Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Entry/Exit Implementation

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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

EXECUTIVE SUMMARY

The Entry/Exit Implementation Strategy analysis attempts to identify and analyze the most important issues in the roadway implementation of the AHS entry and exit associated functions. The analysis takes a broad system engineering approach to assure that all entry/exit occasions on the AHS are considered.

The top level issues addressed were:
- The impact of entry/exit strategies/configurations on the overall performance of the AHS,
- The relative viability of potential AHS entry/exit strategies and configurations, and
- The design parameters and guidelines for these entry/exit strategies/configurations.

The approach to this analysis consisted of the following major steps:
- Develop Detailed Descriptions of the RSCs Used in the Analysis.
- Define Functional Flows.
- Identify Entry/Exit Evaluation Criteria.
- Define Specific Entry/Exit Types and Configurations.
- Map the Functional Flows onto the Entry/Exit Configurations.
- Perform Qualitative Evaluation/Analysis of the Entry/Exit Configurations.
- Perform Quantitative Evaluation/Analysis of the Entry/Exit Configurations.
- Develop Conclusions from the Analyses.

The conclusions and recommendations from this analysis can be generalized as the following key findings:
1). The AHS will be developed in incremental and evolutionary steps as the user market will support with their spending decisions.
2). The AHS must be managed as a system, especially the entries and exits, to achieve the desired levels of efficiency and throughput.
3). Only the most well conceived and carefully managed entry/exit strategies and configurations will allow the AHS to function efficiently at the highest desired traffic flows.

Conclusions insofar as the issue of: Effects of Entry/Exit on Overall Performance of the AHS.
1). The AHS and its entries and exits must be designed and managed as a system if the AHS is to operate efficiently at traffic flow rates higher than is possible on current freeways, i.e.,:
- The volume of vehicles entering at each entry must be controlled to prevent more vehicles from entering than can be accommodated by the downstream section.
- The volume of vehicles entering at each entry must be controlled to reserve sufficient capacity for downstream entrances to receive equitable service.
- The volume of vehicles exiting at each exit must be controlled to prevent back-up onto the AHS lane(s). This may require rejection or alternative routing of vehicles at upstream entrances that are bound for the congested exits.

2). Management of merging activities at entries and exits is necessary if the AHS is to operate efficiently at traffic flow rates higher than is possible on current freeways. It will be necessary to design into the entry/exit pair:

- An ability to detect and evaluate the sizes of available gaps in the established traffic stream of the target lane, and
- An ability to coordinate the entering vehicle's release, acceleration and path (in later configurations) to safely intercept a known, preserved or created gap, and merge into it.

Conclusions relative to the issue of : Viability of Specific Entry/Exit Strategies and Configurations.
1). All of the various entry/exit strategies/configurations analyzed are likely to be present somewhere in a nationally deployed AHS.
2). The most effective and safest of the entry/exit configurations are the surface street-to-AHS and the Freeway-to-AHS dedicated separate entry/exit with simultaneous ramps (see Figure 1). These are the entry/exit strategies/configurations that are most amenable to positive control of entry/exit, management and coordination of merging, and that have the exit positioned just prior to the entry on both the AHS and manual lanes. These are the recommended AHS entry/exit configurations.
3). The least effective strategies/configurations have AHS entry from and exit to contiguous manual freeway lanes, either on a continuous basis or only in designated zones. The entering and exiting vehicles cannot stop or slow significantly, their access between manual and AHS lanes cannot be effectively controlled, and their merging cannot be effectively managed or coordinated. These strategies/configurations have the highest potential for safety problems.
4). Moderately effective entry/exit strategies/configurations are those that provide a transition lane between the freeway manual lanes and the AHS lane(s), either continuous or in designated entry/exit zones.
5). Barriers between the manual freeway and AHS lanes are a recommended safety feature in all entry/exit configurations where possible. They have a negative effect on access and have little impact on effectiveness.
6). The design and operation of the AHS entries and exits external to the AHS itself will have a strong influence on the effective operation of the AHS itself. For the two most important categories of entry/exit strategies/configurations:

- The Freeway-to-AHS entry/exit strategies/configurations cannot escape from their dependence on the freeway. If the freeway is heavily congested and performing poorly as a result, the AHS will also perform poorly.
- The surface street-to-AHS entry/exit strategies/configurations cannot escape their dependence on the surface streets. If the surface streets feeding the AHS entry or fed by the AHS exit are heavily congested, or the AHS entries and/or exits are poorly designed with inadequate capacity, the AHS will perform poorly.

Conclusion insofar as the issue of: Design Features, Parameters and Guidelines for Entry/Exit Strategies and Configurations.
The most important of the design conclusions are:
1). For the recommended entry/exit configurations, a deceleration lane contiguous to the manual and AHS traffic lanes just prior to their exit points, and an acceleration lane contiguous to the manual and AHS traffic lanes just prior to their entry points are strongly recommended.
2). For the recommended entry/exit configurations, the entry/exit ramps and transition lanes

(when merges are managed and coordinated) will only need to accommodate the queues that result from the probabilistic variations in the balance between entry/exit demand and queue service rates (availability of suitable merging gaps).

Recommended Further Investigations:

- System level models that would allow investigation of the AHS system-wide management recommendations made herein do not exist. Such a tool would be invaluable in designing, developing and testing the principles and algorithms necessary to implement AHS system-wide management.
- Mathematical models of the interacting traffic streams at the AHS entry/exits in the ERSCs are incomplete. Accurate mathematical descriptions of the traffic streams involved would be very beneficial for direct use in design and for implementing the AHS system-level simulation model recommended above.
- Design principles, guidelines, and equations for the specific structures, capabilities and features for the AHS entry/exit configurations are incomplete. These cannot be completed until the mathematical descriptions of the interacting traffic streams are completed. These design tools are needed to design, simulate, and develop prototype entry/exit configurations.

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1. INTRODUCTION

This report documents the efforts of the Georgia Institute of Technology, under subcontract to Raytheon Company, to address Entry/Exit Implementation Strategy (Activity J) of the Automated Highway System (AHS) Precursor Systems Analysis (PSA) contract.

1.1 DESCRIPTION OF ACTIVITY AREA

The Entry/Exit Implementation Strategies PSA activity area attempts to identify and analyze the most important issues with the roadway implementation of AHS entry and exit associated functions. It complements several other PSA activity areas, particularly those focusing on the vehicle side of entry/exit behaviors (such as check-in and check-out).

1.2 PURPOSE/SPECIFIC FOCUS OF THIS EFFORT

This analysis will take a broad, systems approach to assure that all necessary entry and exit occasions on the AHS are considered, that the effects of entry/exit on overall AHS performance are understood and considered, and that the necessary details are developed to understand entry/exit options.

1.3 ISSUES ADDRESSED

The top-level issues addressed in this analysis, within the assumed Representative System Configurations (RSCs), are:

- the impact of entry and exit strategies and configurations on the overall performance of the AHS,
- the relative viability of potential AHS entry and exit strategies and physical configurations, and
- the design parameters associated with these entry and exit strategies and configurations, and the design equations/guidelines for these parameters.

Some of the more specific questions that must be answered in addressing the issues are:

- What are the functions that must be performed in order to enter and exit an AHS ?
- What are the specific strategy options for implementing/performing these entry/exit functions (particularly merging and diverging) ?
- What is the significance of entry and exit strategies and configurations to the overall performance of an AHS ?
- What aspects of entry and exit are the controlling factors in it effects on overall AHS performance?
- How do the entry/exit functions and implementation strategies affect AHS roadway (including entry/exit) physical structures and AHS infrastructure electronic system

functions and architecture ?

- What are the potential entry and exit physical configurations, how do they compare, and how can they be optimized ?

- What are the design parameters and design equations/guidelines for entry/exit structures?

- Are there "best" entry and exit configurations (and strategies) that should be adopted AHS wide (perhaps different ones for different RSCs), or is there a place for multiple entry and exit configurations ?

1.4 OVERALL APPROACH

The overall approach to this analysis was comprised of the steps described hereafter. These steps also define the organization of the technical discussions of Section III. It should be noted that these steps, as in most creative activity, are not carried out in a single linear pass, but rather are carried out in an incremental and iterative fashion, with results being refined over time.

1.4.1 Develop Detailed Descriptions of the RSCs Used in the Analysis. The logical first step in any analysis is to carefully define the object(s) of that analysis. The Raytheon team came to an early agreement that the RSCs should represent a number of meaningful interim AHS states in a logical progression, or evolution, of today's vehicle/highway systems toward an ultimate AHS configuration. These RSCs will be referred to as Evolutionary RSCs (ERSCs) throughout this report. Due to the large number of mutually supportive government, corporate, and individual decisions that are necessary to make an AHS possible, and given the potential costs associated with these decisions, the evolutionary process was considered to be perhaps the only realistic AHS development approach.

The primary tasks to be accomplished in this step of the analysis was to define: the basic and supporting vehicle/roadway (including electronic systems in the infrastructure) functions that comprise an AHS; the apparently necessary sequence for achieving these functions; the incremental versions of an AHS that would be feasible; and the ultimate AHS that is likely to result.

1.4.2 Define Functional Flows. The next logical step in the analysis was to lay out the sequence of major travel events in an AHS trip for each ERSC, and to identify the vehicle and roadway functions necessary to support the AHS travel events. This effort attempted to identify both nominal (trouble free) travel events and alternative events dictated by problems at each step. The information generated in this exercise was useful in identifying both the sequence and the approximate location of each of the events with respect to the roadway. Particular attention was given to those travel events and vehicle/roadway functions related to, or occurring at, the entry and exit locations.

1.4.3 Identify Entry/Exit Evaluation Criteria. In order to conduct a disciplined evaluation of the viability of the AHS entry and exit configurations (and of the associated issues, concerns, and risks), it was necessary to identify a set of meaningful evaluation criteria. These criteria must be and were chosen to be independent of the ERSCs and entry/exit configurations and strategies. The criteria were chosen to be determinable (qualitatively, and quantitatively with adequate analytical models and simulation tools) and to provide the most meaningful indicators of overall viability. The five selected evaluation criteria, which will be explained more carefully in later sections, are functional effectiveness, safety, operational access, cost, and evolutionary compatibility.

1.4.4 Define Specific Entry/Exit Types and Configurations. To provide the physical context in which the AHS travel events will occur and are analyzed, this effort identified the possible general types of entries and exits, and specific configurations within each type, for each of the ERSCs. The results of qualitative analyses were used to develop refined versions of the configurations to eliminate or mitigate problems. This iteration resulted in more nearly optimized versions for each of the entry and exit configurations.

1.4.5 Map the Functional Flows onto the Entry/Exit Configurations. The purpose of this effort was to identify the locations of specific travel events on the roadway structures for each of the entry and exit configurations in each of the ERSCs. This is a necessary enabling step for both the qualitative and quantitative analyses. This step also makes obvious some of the structures necessary to support the nominal and problem AHS travel events.

1.4.6 Perform Qualitative Evaluation/Analysis of the Entry/Exit Configurations. The purpose of this step is to identify, for each of the identified AHS travel events, the functional or structural requirements placed on the roadway, the functional requirements placed on the electronic infrastructure (C^3), the impacts on the entering and exiting traffic (for deducing roadway/C^3 design parameters), and the effects on vehicles in all involved traffic streams (also for deducing roadway/C^3 design parameters). Using these impacts, qualitative scores for each of the five evaluation criteria will be assigned for each entry/exit configuration in each ERSC. These qualitative evaluation results are used to refine the entry and exit structures to the degree practical, and to indicate those aspects of the analysis that are most in need of more quantitative analysis. For those evaluation criteria that are sufficiently quantified at this level of analysis, or for those not susceptible to a more analytical approach, this level of analysis will produce the final results. The evaluation criteria of operational access and evolutionary compatibility fall into this category.

1.4.7 Perform Quantitative Evaluation/Analysis of the Entry/Exit Configurations. This effort addresses those aspects of the AHS travel events and traffic interactions that require and are susceptible to an analytical approach. This analysis will, in particular, address entry and exit functional effectiveness, safety and cost of structures. Two approaches to a quantitative analysis of the factors involved with these criteria were attempted: developing and using a probabilistic model and use of an existing simulation program (FREESIM).

1.4.8 Develop Conclusions from the Analyses. After all analysis is completed, or earlier when obvious, conclusions concerning the top-level issues were identified.

1.5 GUIDING ASSUMPTIONS

The most fundamental assumptions were the assignment of responsibilities and assumed capabilities of the driver, vehicle, roadway and command/control/communications (C^3) infrastructure for each of the ERSCs. These are detailed in the descriptions of the ERSCs in Section II. More detailed assumptions will be documented at the appropriate place in the analysis.

2. THE EVOLUTIONARY REPRESENTATIVE SYSTEM CONFIGURATIONS

2.1 DESCRIPTIONS OF THE ERSCs.

General descriptions of the ERSCs are common to the entire Raytheon team, and can be found in their overview for the contract. However, there may be some variation in the details of the vehicle, roadway and C^3 functions assumed by each activity area performer. For this reason, the specifics assumed by Georgia Tech for the Entry/Exit Implementation Strategy are documented in Table 1.

2.2 ASPECTS OF ERSCs RELEVANT TO ENTRY/EXIT.

Certain aspects of the ERSCs are very relevant to analysis of entry and exit issues, AHS capacity and other system performance indicators. These parameters were not addressed to any significant degree during the team discussions while defining the ERSCs. The assumptions concerning these parameters are defined in Table 2.

Table 1. AHS Configuration Parameters for ERSCs																		
Configuration Designation	Driver/Vehicle System							Infrastructure								Relevant Entry/Exit Parameters		
	Vehicle Functions				Driver Functions			C^3 Functions					Roadway Configu-ration					
	Headway/Speed Control	Lane Keeping (Assisted)	Lane Keeping	Lane Changing	Set Headway	Lane Keeping	Lane Changing	Control/Meter Access	Coordinate/Manage Merge & Diverge	Set Speed & Minimum Individual Headways	Set Speed & Headways, Inter/Intra-Platoon	Manage Lane Changing	Dedicated Single Lane	Dedicated Multiple Lanes	Entry/Exit Configurations	Headway Policy	Merge Strategy	Diverge Strategy
1	X				X	X	X	P		X			X		V	T2	T2	T2
2	X	X			X	X	X	P		X			X		V	T2	T2	T2
3	X	X	X		X		X	P	X	X			X		V	T2	T2	T2
4	X	X	X	X				P	X		X		X	X	V	T2	T2	T2
5	X	X	X	X				P	X		X	X	X	X	V	T2	T2	T2
X = Included, P = Where Possible, V= Various Options, Blank = Not Included, T2 = See Table 2-2																		

Table 2. ERSC Analysis Assumptions					
Factor	Manual Lanes	ERSCs			
		1 & 2	3	4	5
Speed (m/sec)	27 (60 mph)	31(70 mph)	31	Variable By Lane	Variable By Lane
Headway Selection	Driver	Driver	System	System	System
Minimum Headway (HW)(sec)	1.7 (Avg)	1.5	1	-	-
Maximum Platoon Size (Veh)	-	-	-	15	15
Minimum Intra-Platoon Gap (sec)	-	-	-	0.3[1]	<0.1[1]
Minimum Inter-Platoon Gap (sec)	-	-	-	3.0[1]	2.0[1]
Gap Detection & Evaluation	Driver	Driver	Driver/System	System	System
Mean/Minimum Acceptable Gap [HW (sec)]	3.0 MEAN	3.0 (From Stop)	2.0 (Coordinated Merge)	1	1
Merge Policy	First Acceptable Gap (FAG)	FAG	FAG	Merge Into Inter-Platoon Gap	System Makes Gap
Diverge Policy	FAG	FAG	FAG	Change Lane	Open Small Gap, Change Lane

1. These intra- and interplatoon gap values are used to provide specific illustrative calculations - they are not proposed as the correct values.

3. TECHNICAL DISCUSSION

This section presents the methods, interim products, and final results of each of the steps in the overall approach.

3.1 DEVELOP DETAILED DESCRIPTIONS OF THE RSCs USED IN THE ANALYSIS.

The results of this step in the approach were presented in Section 2.

3.2 DEFINE FUNCTIONAL FLOWS.

A generic functional flow for an AHS is outlined in Table 3. The AHS entries and exits must be designed to accommodate both the nominal travel functions as well as the associated potential problems.

The sequence and implementation details of each function will vary with the ERSCs and Entry/Exit configurations. This generic functional flow will be adapted to and mapped onto the specific entry/exit configurations for each ERSC later.

3.3 IDENTIFY ENTRY/EXIT EVALUATION CRITERIA.

The evaluation criteria were, after considerable thought, defined as stated below. It should be noted that even though these criteria focus on different characteristics of the AHS entry and exit configurations, they are not totally independent of each other. For example, there are positive correlations between functional effectiveness and safety, between operational access and safety, and between cost and all other criteria.

- Functional Effectiveness, which is characterized by the amount of delay introduced into all traffic streams involved; i.e., the source and target streams of the entering and exiting traffic. Zero total delay to all traffic streams characterizes an ideal entry/exit configuration. The larger the total delay to all streams, the poorer the entry/exit configuration.

- Safety of the entry/exit configuration during normal, degraded and failed operation of the AHS. This criteria is characterized by the degree of potential for spatial conflict between vehicles in the established traffic streams and those entering and exiting. Again, a zero potential for spatial conflict characterizes an ideal entry/exit configuration, while a high potential for conflict reflects a poor safety rating.

- Operational Access to the entry/exit area to enable response to incidents and accidents, and for maintenance of the roadway, sensors and C^3 equipment. Access is needed for snow and debris removal as well.

Table 3. Entry/Exit Functional Flow	
Nominal Travel	Potential Entry/Exit Problems That Must be Accommodated
Enter AHS	Congestion on the Source Road, at the AHS Entry, or on the AHS Itself That Delays or Prevents Entry
Check-In	Vehicle Fails Check-In, Must Be Excluded from AHS
Transition to Automatic	Vehicle Fails to Transition, and Must Be Removed or Excluded from AHS
Merge into AHS Stream	No Suitable AHS Gaps to Merge Into, or Spatial Conflicts Due to Merge Coordination Difficulties
Traverse Sections of AHS	Malfunction Causes Vehicle to Stop and Block AHS, or to Exit to Shoulder & Re-enter AHS After Clearing Problem
Traverse Various Entry/Exit Nodes	Delays Caused by Entering and Exiting Vehicles, and Potential Spatial Conflicts With These Vehicles
Check-Out	Driver Fails Check-Out, Cannot Assume Control of Vehicle
Diverge from AHS Traffic Stream	Congestion in Exit Lane/Ramp, No Gaps or Conflicts Due to Diverge Coordination Problems
Transition to Manual Control	Fails to Transition, Vehicle Cannot be Controlled Manually
Exit AHS	Congestion on Target Roadway, Cannot Exit Promptly

- Cost for roadway structures (Sensors and C^3 equipment will be discussed but no costs will be estimated).

- Evolutionary Compatibility, which is characterized as the quality of requiring minimal additional cost to support the next generation ERSC. A zero cost to support the next generation is ideal, of course.

3.4 DEFINE SPECIFIC ENTRY/EXIT TYPES AND CONFIGURATIONS.

The possible sources from which vehicles can enter an AHS and to which vehicles can exit from the AHS are:

- an adjacent or parallel freeway lane,
- a crossing or parallel surface street,
- a crossing or intersecting AHS, and
- the shoulder or breakdown lane of the AHS.

These four sources define the general types of entries and exits. Within most of these entry/exit types, multiple configurations are possible, with variations based on specific features added to enhance effectiveness, safety, or another criteria. The basic roadway geometry possibilities are identified in Table 4 and shown schematically in Appendix A. Additional refinements of these basic geometries to address identified shortcomings will be developed in Section 3.6.

3.5 MAP THE FUNCTIONAL FLOWS ONTO THE ENTRY/EXIT CONFIGURATIONS.

Prior to performing analyses, it is necessary to adapt and map the functional flows developed in Section 3.2 to the individual entry/exit configurations for each of the ERSCs. This aids in identifying the sequence of events, and the location of structures and equipment to support nominal and alternative/problem functions. These details are an intermediate step, the results of which are not of direct utility in presenting analysis results. For this reason, these tables are contained in Appendix B.

3.6 PERFORM QUALITATIVE EVALUATION/ANALYSIS OF THE ENTRY/EXIT CONFIGURATIONS.

3.6.1 Objectives. This analysis has several objectives. These are to:

- Consider the overall effects of entry and exit on the operation of the AHS, and particularly any effects associated with the entry/exit types and configurations.

- Determine the factors that influence each of the evaluation criteria for each entry/exit functional flow element (nominal and problem).

- Assign qualitative scores in each of the evaluation criteria for each basic entry/exit configuration for each ERSC,

- Identify refinements/variations on the more basic entry/exit configurations that can provide improved effectiveness, safety, operational access, or evolutionary compatibility (usually at additional cost),and

- Identify those issues, criteria, etc., that require more quantitative analysis.

Table 4. Basic Entry/Exit Configurations		
Entry/Exit Category	Basic Entry/Exit Type	Basic Entry/Exit Configurations
Freeway-to-AHS and Reverse	Continuous Entry and Exit Activity Along Interface	Contiguous Manual & AHS Lanes
		With a Transition Lane Separating the Manual & AHS Lanes
	Both Entry and Exit Activity at Designated Locations Only	Contiguous Manual & AHS Lanes
		With a Transition Lane or Ramp Separating the Manual & AHS Lanes
	Separate Entry and Exit Activity at Designated Locations Only	Contiguous Manual & AHS Lanes
		With a Transition Lane or Ramp Separating the Manual & AHS Lanes
Surface Street to AHS and Reverse	Separate Entry and Exit Activity Only at Ramp Locations	No Basic Variations
AHS-to-AHS	Continuing Dedicated Lanes for Diverging & Merging	No Basic Variations
	Exit AHS & Re-enter Other AHS	No Basic Variations
AHS-to-Shoulder & Reverse	Continuous Exit and Re-Entry Along AHS Lane & Shoulder Interface	No Basic Variations

Each of these objectives, except the last, will be dealt with in subsections following the Methods discussion. The results of that objective will be used to introduce Section 3.7, which discusses the quantitative analysis efforts.

3.6.2 Methods. The methods used in this qualitative analysis are mental and manual. A top-down system engineering approach was used to identify the overall effects of entry and exit on the AHS's performance. Tables were constructed to allow systematic identification and consideration of factors affecting each functional flow element for each entry/exit configuration for each ERSC.

3.6.3 Overall Effects of Entry and Exit on AHS Performance. The overall effects of entry and exit capabilities and activity can be ascertained by thinking of the AHS as a network of pipes, electrical wires or other types of links with a specific capacity to carry some product. There are multiple input and output nodes, each with its own capacity to place the product in the network or to remove product from the network.

A fundamental difference exists between a road system and networks such as electrical circuits or water distribution systems. This difference is due primarily to the relative sizes of the "particles" of the product and the "pipeline." Electrons and water molecules are extremely small compared to the size of the conduit in which they are distributed. Clogging of the conduit is not physically possible due only to the presence of the electrons or water molecules, and thus the product can always get through a sound network if proper input and output devices are installed. Vehicles, on the other hand are of approximately the same width as the road on which they travel, and can block the road so that other vehicles cannot pass. The result is that throughput can be reduced to zero on major sections of the AHS when vehicles are blocking the road, due to entering vehicles exceeding capacity or a single exit becoming blocked or congested. Thus, flow theory, which is a macroscopic modeling approach suitable for fluid flow and free-flowing traffic, cannot realistically represent the effects of stoppages and junctions in roadway traffic, which requires a microscopic modeling approach.

The design of entrances and exits also have a major impact on the efficiency of merging and splitting of traffic streams. These are, of course, the functions of an entry and exit, respectively. The merging that occurs upon entry especially, and the diverging upon exit to a lesser degree, are some of the most complex routine activities that occur in driving. This is a difficult and dangerous activity at high flow rates even on today's freeway. At the even higher flow rates desired for the AHS, merging and diverging will become impossibly difficult for most and eventually all human drivers.

These are the primary potential effects, stated negatively, that entries and exits can have on the overall throughput of the AHS, and these become increasingly critical as AHS volume increases. Stated positively, the entries and exits must be designed to prevent AHS blockages and to make the merging and diverging maneuvers efficient.

To prevent blockage of the AHS due to excess numbers of vehicles entering, or an inability of an exit to accommodate the numbers of vehicles desiring to exit, it will be necessary to manage the AHS traffic to achieve the following objectives:

- The volume of vehicles entering at each entry must be controlled to prevent more vehicles from entering than can be accommodated given the capacity of the downstream section.

- The volume of vehicles entering at each entry must be controlled to reserve sufficient capacity for downstream entrances to receive equitable service.

- Congestion at exits must not be allowed to back-up onto the AHS lane(s).

To achieve efficient merging of traffic streams at the AHS entries, it will be necessary to design into the entry/exit pair:

- An ability to detect and evaluate the sizes of available gaps in the established traffic stream of the target lane. This will be an assistance to the human driver in the earlier configurations, and to the automatic vehicle in later configurations. Creation of appropriately sized gaps may also be necessary for certain headway and merge/diverge policies in later configurations during very high flow rates.

- An ability to coordinate the entering vehicle's release, acceleration and path (in later configurations) to safely intercept a known, preserved or created gap, and merge into it. This will be an assistance to the human driver in the earlier configurations, and of the automatic vehicle in later configurations.

3.6.4 Qualitative Evaluation Factors. Tables were constructed to identify the most significant factors affecting the ability of each entry/exit configuration to optimally satisfy each evaluation criteria. These factors were identified for each functional flow element for each entry/exit configuration for each ERSC. These tables appear in Appendices C through K. There are several key factors that affect all of the entry/exit configurations, and are directly related to traffic volume. They are:

- For Operational Effectiveness, the primary delay factors are:
  - delays to the source traffic stream caused by slowdown of the exiting vehicles while trying to find a merging gap in the target stream,
  - delays to the entering/exiting vehicles, which are made up of queuing delays and gap availability in the target traffic stream, and
  - delays to the target traffic stream caused by vehicles merging into gaps that are less than twice the acceptable headway.

- For Safety, the primary factor is potential collision possibilities during the entry and exit processes. The potential collisions could occur between:
  - a slowing vehicle attempting to enter the AHS and the vehicles that are following,
  - between merging vehicles competing to capture acceptable AHS gaps,
  - a vehicle attempting to merge into the AHS and those already on the AHS,
  - a vehicle wishing to exit the AHS and the vehicles that are following,
  - between exiting vehicles competing to capture acceptable gaps in the manual

lane, and
- a vehicle attempting to merge into the manual lane and those already in that lane.

An additional major safety factor is the potential for deliberate or negligent entry of manually controlled vehicles into the AHS lane(s), or of out-of-control vehicles entering or caroming into the AHS lane(s).

- For Operational Access, there are two factors, shoulders and barriers. Shoulders serve vital purposes for failed vehicle storage, snow storage, maintenance access, and emergency access to accidents/incidents that must be serviced and cleared. Other adjacent lanes, such as the manual lanes, can also provide operational access if they are not involved in the problem or the related congestion. Barriers, if present, will limit the degree of access from the manual lanes.

- For Costs, the major factors are all of those structures, sensors and equipment that must be added to today's roads (which are tailored to human controlled vehicles) to make an AHS possible.

- For Evolutionary Compatibility, the key factor, although not apparent from the tables in the Appendices, is to ensure that the overall architecture and the enduring technologies used to achieve each AHS function do not have to be replaced to realize the next increase in capability.

3.6.5 Qualitative Evaluation Results for the Basic Entry/Exit Configurations. This step required assignment of qualitative scores, based on the several decades of combined experience on the evaluation team, to each basic entry/exit configuration after considering the factors identified in Appendices C through K. These overall scores are shown in Table 5.

The qualitative results can be summarized by stating the most significant advantages and disadvantages of each entry/exit configuration, and estimating the conditions under which that configuration might be most useful. This summary is presented in Table 6.

3.6.6 Refinement of Entry/Exit Configurations. The basic configurations shown in Appendix A can be enhanced to improve their effectiveness and safety, usually at increased cost.

One example improvement is the inclusion/addition of separate deceleration lanes prior to exit gates or ramps where possible for the configuration. This design feature will reduce the delays to the source traffic stream by allowing the exiting vehicle to diverge into the deceleration lane prior to slowing, and will reduce the likelihood of being rear-ended by following vehicles.

Another design improvement is to provide the necessary instrumentation to coordinate merges into both the AHS and manual lanes. This feature could reduce the delays to the

Table 5. Entry/Exit Evaluation Results (Qualitative),
More or Less Independent of ERSC

Entry/Exit Configuration Designation			Qualitative Evaluation Results				
			Functional Effective-ness	Safety	Opera-tional Access[1]	Cost	Evolu-tionary Compati-bility
Free-Way To AHS	Contin-uous	Contiguous	C	D	A	A	A
		Transition Lane (TL)	B	C	A	F	A
	Desig-nated Joint	Contiguous	F	F	A	A	A
		TL or Ramp	D	D	A	B	A
	Desig-nated Separate	Contiguous	B	D	A	A	A
		TL or Ramp	A	B	A	B	A
Surface Street to AHS		No Barrier	A	A	A	D	A
AHS to AHS	Continuing Lane		A	A	C	F	A
	Exit and Re-enter		F	A-F[2]	A-C[2]	A	A
AHS to Shoulder & Return			C	F	A-C[2]	A	A

1. Shoulders are assumed, in accordance with freeway design standards ; if no shoulder, all A's become C's and C's become F's.
2. Specific grade depends on the type of Freeway/Street - to - AHS entry/exit.

Table 6. Summary Evaluation Results for Each Basic Entry/Exit Configuration

Entry/Exit Configuration Designation			Summary: Advantages	Summary: Disadvantages	Summary: Best Application
Free-Way To AHS[1]	Contin-uous	Contiguous	Least Expensive & Easy Access	Dangerous in Heavy Traffic	Light AHS & Entry/Exit Volumes
		Transition Lane (TL)	Easy Access	Very Expensive	Moderate AHS & Entry/Exit Volumes
	Desig-nated Joint	Contiguous	Second Least Expensive	Most Dangerous, even in Light Traffic	Very Light AHS & Entry/Exit Volumes
		TL or Ramp	Relatively Inexpensive	Dangerous in Moderate Traffic	Light AHS & Entry/Exit Volumes
	Desig-nated Separate	Contiguous	Third Least Expensive	Dangerous in Moderate Traffic	Light AHS & Entry/Exit Volumes
		TL or Ramp	Most Effective Freeway -to-AHS Entry/Exit	Expensive for Most Effective Configuration	Moderate-Heavy AHS & Entry/Exit Volumes
Surface Street to AHS[2]			Most Effective Under Heavy AHS & Freeway	Very Expensive	Heavy AHS, Freeway & Entry/Exit Volumes
AHS to AHS	Continuing Lane		Most Effective Interchange	Very Expensive	Heavy AHS & Freeway or Surface Street Volumes
	Exit and Re-enter		Relatively Inexpensive	Relatively Ineffective	Light to Moderate Interchange Traffic
AHS to Shoulder & Return			Safe Storage of Malfunctioning Vehicles & Drivers	Difficult to Coordinate Exit & Re-Entry	All Traffic Conditions

1. Freeway-to-AHS Entry/Exit configurations suffer common weakness. Those configurations that cannot control access will become congested if the freeway is congested. Entry to the AHS will be impeded under congested freeway conditions. The AHS will become congested if the sink of the exiting traffic (the freeway) is congested.
2. For the Surface-to AHS configuration, AHS access will be impeded if the surface street is congested. Also, the AHS will become congested if the sink of the exiting traffic (the surface street) is congested.

entering/exiting vehicle by reducing queue lengths and improving the utilization of available gaps in the target streams. Under light to moderate traffic flows, this capability could also be used to reduce delays to the target traffic stream by allowing vehicles to merge only into gaps twice as large as the acceptable headway. Safety for merging vehicles is dramatically improved by eliminating competition among merging vehicles for available gaps, and by assuring the availability of appropriate gaps.

A physical improvement for the freeway-to-AHS category of entry/exit configuration is to design the entry/exit so that both the AHS and manual exits occur prior to their entries. This would allow the gaps created by the exiting vehicles to be available for entering vehicles on both AHS and manual lanes. This feature also eliminates the primary weakness of the separate entry/exit configurations, which is the spatially temporary overloading of traffic between the entry and exit (or vice versa) on either the manual or AHS lane.

Another possibility is to have exits from and entries to the manual lanes on the right, as is the design standard. This is an expensive refinement, since flyovers and additional space would be necessary to cross the manual lanes and provide an at grade entry/exit to the AHS lane(s).

With most of these design refinements incorporated into the best of the freeway-to-AHS entry/exit configuration (the designated separate entry/exit), the result is shown in Figure 1. This appears to represent (from this analysis) close to an optimal design for the freeway-to-AHS category. Both of the ramps could be constructed with flyovers of the manual lanes to provide entry from and exit to the right, but that would be a very expensive enhancement. The surface street-to AHS entry/exit would benefit from the first two of these improvements, but the last two design improvements are inherent in this entry/exit category.

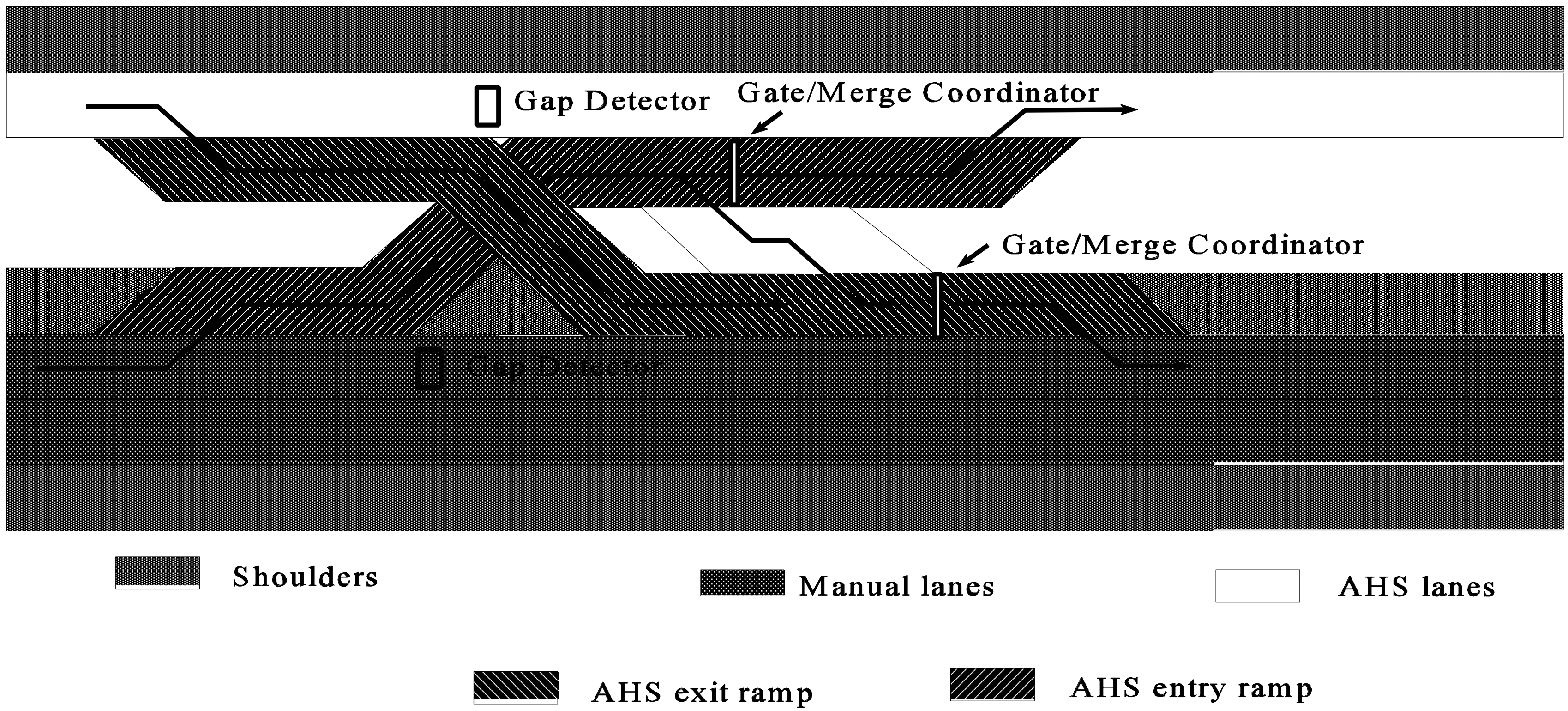

Figure 1. Optimized freeway-to-AHS entry/exit

3.7 PERFORM QUANTITATIVE EVALUATION/ANALYSIS OF THE ENTRY/EXIT CONFIGURATIONS.[1]

3.7.1 Objectives. The objective of this analysis is to better quantify those factors affecting the evaluation criteria that cannot be adequately quantified by less rigorous methods. In particular, several of the evaluation criteria, such as operational effectiveness and cost, are directly affected by factors which cannot be addressed adequately without mathematical or simulation based analysis. Specifically, AHS entry/exit operational effectiveness is determined by the amount of delay caused to all traffic streams due to the entering and exiting traffic. The cost of entry/exit structures can only be estimated after determining their dimensions. These dimensions are determined by the lengths of queues on ramps, travel distances in transition lanes, and the lengths of acceleration/deceleration lanes. All of these factors are currently best estimated via a quantitative approach.

3.7.2 Methods[2]. The primary method employed is to develop probabilistic descriptions of relevant characteristics for all target traffic streams, both manual and AHS. All calculations are based on these probabilistic descriptions. A probabilistic model was identified that seems to adequately describe manual traffic streams. Models for AHS traffic streams were developed for this analysis.

3.7.3 Probabilistic Descriptions of Gaps. The most fundamental of factors in this analysis is the availability of acceptable sized gaps in the "target" traffic stream, into which the entering or exiting vehicle can merge. The target traffic stream is that one already established in the lane into which merging is desired.

The two terms commonly used to describe these available spaces for merging are "headway" and "gap." The term headway almost always refers to the <u>time</u> between the arrivals of the front edges of consecutive vehicles at a fixed point on the roadway. The term gap is used in two different ways. Gap sometimes means the distance equivalent of headway; i.e., the distance between the front edges of consecutive vehicles in a traffic stream. Gap is also used to mean the time or space between the rear of one vehicle and the front of the following vehicle; i.e., the opening between consecutive vehicles in a stream. This latter meaning of gap is the one that will be used consistently in this analysis.

Headways and gaps, as used here, can both be expressed in units of either time or

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[1] This analysis is incomplete due to limitations on resources and time. Only delays to the entering and exiting vehicles are addressed, along with those safety and cost issues that can be addressed with the information developed in the delay analysis.

[2] The methods used in the Highway Capacity Manual are based primarily on observed driver behavior on current roadways. The AHS vehicles, under at least partial automation, will not behave like vehicles under full human control. For this reason, these methods are not applicable to the AHS, except for the adjacent manual lanes.

distance, but time is preferred because it tends to remain relatively constant, independent of speed. Unless otherwise stated, the units of headways and gaps will be seconds.

Note that gaps are used in the analysis, For independent vehicles that select their own headway, average headway is the gap value plus an average vehicle length/passage value. However, when platoons are addressed, the interplatoon headway would be a variable number since the platoons will be of differing lengths. Therefore the more constant (on the average) gap will be the variable for this analysis.

3.7.3.1 Manual Lane PDFs Used for this Analysis. Several types of probability density function (pdf) have been used to describe the distribution of headway and gap values in freeway traffic streams. These pdfs include the normal, exponential, and gamma distributions. The one that seems to best match observed freeway headways/gaps is the so-called Erlang distribution function, which is of the gamma type. The Erlang pdf, as used in this analysis to describe the manual lane traffic stream., is defined by the equation:

$$pdf_{man} = f(t)_{man} = \frac{(aq)^a}{(a-1)!} t^{a-1} e^{-aqt}$$

where: t = gap variable,
q = flow rate, and
a = "Erlang number" which increases with the flow rate.

This pdf has been employed and parameterized in various analyses of the freeway environment. The text on traffic flow theory by Drew (Bibliography item 1) is the general source of the parameters and concepts used here. The resultant graph illustrating the Erlang distribution with parameters pertinent to manual lanes is shown in Figure 2. The values of the variable a used for various traffic flows q are as shown in Table 7.

3.7.3.2 AHS Traffic Stream PDFs Developed for Use in this Analysis. Two types of pdfs will be used to describe the AHS traffic streams, depending on the ERSC.

For ERSCs 1-3, the driver selects the gap between the vehicle and the preceding one in the AHS traffic stream and is responsible for lane changing during merging and diverging. In the assumptions for these ERSCs, the infrastructure C^3 system sets a minimum safe headway, one that the vehicle's longitudinal control equipment will not violate. A single-lane roadway configuration was also assumed for these ERSCs. Because of vehicles merging into AHS traffic stream gaps that are less than twice the minimum headway, and possibly other influences, it seems reasonable that there will be a significant number of vehicles with small headway. In fact, the proportion of vehicles at this minimum headway should increase with traffic flow until all vehicles are at this minimum headway at maximum capacity.

Although probably not valid, it will be assumed, for simplicity sake, that the Erlang distribution (with modifications to account for the system prescribed headway) will adequately describe the distribution of gaps in ERSCs 1, 2 and 3. This would result in gap pdfs that look something like those of Figure 3 and 4. Since all other factors are assumed unchanged between ERSCs 1/2 and 3, the only difference in the pdfs are the assumed minimum allowed gap (1.5 sec for ERSCs 1&2 versus 1.0 sec for ERSC 3). The estimated values of the a parameter also continue to increase with traffic flow.

Table 7. Values of the Erlang Parameter (a) for Various Traffic Flows (q)

Traffic Flow (q)		Erlang Parameter (a)[1]
Vehicles/Second(vps)	Vehicles /Hour (vph)	
0.125	450	2
0.250	900	4
0.375	1350	6
0.500	1800	8
0.62.5	2250	10
0.750	2700	12
0.875	3150	14
1.000	3600	16

1. Figure 9-23, page 218 of reference in footnote 2 (page 20) used as an approximate guide.

The equations which define the AHS ERSC 1 & 2 traffic stream pdfs are:

$$pdf_{AHS1,2} = f(t)_{AHS1,2} = \begin{cases} 0, & \text{for } t < TAHS \\ \dfrac{(aq)^a}{(a-1)!}\displaystyle\int_0^{TAHS} t^{(a-1)} e^{-aqt} dt, & \text{for } t = TAHS \\ \dfrac{(aq)^a}{(a-1)!} t^{(a-1)} e^{-aqt}, & \text{for } t > TAHS \end{cases}$$

where: TAHS = AHS minimum allowed gap (1.5 or 1.0 sec),
all other variables are as previously defined for the manual lanes

With ERSCs 4 and 5, automatic lane changing capabilities will have been incorporated into the AHS systems. Platooning of vehicles with close headways, with automatic merging of

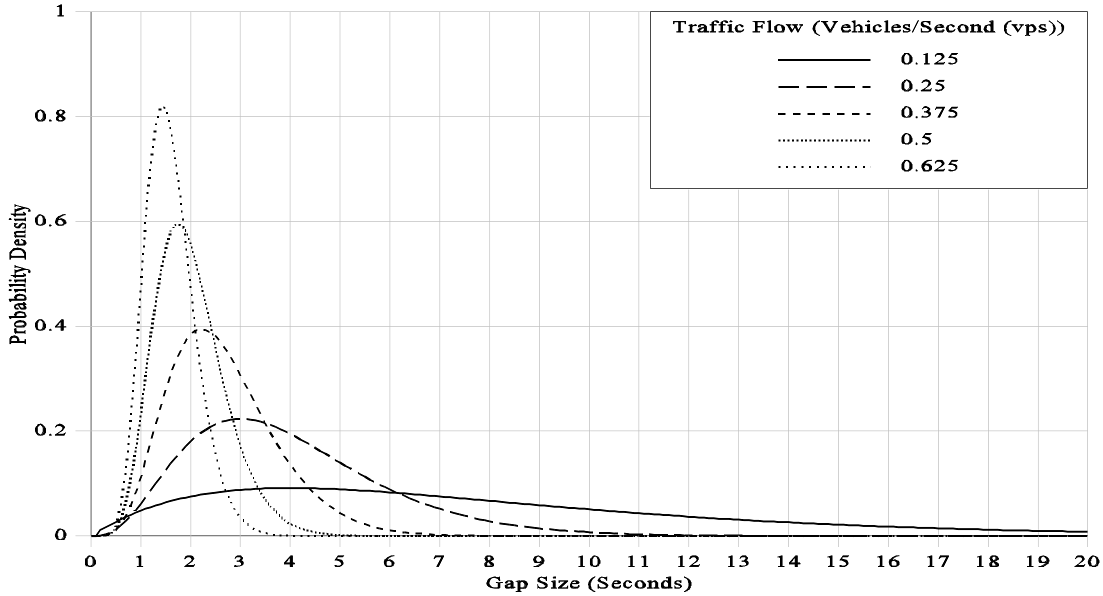

Figure 2. Gap Probability Density Function (pdf) for Manual Lanes

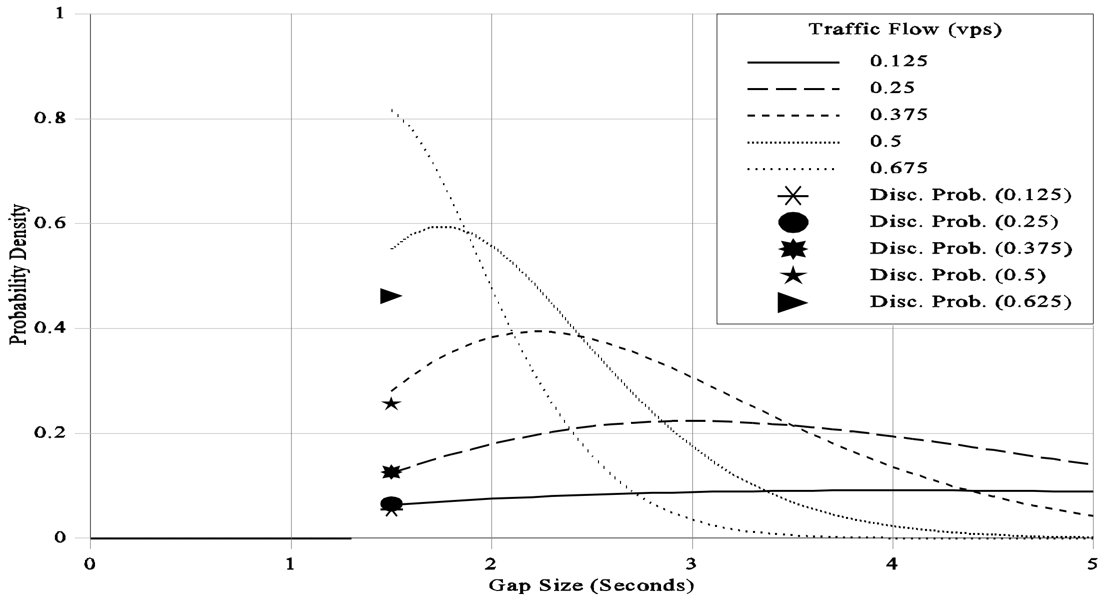

Figure 3. Possible Gap Probability Density Function (pdf) for AHS Lane, for ERSCs 1 &2

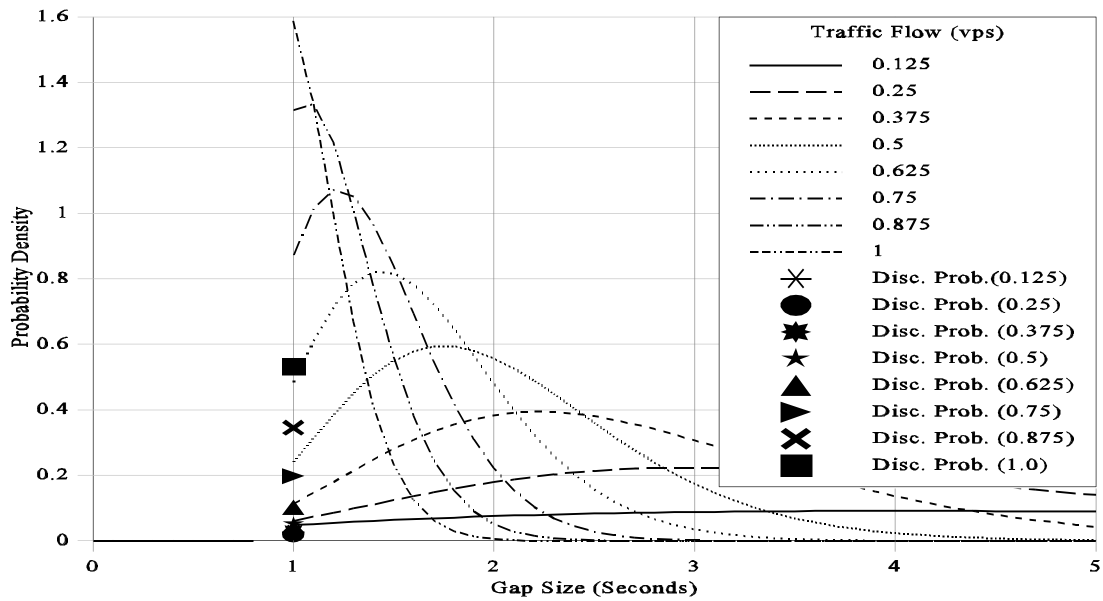

Figure 4. Possible Gap Probability Density Function (pdf) for AHS Lane, for ERSC 3

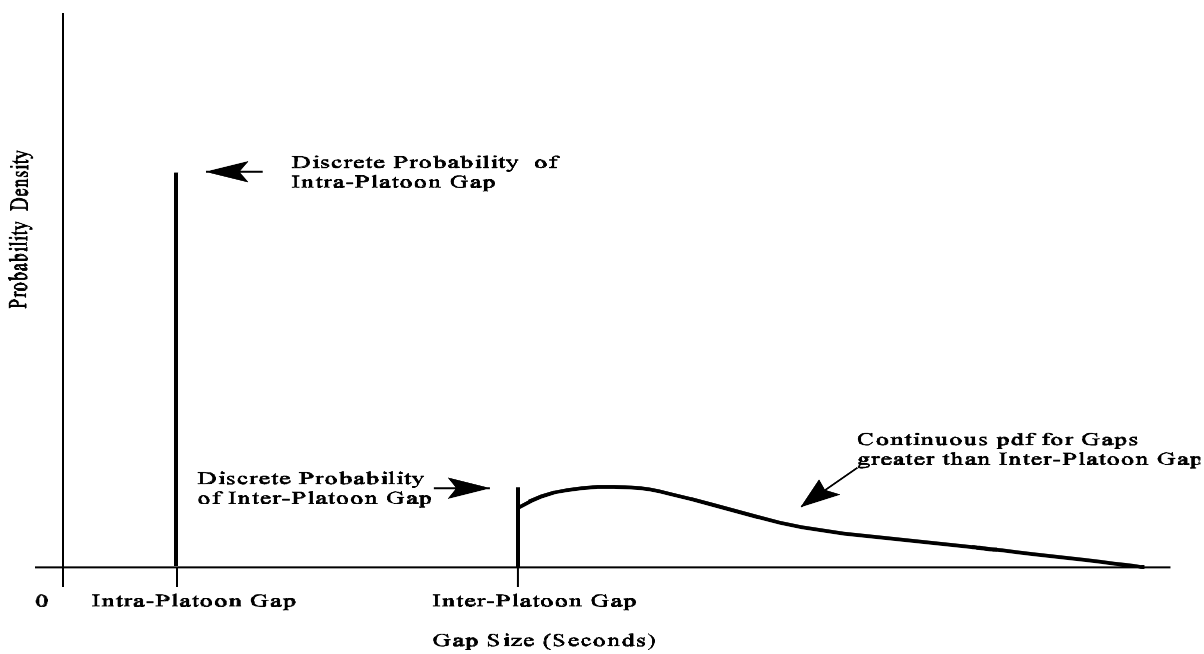

Figure 5. Notional Gap Probability Density Function (pdf) for AHS Lanes, for ERSCs 4 & 5

vehicles into the AHS stream, is assumed. The pdfs that describe the expected gaps in a platooning AHS traffic stream are presented notionally in Figure 5 and is described by the expression:

$$pdf_{AHS3} = f(t)_{AHS3} = \begin{cases} 0, & \text{for } 0 < t \text{ ,IPG} \\ prob(t = IPG), & \text{for } t = \text{intraplatoon gap} \\ 0, & \text{for IPG} < t < \text{PG} \\ prob(t = PG), & \text{for } t = \text{interplatoon gap} \\ \text{some continuous pdf}, & \text{for } t > \text{interplatoon gap} \end{cases}$$

where: prob(x) = discrete probability of x,
IPG = IntraPlatoon Gap
PG = interPlatoon Gap
pdf(x) = probability density function of x

3.7.4 Functional Effectiveness (Delay) Analysis. There are three delays of interest in this analysis: delay to the entering or exiting vehicle; delay to other vehicles in the source traffic stream from which the entering or exiting vehicle came; and delay to the target stream to which the entering or exiting vehicle went. However, due to limitations on the resources and time available for this analysis, only the delays to the entering/exiting vehicle could be addressed analytically.

3.7.4.1 Delay to the Entering or Exiting Vehicle. There are two components of this delay, that due to queuing, and that due to availability of suitable gaps in the target traffic stream for merging.

Queuing Delays. These delays were not addressed quantitatively in this analysis. The qualitative analyses, however, identified the requirement that the overall AHS system must be managed so that any queues that exit must be due only to the probabilistic variations in the entry/exit demand and service rates. This means that, on the average, the entry/exit demand rates cannot be allowed to exceed the entry/exit service rates. This is especially critical at the higher traffic flows where any queues that exceed the queue storage capacity would cause serious degradation of the AHS performance.

Merging Gap Availability. This delay is related directly to the availability of acceptable sized gaps for merging into the target traffic stream. Therefore, it is necessary to first determine the probability of existence of acceptable merging gaps. This probability, which is the probability that a gap's size is larger than the acceptable size, is given by the equation:

$$\text{Prob } (t \geq T) = \int_T^{\infty} f(t)\, dt$$

where: T = size of acceptable gap
f(t) = pdf defined previously for the manual or AHS lane(s)

The probabilities of acceptable gaps as a function of traffic flow for the manual lanes, ERSCs 1/2, and ERSC 3 are graphed in Figures 6 through 8, respectively. The particular values of acceptable gaps were chosen to cover a reasonable range of merging gaps; i.e., 0.5 to 3.0 seconds. However, this is but an interim result. The key information needed to address delays to the entering/exiting vehicle is the time that passes and the distance traveled while waiting/looking for an acceptable merging gap.

Entering or exiting vehicles must evaluate all gaps in the target traffic stream as they pass the vehicle's detection point until an acceptable sized gap is found. The total number of gaps evaluated in the process of finding the first acceptable one is given by the formula:

$$E[n] = [\mathrm{Prob}(t<T)]^{n-1} \bullet \mathrm{Prob}(t \geq T)$$

where : n = number of gaps
E[n] = expected number of gaps evaluated in finding an acceptable one
Prob(t≥T), t, T, and f(t) are as defined previously

This expected number of passing gaps, which correlates to the delay that the vehicle suffers, is graphed as a function of traffic flow for the manual lanes, ERSCs 1/2, and ERSC 3 in Figures 9 through 11, respectively.

The task at hand now is to translate these expected numbers of gaps into delay time. There is, in fact, more than one way to define delay. The time that elapses between when a vehicle first attempts to enter/exit the AHS and when it actually enters/exits is an inverse function of the relative speed of the vehicle with respect to the target traffic stream. This entry/exit delay will have different values for entry/exit configurations in which the entering/exiting vehicle is moving versus standing while waiting for an acceptable sized gap in the target lane.

This entry/exit delay is not true delay. As used here and in all delay analyses, delay will mean the actual amount of time lost (or gained) for the overall trip as a result of the entry/exit maneuver. For given traffic flows, this will be a single value for all the entry configurations and an independent single value for the exit configurations. This delay is dependent only on the levels of traffic flows in the manual and AHS lanes, and is equal to the time spacing between acceptable sized gaps in the target lane (which is equivalent to the time elapsed while stopped and waiting for E[n] gaps to pass). Thus, the delay in entry/exit would be given be the formula:

$$\text{Entry/Exit Delay} = E[n] \cdot E[rhw] = \frac{\int_0^T t \cdot f(t)\,dt}{\int_T^\infty f(t)\,dt}$$

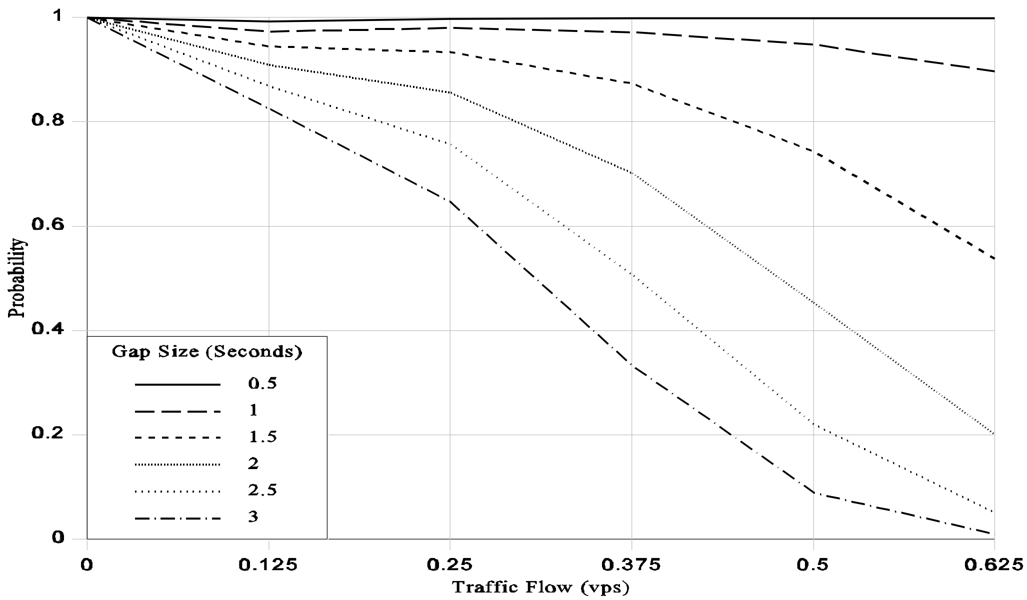

Figure 6. Availability of Gaps of Selected Sizes in Manual Traffic Streams

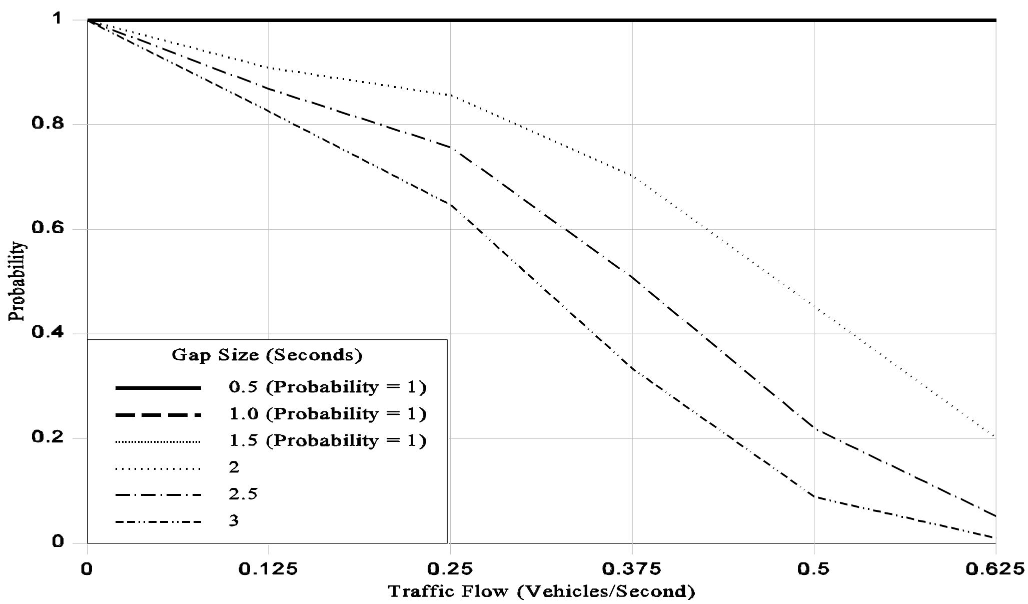

Figure 7. Availability of Selected Sized Gaps in AHS Traffic Stream, ERSCs 1 & 2

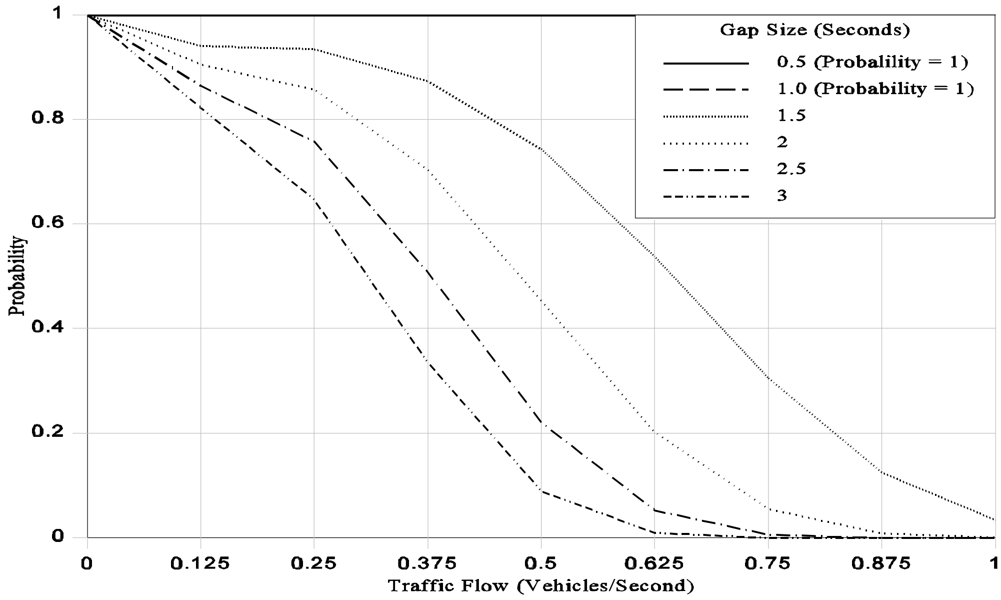

Figure 8. Availability of Selected Sized Gaps in AHS Traffic Stream, ERSC 3

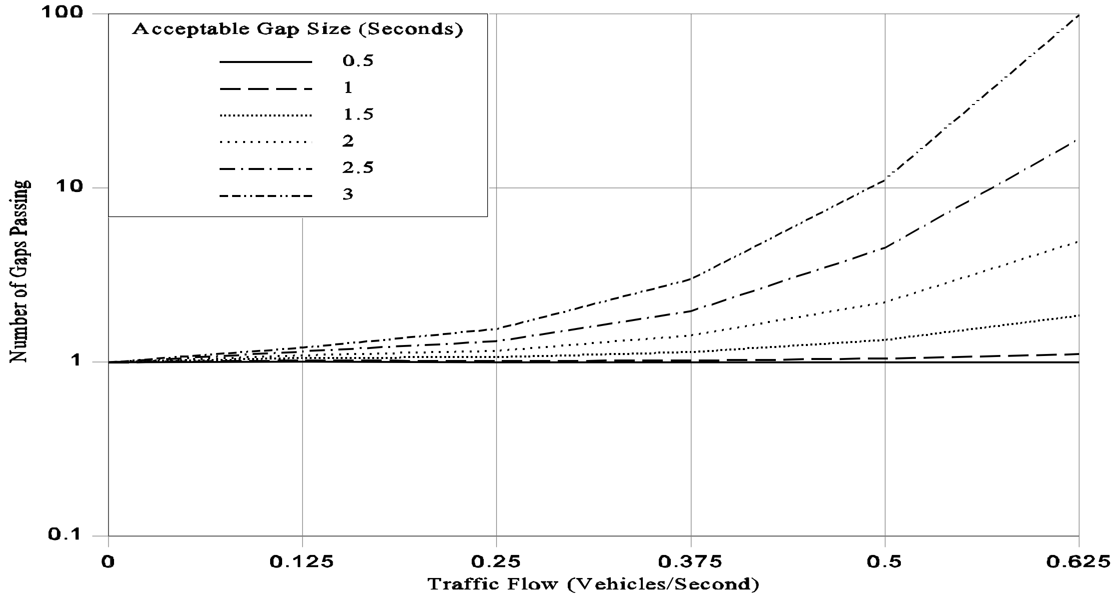

Figure 9. Number of Gaps Evaluated to Find First Acceptable Sized Gap in Manual Traffic Stream

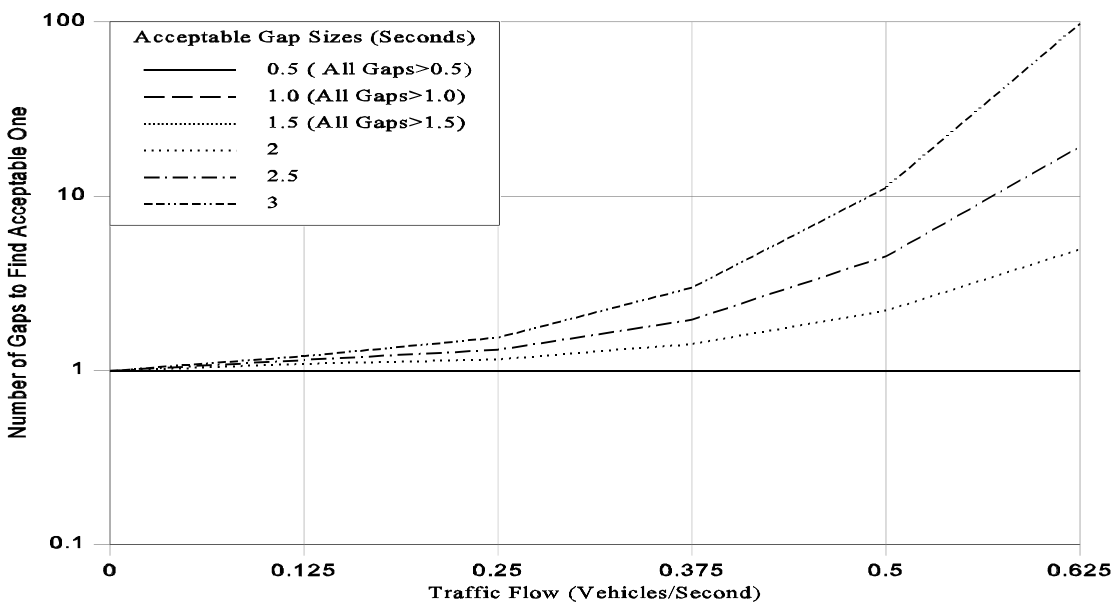

Figure 10. Number of Gaps Evaluated to Find First Acceptable Sized Gap in AHS Traffic Stream, ERSCs 1 & 2

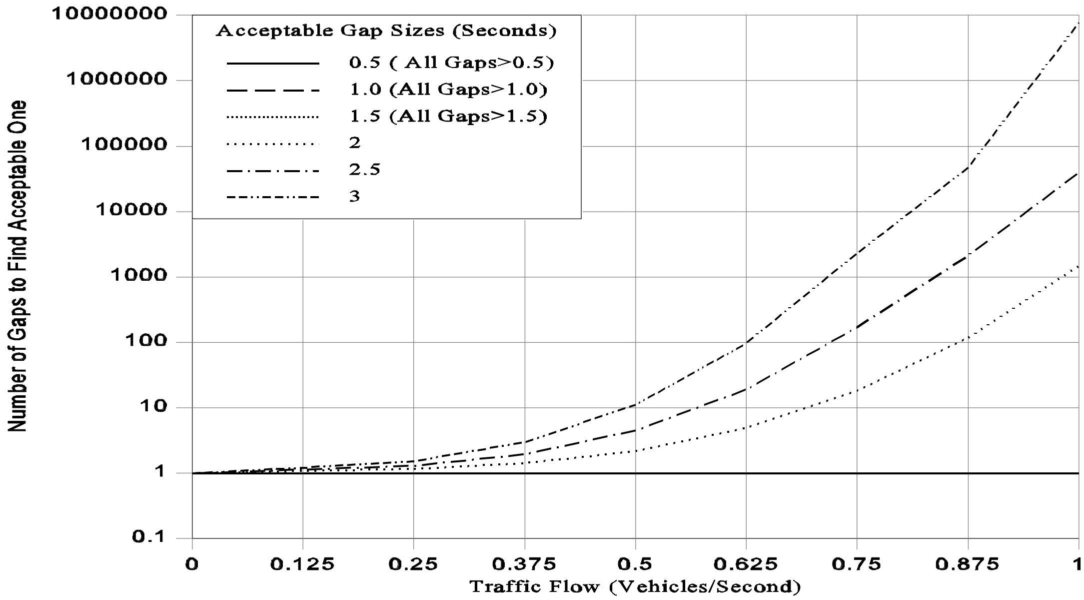

Figure 11. Number of Gaps Evaluated to Find First Acceptable Sized Gap in AHS Traffic Stream, ERSC 3

E[rhw] = the expected (mean) value of headways for rejected gaps, and
t, T, and f(t) are as previously defined

Graphs of this delay as a function of traffic flow, with acceptable merging gap size as a parameter, appear in Figures 12 through 14 for traffic streams in the manual lanes and the AHS lane for ERSCs 1/2 and ERSC 3, respectively.

As can be seen from these graphs (Figures 12 through 14), the delays to the entering/exiting vehicle at the higher values of traffic flow (q) for the manual lanes and for the AHS lane in ERSCs 1/2 are reasonable. However, for AHS ERSC 3, the delay becomes quite excessive for merging gap sizes of 2.5 sec or larger at the higher traffic flows (≥75% of capacity). Notice even for ERSC 3, however, that the delays are still reasonable for the smaller sized merging gaps. The conclusions drawn from these observations is that if the AHS ERSC3 is to function as envisioned at the higher traffic flows, merging aids are necessary that will allow manual merging into very small gaps (by today's standards). Even on the manual and ERSCs 1/2 lanes at near capacity traffic flow, merging aids may be necessary since a merging gap of 3.0 sec is rejected as often as it is accepted.

3.7.4.2 Delays to the Source Traffic Stream. These delays are caused by the slowing of exiting vehicles during the process of detecting, analyzing and intercepting a gap in the target traffic stream. The amount of delay and the number of downstream vehicles affected are a random variable, dependent on the traffic flows in both the AHS and manual lanes, the speed differential between the manual and AHS lanes, the acceptable size for merging gaps, and the headway policy in the source traffic stream. Due to schedule and resources constraints, the characteristics of these delays were not quantitatively analyzed. However, the analyses of delay to the entering/exiting vehicle did produce some thoughts on how the delays to the source stream can be reduced or eliminated. These source traffic stream reduction techniques are:

- Provide a length of dedicated deceleration lane prior to the exit point so that the exiting vehicles can diverge at full speed and then slow to find a suitable merging gap in the target stream or join the exit queue.
- Provide adequate storage space for the inevitable queue (at the higher traffic flows in the target lane) due to statistical variations in the demand and service rates.
- Take the necessary measures to prevent a backup of the exiting vehicle queue into the source traffic stream. This means, in the simplest form, monitoring the queue length and disallowing exits when the queue is threatening to block the source stream.

For the AHS to manual transition, the more satisfactory solution will require a system wide scheme of advising entering vehicles when their desired exit is experiencing congestion and suggesting/requiring alternative exit points.

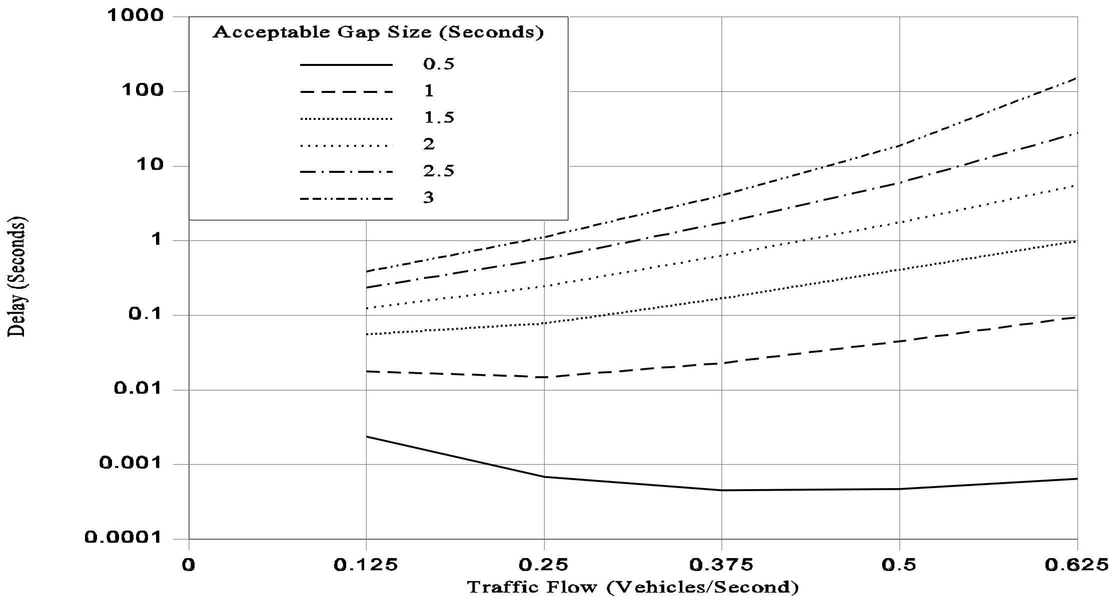

Figure 12. Gap Availability Delay, Manual Lane

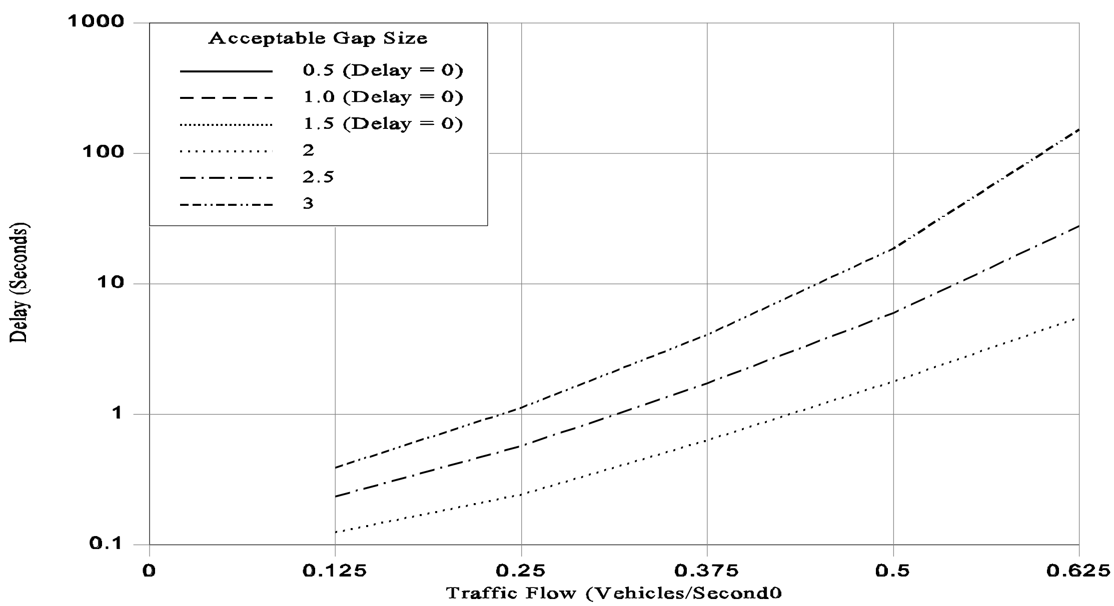

Figure 13. Gap Availability Delay, AHS Lane - ERSC 1 & 2

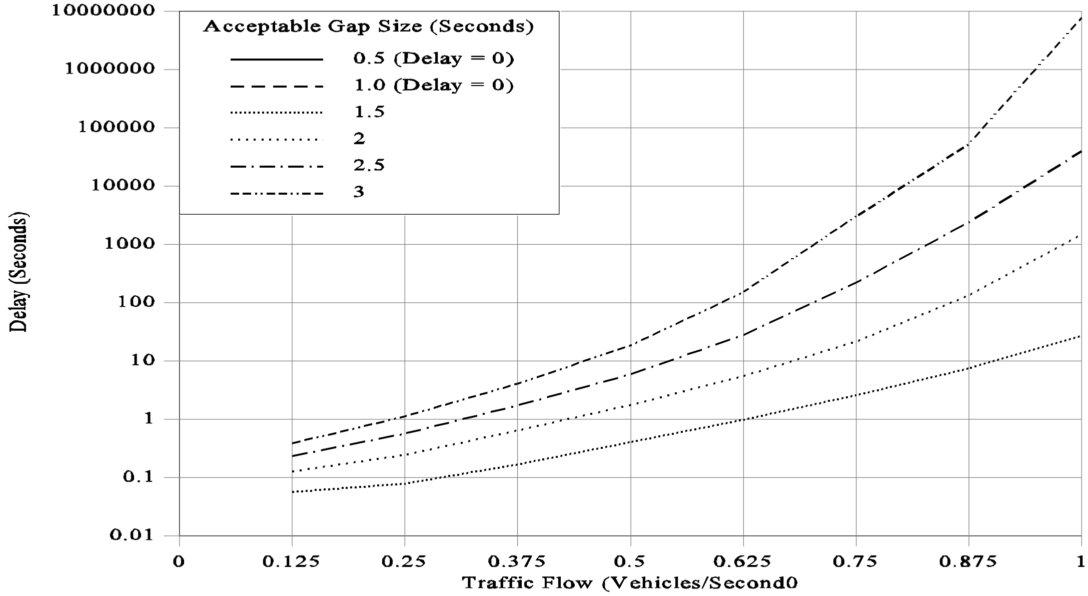

Figure 14. Gap Availability Delay, AHS Lane - ERSC 3

3.7.4.3 Delays to the Target Traffic Stream. These delays are caused by entering vehicles merging into gaps less than twice the size of the acceptable gap plus the length/passage of the vehicle. The downstream vehicles then have to slow down until acceptable gaps are re-established between all vehicles in the stream. The amount of delay and the number of vehicles affected are a random variable, dependent on the traffic flow, acceptable merging gap, and the headway policy in the target traffic stream. Again, due to limitations in the time and resources available to the project, no detailed analysis was accomplished. However, the following potential techniques for minimizing these delays to the target traffic stream seem worth considering:

- The volume of traffic entering and in the established target traffic stream must be managed on a system wide basis as well as at the local entry point to assure that entry service rate capability (the number of available gaps for merging) is at least equal to the allowed entry rate. This will be absolutely necessary at the higher traffic flows to provide equitable service at all entry points and to avoid congestion slowdown.

- Whenever feasible, restrict entering vehicles from merging into gaps that are of a size that would require the downstream vehicles to slow down; i.e., those gaps less than twice the acceptable gap size plus the length/passage of the vehicle. To do this, it will be necessary to detect the presence and size of gaps in the target stream and coordinate the release of entering vehicles to intercept the appropriately sized gaps.

- At exit/entry points, always have the exit precede the entrance and preserve/reserve the gaps created by exiting vehicles for the entering vehicles. Delays to the traffic stream will be reduced to the degree that exiting and entering numbers of vehicles balance. For the AHS-to-freeway entry/exit, the simultaneous entry/exit is the only design capable of implementing this technique for both the AHS and freeway. Other designs will temporally increase traffic flow between the exit/entry points on either the AHS or the freeway by the number of entering/exiting vehicles.

3.7.4 Cost Analysis.

The structures for which a more quantitative analysis is appropriate are the transition lanes, ramps, queue storage lanes/ramps, and acceleration/deceleration lanes/ramps.

3.7.4.1 Basic cost Data. The data presented in Table 8 represents approximate costs based on averaging and rounding of cost data collected as a part of this analysis.

As used here (for cost estimation purposes), the term "transition lane" only applies to the continuous entry/exit configurations, and so the transition lane itself is continuous. The cost then is approximately $1,000,000 per kilometer of the AHS. Those structures referred to as transition lanes in the designated entry/exit configurations are, in fact, used as acceleration and deceleration lanes and for queue storage.

Ramps are assumed to be part of the acceleration/deceleration lanes and queue storage, and to cost approximately the same as traffic lanes plus shoulders on a per kilometer basis.

Table 8. Approximate Costs of AHS Structures

Element	Approximate Cost ($)	Basis
Freeway Lane	1,000,000	per kilometer
Shoulder	500,000	per kilometer
Barrier	70,000	per kilometer
Flyover/Bridge	1,000	per square meter

Acceleration and deceleration lane lengths should be designed for about 0.1g (1g = 9.81 m/sec^2) to 0.2g of acceleration/deceleration. The equation for the length of these lanes is:

$$L = \frac{s^2 - s_o^2}{2a}$$

where: L = length of the acceleration/deceleration lane
s = speed of vehicle at the end of length L
s_o = initial speed of vehicle
a = acceleration/deceleration of vehicle

The two speeds (s and s_o) are the operating speeds of the manual or AHS lanes (which are both assumed to be approximately 30 m/sec) and the completely stopped state of 0 m/sec. This calculation yields a length of about 460 m for an acceleration/deceleration of 0.1g.

The quantitative analysis of queue lengths was not completed. Therefore, the lengths of lanes or ramps for queue storage could not be calculated.

Flyovers proposed for the optimized freeway-to-AHS entry/exit would have minimum dimensions on the order of 50 m in length by 10 m in width, yielding an area of about 500 m^2 for an approximate cost of $500,000. Note that this figure is for the flyover only, and does not include the acceleration/deceleration lanes, ramps and shoulders at grade level.

Completion of this costing exercise would require a rough design of each of the entry/exit configurations to obtain the approximate lengths of all structures.

3.8 DEVELOP CONCLUSIONS FROM THE ANALYSES.

The results of this step in the task are reported in Section 4.

4. CONCLUSIONS AND OTHER RESULTS

This section presents the conclusions and recommendations from this analysis of AHS entry/exit implementation strategies, as formulated for each of the three major issues addressed, which were identified in paragraph 1.3.

4.1 SUMMARY

The specific conclusions and recommendations that are presented in later subsections can be summarized and generalized as follows:

- The AHS is a very complex and expensive system, and its development will be a very complex and challenging undertaking. The AHS cannot be developed in a single massive project - there are too many independent funding decision makers (vehicle owners and road system owners/operators), a large majority of whose benefit/cost based decisions would have to be supportive and timely. The AHS will be developed in incremental and evolutionary steps as the user market will support with their spending decisions.

- AHS entry and exit are key, if not the key, functional components of the AHS. Efficient operation of the entire AHS system will be gained or lost at the entries and exits. Entries are the only points at which demand related congestion can be controlled. Exits are critical because a single blocked or congested exit, if not managed effectively, can bring the entire upstream system to a halt. Lane changing and merging at the entries and exits are the most complex and dangerous routine activities that will occur on the AHS; therefore, most accidents and efficiency problems will occur there.

- Any of the possible entry/exit strategies and configurations will work under light traffic flow conditions. Only the most well conceived and carefully managed entry/exit strategies and configurations will allow the AHS to function efficiently at the highest desired traffic flows.

- Further development of mathematical, simulation and design tools is necessary in order to adequately analyze, design, and develop the AHS prototype(s).

4.2 FIRM CONCLUSIONS AND THE UNDERLYING ASSUMPTIONS

The detailed conclusions are described below and are organized within the three major issues addressed.

4.2.1 Effects of Entry/Exit on Overall Performance of the AHS. The first major conclusion here is that the AHS and its entries and exits must be designed and managed as a system if the AHS is to operate efficiently at traffic flow rates higher than is possible on current freeways. The AHS system is defined as all of the interconnecting AHS links, all of its entries and exits, and the surface streets that feed and sink traffic from the AHS in a metropolitan area.

It is assumed that, to the degree possible, the AHS sections and each entry/exit will be developed and upgraded periodically to accommodate the existing level of demand. AHS capacity will come in discrete increments as additional lanes. Demand will likely outgrow the capacity of a single lane long before multiple lane AHSs are technically possible. The specific types of technical advancements required for each additional AHS lane will depend on how the lanes are to be used, and is therefore somewhat unpredictable. Therefore, it is necessary that access to the AHS be managed to prevent congestion caused by over demand.

Some of the design and operational management requirements for the AHS must be:

- The volume of vehicles entering at each entry must be controlled to prevent more vehicles from entering than can be accommodated given the capacity of the downstream section.
- The volume of vehicles entering at each entry must be controlled to reserve sufficient capacity for downstream entrances to receive equitable service.
- The volume of vehicles exiting at each exit must be controlled to prevent back-up onto the AHS lane(s). This may require rejection or alternative routing of vehicles at upstream entrances that are bound for the congested exits.

A second major conclusion relevant to the effects of entry/exit on the overall AHS is that management of merging activities at entries and exits is necessary if the AHS is to operate efficiently at traffic flow rates higher than is possible on current freeways. This requirement applies particularly to merging when entering the AHS traffic stream, but will also be necessary when exiting onto freeway lanes during heavy traffic flow.

To achieve efficient merging of traffic streams at the AHS entries, it will be necessary to design into the entry/exit pair:

- An ability to detect and evaluate the sizes of available gaps in the established traffic stream of the target lane, or to create appropriate sized gaps, and
- An ability to coordinate the entering vehicle's release, acceleration and path (in later configurations) to safely intercept a known, preserved or created gap, and merge into it.

4.2.2 Relative Viability of Specific Entry/Exit Strategies and Configurations. The first major conclusion as to the viability of the various entry/exit strategies/configurations analyzed is that all are likely to be present somewhere in a nationally deployed AHS.

Overall conclusions concerning the entry/exit strategies/configurations are that:

- The most effective and safest of the entry/exit configurations are the surface street-to-AHS and the freeway-to-AHS dedicated separate entry/exit with simultaneous ramps (see Figure 1). These are the entry/exit strategies/configurations that are most amenable to positive control of entry/exit, management and coordination of merging, and that have the exit positioned just prior to the entry on both the AHS and manual lanes. These are moderately expensive strategies/configurations, and are most appropriate in urban environments where the AHS traffic flows will be the heaviest. These are the recommended AHS entry/exit configurations.

- The least effective strategies/configurations have AHS entry from and exit to contiguous manual freeway lanes, either on a continuous basis or only in designated zones. The entering and exiting vehicles cannot stop or slow significantly, their access between manual and AHS lanes cannot be effectively controlled, and their merging cannot be effectively managed or coordinated. These entry/exit strategies/configurations are the least expensive and have the highest potential for safety problems. However, at light-to-moderate traffic flows on the AHS and similarly light-to-moderate entry/exit volumes, these configurations may be adequate. These are the traffic conditions that may exist in rural and semi-rural areas that are not on major inter-city or cross-country routes. These are the locations where the more expensive, effective and safe entry/exits may not be affordable.

- Moderately effective entry/exit strategies/configurations are those that provide a transition lane between the freeway manual lanes and the AHS lane(s), either continuous or in designated entry/exit zones. If the transition lane is continuous, this is the most expensive configuration. If the transition lanes are limited to designated entry/exit zones, they are an inexpensive enhancement to the contiguous lane entry/exit configurations. These configurations are significantly safer than the contiguous lane entry/exit configurations.
  Entering and exiting vehicles may be allowed to continue in motion while manually searching for a merging gap in the target lane, or their speed and position may be controlled to coordinate with the arrival of a suitable merging gap. The former case places the configuration closer to the capabilities of the contiguous lanes, and the latter case allows and almost requires the transition lane to be configured as a designated separate entry/exit which is closer in capability to the best configurations.

- Barriers between the manual freeway and AHS lanes are a recommended safety feature in all entry/exit configurations where possible. Barriers have a negative effect on access and have little impact on effectiveness. The safety threat addressed by the barriers is strictly that of the manually controlled or out-of-control vehicle in the AHS lane(s), which is a real and legitimate hazard. Barriers do not, however, address the more significant safety hazard associated with conflicts while legitimately merging into the AHS or manual lanes.

A second conclusion with regard to the specific entry/exit strategies/configurations is that the design and operation of the AHS entries and exits external to the AHS itself will have a strong influence on the effective operation of the AHS itself. For the two most important categories of entry/exit strategies/configurations:

- The freeway-to-AHS entry/exit strategies/configurations cannot escape from their dependence on the freeway. If the freeway is heavily congested and performing poorly as a result, the AHS will also perform poorly.

- The surface street-to-AHS entry/exit strategies/configurations cannot escape their dependence on the surface streets. If the surface streets feeding the AHS entry or fed by the AHS exit are heavily congested, or the AHS entries and/or exits are poorly designed with inadequate capacity, the AHS will perform poorly.

4.2.3 Design Features, Parameters and Guidelines for Entry/Exit Strategies and Configurations. These conclusions are based on the assumption that the AHS will be tightly managed to allow only the traffic flows and entry/exit volumes that the AHS sections, entries and exits were designed to accommodate. The most important of the design conclusions are:

- For the recommended entry/exit configurations, a deceleration lane contiguous to the manual and AHS traffic lanes just prior to their exit points, and an acceleration lane contiguous to the manual and AHS traffic lanes just prior to their entry points are strongly recommended. The lengths of these lanes are designed as discussed on page 34.

- For the recommended entry/exit configurations, the entry/exit ramps and transition lanes (when merges are managed and coordinated) will only need to accommodate the queues that result from the probabilistic variations in the balance between entry/exit demand and queue service rates (availability of suitable merging gaps). Since the queuing analysis was not accomplished in this effort, the design equations for this queue length were not derived.

4.3 DISCUSSIONS OF INDICATIONS ("TENTATIVE CONCLUSIONS") AND THE CONDITIONS FOR SETTLING THE UNDERLYING UNCERTAINTIES

The most significant tentative conclusions drawn during this analysis were the numbers and characteristics of the projected Evolutionary Representative System Configurations (ERSCs). The uncertainties associated with the ERSCs will obviously be resolved with time and via the real evolution of the AHS. However, it is imperative that the prototype AHS be designed in a manner that allows each function and the implementing technology to evolve with minimum replacement of either vehicular or infrastructure capabilities and equipments. To make this happen, both the engineering and market aspects of the problem must be given careful consideration:

- Good system engineering practices and implementation technology selection must be applied in the initial stages of the AHS prototype development. Specific attention will be required to avoid functional architectures or implementing technologies that are either dead-end or limited in potential, and that cannot be modified without total replacement.

- A market dictated, incremental (evolutionary) development of the AHS is unavoidable- only those capabilities that both sets of customers (vehicle and infrastructure owner/operator) will pay for at a particular time and place can be implemented. Further, developers and manufacturers of equipment will only develop and manufacture those AHS equipments that they think can be sold at a profit. Vehicle purchasers will not pay for AHS vehicular equipment when insufficient infrastructure exits to provide commensurate benefit. Infrastructure owners/operators will not invest in the necessary AHS facilities and equipment until there are sufficient numbers of vehicles with the vehicular systems installed. This is a significant chicken-and-egg problem. The AHS system design must consider these market forces, with the architecture and projected evolutionary path selected wisely.

4.4 UNRESOLVED ISSUES AND RECOMMENDED RESEARCH TO RESOLVE THEM

There are several unresolved analysis issues associated with the ERSCs addressed herein. Further research is recommended in each of the following areas:

- System level models that would allow investigation of the AHS system-wide management recommendations made herein do not exist. Such a tool would be invaluable in designing, developing and testing the principles and algorithms necessary to implement AHS system-wide management.

- Mathematical models of the interacting traffic streams at the AHS entry/exits in the ERSCs are incomplete and those used herein are not well justified. Once the AHS prototype system configuration (one or a set) is accepted for development, accurate mathematical descriptions of the traffic streams involved would be very beneficial for direct use in design and for implementing the AHS system-level simulation model recommended above.

- Design principles, guidelines, and equations for the specific structures, capabilities and features for the AHS entry/exit configurations are incomplete. These cannot be completed until the mathematical descriptions of the interacting traffic streams are completed. The design tools are needed to design, simulate, and develop prototype entry/exit configurations.

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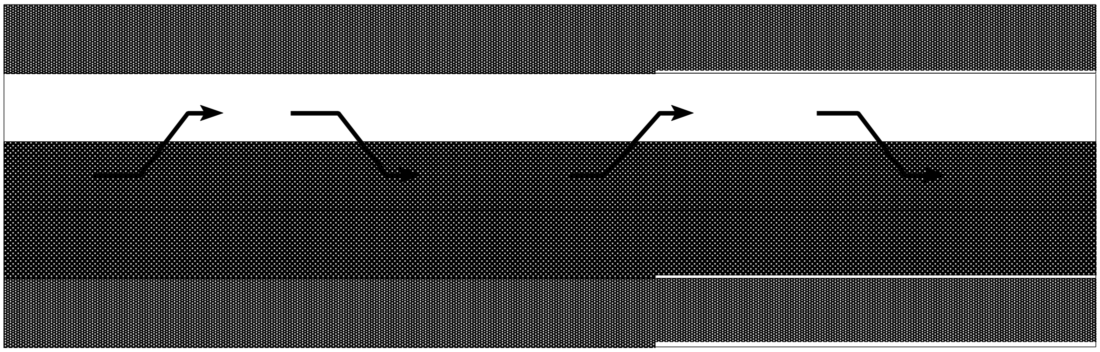
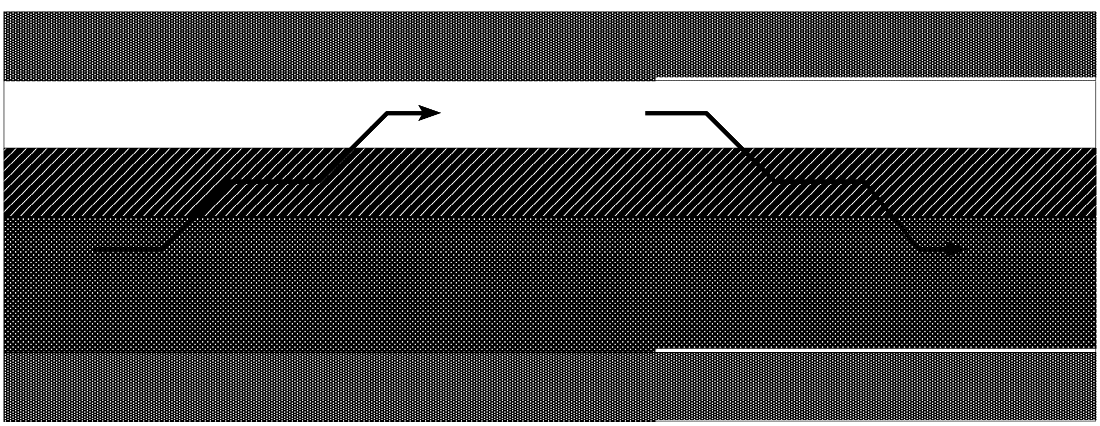
3. Highway Capacity Manual, Special Report 209, Transportation Research Board, Washington DC, March 1988.

APPENDIX A,
BASIC ENTRY/EXIT CONFIGURATION SCHEMATIC DIAGRAMS



Shoulder   Manual Lanes   AHS Lane

Figure 15. Continuous Entry/Exit, Contiguous Lanes Configuration



Shoulder   Manual Lanes   AHS Lane   Transition Lane

Figure 16. Continuous Entry/Exit, Transition Lane Configuration

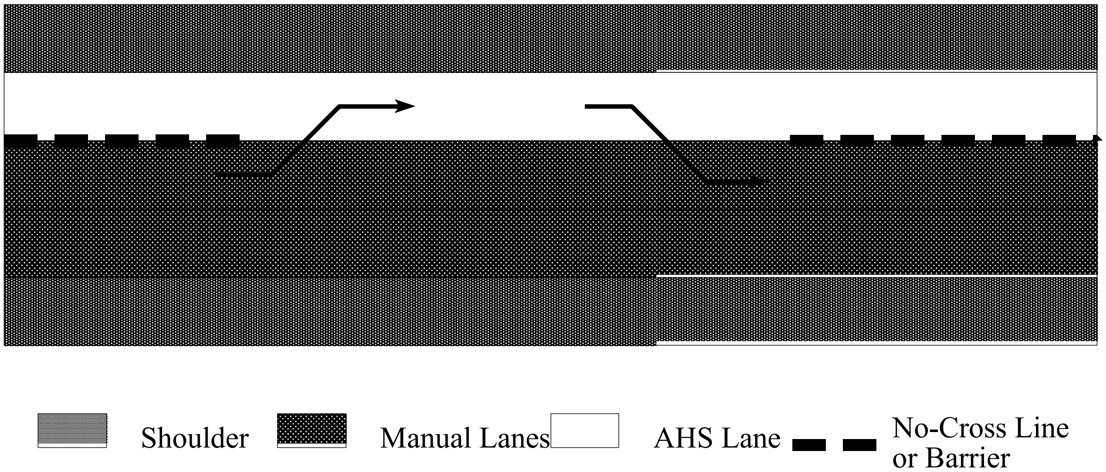


Figure 17. Designated Joint Entry/Exit, Contiguous Lanes Configuration
(With or Without Barriers)

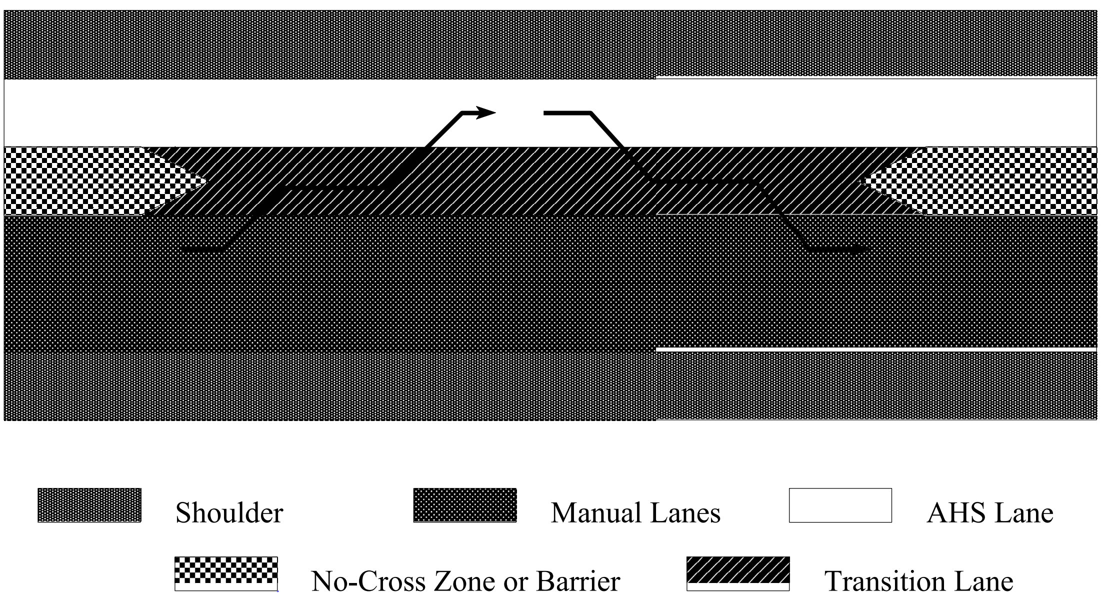


Figure 18. Designated Joint Entry/Exit, Transition Lane Configuration
(With or Without Barriers)

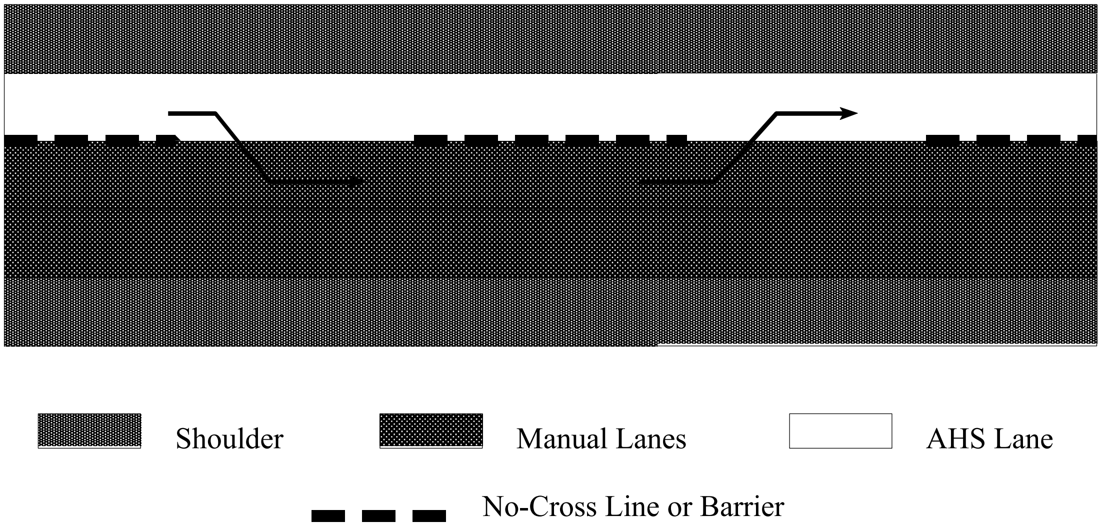


Figure 19. Designated Separate Entry/Exit, Contiguous Lanes Configuration
(With or Without Barrier)

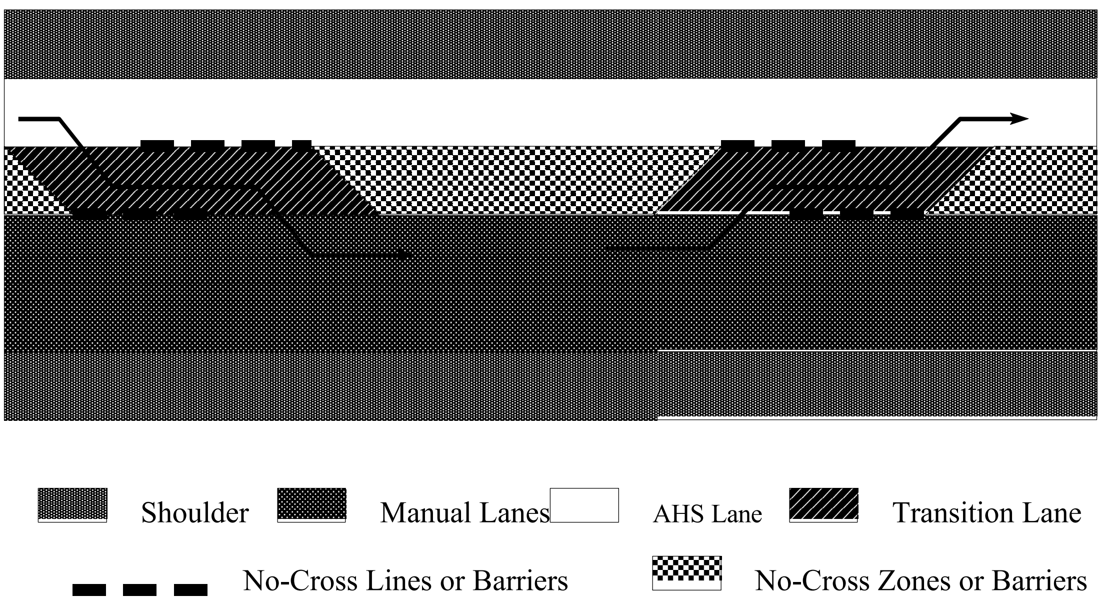


Figure 20. Designated Separate Entry/Exit, Transition Lane Configuration
(With or Without Barriers)

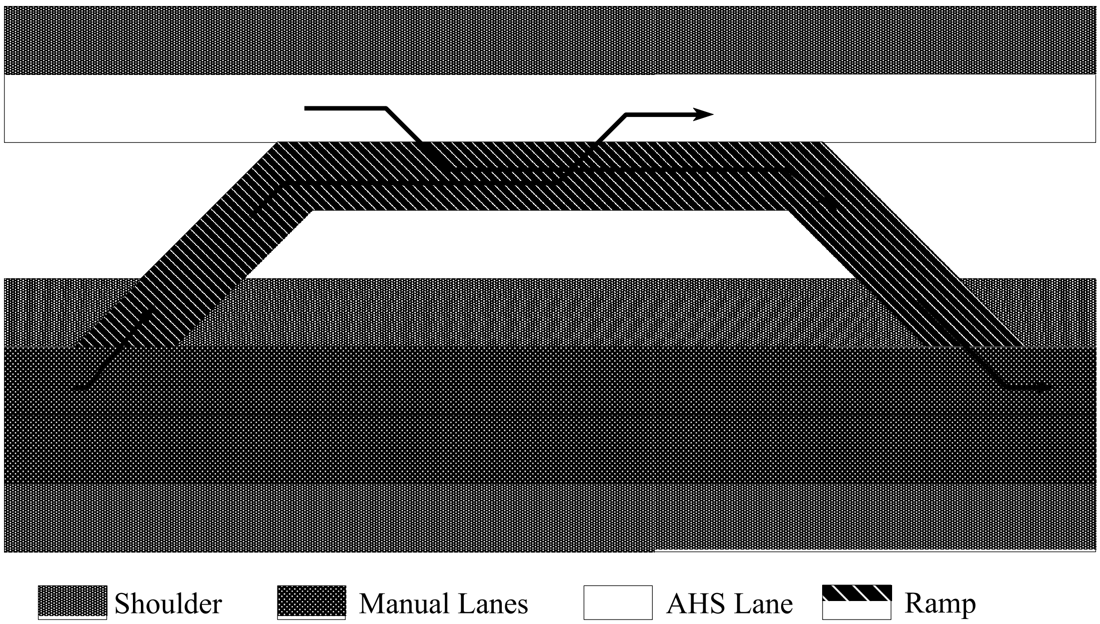


Figure 21. Designated Joint Entry/Exit, Ramp Configuration

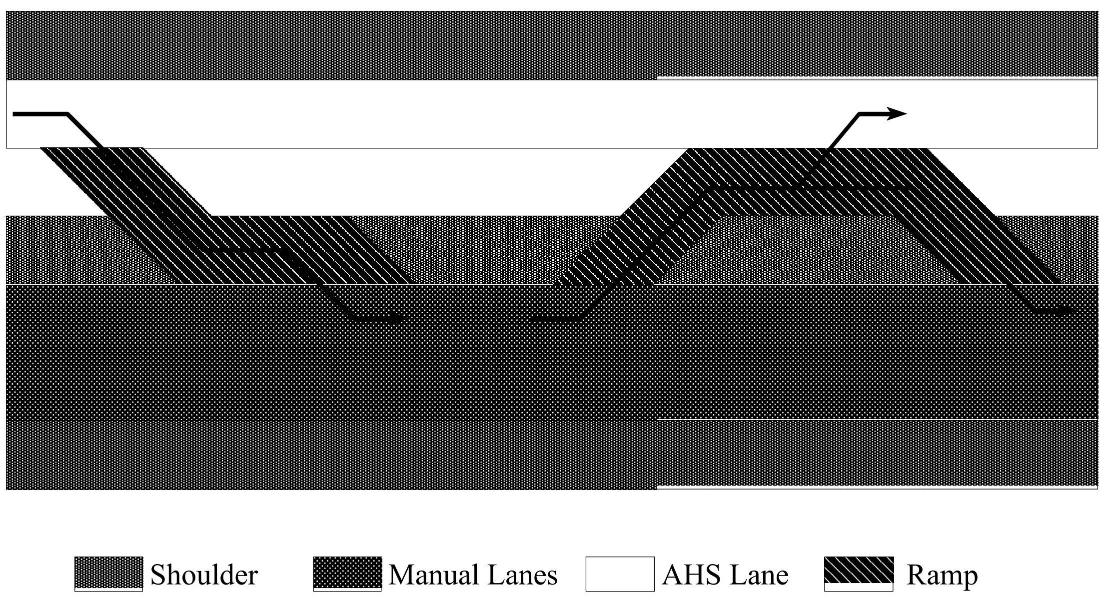


Figure 22. Designated Separate Entry/Exit, Ramp Configuration

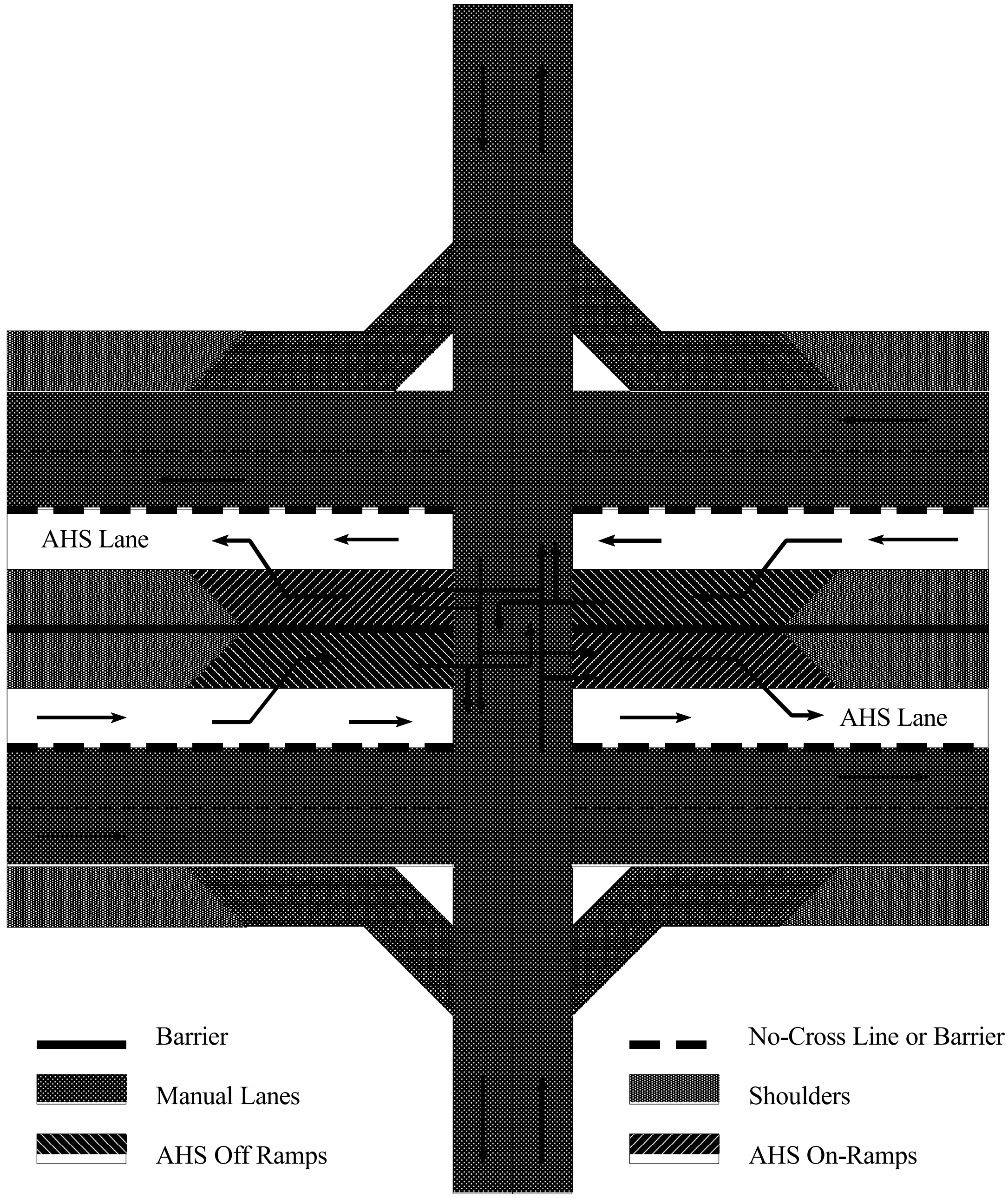


Figure 23. Surface Street to AHS Entry and Exit (With or Without Barrier)

APPENDIX B, MAPPING OF FUNCTIONAL FLOWS ONTO ERSCs

Table 9. ERSC Numbers 1-3 Functional Flow

Entry/Exit Configurations		Entry				Travel			Exit			
		Enter/Queue to Enter AHS	Check-In	Transition to Automatic	Merge Into AHS Stream	Traverse AHS Sections	Traverse Exit Nodes	Traverse Entry Nodes	Check-Out	Diverge From AHS Stream	Transition to Manual	Exit/Queue to Exit AHS
Free-way-to-AHS	Continuous	1	2	4	3	5	6	7	8	11	9	10
	Designated Joint	1	2	4	3	5	6	7	8	11	9	10
	Designated Separate	1	2	4	3	5	6	7	8	11	9	10
Surface Street - to - AHS		1	2	4	3	5	6	7	8	10	9	11
AHS-to-AHS	Continuous Lanes			(4)	3					1	(2)	
	Exit & Return	5	6	8	7				1	4/3	2	3/4
Shoulder - to - AHS			4	6	5				1	3	2	

Table 10. ERSC Numbers 4-5 Functional Flow												
Entry/Exit Configurations		Entry				Travel			Exit			
		Enter/Queue to Enter AHS	Check-In	Transition to Automatic	Merge Into AHS Stream	Traverse AHS Sections	Traverse Exit Nodes	Traverse Entry Nodes	Check-Out	Diverge From AHS Stream	Transition to Manual	Exit/Queue to Exit AHS
Freeway- to - AHS	Continuous	1	2	3	4	5	6	7	8	10	11	9
	Designated Joint	1	2	3	4	5	6	7	8	10	11	9
	Designated	1	2	3	4	5	6	7	8	10	11	9
Surface Street - to - AHS		1	2	3	4	5	6	7	8	9	10	11
AHS- to- AHS	Continuous Lanes				2					1		
	Exit & Return	5	6	7	8				1	3/2	4/3	2/4
Shoulder - to - AHS			4	5	6				1	2/3	3/2	

APPENDIX C, DETAILED QUALITATIVE ANALYSIS RESULTS FOR CONTINUOUS ENTRY/EXIT, CONTIGUOUS LANES - ALL ERSCs

Table 11. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Continuous Entry/Exit ,Contiguous Lanes - ERSCs 1 & 2

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap	Rear-end Collision Possibilities	No Constraints Added	None	No Constraints Added
Check-In	Minimum Required (Probably Self-Test)	Cannot Control Access	No Constraints Added	None	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment	Conflicts Due to Speed Differential, Exiting Vehicles & Gap Availability	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Lane Traffic Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	None	No Constraints Added

Table 11. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Continuous Entry/Exit ,Contiguous Lanes - ERSCs 1 & 2					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles	Conflicts With Weaving Vehicles Due to Gap Availability	No Constraints Added	None	No Constraints Added
Check-Out	None Required	None	No Constraints Added	None	No Constraints Added
Transition to Manual	Delays to AHS Lane Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane	Rear-end Collision Possibilities	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream Due to Re-establishing Headways	Conflicts Due to Speed Differential, Entering Vehicles & Gap Availability	No Constraints Added	None	No Constraints Added

Table 12. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, Contiguous Lanes - ERSC 3					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap	Rear-end Collision Possibilities	No Constraints Added	Sensors & C^3 for Controlling Access During Saturated Conditions	No Constraints Added
Check-In	Must Be Done at Highway Speeds	Cannot Deny Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment	Speed Differential & Weaving Conflicts Due to Gap Availability	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Lane Traffic Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	Possibly, Sensors & C^3 to Detect/Warn of Manually Controlled Vehicles	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles	Weaving Conflicts Due to Gap Availability	No Constraints Added	None	No Constraints Added

Table 12. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, Contiguous Lanes - ERSC 3

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors/Devices, C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Transition to Manual	Delays to AHS Lane Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane	Rear-end Collision Possibilities	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream	Conflicts Due to Speed Differential, Weaving & Gap Availability	No Constraints Added	None	No Constraints Added

Table 13. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, Contiguous Lanes - ERSCs 4 & 5					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap	Rear-end Collision Possibilities	No Constraints Added	Sensors & C^3 for Controlling Access During Saturated Conditions	No Constraints Added
Check-In	Must Be Done at Highway Speeds	Cannot Deny Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Transition to Automatic	Delays to AHS Lane Traffic Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	Possibly, Sensors & C^3 to Detect/Warn of Manually Controlled Vehicles	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment	Speed Differential & Weaving Conflicts Due to Gap Availability	No Constraints Added	Sensors & C^3 for Managing AHS Gaps and Merges All Along Lane Boundary.	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	Sensors & C^3 for Detecting Gaps and Coordinating Emergency Entry/Exit All Along Lane Boundary.	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles	Weaving Conflicts Due to Gap Availability	No Constraints Added	Sensors & C^3 for Managing/Detecting Gaps & Managing/Coordinating Merges/Diverges	No Constraints Added

Table 13. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, Contiguous Lanes - ERSCs 4 & 5

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors & C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane	Rear-end Collision Possibilities	No Constraints Added	Sensors & C^3 for Controlling Exiting During Saturated Conditions	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream	Conflicts Due to Speed Differential, Weaving & Gap Availability	No Constraints Added	Sensor & C^3 for Detecting Manual Lane Gaps and Coordinating Diverges All Along Lane Boundary.	No Constraints Added
Transition to Manual	None	Vehicles That Will Not Transition	No Constraints Added	Sensors & C^3 and for Vehicles that Fail To Transition (Storage Assumed on Shoulder)	No Constraints Added

APPENDIX D, DETAILED QUALITATIVE ANALYSIS RESULTS FOR CONTINUOUS ENTRY/EXIT, WITH TRANSITION LANE - ALL ERSC

Table 14. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Continuous Entry/Exit ,With Transition Lane - ERSCs 1 & 2

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream, Some Delay to Entering Vehicle Due to Exiting Vehicles	Weave Conflicts With Exiting Vehicles	No Constraints Added	Additional Lane	No Constraints Added
Check-In	Minimum Required (Probably Self-Test)	Cannot Control Access	No Constraints Added	None	No Constraints Added
Queue for Entry into AHS	Delays while Finding Acceptable Gap	Merge Conflicts With Exiting Vehicles	No Constraints Added	None	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Headways	Conflicts Due to Gap Availability	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added

Table 14. Qualitative Analysis Factors (Problems or Design Challenges):
Freeway-to-AHS, Continuous Entry/Exit ,With Transition Lane - ERSCs 1 & 2

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles	Conflicts With Weaving Vehicles Due to Gap Availability	No Constraints Added	None	No Constraints Added
Check-Out	None Required	None	No Constraints Added	None	No Constraints Added
Transition to Manual	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream Into Transition	Minimal Delays to AHS Stream	Weave Conflict With Entering Vehicles	No Constraints Added	Additional Lane	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap	Merge Conflicts With Entering Vehicles	No Constraints Added	None	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Headways	Conflicts Due to Gap Availability	No Constraints Added	None	No Constraints Added

Table 15. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, With Transition Lane - ERSC 3					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream	Weave Conflicts With Exiting Vehicles	No Constraints Added	Additional Lane. Sensors & C^3 for Controlling Access During Saturated Conditions.	No Constraints Added
Check-In	Must be at Highway Speeds	Cannot Control Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Queue for Entry into AHS	Delays while Finding Acceptable Gap	Merge Conflicts With Exiting Vehicles	No Constraints Added	Sensors & C^3 for Detecting AHS Lane Gaps	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Headways	Conflicts While Entering Gap Due to Size, Speed, etc.	No Constraints Added	Sensors & C^3 for Coordinating Merges Into AHS Lane	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	None	No Constraints Added

Table 15. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, With Transition Lane - ERSC 3

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles	Conflicts With Weaving Vehicles Due to Gap Availability	No Constraints Added	Sensors & C^3 for Coordinating Merges Into AHS Lane	No Constraints Added
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors/Devices, C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Transition to Manual	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream Into Transition Lane	Minimal Delays to AHS Stream	Weave Conflict With Entering Vehicles	No Constraints Added	Additional Lane	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap	Merge Conflicts With Entering Vehicles	No Constraints Added	None	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Headways	Conflicts While Entering Gap Due to Size, Speed, etc.	No Constraints Added	Sensors & C^3 to Control Exits At Saturated Locations	No Constraints Added

Table 16. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, With Transition Lane - ERSCs 4 & 5					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream	Conflicts With Weaving Vehicles. Mixed Manual & Automatic Vehicles	No Constraints Added	Sensors & C^3 for Controlling Access During Saturated Conditions. Additional lane	No Constraints Added
Check-In	Must be at Highway Speeds	Cannot Control Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Queue for Entry into AHS	Delays While Waiting for Gap. Delays Due to Exiting Vehicles Slowing.	Conflicts With Exiting Vehicles. Mixed Manual & Automatic Vehicles	No Constraints Added	Sensors & C^3 for Detecting/Creating Gaps	No Constraints Added
Transition to Automatic	None	Vehicles that Fail to Transition Must Exit to Manual Lane	No Constraints Added	Sensors & C^3 for Detecting & Warning of Manually Controlled Vehicles	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Headways	Conflicts While Entering Gap Due to Size, Speed, etc.	No Constraints Added	Sensors & C^3 for Managing Merges	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	Sensors & C^3 for Managing Emergency Entry/Exit	No Constraints Added

Table 16. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Continuous Entry/Exit, With Transition Lane - ERSCs 4 & 5

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles	Conflicts With Weaving Vehicles Due to Gap Availability	No Constraints Added	Sensors & C^3 for Managing/Detecting Gaps & Managing/Coordinating Merges/Diverges	No Constraints Added
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors/Devices, C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Diverge from AHS Stream Into Transition Lane	Minimal Delays to AHS Stream	Conflicts With Weaving Vehicles. Mixed Manual & Automatic Vehicles	No Constraints Added	Additional Lane. Sensor & C^3 for Detecting Transition Lane Gaps, & Coordinating Diverges.	No Constraints Added
Transition to Manual	Delays to Vehicles Accelerating to Enter AHS	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap	Merge Conflicts With Entering Vehicles	No Constraints Added	Sensor & C^3 for Detecting Manual Lane Gaps	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Headways	Conflicts While Entering Gap Due to Size, Speed, etc.	No Constraints Added	Sensor & C^3 for Coordinating Diverges and Controlling Exits at Saturated Locations	No Constraints Added

APPENDIX E, DETAILED QUALITATIVE ANALYSIS RESULTS FOR DESIGNATED JOINT ENTRY/EXIT, CONTIGUOUS LANES - ALL ERSCs

Table 17. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Designated Joint Entry/Exit, Contiguous Lanes - ERSCs 1 & 2

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap In AHS Lane[2]	Rear-end Collision Possibilities[2]	No Constraints Added	None	No Constraints Added
Check-In	Minimum Required (Probably Self-Test)	Cannot Control Access	No Constraints Added	None	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment[2]	Conflicts Due to Speed Differential, Exiting Vehicles & Gap Availability[2]	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Lane Traffic Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicle[3]	No Constraints Added	None	No Constraints Added

Table 17. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Designated Joint Entry/Exit, Contiguous Lanes - ERSCs 1 & 2					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Weaving Vehicles Due to Gap Availability[2]	No Constraints Added	None	No Constraints Added
Check-Out	None Required	None	No Constraints Added	None	No Constraints Added
Transition to Manual	Delays to AHS Lane Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane[2]	Rear-end Collision Possibilities	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream Due to Re-establishing Headways[2]	Conflicts Due to Speed Differential, Entering Vehicles & Gap Availability[2]	No Constraints Added	None	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

Table 18. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Joint Entry/Exit, Contiguous Lanes - ERSC 3

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap in AHS Stream[2]	Rear-end Collision Possibilities[2]	No Constraints Added	Sensors & C^3 for Controlling Access During Saturated Conditions	No Constraints Added
Check-In	Must Be Done at Highway Speeds	Cannot Deny Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment[2]	Speed Differential & Weaving Conflicts Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Detecting AHS Gaps and Coordinating Merges	No Constraints Added
Transition to Automatic	Delays to AHS Lane Traffic Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	Possibly, Sensors & C^3 to Detect/Warn of Manually Controlled Vehicles	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Weaving Conflicts Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Detecting AHS Gaps and Coordinating Merges	No Constraints Added

Table 18. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Joint Entry/Exit, Contiguous Lanes - ERSC 3					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors/Devices, C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Transition to Manual	Delays to AHS Lane Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane[2]	Rear-end Collision Possibilities	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream[2]	Conflicts Due to Speed Differential, Weaving & Gap Availability[2]	No Constraints Added	None	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier <u>or</u> no shoulder limits Operational Access by about 50%. Presence of a barrier <u>and</u> no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

Table 19. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSCs 4 & 5					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap[2]	Rear-end Collision Possibilities[2]	No Constraints Added	Sensors & C^3 for Controlling Access During Saturated Conditions	No Constraints Added
Check-In	Must Be Done at Highway Speeds	Cannot Deny Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Transition to Automatic	None	Mixed Manual & Automatic Vehicles In Transition Lane[2]	No Constraints Added	Possibly, Sensors & C^3 to Detect/Warn of Manually Controlled Vehicles	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment[2]	Speed Differential & Weaving Conflicts Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Managing AHS Gaps and Merges All Along Lane Boundary.	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	Sensors & C^3 for Detecting Gaps and Coordinating Emergency Entry/Exit All Along Lane Boundary.	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Weaving Conflicts Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Managing/Detecting Gaps & Managing/Coordinating Merges/Diverges	No Constraints Added

Table 19. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSCs 4 & 5					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors & C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane[2]	Rear-end Collision Possibilities	No Constraints Added	Sensors & C^3 for Controlling Exiting During Saturated Conditions	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream	Conflicts Due to Speed Differential, Weaving & Gap Availability	No Constraints Added	Sensor & C^3 for Detecting Manual Lane Gaps and Coordinating Diverges All Along Lane Boundary.	No Constraints Added
Transition to Manual	None	Vehicles That Will Not Transition. Mixed Manual & Automatic Vehicles in Transition Lane[2]	No Constraints Added	Sensors & C^3 and for Vehicles that Fail To Transition (Storage Assumed on Shoulder)	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

APPENDIX F, DETAILED QUALITATIVE ANALYSIS RESULTS FOR DESIGNATED JOINT ENTRY/EXIT, WITH TRANSITION LANE - ALL ERSCs

Table 20. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Joint Entry/Exit ,With Transition Lane - ERSCs 1 & 2

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream	Weave Conflicts With Exiting Vehicles[2]	No Constraints Added	Length of Transition Lane	No Constraints Added
Check-In	Minimum Required (Probably Self-Test)	Cannot Control Access	No Constraints Added	None	No Constraints Added
Queue for Entry into AHS	Delays while Finding Acceptable Gap[2]	Weave Conflicts With Exiting Vehicles[2]	No Constraints Added	None	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Headways[2]	Conflicts Due to Gap Availability In AHS Lane[2]	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Weaving Vehicles Due to Gap Availability[2]	No Constraints Added	None	No Constraints Added

Table 20. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Joint Entry/Exit ,With Transition Lane - ERSCs 1 & 2					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C[3] Costs	Evolutionary Compatibility
Check-Out	None Required	None	No Constraints Added	None	No Constraints Added
Transition to Manual	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream Into Transition	Minimal Delays to AHS Stream	Weave Conflict With Entering Vehicles[2]	No Constraints Added	Length of Transition Lane	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap[2]	Weave Conflicts With Entering Vehicles[2]	No Constraints Added	None	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Headways[2]	Conflicts Due to Gap Availability, Size, Etc.[2]	No Constraints Added	None	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

Table 21. Qualitative Analysis Factors (Problems or Design Challenges):
Freeway-AHS, Designated Joint Entry/Exit, With Transition Lane - ERSC 3

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream	Weave Conflicts. Mixed Manual & Automatic Vehicles in Transition Lane	No Constraints Added	Additional Lane. Sensors & C^3 for Controlling Access During Saturated Conditions.	No Constraints Added
Check-In	Must be at Highway Speeds	Cannot Control Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Queue for Entry into AHS	Delays while Finding Acceptable Gap[2]	Weave Conflicts With Exiting Vehicles[2]	No Constraints Added	Sensors & C^3 for Detecting AHS Lane Gaps	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Headways[2]	Conflicts With AHS Traffic.	No Constraints Added	Sensors & C^3 for Coordinating Merges Into AHS Lane	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Weaving Vehicles Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Coordinating Merges	No Constraints Added

Table 21. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Joint Entry/Exit, With Transition Lane - ERSC 3					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out[2]	Vehicles Without Capable Drivers[2]	No Constraints Added	Sensors/Devices, C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Transition to Manual	Delays to AHS Stream Due to Manual Operation of Vehicle	Mixed Manual & Automatic Vehicles in Transition lane	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream Into Transition	Minimal Delays to AHS Stream	Weave Conflict With Entering Vehicles	No Constraints Added	Length of Transition Lane. Sensors & C^3 for Coordinating Diverges	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap[2]	Merge Conflicts With Entering Vehicles[2]	No Constraints Added	None	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Headways[2]	Conflicts Merging Into Gap Due to Size, Speed, etc.[2]	No Constraints Added	Sensors & C^3 for Coordinating Merges & to Control Exits At Saturated Locations	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier <u>or</u> no shoulder limits Operational Access by about 50%. Presence of a barrier <u>and</u> no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

Table 22. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Joint Entry/Exit, With Transition Lane - ERSCs 4 & 5					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream	Conflicts With Weaving Vehicles. Mixed Manual & Automatic Vehicles[2]	No Constraints Added	Sensors & C^3 for Controlling Access During Saturated Conditions.	No Constraints Added
Check-In	Must be at Highway Speeds	Cannot Control Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Queue for Entry into AHS	Delays While Waiting for Gap. Delays Due to Exiting Vehicles Slowing Down[2].	Conflicts With Exiting Vehicles[2]	No Constraints Added	Lane Length for Moving Queue. Sensors & C^3 for Detecting/Creating Gaps	No Constraints Added
Transition to Automatic	Delays Suffered if Transition Not at Full Speed	Vehicles that Fail to Transition Must Exit	No Constraints Added	Lane Length for Standing Queue. Sensors & C^3 for Detecting &Warning of Manual Vehicles	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Headways[2]	Conflicts Merging Into Gap Due to Size, Speed, etc.[2]	No Constraints Added	Acceleration Lane Length (If Standing Queue). Sensors & C^3 for Managing Merges.	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	Sensors & C^3 for Managing Emergency Entry/Exit	No Constraints Added

Table 22. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Joint Entry/Exit, With Transition Lane - ERSCs 4 & 5					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Weaving Vehicles[2]	No Constraints Added	Sensors & C^3 for Managing/Coordinating Merges/Diverges	No Constraints Added
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors/Devices, C^3 and Storage for Vehicles that Fail Check-Out	No Constraints Added
Diverge from AHS Stream Into Transition Lane	Delays to AHS Stream Due to Entry/Exit Length and Concentration of Vehicles[2]	Conflicts With Entering Vehicles. Mixed Manual & Automatic Vehicles[2]	No Constraints Added	Length of Transition Lane. Sensor & C^3 for Managing Diverges.	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap	Merge Conflicts With Entering Vehicles	No Constraints Added	Sensor & C^3 for Detecting Manual Lane Gaps	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Headways[2]	Conflicts Due to Limited Exit length & Gap Availability.[2]	No Constraints Added	Sensor & C^3 for Coordinating Merges and Controlling Exits at Saturated Locations	No Constraints Added
Transition to Manual	Delays Vehicles Accelerating to Enter AHS[2]	Vehicles That Will Not Transition	No Constraints Added	Sensors/Devices, C^3 and Storage for Vehicles that Fail to Transition.	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

APPENDIX G, DETAILED QUALITATIVE ANALYSIS RESULTS FOR DESIGNATED SEPARATE ENTRY/EXIT, CONTIGUOUS LANES - ALL ERSCs

Table 23. Qualitative Analysis Factors (Problems or Design Challenges):
Freeway-to-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSCs 1 & 2[4]

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane While Searching for Gap In AHS Lane[2]	Rear-end Collision Possibilities[2]	No Constraints Added	Sensors & C^3 for Controlling Access During Congestion on AHS.	No Constraints Added
Check-In	Minimum Required (Probably Self-Test)	Cannot Control Access	No Constraints Added	None	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment[2]	Conflicts Due to Limited Entry Length, Speed Differential & Gap	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Lane Traffic Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicle[3]	No Constraints Added	None	No Constraints Added

Table 23. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSCs 1 & 2[4]

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering & Exiting Vehicles Due to Gap Availability[2]	No Constraints Added	None	No Constraints Added
Check-Out	None Required	None	No Constraints Added	None	No Constraints Added
Transition to Manual	Delays to AHS Lane Due to Manual Operation of Vehicle	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane[2]	Rear-end Collision Possibilities	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream Due to Re-establishing Headways[2]	Conflicts Due to Limited Exit Length, Speed Differential, &Gap Availability[2]	No Constraints Added	Sensors & C^3 for Controlling Exits at Congested Locations.	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.
4. A SYSTEM LEVEL FACTOR - EITHER THE AHS OR MANUAL LANES WILL CARRY EXTRA TRAFFIC FLOW BETWEEN THE TWO PARTS OF AN ENTRY/EXIT PAIR. THAT EXTRA FLOW IS THE DIFFERENCE BETWEEN ENTERING AND EXITING TRAFFIC OR VICE-VERSA.

Table 24. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSC 3 [4]					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap in AHS Stream[2]	Rear-end Collision Possibilities[2]	No Constraints Added	Sensors & C^3 for Controlling Access During Congested Conditions	No Constraints Added
Check-In	Must Be Done at Highway Speeds	Difficult to Deny Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment[2]	Mixed Manual & Automatic Traffic in AHS Lane. Conflicts With AHS Traffic.	No Constraints Added	Sensors & C^3 for Detecting AHS Gaps and Coordinating Merges	No Constraints Added
Transition to Automatic	Delays to AHS Lane Traffic Due to Manual Operation of Vehicle	Must Transition at Speed.[2] Vehicles that Fail to Transition Must Exit	No Constraints Added	Possibly, Sensors & C^3 to Detect/Warn of Manually Controlled Vehicles	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering and Exiting Vehicles Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Detecting AHS Gaps and Coordinating Merges	No Constraints Added

Table 24. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSC 3 [4]					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out[2]	Vehicles Without Capable Drivers[2]	No Constraints Added	Sensors/Devices, C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Transition to Manual	Delays to AHS Lane Due to Manual Operation of Vehicle	Mixed Manual & Automatic Vehicles in AHS Lane[2]	No Constraints Added	None	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane[2]	Rear-end Collision Possibilities	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane While Re-Establishing Headways[2]	Conflicts Due to Limited Exit Length, Speed Differential & Gap Availability[2]	No Constraints Added	Sensors & C^3 for Controlling Exits At Congested Locations & for Coordinating Merges.	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.
4. A SYSTEM LEVEL FACTOR - EITHER THE AHS OR MANUAL LANES WILL CARRY EXTRA TRAFFIC FLOW BETWEEN THE TWO PARTS OF AN ENTRY/EXIT PAIR. THAT EXTRA FLOW IS THE DIFFERENCE BETWEEN ENTERING AND EXITING TRAFFIC OR VICE-VERSA.

Table 25. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSCs 4 & 5 [4]					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter/Queue to Enter AHS	Delays to Manual Lane Traffic While Searching for Gap[2]	Rear-end Collision Possibilities[2]	No Constraints Added	Sensors & C^3 for Controlling Access During Saturated Conditions	No Constraints Added
Check-In	Must Be Done at Highway Speeds	Cannot Deny Access	No Constraints Added	Sensors & C^3 for Check-In	No Constraints Added
Transition to Automatic	None	Must Transition at Speed. Mixed Manual & Automatic Vehicles In Manual	No Constraints Added	Possibly, Sensors & C^3 to Detect/Warn of Manually Controlled Vehicles	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Speed Differential, Headway Re-establishment[2]	Speed Differential & Weaving Conflicts Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Managing AHS Gaps and Merges All Along Lane Boundary.	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles	No Constraints Added	Sensors & C^3 for Detecting Gaps and Coordinating Emergency Entry/Exit All Along Shoulder.	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Weaving Conflicts Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Managing/Detecting Gaps & Managing/Coordinating Merges/Diverges	No Constraints Added

Table 25. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, Contiguous Lanes - ERSCs 4 & 5 [4]					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers that Fail Check-Out	Vehicles Without Capable Drivers	No Constraints Added	Sensors & C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Exit/Queue to Exit AHS	Delays to AHS Stream While Locating Gap in Manual Lane[2]	Rear-end Collision Possibilities	No Constraints Added	Sensors & C^3 for Controlling Exiting During Saturated Conditions	No Constraints Added
Diverge from AHS Stream	Delays to Manual Lane Stream	Conflicts Due to Speed Differential, & Gap Availability	No Constraints Added	Sensor & C^3 for Detecting Manual Lane Gaps and Managing Diverges.	No Constraints Added
Transition to Manual	None	Must transition at Speed. Mixed Manual & Automatic Vehicles in Manual Lane[2]	No Constraints Added	Sensors & C^3 and for Vehicles that Fail To Transition (Storage Assumed on Shoulder)	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier <u>or</u> no shoulder limits Operational Access by about 50%. Presence of a barrier <u>and</u> no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.
4. A SYSTEM LEVEL FACTOR - EITHER THE AHS OR MANUAL LANES WILL CARRY EXTRA TRAFFIC FLOW BETWEEN THE TWO PARTS OF AN ENTRY/EXIT PAIR. THAT EXTRA FLOW IS THE DIFFERENCE BETWEEN ENTERING AND EXITING TRAFFIC OR VICE-VERSA.

APPENDIX H, DETAILED QUALITATIVE ANALYSIS RESULTS FOR DESIGNATED SEPARATE ENTRY/EXIT, WITH TRANSITION LANE - ALL ERSCs

Table 26. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Separate Entry/Exit ,With Transition Lane Or Ramps- ERSCs 1 & 2 [4]

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	None	Conflict Between Entering Vehicles Due to Sequence of Entry	No Constraints Added	Length of Transition Lane. Sensors & C^3 for Controlling Access During Congestion on AHS.	No Constraints Added
Check- In	Minimum Required (Probably Self-Test)	None	No Added Constraints	None	No Added Constraints
Queue for Entry into AHS	Delays to Entering Vehicle While Finding Acceptable Gap[2]	Back-up Onto Freeway During Congestion[2]	No Added Constraints	Lane Length for Queue. Sensors & C^3 for Controlling Access During Congestion at Entry.	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Safe Headways[2]	Conflicts Due to Gap Availability In AHS Lane[2]	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering & Exiting Vehicles[2]	No Constraints Added	None	No Constraints Added

Table 26. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-to-AHS, Separate Entry/Exit ,With Transition Lane Or Ramps- ERSCs 1 & 2 [4]					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	None Required	None	No Added Constraints	None	No Added Constraints
Transition to Manual	Delays to AHS Stream Due to Manual Vehicle	Vehicles That Will Not Transition	No Constraints	None	No Added Constraints
Diverge from AHS Stream Into Transition Lane	Minimal Delays to AHS Stream	Conflicts Between Exiting Vehicles Due to Slowing & Sequence of Exit	No Constraints Added	Length of Transition Lane for Decelerating. Sensors & C^3 for Controlling Exits At Congested Locations	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap[2]	Back-up Onto AHS if Exit is Congested	No Constraints Added	Length of Lane for Queue.	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Safe Headways[2]	Conflicts Due to Limited Exit Length, Gap Availability[2]	No Constraints Added	None	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.
4. A SYSTEM LEVEL FACTOR - EITHER THE AHS OR MANUAL LANES WILL CARRY EXTRA TRAFFIC FLOW BETWEEN THE TWO PARTS OF AN ENTRY/EXIT PAIR. THAT EXTRA FLOW IS THE DIFFERENCE BETWEEN ENTERING AND EXITING TRAFFIC OR VICE-VERSA. THIS PROBLEM CAN BE ELIMINATED WITH SIMULTANEOUS RAMPS WITH ONE A FLYOVER OF THE OTHER. SEE FIGURE A-XX.

Table 27. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, With Transition Lane or Ramps - ERSC 3 [4]

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream	Conflict Between Entering Vehicles Due to Sequence of Entry.	No Constraints Added	Length of transition Lane. Sensors & C^3 for Controlling Access.	No Constraints Added
Check- In	Dealys If Not Done at Highway Speeds	None	No Constraints Added	Lane Length,Sensors & C^3 for Check-In. Exit Path for Failed Vehicles.	No Constraints Added
Queue for Entry into AHS	Delays while Finding Acceptable Gap[2]	Back-up Onto Manual Lanes During Congestion	No Constraints Added	Sensors & C^3 for Detecting AHS Lane Gaps.	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Headways[2]	Conflicts With AHS Traffic Due to Gap Size, Speed, etc.[2]	No Constraints Added	Sensors & C^3 for Coordinating Merges Into AHS Lane.	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering & Exiting Vehicles[2]	No Constraints Added	Sensors & C^3 for Coordinating Merges Into AHS Lane	No Constraints Added

Table 27. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, With Transition Lane or Ramps - ERSC 3 [4]

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out[2]	Vehicles Without Capable Drivers[2]	No Constraints Added	Sensors/Devices, C^3 and for Vehicles that Fail Check-Out (Storage Assumed on Shoulder)	No Constraints Added
Transition to Manual	Delays to AHS Stream Due to Manual Vehicles	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Diverge from AHS Into Transition Lane	Minor Delay to AHS Stream	None	No Constraints Added	Length of Transition Lane. Sensors & C^3 to Control Exits At Saturated Locations	No Constraints Added
Queue for Entry Into Manual Lanes	Delays to Exiting Vehicle While Finding Acceptable Manual LaneGap[2]	Back-up Into AHS Lane if Exit Congested[2]	No Constraints Added	Length of Lane for Queue.	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Headways[2]	Conflicts Due to Limited Exit Length &Gap Availability[2]	No Constraints Added	Sensors & C^3 to Coordinate Merges	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.
4. A SYSTEM LEVEL FACTOR - EITHER THE AHS OR MANUAL LANES WILL CARRY EXTRA TRAFFIC FLOW BETWEEN THE TWO PARTS OF AN ENTRY/EXIT PAIR. THAT EXTRA FLOW IS THE DIFFERENCE BETWEEN ENTERING AND EXITING TRAFFIC OR VICE-VERSA. THIS PROBLEM CAN BE ELIMINATED WITH SIMULTANEOUS RAMPS WITH ONE A FLYOVER. SEE FIGURE A-XX.

Table 28. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, With Transition Lane or Ramps- ERSCs 4 & 5 [4]					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter Transition Lane	Minor Delay to Manual Stream	Conflict Between Entering Vehicles Due to Sequence of Entry.	No Constraints Added	Sensors & C^3 for Controlling Access During Congested AHS Conditions.	No Constraints Added
Check- In	Delays If Not Done at Speed	None	No Constraints Added	Lane Length, Sensors & C^3 for Check-In. Exit Path for Failed Vehicles	No Constraints Added
Queue for Entry into AHS	Delays While Waiting for Gap In AHS Traffic[2]	Back-up Onto Manual Lane During Congestion On AHS[2]	No Constraints Added	Lane Length for Queue. Sensors & C^3 for Controlling Access During Entry Congestion	No Constraints Added
Transition to Automatic	Delays Suffered if Transition Not at Full Speed	Vehicles that Fail to Transition Must Exit	No Constraints Added	Sensors & C^3 for Detecting &Warning of Manual Vehicles	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Safe Headways[2]	Conflicts With AHS Traffic Due to Gap Availability[2]	No Constraints Added	Acceleration Lane Length. Sensors & C^3 for Managing Merges.	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	Sensors & C^3 for Managing Emergency Entry/Exit	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering & Exiting Vehicles[2]	No Constraints Added	Sensors & C^3 for Managing/Coordinating Merges/Diverges	No Constraints Added

Table 28. Qualitative Analysis Factors (Problems or Design Challenges): Freeway-AHS, Designated Separate Entry/Exit, With Transition Lane or Ramps- ERSCs 4 & 5 [4]					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out[2]	Vehicles Without Capable Drivers[2]	No Constraints Added	Sensors, C^3 and Storage for Vehicles that Fail Check-Out	No Constraints Added
Diverge from AHS Stream Into Transition Lane	Delays to AHS Stream Due to Entry/Exit Length and Concentration of Vehicles[2]	None	No Constraints Added	Lane Length for Decelerating. Sensor & C^3 for Controlling Exits at Congested Locations	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap	Back-up Onto AHS If Exit Is Congested	No Constraints Added	Lane Length for Queue.	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Safe Headways[2]	Conflicts Due to Limited Exit Length & Gap Availability[2]	No Constraints Added	Sensor & C^3 for Coordinating Merges.	No Constraints Added
Transition to Manual	None	Vehicles That Will Not Transition	No Constraints Added	Sensors, C^3 and Storage for Vehicles that Fail to Transition	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.
4. A SYSTEM LEVEL FACTOR - EITHER THE AHS OR MANUAL LANES WILL CARRY EXTRA TRAFFIC FLOW BETWEEN THE TWO PARTS OF AN ENTRY/EXIT PAIR. THAT EXTRA FLOW IS THE DIFFERENCE BETWEEN ENTERING AND EXITING TRAFFIC OR VICE-VERSA. THIS PROBLEM CAN BE ELIMINATED WITH SIMULTANEOUS RAMPS WITH ONE A FLYOVER OF THE OTHER. SEE FIGURE A-XX.

APPENDIX I, DETAILED QUALITATIVE ANALYSIS RESULTS FOR SURFACE STREET TO AHS ENTRY/EXIT - ALL ERSCs

Table 29. Qualitative Analysis Factors (Problems or Design Challenges): Surface to AHS Entry/Exit - ERSCs 1 & 2

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter AHS	Delays to Surface Street Traffic	Crossing, Turning Traffic.	No Constraints Added	Entry Structure. Sensors & C^3 for Controlling Access During Congestion On AHS.	No Constraints Added
Check- In	Minimum Required (Probably Self-Test)	None	No Constraints Added	None	No Constraints Added
Queue for Merging Onto AHS	Delays to Entering Vehicle While Finding Acceptable Gap[2]	Back-up Onto Surface Street During Congestion[2]	No Constraints Added	Ramp Length for Queue. Sensors & C^3 for Controlling Access During Congestion at Entry.	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Safe Headways[2]	Conflicts Due to Gap Availability In AHS Lane[2]	No Constraints Added	None	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added

Table 29. Qualitative Analysis Factors (Problems or Design Challenges): Surface to AHS Entry/Exit - ERSCs 1 & 2

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering & Exiting Vehicles Due to Gap Availability[2]	No Constraints Added	None	No Constraints Added
Check-Out	None Required	None	No Constraints Added	None	No Constraints Added
Transition to Manual	Delays to AHS Stream Due to Manual Operation of Vehicle	VehiclesThat Will Not Transition	No Constraints Added	None	No Constraints Added
Diverge from AHS Stream Onto Exit Ramp	Minimal Delays to AHS Stream	Conflicts Between Exiting Vehicles Due to Slowing & Sequence of Exit	No Constraints Added	Length of Exit Ramp for Decelerating. Sensors & C^3 for Controlling Exits At Congested Locations	No Constraints Added
Queue for Exit Onto Surface Street	Delays while Finding Acceptable Gap or Receiving Right-of-Way[2]	Back-up Onto AHS if Exit is Congested[2]	No Constraints Added	Length of Ramp for Queue.	No Constraints Added
Exit Onto Surface Street	Delays Due to Turning, Street Geometry, Etc	Conflicts With Surface Street Traffic	No Constraints Added	Exit Structure.	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier <u>or</u> no shoulder limits Operational Access by about 50%. Presence of a barrier <u>and</u> no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

Table 30. Qualitative Analysis Factors (Problems or Design Challenges): Surface Street to AHS Entry/Exit - ERSC 3					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter AHS	Minor Delay to Manual Stream	Conflict Between Entering Vehicles Due to Sequence of Entry.	No Constraints Added	Entry Structure. Sensors & C^3 for Controlling Access During Congestion on AHS	No Constraints Added
Check- In	Dealys If Not Done in Motion	None	No Constraints Added	Lane Length,Sensors & C^3 for Check-In. Exit Path for Failed Vehicles.	No Constraints Added
Queue for Merging Onto AHS	Delays while Finding Acceptable Gap[2]	Back-up Onto Surface Street During Congestion	No Constraints Added	Ramp Length for Queue	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Safe Headways[2]	Conflicts With AHS Traffic Due to Gap Availability[2]	No Constraints Added	Sensors & C^3 for Detecting Gaps & Coordinating Merges	No Constraints Added
Transition to Automatic	Delays to AHS Stream Due to Manual Operation of Vehicle	Vehicles that Fail to Transition Must Exit	No Constraints Added	None	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	None	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering & Exiting Vehicles[2]	No Constraints Added	Sensors & C^3 for Coordinating Merges and Diverges	No Constraints Added

Table 30. Qualitative Analysis Factors (Problems or Design Challenges): Surface Street to AHS Entry/Exit - ERSC 3					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out[2]	Vehicles Without Capable Drivers[2]	No Constraints Added	Sensors, C^3 and Storaage for Vehicles that Fail Check-Out	No Constraints Added
Transition to Manual	Delays to AHS Stream Due to Manual Vehicles	Vehicles That Will Not Transition	No Constraints Added	None	No Constraints Added
Diverge from AHS Onto exit Ramp	Minor Delay to AHS Stream	None	No Constraints Added	Length of Deceleration Ramp. Sensors & C^3 to Control Exits At Congested Locations	No Constraints Added
Queue for Entry Onto Surface Street	Delays while Finding Acceptable Gap or Receiving Right-of-Way[2]	Back-up Onto AHS if Exit is Congested[2]	No Constraints Added	Length of Ramp for Queue.	No Constraints Added
Merge Onto Surface Street	Delays Due to Turning, Street Geometry, Etc	Conflicts With Surface Street Traffic	No Constraints Added	Exit Structure	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.

Table 31. Qualitative Analysis Factors (Problems or Design Challenges): Surface Street to AHS Entry/Exit- ERSCs 4 & 5

Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Enter AHS	Minor Delay to Manual Stream	Conflict Between Entering Vehicles Due to Sequence of Entry.	No Constraints Added	Sensors & C^3 for Controlling Access During Congested AHS Conditions.	No Constraints Added
Check- In	Delays If Not Done at Speed	None	No Constraints Added	Lane Length, Sensors & C^3 for Check-In. Exit Path for Failed Vehicles	No Constraints Added
Queue for Merging Onto AHS	Delays While Waiting for Gap In AHS Traffic[2]	Back-up Onto Manual Lane During Congestion On AHS[2]	No Constraints Added	Lane Length for Queue. Sensors & C^3 for Controlling Access During Entry Congestion	No Constraints Added
Transition to Automatic	Delays Suffered if Transition Not at Full Speed	Vehicles that Fail to Transition Must Exit	No Constraints Added	Sensors & C^3 for Detecting &Warning of Manual Vehicles	No Constraints Added
Merge Into AHS Stream	Delays to AHS Lane Due to Re-establishing Safe Headways[2]	Conflicts With AHS Traffic Due to Gap Availability[2]	No Constraints Added	Acceleration Lane Length. Sensors & C^3 for Managing Merges.	No Constraints Added
Traverse AHS Sections	Delays Due to Vehicles Exiting/Entering to Shoulder	Errant Manual or Out-of-Control Vehicles[3]	No Constraints Added	Sensors & C^3 for Managing Emergency Entry/Exit	No Constraints Added
Traverse Entry/Exit Nodes	Delays to AHS Stream Due to Entering/Exiting Vehicles[2]	Conflicts With Entering & Exiting Vehicles[2]	No Constraints Added	Sensors & C^3 for Managing/Coordinating Merges/Diverges	No Constraints Added

Table 31. Qualitative Analysis Factors (Problems or Design Challenges): Surface Street to AHS Entry/Exit- ERSCs 4 & 5					
Functional Flow Elements	Functional Effectiveness	Safety	Operational Access[1]	Entry/Exit Structures and C^3 Costs	Evolutionary Compatibility
Check-Out	Delays in Dealing with Drivers/Vehicles that Fail Check-Out[2]	Vehicles Without Capable Drivers[2]	No Constraints Added	Sensors, C^3 and Storage for Vehicles that Fail Check-Out	No Constraints Added
Diverge from AHS Stream Into Transition Lane	Delays to AHS Stream Due to Entry/Exit Length and Concentration of Vehicles[2]	None	No Constraints Added	Lane Length for Decelerating. Sensor & C^3 for Controlling Exits at Congested Locations	No Constraints Added
Queue for Entry into Manual Lanes	Delays while Finding Acceptable Gap	Back-up Onto AHS If Exit Is Congested	No Constraints Added	Lane Length for Queue.	No Constraints Added
Merge Into Manual Lane	Delays to Manual Stream Due to Re-establishing Safe Headways[2]	Conflicts Due to Limited Exit Length & Gap Availability[2]	No Constraints Added	Sensor & C^3 for Coordinating Merges.	No Constraints Added
Transition to Manual	None	Vehicles That Will Not Transition	No Constraints Added	Sensors, C^3 and Storage for Vehicles that Fail to Transition	No Constraints Added

1. Assumes shoulder and no barrier between AHS and manual lanes. Presence of a barrier or no shoulder limits Operational Access by about 50%. Presence of a barrier and no shoulder limits Operational Access to near zero.
2. Italics indicate most significant factors for this entry/exit configuration and ERSC(s).
3. Degree of danger from errant manual or out-of-control vehicles depends on whether barriers are present.