Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS Roadway Operational Analysis

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FOREWORD

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

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

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

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

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NOTICE

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1.0 EXECUTIVE SUMMARY

1.1 OVERVIEW

Successful deployment of an AHS requires examination of all operational scenarios and associated operational elements under which an AHS will be utilized. The promise and the nature of automated highways, which involve instrumentation through electronic means, requires consideration of applications completely different from those associated with the way we operate and maintain our existing highway systems. For example, a fully instrumented infrastructure is subject to a wider range of preventive maintenance repairs and supervisory control as compared to existing highways. Due to the fact that the representative system configurations (RSCs) vary in characteristics of infrastructure, communication, command and control, and vehicle type, the AHS roadway operational analysis is subject to a range of issues and impacts. Assuming the evolutionary deployment of AHS, there are no show stoppers or operational barriers with regard to AHS deployment.

1.2 KEY FINDINGS

Some of the key findings and considerations are as follow:

Current traffic management systems are primarily passive (and at best semi-automatic) and rely on macroscopic state variables such as density and speed to identify congestion and incidents. While traffic flow management requirements of an AHS would vary by RSC, configurations with central control will require a more discrete, microscopic orientation of traffic monitoring and management. The characteristics of traffic flow monitoring and management need to be examined and defined as AHS evolves.

Although it is the promise of the AHS to reduce the occurrence of incidents, the impacts of any incident on AHS will be catastrophic with regard to traffic operation. Therefor AHS must improve incident detection and shorten incident response time. The impact of traffic congestion and delay on an AHS lane will be much greater than current impacts to the existing highway system. Therefore, the incident response time must be reduced in order to maintain current highway levels-of-service.

For operation of an AHS, new or hybrid operating agencies and their organizational frameworks will need to be defined along with their potential operations responsibilities. The levels of association, coordination, and autonomy among the operations elements of existing highways, such as management, maintenance, police and emergency services need to be identified along with potential problems with existing arrangements of these operations elements. Each operating agency scenario and the operational impacts of a multi-jurisdictional framework need to be evaluated and studied. Evaluation criteria should include operations uniformity, effectiveness, and practicality of providing such service.

Current levels of expertise and staffing available at existing operating agencies can not support the requirements neccessary for an AHS. The areas of expertise required for operation and management of an AHS need to be evaluated. Survey and review of current practices of in-house versus contracted-out functions at state DOTs and highway authorities are essential to final deployment of AHS.

AHS operations require preventive maintenance on a level similar to the airline industry. Existing levels of preventive maintenance performed by highway operating agencies, including operators of traffic management systems, will not satisfy the requirements of AHS. A target level of preventive maintenance for AHS needs to be defined through investigations of comparable systems.

It is anticipated that the AHS will need policing and involve policing tactics different from those practiced today. Dependent upon the RSC, the level of policing, police functions, and tactics will vary. Current policing practices need to be examined, including the level of policing, functions and tactics applicable to deployment of an AHS.

1.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Successful deployment of a fully-automated AHS is highly dependent to it’s reliability, efficiency and safety. In fact implementation of AHS concept will require careful and prudent planning, implementing, operation, maintenance, and mitigation efforts based on a clear understanding of the potential issues and potential problems. We believe in particular that further research is required in the following three areas: incident management techniques, maintenance requirements, and environmental monitoring.

2.0 INTRODUCTION

The primary objective of this task is to evaluate the management and operational requirements of AHS from the perspective of day to day facility operations. From that focus, three categories of generic operational elements for a typical AHS configuration were identified as follows:

- Organization
- Operations
- Maintenance

These three categories of operational elements were further broken down to the following levels:

- Organization
  - operating entity
  - responsibilities / jurisdictions
  - staffing skills/levels
- Operations
  - traffic flow management
  - incident management

- policing/enforcement

- Maintenance
    - procedures
    - equipment

3.0 TECHNICAL DISCUSSIONS

Each operational element was evaluated primarily in a general context of a national AHS deployment. Some consideration of the deployment scenarios selected for analysis and the Representative Systems Configurations (RSC's) were incorporated into the more general analysis. Our overall approach consisted of reviewing existing systems, procedures and resources currently available or in use by operating agencies. The applicability of each of the elements was evaluated for an AHS and where feasible those elements requiring modifications were identified.

3.1 ORGANIZATIONAL ISSUES

3.1.1 Operating Entity Options - Jurisdictional Issues

Operations of existing highways, bridges and tunnels are under the jurisdiction of various governmental agency structures. Since the basic premise of an AHS is that automated vehicles will be monitored at all times and the system will immediately respond to changes and problems; responsibilities for operation and control must cross jurisdictional boundaries. Each agency structure commonly assumes responsibility for certain operating functions while others are provided by related agencies or private contractors. Various funding structures for specific operational elements is also common. Jurisdictions within a region must coordinate responsibilities, such as; police, fire, emergency response, and maintenance for this automated control mode of travel. One method of avoiding jurisdictional conflicts is to contract regional services to private firms. The operation of major public highway facilities by private operators is currently a serious consideration.

Responsibility for operations and maintenance of an automated highway system will be assumed either by an existing public entity or a new public entity created to assume this role, or assigned to a private operator. Each roadway operations framework may engender unique utilities or disutilities with respect to automated highways. Furthermore, the need may arise, due to various limitations of existing operating structures in providing the proper level of roadway operational services for AHS, to devise new or hybrid operational frameworks for this highway concept. It is the intent that this issue examine all feasible operating options and evaluate their advantages and disadvantages with respect to the unique characteristics of automated highways.

The following table describes the general categories of existing highway operating agencies and their operational responsibilities.

Table 3-1. Typical Operating Responsibilities

Operating Agency	Typical Responsibilities	Funding
DOTs (Department of Transportation/Highways) /De-partments of Public Works	Facility management Traffic Management Maintenance	State/Local
Public Authorities	Facility management Traffic management Maintenance Policing	User fees

New or hybrid operating entities that could be developed to operate automated highway systems include:

- Private Facility-Specific Operators
- National Operating Agency
  - federal
  - private
  - quasi-public

The AHS will most likely be implemented in phases with initial systems placed on existing highways in congested areas. This approach may result in various levels of systems or configurations operating in different areas simultaneously. It is important that despite the variation in configuration or system, compatibility between them will be maintained. This will require a great deal of coordination between public and private sectors. This involvement of public and private sectors in the development and operation of different levels of systems, will create the potential for a variety of technologies and standards. National standards and specifications should be developed by an overseeing agency to maintain uniformity. As technologies improve, the standards and specifications should be modified and updated. Possible sources to provide input might be the National Institute of Standards and Technology, American Association of State Highway and Transportation Officials, International Standards Organization and the Institute of Transportation Engineers. An example of a comparable system is the nation's air traffic control system. While a significant number of airports have less sophisticated control systems than others, they operate as part of an overall interconnected system which is overseen by and subject to national standards set by the FAA.

3.1.2 Skills Requirements

The introduction of a completely new technology will require significant modification to existing highway operations practices in the areas of management, operations and maintenance. Therefore, the skills and staffing required for operating an automated highway system will be an important issue. Complex communications systems, automated and robotics maintenance equipment, and automated roadway vehicle control systems will require highly skilled, specialized operations and maintenance staff. Management of an AHS will require extensive involvement with coordination of agencies and the management of various resources.

Specific expertise and skills will be required for the management, operation and maintenance of an automated highway system. Major skills categories will include:

- Management
  - ability to utilize and coordinate various resources
  - ability to foster cooperation and collaboration among agencies

- Operation
  - information management
  - communications technology
  - control software algorithms
  - electrical and systems engineering

- Maintenance
  - computers / automation
  - robotics

Several research findings of current and previous levels of expertise and staff available at existing highway agencies suggest that significant staffing shortfalls could be likely in the future with regard to AHS. For example, an FHWA 1990 survey of control systems indicated that 87 percent of the systems did not meet minimum performance standards because of inadequate expertise, insufficient staffing, and funding constraints. (Ghaman, 1993) Forty-three of the fifty respondents to a 1984 Transportation Research Board (TRB) survey of state highway agencies expected their greatest increase in skill would be needed in the area of computer programming and systems analysis during the next five years. The survey also indicated that low wages and hiring freezes were cited most often as problems encountered in recruiting, hiring, retaining, or utilizing staff. (TRB, Special Report 207, 1985) Considering the increase in complexity of an AHS compared with the existing traffic control systems surveyed, this is certain to be a major issue.

In-house and contracted-out types of services at state DOTs and highway agencies/ authorities may be a valid indication of the types of skills and expertise available in such agencies today, some of which may be applicable to the operation of an AHS in the future. Services which are currently contracted-out and may apply to the operation of an AHS most likely will continue to be contracted-out. Studies indicate that contracting for operations and maintenance services may be a more cost-effective alternative, directly related to the difficulties many agencies face in retaining a highly skilled staff due to hiring freezes and budget cuts. Respondents to a 1990 AASHTO sponsored survey of highway agencies cited that limitation of in-house staff, need for specialized equipment and need for specialized personnel as the three greatest reasons for deciding to contract for maintenance. (NCHRP Report 344, 1991)

3.1.3 Policing and Enforcement

It is anticipated that the AHS will need policing and involve policing tactics different from those practiced today. Current policing practices for highway facilities consist of enforcement of traffic laws, response to incidents and conduct of scheduled patrols. Automated highway system characteristics may significantly alter the policing requirements and tactics in operation today. Enforcement may be implemented directly through the system, scheduled patrols may be significantly reduced and procedures for responding to visual observations and pulling over of vehicles will be significantly altered. Access procedures to the system by police vehicles will need to be determined in addition to how they will respond to visual observations. Depending on the system configuration and the vehicle operations, police vehicles may require additional capabilities in instrumentation and performance.

A means to allow the police officer to differentiate an automatic vehicle from a non-automatic one will need to be developed. It will need to be a system which will be able to be focused upon a single vehicle, even if within a dense platoon, positively detect working automatic vehicle control systems, and not be easily circumvented by violators. It should also be able to be used from either a moving or stationary vehicle.

There are multi-faceted issues regarding AHS operations (as well as conventional highways) and policing. Police presence is important to ensure proper operation. If there are too few officers in the field, intrusions by unauthorized vehicles could increase resulting in reduced safety. Numerous studies of the effectiveness of enforcement policies and procedures indicate that police presence is a deterrent to traffic violations. (Billheimer, et al., 1990) Conversely, too many officers visible may be counterproductive, as the heightened police activity may instill congestion. (SYSTAN, Inc., 1990) Also, it has been shown that the relationship between policing levels and violation levels is curvilinear. Thus, there would be the need to determine the point of diminishing returns.

When a violator is located on most existing highways, the officer usually has to escort the violator across one or more lanes of traffic to the shoulder. This can create turbulence leading to congestion. The provision of enforcement areas, areas especially designed for police use, can provide several benefits. They are dedicated areas, typically 14 feet wide and 1000 to 1200 feet long and placed at strategic locations. Many agencies currently employ these areas where police may safely station themselves, observe violators, and issue citations.

Among their benefits are:

- Officers feel more comfortable looking for violations from a stationary position, rather than while moving in traffic. The enforcement area provides an area from where the officer may be stationed to observe passing traffic.
- Provides a safe area, protected from moving traffic, to where violators may be escorted and ticketed.
- Being positioned between the automatic and conventional lanes, the number of lanes necessary to escort the violator across would be minimized.
- Knowledge of the area's existence would carry the threat of possible enforcement, even though an officer may not actually be present.

Complete transfer moves between the automatic and conventional lanes would not be possible near the enforcement areas. Thus. the enforcement areas should be placed in locations where low demand for transfer movements would be likely. They would also need to be well-signed to deter motorists from mistakenly entering the area. Barriers at the entrance to the area would need to be protected with impact attenuators.

Police should work alone when enforcing traffic violations. More than one police vehicle with a violator, unless necessary, is an inefficient deployment of forces and creates a distraction to passing traffic.

Studies to measure the effectiveness of enforcement levels should be conducted periodically. Violation data should be collected during periods of low, normal, and increased police deployment levels. Such studies should provide indices of at what point increased police presence yields diminishing returns, and how often increased enforcement drives need to be conducted. This data should also be helpful in determining staffing levels required to police the AHS.

The level of police staffing necessary for an AHS should be below what is needed today based on the automation of an AHS itself. Staffing levels of police required for an AHS would decrease as the level of communication, command and control (C^3) associated with each RSC increases. Police tactics and procedures would vary by the RSC, based on the type of infrastructure (I1,I2,I3) in place and the level of C^3. For example, an I1 infrastructure would require ability to police both automated and non-automated vehicles. The presence of non-automated vehicles sharing the same travel space as the automated vehicles, as seen in I1, will require higher policing levels and current tactics in addition to newly developed ones designed to police the automated vehicles. An I2 infrastructure requires police vehicles and tactics to address operations in automated and non-automated lanes. This infrastructure probably lends itself to one of the more serious concerns associated with policing the automated lanes; access by an unapproved vehicle. The I3 infrastructure will require lower levels of policing since the roadway will be restricted to automated vehicles only.

3.2 OPERATIONAL ISSUES

3.2.1 Traffic Flow Management

There are two types of congestion that can be expected with AHS roadways: recurrent and nonrecurrent. Non-recurrent congestion is caused by random incidents, and will be discussed in the next section. This section discusses the concepts for managing normal traffic operations and recurrent congestion that results from forced traffic flow (i.e., when demand exceeds capacity). In many instances both the location and time of occurrence of congestion can be predicted. Currently the best traffic flow management techniques will enable the operator to manage available roadway capacity through the following techniques:

- Mainline traffic monitoring and control.
- Integrating the monitoring and control system with the adjacent corridor arterial street network.

Recurrent congestion on existing highways is characterized by slow operating speeds, stop-and-go movement, inconsistent travel times, increased accident potential, inefficient operation, and other undesirable conditions during daily peak travel periods. Mainline monitoring and control will facilitate the elimination of these congestion impacts by the selection of the operational strategy best suited for the traffic demands.

Traffic flow data obtained from mainline detectors will be used as input to a computer-based traffic simulation model. The model will test control strategies to identify those most likely to improve recurring in traffic flow characteristics. The selected strategy(ies) will be implemented to achieve the following:

- More uniform and stabile traffic flow, forestalling the onset of congestion.

- Diversion of main roadway traffic to alternate routes to maximize corridor traffic through-put and utilize total available capacity.

- Limit/prevent additional traffic from entering congested segments.

Currently, roadway traffic control has been implemented through the motorist information system, via variable message signs. These signs are also used to indicate reduced operating speeds during peak hours, and to warn motorists of hazardous conditions (e.g., fog, or icy or slippery pavements).

Integration of the AHS traffic control system with the non-AHS roadway network will be essential in maintaining a consistent flow of traffic in the AHS roadways, improve the efficiency and safety, facilitate emergency procedures, and maximize the utilization of main roadway capacity. This integration needs to be accomplished through entrance ramp metering, with traffic control devices installed at each major entrance ramp. The concept will be to meter the number of vehicles entering the AHS so that traffic demand does not exceed capacity. Consequently, some of the traffic desiring to use the AHS will be required to wait at the entrance ramps or use non-AHS routes (diversion strategy). In cases where alternate routes will not be available, or when traffic conditions on local streets are such that diversion is inadvisable, ramp meter rates will be increased (non-diversion strategy).

The ramp metering strategy must rely upon continuously updated traffic information via electronic means. This information will allow assessment of the current overall level of service on the AHS ramps.

For free-flow conditions (i.e., no congestion), data from detectors throughout the AHS lanes must be analyzed at the AHS operation control center where metering rates will be established for a system of entrance ramps. Metering rates established at one location will automatically affect the selection of metering rates imposed at downstream ramps.

When the metering rates at individual ramps become restrictive, (i.e., when ramp queues interfere with local street operations), a diversion strategy can be enacted via the variable message signs or blank-out signs visible from the local street approaches to the ramp. This will require coordination between the ramp metering signal controller and the traffic signal controller(s) at the local street ramp junctions.

However, when taking into consideration practical constraints associated with ramp metering, such as queue storage capacity, available excess capacity on alternative routes, diversion of motorists to other AHS entrance ramps, the actual amount of reduction in the traffic demand practically feasible is likely to be less than the theoretical maximum.

A further study will be needed to assess the most likely outcome of the implementation of current techniques i.e., ramp metering (including analysis of entrance ramp queue storage capacity, availability of alternative routes, selection of proper ramp metering type, fostering of public acceptance, careful selection of the AHS entrance ramps for the ramp metering considering their location-specific conditions).

3.2.2 Incident Management

AHS can reduce the occurrence of incidents, improve incident detection and shorten incident response time. However, the extent of any benefits will be dependent upon the inclusion of incident response and mechanism considerations as part of the automated highway system during its development.

The specific way in which AHS will impact incident detection and response was determined by reviewing existing systems and evaluating likely methods, procedures and plans for AHS, such as immediate detection, immediate response and modified response plans.

Incident management consists of three major areas: detection, identification and response. Research of existing systems and technology being developed provided the following characteristics of current incident management systems:

- Current methods of detection - detectors, calls from cellular phones and roadside call boxes, patrol reports, ultrasonic and video-image detection, and the Mayday system.
- Current methods of incident identification/verification - primarily verification at site or through CCTV.
- Current response elements - variable message signs, highway advisory radio, in-vehicle audio messages and displays, computer aided dispatch and contracted towing services.
- Successful response plans must encompass the following elements - inter-agency coordination, an approach to managing incidents, working relationship among agencies, communication links between agencies, detailed procedures, and post-incident critiques.

Incidents can be defined as accidents, disabled vehicles, debris on the roadway, cargo spills or other random events that temporarily reduce roadway capacity. Studies performed by the Federal Highway Administration (FHWA) have shown that over half the freeway congestion in urban areas is attributable to incidents. (Judycki, Robinson, 1992) In the Seatle area, 58 percent of the delay experienced in 1984 was estimated to be incident related. (Berg, et al., 1992) By year 2005, incident-related congestion is expected to account for 70 percent of all congestion. (NCHRP Synthesis of Highway Practice 177, 1992) Traffic congestion is created when the traffic demand upstream from the incident exceeds the roadway capacity reduced by the incident. Minor incidents, mechanical problems, flat tires, vehicles out of gas, fender-bender accidents, comprise 80 percent of all incidents occurring in urban areas. (Judycki, Robinson, 1992) For example, 50 to 60 percent of Toronto-area congestion is caused by incidents and 85 percent of the incidents are considered minor. (Korpal, 1992)

Preliminary conclusions indicate a probable reduction in incidents on an automated highway system. Congruent to the implementation of an AHS, vehicle operations will be reviewed at check-in, regular inspections of vehicles will be performed and driving will be fully automated. As a result, most if not all, minor incidents occurring today, depending on the RSC, will be eliminated for an AHS. Current statistics indicate that over 90 percent of all accidents involve human error. AHS will eliminate driver error and therefore would be expected to reduce the number of accidents. Accidents should only occur as the result of vehicle or system malfunction.

The duration of the incident or the amount of time that passes prior to clearing the incident is a critical factor of incident management. Current studies have shown that for lane-blocking incidents, each minute of duration produces at least four minutes of congestion. An incident blocking one lane of a three-lane freeway reduces the capacity in that direction of travel by 50 percent. If traffic upstream of the incident is at or near capacity, queuing can build at a rate of about 8.5 miles per hour. The potential impact of incidents on AHS operations, as shown in figures A-1 - A-12, was estimated by applying the following assumptions to queuing theory;

- peak demand and non-incident capacity for an AHS lane is estimated to be 4500 vphpl
- the single AHS lane will be completely blocked during an incident
- no upstream demand restriction will be implemented

For a peak period of two hours, an incident lasting six minutes on the AHS lane will result in more than two hours of congestion, generating queues of over a mile in length. As the duration of the incident increases to one hour, the congestion will last for over 4 hours and the length of the queue on the AHS lane will extend beyond 17 miles. Although, as stated above, incidents will be less frequent on an AHS lane, especially for RSC's involving the highest level C^3, the impacts resulting from them will be much greater and therefore, it is imperative that an AHS incorporate immediate detection and response systems.

3.3 MAINTENANCE

3.3.1 Maintenance Procedures

As for conventional highway systems, the AHS will undergo periods of varied maintenance activities to assure optimum performance is maintained. Many activities, such as repaving and restriping, mowing, and cleaning are common to both systems and impact traffic flow to varying degrees; for example, mowing operations cause little or no disruption to traffic while repaving has significant impact, especially during peak traffic periods. However, these impacts are more critical on an AHS with its higher capacity. For example, given an operation requiring a lane closure on a two-lane highway system, a 50 percent reduction of capacity on either a conventional system or an AHS would result. However, since the capacity of an AHS is estimated in excess of 4000 vphpl, such a closure is analogous to closing two lanes of a conventional highway.

As maintenance operations on an AHS would have the potential of impacting a greater number of people and goods, major issues will center upon maintenance plans and procedures. It will be necessary to prepare and implement a preventive maintenance program to deter the occurrence of major failures to the various AHS components, including infrastructure. Another issue would be the development of sophisticated procedures and equipment allowing the repairs to be affected with reduced disruption to normal traffic operations.

An effective maintenance program applies maintenance at critical intervals to avoid component failure. This maintains the highest level of system performance possible, with regard to safety, comfort, and function, within a set budget and target level. It also enables the system to be operated with down-time scheduled during relatively low usage periods. Existing levels of preventive maintenance performed by highway operating agencies and comparable systems will provide a basis for determining the appropriate target level of preventive maintenance for an AHS. Comparable systems of an AHS might be:

- Air Traffic Control System - "time-change" system
- Nuclear power plant

Like an AHS, both of these systems must avoid failure or have zero-level error, primarily due to safety issues.

Maintenance activities may be classified into three groups. These along with some examples are:

- Preventive - Maintenance activities to repair relatively minor faults which may potentially evolve into major defects if left untreated. Examples of preventative maintenance would include pavement crack sealing, pothole repair, and VMS bulb replacement.
- Periodic - These are activities which need to be performed at regular, and possible scheduled, intervals. These intervals will vary depending upon the nature of the specific maintenance activity. Examples of periodic maintenance would include mowing, roadway cleaning, sign cleaning, resurfacing/restriping, and inspections.
- Overhaul - These are activities which usually require heavy construction of relatively long duration. This type of maintenance normally is not scheduled, but its undertaking is usually driven by need. Examples would include major roadway repairs made necessary by structural failure or natural disaster, highway widening, or bridge rehabilitation.

This section will identify the maintenance issues relative to I2-$C^3$2-V3, many of which will also apply to other RSC configurations.

This following discussion will identify the issues related to specific maintenance activities on an AHS of I2-$C^3$2-V3 configuration. All three categories, preventive, periodic, and overhaul maintenance, will be addressed.

Preventive

Crack Sealing and Pothole Repair - These activities usually require temporary closure of at least, but usually no more than, one lane. The affected lanes can be reopened to traffic during non-working hours. Current procedures require a series of sign, drums, cones, and other devices placed in advance of the work zone to alert motorists of the lane closure and to guide them around the area. Flaggers may also be utilized. It will be necessary to utilize similar procedures for work within the non-automated lanes of the AHS.

For similar work in the automated lanes, the repair vehicles/equipment should be fitted with communication devices so its exact location at any time can be determined by the operations control center (OCC). Knowing the location of the precise work area location, the OCC can create a safety zone and lane transitions. This information would be transmitted to the automatic vehicles, which would automatically perform lane changes out of the work lane, reduce speed, and resume normal travel operation once the work area is passed. With this artificial safety zone, the work in the AHS lanes would be able to be completed in less time than similar work in conventional lanes due to the elimination of the need to place and remove traffic control devices. However, this also depends upon the prevention of non-automated vehicles from entering the automated and transition lanes. Unless non-automated vehicles are positively prevented from encroaching the automated lanes, it will still be necessary to place safety devices to protect the work zone and workers. This would make maintenance operations in the automated lanes less efficient than potentially possible, and result in an unnecessary loss of capacity.

For work in the transition lane, placement of traffic control devices will be required to warn both the non-automated traffic, and the automatic vehicles which would be operating under manual control during transfer between the automatic and non-automatic lanes. The issue of how automated vehicles will be allowed to use the transition lane in advance of the work zone will need consideration. In the case of an automated vehicle which would be making a transfer to the conventional lanes, it may be desirous to place the vehicle under manual control at an earlier point than which would otherwise be done and advise the motorist to make the lane change thusly. Or, it may be preferred to prevent the motorist from operating in manual mode until the work zone is passed.

An issue which will need to be addressed will be how the transition lane will be operated through the construction zone. If the work zone is in the conventional lanes, non-automated vehicles may tend to enter the transition lane, especially if congestion is present. The presence of traffic in the transition lane would reduce the ability of vehicles to transfer from the automated lanes to the conventional lanes. This reduced ability would, in turn, reduce the capacity of the automated lanes. A policy should be developed to determine if and when traffic conditions warrant the temporary use of the transition lane by conventional traffic, provided the automated lanes are not seriously impacted.

Variable Message Sign (VMS)/Lane Use Signal (LUS) Bulb Replacement - This work is typically of short duration, but may require a lane closure during its performance. Currently, this type of work is performed from either a vehicle-mounted raisable platform, or a "cherry picker" - a bucket attached to the end of an movable, extendible boom which can be operated from either the ground or the bucket. Permanent catwalks on the sign support structure normally are not used at VMS/LUS locations as they can partially obstruct view of the sign. Even if a catwalk was supplied, a worker would not be able to reach the upper portions of the VMS to replace bulbs, or perform other repairs other than sign cleaning.

Bulb replacement would require a lane closure in most cases, and the treatment and associated issues would be the same as discussed above for crack sealing and pothole repair. Some work may be performed from cherry pickers with the vehicle parked on the shoulder or just off the pavement area, but the vehicle would need to be highly counterbalanced or anchored to permit parking off the traveled way and greater boom extension to the more remote signs. An issue to consider would be to provide a winch on each sign support structure which would enable the VMS to be moved temporarily over the shoulder, where the maintenance vehicle may be parked out of the traveled way. Once the repairs are completed, the VMS would be repositioned to its proper location.

Closed-Circuit Television (CCTV) and Remote Terminal Unit (RTU) Repair - These activities would not require lane closures, so traffic operations would not be impacted by performing the maintenance. However, the efficiency of the AHS facility would be affected by having these elements out of service. An inoperative CCTV would result in a loss of video image detection (VID) information and the ability to rapidly detect, confirm, and locate incidents. Therefore, CCTV repair should receive high priority. RTC repair would be given a slightly lesser priority, assuming redundancy is built into the communications system to assure communications are maintained. This does not suggest that repairs can be delayed for significant lengths of time; to do so would risk total communications loss should the redundant system also fail. Conventional traffic would be impacted by RTC failure through the loss of incident detection, and the loss of electronic informational signing. In free-flowing conditions, RTC failure probably would go unnoticed by the conventional motorist. The motorist in the automatic lanes, however, would perceive the failure in any traffic condition as it would not be possible to maintain automatic operation through the affected highway section. An important issue arising from this scenario is how will the motorist approaching the affected highway section be alerted that manual operation must be implemented, and then advised when automatic operation may be resumed.

<u>Periodic</u>

Roadway/Bridge Inspections - These inspections would be performed at scheduled intervals to detect defects and to assist in the programming of repair projects. In this light, they may also be considered as preventative maintenance. Formal roadway inspections are currently performed by 100 percent of the states, provinces, and toll road agencies in the United States and Canada. Over 70 percent of these perform them annually. The techniques employed, however, differ, including automatic sensing, photo logging, and visual inspection and manual notation. Bridge inspections are mandated by the FHWA to be performed at minimum 2-year intervals. Since the defects that the inspections are intended to detect would have a greater affect upon an AHS than the conventional highway system, it would become necessary to reduce the inspection time requirements while improving the ability to detect roadway faults. A significant improvement over existing capabilities would be to locate subsurface faults.

Snow and Ice Removal - These activities are necessarily performed out of need rather than schedule, however, they are planned for. Snow and ice greatly reduce capacity and safety, and, if accumulations are great enough, completely close the highway. Priority is usually given to clearing the right-most lane first, then progressing toward the center median. This is to assure that at least one lane is operational, and one that is accessed most easily by ramps. In the I2-C^{3}2-V3 configuration, the automated lanes are toward the median. Thus they would be the last to be plowed and would be most affected by snow and ice. To minimize the down time of the automatic lanes, it would be necessary to maintain an ample amount of trucks fitted with plows, salt spreaders sufficient to gang-plow the highway; that is, a convoy of vehicles traveling in a slant formation such that each successive vehicle pushes the snow cleared by the previous vehicle further toward the shoulder. Supplies of salt and sand should be stockpiled at the vehicle maintenance yards and loaded onto the vehicles<u>prior</u> to the storms arrival.

Mowing, Drainage System Cleaning, and Debris Removal - Mowing is a necessary operation performed at regular intervals typically ranging from 2 weeks to 1 month in duration. It keeps the highway landscape in a more attractive state. It also maintains safety by discouraging the uncontrolled growth of bushes and trees which may prove hazardous if hit by an errant vehicle. Since this operation takes place off the traveled way, it has little if any impact upon highway capacity and safety to the passing traffic.

Drainage system cleaning is an operation which is routinely performed by some operating agencies at two-year intervals; others do it on an as-needed basis. A clogged catch basin can result in ponding, which is difficult to see in night conditions, and can cause a vehicle to hydroplane and perhaps go out of control. This would be especially critical if it would occur in an automatic lane as it may be necessary for the vehicle to immediately go to manual operation.

Sign Cleaning - Sign cleaning is a regularly scheduled activity by most states and operating agencies. This operation is required for electronic and fixed message signing alike to assure readability and reflectivity is maintained. Twice yearly cleanings are the norm and is adequate in most climes. More frequent cleaning may be required where environmental conditions dictate, such as within tunnels, or in urban areas subject to slower traffic and higher levels of trucks.

This activity usually requires at least a single lane closure. When performed in tunnels, it may be required to close the entire bore to traffic. To minimize disruption of traffic operations, it would be required to both schedule the work during off-peak traffic periods and to rely on mechanized techniques to speed the process. Routinely replacing bulbs for VMS and LUS should be considered to be performed during the cleaning operation. This would reduce the number of anticipated failures due to bulb burnout which may otherwise occur.

Repaving - This work item is required on most highways at least once each five to ten years. A variety of factors contribute to the repaving need, such as traffic volumes, volume of heavy vehicles, and pavement structure. Snow melting policies (salting) can also be a factor.

Repaving is a major operation requiring large work areas, and numerous workers and pieces of heavy machinery. Construction materials also need to be trucked to and from the construction area. Milling (a process where a portion of the worn surface course is removed) is often required, especially where to final surface elevation is critical, or where the existing surface is severely rutted or cracked. Milling can "correct" the pavement cross slope and improve the paving operation and finished quality by allowing paving in uniform depths and providing a rough surface for the new material to better adhere to.

As this is major construction, it will require a far greater work zone than short-term operations such as pothole repair. Also, it would require a greater lane closure due to the heavy equipment and workers present. Typically, two lanes need to be closed while a single lane is actually being repaved. Operations in center lanes would require temporary lane shifts around either side of the work zone, if the existing highway width does not have enough lanes to allow full lane closure on either side of the work zone. It is obvious that capacity would be severely reduced for any type of highway. But if work was being performed in the automated lanes, automatic operation would be lost if the AHS was furnished with only two automatic lanes.

The maintenance issues and procedures previously cited for pothole repair would also apply to repaving, but to a larger scale. Traffic control devices would need to be placed in advance of the work zone, regardless of its location, to protect it from manual-operated vehicles. For work in the automated lanes, the necessary lane closures could result in the loss of automatic operation capability, requiring the automated vehicle to switch to manual operating mode prior to reaching the construction zone. As an alternative to maintain a minimal level of automatic operation, it would be necessary to design the central computer with the capability to create a temporary lane shift around the work area, utilizing either the shoulder or the transition lane, and transmitting the alignment data to the automatic vehicle. This capability would also need to monitor the shoulder area to assure that it is not blocked by broken down vehicles or construction equipment, etc.

Overhaul

Like repaving, roadway overhaul, or reconstruction, requires generally large work areas, sizable equipment and labor forces, and special care to guide motorists safely around and past the work area. In contrast, however, lane closures, alignment shifts, and detours necessitated by overhaul usually must remain in place during non-working hours; the nature of this work seldom allows the work area to be opened to traffic during peak and heavy demand periods. Thus, a long-term capacity reduction results.

Heavy construction on an AHS would have different impacts upon traffic operations, depending upon which lanes were closed for construction.

Closing a conventional lane on an AHS with two conventional lanes would result in a greater than 50 percent reduction in conventional capacity, due to the loss of one lane and additional congestion/friction factors. Access from the ramps to the automated lanes would be made more difficult. The increased congestion on the conventional lane may encourage usage of the transition lane, making movements into and out of the automated lanes more difficult.

Closing the transition lane would not have as large an impact on AHS capacity as it is not intended to be a main travel lane. However, movements between the automated and conventional lanes would be prevented through the work area. This closure would be most critical in the vicinity of ramps. Automated vehicles desiring to exit would have to switch over to the conventional lanes at an earlier point than they would under normal conditions.

Closing an automated lane would have the most severe impact, especially if the automated lanes normally operate at high traffic levels. The displaced automated traffic would absorb all reserve capacity, both on the automated and conventional lanes, creating congested conditions. As a mitigation measure, it would be of benefit to create a temporary automated lane(s) out of the transition lane, or possibly a conventional lane.

Mitigating measures will need to be developed to reduce the frequency of need for major reconstruction projects, and to complete them in the most timely manner when the needs arise. Possible considerations would include:

- Development of robotics to perform roadway construction
- Extending work hours
- Consolidate improvement projects; include periodic maintenance projects as part of the total project
- Develop more durable pavement materials and structures

3.3.2 Equipment and Instrumentation Requirements

3.3.2.1 Existing Technologies

There exist several technologies to make inspection, traffic control, and repair operations at least partially automated. As their use is increased, improvements will continue to be made such that by the time the AHS becomes a reality, they will become a vital part of the overall AHS facility. Examples of these devices are: (Hsieh, Haas, 1993)

- Automatic Pavement Distress Survey System - Komatsu Ltd., Japan - measures cracking, rutting, and longitudinal profile utilizing laser, video, and image processing techniques. The surveys can be performed at speeds up to 60 kmh.

- Automatic Road Analyzer - Highway Products International, Inc., Canada - measures rut depth, transverse profile, ride quality, and distress. The on-board equipment consists of ultrasonic sensors, accelerometer, video cameras, and a microprocessor. It can operate at speeds up to 88 kmh.

- Laser Road Surface Tester, Swedish Road and Traffic Research Institute - Equipped with eleven laser range finders and as accelerometer, measures crack depths and widths, ruts, roughness and cross profile while traveling at speeds of 30 to 88 kmh.

- Addco Cone, Addco Manufacturing Co., Minnesota - a device which attaches to a pickup truck from which a worker may sit protected from traffic while placing or retrieving traffic cones.

- Quickchange Movable Barrier System, US Barrier Systems, Inc., California -- Consists of a 3-km chain of concrete barriers and a special machine to pick up the barriers and accurately place them in a new location. The entire chain can be repositioned in less than 30 minutes.

- Automatic Crack-Filling Robot, Carnegie-Mellon Univ. and Univ. of Texas at Austin - The device uses a video-based raster scan image with a laser range detector to detect cracks, and a heated air torch and a sealing wand to effect the repairs.

- Robotic Crack Sealing System, California DOT and Univ. of California at Davis - uses a machine vision system to detect and locate cracks, and a robot manipulator to seal the cracks.

3.3.2.2 Future Requirements and Other Issues

The AHS will require a sophisticated series of diagnostics and robotic equipment to maintain optimum operating capacity and efficiency. The devices stated in the previous subsection and similar equipment and their refinements will have a place in the maintenance arsenal. However, other capabilities will need to be developed, including:

- Robotic pavement survey equipment with the capability to detect subsurface flaws while traveling at or near normal operating speeds. Normal speed operation would negate the need for warning devices.

- Combined-task robotic pavers capable of performing milling, pavement placement and compaction, and restriping in a single pass. It may also be desired to provide the capability to recycle the material from the milling operation into the new pavement mix to reduce construction time and material costs.

- Provide overhead sign and Lane-Use Signal (LUS) locations with a mechanism to "unplug" the signs and transport them to ground level, off the side of the road, via remote control so they may be cleaned or repaired without the need to close any travel lanes. Once the maintenance is complete, they would be returned to their normal position.

- All electronic devises on the AHS, from the central computer to each VMS, should be equipped with self-diagnostics, to not only detect and report failures, but to predict failures before they occur. This would allow the operators to determine which AHS components should be repaired before failure occurs and traffic operations are diminished in a less-controlled environment.

- All maintenance vehicles should be fitted with telemetry equipment to permit constant monitoring of its location. Using this location information and the nature of the construction, the central computer can create an artificial safety zone, and guide automatic vehicles safely around the construction area.

- Research will need to be conducted to find more durable pavement materials and pavement section designs which will resist crack and pothole formation, and will require less frequent repaving.

- Research should continue to seek pavement additives to deter ice formation and promote snow removal. Also continue to develop non-corrosive alternatives to salt and other chemicals for purposes of ice melting.

4.0 CONCLUSIONS

The primary objective of this activity was to identify roadway operational analysis associated with the deployment of AHS. After reviewing a full range of operational and maintenance issues regarding today's traffic operation and assuming the evolutionary deployment of AHS, there are no show stoppers or operational barriers with regard to AHS deployment.

4.1 SUMMARY OF ISSUES

Table 3-2 presents a summary of the issues and risks identified under this activity. The table also includes possible solutions and/or recommendations to the raised issues and the impact of each issue on the RSCs or other acrivities. For a detailed description of each issue, the reader may referto the related subsections of this chapter.

4.2 FUTURE STUDY REQUIRED

Successful deployment of a fully-automated AHS is highly dependent on its reliability, efficiency and safety. In fact implementation of AHS concept will require careful and prudent planning, implementing, operation, maintenance, and mitigation efforts based on a clear understanding of the potential issues and potential problems. We believe in particular that further research is required in the following three areas: incident management techniques, maintenance requirements, and environmental monitoring.

Table 3-2. Summary of Issues and Risks

Issue No.	Issues/Risk Descriptive Title	Description/ Recommendation	RSC Impact
RO-1	What are the operational considerations of various AHS operating agency options?	Define existing highway operating agencies and their operational responsibilities. Conceptualize feasible new or hybrid operating agencies, their organizational framework, and potential operations responsibilities. Evaluate each operating agency scenario with each AHS RSC including the operational impacts of a multi-jurisdictional framework. Evaluation criteria would include operations uniformity, effectiveness, and practicality of providing such service.	All RSCs
RO-2	What are the skills required to manage and operate an AHS and to what degree are the skills available at existing highway operating agencies?	Define areas of expertise necessary for operation and management of an AHS and evaluate current levels of expertise and staffing available at existing operating agencies. Survey and review current practices of in-house versus contracted-out functions at state DOTs and highway authorities. Evaluate skills available with respect to each RSC.	All RSCs
RO-3	What would be the likely traffic flow management characteristics of an AHS?	Current traffic management systems are primarily passive and rely on macroscopic state variables such as density and speed to identify congestion and incidents. While traffic flow management requirements of AHS would vary by RSC, configurations with central control will require a more discrete, microscopic orientation of traffic monitoring and management. The characteristics of traffic flow monitoring and management will be defined for each RSC.	All RSCs
RO-4	What are the potential effects on incident occurrence, detection, and response by automated highway systems?	AHS can reduce the occurrence of incidents, improve incident detection and shorten incident response time. However, the extent of any benefits will be dependent upon the AHS configuration. Also, incident response will, for certain RSCs, require response vehicles to be under the command of the control center. The probable impacts will be evaluated for each RSC on the occurrence of incidents, incident detection and response procedures.	All RSCs
RO-5	How would the enforcement, policing requirements and policing tactics likely vary for each of the AHS configurations?	It is anticipated that the AHS will need policing and involve policing tactics different from those practiced today. Dependent upon the RSC, the level of policing, police functions, and tactics will vary. Current policing practices will be examined, including appropriate information from the agency survey, and the level of policing, functions and tactics applicable to each RSC will be identified.	All RSCs
RO-6	What are the various levels of association, coordination and autonomy among the operations elements of existing highways and how would these levels impact an AHS?	Identify the levels of association, coordination, and autonomy among the operations elements of existing highways, such as management, maintenance, police and emergency services. Evaluate potential problems for each RSC of existing arrangements of these operations elements. Develop recommendations as appropriate.	All RSCs
RO-7	How would a target level of preventative maintenance for an AHS differ from that currently provided by highway operating agencies?	Existing levels of preventive maintenance performed by highway operating agencies, including operators of traffic management systems, will be researched. A target level of preventive maintenance for AHS will be defined through investigations of comparable systems and varied by RSC as appropriate.	All RSCs

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