Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS Roadway Deployment Analysis

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PRECURSOR SYSTEMS ANALYSES

OF

AUTOMATED HIGHWAY SYSTEMS

Activity Area H

AHS Roadway Deployment Analysis

Results of Research

Conducted By

Delco Systems Operations

FOREWORD

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

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

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

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

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

NOTICE

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16. Abstract

This activity addresses highway infrastructure topics that will be encountered when an automated highway system (AHS) is deployed. AHS right-of-way requirements were analyzed, based on the following criteria: width of AHS vehicle, ability of the system to keep the vehicle on the desired path, barrier width (for dedicated systems), presence or absence of shoulder (breakdown lane), and width of the shoulder.

AHS capacity was established by utilizing traffic densities based on platoon sizes, inter-platoon spacings, and intra-platoon spacing. Inter-platoon spacing considered several failure assumptions and the requirement that inter-platoon spacing provide safe braking distances based on the failure assumptions. Based on this analysis, it is concluded that AHS capacities as high as 6,000 vehicles per lane per hour would be feasible. This established the range of capacity used in further Precursor Systems Analyses.

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EXECUTIVE SUMMARY

Activity Area H — AHS Roadway Deployment Analysis, covers the entire range of highway infrastructure topics that will be encountered when AHS is deployed. Impact on the surrounding non-AHS facilities and entry/exit could be viewed as part of roadway deployment, but their coverage is included in their own activity reports. Deployment of the AHS lanes themselves is addressed in this activity report.

In an effort to organize the various activity reports and to avoid gaps or overlaps in coverage, Roadway Deployment Analysis was treated as a clearinghouse through which findings for the various lower-level analyses were coordinated.

The research team approached the deployment analysis problem by considering several alternative highway configurations, then making various sets of assumptions and conducting what-if analyses. Hypothetical freeway sections, based on sections of Interstate Highway 17 (I-17) in and near Phoenix, Arizona, were used for the analyses. Various design years were used for the traffic volumes used in the analyses. The design years were selected in conjunction with the needs of Activity Area P — Preliminary Cost/Benefit Factors Analysis. Therefore, both the economic and operational measures of effectiveness were based on the same base of background data for several different activity areas.

Urban and rural sections of freeway were analyzed and modeled separately. The modeling tool FREQ was used for the urban section, while FRESYS was used for the rural section. In both cases, the modeling work was conducted using operational models, not demand models. Operational models do not reassign travel over links of a network based on travel conditions, while demand models do. Operational modeling was appropriate for the precursor work, given the level of analysis desired, the greater number of scenarios that could be analyzed, and the measures of effectiveness reported by the models. The modeling was conducted in conjunction with the AHS capacities developed in this activity report. The modeling results are found in the Activity Area I — Impact of AHS on Surrounding Non-AHS Roadways, and Activity Area J — AHS Entry/Exit Implementation reports.

The principal consideration for deployment of AHS on a constant-width section of freeway (between areas influenced by entry and exit ramps) is the incremental width required for an AHS lane and its accompanying shoulder and barrier. AHS width criteria evaluated to establish the total width include the following:

- Width of the AHS vehicle.
- Ability of the system to keep the vehicle on the desired path.
- Barrier width (for dedicated systems).
- Presence or absence of shoulder (breakdown lane).
- Width of the shoulder.

Central to all operations modeling and analysis is the volume of traffic that can reasonably be expected to utilize the AHS. It is necessary to establish these volumes for use as input to various modeling tasks including entry and exit facility design and impact of AHS traffic on surface streets near the entry and exit facilities.

AHS capacity was established by utilizing the traffic densities that could result from the three RSC's analyzed. These RSC's are:

- RSC1 — Infrastructure-centered platoon control.
- RSC2 — Vehicle-centered platoon control.
- RSC3 — Space-time slot control.

Densities were based on platoon sizes, inter-platoon spacings, and intra-platoon spacings. Inter-platoon spacings were based on several failure assumptions and the requirement that inter-platoon spacing be equal to braking distances based on the failure assumptions. Braking distances were based on AASHTO design values for wet and dry pavements.

For the platoon RSC's, these assumptions and calculations resulted in extremely high volumes compared to lane capacities of manually operated vehicles on today's freeways. Actual analyses were based on AHS capacities no higher than 6,000 vehicles per hour per lane. Capacities of this magnitude were used to take into account safety factors in real life AHS operation while still identifying volumes dramatically higher than capacities of today's manually operated lanes.

The AHS capacities determined in this activity report were used as AHS demand in Activity Areas J — AHS Entry/Exit Implementation, and I — Impact of AHS on Surrounding Non-AHS Roadways.

INTRODUCTION

The objective of the activity is to provide a hypothetical laboratory within which to analyze and in some cases model existing conditions and various AHS scenarios side by side. By doing so, various measures of effectiveness can be compared to give a somewhat objective picture of which AHS configurations are more promising than others. Equally important, this approach gives us the ability to examine which variables have the most influence on operating conditions in the AHS, on the parallel freeway, on parallel arterial streets within the freeway corridor, on the cross streets, and at the AHS entry/exit locations.

An additional objective is to limit the analysis and modeling to the extent that the modeling that is done is meaningful. It is possible to model a larger number of scenarios but at a superficial level, just as it is possible to model a smaller number of scenarios to more detail than is necessary or meaningful for the intended purpose. It is believed that this study is designed at a level that will achieve meaningful and interesting results.

The precursor systems analyses include the following highway infrastructure-intensive activities areas:

- H — AHS Roadway Deployment Analysis
- I — Impact of AHS on Surrounding Non-AHS Roadways
- J — AHS Entry/Exit Implementation
- K — AHS Roadway Operational Analysis

There is considerable overlap among these four activities; this is especially true of the first three. The work done in this study is organized and reported as shown in table 1.

Table 1. Report Organization.

Topic	Predominant Activity Area Report
AHS mainline capacity and operation.	H — AHS Roadway Deployment Analysis
Implications of constructing an AHS within an existing freeway right-of-way.	H — AHS Roadway Deployment Analysis
AHS entry point and exit point design.	J — AHS Entry/Exit Implementation
AHS traffic volumes as they influence streets near the AHS entry and exit points.	I — Impact of AHS on Surrounding Non-AHS Roadways
Modeling scenarios to evaluate conventional freeway operating conditions where AHS is deployed.	I — Impact of AHS on Surrounding Non-AHS Roadways
Implications of on-site versus offsite check-in and check-out facility design.	J — AHS Entry/Exit Implementation

The table above is only a guide to the organization of the activity reports. The activity reports contain a certain amount of overlap, but this is expected and desirable, considering that each activity is an element of the same system.

Throughout this report, standards and practices of the American Association of State Highway and Transportation Officials (AASHTO) are used as benchmarks. AASHTO standards are recognized for all elements of highway design by all States as well as the Federal Highway Administration.

REPRESENTATIVE SYSTEM CONFIGURATIONS

The representative system configurations (RSC's) were generated very early in this Precursor Systems Analyses of AHS program. These RSC's are used throughout the various areas of analysis whenever a diversity of system attributes is required by the analysis at hand. The RSC's identify specific alternatives for twenty AHS attributes within the context of three general RSC groups.

Since the RSC's have such general applicability to these precursor systems analyses, they are documented in the Contract Overview Report.

TECHNICAL DISCUSSIONS

Task 1. Refine Highway Configurations

Study Approach

The research team has taken the approach of using hypothetical freeway sections as a base case to identify the issues and risks of implementing an AHS. Two hypothetical sections are used in the studies; one urban and one rural. The attributes of each section are given in figures 1 and 2.

The research is based on three Representative System Configurations (RSC's):

- RSC 1 — Infrastructure-centered platoon control.
- RSC 2 — Vehicle-centered platoon control.
- RSC 3 — Space-time slot control.

This activity report focuses on those attributes of the RSC's that are important from the highway infrastructure point of view. Generally, these attributes are those related to the physical dimensions of vehicles, traffic volumes, weight, performance, turning radius, and amount and type of control equipment on the facility. Also important are the attributes that determine whether separate lanes, barriers, and separate entry/exit facilities are required. Activity A — Urban and Rural AHS Comparison considerations, dictate that both urban and rural attributes of AHS be considered. In addition, it is required that variations within the highway environment be analyzed under various RSC's to obtain information on operational variables within the highway network. These variations are designated as alternative highway configurations (AHC). The research work is based on the three AHCs listed and discussed below.

- Construct new automated highway on new alignment.
- Construct new AHS in existing freeway right-of way.
- Convert an existing mixed flow or HOV lane into an AHS lane.

While any of these three AHCs are physically possible, the research approach has been to do the most analysis on those configurations considered most likely to be achieved, especially in the early stages of AHS deployment. Therefore, the second and third AHCs are given analysis in this study while the first one is identified as a possibility. It is noted that, while many of the analysis findings are specific to the actual configuration modeled, the conclusions reached through modeling and analysis in many cases are applicable to other configurations. The modeling approach, assumptions, and results are reported in Activity Areas I and J.

The use of reality-based hypothetical sections brings several benefits to the study:

- The highway infrastructure subconsultants are based in Phoenix and are intimately familiar with the sections, having experience on numerous past and current highway design and planning projects.
- The urban section was being studied for the addition of High-Occupancy Vehicle (HOV) lanes by one of the subconsultants at the time the Precursor Systems Analyses were underway.
- The urban section is regular and suitable for “what-if” modeling and testing of various hypothetical revisions. It has service interchanges at 1.6 km intervals and is situated in a grid system of arterial streets at 1.6 km intervals and collector streets at 0.8 km intervals.
- The urban section is developed with land uses and densities typical of many western and midwestern cities.
- Current traffic volumes and forecasts for future design years, based on expected population, employment, and infrastructure growth, are readily available.
- The rural section includes several stretches of highways with sustained grades of six percent. This is the maximum allowable grade on interstate highways and provides the opportunity to test the influence of trucks on the AHS and adjacent lanes.
- The rural section extends from elevations of approximately 600 m to over 1,200 m above sea level. At the higher elevations, snow and ice are occasionally experienced.
- The use of sections of actual highway are felt to provide a “reality check” for the researchers in testing different scenarios and reviewing results. Notwithstanding the deliberate resemblance of the hypothetical sections to existing highways, it must be emphasized that this study is in no way intended as an analysis of an existing highway. Volumes at ramps have been revised, and interchanges have been relocated and in some cases deleted.

Urban Freeway Section

The hypothetical urban freeway section which was modeled is based on a section of I-17 in Phoenix, Arizona between the I-10 interchange and Peoria Avenue, approximately 13 kilometers to the north. Figure 1 illustrates the interchange configurations and 1990 peak hour traffic volumes for the section.

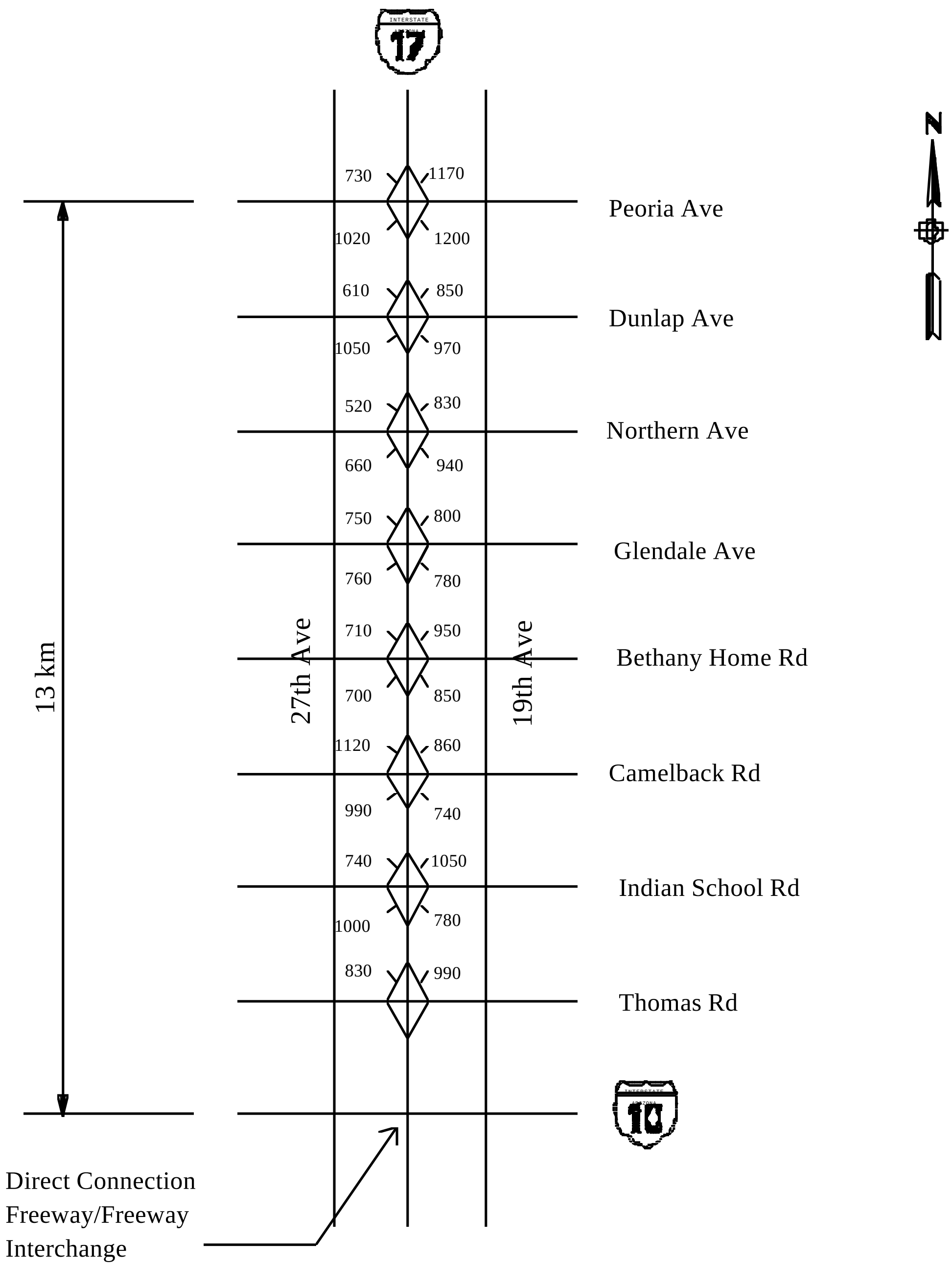

Figure 1. Hypothetical Urban Freeway Section and 1990 PM Peak Hour Volumes

The base mainline lane configuration for the urban freeway section is three general purpose lanes plus an HOV lane in each direction. The travel demand for the urban analysis is based on the current mainline and ramp peak-hour traffic volumes of the I-17 urban section. Table 2 gives ramp lane configuration data for the I-17 urban freeway section.

Table 2. AHS Urban Freeway Section — Physical & Traffic Data

Northbound			
Segment	**Length (meters)**	**On Ramp Lanes**	**Off Ramp Lanes**
Lane Drop — Thomas Road On	660	0	0
Thomas On — Indian School Off	772	1	1
Indian School Off — Indian School On	853	0	0
Indian School On — Camelback Off	772	1	1
Camelback Off — Camelback On	853	0	0
Camelback On — Bethany Home Off	740	1	1
Bethany Home Off — Bethany Home On	901	0	0
Bethany Home On — Glendale Off	740	1	1
Glendale Off — Glendale On	885	0	0
Glendale On — Northern Off	724	1	1
Northern Off — Northern On	917	0	0
Northern On — Dunlap Off	724	1	1
Dunlap Off — Dunlap On	1,191	0	0
Dunlap On — Peoria Off	306	1	1
Peoria Off — Peoria On	1,255	0	0

Note: Capacity of general purpose (non-automated) lanes is 2,200 passenger vehicles per lane per hour. Maximum speed is 100 km/h.

The hypothetical non-AHS surrounding roadways to be studied are based on:

- The interchange cross streets (diamond interchanges with signalized ramps).
- The major parallel arterials 19th Avenue (1.2 kilometer to the east) and 27th Avenue (0.4 kilometer to the west) between McDowell Road and Peoria Avenue.
- The I-17 non-AHS freeway lanes.

Rural Freeway Section

The hypothetical rural freeway section modeled is based on a section of I-17 in Arizona between Deer Valley Road in Phoenix and State Route 69, approximately 70 km to the north. Figure 2 illustrates the interchange spacing and vertical grades. Table 3 provides physical and traffic data for the rural section. The basic section provides two lanes in each direction separated by a median. Interchanges with cross streets are a diamond interchange configuration that are unsignalized.

RSC — AHC — Urban/Rural Scenarios

To accurately define the impact of an AHS on the overall transportation system, it is desirable to evaluate or model mainline, entry/exit points, cross streets, and parallel streets for a reasonable number of the possible combinations of AHC, RSC, and urban/rural. The modeling methodology and results are presented in Activity I, Impact of AHS on Surrounding Non-AHS Facilities.

It became evident during the project that many of these combinations need not be modeled due to the definitions of RSC. RSC’s 1 and 2, the platoon-based RSC’s, are most conducive to higher volumes and are therefore considered the most applicable in an urban environment. RSC 3, point-following, is not considered to provide a dramatic capacity increase and is therefore considered more applicable in a rural setting, where speed and comfort over long periods of time are relatively more important than capacity improvements. A total of eight AHC-RSC-urbanrural combinations were modeled or analyzed, as presented in Activity Area I.

Task 2. Establish Interface Alternatives

Interface between the AHS and the conventional highway system presents a separate set of issues. Interfaces can be divided into two types:

1. Interface between urban and rural AHS sections.
2. Interface between the AHS and the non-AHS system.

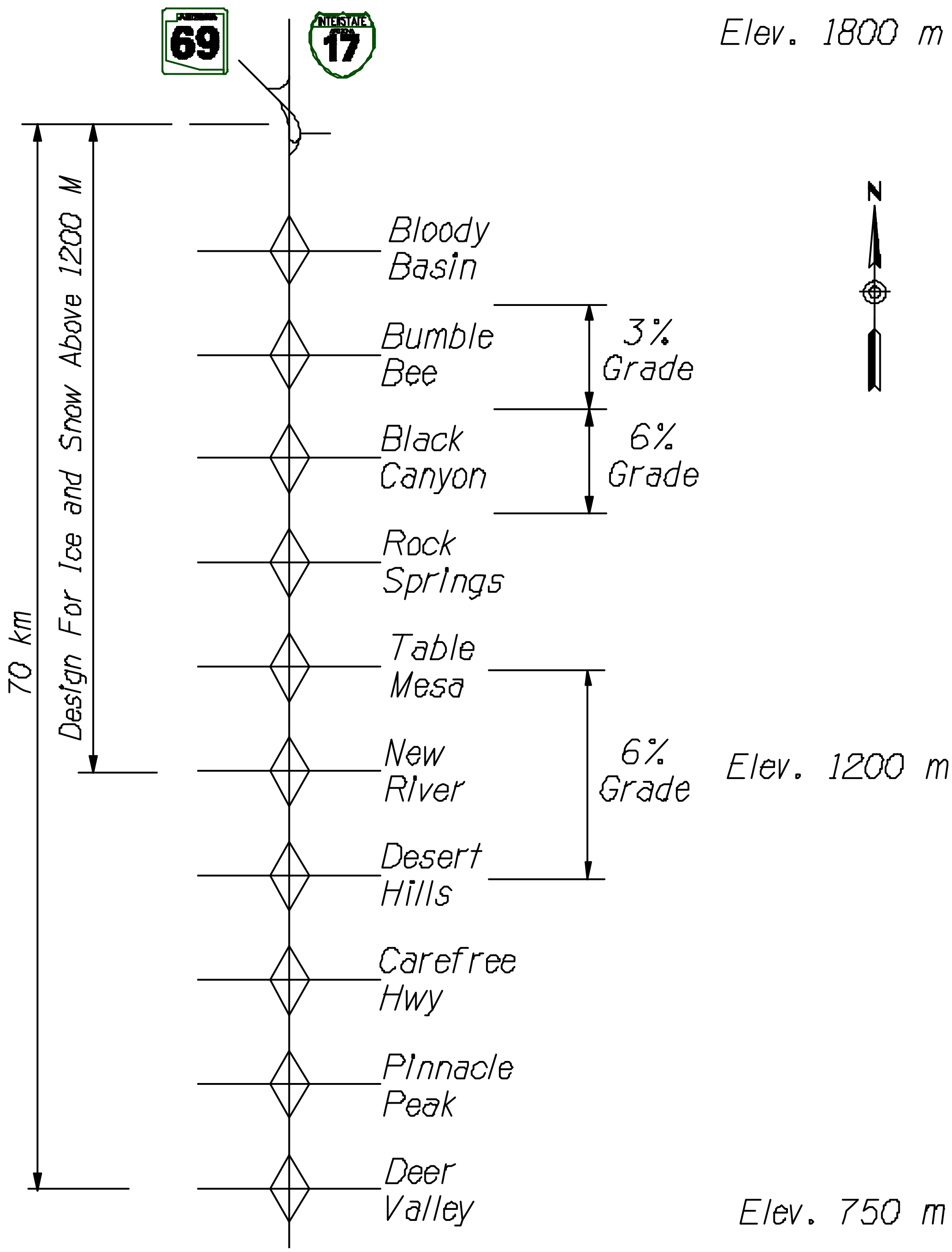

Figure 2. Hypothetical rural freeway section.

Table 3. Rural AHS Freeway Section Physical and Traffic Data

Segment	Length (m)	Capacity (vph)	Lanes	Base Volumes (vph)			
				Cars	Buses	Trucks	RV's
Deer Valley — Pinnacle Peak	4,875	2,200	2	3,043	306	17	34
Pinnacle Peak — Carefree Hwy.	7,925	2,200	2	2,842	286	16	32
Carefree Hwy. — Desert Hills	9,450	2,200	2	2,094	211	12	23
Desert Hills — New River	4,875	2,200	2	2,184	220	12	24
New River — Table Mesa	6,400	2,200	2	2,005	202	11	22
Table Mesa — Rock Springs	9,450	2,200	2	1,745	176	10	20
Rock Springs — Black Canyon	3,110	2,200	2	1,920	193	11	22
Black Canyon — Bumble Bee	9,450	2,200	2	1,745	176	10	20
Bumble Bee — Bloody Basin	17,525	2,200	2	1,571	158	9	18
Bloody Basin — SR 69	4,875	2,200	2	1,660	7	9	19

a. Urban AHS/urban non-AHS.

b. Rural AHS/rural non-AHS.

Issues associated with each type of interface are treated in the following sections.

Interface Issues: Urban AHS – Rural AHS

This report is based on the assumptions that the AHS universe will utilize a single RSC. Under this assumption there is no requirement for an RSC to RSC interface. Although it is conceivable that AHS could consist of, for example, platoon operation in urban areas and point following without platoons in rural areas, any interface requirements of such a scenario are only mentioned, but not dealt with in detail, in this work.

Performance and physical characteristics vary widely between light vehicles (passenger cars) and truck/transit vehicles. At the interface points the issues related to large volumes of truck/transit vehicles include check-in processing. Is a check-in process required at an interface point between urban and rural AHS? How will trucks be handled at an interface point from point following operation, light and heavy vehicles, to platoon operation? Can the interface be handled "on the fly" (i.e. without stops or significant speed reductions), or will an off-line facility be needed?

Typically, more space will be required for interface points if truck/transit traffic is included in the mix. The ranges of entry/exit point sizes in the Activity F — Commercial and Transit AHS Analysis report address this issue.

Check-In/Check-Out Requirements at Interface Points (Any Required)

Urban AHS-rural AHS interface points may have to have some of the same check-in/check-out tests as AHS-non AHS interface points have. This may be of greater importance for traffic leaving point following operation and entering platoon operation due to the tighter tolerances platoon operation may require. Different systems may require a recheck (i.e. fuel on board) for the platoon (urban, shorter trip) to point following (rural, cross country trip) interface.

Implications of Unauthorized Vehicles

RSC 3 is not physically separated from non-AHS traffic and, by this definition, is somewhat more tolerant of unauthorized traffic than the platoon-oriented RSC's. Based on an RSC 1 or RSC 2 interface, what measures should and can be taken to deal with unauthorized vehicles? One possibility is a more stringent unauthorized vehicle detection system as the interface point is approached.

Implications of High Volume at the Urban/Rural Interface Point

A platoon-oriented AHS in urban areas interfacing with a point following, non-platoon oriented AHS in rural areas, could evolve. Consider the case of an interface point from platoons to point-following. Such an interface point would have to fully disassemble platoons and download individual vehicles into the point-following AHS lane. Such a system would have to deal with the capacity of the point-following AHS, assumed to be significantly lower than the platoon-based AHS, and would have to take measures to ensure that no more vehicles are injected into the point following AHS than its capacity. Issues raised by this requirement include the need for a storage facility at the interface point, or the involuntary shedding of excess vehicles in advance of the interface point.

Interface Issues: Urban AHS – Urban Non-AHS

These issues are treated in depth in Activity Areas J — AHS Entry/Exit Implementation, and I — Impact of AHS on Surrounding Non-AHS Roadways and are listed here only as issues:

- Cross-street congestion due to increased volumes.
- Interchange congestion due to increased volumes.
- Attracted traffic.
- Latent demand.
- Barrier treatment.
- Speed transition.
- Volume differentials.
- Occupancy requirements.
- Termination of AHS at a non-interchange point.

Alternatives for interface points between the AHS and conventional highway system are presented, discussed in detail, and analyzed in Activity Area J — AHS Entry/Exit Implementation.

Interface Issues: Rural AHS — Rural Non-AHS

The rural AHS-rural non-AHS interface can be divided into two interface types:

- In the case of RSC 3 (no barrier between AHS and conventional traffic), the entire length of the AHS is an interface. This interface type is termed "linear interface" in the following discussion.
- The end or beginning of the AHS is an interface point with its own issues. Such an interface point could be at an interchange or could be a non-interchange beginning or end of automatic control. This interface is termed "point interface" in the discussion below.

<u>Linear Interface Issues</u>

Speed differential between adjacent lanes is an important safety and comfort issue. Any law abiding drivers in the conventional lanes may be intimidated by vehicles (especially heavy vehicles) traveling at much higher speeds in the adjacent AHS lane. Dozing or inattentive drivers in the manual lanes would create a serious hazard if they strayed into the AHS lanes. Unexpectedly high AHS speeds would also create hazards for non-AHS intruders who may use the AHS lane for passing. On-board collision warning may mitigate this hazard but it may not be possible to design it out by treating AHS vehicles alone. If AHS/Non-AHS vehicles are allowed to mix in the AHS lane, similar problems could occur regardless of AHS speeds. While difficult to prove through analysis, it is the conclusion of the researchers that an unbarriered, dedicated, high-volume AHS would place a heavy burden on the system to achieve a level of safety equal to or better than today's freeway mainline. Thus, barriers are included in the AHS system.

Point Interface Issues

If a rural AHS terminates or begins at a check-in/check-out facility, the issues are similar to urban interface points and are not repeated here. If the rural AHS interface is the result of beginning or ending control at a non-interchange point, the following issues are seen.

Not-Ready Drivers

The extent of the not-ready driver issue must be assessed and treated. Possibilities include ignoring the issue (if it is found to be negligible), parking the vehicle on a shoulder, in-vehicle or infrastructure wake-up techniques, etc. Detection of and response to not-ready drivers may require more electronics and communications infrastructure at the interface point than is required along the route.

Task 3. Assess Impact of Construction

AHS Lane Widths

The AHS lane width envelope can be developed using the design vehicle width as the minimum (perfect tracking, no deviation from the intended course), and present day American Association of State Highway and Transportation Officials (AASHTO) lane widths as the maximum.

Intermediate lane widths based on design vehicle widths and deviations of 200 mm and 300 mm from the desired track are also presented for comparison. Based on our conversations with control researchers, we believe +200 mm to be the lower practical limit of tracking.

AHS Shoulders

AASHTO standard right shoulder widths are 3.0 m which are for mixed traffic (cars plus trucks). For our car-only AHS right shoulder, we have deducted the car-truck design vehicles width differential (0.5 m) from the AASHTO right shoulder standard.

The AASHTO minimum left shoulder width is 1.2 m for 4-lane freeways. The following tables reduce this to 0.6 m in recognition of a requirement for some separation between AHS vehicles and barrier. This reduction is somewhat arbitrary and is based on the perceived need for a minimum separation based on driver comfort.

Table 4 shows widths based on several one and two-lane AHS scenarios. Variables in the table include right and left shoulder width, trucks or no trucks, and various tracking deviations. The table is based on the assumption that a two-lane AHS could operate with a breakdown lane on the right only.

Table 4. AHS Lane and Shoulder Widths.

	One-Lane AHS						
		Min. (Perfect Tracking)		Low (±200 mm deviation)		High (±300 mm deviation)	
	AASHTO	Pass Only	Truck	Pass Only	Truck	Pass Only	Truck
Left Shldr.	1.2 m	0.6	0.6	0.6	0.6	0.6	0.6
Lane	3.6	2.1	2.6	2.5	3.0	2.7	3.2
Right Shldr.	3.0	2.6	3.0	2.6	3.0	2.6	3.0
Barrier		0.7	0.7	0.7	0.7	0.7	0.7
Total	7.8	6.0	6.9	6.4	7.3	6.6	7.5

Table 4. AHS Lane and Shoulder Widths. (Continued)

	Two-Lane AHS						
Left Shldr.	3.0	0.6	0.6	0.6	0.6	0.6	0.6
Lane	3.6	2.1	2.6	2.5	3.0	2.7	3.2
Lane	3.6	2.1	2.6	2.5	3.0	2.7	3.2
Right Shldr.	3.0	2.6	3.0	2.6	3.0	2.6	3.0
Total	13.2	7.4	8.8	8.2	9.6	8.6	10.0

Even though we have included two-lane AHS dimensions in the table, no analysis nor modeling of a two-lane AHS is included in this report. The characteristics of our alternative highway configurations do not justify a two lane AHS except in the rural scenarios where they are required by truck operations on grades.

It is noted that the lane widths developed above are based on perfect driving conditions and do not account for lane width variables such as off-tracking on curves and trailer sway. These variables primarily affect trucks and are discussed in detail in Activity Area F — Commercial and Transit AHS Analysis.

Figures 3 through 5 show half sections for the hypothetical freeway existing condition, a one-lane passenger car only AHS, and a truck plus passenger car AHS. It is noted that in the case of both light and heavy vehicle AHS scenarios, the shoulder widths are approximately equal to the width of the AHS lane itself. As previously mentioned, the shoulder width is based on the premise that its users are under manual control and the occupants need (or want) to be able to exit the disabled vehicle.

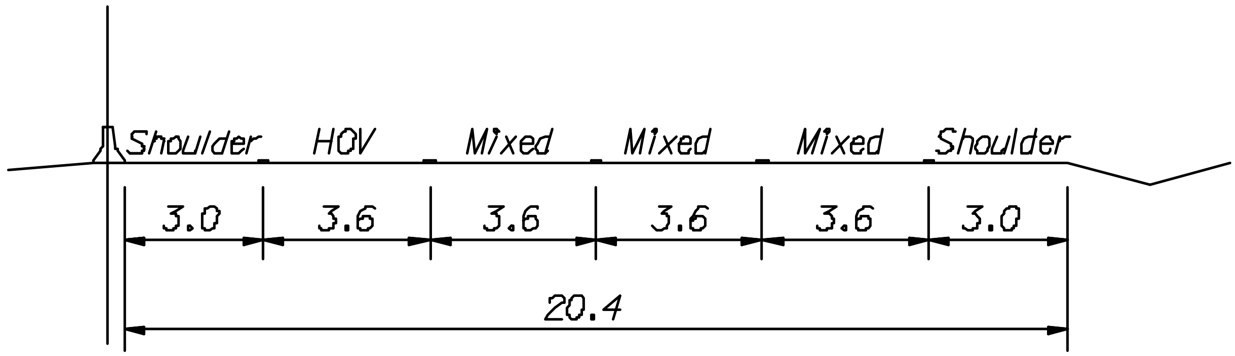

Figure 3. Hypothetical Freeway Half Section (Existing Condition)

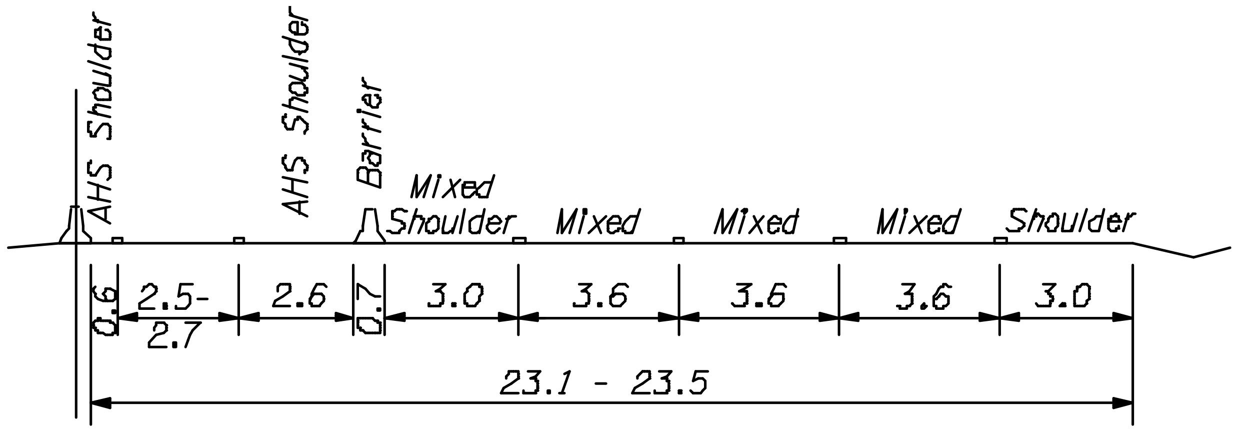

Figure 4. Hypothetical Freeway with One AHS Lane Plus Shoulder (Passenger Cars Only)

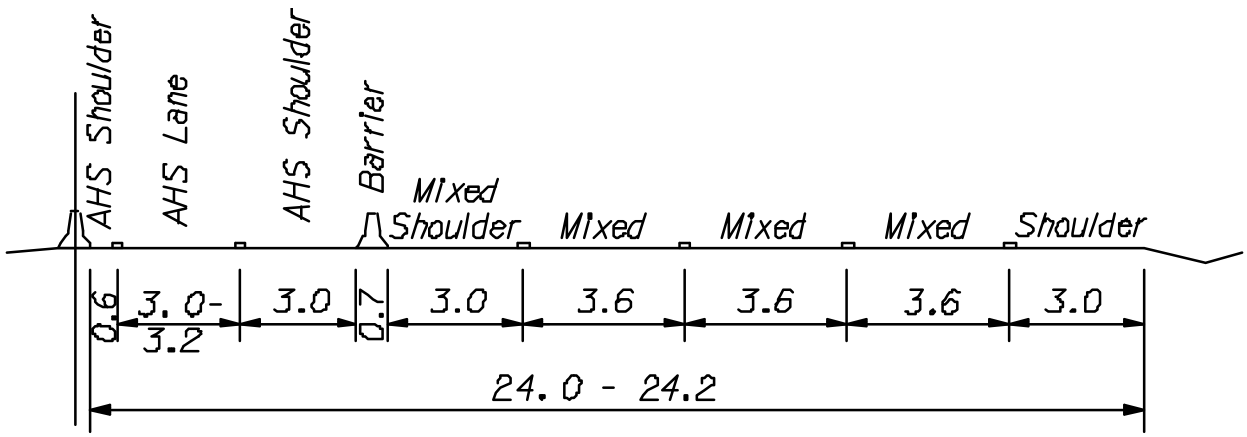

Figure 5. Hypothetical Freeway with One AHS Lane Plus Shoulder (Passenger Cars and Trucks)

The width of the shoulder brings up numerous issues:

- Could the shoulder be operated as a second AHS lane in the absence of incidents, with all vehicles shunted into the adjacent lane when required by an incident? What (if any) incremental change in incident detection would be required? What benefits would accrue from such operation?
- Could the shoulder serve the function of a transition lane at some times, and as a break-down lane when required by incident?
- Could system control allow a system in which the lane where an incident occurs becomes the ad hoc breakdown lane, with all traffic shunted into the other lane?

- Could the system provide a certain distance between vehicle and the left barrier during normal operation, but steer vehicles closer to the barrier in the event of an incident (disabled vehicle) in the breakdown lane? Such operation could provide more comfortable separation from the barrier during normal operation, and enhanced clearance between operating AHS vehicles and broken down vehicles during incidents.

The above issues could have varying impacts on operations under incident conditions. Under light traffic volumes, any automated shunting of vehicles around a disabled vehicle or spilled load would have a minor influence on flow.

In the case of a de facto two-lane AHS operation, combining two lanes into one would degrade operation more and more as the capacity of the system to merge two lanes into one is approached. The theoretical single lane capacity would be the upper limit of incident capacity. As demand exceeds this flow rate, upstream operations will be degraded.

Another possibility for normal (non-incident) operation is shown in figure 6. Under this scenario, emergency response to an incident ahead is a lane changing maneuver or a combination of braking and lane changing. With lane changes alone (no braking), following distances less than those possible for braking alone are feasible.

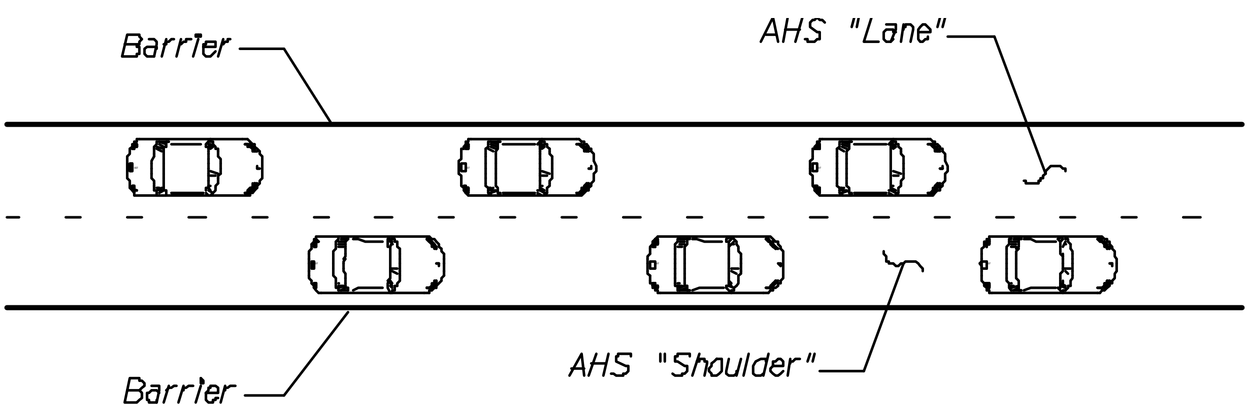

Figure 6. Two-Lane AHS With Staggered Operation

A recommendation for the possible deployment of such a scenario is that, in early stages of deployment, the AHS facility be striped to give the appearance of a lane plus a shoulder. The recommendation is based on the following rationale:

Early in the deployment of AHS, market penetrations may not be high enough to “fill up” two lanes, even though two-lane operation may be desirable or even required for the various reasons given throughout this report. The public may be inclined to accept a lane plus shoulder if it appears the lane is well utilized. However the public may reject two apparently under-utilized lanes, leading to bad publicity, opposition, and rejection of the AHS program. It is felt that the simple approach of marking the AHS facility as recommended helps avoid this empty lane syndrome without compromising the design and operation of AHS in any way.

During construction, traffic control is essential. A temporary reduction in the existing land and shoulder widths may be required, first, for the widening of the existing highway, and second, to provide the desired work zone for the implementation of the center lane HOV ramps. In both cases, temporary concrete barriers or barrels may be used to direct traffic. If concrete barriers are used, a clearance of at least 1 meter should be provide between the work zone and the barrier to allow for sliding. If this area is not available, the barrier should be anchored (AASHTO Roadside Design Guide). Left shoulder widths, on a temporary basis, may be reduced to a minimum width of 0.6 meters. A flare rate of 11:1 may be used for travel velocities up to 80 km/h. Lane widths may be reduced to 3.0 meters, with 3.3 meters being preferable. Effects of these reductions include a loss in highway capacity due to the lateral reduction in driver comfort. As comfort lessens, the speed at which the driver travels is lowered. Highway capacity is also a function of allowed driver velocity with regard to stopping sight distance. The reduction in width changes the M distance, or the distance from the center line of the inside lane to the face of the obstruction. The lower the M distance, the shorter the drivers line of sight becomes. Should this distance be reduced beyond acceptable limits (reference AASHTO 1990), the allowed speed must be lowered.

Summary

The work under this task is based on the assumption that a breakdown area is required. The breakdown area can be a dedicated lane analogous to shoulders on existing freeways. The width of the breakdown lane is essentially equal to the width of an AHS lane. This opens the possibility of normal dual lane operation, with one lane closure and automatic diversion during incidents.

Impact of AHS Configuration on Right-of-Way

The deployment of AHS as depicted in figure 5 requires a net roadway width increase of 3.8 m per direction of travel, given the criteria used to arrive at the total one-way roadway width of 24.2 m. In the hypothetical corridor selected for this study, this additional roadway widening could probably be accommodated without the purchase of right-of-way; however, the following construction issues would be encountered:

- Existing mainline overpasses and underpasses would have to be widened. Local right-of-way takes could be required at existing interchanges.
- Steeper slopes of landscaped areas could be required, probably to the extent that slope paving, terraced landscaping, or retaining walls would be needed.

Even though the AHS scenario could be deployed without additional right-of-way, the widening envisioned, by moving traffic closer to the right-of-way line, has noise and air quality implications for nearby land uses.

It should be noted that many candidate locations for AHS already fully utilize existing roadway for vehicle travel, resulting in non-standard shoulders and lane widths. An issue to be addressed on a site specific basis is how these non-standard features will be handled where AHS is deployed. Possibilities include:

- Construct AHS, returning the non-AHS lanes to AASHTO standards.
- Construct AHS, leaving the conventional roadway as it is (perpetuate the non-standard conditions).

These two alternatives cover the range of construction costs and impacts. Compromises between these two extremes are also possible.

Maintenance and Protection of Conventional Traffic During Construction of AHS

The construction impacts of AHS deployment differ little from the impacts of conventional highway construction under traffic. The chief issues are the degradations of safety, capacity, and level of service due to the following construction-related factors:

- Alignment changes.
- Lane width reductions.
- Driver curiosity (gawking).

- Non-standard geometry.
- Reduction or elimination of shoulders.

It is imperative that a strong traffic management plan for the construction of AHS be developed in concert with the AHS construction sequence. In urban areas it is very likely that construction activities impacting capacity will be limited to off-peak or late night and early morning periods.

Safe flow of traffic must be maintained throughout the construction process. It is preferred that traffic be detoured around the construction area, but in areas of limited right of way, travel lanes must be configured to allow construction. In this task issues and risks will be identified with respect to non-AHS traffic.

The following highway configurations will be considered when identifying issues and risks associated with rural and urban highways:

- Construct new AHS in existing freeway.
- Convert an existing mixed flow lane or an HOV lane to AHS.

Construction of a new AHS on a new alignment will not be discussed because of the limited impacts that it poses to existing traffic.

Expansion of an existing freeway to accommodate the AHS within the current right-of-way has the following impacts during construction:

The development of a construction work zone through the use of temporary concrete barriers, and temporary striping to reduce shoulder and lane widths, is a typical requirement. The reduction in shoulder width will result in a lower value for stopping sight distance if horizontal curvature is present. Should this value correspond to a design speed less than the posted speed limit, the speed limit must be reduced.

Reduced lane and shoulder widths can also result in a reduction in driver velocity due to a lesser degree of driver comfort. This in turn would reduce highway capacity.

Should lane and shoulder reductions not produce the required work zone width, it may be necessary to eliminate a lane altogether. As a result of this, overall capacity would be reduced by the capacity of the “lost” lane.

Task 4. Analyze Corridor Operating Conditions

This task establishes reasonable vehicular capacities for the AHS mainline. These capacities are the basis for the modeling work done in Activity I — Impact of AHS on Surrounding Non-AHS Roadways and J — AHS Entry/Exit Implementation. This task outlines the overall application of AHS volumes to the network of highways considered, while the other activity reports contain the detailed results of the analyses.

Issues

The following issues are considered important to the project. They will be considered and evaluated as they are pertinent to each combination of RSC and AHC examined.

Environmental

Issues include air quality, water quality, wildlife habitat, and noise. Generally, any highway improvement that increases the capacity of a corridor to move traffic may influence these issues. Site-specific AHS planning must qualitatively list and discuss the net environmental impacts that could be expected to result from an implemented AHS project.

Service to the Corridor

It is expected that some AHCs will serve demands better than others. Variations within each configuration will also have influences on service. These issues are covered within each scenario analyzed.

Cost

Costs of highway improvements vary widely based on site-specific conditions. Generally, costs would vary from lowest to highest based on the following alternatives for AHS deployment:

- Convert an existing lane to AHS without any pavement widening. Reduce conventional lanes and shoulders as needed.
- Convert an existing lane within existing right-of-way; provide widening as needed to maintain pre-existing levels of safety and operation on the non-AHS freeway.

- Construct an AHS within existing median space without impacting existing lanes or shoulders.
- Construct an elevated AHS within existing right-of-way.
- Widen an existing freeway to add AHS, maintaining existing conventional lane configuration. If necessary, provide retaining walls to avoid right-of-way takes.
- Construct new AHS on new alignment.
- Widen an existing freeway to add AHS, maintaining existing conventional lane configuration. Take right-of-way as needed to meet standards for clear zone, cut slope, fill slope and ramp length.

This is only a general ranking. Site specific factors could change the rankings significantly. The levels of service and societal issues of these alternatives will also vary widely based on the site under consideration.

Attraction of Traffic

Different scenarios will attract traffic at different extents. These variations in attracted traffic are identified in the analyzed modeling scenarios.

Capacity of the AHS

This team's approach to deployment analysis is to test the impact of an AHS that is overlaid on an existing hypothetical highway network.

Of great interest and importance is the volume of traffic that will use the AHS. Given that one primary objective of the AHS program is to increase the capacity of freeway corridors without the need for widening, it is obvious that, at least in the urban environment, modeling of the AHS system should only be done for scenarios that offer a significant improvement in corridor throughput. "Significant" means enough higher than present day lane capacities (2,200 vehicles/h) that the vehicle and infrastructure costs are justified. For the purposes of this study this volume is considered to be 3,000 vehicles/h.

It is also of interest to establish an upper limit of volumes that can reasonably be expected to use the AHS. While it is not a requirement that the "true" capacity be known, it is important to use a methodology based on reasonable assumptions and experience in highway traffic operations to develop volumes for use in the modeling analyses. The following paragraphs give the process used to develop these capacities.

Capacity Parameters — Platoons and Point-Following

Because knowledge of capacity is important for modeling, the initial assumption was based on platooning. Based on past research and discussions with PATH, and to conform to the RSC's, it was concluded that two platoon sizes would be examined: Large platoons (15 vehicles/platoon) and small platoons (5 to 10 vehicles/platoon). For the purposes of capacity, space-time slot RSC 3 (non-platooned) vehicles can be treated as single vehicle platoons, so this possibility is also calculated.

Once platoon size is determined, inter-platoon spacing is required. When inter-platoon spacing is known, the average number of vehicles per mile (density) can be calculated and volume can be determined by multiplying speed by density.

Inter-platoon spacing must be large enough to allow a following platoon to safely stop without colliding with a stopping platoon ahead. The elements of this stopping distance include:

- Speed of the stopping platoon.
- Reaction time.
- Initial speed of the object to be avoided.
- Deceleration rate of the object to be avoided.
- Deceleration rate of the stopping platoon.
- Avoidance action.

The first iteration of determining volume is to make conservative assumptions regarding failures and to look at the resulting volumes. The assumptions were:

Speed of the Stopping Platoon

Capacities were calculated for a range of speeds from 60 to 160 km/h.

Reaction Time

A value of 300 milliseconds was used for the total time from the event through the application of the appropriate avoidance action. This value was based on input from various team members. Use of a value of zero for reaction time changes the capacities calculated by only a few percentage points.

Initial Speed of the Object to be Avoided

Three failure modes were considered. The most conservative of these assumes that the object to be avoided is an object that falls from a vehicle in the platoon ahead and comes to an instantaneous stop. This has been termed “brick wall” failure in other research and will be so called in subsequent sections of this study. In scenarios involving deceleration of a vehicle ahead, the vehicle ahead is assumed to have the same initial speed as the vehicle taking the avoidance action. Capacity curves based on brick wall failure and AASHTO wet pavement braking distance at various speeds are plotted.

The second failure mode involves braking at a rate of one g by a vehicle ahead. Capacity curves are plotted based on this failure mode combined with wet pavement braking distances by the following platoon.

The third failure mode involves one g braking of a vehicle ahead and braking distances based on dry pavements.

Deceleration Rate of the Following Platoon

Wet and dry braking distances are based on the AASHTO Green book. These distances take into account coefficients of friction (based on wet pavements) that vary with speed.

Avoidance Action

In this case the avoidance action is the application of brakes. It is assumed that there is no possibility of steering around a hazard. While hazard avoidance by steering or combinations of steering and braking would result in even closer inter-platoon spacings than from braking alone, the capacity values found by the procedures described above are felt to be sufficiently high to justify AHS and to allow the modeling scenarios desired for entry/exit analysis and traffic operations on surrounding streets.

The following equation is used to determine inter-platoon distances:

L = D + S1 - S2, where:

L = inter-platoon spacing
D = distance traveled during system delay time
S1 = Braking distance for stopping platoon
S2 = braking distance for stopping vehicle to be avoided

Table 5 shows the braking distances used to determine the inter-platoon spacings for a range of speeds, pavement conditions, and failure assumptions. Figures 7 through 9 present the capacities possible for each of the scenarios named above. It is interesting to note that capacities do not indefinitely increase with speed. This is due to the kinetic energy element of stopping distance, which is a function of the square of vehicle velocity.

Table 5. Braking Distances Used in Hypothetical Capacity Calculations

AASHTO Design Speed (km/h)	**Wet Pavement Braking Distance (m)**	**Dry Pavement Braking Distance (m)[1]**	**1 g Deceleration Braking Distance (m)**
40	17	10	6
50	27	15	10
60	42	22	14
70	60	30	19
80	81	39	25
90	106	50	32
100	136	62	39
110	170	78	48

1 Based on AASHTO Green Book Figure III-1, curves 8 and 11 (worst case)

Figure 7 shows AHS capacity curves based on platoons of 15, 5, and 1 vehicle. Inter-platoon spacing is based on AASHTO wet pavement stopping distances and brick wall failure of the platoon ahead.

Figure 8 shows curves based on platoons of 15, 5, and 1 vehicle. Inter-vehicle spacing is based on 1 g braking of the vehicle ahead and AASHTO wet pavement stopping distance.

Figure 9 shows curves based on platoons of 15, 5, and 1 vehicle. Inter-vehicle spacing is based on 1 g braking of the vehicle ahead and AASHTO worst case dry pavement stopping distance.

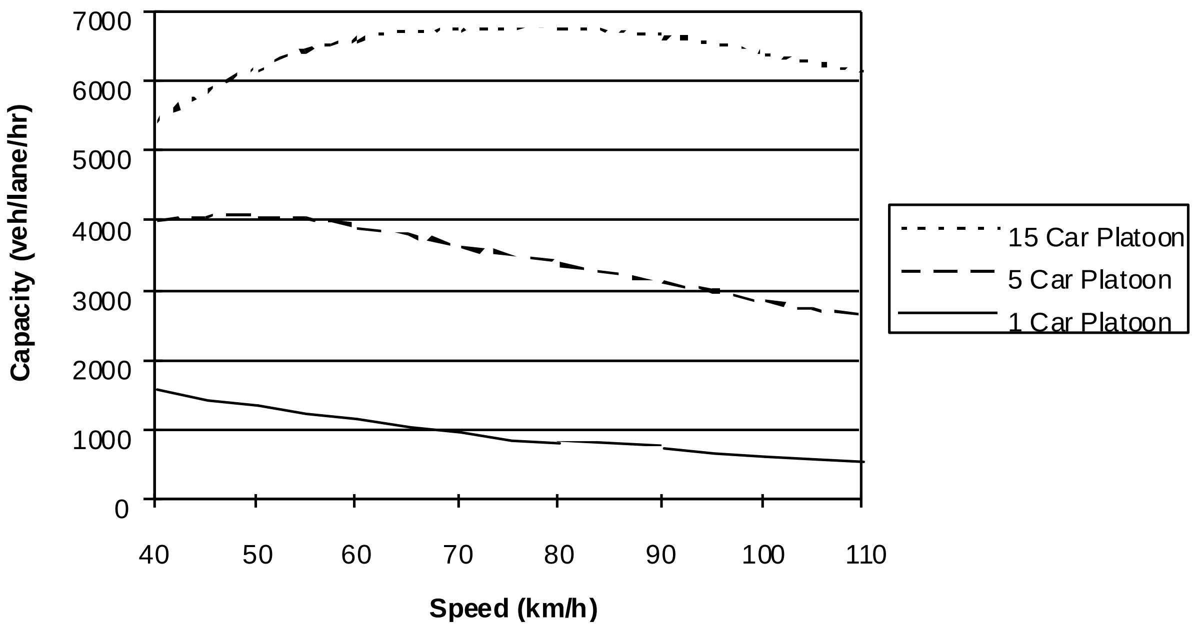

Figure 7. AHS Lane Capacities, AASHTO Wet Pavement Braking, Brick Wall Failure

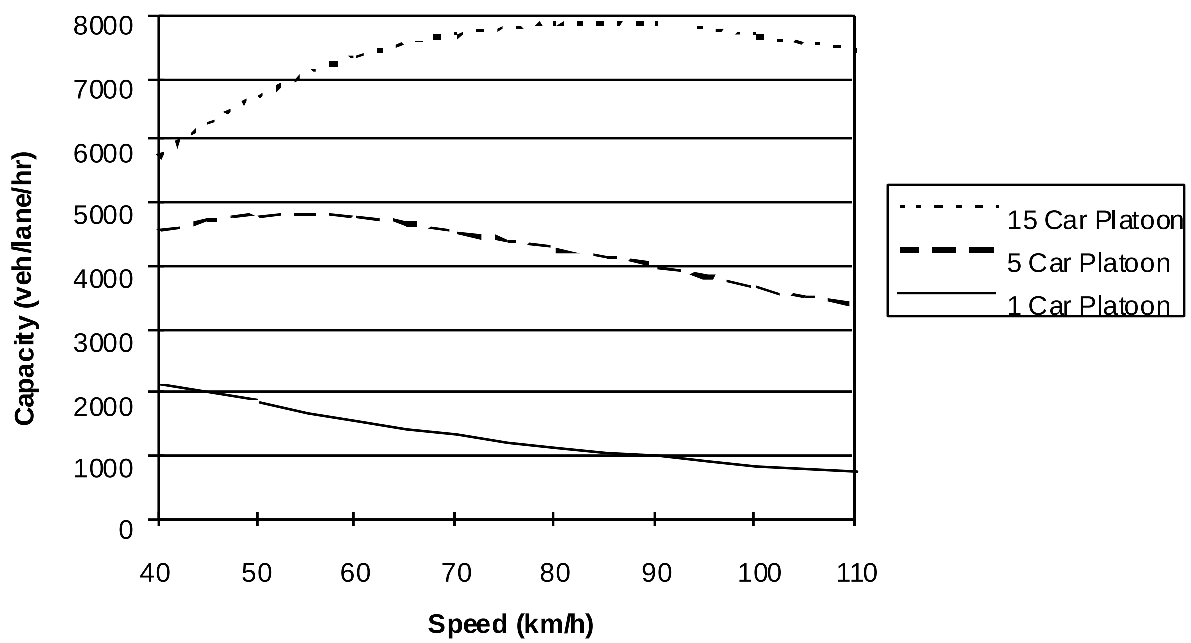

Figure 8. AHS Lane Capacities, AASHTO Wet Braking, 1 g Failure

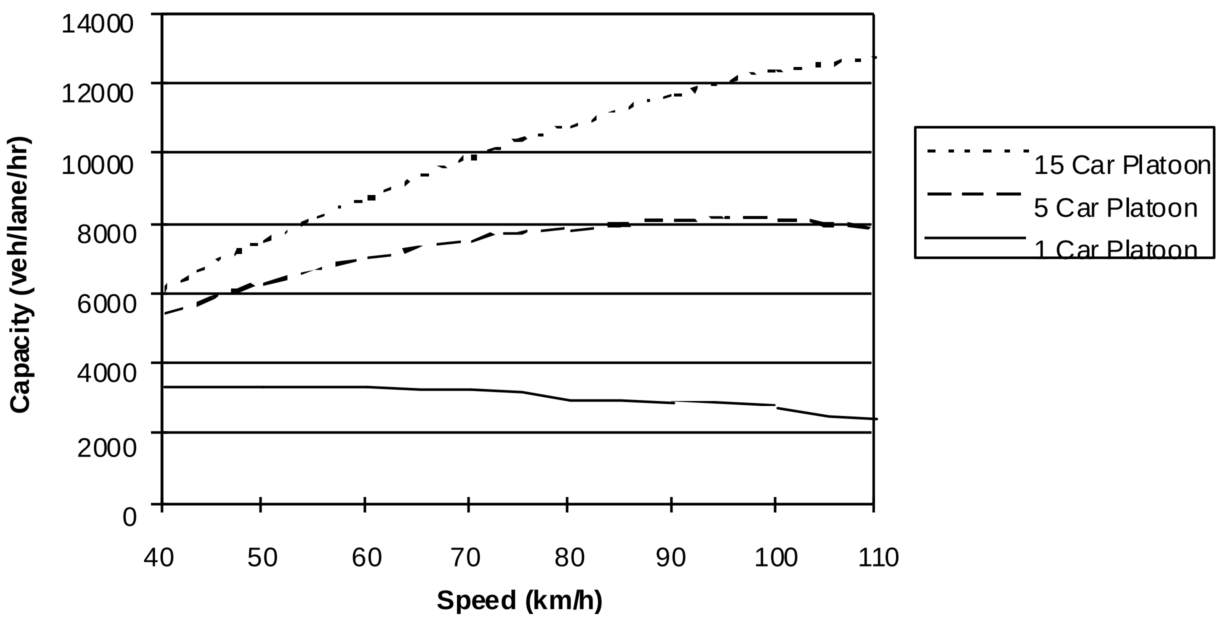

Figure 9. AHS Lane Capacities, AASHTO Dry Braking, 1 g Failure

While the capacity increases derived for non-platoon operation from these assumptions are not significantly higher than flow rates commonly seen on conventional highways, there is an important distinction to be made between hourly capacity and long range (several hours) throughput. The elimination of congestion and many accidents and incidents should result in significant improvement in the repeatability of travel time.

Hourly capacity, as calculated here for AHS or as defined in the Highway Capacity Manual (HCM), is the maximum possible flow. Under manual control, service volumes begin to degrade when demand exceeds capacity. Incidents (accidents, stalled vehicles in lanes, and even incidents visible but not in a travel lane) have an unpredictable but very often dramatic negative impact on flow rates.

It is possible or likely that Intelligent Transportation Systems (ITS) or even certain AHS scenarios would not greatly increase the capacity of a highway compared to the HCM capacity. What these enhancements do, however, is to increase the long term daily throughput of a section. Higher levels of control (ATMS, ITS, AHS, and combinations) reduce the frequency of incidents by operating more safely and by detecting, avoiding, and responding to incidents sooner. They also avoid or lessen the situation of demand exceeding capacity thereby breaking down free flow. Finally, they provide information to users in time for alternative action to be taken.

While these are tangible benefits, they are not addressed or noticed in side by side comparisons of capacities under ideal conditions. On the other hand, the benefits are, or should be, a primary justification for ATMS, ITS, and AHS.

Rural Modeling

Overall traffic operations and ramp configurations of rural freeways differ from corresponding urban freeways. Traffic volumes are often much lower on rural freeways while interface points are much further apart due to the lack of demand and less development of land along the freeway. Lower mainline traffic volumes with low demand for ramps provide acceptable ramp level of service. As a result of these characteristics, a simplified modeling approach for the hypothetical rural freeway corridor reported in Activity I was applied for this study.

While modeling a range of AHS densities is outside the scope of this project, it is again noted that higher AHS densities (if they are safely achievable) have a profound effect on AHS volumes at given speeds. A fundamental result of this activity is that more knowledge of achievable densities is a requirement for good forecasting of AHS volumes and system operating conditions.

Although not modeled, a scenario combining the two scenarios discussed could be considered. Where terrain and/or right-of-way requirements make it feasible to construct an extra traditional lane, traffic operations may improve over the exclusive conversion scenario. It is noted that additional lanes may not be required on both directions of the freeway. For example, in mountainous terrain there may be limited cross section available due to rock faces, etc. where perhaps one additional lane could be added. Adding this lane to the up-hill side would significantly improve overall speed on the non-AHS lanes as the ability for passenger vehicles to overtake slow moving vehicles would exist. A disadvantage of providing only partial lane addition would be the potential for bottleneck areas on the non-AHS lanes causing not only operational and problems, but also increased safety problems.

It is reiterated here that these results are derived from this particular hypothetical corridor and may not be indicative of all rural corridors.

CONCLUSIONS

A requirement fundamental to the modeling of every operational measure of effectiveness of the AHS/non-AHS system is the capacity of the AHS system. This analysis activity made assumptions regarding AHS mainline throughput capacities and determined that, given the assumptions used, the platoon-oriented RSC's will have extremely high mainline capacities. These top-level capacities must be degraded to provide for entry and exit operations. Even so, AHS capacities double or triple those of conventional lanes should be achievable. These capacities (4,000 to 6,000 vehicles per hour) were therefore selected for modeling use throughout the report.

Capacity assumptions were also developed for non-platooning operations. If assumptions regarding inter-vehicle spacing are the same as those for inter-platoon spacing, much lower capacities result. In fact, in some cases the capacities are even lower than those of manually operated lanes. It is necessary to assume coordinated braking for non-platoon operations to have capacities similar to those of platoons. (Coordinated braking, or at least coordinated deceleration, is also a requirement for safe operation of platoons.)

While more difficult to quantify than capacity, repeatability of travel time is an important AHS advantage. By significantly reducing the number, severity, and duration of accidents and incidents, AHS will allow more dependable forecasting of travel times.

Various configurations of AHS lanes and shoulders for the AHS were considered. It was concluded that AHS shoulders are desirable for operational benefits they bring. With shoulders, broken-down vehicles as well as snow debris or spilled loads can be stored, while automated operations continue unimpeded. Without shoulders, these events would require the complete shutdown of the automated facility.

The AHS lane need not be as wide as present-day manual lanes, due to the superior lateral control AHS will bring. Lane widths of 2.5 m (passenger cars only) and 3.0 m (trucks and transit vehicles) are expected to be adequate if a deviation of plus or minus 200 mm from the desired path is achievable. However, AHS vehicles may require restrictions on the design of side mirrors to be compatible with these reduced lane widths. Shoulder width requirements are essentially the same as travel lane width, although slightly greater widths may be considered, due to the requirement for manual operation within the breakdown lane.

While improved lateral control results in a reduction in lane width, deployment of a dedicated- lane AHS scenario still involves construction of new pavement if the number of non-AHS lanes is to remain the same. Even if an existing HOV or mixed-traffic lane is taken over for AHS, the requirement for the AHS lane, its shoulders, and its barrier result in a new pavement widening. This can be mitigated by using narrower lanes and shoulders on the conventional freeway, but generally not without compromises to safety and traffic operations.

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