOT-3M snowplow's initial winter of testing was severely impacted by early failure of the collision warning radar system, which was never resolved during that Phase Two winter. Worse yet, the 3M tape embedded in the new US 89 pavement was not aligned with the temporary construction lane striping, which prevented any valid tests of the lane awareness system. On the positive side, Flagstaff received 15 percent more snowfall than average, a total of 125 inches, for 2000-01.

YEAR FOUR ROADVIEW EVALUATIONS

With the various technical problems now resolved for 2001-02, the RoadView ASP evaluation was organized with high hopes of finally getting meaningful direct comparisons in Year Four with the ADOT-3M advanced snowplow. The Caltrans RoadView plow was carefully prepared and tested before being shipped to Flagstaff in early February, and it was fully operational during the five-week testing period in Arizona.

For the Caltrans project team, the key goals of Year Four's Arizona tests were threefold:

- To evaluate the effectiveness of the latest RoadView refinements to the ASP system.
- To determine in what ways the ASP system affects driver behavior.
- To determine what changes to the driver interface might be recommended.

For ADOT, a key long-term project goal was to evaluate the effectiveness and ease of operation of the RoadView ASP magnet-guidance system on US 180 at Kendrick Park for a fourth winter. The second key goal was to directly compare the RoadView plow with the ADOT-3M advanced snowplow using the magnetic tape-guidance system on US 89 at Sunset Crater.

ROADVIEW TESTING AND EVALUATION

After a disappointing experience the winter before, ADOT's plan focused on scheduling a large number of snowplow drivers from across the I-40 corridor for training on both systems in the same day. A key secondary focus was on operational testing, however, the system performance in previous winter seasons had already been well established for the Caltrans snowplow.

The key in the fourth winter season was to capture the drivers' reactions to learning and driving with both technologies in a single day of training. The ATRC's detailed workplan for Year Four is included as Appendix B, but the key schedule elements of the five-week Caltrans testing and evaluation program (February 4 - March 8, 2002) were:

- Initial site testing & commissioning - week 1.
- Caltrans training for core staff & Team Leaders - week 1.
- Training & evaluations with regional testers - weeks 1 & 2.
- Long-term field evaluation by Flagstaff District Maintenance - weeks 3 to 5.

This schedule was generally met, as the RoadView plow was commissioned by the Caltrans project team in the first three days at the site. Training for the other ADOT drivers from the three partner districts began at both test sites on Friday of Week 1.

A great deal of effort was required to organize and initiate the project workplan for each phase of evaluation at the 3M and Caltrans test sites. These steps were most critical with regard to the RoadView snowplow, due to its limited time schedule for travel to Arizona, the logistics of its round-trip shipment by commercial transport, and the many extra checks and calibrations needed upon its arrival at Flagstaff. The following activity list from the ATRC's workplan illustrates the prior planning involved and the roles of the key ADOT participants in the field:

<u>RoadView Training & Evaluation Workplan – Year Four Goals and Tasks</u>

- Accept snowplow from Caltrans staff; confirm care & maintenance procedures.
- Installation of spare ADOT radio by DPS at Flagstaff shop - arranged by District.
- Confirm conditions at test site; make field repairs or changes.
- Training of Team Leaders by Caltrans, with completed driver surveys.
- Regional testers training; complete NAU & ATRC driver surveys (*both sites / same day).*
- ADOT Team Leaders to complete testing activity shift reports.
- Long-term Flagstaff District evaluation with Caltrans RoadView plow on US 180.
- Full US 180 plow route for evaluation: Milepost 215 (Flagstaff) to MP 250.
- Test site at Kendrick Park runs both directions - MP 235 to MP 238.

Due to a variety of scheduling, weather, and other complicating factors, the season's results were mixed. The training program for regional partners was quite successful, as most of the ADOT plow operators were in fact able to travel to Flagstaff and visit the two test sites at Kendrick Park and at Sunset Crater in a single long day. Despite occasional scheduling issues, a total of 27 ADOT plow operators from three districts participated in the RoadView training, conducted at intervals through February 20. Most of these drivers (18 total) also received equivalent training on the ADOT-3M snowplow on the same day.

Night driving exercises were also conducted by PATH on US 180, in the final days of the joint RoadView evaluation effort, to collect operations-based data with several Arizona snowplow operators. Accompanied by Caltrans-PATH research staff, the drivers made multiple limited-visibility runs in darkness, to replicate the white-out conditions that often are encountered in the Kendrick Park area in a major winter storm. This nighttime activity had to be substituted for the expected February-March storms that never arrived during the five weeks of Arizona testing. The PATH workplan for this "no snow" contingency evaluation is included as Appendix C.

The results of the training and evaluation were documented and analyzed by the PATH members of the Caltrans project team. The key Arizona findings of the PATH study will be reported in the AHMCT's (pending) final report on California's RoadView research program, "A Rural Field Test of the RoadView System" (Yen, *et al*)[5].

ROADVIEW OPERATIONS IN ARIZONA: YEAR FOUR

Operationally, as implied above, the evaluation of the Caltrans RoadView snowplow was not conclusive since no measurable snow fell in the Flagstaff area between February 4 and March 8, when it was loaded for shipment home. A related setback was the inability to obtain and install an ADOT radio in the RoadView plow, so that it could be safely used as the primary snowplow on remote US 180 in any severe storm conditions. A mobile radio was installed in Year Three, but no spare unit was available for this winter's evaluations. The absence of reliable radio communications for operational testing was a serious problem for the Year Four research effort.

The Caltrans RoadView snowplow actually was not dispatched at all for operational testing on US 180, as no storms delivered any plowable snow in this time period. Late in the test period, a limited amount of filming was done by ADOT's video services, in order to document the project scope and the systems being deployed. Overall, during the Year Four winter in Arizona, the RoadView plow completed 1,507 miles of operations, training, and evaluation activity. In the final few days, 574 miles were logged by three drivers in PATH's intensive night-testing activity.

CALTRANS-PATH EVALUATION

Introduction

The Caltrans project team was focused specifically on the RoadView research and development concerns noted earlier, to improve the body of data on the guidance system, the collision warning system, and the advanced driver-vehicle interface. Most of the operational testing in California involved only the two or three experienced drivers normally assigned to man this snowplow on Interstate 80, working in tandem with other plows on Donner Summit. More variety and depth in operator perspectives, especially on the Driver Vehicle Interface, was a key Caltrans goal of the Arizona evaluation program.

The Arizona tests offered a much larger pool of plow operators, giving limited depth but much-needed breadth to the results, as well as validating recommendations for possible refinements in the human factors aspects of the Caltrans RoadView system. In Year Four, a total of 27 ADOT snowplow operators were introduced to the Caltrans system on US 180.

In addition, three of the ADOT plow operators took part in extensive field testing at Kendrick Park, most of which was conducted at night to better approximate the missing low-visibility storm conditions. These tests involved a series of both aided and unaided runs, and key aspects of driver performance were monitored and recorded by the Caltrans-PATH team.

Complete results of the training evaluations and field tests will be published by AHMCT in the RoadView 2002 project report "A Rural Field Test of the RoadView System."   The following discussion, which borrows heavily from AHMCT's draft report, summarizes the Caltrans-PATH Arizona testing plan, including the data collection activities and preliminary results of the joint program with ADOT in Year Four.

Summary Of Human Factors Assessments

The key benefit to California of the joint evaluation program in Arizona was the diversity of responses and experience levels of the various ADOT snowplow operators. Table 4 gives the mean amount of experience both for normal snowplow driving and for RoadView evaluations, and shows the number of ADOT and Caltrans drivers who completed the evaluation survey in three winters of the program.

It should be noted that Arizona's training program in Year Four was directed towards introducing a larger number of operators to the two distinct advanced snowplow concepts than in prior years. As Table 4 shows, the 2001-02 result was a larger test group than in prior years, with somewhat less time for each individual to experience the RoadView snowplow. Not surprisingly, the table shows that the overall regional experience level for the Arizona operators was much less than for those drivers assigned by Caltrans to the critical Donner Summit snowplow route on I-80.

Table 4: Driver Plow Experience Levels

	ADOT Operators 1999-2000		ADOT Operators 2000-01		**ADOT Operators 2001-02**		Caltrans Operators Burney-Kingvale 2001-02	
	Mean response	# of Drivers	Mean response	# of Drivers	**Mean response**	**# of Drivers**	Mean response	# of Drivers
Experience (years)	6.43	15	8.75	20	**7.8**	**27**	13.3	3
Time on RoadView	1.8 (hours)	10	2.91 (hours)	14	**1.5 (hours)**	**27**	1.67 (seasons)	3

Source: "A Rural Field Test of the RoadView System."[5] AHMCT draft unpublished report.

The PATH report suggests that for some drivers, "information overload" may have set in with this approach, or, the brief training period may have been less thorough. It also noted that there may have been some confusion for a few drivers between the RoadView and ADOT-3M systems, which was reflected in their responses. The overall survey responses by the ADOT operators on the RoadView system were positive and were generally similar to the ratings and comments of the Caltrans drivers.

Two areas of interest, or concern, were noted by PATH as to the overall driver-confidence levels for the RoadView system. First, some of the operators from both states were found to be using the roadway predictive display incorrectly in their normal operations with the snowplow. This was found to be the result of training inconsistencies in past seasons.

Second, some problems with the radar warning system carried over from prior years, despite ongoing enhancements for RoadView. According to the PATH report, the comments were summed up by one ADOT driver who said that "the guidance part was flawless," but he added "they didn't have much confidence in the radar."

Specific driver concerns about the collision warning feature included inconsistent or missed warnings for both oncoming and roadside objects. Analysis of the radar performance was a factor in adding night testing to the Caltrans-PATH evaluation plan, when it became clear to all that no snowfall would bless the Arizona test site as planned.

Collision Warning Radar Evaluation

Since the data collection phase was completed in Arizona, there has been an ongoing team effort within the Caltrans ASP program to analyze and interpret the performance data from these tests. The RoadView on-board instrumentation not only saved the radar system data but also recorded a video image of the CWS display screen and the view forward of the roadway (see Figure 18). After the conclusion of the field test phase, the video data was synchronized with the plow's radar system data to determine when, where, how often, and in what conditions each of the CWS warnings was issued.

Figure 10: Night Training and Evaluation on US 180

The radar data and video records were correlated in three categories: "correct," "missed," and "false" detections. The test corridor location and road curvature were recorded for each warning situation as shown in the videotape. The radar warning zone indicated (oncoming left lane, snowplow center lane, or right lane/shoulder) was also noted. These records allowed the project team of PATH, AHMCT and Caltrans to collaborate on identifying the successful or missed warnings, and the nature of the warnings. An ongoing analysis of this data by the Caltrans team will identify potential areas for future refinements to RoadView's CWS system and software.

To document the frequency, accuracy and nature of the radar warnings, the project team analyzed 4 hours, 52 minutes and 38 seconds of videotape recorded in numerous day and night runs during the human factors testing in Arizona. The majority of the filmed runs (3 hours, 20 minutes) were at night, and these records include information from multiple runs with all three of the ADOT night-testing drivers. Overall, there were 67 RoadView evaluation runs with over 250 miles of documented driving activity on the US 180 test site. Of these, 46 runs were at night.

It should be noted that the Caltrans RoadView radar system was initially designed for multilane divided roadways such as Donner Summit on Interstate 80. The RoadView ASP system has gradually been refined over several years to develop better performance on narrow two-lane roadways, with tighter curves, more roadside obstacles and oncoming traffic. The nature of the Arizona test site challenged the ability of the CWS system. In this year's tests, the RoadView CWS radar system was field-calibrated by AHMCT researchers riding along with the ADOT operators to fine-tune the warning selectivity for this narrow, winding road with two-way traffic.

Overall, a total of 187 radar warnings were issued during the day and night recorded runs. The main focus for CWS analysis is on dynamic "car events" (oncoming or passing cars) rather than on roadside obstacles, since the lane guidance components of RoadView minimize the danger of striking a fixed object outside the snowplow's path. The final results of the RoadView team's collision warning radar analysis will appear in the AHMCT report on this phase of the program.

Guidance System Evaluation

The primary goal of the night testing effort in Arizona was to analyze driver performance both with and without the RoadView predictive guidance technology and the driver-vehicle interface display. As noted earlier, three ADOT snowplow operators participated in extensive field testing over the final three-day period. A PATH human factors researcher rode along on each run to collect observational data, to communicate tasks to the driver, and to collect driver feedback.

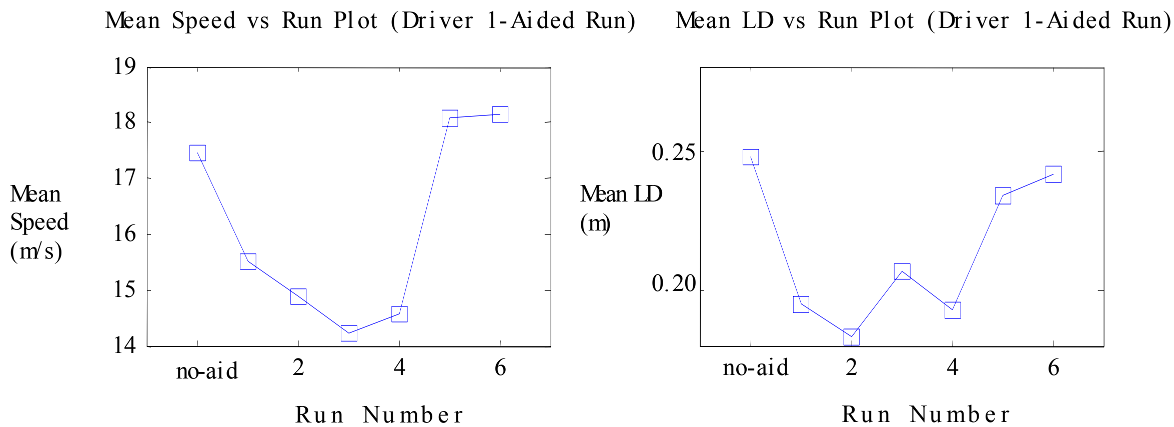

Figure 11: Driver 1 Performance on DVI-Aided vs Normal Runs

[graphic courtesy of PATH / AHMCT RoadView draft report[5]]

These three drivers included a Team Leader who had trained other ADOT operators on the evolving ASP system in the three prior years (Driver 1 in Figure 11), an experienced Team Leader who was a trainer on the ADOT-3M plow, and an inexperienced driver who had not driven the RoadView system. Most of the testing began in late afternoon or early evening, and ended about 11:00 PM. The night testing was scheduled to accommodate the operators' normal operational tasks, and it often occurred after they had already completed a full workday.

With each ADOT operator, the on-board PATH researcher directed a series of both "DVI-aided" and "normal" plow runs over the magnet-guidance test lane in darkness. Data collected for each type of run included lateral deviation (LD) from the magnet line, mean speed through the test zone, and deviations in steering wheel angle for various curve radii.

As described in the AHMCT's RoadView draft report [5], analysis of the data derived from test runs by the first driver (RoadView Team Leader) shows that in doing the aided runs, the driver initially slowed down and became more accurate (Figure 11). Then, as the trials progressed, his speed increased to slightly above the normal run, with a mean lateral deviation approaching that of the non-aided run. This indicates that after only four "aided" trial runs, this operator was able to drive nearly as accurately at a slightly higher speed.

These results will appear in more detail in the AHMCT RoadView field test report, referenced earlier, and this sample is included here to illustrate the approach and the nature of the results. While not a large sample group, the three ADOT drivers were able to improve their night testing performance significantly after just a few runs, and they could quickly transition between obtaining relevant information from the DVI display and performing normal driving tasks.

Overall DVI Conclusions

Based on the recent evaluations in both states, the PATH findings from the lateral-assistance portion of the display suggest that even with limited instruction, the system is easy to learn and that drivers can easily transition from normal driving to guidance-assisted driving.

This study has validated earlier PATH findings that a simple, low-fidelity display reminiscent of early video games increases the effectiveness of the system, and improves its level of acceptance by the drivers. The original decision to use a "low-tech" image was based on computational concerns and a need for simplicity and clarity. The field results show that high performance can be achieved without complex graphics or costly custom hardware, which has direct ramifications for RoadView's potential commercialization or deployment in the future.

Drivers' comments on the CWS radar system suggest a need to decrease the number of false and missed detections while improving the rate of correct detections. Any advances in this area will enhance driver trust and use of the system.

Feedback from the drivers suggests that in whiteout conditions, the display will allow snowplows to operate in low-visibility situations where it would normally be unsafe to plow. The results show that the DVI meets the key design goals of allowing drivers to acquire vehicle lateral information at a glance, and to switch between normal and guidance-assisted driving with ease.

The complete results of the training and evaluation will be reported in the final AHMCT report on the RoadView research program, "A Rural Field Test of the RoadView System."

NAU PERSPECTIVES ON YEAR FOUR

A key aspect of ADOT's intelligent vehicles research program from 2000 through 2002 was the evaluation partnership with Northern Arizona University. The NAU team provided ATRC with both resources and perspective for the ongoing evaluation of the two advanced snowplow lane guidance systems. Over two winters, NAU studied and experienced the two ASP lane guidance systems and their related subsystems, and they sought to develop a fair and impartial analysis for ADOT of the range of objective and subjective data as collected by ATRC, the Caltrans team, and, of course, the NAU team members.

The complete 2001-02 project report prepared by Northern Arizona University is included as Appendix F of this ATRC Phase Two(b) report. With regard to the 2001-02 Caltrans field evaluation, some of the training survey findings were reported independently by both PATH and NAU. Elements of the NAU conclusions appear in several sections of this ATRC report.

A few representative samples of ADOT driver responses to the PATH debriefing survey on the RoadView ASP are listed in Tables 5 and 6. These opinions offer an excellent summary of the perceptions of the ADOT trainers and trainees on the Caltrans phase of this project. Complete tables with all of the ADOT survey responses appear in Appendix F.

Table 5. CALTRANS Program Evaluation – Sample Comments on SYSTEM

Plow Exper. (yrs)	How would you describe the Caltrans ASP system to a new driver?	How long before comfortable?	When most helpful?
8	This system requires you to take eyes off the road and watch a screen to keep you on the road and away from oncoming traffic. It takes awhile, but not that hard to do, but you need to trust the system.	A few trips	Darkness or low visibility, any accumulation.
18	Very simple, easy to use screens, keeps you on the road, for our Roads it would be a great benefit due to mostly two lane roads with a lot of traffic. Note: this system was much easier to use than the 3M.	2 weeks	Drove only in daylight hours, it seems to work very well.
6	This is so simple I would say just do it because it explains itself.	8 hrs.	Roadway geometry (no experience with low light or white-out)

Source: "Advanced Snowplow Evaluation Program–Winter 2001–02" [6] AZTrans - NAU

Table 6. CALTRANS Program Evaluation – Sample Comments on COMPONENTS

Collision Warning comments	Lane Keeping comments	What one feature would you add?	What one feature would you remove?	Display comments
I like the 3M better, but this is very helpful too.	I like the 3M better, but this is very helpful too.	None	None	This is really good for what it is.
		Warning "Beep" when someone is in front of you.	None	Take out the governor (Hull) in a white-out to see for herself.
It works good, but it is hard to take your eyes off the road.	It works good, but it is hard to take your eyes off the road.	I like the vibrating seat from 3M would help.	None	There is more than enough information.
Gives the road features very well, in balance with driving.	Gives the road features very well, in balance with driving.	N/A, no comment, leave it the way it is.	Seems to me that the right features are on it-no change.	Work with ADOT trucks and use for a couple of years see how it works over the years, then re-assess
This is the system. We can only go forward.	This is the system. We can only go forward.	Can't see an addition	Not one	Again, this is so simple anyone with basic knowledge could get in and do it.

Source: "Advanced Snowplow Evaluation Program–Winter 2001–02" [6] AZTrans - NAU

It should be noted that most of this information documented by the Northern Arizona University project team is subjective, based on evaluation survey responses by the ADOT operators in debriefings by PATH after the individual RoadView training sessions. The NAU team's overall perspective on the results of the post-training surveys is expressed to ATRC in their unpublished project report (Appendix F) as follows:

> *"The survey instruments included several areas where comments were solicited. The responses are just as useful in evaluating the systems as is the numerical data, perhaps more so. The comments do not yield any general 'trends' that can be discerned and reported here. All the comments are important vis-à-vis improving the systems, but do not seem to universally target any specific components or features."*

VII. ADOT-3M ADVANCED VEHICLE TESTING: YEAR TWO

Arizona hosted four consecutive years of increasingly successful joint testing of the Caltrans advanced snowplow concept, but it soon became clear that ADOT needed its own full-time test program, and ownership of the evaluation process. With sponsorship from the Flagstaff District, an ADOT snowplow was equipped with a 3M commercial lane guidance system in mid-2000, and a new ASP test site was established on US 89. The development of the test lane and the equipping of the ADOT-3M snowplow were described in detail in this project's Phase Two report on the 2000-01 winter season, and are briefly discussed below.

Although the 3M magnetic tape installation in the roadway was a success, numerous problems plagued the first winter's evaluation program. Due to construction project delays, the final lane striping could not be completed in the test area, so the embedded tape was effectively misaligned with the temporary striping for the first year with the new lane guidance system. The ADOT-3M plow was also equipped with collision warning radar, but hardware problems as well as contract issues prevented the unit from being fully operational for the Phase Two winter.

This section of the report describes the magnetic tape-based research program in Year Four of the project, the culminating year of the comparative evaluation of the 3M and Caltrans concepts. Despite a near-record dry winter in 2001-02, the joint project team persevered to operate and test both advanced snowplow systems. As a result, ADOT gained the experience necessary to make sound decisions on the value of roadway-based snowplow guidance systems for Arizona.

This chapter briefly reviews the basis of the 3M tape-guidance program, and the key elements of the system's technology, with some reference text from the ATRC's Phase Two report. The next chapter discusses winter operations, and the training and evaluation effort for 2001-02.

BACKGROUND – THE 3M PARTNERSHIP

After the initial two years of the joint Caltrans ASP testing program, it was clear that Arizona's four-week time window for training and operational evaluation was insufficient to support deployment decisions by ADOT in the future. Caltrans, however, was not able withdraw the ASP from operations on the critical I-80 section at Donner Summit for longer than one month of each winter. Therefore, in 2000, the ADOT research TAC decided to acquire a guidance system for an Arizona snowplow, to determine the real benefits and costs of this IV technology.

ADOT had already invested major resources in the PATH embedded magnet infrastructure, and at first it seemed logical to purchase the Caltrans RoadView ASP equipment, but the Caltrans system was not yet ready to be deployed in 2000. The program was still in its research and development phase, and was not sufficiently staffed to provide full technical support for new customers, even long-term partners. ADOT turned to the 3M Lane Awareness System (LAS). The 3M system, based on magnetized roadway striping tape, was the only other viable guidance technology available, and it was available commercially in 2000.

The Phase Two program expansion with 3M was a critical step so that ADOT could conduct a full winter of training and testing. The LAS was fully developed, marketed, and supported by the 3M Company. Compared to the Caltrans PATH magnet system, it offered a less expensive vehicle package, and a simpler magnetic tape installation process. The costs of the magnetized striping tape material, however, would be an issue, as is discussed in the Phase Two report[2].

A Balanced Evaluation Program

For ADOT's research project, the LAS research partnership with 3M gave ATRC a sound basis for further evaluation of the new RoadView version of the Caltrans ASP system, in that ongoing joint effort. Arizona could now conduct concurrent training and testing at adjacent test sites for the two infrastructure-based snowplow guidance concepts.

As was also the case with Caltrans, an ADOT partnership offered 3M the opportunity to develop more experience in a state with its own unique climatic conditions, rural highway designs, and operating practices. In particular, Arizona's testing on mountain highways would be ideal to validate the wider marketing of this commercial product.

Figure 12: The 3M Operator Display Screen (DVI)

For ADOT to fairly evaluate the 3M commercial lane-awareness technologies on an equal basis with the Caltrans integrated guidance and warning system, some additional enhancements were indicated. To effectively match the safety features of the more advanced RoadView prototype, it was decided to also equip the ADOT plow with collision warning radar (CWS). Also, to better monitor the testing activity, the same GreyLink Automatic Vehicle Location (AVL) system that was being used by Caltrans was installed on the 3M snowplow.

While these commercial on-board systems could not be integrated with the lanekeeping system, they would raise the ADOT-3M snowplow's suite of capabilities to a nearly-even level with the Caltrans system, except for the roadway-predictive feature. The trainees could then focus their evaluations chiefly on the similarities and differences between the two lane guidance systems, including the DVI display formats, the secondary warning modes, and the lane predictive ability.

3M SYSTEM: CONCEPTS & COMPONENTS

The Lane Awareness System was designed around a magnetized form of 3M's durable striping tape. This tape has a molded surface with magnetic material embedded in it, which can be applied on the road surface, or grooved below grade, or fully embedded in the roadway paving operation. Surface mounting of this colored tape can provide lane delineation and allow striping cost savings, but the tape is also more exposed to damage during plowing.

3M's magnetic guidance tape is manufactured in 200-foot (60-meter) rolls, and is four inches (100 mm) wide and about 1/8 inch (2.3 mm) thick. The magnetic polarity alternates at one-meter intervals. This positive-negative field reversal is detected by on-board magnetometers to define the truck's lateral position relative to the embedded tape.

Figure 13: Installation of 3M Tape During US 180 Roadway Construction

This 3M Lane Awareness System provided a fully developed, robust and less complex product as a proven commercial baseline for ADOT's comparative evaluations of the Caltrans RoadView ASP system. The 3M concept offered a practical option that could be deployed immediately, if it proved to be suitable for the regional needs and conditions in Arizona.

The 3M Magnetic Tape Test Site

ADOT selected US 89 for the 3M installation, ten miles north of Flagstaff near Sunset Crater. This route was being rebuilt as a divided highway. ADOT decided to install a single five-mile line of 3M tape between the two lanes of the northbound roadway, to use one tape for plowing snow in either lane. This halved the 3M tape cost, but required dual sensors on the snowplow. The tape was embedded between two layers of new asphalt pavement, a construction method that minimized concerns about long-term durability or possible surface damage to the pavement.

This test corridor was also selected for its several parallels with the Kendrick Park-Caltrans test site on US 180. It climbs steeply from plain into forest, runs for about a mile at 7300 feet, and then descends steeply into open country. The site is directly over the mountain from Kendrick Park, and has similar weather conditions in major storms. US 89 carries about twice the average traffic volume as US 180, and it also carries a higher number of commercial vehicles.

The Sunset Crater test site is about 30 road miles, or a 45-minute drive through Flagstaff, from the US 180 Caltrans test site. This proximity would enable the evaluation program to proceed more efficiently, with ADOT snowplow operators being trained at both sites in one day.

After the 3M tape was embedded in the new pavement, temporary lane striping was applied and traffic was routed onto the new northbound roadway. The US 89 construction project would not be finished until the following summer, so the temporary striping would provide the northbound lane alignment for the Phase Two, 2000-01 winter.

This striping layout presented major problems for the ADOT snowplow testing. The magnetic tape was laid on the final design centerline of the lanes, but the temporary paint stripe was offset by as much as three feet to either side of the buried tape. Under these conditions, the 3M Lane Awareness System could not be fully effective in either training or during storms, although short segments were still usable with calculated offsets during Phase Two.

For Phase Two(b), this 2001-02 winter, the striping problem was eliminated, as the construction project was completed in mid-2001.

Vehicle System Installation – ADOT-3M Snowplow

Given the opportunity to develop an ADOT advanced snowplow for the 3M evaluation, the Flagstaff District selected a 400 horsepower 1999 Mack tandem axle Model RD688S, assigned to the Gray Mountain maintenance camp on US 89. These trucks are equipped with 11-foot nose plows, wing plows, sanders and chemical tanks. This plow truck, F342, was one of the district's newest, as ADOT was then upgrading its fleet of older International, White, and Autocar plows.

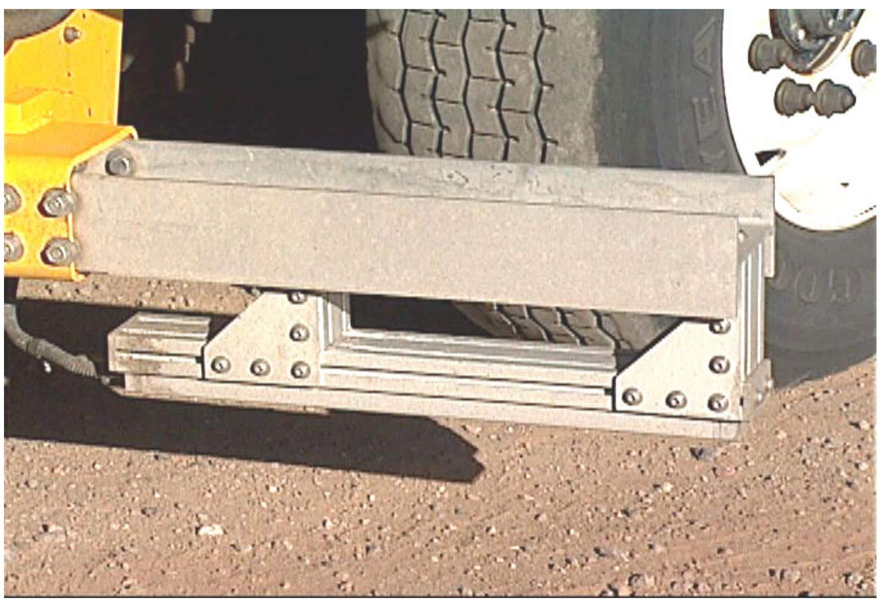

Figure 14: The 3M Sensor Bar on ADOT Plow F342

The 3M tape sensor bars, 24 inches long, were mounted on the left front bumper and the right cab step on the frame of the vehicle. The optimal mounting height is 12 inches above the tape. As the bars sense the magnetic field a lane-position reference is provided to the operator on a display screen, as well as lights and by vibrotactile alerts.

The LAS display screen was positioned on the dashboard, just below the operator's line of sight to the right-hand rearview mirror. For the ADOT evaluation, two peripheral-vision warning lights were also mounted on the windshield, four inches above the dashboard, but the primary driver warning method for the 3M LAS concept was a pair of vibratory warning alerts in the operator's seat cushions.

The 3M system offered a choice of operator-warning modes to the ADOT drivers, who could switch between the peripheral-vision lights and the seat vibrators. Both would be triggered if the truck drifted outside of its lane alignment. Driver reactions were quick and intuitive, to steer away from the stimulus and to scan the display screen for guidance. To keep the driver's focus on the road, the lights and seat vibrators were the primary warnings, but they were augmented with a display screen that served as a secondary reference to graphically show position details and on-board system data (Figure 12).

Early in Phase Two, in December 2000, the project suffered a major setback when the 3M Company discontinued the commercial production of the Lane Awareness System. For ADOT's benefit, 3M committed to provide full technical support and product services, including the warranties on all system elements. This support carried over into Phase Two(b) of the project.

ADOT achieved its key research goal by creating a second test lane in Arizona for a guidance system comparable to the RoadView ASP. The 3M system was the commercial state-of-the-art, and it was a valid baseline for ADOT to evaluate the Caltrans system, and for future decisions. Arizona now had the only high-altitude testing area in the country with both magnet-based concepts in practical quantities, and in regular use in winter storm operations and research.

ADOT-3M ASP SECONDARY SYSTEMS

Eaton VORAD Radar System

Knowing that the cost would be quite high to retrofit ADOT snowplows with lane guidance systems, the project TAC also was interested in on-board warning systems with no permanent infrastructure, which may add only a small premium to a vehicle's total cost. Based on the RoadView model for advanced snowplows, a collision warning radar system (CWS) would be needed, so an Eaton VORAD EVT-300 radar system was added to F342, the ADOT-3M ASP.

This stand-alone commercial CWS would provide a robust, reliable and proven warning system not only in the worst winter storms, but in normal highway operations year-round. This safety system could apply not only to snowplows, but also to other heavy trucks in the ADOT fleet. The EVT-300 was also the same basic CWS as was used on the Caltrans RoadView snowplow, but with significant additional refinements and fully integrated warning displays.

ADOT snowplows use large, relatively high plow blades that restrict visibility directly in front of the truck, so F342 required a rooftop mounting for the CWS radar antenna (Figure 15). Also, a small blind-spot antenna was mounted on the right side of the vehicle.

Unfortunately, there were both hardware and warranty problems shortly after the installation, and the forward-warning system was not in use for the winter of 2000-01. However, all issues were resolved and the EVT-300 system was made fully operational for this Year Four evaluation.

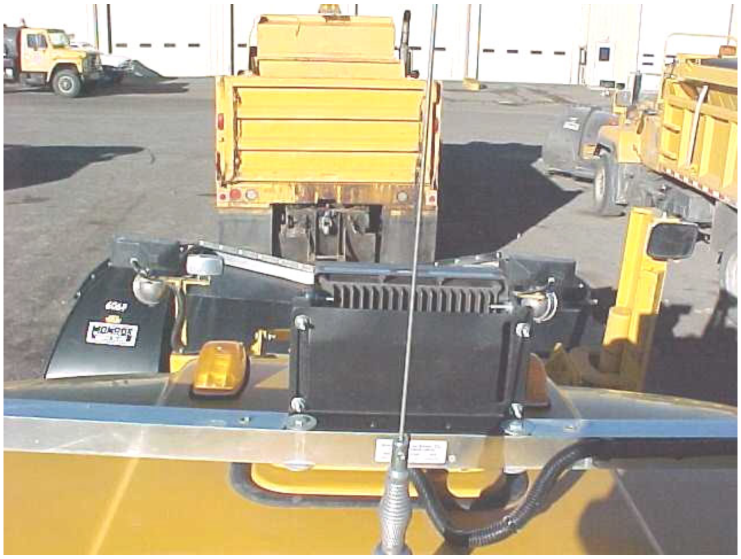

Figure 15: Eaton VORAD Radar Antenna Installed on ADOT Plow

GreyLink AVL System

The other key element for the desired direct comparison with the Caltrans RoadView snowplow was an Automatic Vehicle Location system. As noted earlier, the RoadView ASP was equipped with the cellular-based GreyLink 1000 AVL system from Greystone Consultants. ADOT was logically constrained to test the same AVL system, in order to monitor both ASP vehicles in the joint evaluation program.

Two mobile AVL units were procured for testing, with the software installed on a workstation at the Flagstaff District Snow Desk. Plow F342 was equipped with a basic hard-wired installation, and a portable unit was also evaluated in several other ADOT vehicles.

Operationally, due to spotty cellular service and very heavy call traffic, especially during storms, it was difficult for Flagstaff's Snow Desk staff to get consistent AVL tracking results with either the Caltrans or the ADOT-3M research snowplows. Nonetheless, the GreyLink AVL system was a functional resource that provided location and traveled-route information, but it was always hampered in Flagstaff by poor cellular service, phone-line and modem problems, training issues, and other concerns.

VIII. THE ADOT-3M SYSTEM: US 89 TRAINING & OPERATIONS

With the numerous first-year system and roadway infrastructure problems of 2000-01 finally resolved, the primary Year Four goals of the ADOT-3M evaluation program were to conduct a full winter of normal snowplowing operations with the on-board IV systems, and at the same time, to support the training and evaluation efforts of the research project.

The long-delayed research focus would be to evaluate the general effectiveness and ease of operation of the 3M magnetic-tape lane guidance system on US 89 at Sunset Crater for a full winter. The second key research objective was to directly compare the ADOT-3M plow with the RoadView ASP using the Caltrans magnet-guidance system on US 180 at Kendrick Park. A basic goal of the comparison was for the driver training and evaluations to be done on the same day, in back-to-back sessions at the two ASP test sites.

LANE AWARENESS SYSTEM TESTING AND EVALUATION

The ATRC's evaluation plan depended on scheduling a large number of ADOT equipment operators from across the I-40 corridor to be trained on both advanced snowplow systems in the same day. During this phase of the program, each district was to send two or three snowplow operators each day for orientation and training on the two ASP systems. These drivers would provide evaluation perspectives that were based upon their diversity of age, experience, training, equipment, local terrain and conditions, and also their receptiveness to new technology.

The key metric in Year Four would be the ADOT operators' reactions to learning about and test-driving both advanced snowplow systems in a single day of training. For the LAS evaluation, the ADOT-3M field activity was phased over the winter as operational schedules would permit, except for the brief but intensive joint ASP training phase with Caltrans. The project's detailed workplan for Year Four is included as an Appendix, but the key ADOT-3M program schedule elements were:

- 3M system calibration and validation – November/December.
- System upgrades (e.g. AVL Cellular Antenna) – November.
- Regional testers training & evaluations - weeks 1 & 2.
- Phases of evaluation by Gray Mountain crew - early winter vs. late winter.
- Long-term field evaluation on US 89 - November through March.

Overall, the schedule was achieved, with excellent support in both operations and training by the ADOT Gray Mountain personnel involved. This level of participation was a greater challenge for a snowplow in the ADOT maintenance fleet, rather than a research prototype. This vehicle had an assigned plow route as well as other maintenance functions to support, as did its crew. Nevertheless, the Team Leader operators assigned to snowplow F342 carried out the 3M system orientations and training exactly as planned for the other drivers from across the three districts. This commitment by Gray Mountain to concurrent support of the Caltrans team's joint training efforts on US 180 enabled ADOT's side-by-side ASP evaluation concept to succeed.

A great deal of effort was required to organize and initiate the project workplan for each phase of evaluation at both the 3M and Caltrans test sites. The following activity list from the ATRC's workplan illustrates the extent of the prior planning involved and the roles of the key ADOT participants in the field:

ADOT-3M System Training & Evaluation Workplan - Goals and Tasks

- Confirm F342 snowplow system is operational; define maintenance procedures.
- Confirm site conditions & traffic control at US 89 test site.
- Concurrent evaluation of peripheral systems: CWS radar and AVL.
- Training of ADOT Team Leaders (TL self-training).
- Regional testers training; complete NAU & ATRC driver surveys *(both sites / same day)*.
- ADOT Team Leaders to complete testing activity shift reports.
- Long-term Flagstaff District evaluation site: northbound US 89 at MP 428 to 433.
- Full plow route for evaluation: East Flagstaff to Antelope Hills (US 89 MP 418 to 440).

As discussed earlier with regard to the Caltrans activity, the regional training program was quite successful. Snowplow operators from across northern Arizona came to Flagstaff to get an introduction to both systems. Most of the ADOT plow operators were able to visit the two test sites, at Kendrick Park on US 180 and at Sunset Crater on US 89 in a single long day. Despite occasional scheduling issues, 18 ADOT snowplow operators from three districts participated in the 3M system evaluation survey, as well as two Caltrans ASP program staff.

In general, the results of the second season of snowplow tests with the ADOT-3M system are a valid basis for agency decision making, and a great deal was learned about both the system's potential, and its merits relative to the Caltrans RoadView system. Both the training evaluation and the full winter's evaluation were completed successfully, as discussed in the sections below.

ADOT-3M: YEAR FOUR OPERATIONS

The ADOT-3M research snowplow F342 was used operationally on US 89 in the Sunset Crater area in a number of moderate snowstorms during this Year Four winter. Although the overall winter weather was relatively mild in 2001-02, the radar repairs and striping issues were fully resolved for this season and the snowplow was frequently out plowing or patrolling on US 89.

During this winter, significant snow events from November to March produced a measurable total of only 39 inches of snow. The records of the Sunset Crater, Walnut Canyon, and Flagstaff Pulliam Airport regional weather sites show 11 days when one or more locations had more than one inch of snow, and a total of 35 days recorded at least a trace of snow.

Depending on the forecast conditions, ADOT snowplows would be on call or on patrol during many if not most of these potential storm dates. The ADOT-3M snowplow logged over 4,000 miles in Year Four just between December and February, primarily on the 22-mile Sunset Crater route between Flagstaff and Antelope Hills. These miles included both the training program and the sporadic snow patrol and plowing activities. While a few of the F342 snowplow activity reports were lost, they showed heavy snow and zero visibility in at least one storm.

Overall, the Gray Mountain snowplow operators reported that the 3M system was very effective in low visibility and blowing snow. They also noted that the vibrating seat was effective and did not require them to frequently look away from the road to the display screen. The only drawback noted for the 3M display, from the operators' perspectives and training on the RoadView ASP, was that it showed the truck's lane position but could not predict the curvature of the road ahead.

Since many ADOT snowplow operator had prior experience with the Caltrans predictive system, there were frequent references over the winter to the more powerful and costly second-generation concept. On the other hand, in the spirit of two-way technology transfer, several of the ADOT operators also suggested that Caltrans should install one of the 3M vibrating seats on the RoadView snowplow.

ADOT PARTNERSHIP WITH NAU

A key aspect of ADOT's intelligent vehicles research program from 2000 through 2002 was the evaluation partnership with Northern Arizona University. The NAU research team provided ATRC with both resources and perspective on the Caltrans and 3M systems.

Over two winters, the university team studied and experienced both competing guidance systems and their related subsystems, and they sought to develop a fair and impartial analysis of the range of objective and subjective data that was collected by ATRC, the Caltrans team, and NAU.

NAU had several key contract tasks to complete the evaluation plan for Year Four. For several reasons, this plan could not be fully executed, and the workscope eventually was reduced. For 2001-02, the critical factor in conducting a thorough evaluation was the weather. As noted earlier, there was fundamentally no snowfall in the Flagstaff region during the month when both the Caltrans RoadView and the ADOT-3M plows were being tested simultaneously.

Figure 16: ADOT Plow F342 Ride-Along Simulation on US 89 In Clear Weather

The key comparative activity that could not be effectively performed by the NAU team was "ride-along" monitoring of CWS radar and AVL tracking systems in severe weather. A second goal that was not achievable was to recreate and analyze the snowplow operations from a major storm event. With no major storms and poor AVL performance, this task was not feasible.

On the other hand, the NAU team was successful in developing several other key deliverables, including the third-party analysis of driver survey rankings for both lane guidance systems, and the review and interpretation of driver subjective feedback. Another accomplishment was to refine and carry out an update to an earlier Phase Two survey of low-visibility lane miles for the entire state highway system (a process repeated again in Year Five, to better capture ADOT's increased awareness of regional-scale visibility issues and advanced technology capabilities).

It should be emphasized that the ADOT-3M advanced snowplow systems were not equipped for recording of driver and system performance. Because this F342 plow was in use operationally all winter, there was not a requirement for testing in a repetitive on-board simulation program, as was done by Caltrans and PATH due to the mild weather and lack of snowstorms in February.

Results of the LAS Test Program: NAU Perspective

The results of the training and evaluation were documented and analyzed for ADOT by the Northern Arizona University project team, with driver surveys provided by ATRC and with supporting interviews and orientation rides. Most of the information developed is subjective, based on evaluation perspectives provided by the operators following their training. NAU's perspective on the survey responses overall is expressed in their project report as follows:

> *"The survey instruments included several areas where comments were solicited. The responses are just as useful in evaluating the systems as is the numerical data, perhaps more so. The comments do not yield any general 'trends' that can be discerned and reported here. All the comments are important vis-à-vis improving the systems, but do not seem to universally target any specific components or features."*

Representative samples of Lane Awareness System driver comments, as summarized by NAU's evaluation team, are presented in Table 7 below. The complete NAU report for Year Four, with all of the ADOT driver survey responses tabulated, is provided as Appendix F to this report.

Table 7: ADOT-3M Evaluation Questionnaire Sample Comments on SYSTEM

SnowPlow Exper. (yrs)	How would you Describe the 3M ASP system to a new driver?	Time to be comfortable?	When most helpful?	System may cause error?
6	It keeps your truck in the proper lane and position within a foot or so, and gives correction if truck strays.	A day or so	In white out or near conditions, day or night.	No, did not see how you can get wrong info.
3	Like the seat & light system, screen has too many things to pay attention to.	1 day	89A Airport to Rim Camp	No
18.7	Its lets you know where you are during white outs, where the traffic is on side & ahead of you, from running into the ditch and running into someone else, staying on the road.	My first test drive I felt that, I was comfortable.	In any conditions (low visibility), preferred night time. Roadway alignment for two lane roads I think it would benefit the most.	Not really familiar with it to make a comment.
7	Magnetic tape keeps you in lane, radar makes you aware of obstacles around you.	A few shifts of plowing	Darkness, low visibility, high visibility. You could clear a lane easily with this system in snow depth due to the 3M systems.	Not really
17		One trip with experienced operator.	Darkness, low visibility	Yes, if the system doesn't function correctly.

Table 8: ADOT-3M Evaluation Questionnaire Sample Comments on COMPONENTS

3M Lane Position Display comments	3M Warning System comments	Eaton VORAD Radar comments
Did not use as much as the seat	I liked it, think it could make plowing less stressful, safer, more efficient.	Could be used year round, not just snow season.
With the big screen very easy to notice, you just have to glance over to know where you fit.	Very informative, lets you know where you are. Anything helps after operating a plow truck for 18 yrs.	Very good for traffic in front of you, but traffic coming up behind you I cannot tell if there was one.
Very easy to understand.	Would be nice to have something like this to use during storms.	I wish all trucks throughout the state had this (for safety if nothing else).
Keeps you in safe manner, lane position for snowplowers.	Need a beeping warning sound same with lighting systems.	Warning systems is…need Radar for what up in front of you.
Very well done, very positive.	Vibrating seat is best, but lights are good too.	I wish they would put this on all trucks now! I could use this.

Source (both): "Advanced Snowplow Evaluation Program–Winter 2001–02" [6] AZTrans - NAU

As with the responses to the Caltrans RoadView survey questions, these driver opinions provide interesting and sometimes unintended insights on the success (and pitfalls) of the back-to-back, same-day introductory training. Many drivers alluded to Caltrans in commenting on the 3M system, and vice versa.

While the 3M guidance system design was long since crystallized as a commercial product, the prototype Caltrans RoadView ASP system was still open for positive feedback with regard to the driver interface and to other key features. Constructive feedback from ADOT drivers with experience on other systems was a key reason for Caltrans to maintain the joint ASP evaluation partnership through four winters.

The ADOT-3M research snowplow carried three stand-alone ITS systems (3M lane guidance, CWS radar, and AVL), and the long-term prospects for each individual component would be determined by the ADOT snowplow operators' feedback through this research project.

IX. YEAR FOUR RESEARCH RESULTS: WINTER 2001-02

SUMMARY OF RESULTS

This Phase Two(b) winter of ADOT's advanced snowplow research program was considered a success by the key partners and stakeholders, despite the lack of snowfall during the evaluation. As noted in earlier chapters, the research project for the first time was able to conduct parallel introductions to the two competing systems for a large group of ADOT snowplow operators from all across the northern third of Arizona.

The comparison of system concepts, and approaches to the human-machine interface, allowed ATRC to record a variety of subjective and objective results from the participating snowplow drivers, with a spectrum of prior experience. The season's results would effectively support further decisions by the TAC regarding recommendations for future research and deployment.

System Concepts

The two sets of tabulated ADOT driver reactions to the individual Caltrans and 3M concepts are combined below. This table is a summary of the subjective rankings, and is not a direct side-by-side comparison. The Year Four survey instruments and the training regimen were not identical, either in general focus or in detail. Still, these strong positive rankings for both systems reflect the potential to improve snowplowing operations in rural Arizona through such technologies.

Table 9: Subjective Independent Rankings – Comparable Factors For Two Concepts

Comparison of ASP Training & Evaluation Surveys: March 2002	CALTRANS (US180) (27 surveys)	3M (US89) (20 surveys)
	Mean	**Mean**
Operator Background Information		
How many years have you been a snowplow operator?	**7.8**	**7.7**
Rate your own level of expertise (1 = novice → 5 = expert)	**3.7**	**3.8**
Overall Satisfaction with Driver-Assistance / Guidance System		
How easy is the system to use overall? (1 = very easy → 5 = not easy)	**2.1**	**1.9**
How much do you like the system overall? (1 = a lot → 5 = not at all)	**2.0**	**1.6**
If you had more time to practice with the system, would you like it more? (1 = yes → 5 = no)	**1.7**	**1.7**
Would this system increase your safety in snow removal activities? (1 = yes → 5 = not at all)	**1.6**	**1.3**
Would this system increase your efficiency in snow removal? (1 = helpful → 5 = not helpful)	**1.9**	**1.6**

Source: "Advanced Snowplow Evaluation Program–Winter 2001–02" [6] AZTrans - NAU

Table 9 above was derived from the more detailed summaries developed by NAU, from their final project report (see Appendix F). This table does not provide a direct comparison between systems. It is a reflection of the level of satisfaction with each system, captured after the on-site training session. All of these response-means show a relatively high degree of acceptance on this 1 – 5 scale.

While the differences are not statistically significant, they do provide some insights on the ability of these skilled snowplow operators to quickly evaluate the two lane guidance systems, and key individual elements, with regard to the potential benefits during severe winter storm conditions.

Table 10: Subjective Independent Rankings For System Components

Comparison of ASP Training & Evaluation Surveys: March 2002	CALTRANS (US180) (27 surveys)	3M (US89) (20 surveys)
	Mean	**Mean**
Operator Ratings of Individual Driver Assistance Functions		
LANE GUIDANCE: How easy is this to use? (1 = very easy → 5 = not easy)	**2.0**	**2.0**
LANE GUIDANCE: How much do you like it? (1 = a lot → 5 = not at all)	**1.9**	**1.7**
COLLISION WARNING: How easy is this to use? (1 = very easy → 5 = not easy)	**2.0**	**1.9**
COLLISION WARNING: How much do you like it? (1 = a lot → 5 = not at all)	**1.9**	**1.8**

Source: "Advanced Snowplow Evaluation Program–Winter 2001–02" [6] AZTrans - NAU

Table 10 above aggregates the ADOT snowplow operators' perceptions of the primary warning components of the 3M and Caltrans advanced snowplow systems. Because the two concepts, and the evaluation programs, each had a certain number of unique elements, it is not possible to present the responses as direct comparisons with conclusive results. This table was derived from the more detailed summaries developed by NAU for their final project report.

The driver rankings are also reflected in the trends of their comments on the ASP systems and components, as excerpted in the earlier chapters on system training and evaluations. Some issues were also noted that would require further attention by the system developers. As noted by the NAU research team in their report, these subjective responses to open-ended questions provide a great deal of insight, and reinforce the level of confidence with regard to the ability of ADOT's plow operators to take full advantage of these advanced systems if they are available.

Training And Evaluation

Both advanced snowplow systems were the focus of brief but intensive training cycles during February of the Year Four winter of the project. For most of the ADOT drivers, the training was done consecutively, with 27 being trained on the Caltrans RoadView plow and 18 of those also receiving training on the 3M system; two RoadView staff also evaluated the ADOT-3M ASP.

As described in the preceding chapters, this side-by-side approach was quite successful as a large contingent of ADOT operators from across northern Arizona did in fact come to Flagstaff and take training on both snowplows, at both sites, in the same day.

Figure 17: Advanced Snowplow Research Partnership
(At left: Caltrans RoadView ASP; at right: ADOT-3M ASP)

The ATRC's evaluation program was validated by the overall level of training and testing done, and by the level of ASP system reliability that was achieved during the 2001-02 winter. The previous Phase Two winter had provided valuable experience, but both systems had suffered major setbacks due to technical and radio problems with the Caltrans plow, and striping and radar issues for the ADOT plow. Now, during Phase Two(b), both research snowplows were almost universally operational, and they logged sufficient training and operating miles to provide meaningful results.

A particular success in 2001-02 was the ability of the Caltrans team to conduct prolonged night training exercises with three ADOT snowplow operators. This provided significant new data regarding individual driver reactions to the system, and a better perspective on the learning process. Other significant information was also collected, including warning radar performance data for two-lane roadways.

Winter Operations

Earlier chapters of this report described the limited operational usage of both snowplows due to the dry winter season overall. In particular, the Caltrans snowplow was never effectively put to use on US 180 during any significant storm, as no snowfall occurred during its Arizona activities.

This situation was a disappointment to the entire Caltrans ASP project team, as previous visits to Arizona had resulted in significant and effective field activity for the RoadView snowplow. One other negative factor was the failure to install an ADOT radio to allow full operational usage in storms. Nonetheless, the RoadView plow was fully functional during the five-week Arizona test period. It logged over 1,500 miles of activity, primarily in training, for the 2001-02 winter.

The ADOT-3M snowplow had better operational results in a number of minor storms on US 89, although the entire winter season brought only a fraction of the normal average snowfall. As described earlier, snowplow F342 was used extensively through the winter for training, storm patrol, and snowplowing, and it recorded over 4,000 miles in less than three months. On at least eleven dates from November through March, significant snowfall was recorded in the region patrolled by F342 along its US 89 route.

YEAR FOUR CONCLUSIONS

Phase Two(b), the 2001-02 winter, was the most critical season to date for the ADOT snowplow research project. This was the year when the key systems performed consistently and reliably, but the Arizona winter did not. While these two advanced snowplows did not face any record snowstorms during the winter, the level of system reliability, extensive driver feedback analysis, and weather-limited operational success all contributed to a high level of satisfaction for the project team and its sponsors.

This project phase completed a second winter season of side-by-side training, evaluations and testing on each of ADOT's two infrastructure-based vehicle guidance system test sites. This Year Four project winter was the second full season of operations and training for the ADOT-3M snowplow, fulfilling the TAC's most fundamental mandate for the research project. This was also the fourth year of Caltrans RoadView snowplow partnership activities, demonstrating the long-term potential for the concept as it became more reliable and robust for each winter season.

Nevertheless, critical issues existed for the research program. While the winter weather could not be forecast, it was clear to the Arizona TAC members and the project team that enough had been learned, after four winters, to make some realistic decisions on the future for ADOT of these roadway-based guidance systems.

Future Project Planning

Further ADOT testing of these roadway-based systems would be redundant unless there are significant new enhancements by the development teams. However, new developments are not planned by Caltrans for RoadView, which will be deployed operationally. New efforts are not expected from the 3M Company, which no longer markets the Lane Awareness System.

Considering the costs, the limited availability of both roadway-based systems, and the near-term resources for the project, ADOT's research TAC concluded that the snowplow program should continue for another winter, but that further efforts should be radically redirected.

The TAC decision process and future research plans will be discussed in the following chapter, which also provides a detailed review of the program results from the past four years of ADOT's research into advanced snowplow guidance systems.

X. JOINT TEST PROGRAM REVIEW AND RESULTS: 1997 - 2002

FOUR WINTERS OF ADVANCED SNOWPLOW EVALUATIONS

Since the first Arizona demonstrations in 1997 and 1998, this long-term research project has explored AHS and IV technologies and concepts as potential solutions for a variety of highway congestion and safety problems. From the outset, the goals of this Arizona Intelligent Vehicle Research Program have been to improve highway safety for travelers and for ADOT personnel, to defer more highway lane construction, and to improve regional air quality across Arizona.

Figure 18: Caltrans Instrumentation for Night Testing on US 180

[graphic courtesy of PATH]

Winter maintenance activity, especially snowplow operator safety and efficiency, became the primary research focus almost from the beginning, due in part to the willingness of California to partner in a joint research program that would create an Arizona winter testing facility.

ATRC's advanced snowplow systems research program initially invested two years in evaluating the Caltrans ASP guidance technology in Arizona. This effort was expanded over two additional winters to compare the commercial 3M Lane Awareness System with the upgraded Caltrans RoadView prototype ASP. Several global issues constrained the Year Three evaluations, and the Year Four side-by-side training and testing program was hampered by mild winter weather.

Roadway-Based Lane Guidance Systems Comparison

Partnering with California provided Arizona with an ideal opportunity to participate in a very sophisticated research program, despite the funding limitations of the ATRC research program. ADOT and ATRC had only a limited Intelligent Vehicle project budget, with no facilities to conduct ITS system development of this magnitude for an ADOT snowplow. While other states were invited to join the Caltrans ASP project, only Arizona made the actual commitment to a research partnership that offered full hands-on access, for one month each winter, to one of the most advanced snowplow technology concept vehicles in the United States.

In committing to this joint project, ADOT's key contribution was to create an independent test lane or corridor, for which US 180 near Flagstaff was selected. While the direct project cost of installing six lane-miles of magnets was substantial, ADOT also provided crucial intangible support from the three district staffs, the involved maintenance camps, and the equipment shops.

Overall, ADOT has gained four winters of experience with the Caltrans ASP program, including two years of side-by-side comparisons with the 3M concept. Despite occasional problems with equipment and setbacks due to the weather, this comparative evaluation over the past two winters was successful in every respect. For both the primary and secondary IV systems, ADOT and its project partners have developed realistic cost information as well as valuable training and performance records.

Costs of Roadway-Based Driver-Assistance Systems

As reported in full detail in ATRC's two earlier project reports, the real cost to ADOT for either infrastructure-based guidance system becomes a complex question. The cost of the 3M Lane Awareness System was $132,000 for five miles of magnetic tape, installed at negotiated rates and markups by the US 89 construction contractor. Placing the 3M tape between the travel lanes of the northbound roadway allowed two lane-miles to be effectively instrumented with each mile of 3M tape. The approximate ADOT tape infrastructure cost therefore was only $13,200 per lane-mile in mid-2000. This approach could be similarly effective on all roads with two-way traffic.

This compares to the $17,500 average lane-mile cost of the Caltrans magnet infrastructure as installed by ADOT in 1998 and 1999. However, that figure reflects relatively low ADOT labor rates, and other internal support such as equipment loans and other resources, and ADOT's labor-intensive magnet installation cost figures include no profit factors.

By early 2002, the potential did not appear promising to improve the cost situation for either of the roadway-based vehicle-guidance systems. The use of 3M tape on the centerline between two lanes halved the effective cost of installation, as noted above, but left and right sensors added incrementally to the cost of the vehicle system. The tape cost was discounted to some extent for the research effort, but the construction contractor's costs for a late project change order were higher than if included in the original US 89 project design and specifications.

Therefore, this 3M infrastructure cost of $13,200 per lane-mile would be reasonably close to the cost of adding further sections of tape as an element of Arizona roadway construction projects. The equivalent unit cost for the Caltrans magnet infrastructure, as installed by ADOT forces, was $17,500 per lane-mile. The costs of labor, burdens, profit and other factors would be higher for this work also, if done with contractor crews and equipment.

The Caltrans team, meanwhile, has used an estimated capital cost of $18,000 per lane-mile for planning purposes in 2002. The Caltrans research program has recently achieved some savings with the use of heavier drilling equipment, but without accelerating the magnet layout, drilling, and placement steps, any gains at this point have not been significant. This is a critical issue for future commercialization of the magnet-guidance concept by Caltrans and its partners.

A second major concern is the on-board vehicle system. The RoadView ASP integrated vehicle system had originally been targeted for deployment at $25,000 per unit, while estimates from the Caltrans team in 2002 indicated an installed cost estimate of around $30,000 per vehicle. This is higher than the 3M on-board system cost of $14,500, plus $3,000 for CWS radar, and it is not yet considered achievable as the Caltrans program moves toward regional deployment in 2002-03.

From ADOT's perspective it seems reasonable to conclude that, at current 2002 levels of cost, the RoadView system would be cost effective only in areas with very high traffic volumes and numerous road closures due to severe winter weather.

Other Roadway Infrastructure Issues

The costs described above for the infrastructure-based lane guidance systems would definitely challenge the resources of the Arizona Department of Transportation. While construction projects offer the potential to install roadway guidance systems, their installation must be coordinated with reconstruction projects for the critical highway corridors where these systems may be needed the most. Otherwise, maintenance-budget funding must be used, which is a fixed amount for the individual ADOT districts. In that case, a roadway-based ASP system would require a significant share of the local roadway preservation budgets.

A second factor is the long-term life cycle cost of embedded magnetic materials. While they are safely buried in the roadway, the highway pavement itself has a finite life, and extreme winter weather is a destructive factor to the roadways where the guidance systems are needed the most. One key concern for ADOT is whether tape or magnet design modifications would be feasible in order to survive a mill-and-replace operation once the instrumented section of pavement had worn out. Otherwise, either magnetic system would have to be completely removed and replaced with the pavement. Overlays, however, would not seriously impact either embedded system.

In the larger view, these concerns were largely hypothetical in early 2002 since neither system was commercially viable, or available, at that point in time. In addition, Arizona's budget issues would defer any plans to expand the roadway-based guidance program. Finally, the recent mild winter weather also had an undeniable dampening effect on efforts to win more ADOT funding for either of the permanent-infrastructure guidance systems.

FOUR WINTERS - PROGRAM CONCLUSIONS

Through Phase One, Phase Two, and the current Phase Two(b), this research program has been quite successful in training ADOT snowplow operators on new concepts, and in evaluating the abilities and limitations of the primary and secondary ITS systems on both of the advanced research snowplows. For the Team Leader operators on this project's two dedicated snowplow routes, these systems have consistently been a significant aid to plowing operations in the low visibility of severe storms. For the project partners, their key goals were supported in Arizona.

Operationally, the research program during Years Three and Four has proven the viability of the two ASP systems, but each winter of activity suffered from negative factors. Both advanced snowplows logged significant total miles during each winter with the ASP systems in use. The operator reports from plowing in the field during these years have been consistently positive.

As noted by Northern Arizona University, both roadway-based systems received positive survey rankings from the operator introductory sessions, indicating a high degree of acceptance for the concepts of low-visibility snowplow guidance systems. The driver comments were consistently positive as well, while predictably offering numerous suggestions for further improvements to both system concepts.

The most basic result of four years of the ADOT snowplow research program is the confirmation that both Caltrans and 3M had successfully developed effective, user-friendly, robust and reliable driver-assistance systems, which if deployed on Arizona's highways would provide significant benefits for winter maintenance operations in extreme storm conditions.

For this research program to date, the impacts of the variable weather, equipment and roadway problems have constrained a clear identification of the potential benefits. At the present time, commercial system sourcing and cost issues preclude any clear determination of the relative value of each of these infrastructure-based guidance systems for a wider deployment.

TECHNICAL ADVISORY COMMITTEE SURVEY ON FUTURE RESEARCH

The ATRC in early 2002 was faced with dwindling research project resources, and was receiving growing sponsor input that little more could be learned from further joint lane guidance testing. It was clear that realistically, ADOT needed another approach to provide effective support for its snowplow operators in the range of winter storm conditions that exist all across Arizona.

Over four winters, the project's TAC members had learned a great deal about the potential of ITS technology to enhance the safety and efficiency of winter operations. Both of the magnet-based concepts were found to be relatively high in their roadway installation cost, and the overall durability of the embedded magnetic materials depends on the useful life of the pavement. The significant vehicle system costs were also a factor.

The TAC and the ATRC initiated a review of the Intelligent Vehicles research program in May 2002. A project survey was sent to the stakeholders to review what had been learned, and what other research was warranted in the area of advanced snowplow technologies. Questions included the "pros and cons" of each snowplow system, and the overall value of each for ADOT.

The responses of the TAC members to this survey dictated a clear change in the future direction of the research. Feedback came from the department's state management level, from the partner districts and maintenance camps, and from the project's Team Leader snowplow operators.

The key TAC opinions are summarized below, and the complete survey appears in Appendix E. After four years of this research program, the overall ADOT stakeholder consensus on *the future potential in Arizona* for the several guidance and warning system types is summarized as follows:

TAC Survey Consensus on Direction – Summer 2002

- Caltrans RoadView Guidance System - <u>Negative</u>
- 3M Lane Awareness System - <u>Neutral</u>
- Collision Warning Radar - <u>Positive</u>
- AVL Tracking System- <u>Negative</u>
- Infrared Night Vision (untested) - <u>Positive</u>

The ratings for each concept are discussed in more detail below:

- **Caltrans RoadView Guidance System -** The key to the TAC's negative rating is that this successful but costly prototype system does not have a deployment potential for ADOT in the near future. It is the more advanced driver-guidance system, but the costs of both the on-board system and the roadway magnets are quite high. The effect on pavement life, the magnet maintenance and durability concerns, and the lack of progress on installation costs are all negative factors; more testing was not recommended at this time.

- **3M Lane Awareness Guidance System -** The TAC was split on the 3M system, resulting in a neutral rating. It is simple and effective, but costly. It works well, but does not predict the road ahead. Technical support from 3M was very good, but there is no realistic potential to deploy it beyond the single US 89 site, since 3M has given up this market segment. The TAC recommended the continued use of the 3M LAS system on US 89 for normal roadway operations.

- **Collision Warning Radar -** The EVT-300 collision warning radar had favorable ratings in the survey. Driver comments have been positive, but more winter testing is required. The TAC decided that the evaluation of this relatively low-cost, add-on system should continue next winter. Adaptive cruise control will also be installed so that summer tests can be conducted (without the plow blade). This feature has the potential to reduce rear-end accidents for all areas of the ADOT heavy truck fleet.

- **AVL Vehicle Tracking -** The survey indicated general disappointment with the GreyLink AVL system, and with the concept, although this system was shared with and recommended by Caltrans. This was a valuable test overall, showing that the value of a cellular-based AVL system was limited in mountainous rural Arizona operations. The TAC recommended discontinuing the current GreyLink AVL system tests for the next winter season.

- **Infrared Night Vision (untested)** – The TAC survey was quite positive about this low-cost, add-on system. While originally proposed earlier, during the snow season, a Bendix XVision unit was installed and nighttime demonstrations were held in May for project stakeholders. The TAC has recommended a full season of winter storm evaluation to verify this system's potential for Arizona conditions and practices.

PHASE TWO(B) RECOMMENDATIONS

The extensive Arizona field testing program was sufficient to support future ADOT decisions on the low-visibility, low-speed operational potential of these two roadway-infrastructure guidance concepts. <u>The original project goal was to evaluate semiautomated vehicle systems for ADOT's winter maintenance operations</u>. As described in this Phase Two(b) report, both the 3M and the Caltrans systems have been thoroughly tested and while quite effective, their future deployment in Arizona does not appear practical.

The issue now became what the project's future mission and focus should be. The crucial project decision in early 2002 was for the research to move in a more practical direction, in light of Arizona's constraints and unique conditions. The experience gained on the primary and secondary advanced snowplow systems, as expressed in the TAC survey, was clear enough to lead into a new phase of the project, with further tests of the night vision and CWS radar concepts. These two fully developed, low-cost, off-the-shelf commercial warning systems could directly benefit the ADOT snowplow operators, and therefore the public, during winter storms.

A consistent weakness of the research plan had been the inability to train snowplow operators in storm conditions. The key problem was that the partner maintenance camps could send trainees to Flagstaff only during fair weather and in daylight. Additionally, the training surveys provided by ATRC, Caltrans, and 3M were fairly general and subjective. Unfortunately, evaluations based on first impressions are of only limited value. Finally, there had never been a large sample size. The key performance data, if any, had to come from only one or two Team Leader operators in every case. None of the systems, except the Caltrans ASP, had the ability to record data to document performance and to quantify benefits.

A significant long-term problem would be how to involve project partners who were sidelined by the decision to de-emphasize the vehicle guidance systems. There would be no further group training planned for the coming 2002-03 season. The TAC felt that a much better evaluation plan would be to deploy additional on-board systems in other districts. This approach would expand the operator pool and increase the system exposure to local severe storms, as well as statewide or regional storms. On that basis, the Holbrook and Kingman Districts would each be allocated additional on-board systems for evaluation.

FUTURE RESEARCH IN YEAR FIVE: WINTER 2002-03

The Arizona advanced snowplow research program will continue with expanded operational evaluations of key systems in Year Five (2002–03). The fifth winter of this research project, in Phase Three, will refocus in two key areas. ATRC was directed to explore commercial on-board warning systems to assist the snowplow drivers, and was also directed to involve other ADOT districts in the test program, in addition to Flagstaff. These TAC decisions were due to realities of ADOT funding, and to the relative infrequency of white-out visibility conditions over long sections of Arizona highways in “typical” winter storms.

The project’s new warning-system emphasis would be on plowing more safely when vision was impaired by blowing snow, rather than on pushing ahead in near-zero-visibility storm conditions. With this mandate, and based on the TAC’s requests and recommendations for system testing, the ATRC began the process to investigate and procure several collision warning radar systems (CWS) as well as several passive-infrared (IR) night vision devices.

There was already a great deal of vendor information available to the ATRC on certain systems, and the TAC’s level of interest was significant. The project had already gained some experience with standalone systems such as radar and AVL, and other related vendor contacts were being made as well. While not all issues had been resolved, a night vision device had recently been demonstrated to the TAC, and was recommended for further evaluation.

The first new on-board system to be evaluated in depth will be the Eaton VORAD EVT-300 Collision Warning Radar. This CWS system is already installed on Gray Mountain snowplow F342, in support of the 3M system. Eaton has expressed strong interest in supporting further ADOT tests, to include additional standard CWS units and also SmartCruise, a new *adaptive cruise control* feature of the system, which has year-round potential to improve fleet safety for ADOT. The new EVT-300 units will be deployed to the Seligman, Flagstaff, and Chambers maintenance yards for testing on I-40 and on other secondary routes.

The second driver–support concept selected for testing will be the Bendix XVision system, a passive-infrared night vision system. Early contacts with Bendix indicated that ADOT could initiate evaluations of this system in various conditions by mid-2002, so that it could be fully operational before the 2002-03 winter season. While the winter storm effectiveness of the system was still unproven, the potential benefits justified the decision to include Bendix XVision in the program. With a trial unit recently installed in May at Little Antelope Camp on I-17, two more XVision units will be deployed to ADOT maintenance yards at Kingman, for evaluation on I-40, and at Winslow, for testing on the US 87 Blue Ridge plow route.

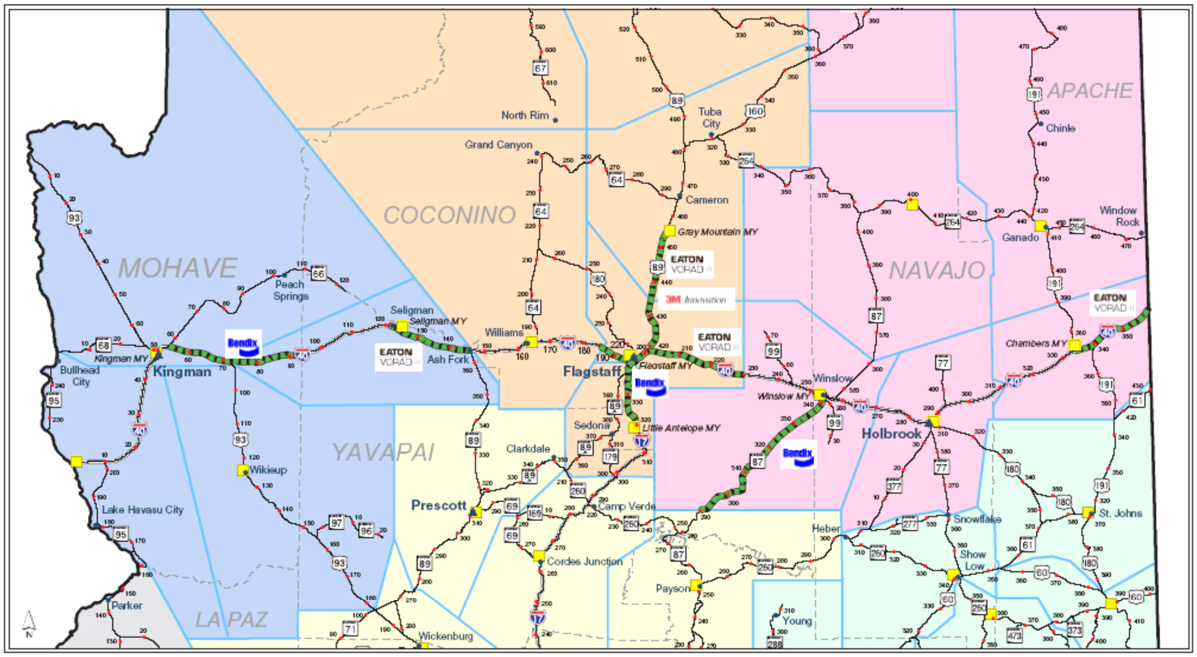

Figure 19: Proposed On-Board Systems Evaluation Sites For 2002-03

The ADOT advanced snowplow research program will focus in Year Five on field operational evaluations of the two new commercial on-board systems. The TAC's crucial project decision, to expand the number of units and test areas across northern Arizona, will allow the other partner maintenance districts to participate fully in the program for the first time, along with Flagstaff.

The TAC has recommended seven snowplow routes, shown in bold in Figure 19, for on-board system testing in Year Five. The project's seven maintenance camps are Kingman, Seligman, Flagstaff, Little Antelope, Winslow, Chambers, and Gray Mountain (both CWS and 3M).

The ATRC initiated procurement of the test units in mid-2002, and at the same time, installation support was being coordinated with the northern districts. The fifth winter of this program will be the subject of a future ATRC research report on Phase Three, the winter of 2002-03.

APPENDIX A

FLAGSTAFF DAILY SNOWFALL: WINTER 2001–2002

Flagstaff Daily Snowfall - Winter 2001 – 2002 SPR 473: Intelligent Vehicles / Snowplow Guidance Research				
Snowplow:	**n/a**	**F342**	**n/a**	
WX SITE	Pulliam Airport	Sunset Crater	Walnut Canyon	
ROUTE	I-17	US 89	I-40	
MP Loc'n	337	430	204	
Summary of Dates and Recorded Snowfall Totals				
11/23/01	-	T	-	
11/25/01	T	2.5	2.0	
11/26/01	1.5	-	-	
11/27/01	T	T	T	
11/28/01	-	1.0	-	
11/30/01	4.7	0.5	3.0	
12/04/01	-	T	1.0	
12/05/01	7.2	3.0	2.0	
12/11/01	9.6	3.0	6.0	
12/12/01	1.2	-	1.0	
12/13/01	-	T	-	
12/14/01	-	T	-	
12/15/01	4.0	0.5	2.0	
12/16/01	-	T	-	
12/22/01	3.0	T	-	
12/24/01	1.1	1.0	0.5	
12/30/01	T	T	1.0	
12/31/01	T	T	-	
01/01/02	0.5	2.0	-	
01/04/02	-	T	T	
01/17/02	T	-	T	
01/24/02	T	-	-	
01/29/02	T	0.5	-	
01/30/02	T	2.0	-	
01/31/02	-	T	-	
02/18/02	T	T	-	
02/19/02	T	T	-	
03/08/02	T	T	T	
03/09/02	-	-	T	
03/16/02	T	-	-	
03/17/02	T	0.5	-	
03/18/02	4.1	2.0	2.0	
03/19/03	-	T	-	
03/24/02	T	T	-	
03/25/02	2.0	T	-	*Average of Totals:
SUM	**38.9**	**18.5**	**20.5**	**26.0 inches**
WX SITE	Pulliam Airport	Sunset Crater	Walnut Canyon	
ROUTE	I-17	US 89	I-40	

APPENDIX B

ADOT-ATRC WINTER EVALUATION PROGRAM:
NOVEMBER 2001 – MARCH 2002

ADOT-ATRC Advanced Snowplow Research
Winter Evaluation Program
November 2001 - March 2002

*****Rev3 – 01 Feb 2002***

ADOT Snowplow F342 (Gray Mountain)

1. 3M Testing & Evaluation Schedule (November 2001 – March 2002)

- 3M System Calibration / Validation - November - December
- System Upgrades (Cell Antenna) - November
- Regional Testers Training & Evaluation: Weeks 1 & 2: **Feb 6 → 15**
- Phases of Evaluation by Gray Mountain: Early Winter vs. Late Winter
- Long-Term Field Evaluation - November through March
- ADOT Video Services – Documentation - February / March

2. 3M System T&E Workplan - Goals and Tasks – 3 Districts on 5-day weeks

- Confirm 3M Snowplow System is Operational – Maintenance Procedures
- Confirm Site Conditions & Traffic Control at US 89 Test Site
- Concurrent Evaluation of Peripheral Systems – Radar and AVL
- Training of Team Leaders - **** TL Self-Training***
- Regional Testers – Complete NAU & ATRC Driver Surveys, ***** Both Sites / Same Day***
- Team Leaders – Complete Testing Activity Shift Reports
- Long-Term District Evaluation: Sunset Crater Test Site – US 89 NB at MP 428 to 433
- Full Snowplow Route – East Flagstaff to Antelope Hills (US 89 MP's 418 - 440)

Caltrans Snowplow ASP 7005 (Flagstaff Maintenance)

3. Caltrans Testing & Evaluation Schedule (February 4 / March 8, 2002)

- Initial Site Testing & Commissioning: February 4 - 8, Week 1
- Caltrans Training – Core Staff / Team Leaders: February 6 - 8, Week 1
- Regional Testers Training & Evaluation: Weeks 1 & 2: Feb 6 → 15
- Long-Term Field Evaluation by Flag Maint - Weeks 3 to 5
- ADOT Video Services – Documentation - February / March

4. Caltrans T&E Workplan – Goals and Tasks

- Accept Snowplow from Caltrans Staff – Confirm Care & Maintenance Procedures
- Installation of Spare ADOT Radio – by DPS at Flag East Shop – Set Up by District
- Confirm Conditions at Test Site – Field Repairs or Changes
- Training of Team Leaders by Caltrans / Complete Driver Surveys
- Regional Testers – Complete NAU & ATRC Driver Surveys, ***** Both Sites / Same Day***
- Team Leaders – Complete Testing Activity Shift Reports
- Long-Term District Evaluation – Flagstaff Maint Yard - Use Caltrans Plow on US180
- Full Snowplow Route – MP 215 (Flagstaff) to MP 250
- Test Site at Kendrick Park – Both directions, MP 235 to 238

Winter Evaluation Program 2001-02

ADOT Snowplow F278 (Williams)

(*Note – system tests delayed to Phase Three)

5. Bendix XVision Testing & Evaluation Schedule (February – March 2002)

- Bendix System Installation / Calibration - February, Week 1
- Team Leader Operator-Training: Weeks 1 & 2: **Feb 6 → 15**
- Phases of Evaluation by Williams: Late Winter
- Long-Term Field Evaluation - February / March / April
- ADOT Video Services – Documentation - February / March

6. Bendix XVision T&E Workplan - Goals and Tasks – Williams Maintenance Org

- Confirm System is Fully Operational - Verify Maintenance Procedures
- Concurrent Evaluation of Peripheral Systems – Second GPS-AVL Unit (for District)
- Training of Team Leaders - **** TL Self-Training***
- Team Leaders – Fill Out ATRC's Test Activity Shift Reports & Bendix Report Sheets
- Long-Term District Evaluation: Primary I-40 Route, Secondary Route & Driver Options
- Full Snowplow Route: I-40, Williams-to-Flagstaff Corridor

Project Goals & Planning

7. Snowplow Project Workplan 00-01: Project Team Goals

7a. All System Partners' Goals:

- To Test and Document Guidance System, Warning System & Display Performance - - -
  - In Northern Arizona Winter Storm Weather and Visibility Conditions
  - With ADOT Winter Maintenance Operating Practices
  - With an Independent Pool of Skilled ADOT Operators
  - With Two-Lane Roadway – Oncoming Traffic & Shoulder Obstacles

7b. ADOT Goals:

- Operator Training – New Skills, Confidence Levels, Learning Curve, Perceived Benefits:
  - Vision / Awareness / Confidence / Efficiency / Accuracy / Stay in Lane / Reliability
- Operator Feedback to Vendors – Comments and Suggestions from ADOT Viewpoint
- Impartial Third-Party Evaluations with Northern Arizona University as Consultant
- Evaluate Each ASP System – Efficiency & Safety Measurements vs. Cost to Deploy
- Evaluate Durability and Reliability of Each Embedded Roadway Installation
- Inform and Educate Within ADOT, & Technology Transfer to Other Agency Partners

8. ADOT Personnel - All Districts – Training, Testing & Support

- Team Leader Operators - Previous Winter and New - Three Flagstaff Maint Orgs
- District Operator Testers – Local & Regional, 3 Districts, ***** Both Sites / Same Day***

9. Logistics – Storage, Fuel, Travel & Lodging, Cost Elements

- Servicing Requirements / Record-keeping - 700-790 (and any Caltrans records)
- Operator-Trainee Lodging – Same as prior year (ATRC) if necessary
- Per Diem Procedures – Same as prior year (ATRC) for overnight if necessary
- BTS Guidelines – Straight Time Maintenance Org charges except for travel overtime
- Radios – Not compatible w/ Caltrans – install spare ADOT unit – required ……(FRS?)

APPENDIX C

CALTRANS-PATH (NO SNOW) ADVANCED SNOWPLOW EVALUATION PROPOSAL: ARIZONA - FEBRUARY 2002

Revised (No Snow) Advanced Snowplow Evaluation Proposal
Arizona February 2002

Purpose of the study
To evaluate the effectiveness of the advanced snowplow system
To determine in what ways the system changes snowplow driver behaviors
To investigate what recommended changes to the driver vehicle interface can be made

ADOT Participants
2 trainers (team leaders) familiar with the advanced snowplow system.
1 driver trained but inexperienced with the advanced snowplow system.
1 driver trained but inexperienced with the advanced snowplow system (contingency driver).

Testing plan
Testing to be run Monday thru Wednesday (March 4-6th), one driver per night with an additional driver available for testing on Wednesday during the day, if require more data.

Testing will take approx 6-1/2 hours per driver. This will allow 4-5 hours testing time. (includes a break), 1 hour to get to test site and back, plus an additional ½ hour discussion time.

Design
Data to be collected at night (low light), data to be collected for 5 runs in two conditions (equals total of 10 runs per driver, more if time allows):

- Have the driver drive and ask them to maintain center position with the screen off.
- Have the driver drive with the screen on and ask them to maintain center position in the lane using the screen for primary navigation, (where it is safe to do so, during these periods the observer will monitor the forward view for safety purposes).

Drivers to be video taped during the testing.

Discussion with trainers (ADOT team leaders)
Discussion to focus on:
- What were the most common questions or causes of confusion for drivers learning the system?
- What redesign recommendations can the trainers make?
- Show the Trainers some redesign suggestions and get their feedback on them.

Human factors driver ride-along evaluation (subjective)
- Incidents where drivers are unsure of system status or meaning.
- Differences in operating behavior when using the system compared to not using the system.

APPENDIX D

ADOT-ATRC SNOWPLOW RESEARCH DAILY ACTIVITY REPORT

ADOT-ATRC SNOWPLOW RESEARCH

DAILY ACTIVITY REPORT

ADOT OPERATIONAL TESTING

Date: _______________ Time Start: ______________ Time End: ________________

Team Leader-Operator's Name: _______________________________Org No: __________

* * * *TEST AREA CONDITIONS WHILE PLOWING* * * *

Route:	**US 180**	**US 180**	**US 89**	**US 89**
Mileposts:	**235.0 – 237.0**	**237.0 – 238.0**	**428.0 – 430.5**	**430.5 – 433.0**
CONDITIONS: *(check or circle all)*	**Hart Prairie Rd to Kendrick Park**	**Kendrick Park to End of 8% Grade**	**Lenox Park to Sunset Crater**	**Sunset Crater to Deadman Flat**
Windy?	Yes - No	Yes - No	Yes - No	Yes - No
Wind Speed	Low – Med – High	Low – Med – High	Low – Med – High	Low – Med – High
Wind From Direction	N - S - E - W	N - S - E - W	N - S - E - W	N - S - E - W
Snowfall?	No – Lt - Med -Hvy	No – Lt - Med -Hvy	No – Lt - Med -Hvy	No – Lt - Med -Hvy
Sunny?	Sunny	Sunny	Sunny	Sunny
Cloudy?	Cloudy	Cloudy	Cloudy	Cloudy
Day or Night	Day - Night	Day - Night	Day - Night	Day - Night
VISIBILITY (circle):				
	Zero	Zero	Zero	Zero
	50 feet	50 feet	50 feet	50 feet
	100	100	100	100
	200	200	200	200
	300	300	300	300
	> 300 ft	> 300 ft	> 300 ft	> 300 ft
ROADWAY (circle):				
	Icy	Icy	Icy	Icy
	Snowpack	Snowpack	Snowpack	Snowpack
	Slush	Slush	Slush	Slush
	Clear	Clear	Clear	Clear
ACTIVITY (circle):				
	Plowing	Plowing	Plowing	Plowing
	Spread Sand / Chemical	Spread Sand / Chemical	Spread Sand / Chemical	Spread Sand / Chemical
	Test Runs	Test Runs	Test Runs	Test Runs
	Operator Training	Operator Training	Operator Training	Operator Training

Other Route?________ Start Milepost: _________ End Milepost: _________

Snowplow #: _________ Start Mileage: _________ End Mileage: _________

Truck Status (*check one*): **Good? _______ Problems? ______ (Note below)**

System Status (*check one*): **Good? _______ Problems? ______ (Note below)**

Problems and / or Comments: ____

____

____***(Use back of page if needed)***

APPENDIX E

TECHNICAL ADVISORY COMMITTEE
PROJECT REVIEW SURVEY RESULTS - JUNE 2002

IVI / SNOWPLOW GUIDANCE RESEARCH PROJECT No. 473
TECHNICAL ADVISORY COMMITTEE

TAC OPINION SURVEY RESULTS
PROJECT RESULTS & PROJECT DIRECTION

(Survey Date May 8 / Results Compiled July 23, 2002)

Introduction – Since late 1997 this project has studied advanced vehicle topics, to identify the advantages of ITS to help ADOT improve the function and safety of the state highway system. ADOT has installed magnetic media in two Arizona highways, and has acquired new systems to the point that we now have access to three Advanced Snowplows in the Flagstaff area. *(Note- Night Vision added in Spring 2002, not tested)*

After four years of field research, we have answered some basic questions, and learned a great deal about some ITS-IV systems. And, we have just begun to work with others. Now, ATRC has surveyed the TAC members on where ADOT and partners should go with this research project.

This short survey asked for the TAC's views on each major ITS-IV system that the project has deployed for testing and evaluation. It also asked what the TAC feels has been achieved, and what the project can practically do next, with our budget and available ADOT resources.

* * * * * *

BACKGROUND – CURRENT PROJECT STATUS - MAY 2002:

3M – Magnetic Tape is in place for 5 miles of US 89 (10 lane miles) at Sunset Crater.
Since 2000 (3M Corp. is on hold, but will still provide new mat'ls and repairs).
Truck System installed and supported (off warranty - repairs at ADOT's cost).

Caltrans – Magnets are in place for 6 lane-miles of US 180 at Kendrick Park.
Since 1998 (the IGA is open for another year, to June 03).
ASP System is available to ADOT for future winter evaluations (*radio required).

F342 3M and Collision Warning Radar – Both Installed and operating, over the past winter.
Support by 3M for repairs has been prompt and efficient – *our costs from now on.
Radar tech support & service has been spotty / Eaton hasn't invoiced, nor been paid.

F235 Night Vision System – Installed & functional on I-17 plow route / truck cab issues.
Evaluation agreement at no cost / no tests or demos done yet / need different truck?

AVL GreyLink Vehicle Tracking System – two units – F342 and portable - both functional.
Flagstaff Snow Desk workstation / needs dedicated phone line, modem, and PC.
Problem areas: phone service / cell coverage / shared line / training materials.

Responses – 14 – TAC Members and Snowplow Operators-Team Leaders

A. SYSTEM CONCEPT PROS AND CONS? HOW IMPORTANT TO ADOT?

- **Caltrans Roadway-Magnet Guidance System?**

Position	Org	Comments
State Manager	Phoenix	I think this is an interesting technology. I think it might have merit for further deployment. Unfortunately, given budget shortfalls, this will not be a high priority in the near future. We are doing good right now just to keep snowplows running.
State Manager	Phoenix	Issue is cost / versus benefit to the state.
State Eqpt Mgr	Phoenix	This appears to be old technology relative to progress in other areas.
Maint Engineer	I-40 Dist	The infrastructure (embedded magnets) appears impractical for use on rural asphaltic concrete roadways. Application seems appropriate for PCCP. Low importance for ADOT.
Maint / District Engineer	I-40 Dist	The best system for guidance, but most labor intensive to install. Not fully developed to point of production. Most favored by drivers.
District Engineer	I-40 Dist	Pro: it is a positive control system with the magnets, truck system seems a little complicated but may be possible to modify to meet local needs in the future. Con: expensive to install in both roadway and truck, magnet life may be limited by future maintenance actions on the paved surface, system may be only limited to those areas that require the positive control, is dedicating truck to the one site reasonable?
Superintendent	I-40 Dist	N / C
Superintendent	I-40 Dist	The system seems to work well but it can only be tested when we have the Caltrans truck plus it would be unrealistic to try and install this type of system for at a large scale.
Dist Eqpt Mgr	I-40 Dist	Very interesting, however I feel we will never have the resources to purchase and install this elaborate a system.
Org Supervisor	I-40 Dist	The system has proven itself, with some changes – it all depends on money.
Org Supervisor	I-40 Dist	According to my crew, it's a little different from F342 (3M) but agree with magnet system and would help them out during snowstorms.
Operator	I-40 Dist	Fairly good idea. But cost and installation is too much to think about a longer area.
Operator	I-40 Dist	Some places we do need it.
Operator	I-40 Dist	Will work good during whiteouts.
ATRC		Caltrans says the 3 RoadView plows are successful, but the data is too poor to support more deployments now. Will work to improve hardware, but focus will be on rotary plows. Only Alaska and AZ have partnered. Caltrans plow available next winter.

- **3M Tape – Lane Awareness System?**

Position	Org	Comments
State Manager	Phoenix	I think this is an interesting technology. I think it might have merit for further deployment. Unfortunately, given budget shortfalls, this will not be a high priority in the near future. We are doing good right now just to keep snow plows running.
State Manager	Phoenix	Cost / installation. Maintenance of the tape ?
State Eqpt Mgr	Phoenix	A good product but the business failed. Practical where it can be overlaid one or more times.
Maint Engineer	I-40 Dist	Good potential due to concept and ability to sustain function after rehabilitation (overlays). Concern over product availability. Importance to ADOT – Moderate.
Maint / District Engineer	I-40 Dist	Good basic system. Concerns over lack of support from 3M due to them getting out of the business.
District Engineer	I-40 Dist	Pro: another positive control system with the tape, truck system seems a little less complicated then the magnet system Con: similar to the magnet system with the exception that the limitation on the number of trucks equipped to read the system may not apply.
Superintendent	I-40 Dist	Seems like this is a dying product.
Superintendent	I-40 Dist	This system seems to also work well and is more feasible to set up in a larger scale.
Dist Eqpt Mgr	I-40 Dist	If we were to pursue any system, this appears to be the one most compatible with our limited resources.
Org Supervisor	I-40 Dist	Is very costly and has some concerns on other pavement jobs going over the top.
Org Supervisor	I-40 Dist	My crew sure likes it. If only they had put 3M tape on both lanes, going southbound too.
Operator	I-40 Dist	The use of this is fairly simple. Everyone that I trained on it could run it their first try. Tape was a good idea but now that it is no longer made what good is it to keep testing unless we combine the different systems pros, to create a new system that works for everyone. But cost is an issue.
Operator	I-40 Dist	Works good.
Operator	I-40 Dist	Works good but tape goes on too small a section of road – need southbound 89 also.
ATRC		3M reports that there is no corporate interest in reopening the marketing of the tape product, although more material or hardware can be obtained. This snowplow is fully operational as regards the 3M system, US 89 NB.

- **Eaton VORAD Collision Warning Radar?**

Position	Org	Comments
State Manager	Phoenix	This has merit for warning snowplow operators of potential problems. As we begin to purchase new snowplows, we should consider including this as a standard item.
State Manager	Phoenix	I think this is more important than above items
State Eqpt Mgr	Phoenix	Good product that is soon to be OEM on more heavy trucks.
Maint Engineer	I-40 Dist	Not familiar with details of performance. Importance of application – high.
Maint / District Engineer	I-40 Dist	Great concept, but am not convinced that we have sold the idea to the drivers.
District Engineer	I-40 Dist	Pro: interesting concept that could help even in clear and dry weather in the future Con: I'm not sure we know where we're headed at this point and that Eaton has been somewhat non-responsive to our questions.
Superintendent	I-40 Dist	N / C
Superintendent	I-40 Dist	Most operators seem to like this system but it kind of gives you false impression of the obstacles that are out there.
Dist Eqpt Mgr	I-40 Dist	Let's take it to its limits before we judge.
Org Supervisor	I-40 Dist	Very helpful and can be used any time other than winter – Good Deal.
Org Supervisor	I-40 Dist	According to my operators the radar is a good system, it really helps when you need it. The question is will it really work during a whiteout snowstorm.
Operator	I-40 Dist	I like every part of this because we ,the operators, can use this all year round. I have used this and found that it increases the time for you to avoid a collision with an object that is in front of you. It also has the capabilities to record 20 seconds of an accident, that could be used in court or for equipment services.
Operator	I-40 Dist	Gives warnings ahead of you.
Operator	I-40 Dist	Warning system works good, we could use it.
ATRC		Radar worked well, within its design limits, in the second winter, but without snow. Several storms are needed for a valid test. The plan to test the SmartCruise feature should proceed, we have the funds and the vendor is interested in doing this.

- **GreyLink Automatic Vehicle Logging/Tracking (AVL) System?**

Position	Org	Comments
State Manager	Phoenix	Additional research should be done in the area of AVL. The technology seems to be catching on throughout the US, but Arizona does not have a lot of experience with this technology. AVL is more prevalent in the emergency services industry.
State Manager	Phoenix	Low priority
State Eqpt Mgr	Phoenix	A good resource for management, operational responsibility always lies with the driver.
Maint Engineer	I-40 Dist	Not satisfied with benefits or intention of utilization; concern with liability aspects. Importance to ADOT – low.
Maint / District Engineer	I-40 Dist	The AVL concept is good. However from what I have seen so far, the Greylink product is less than what I had envisioned and hoped it would accomplish. We need a system that an end user can operate easily, with little or no training and data is easily read and understood.
District Engineer	I-40 Dist	Pro: this is another system that would help during not only winter storms but during the clear and dry weather as well; system has possibilities in monitoring material usage, etc. in the future. Con: I'm not sure we totally know what technology infrastructure is required and how the way we do business fits with this device.
Superintendent	I-40 Dist	May need to go to satellite phone system for truck.
Superintendent	I-40 Dist	I don't see us using this system much until we have a more reliable phone system. It makes more sense trying to get the operators equipment that will make it safer for them to operate the equipment, than in tracking them with the limited funds we have.
Dist Eqpt Mgr	I-40 Dist	No real feel for this – no comment.
Org Supervisor	I-40 Dist	This can be very good for quick response to incidents, and if the truck needs help.
Org Supervisor	I-40 Dist	I've seen some papers on the tracking system (AVL). I agree with the research going on.
Operator	I-40 Dist	This is some what of a good idea but with being hooked up to a cell phone doesn't really give us a reliable way of communicating between that computer and AVL. There are other AVL that can be accessed through the internet that could be easier to communicate.
Operator	I-40 Dist	Works good, would use it.
ATRC		The concept of AVL seems very valuable to local & state fleet managers. This system, and support, has improved since the purchase, but is not so rural-user-friendly. Combined with phone and modem problems it has not proven out yet. Research can fund better hardware for SnowDesk, can upgrade the software again, and get more training. A test of this AVL or a different system in Phoenix may also answer our questions.

- **Bendix X-Vision Night Vision Camera? *(Installed but no test or demo at time of survey)***

Position	Org	Comments
State Manager	Phoenix	Could use some additional testing and demonstrations.
State Manager	Phoenix	Important – especially in those blizzard type of situations
State Eqpt Mgr	Phoenix	A good product, no chance to use it yet.
Maint Engineer	I-40 Dist	Potential for deployment is high – but mounting location and vibration concerns need more work.
Maint / District Engineer	I-40 Dist	This could be as important to ADOT as the snowplow guidance system, although I'll be the first to admit that I only know a little about the concept – that's all - don't know enough to comment.
District Engineer	I-40 Dist	Pro: It's really nice to know what is ahead of you before your headlights find it. Con: Do we really need it?
Superintendent	I-40 Dist	Need to do the tests and demo. Use existing truck if we can and new one if necessary.
Superintendent	I-40 Dist	I am hoping this will provide the operators with better vision of what they can't see with their eyes thus making it safer for the operators to perform their work.
Dist Eqpt Mgr	I-40 Dist	We need to fully test this, then evaluate.
Org Supervisor	I-40 Dist	N / C
Org Supervisor	I-40 Dist	My people said they really like it. They agree with the night vision system, it should help them during snowstorms.
Operator	I-40 Dist	This system is still new. I have used it during dry conditions and I thought it worked great but I would like to see how it would work under snow or rainy conditions.
Operator	I-40 Dist	Great distance vision.
Operator	I-40 Dist	Works good, I would use it.
ATRC		This unit deserves a full winter's testing to determine how it performs in various storm conditions. A summer partner is unlikely now, and snow is the key issue. We could move this to other snowplows every month or six weeks, to get a better cross-section of users and conditions.

B. THIS PROJECT'S FUTURE DIRECTIONS?

- **WHAT HAVE WE LEARNED?**

Position	Org	Comments
State Manager	Phoenix	The technology has potential benefits. There are still many issues around who will market this technology, and what is the business case?
State Manager	Phoenix	Not sure… delegated to others at district – thus do not feel comfortable answering this
State Eqpt Mgr	Phoenix	N / C
Maint Engineer	I-40 Dist	In my opinion, the 3M guidance, Bendix, and Vorad should be considered for expansion. The 3M system needs additional testing in a heavy winter.
Maint / District Engineer	I-40 Dist	We learned a lot about teamwork. We've learned a lot about 2 different guidance systems. We're received a lot of feedback on other things we should be studying. We've also learned that funding is a big issue and overshadows much of what we want to do. We learned a little about AVL.
District Engineer	I-40 Dist	The positive control systems have potential despite the initial costs in saving on equipment accidents, etc. There is a high cost in constructing positive control systems. There might be greater opportunities in focusing on the individual vehicle systems that are not totally tied to some hardwired or positive control systems.
Superintendent	I-40 Dist	There are a lot of things out there technically that should make it safer for the operators to perform their work It is not feasible to implement some of the new systems.
Dist Eqpt Mgr	I-40 Dist	3M System works, radar works but not fully tested, the night vision works but value uncertain.
Org Supervisor	I-40 Dist	That it takes a lot of time and effort to research all all that has been done. We have learned a lot about vendors that are out there, materials, and ways to use them.
Org Supervisor	I-40 Dist	My crew are saying IF only it would snow really bad to see if the systems really would help them.
Operator	I-40 Dist	We have learned that there are ways of keeping us and the public safe during a snow storm. But also we have found out the cost of that and it is more than people are willing to spend.
Operator	I-40 Dist	More safety on the road at night.
Operator	I-40 Dist	Need more snow and whiteouts to use the systems.
ATRC		We have learned a lot about the state of the art in guidance and warning systems. We've learned that rural AZ conditions, even in a mild winter, can limit the use of some of these systems. We have also learned what ITS systems may be most valuable, considering ADOT's slim resources. We have learned the costs, benefits, and limits, of both guidance systems.

- **WHAT HAVE WE NOT LEARNED YET?**

Position	Org	Comments
State Manager	Phoenix	Would be nice to have more time and experience in live winter conditions.
State Manager	Phoenix	N / C
State Eqpt Mgr	Phoenix	What is the ideal snowplow (blade system) design? What is the ideal snowplow truck, and, what is feasible?
Maint Engineer	I-40 Dist	N / A
Maint / District Engineer	I-40 Dist	Implementation plan. Night Vision. Other AVL product possibilities.
District Engineer	I-40 Dist	The cost/benefit of the different systems, mainly due to the fact that we have not been able to compare data of accidents, closures, delays due to plow downtime that these systems would impact. How the data collected will inter-relate with the data from the free agent vehicle systems to provide choices between hardwired and free agent approaches.
Superintendent	I-40 Dist	N / C
Superintendent	I-40 Dist	How to provide more vision for our operators through wipers/lighting.
Dist Eqpt Mgr	I-40 Dist	Radar and night vision – usefulness.
Org Supervisor	I-40 Dist	How to get things at a lower price. Are there other vendors out there?
Org Supervisor	I-40 Dist	Don't know at this time, but what information we have should help us.
Operator	I-40 Dist	We have to learn how to make things safe with out increasing the cost that people are willing to spend.
Operator	I-40 Dist	N/C
Operator	I-40 Dist	N/C
ATRC		We have not learned <u>how much</u> any specific system can help our plow operators and supervisors. We can't measure improvements or benefits, especially in mild winters. We know costs and driver satisfaction levels, but not the specific benefits on the roadway or at the District office. We still have specific on-board systems waiting to be evaluated.

- **<u>WHAT ELSE</u> COULD THE I.T.S. SNOWPLOW PROJECT STUDY EFFECTIVELY?**

Position	Org	Comments
State Manager	Phoenix	More work on AVL and night vision would be a good idea. Also, more work on cost benefit analysis.
State Manager	Phoenix	N / C
State Eqpt Mgr	Phoenix	N / C
Maint Engineer	I-40 Dist	No new concepts with this study.
Maint / District Engineer	I-40 Dist	Two-way communication between the plow and the 'Central office'. Would probably require satellite communications. Could tie AVL and a number of other concepts and functions for data collection. GPS Guidance could be studied.
District Engineer	I-40 Dist	Cost/benefit possibilities to determine what system should be used. Can this research be tied to the individual vehicle telematics being developed in private industry? How can this research be applied to the way ADOT does business?
Superintendent	I-40 Dist	GrayLink with satellite phone
Superintendent	I-40 Dist	We need to see what the night vision system does and what is out there, that will help all the operators see better at night, and when you have white outs.
Org Supervisor	I-40 Dist	Collision radar and night vision.
Org Supervisor	I-40 Dist	I think we have enough equipment to work with at this time. I don't know about the cost.
Operator	I-40 Dist	I think lighting on plows, wipers, and plow sizes could be a good start. I think studying the use of training personnel to see if it also increases safety.
Operator	I-40 Dist	N/C
Operator	I-40 Dist	Lights on snowplows.
ATRC		This effort can coordinate with Maintenance Research, which has been funded in the past for lighting, visibility and AVL studies. This project has pretty limited resources for the next winter, depending on TAC decisions regarding Caltrans and also NAU.

- **SHOULD THIS PROJECT DO MORE NEXT WINTER, AND IF SO, WHERE?**

Position	Org	Comments
State Manager	Phoenix	Given the need to better assess live winter conditions, I think it is very important that additional work be done next year.
State Manager	Phoenix	No – I think the focus now should be – what does Maint. want – in regards to safety features, enhancements to their vehicles to support them
State Eqpt Mgr	Phoenix	Yes, on specific on-board systems.
Maint Engineer	I-40 Dist	Additional 3M testing, CalTrans plow does not need to return
Maint / District Engineer	I-40 Dist	I think there are at least 2 ways to approach this: 1. See what kind of support you receive from the District to continue. Without it, we are not going to go very far and it will be very frustrating. 2. Discuss the results with the TAC for input. You may get the same or differing opinions between 1 and 2. Do we have enough data to finish up the snowplow guidance portion of the study? If not, what is left undone that needs follow up next winter season? The answers to these questions are essential to being able to determine an answer to your question above. I believe you will find that the District, most likely, thinks we squeezed out all we can regarding the snowplow guidance system beyond finding the funding to implement and fine tune the system. So if there are things left undone that you need to study, then we need to make that case to the District.
District Engineer	I-40 Dist	We should reach out and possibly start introducing the technology in the Prescott, Globe, and Holbrook Districts, starting with the introduction of some of the individual vehicle devices rather than the positive control systems.
Superintendent	I-40 Dist	Finish test on the night vision.
Superintendent	I-40 Dist	We probably should not do anymore with the Magnets, 3M tape or AVL but we should see what the night vision is going to do and what else is out there that can help the operator see at night and when it is snowing.
Org Supervisor	I-40 Dist	Collision radar and night vision.
Org Supervisor	I-40 Dist	I think it is working now, and we should wait until we have a good snowstorm.
Operator	I-40 Dist	With the state budget the way it is I think that we should look into the cost of bringing the plow from Cal Trans to see if we have enough information to make a good enough project analysis from it. I feel as some of the operators are not into the different projects and don't want to continue writing all the reports and taking time out their work schedule to train the different people on the equipment. I feel it should be up to the managers to see if there is money and time to keep up the different projects. The 3M project can keep going on next year since there is really no cost in using the equipment because it is already going to be out on the road.
Operator	I-40 Dist	Yes
Operator	I-40 Dist	Yes
ATRC		We have big gaps in our knowledge of our new systems in severe winter weather. Primarily these are night vision, collision radar, & 3M performance. As to training, there are not any new aspects of the 3M or Caltrans systems.

APPENDIX F

ADVANCED SNOWPLOW EVALUATION PROGRAM:
WINTER 2001-2002 FINAL REPORT
Prepared by
AZ*Trans*: The Arizona Laboratory for Applied Transportation Research
Northern Arizona University

Attachment A - ADOT-3M Snowplow Training & Evaluation Survey 01-02

Attachment B - Caltrans-Advanced Snowplow Evaluation Questionnaire AZ-02

Attachment C - 3M Advanced Snowplow Evaluation Questionnaire 01-02 Comments

Attachment D - Caltrans ASP Snowplow Evaluation Questionnaire AZ-02 Comments

Attachment E - Arizona Winter Conditions Visibility Survey by Lane Miles (2002)

ADOT-ATRC Introduction to Appendix F:

The evaluation program planned by Northern Arizona University (NAU) for the 2001-02 winter was severely limited by forces beyond their control. The key negative factor was the weather, with very little snow over the winter, and none at all during the side-by-side training and field evaluation period for both advanced snowplows in northern Arizona.

Project evaluation tasks and support activities that were planned but not feasible due to weather and technical issues included:

- Evaluation support for a night vision system that was not operationally commissioned during the storm season.
- Evaluation support for an automatic vehicle location system (AVL) that could not deliver consistent results due to cellular service and terrain issues in the Flagstaff District.
- Recreation of ADOT storm operations history based on AVL tracking and project records.
- Ride-along third-party evaluations and observations of the ASP systems during storms.
- Ride-along third-party evaluations and observations of the CWS systems during storms.

Another task referenced in this report was the ADOT management survey of potential advanced snowplow system deployment in Arizona. The first global management survey in Year Three (2001) did not produce consistent results in one key area – low-visibility estimates as to the need for roadway-infrastructure lane guidance systems, or for other supporting ASP technologies.

In Year Four (2002) the TAC requested that a revised survey be developed which focused solely on the district maintenance engineering staff, and which dealt solely with impaired visibility. This is the "second survey" referenced in the current report and in this Appendix by NAU. As described in the report text and this Appendix, the second survey was completed, but the results were not consistent and again were not accepted by the Technical Advisory Committee. Later, in 2003 (Year Five) ATRC conducted a third survey, which will appear in the next project report.

Overall, weather and technical problems constrained and ultimately prevented the comprehensive project evaluation effort as planned by NAU, as several significant tasks could not be carried out. The report completed by NAU in this Appendix describes the efforts that were completed, and reviews the results of the Caltrans and ATRC training and operational surveys.

Arizona Advanced Snowplow Research Program
ADOT ECS File: JPA 00-193
Project: SPR-473 / R0473 08P
NAU: EGR373R
AZ*Trans*: 2001.01

Advanced Snowplow Evaluation Program - Winter 2001-2002

Final Report

Prepared by:
AZ*Trans*: The Arizona Laboratory for Applied Transportation Research
Northern Arizona University

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15 October 2003

Prepared for:
Arizona Department of Transportation
Arizona Transportation Research Center
Stephen R. Owen, P.E.
ADOT Project Manager – SPR 473

Advanced Snowplow Research Project
Evaluation Program
Winter 2001 - 2002
Final Report

PURPOSE OF REPORT

This is a final report to the Arizona Transportation Research Center of the Arizona Department of Transportation on the Evaluation Program for the Advanced Snowplow (ASP) Research Program conducted by AZ*Trans:* The Arizona Laboratory for Applied Transportation Research of Northern Arizona University. The report includes the reportable activities conducted by AZ*Trans* during the winter of 2001-2002. The AZ*Trans* team consisted of Craig A. Roberts, Ph.D., P.E., Principal Investigator, with the assistance of Jamie Brown-Esplain, E.I.T., Research Engineer, and Rachel LaMesa, Research Assistant.

EVALUATION PROGRAM GOALS

The goals of the AZ*Trans* evaluation program for the winter of 2001-2002 were narrower than previously. While several activities were undertaken which supplemented the general understanding of the AZ*Trans* team regarding the Advanced Snowplow Research Project, only two activities resulted in reportable findings:

1. Summary of Trainee Observations During Actual Winter Snow Removal Conditions Using the Advanced Snowplows

2. Winter Conditions Visibility Survey Disaggregated by District and Organizations within each District

The role of AZ*Trans* in the Evaluation Program was to act as an independent evaluator. These evaluations rely on the interpretation of the judgments, opinions, and attitudes of involved ADOT personnel, and not on direct observations of the AZ*Trans* team members. In other words, this is an evaluation of the perceptions of others, not a technical evaluation of the efficacy of the systems themselves. Direct observations of the snowplow systems were made during familiarization rides by members of the AZ*Trans* team, however the purpose of these were limited to acquainting the team members with the snowplow operator's general environment, work tasks, and the basics of the two advanced snowplow systems.

Reported here are the evaluations of two Advanced Snowplow (ASP) guidance systems: one developed by the California Department of Transportation (CALTRANS) and the other developed by the 3M Corporation (3M). Also evaluated, as an adjunct to the 3M system, was a separate Collision Warning System (CWS) developed by Eaton VORAD. The CALTRANS system also includes a CWS, however it is an integral part of the CALTRANS system itself.

SUMMARY OF TRAINER OBSERVATIONS DURING ACTUAL WINTER SNOW REMOVAL CONDITIONS USING THE ADVANCED SNOWPLOW SYSTEMS

In addition to participating in limited ride-along orientations for each of the two systems, two survey instruments were administered by ADOT. These instruments were similar in nature and content, customized to the ASP system being evaluated (CALTRANS or 3M), and administered to each snow plow operator just after receiving in-vehicle training on an ASP system. Copies of the two survey instruments are included in the appendices.

1. ADOT SNOWPLOW TRAINING & EVALUATION SURVEY; 3M Systems – US 89 Test Lane – ADOT Plow F342' Flagstaff, Arizona - February 2002 (*Attachment A*)

2. Advanced Snowplow Evaluation Questionnaire; [CALTRANS SYSTEM] Arizona - February 2002 (*Attachment B*)

Evaluation of Numerical Data

The data gathered from these survey instruments falls into two categories. One category is numerical data that can be summarized and analyzed statistically. The other category is comments, which does not lend itself to statistical summaries. Training occurred from January through March, 2002, in non-snow conditions. Surveys (questionnaires) were completed by 27 trainees on the CALTRANS system snowplow and 20 trainees on the 3M system snowplow.

The numerical data is summarized in Table 1. A general conclusion regarding overall satisfaction is that both ASP systems, on average, rated in the 1.3 to 2.1 range, on a 5-point scale with 1 being "best" and 5 being "worst." Likewise, the ease and usefulness of both ASP systems' features, on average, rated in the 1.7 to 2.0 range, on a similar 5-point scale. Together, these indicate a generally favorable response by trainees toward the ASP systems.

Of particular interest are the responses regarding safety and snow plowing efficiency. The trainees indicate that both systems are beneficial in increasing safety, rating both systems, on average, within 95% confidence interval limits from 1.0 to 1.9, on a 5-point scale, with 1 being "yes" and 5 being "not at all." Likewise, the trainees indicate that both systems increase the efficiency of their snow removal tasks, on average, within 95% confidence interval limits from 1.3 to 2.2, on a 5-point scale, with 1 being "helpful" and 5 being "not helpful." Together, these indicate a generally favorable response by trainees toward the ASP systems regarding improvements to safety and operations efficiency.

What the survey instruments do not tell us is if one system is favored over another. On the contrary, the differences in ratings of all attributes between the two systems are statistically insignificant. It is important to note that no direct comparison questions were administered on the surveys, so a truly "head-to-head" comparison is not possible.

Table 1: Means and 95% Confidence Intervals of Responses to Training and Evaluation Survey of Second-Tier Trainees

Topic	CALTRANS (US180) (27 surveys)			3M (US89) (20 surveys)		
	Lower Bound (2.5%)	Mean	Upper Bound (97.5%)	Lower Bound (2.5%)	Mean	Upper Bound (97.5%)
Operator Background Information						
How many years have you been a snowplow operator?	5.1	**7.8**	10.1	5.1	**7.7**	10.3
Self rating of level of expertise (1 = novice → 5 = expert)	3.4	**3.7**	4.1	3.4	**3.8**	4.3
Overall Satisfaction with Driver-Assistance/Guidance System						
How easy is the system to use overall? (1 = very easy → 5 = not easy)	1.8	**2.1**	2.5	1.5	**1.9**	2.3
How much do you like the system overall? (1 = a lot → 5 = not at all)	1.6	**2.0**	2.4	1.3	**1.6**	1.9
If you had more time to practice with the system, would you like it more? (1 = yes → 5 = no)	1.3	**1.7**	2.1	1.3	**1.7**	2.2
Do you think that the system is beneficial in terms of increasing your safety? (1 = yes → 5 = not at all)	1.2	**1.6**	1.9	1.0	**1.3**	1.6
Rate the system in terms of increasing the efficiency of your snow removal tasks. (1 = helpful → 5 = not helpful)	1.5	**1.9**	2.2	1.3	**1.6**	1.8
CALTRANS Driver Assistance Functions						
CALTRANS Collision Indicator: How easy is this to use? (1 = very easy → 5 = not easy)	1.7	**2.0**	2.3	Na	na	na
CALTRANS Collision Indicator: How much do you like it? (1 = a lot → 5 = not at all)	1.5	**1.9**	2.2	Na	na	na
CALTRANS Lane Keeping: How easy is this to use? (1 = very easy → 5 = not easy)	1.6	**2.0**	2.4	Na	na	na
CALTRANS Lane Keeping: How much do you like it? (1 = a lot → 5 = not at all)	1.5	**1.9**	2.2	Na	na	na

Topic	CALTRANS (US180) (27 surveys)			3M (US89) (20 surveys)		
	Lower Bound (2.5%)	Mean	Upper Bound (97.5%)	Lower Bound (2.5%)	Mean	Upper Bound (97.5%)
3M Lane Awareness Functions						
3M Lane Position Indicators: How easy is this to use? (1 = very easy → 5 = not easy)	na	na	na	1.6	**2.0**	2.4
3M Lane Position Indicator: How much do you like it? (1 = a lot → 5 = not at all)	na	na	na	1.3	**1.7**	2.1
3M Lane Departure Warnings: How much do you like the warning lights? (1) (1 = very easy → 5 = not easy)	na	na	na	1.4	**1.9**	2.4
3M Lane Departure Warnings: How much do you like the vibrating seat? (1 = a lot → 5 = not at all)	na	na	na	1.1	**1.7**	2.2
Eaton VORAD Collision Warning Radar						
How easy is this to use? (1 = very easy → 5 = not easy)	na	na	na	1.5	**1.9**	2.4
How much do you like it? (1) (1 = very easy → 5 = not easy)	na	na	na	1.3	**1.8**	2.3

(1) Although the wording of the scale doesn't match the question, this is the actual wording used on the survey.

Summary of Comments

The survey instruments included several areas where trainee comments were solicited. The responses are just as useful in evaluating the systems as is the numerical data, perhaps more so. This data is summarized in the appendices for each system. Comments concerning the 3M system are detailed in *Attachment C-1* and *Attachment C-2*. Trainee comments concerning the CALTRANS system are detailed in *Attachment D-1* and *Attachment D-2*.

The comments do not yield any general "trends" that can be discerned and reported here. All the comments are important vis-à-vis improving the systems, but do not seem to universally target any specific components or features.

One critical question probed was if the systems impaired operator judgment, with each system's questionnaire having slightly different wording: "Did the system ever lead you to make an inappropriate maneuver or error in judgment? [CALTRANS]" and "Could 3M's system cause you to make an (sic) wrong move or error in judgment?". Although some answers were vague, it appears that only one trainee believed that the CALTRANS system impaired his judgment. He attributed this impairment as being "…used to the 3M system and on that you move the opposite direction." Again, although some answers were vague, it appears that no trainee on the 3M system believed the system impaired his judgment.

WINTER CONDITIONS VISIBILITY SURVEY DISAGGREGATED BY DISTRICT AND ORGANIZATIONS WITHIN EACH DISTRICT

During the evaluation program for the winter 2000-2001, AZ*Trans* conducted an "*Advanced Snowplow Research - ADOT Management Survey 2000-2001*." This survey sampled opinions on several topics from several district and statewide management personnel. One question attempted to quantify the lane miles of roadway that would be candidates for ASP systems. The information gathered from the responses to this question was deemed to be erratic and unusable. This was attributed to a combination of (a) a series of poorly worded questions and (b) the lack of knowledge of several of the respondees to make such an estimate. However, the usefulness of such information remained.

As part of the evaluations conducted by AZ*Trans* that are reported here, a new survey was developed to ascertain this information. This survey was only sent to the District Maintenance Engineer (DME) in each ADOT District in November 2002. The specific definitions used in the survey were developed collaborative with the Flagstaff DME and District Maintenance Superintendent (DMST). The instructions to the DMEs included a completed survey by the Flagstaff District that served as a detailed example. The DMEs were encouraged to contact the Flagstaff DME and/or DMST if they had questions.

In order to conduct the survey, specific definitions of two levels of poor visibility were developed. The two specific categories of reduced-visibility conditions are:

A. **White-Out Visibility Conditions**: Unable to continue plowing; cannot see beyond the hood or make out any surroundings. May last 15 to 20 minutes or more. Occurs 3 or more times each winter season: Oct 15 - Apr 15.
B. **Impaired Visibility Conditions**: Plows have to slow significantly, even occasionally stop. May last 15 to 20 minutes or more, but is not bad enough to be considered a "white-out." Occurs 3 or more times each winter season: Oct 15 - Apr 15.

The metric used for these two reduced visibility conditions were 12-foot lane miles-traveled way only. Within each district, this information was collected for each "org" (organization, a sub-district geographic area/maintenance group). It was summed to develop the district totals. A summary of the results, disaggregated by District, is shown in Table 2.

In order to obtain a metric for the proportion of reduced visibility lane miles to total miles maintained by each District, district-wide lane mile totals were solicited in the survey. The metrics for totals were of two types:

A. **12-foot Lane Miles (ALL)**: This includes all miles of system roadway within the district, counting the full width of pavement for each mile. For example, if a roadway has 40 feet of paved width, each mile of this roadway would count as 3.33 "12-foot lane miles" (3.33 = 40/12).

B. **8-foot Lane Miles (SNOW)** : This includes all miles of the system roadway within the district, but excludes the paved shoulders, which are not plowed during snow removal operations. For example, say a roadway has 40 feet of paved width, which includes two 8-foot shoulders. Then this roadway would count as 3.0 "8-foot lane miles for snow plowing purposes (3.0 = (40 width - 16 shoulders) / 8). The rational for this metric is that a snow plow typically *plows an 8-foot width* and shoulders are not plowed.

Table 2: ADOT Winter Conditions Visibility Survey by Lane Miles (2002)

*[***ATRC Note - Caution: Apparent inconsistencies in these survey results were noted by the project's Technical Advisory Committee. The survey was subsequently redone by ATRC and those final survey results will be reported for 2002-03.]*

District	White Out Total(1) (2)	Impaired Vision Total(1) (3)	Total for Both Conditions(1)	Total Snow 8-foot Lane Miles in District	Total All 12-foot lane Miles in district
Flagstaff	168.0	260.0	428.0	3,740	2,929
Globe	323.6	512.2	835.8	2,904	2,575
Holbrook	666.0	738.0	1,404.0	2,901	1,894
Kingman	4.0	18.0	22.0	1,531	2,054
Phoenix	24.0	0.0	24.0	78	725
Prescott	346.4	631.4	977.8	1,713	2,483
Safford	94.0	104.0	198.0	2,718	2,472
Tucson	22.0	36.0	58.0	6,042	4,057
Yuma	0.0	0.0	0.0	0	2,780
State-wide Totals	*1,648.0*	*2,299.6*	*3,947.6*	*21,627*	*21,969*

(1) 12-foot lane miles--traveled way only

(2) White-Out Visibility Conditions: Unable to continue plowing; cannot see beyond the hood or make out any surroundings. May last 15 to 20 minutes or more. Occurs 3 or more times each winter season: Oct 15 - Apr 15.

(3) Impaired Visibility Conditions: Plows have to slow significantly, even occasionally stop. May last 15 to 20 minutes or more, but is not bad enough to be considered a "white-out". Occurs 3 or more times each winter season: Oct 15 - Apr 15.

The reduced visibility lane miles, disaggregated by each org within a district, are detailed in *Attachment E*. However, after careful review by the ADOT Technical Advisory Committee (TAC) for this project, several inconsistencies were found in the data. These were attributed to misunderstandings of the definitions used on the surveys. Although redoing the survey was beyond the scope of AZ*Trans*, others subsequently redid it in an attempt to remove the inconsistencies in reporting methods among the ADOT Districts.

Once reliable survey data is collected, the reduced visibility lane miles data can be used to estimate the costs of various types of technology, both that which has been evaluated as a part of this ASP program and others as they emerge in the future. Such estimates are beyond the scope of this report, however ADOT personnel can make these estimates using the data gathered in this type of survey.

ATTACHMENT A

ADOT-3M SNOWPLOW TRAINING & EVALUATION SURVEY 01-02

3M Systems – US 89 Test Lane – ADOT Plow F342
Flagstaff, Arizona - February 2002

Date: _______________ Time Start:______________ Time End: _________________
Name (Optional): _____________________________ Org No: ________________
Trainee: Years of Snowplow Experience: _________Hours on the Test Plow: ________

A. Background Information:

- How many years have you been a snowplow operator? ___________
- Please rate your level of expertise (1 being novice and 5 being expert)? _________
- About how many hours have you spent on both the Caltrans and 3M snowplows?______

B. General Assessment:

Please describe the 3M Lane Awareness system and how it works, as you would to another snowplow driver that has not yet seen or used the system *(use back of page if needed).*
____
____

1. Please rate how well 3M's Lane Awareness system performs:

How easy is the system to use overall?	(very easy) 1 2 3 4 5 (not easy)
How much do you like the system overall?	(a lot) 1 2 3 4 5 (not at all)
If you had more time to practice with the system, would you like it more?	(yes) 1 2 3 4 5 (no)
Do you think that they system is beneficial in terms of increasing your safety?	(yes) 1 2 3 4 5 (not at all)
Rate the system in terms of increasing the efficiency of your snow removal tasks.	(helpful) 1 2 3 4 5 (not helpful)

2. How long do you think you would need to become comfortable with the 3M system?
____

3. When or where would the 3M system help you the most? (Daylight vs darkness? Low visibility vs. high visibility? Snow depth? Roadway geometry or alignment features?)
____

4. Could 3M's system cause you to make an wrong move or error in judgment? If so, how?
____

C. 3M Lane Awareness Functions:

1a. 3M Lane Position Indicators:

How easy is this component to use?

(very easy) 1 2 3 4 5 (not easy)

How much do you like this component?

(a lot) 12 3 4 5 (not at all)

2a. 3M Lane Departure Warnings:

How much do you like the warning lights?

(very easy) 1 2 3 4 5 (not easy)

How much do you like the vibrating seat?

(a lot) 1 2 3 4 5 (not at all)

1b. Comments – Lane Position Display: ____

____

2b. Comments – 3M Warning Systems: ____

____

3a. Eaton VORAD Collision Warning Radar:

How easy is this component to use?

(very easy) 1 2 3 4 5 (not easy)

How much do you like the warning systems?

(very easy) 1 2 3 4 5 (not easy)

3b. Comments – Eaton VORAD Radar: ____

____

D. Suggested Changes:

1. If you could add one feature or display method, what would it be & why? ___________

   ____

2. If you could remove one feature or display method what would it be & why?

   ____

3. Please list any other comments on the different ways of presenting the information:

   ____

ATTACHMENT B

Caltrans Advanced Snowplow Evaluation Questionnaire AZ-02
Arizona - February 2002

We would like to ask you some questions regarding your opinion of the California ASP driver-assist system. We will not be recording your identity and this information will not be 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 information 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 have no bearing on you standing in your job.

Background Information:

- How long have you been driving snowplows? ___________
- Please rate your level of expertise (1 being novice and 5 being expert)? ________
- Approximately how many hours of service have you accumulated in the ASP automated snowplow? _________

General Assessment:

4. Please describe the ASP system and how it works, in the way that you would to another plow driver that has not yet seen or used the system.

____

____

____

____

____

For the following questions, please rate how well the ASP system performs:

How easy is the system to use overall?	(very easy) 1 2 3 4 5 (not easy)
How much do you like the system overall?	(a lot) 1 2 3 4 5 (not at all)
If you had more time to practice with the system, would you like it more?	(yes) 1 2 3 4 5 (no)
Do you think that they system is beneficial in terms of increasing your safety?	(yes) 1 2 3 4 5 (not at all)
Rate the system in terms of increasing the efficiency of your snow removal tasks.	(helpful) 1 2 3 4 5 (not helpful)

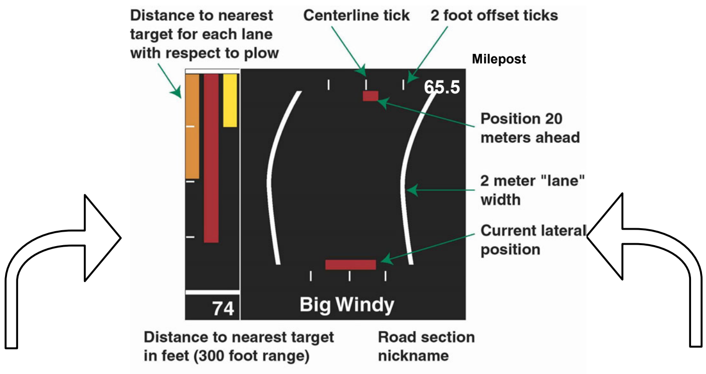
5. How long do you think you would need to become comfortable with this system? ______________________

6. Under what conditions was the system most helpful to you? (Daylight vs. darkness? Low visibility vs. high visibility? Snow accumulations of what depth? Roadway geometry or alignment features?)
____

7. Did the system ever lead you to make an inappropriate maneuver or error in judgment? (If so please describe)
____

Driver Assistance Functions:

For each component: Collision Indication, and, Lane Keeping:



Collision Indication	*Lane Keeping*
How easy is this component to use?	How easy is this component to use?
(very easy) 1 2 3 4 5 (not easy)	(very easy) 1 2 3 4 5 (not easy)
How much do you like this component?	How much do you like this component?
(a lot) 1 2 3 4 5 (not at all)	(a lot) 1 2 3 4 5 (not at all)
Comments:	Comments:

____

____

Suggested Changes:

8. If you could add one feature what would it be & why? ______________________
____

9. If you could remove one feature/display method what would it be & why?
____

10. Please draw, on the back of this sheet, what you feel would be an ideal display?

11. Please list any other comments/suggestions regarding the different ways of presenting the information: ______________________________________

ATTACHMENT C-1
3M Advanced Snowplow Evaluation Questionnaire 01-02
Trainee Comments - SYSTEM

Sample No.	Snow Plow Exp. (yrs)	Expertise (1=novice 5=expert)	ASP Plow Exp. (hrs)	Describe ASP system	How long before comfortable?	When most helpful?	System cause error?
3M 1	6	4		It keeps your truck in the proper lane and position within a foot or so, and gives correction if truck strays.	A day or so	In white out or near conditions, day or night.	No, did not see how you can get wrong info.
3M 2	3	4	1	Like the seat & light system, screen has too many things to pay attention to.	1 day	89A Airport to RimCamp	No
3M 3	11	4	3.5	Keeps you on the road, helps maintain lane position if not, seat vibration lets you know.	2 hrs	Darkness, low visibility	No
3M 4	18.7	5	2 hrs 3 mins.	Its lets you know where you are during white outs, where the traffic is on side & ahead of you, from running into the ditch and running into someone else, staying on the road.	My first test drive I felt that, I was comfortable.	In any conditions (low visibility), preferred night time. Roadway alignment for two lane roads I think it would benefit the most.	Not really familiar with it to make a comment.
3M 5	5 (6 season s)	4.5	1.5 (on both)	Vibrator lets you know if you're too far left or right, upper left toggle selects lane, dials adjust center of lane.	40 hrs	White out conditions at night on I-40 from mp 80 to 90.	Not that I could perceive during test.
3M 6	8	4	0		24 hrs	Low visibility at darkness.	No

Sample No.	Snow Plow Exp. (yrs)	Expertise (1=novice 5=expert)	ASP Plow Exp. (hrs)	Describe ASP system	How long before comfortable?	When most helpful?	System cause error?
3M 7	5	5	0.5	It uses tape in the roadway to tell you where you are on the road and should work great in a white out.	1 season would be nice.	In dark, low visibility times.	Not once, you have a little time to get used to it.
3M 8	4	4	0	It would be safety manner for other snowplowers.	2 or 3 snow storms	Nighttime and zero visibility.	No
3M 9	N/A	N/A	N/A			Beneficial during reduced visibility and with heavy new snow.	Should not cause problems if proper speed is maintained.
3M 10	5.5	3	0.5	Needed in white out conditions.	40 hrs	Darkness, low visibility, 12"	No
3M 11	20	5	40 hrs(CT) 5 (3M)	Very user friendly, easy to use, does not affect the operator, enhance driving skills.	1 to 2 shifts	All the above, I would utilize the system day/night.	
3M 12	3	3	first time	The component are easy to understand.	The more training you can get.	Low visibility and depth snow.	No, it keeps your eye on the road. The system is safe and easy to understand.
3M 13	1	1	0	Getting used to the system is easy, set time to get used to the system. A test track, so there is no traffic to watch for, level one, level two night running on test track. This way, for me you get used to the system.	40 hrs	Darkness, low visibility, snow depth, roadway geometry.	Things to work on 3M system, with time on the system, you train your eyes, and you trust the system to find the road.

Sample No.	Snow Plow Exp. (yrs)	Expertise (1=novice 5=expert)	ASP Plow Exp. (hrs)	Describe ASP system	How long before comfortable?	When most helpful?	System cause error?
3M 14	9	4	3	The vehicle has both a visual and audio warning system as well as a vibrating seat, which are designed to keep the snowplow vehicle centered on driving lane.	2 or 3 snowplow shifts(12 hrs) should do it.	At night driving heavy snowfall.	Only if the system malfunctions.
3M 15	7	4	4	Magnetic tape keeps you in, lane radar makes you aware of obstacles around you.	A few shifts of plowing	Darkness, low visibility, high visibility. You could clear a lane easily with this system in snow depth due to the 3M systems.	Not really
3M 16	4	3			6 months	Darkness, low visibility	
3M 17	10	4	0.5	It's computerize system that tell you how far away the plow is from the centerline on the road is when plowing in white-outs.	1 hr.	Low visibility, darkness	No
3M 18	3	3	1		3 months	Night	No
3M 19	17	4	N/A, don't have any on hand.		One trip with expericed operator.	Darkness, low visibility	Yes, if the system doesn't function correctly.
3M 20	6	4	3		About 2 weeks to learn it better	I used it on daylight only	On my 3 hrs of driving, I didn't get too much training.

ATTACHMENT C-2
3M Advanced Snowplow Evaluation Questionnaire 01-02
Trainee Comments - COMPONENTS

Sample No.	Lane Position Display comments	3M Warning System comments	Eaton Vorad Radar comments	What one feature would you add?	What one feature would you remove?	Display comments
3M 1	Did not use as much as the seat	I liked it, think it could make plowing less stressful, safer, more efficient.	Could be used year round, not just snow season.			
3M 2			Lane change warning could be useful year round.	Smaller screen only used to set I up or change lanes.		Very easy to use during Emergency conditions.
3M 3	Helps maintain road position, so you don't go off the roadway.	Very good profit	Radar is clear and easy to read.	None	None	Send description sheets to each district that is interested.
3M 4	With the big screen very easy to notice, you just have to glance over to know where you fit.	Very informative, lets you know where you are. Anything helps after operating a plow truck for 18 yrs.	Very good for traffic in front of you, but traffic coming up behind you I cannot tell if there was one.	Have the screen set up like the highway (drawing).	The seat vibrating, it was annoying for long hrs. of shift work.	Give a test like today, then come back, but some of them for test purposes at org level let them use it for a year, then you would get more detail information on hit really works. If you just barely use it then you really wouldn't really know the pro's and con's.
3M 5	95% there	95% there	Needed to use it on actual conditions of low visibility.	I'm still stuck on the need for a heads up display, but could get more used to current monitor with use.	Wouldn't take anything away.	Practical was excellent, suggest 2 to 4 hrs class room instruction with bigger than life size mock up system.
3M 6	Very easy	Very easy	Very helpful	Very effective the way it is now	I wouldn't	Simple and helpful.

Sample No.	Lane Position Display comments	3M Warning System comments	Eaton Vorad Radar comments	What one feature would you add?	What one feature would you remove?	Display comments
3M 7	Very easy to understand.	Would be nice to have something like this to use during storms.	I wish all trucks throughout the state had this (for safety if nothing else).			I like how it is, it seems to work good how it is.
3M 8	Keeps you in safely manner lane position for snowplowers.	Need a beeping warning sound same with lighting systems.	Warning systems is…need Radar for what up in front of you.	N/A	Vibrator seat.	The info was presented ok.
3M 9	After explanation, display is easy to understand.		Vorad display should be close to 3M display.	Move both 3M and Vorad displays together in front of driver.		
3M 10						
3M 11	Easy to read	Overall good system.	Good for blind spots.			
3M 12	Place the lane indicator in front and top of driver, so you keep eyes on road.	A warning systems keep driver safer.	The radar well increases your safety.			
3M 13	Place it more in front of driver.	Getting use to warning systems.		Have the display in front of driver, easy look at truck gauge then display and to make adjustments.		Booklet on system, to read up on it. But, hands on is more easy to learn. Reading helps to get….

Sample No.	Lane Position Display comments	3M Warning System comments	Eaton Vorad Radar comments	What one feature would you add?	What one feature would you remove?	Display comments
3M 14	Very helpful	Extremely helpful especially the vibrating seat.	Very helpful	So, far everythings good.	I wouldn't	
3M 15	Very well done, very positive.	Vibrating seat is best, but lights are good too.	I wish they would put this on all trucks now! I could use this.	None	None, I like them all.	Very well done, needs no improvement.
3M 16						
3M 17	I liked it a lot. Tells you which way to turn.	Distance to warn. How far a truck is(feet).	Warns about distance objects are.	None	None	At night with a lot of snow-windy.
3M 18	Good	Good				
3M 19	Let's you know where your at on the roadway.					
3M 20						I didn't have any training it was spur of the moment.

ATTACHMENT D-1
CALTRANS Advanced Snowplow Evaluation Questionnaire 01-02
Trainee Comments - SYSTEM

Sample No.	Snow Plow Exp. (yrs)	Expertise (1=novice 5=expert)	ASP Plow Exp. (hrs)	Describe ASP system	How long before comfortable	When most helpful?	System cause error?
CT 1	8	5	200		30 hrs.	Darkness	Yes, I am used to the 3M system and on that you move the opposite direction.
CT 2	6	4	6	It's a nice ASP system, for future snow storm with ADOT.	2 days	It would be more helpful @ 0 visibility snow storm.	N/A
CT 3	11	4	2	Tells you where you are at on the roadway, gives mm and location in which you are at, visual is on the computer screen.	2 hrs/day for 2 wks.	Darkness	No
CT 4	5.5	3		This system shows the position in lane, also warns of oncoming traffic. This is good in fog or white-out conditions.	40 hrs.	Darkness, low visibility, 12"+ of snow	
CT 5	10	4	15 mins.	It's work with sensor off Hwy from 235 to 238.	2 months		
CT 6	9	4	4		8-10 hrs. of use in conditions.	Only operated in clear weather daylight conditions.	No
CT 7	7	4	6	It is a lateral lane display like a video game and a forward obstacle screen. Nice set up.	A few snow shifts in bad conditions.	Operated in daylight, clear conditions.	No
CT 8	3	3	0	Is a GUI on roadway to keep you on the road, when your visibility is low	40 hrs.	Low visibility	No

Sample No.	Snow Plow Exp. (yrs)	Expertise (1=novice 5=expert)	ASP Plow Exp. (hrs)	Describe ASP system	How long before comfortable	When most helpful?	System cause error?
CT 9		1	0	The system, tracks on the display front and back of truck, central line, middle of lane. When the visibility is poor to zero you know where you are.	40 hrs.	Darkness, low visibility	
CT 10	10	4	0.5	It tells you where your location is on the roadway. The white line on the roadway. Curves. Mp.	More time in seat.	Roadway Alignment	No-tell you location on roadway.
CT 11	8.5	4	2	Let him get area, good feel of the place of where he is plowing. To know the system an it would be a real good asset for a white-out.	40 hrs.	Darkness, low visibility with snow accumulation.	Yes
CT 12	5	5	0.5	It tells you where you are on the road.	Few days	Darkness and white-out	No
CT 13	8	4	0.5	This system requires you to take eyes off the road and watch a screen to keep you on the road and away from oncoming traffic. It takes awhile, but not that hard to do, but you need to trust the system.	A few trips	Darkness or low visibility, any accumulation.	None
CT 14	2.5	3	1	It works good, shows cars going by you and it shows edge of the lane from the middle yellow line and the edge of the road on right hand. It will help a lot, when there is a white-out snow storm.	About 1 week	White-out snow storm	None
CT 15	6.5	4	2				
CT 16	2	4	0		1 month		No
CT 17	6	4	0.5	That it senses the trucks position in the lane, useful in poor conditions!	A few days	Low visibility, white-out	No

Sample No.	Snow Plow Exp. (yrs)	Expertise (1=novice 5=expert)	ASP Plow Exp. (hrs)	Describe ASP system	How long before comfortable	When most helpful?	System cause error?
CT 18	16	4	0	The system works off a magnet placed in roadway. Screen inside cab picks this up. The screen shows the vehicle and your steering. The objective is to drive with the screen only.	Couple of snow storms		No
CT 19	3	4	0	Its pretty easy to use, not complicated at all. After the instructor showed me how to use it, and where I had to be it was easy to read.	More practice	Basically in a white-out condition, to where you can't see the road.	No, it wasn't
CT 20	24	4	1	It works good, but we need more practice to get used to the truck, how it works A.S.P.	More practice	Daylight, first time driving, Haven't driven in darkness.	
CT 21	18	5	1	Very simple, easy to use screens, keeps you on the road, for our Roads it would be a great benefit due to mostly two lane roads with a lot of traffic. Note: this system was much easier to use than the 3M.	2 weeks	Drove only in daylight hours, it seems to work very well.	No
CT 22	17	4		Seems beneficial to everybody, if you get familiar with the system.	1 day	Even in snow the system works pretty good.	
CT 23	3	3			3 months	N/A	No
CT 24	4	3		Try to keep the truck in the center.	1 year	Low visibility, darkness	
CT 25	3	3	1		6 months		Yes, keeps you from going over centerline.
CT 26	0.25	2	1	This system is a good concept for plowing snow, however it takes some time to know the system.	1 week	Unknown at this time.	No
CT 27	6	4.5	2.5	This is so simple I would say just do it because it explains itself.	8 hrs.	Roadway geometry (no experience with low light or white-out)	No

ATTACHMENT D-2
CALTRANS Advanced Snowplow Evaluation Questionnaire 01-02
Trainee Comments - COMPONENTS

Sample No.	Collision Indication comments	Lane Keeping comments	What one feature would you add?	What one feature would you remove?	Display comments
CT 1				Having to look away from the road.	
CT 2			Screen at far left, need additional warning hazard lights for oncoming traffic or object.	None at all, just need to add additional oncoming hazard lights.	The info about ASP systems was good on behalf of future vision or zero visibility.
CT 3			None	None	Send sheet of info to Districts that are interested.
CT 4					
CT 5					
CT 6		Easy to read.	Vibrating Seat	None	Needs to be done during conditions (weather) for which it was designed.
CT 7	I like the 3M better, but this is very helpful too.	I like the 3M better, but this is very helpful too.	None	None	This is really good for what it is.
CT 8					
CT 9			Right and left light to go right or left.		
CT 10	Hard to see during daytime.	Hard to see during daytime.	None	None	On windy, snowing night training.

Sample No.	Collision Indication comments	Lane Keeping comments	What one feature would you add?	What one feature would you remove?	Display comments
CT 11			Warning "Beep" when someone is in front of you.	None	Take out the governor in a white-out to see for herself.
CT 12			Maybe move the screen just in front of you.		
CT 13	It works good, but it is hard to take your eyes off the road.	It works good, but it is hard to take your eyes off the road.	I like the vibrating seat from 3M would help.	None	There is more than enough information.
CT 14	It's like playing a video game.	It's like playing a video game.	None	None, keep it the same.	Video tape, put more people in it.
CT 15					
CT 16			No	None	
CT 17					
CT 18	Need a longer range.				
CT 19	It was pretty simple, I'm sure if I had more time and practice in it, it would become pretty easy.	It was pretty simple, I'm sure if I had more time and practice in it, it would become pretty easy.	Different kind of snowplow set up.	Different snowplow set up to where you can see the snowplow itself.	The collision indication it reads to late. By the time it reads it your nearly next to the vehicle.
CT 20					
CT 21	Gives the road features very well, in balance with driving.	Gives the road features very well, in balance with driving.	N/A, no comment, leave it the way it is.	Seems to me that the right features are on it-no change.	Work with ADOT trucks and use for a couple of years see how it works over the years, then re-assess

Sample No.	Collision Indication comments	Lane Keeping comments	What one feature would you add?	What one feature would you remove?	Display comments
CT 22	At least you know where your at all the time.	At least you know where your at all the time.			
CT 23			None	None	
CT 24					
CT 25	I like that it told you where you were at. I.e. the dip, backside, etc.	I like that it told you where you were at. I.e. the dip, backside, etc.		Smaller screen and more centered in field of view.	
CT 26	Being a truck driver, it is hard to not look at the road. When on coming cars are coming, but I like this.	Being a truck driver, it is hard to not look at the road. When on coming cars are coming, but I like this.	Night	None	
CT 27	This is the system. We can only go forward.	This is the system. We can only go forward.	Can't see an addition	Not one	Again, this is so simple anyone with basic knowledge could get in and do it.

ATTACHMENT E
Arizona Winter Conditions Visibility Survey by Lane Miles - 2002
Summarized for Each District, Disaggregated by Org

ADOT Districts Included in this Appendix

A. Flagstaff
B. Globe
C. Holbrook
D. Kingman
E. Phoenix
F. Prescott
G. Safford
H. Tucson
I. Yuma

The two specific categories of reduced-visibility conditions are summarized. The metric used is **12-foot lane - traveled way only***:*

A. **White-Out Visibility Conditions**: Unable to continue plowing; cannot see beyond the hood or make out any surroundings. May last 15 to 20 minutes or more. Occurs 3 or more times each winter season: Oct 15 - Apr 15.

B. **Impaired Visibility Conditions**: Plows have to slow significantly, even occasionally stop. May last 15 to 20 minutes or more, but is not bad enough to be considered a "white-out." Occurs 3 or more times each winter season: Oct 15 - Apr 15.

In order to obtain a metric for the proportion of reduced visibility lane miles to total miles maintained by each District, district-wide lane mile totals are included in the survey. The metrics for totals were of two types:

A. **12-foot Lane Miles (ALL)**: This includes all miles of system roadway within the district, counting the full width of pavement for each mile. For example, if a roadway has 40 feet of paved width, each mile of this roadway would count as 3.33 “12-foot lane miles” (40/12).

B. **8-foot Lane Miles (SNOW)** : This includes all miles of the system roadway within the district, but excludes the paved shoulders, which are not plowed during snow removal operations. For example, say a roadway has 40 feet of paved width, which includes two 8-foot shoulders. Then this roadway would count as 3.0 “8-foot lane miles for snow plowing purposes ((40 width - 16 shoulders) / 8). The rational is for this metric is that a snow plow typically *plows an 8-foot width* and shoulders are not plowed.

*[*****ATRC NOTE - Caution:** Apparent inconsistencies in these SECOND survey results were noted by the project’s Technical Advisory Committee. The survey, designated here as PRELIMINARY, was subsequently redone by ATRC, and the final third survey results will be reported for 2002-03.]*

* PRELIMINARY *

ADOT Winter Conditions Visibility Survey by Lane Miles (2002)

District	White Out Total[(1) (2)]	Impaired Vision Total[(1) (3)]	Total for Both Conditions[(1)]	Total Snow 8-foot Lane Miles in District	Total All 12-foot lane Miles in district
Flagstaff	168.0	260.0	428.0	3,740	2,929
Globe	323.6	512.2	835.8	2,904	2,575
Holbrook	666.0	738.0	1,404.0	2,901	1,894
Kingman	4.0	18.0	22.0	1,531	2,054
Phoenix	24.0	0.0	24.0	78	725
Prescott	346.4	631.4	977.8	1,713	2,483
Safford	94.0	104.0	198.0	2,718	2,472
Tucson	22.0	36.0	58.0	6,042	4,057
Yuma	0.0	0.0	0.0	0	2,780
State-wide Totals	*1,648.0*	*2,299.6*	*3,947.6*	*21,627*	*21,969*

(1) 12-foot lane miles--traveled way only

(2) **White-Out Visibility Conditions**: Unable to continue plowing; cannot see beyond the hood or make out any surroundings. May last 15 to 20 minutes or more. Occurs 3 or more times each winter season: Oct 15 - Apr 15.

(3) **Impaired Visibility Conditions**: Plows have to slow significantly, even occasionally stop. May last 15 to 20 minutes or more, but is not bad enough to be considered a "white-out". Occurs 3 or more times each winter season: Oct 15 - Apr 15.

Survey conducted by AZ*Trans* at NAU during month of January 2003.

*[******ATRC NOTE - Caution:*** *Apparent inconsistencies in these SECOND survey results were noted by the project's Technical Advisory Committee. The survey, designated here as PRELIMINARY, was subsequently redone by ATRC, and the final third survey results will be reported for 2002-03.]*

REFERENCES: ATRC REPORT 473(3)

1. Owen, Stephen R., Arizona Intelligent Vehicle Research Program – Phase One: 1997-2000, Report Number FHWA-AZ-01-473(1), Arizona Department of Transportation, February 2001.

2. Owen, Stephen R., Arizona Intelligent Vehicle Research Program – Phase Two: 2000-2001, Report Number FHWA-AZ-02-473(2), Arizona Department of Transportation, May 2002.

3. *2001 Motor Vehicle Crash Facts for Arizona*, Traffic Records Section, Traffic Engineering Group, Arizona Department of Transportation, Phoenix AZ, 2002.

4. *2002 Motor Vehicle Crash Facts for Arizona*, Traffic Records Section, Traffic Engineering Group, Arizona Department of Transportation, Phoenix AZ, 2003.

5. Yen, Kin S., Bahram Ravani, *et al,* A Rural Field Test of the RoadView System, AHMCT Report No. UCD-ARR-02-06-30-01 (*Draft-unpublished*), Advanced Highway Maintenance and Construction Technology Research Center, University of California at Davis, June 2002.

6. Roberts, Craig, Brown-Esplain, Jamie, and Rachel LaMesa, Final Report: Advanced Snowplow Evaluation Program – Winter 2001 – 2002, Report Number 2001.01 (unpublished), AZTrans: The Arizona Laboratory for Applied Transportation Research, Northern Arizona University, Flagstaff AZ, October 2003.

BIBLIOGRAPHY

3M Company – Intelligent Transportation Systems – 3M Safety and Security Systems Division, 3M Lane Awareness System: Keeping Snow Removal On Track, St. Paul, Minnesota, 75-0500-2243-5(80.5)ii, 2000.

Roberts, Craig and LaMesa, Rachel, Final Report: Advanced Snowplow Evaluation Program – Winter 2000 – 2001, Report Number 2000.01 (unpublished), AZTrans: The Arizona Laboratory for Applied Transportation Research, Northern Arizona University, Flagstaff AZ, December 2001.

Yen, Kin S., Bahram Ravani, *et al,* Advanced Snowplow Development and Demonstration, Phase I: Driver Assistance, AHMCT Report No. UCD-ARR-99-06-30-03, Advanced Highway Maintenance and Construction Technology Research Center, University of California at Davis, June 1999.

Yen, Kin S., Bahram Ravani, *et al,* Development of an Advanced Snowplow Driver Assistance System (ASP-II), AHMCT Report No. UCD-ARR-00-06-30-02, Advanced Highway Maintenance and Construction Technology Research Center, University of California at Davis, June 2000.