Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS Entry/Exit Implementation

U.S. Department of Transportation
Federal Highway Administration
Publication No. FHWA-RD-95-146
November 1994

PRECURSOR SYSTEMS ANALYSES

OF

AUTOMATED HIGHWAY SYSTEMS

Activity Area J

AHS Entry / Exit Implementation

Results of Research

Conducted By

Delco Systems Operations

FOREWORD

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

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

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

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

Original signed by:

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

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PRECURSOR SYSTEMS ANALYSES OF AUTOMATED HIGHWAY SYSTEMS Activity Area J AHS Entry / Exit Implementation		5. Report Date 6. Performing Organization Code
7. Author(s) S. O'Brien*, R. Schulze*, P. Lima**		8. Performing Organization Report No.
9. Performing Organization Name and Address Delco Electronics Corporation Delco Systems Operations 6767 Hollister Avenue Goleta, CA 93117-3000		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-93-C-00194
12. Sponsoring Agency Name and Address IVHS Research Division Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		13. Type of Report and Period Covered Final Report September 1993–November 1994 14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative (COTR)–J. Richard Bishop HSR 10
* Daniel, Mann, Johnson, and Mendenhall, Phoenix, AZ; ** Lima and Associates, Phoenix, AZ

16. Abstract
This activity focuses on the traffic operational impacts of Automated Highway Systems (AHS) entry/exit facilities at the points where they interface with the local street network. Information and results from several of the other Precursor Systems Analyses (PSA) activity areas are utilized in the conduct of the entry/exit research.

Various strategies for AHS entry and exit are considered and their attributes identified. Analyses determined the operating conditions based on AHS volumes and ramp volumes from other PSA studies. Measures of effectiveness were established to allow comparison of different entry and exit strategies.

17. Key Words	18. Distribution Statement
automated highway systems, AHS entry, AHS check-in, AHS exit, AHS check-out, queues, measures of effectiveness, AHS infrastructure design, AHS capacity, ramp capacity	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72)Reproduction of completed page authorized

(PF V2.1, 6/30/92)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

AHS entry and exit implementation consists of the infrastructure elements required for accessing an AHS lane or freeway. Infrastructure requirements are a function of the AHS entry/exit strategy utilized, the level of performance desired, and the traffic demand on the facility. AHS check-in and check-out procedures have a profound effect on the entry and exit facility size.

Various measures of effectiveness (MOE) were used to evaluate AHS entry and exit strategies. They can be categorized into two areas: safety MOE's and operational MOE's. Safety MOE's pertain to operator interface errors with the equipment and false entry and exit rate. Operational MOE's pertain to more typical freeway parameters such as delay and queue lengths.

Two main check-in and check-out procedures are possible with AHS; on-site testing and off-site testing. On-site testing, requiring a testing duration delay to users, results in entry and exit facility sizes that are extremely large and infeasible to implement, especially in an urban environment. It was determined that even a five second delay during check-in or check-out would require multiple check-in or check-out stations to handle modest demands. Many freeway ramp metering systems operate on a five second cycle. Dynamic on-site check-in or check-out testing would most likely require more than five seconds. At a 15 second delay and a demand of 1,500 vehicles per hour, a check-in or check-out facility would require seven stations to maintain manageable queue lengths and vehicle delay.

AHS entry and exit facilities can also be separated into two categories; dedicated facilities and non-dedicated facilities. Dedicated facilities are entry and exit configurations that provide direct access to and from the AHS lane(s). Non-dedicated facilities do not provide direct access to AHS lane(s). In a corridor that shares both AHS and conventional freeway lanes, AHS traffic must enter the conventional freeway first prior to entering the AHS lane(s). This report focuses on dedicated AHS entry and exit facilities. Various conceptual configurations were developed. The AHS configuration considered the most appropriate, when considering an off-site check-in or check-out procedure, is a slip ramp design with entry and exit to the AHS from the left.

Location and spacing of dedicated AHS entry and exit facilities were analyzed as part of this work. This effort was concentrated on urban applications as an urban setting was considered to be a worse case scenario. A range of demands, from 500 to 2,000 vehicles per hour, were analyzed.

AHS entry/exit facilities located at the same cross street as the conventional freeway interchange will cause severe operational problems on the cross street and the ramps. Offsetting the AHS interchange from the conventional freeway interchange will be required for dedicated AHS entry and exit movements.

Alternative spacing of the AHS entry/exit facilities were analyzed to determine the impacts on ramp operation and overall corridor performance. 1.6 and 4.8 kilometer spacing of facilities were compared. In an urban setting, the 4.8 kilometer spacing resulted in very large ramp volumes and long ramp delay. The ramp delay affected the overall corridor performance at a market penetration rate of approximately forty percent. Market penetration rates greater than forty percent result in ramp delays so large that the full benefits of improved AHS capacity can not be obtained. Fairly short AHS interchange spacing will be required as market penetration of AHS exceeds the thirty five to forty percent range.

Ramp terminal analyses were performed to determine the impacts of AHS entry and exit maneuvers on the local cross street system. In urban areas, these points will typically be signalized and the operation of the signal must accommodate all items associated with a normal signalized intersection. The large ramp volumes associated with AHS even at lower market penetration rates will overload the signal operation. To accommodate these large ramp volumes, the ramp terminal points will have to be configured so free flow operation to and from the ramps is possible.

One method for providing for free flow ramp movements is to separate AHS entry facilities from exit facilities and implementing one way operation on the connecting cross street. Cross street through movements are eliminated at the interchange location itself. This scenario eliminates conflicting movements at the intersection which allows it to operate unsignalized. By converting the closest parallel roadways to the freeway to one way operation, the resulting intersection with the cross street can accommodate approximately 5400 vehicles per hour under normal signalized operation. This will enable the local system to disperse and collect the AHS traffic without the major expense of having to widen all of the local streets adjacent to AHS interchanges.

However, even if modifications to local street operations is feasible and separate interchanges for direct access to AHS are implemented, management of AHS demand at the interchanges will be required. Demand management means the reduction of peak demands on the system by redistributing the trips over time or by rerouting over less congested routes. Intelligent Transportation Systems (ITS) have defined several user services that can be utilized to accomplish effective demand management.

INTRODUCTION

The research approach for AHS Entry/ Exit Implementation was to focus on the traffic operational impacts of AHS entry/exit facilities and the point where they intersect the local street network. Information and results from work conducted under Activity B – Automated Check-In, Activity C – Automated Check-Out, Activity H – AHS Roadway Deployment Analysis, and Activity I – Impact of AHS on Surrounding Non-AHS Roadways were utilized to help configure and analyze various entry and exit scenarios.

The work conducted under this Activity was separated into three tasks:

- Define AHS entry/exit strategies.
- Define measures of effectiveness for entry/exit strategies.
- Analyze AHS entry/exit strategies.

Most of the approaches developed and results drawn under this work are generic in freeway corridors. Specific reference to the corridor modeled by this team is fully described in the Activity I – Impact of AHS on Surrounding Non-AHS Roadways report. AHS entry and exit demands derived from that modeling effort were used in the present study in developing viable alternative AHS entry and exit configurations.

REPRESENTATIVE SYSTEM CONFIGURATIONS

The representative system configurations (RSC's) were generated very early in this Precursor Systems Analyses of AHS program. These RSC's are used throughout the various areas of analysis whenever a diversity of system attributes is required by the analysis at hand. The RSC's identify specific alternatives for 20 AHS attributes within the context of three general RSC groups.

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

TECHNICAL DISCUSSION

Task 1. Define AHS Entry/Exit Strategies

Introduction And Definitions

AHS Entry

An entry to the AHS is defined as the sequence of events that takes place between the time the desire to enter the AHS is entered into the system and the time the AHS vehicle is part of the AHS through traffic stream, traveling at the prevailing speed. This activity report is primarily concerned with entry as it influences infrastructure facilities, the non-automated street network near the AHS, and the design of the entry ramps or transition lanes themselves. AHS will require vehicles to undergo and pass various check-in procedures before being allowed on the AHS lane. This is to assure that both the vehicle and the driver meet the operating requirements of the AHS. Issues related to the check-in process are addressed in Activity B – Automated Check-In. This Activity Report was coordinated with Activity B during the conduct of the research project.

AHS Exit

Exit from the AHS is defined as beginning when the vehicle initiates the check-out procedure, and ending when the vehicle is utilizing the manually controlled street or highway system after completing the automated through trip and the automated part of the transition from automated to manual control. Again, AHS will require vehicles and drivers to undergo and pass various check-out procedures before control of the vehicle is returned to the driver. This does not preclude the vehicle leaving the AHS lane(s) however. A vehicle, while still under system control, may leave the AHS lane and be taken to a holding facility until a malfunction can be repaired.

Entry Strategies

The AHS entry strategy is dependent on a number of vehicular, infrastructure, and economic characteristics. However, in defining the physical characteristics of the entry infrastructure, the key elements are related to type of vehicle using the AHS and the type of AHS operation allowed. Facilities that must provide for commercial trucks and transit vehicles will require larger facilities due to their operational and physical characteristics. Type of AHS operation refers to whether AHS is operated separate from or in conjunction with normal freeway traffic.

If operated separately, the AHS is referred to as a dedicated system and is physically separate from the non-AHS freeway. This does not preclude using the same location or right-of-way of conventional freeways, but the two vehicle types operate independently and do not mix.

If AHS is operated in conjunction with non-AHS freeway traffic, the AHS is referred to as a non-dedicated system. There is no physical or only partial physical separation of the two vehicle types. The AHS lane is intended for only AHS equipped vehicles; however, there is no physical constraint preventing non-AHS vehicles into the lane. Dedicated entry facilities are those where traffic enters the AHS from the manual system utilizing direct-connection ramps. Facilities with transition lanes require AHS vehicles to enter the freeway using existing interchanges, then weave across conventional traffic lanes before making a lane change maneuver either into a transition lane or possibly directly into the AHS. RSC 1 and 2 are dedicated facilities while RSC 3 is a non-dedicated facility.

From the standpoint of entry/exit strategy, there are two AHS configurations: Dedicated and non-dedicated. Most of the analysis in this report pertains to dedicated facilities, while other Precursor Systems Analyses (PSA) researchers have dealt with issues related to non-dedicated entry/exit.

Dedicated AHS Facilities

The entry facilities and requirements for dedicated AHS freeways will differ from those of non-dedicated AHS freeways. Dedicated AHS entry facilities will provide some mechanism to prevent non-equipped or non-authorized vehicles from entering the AHS freeway. Non-authorized vehicles are vehicles that do not pass the check-in requirements established for the system. This includes errant vehicles (non-equipped) that were never intended to use the AHS freeway. RSC 1 and RSC 2 are dedicated facilities with differing means for preventing unqualified vehicle entry into the system. RSC 1 provides a physical barrier while RSC 2 an electronic barrier, but both are predicated on the AHS operation being totally separate from the conventional freeway system.

The dedicated facility considered for this work is a median-located, separated AHS lane. Entry can be at the “beginning of the line,” at predetermined locations along the AHS (barriered transition lane), or from cross streets with direct connection ramps. AHS entry/exit configurations are affected by the inclusion of a barriered system. Barrier related concerns are addressed in the Activity H – AHS Roadway Deployment Analysis.

The configuration of an entry facility for a dedicated AHS system is dependent on four main items:

- The check-in procedure required to gain access to the freeway.
- The number of vehicles desiring access to the system at any one location.
- The procedure for merging vehicles onto the AHS freeway.
- The physical and performance characteristics of vehicles using the AHS.

On-Site Check-In At Dedicated Facilities

Dedicated entry facilities offer the opportunity to consider issues related to on-site check-in. This is because the dedicated facility tends to have to be designed from the ground up. If on-site check-in is found to be desirable it can theoretically be integrated into the design of the entry ramp system.

Off-Site Check-In Dedicated Facilities

An alternative to an on-site check-in facility is a remote, or off-site facility. Such a facility could be part of a system where rigorous testing is conducted off-site, while less detailed testing or verification that the rigorous tests are current is conducted on the fly at the at the on-site facility. The remote facility might operate similar to today's emissions testing stations, and could even share the same locations as those sites. The frequency of testing and the time to complete the tests is not within the scope of the PSA studies. While the public may find the frequency, time to test, and delays at the stations objectionable, such testing (if needed) is clearly preferable to the same delay on a per trip basis.

Check-In Procedure

The check-in procedure assures that both the vehicle and driver meet the operating requirements of the AHS freeway. The length of time required to complete the check-in procedure and the location at which check-in occurs has a dramatic effect on the physical characteristics of the entry facility. If the system can perform the check-in procedures on local streets without specialized equipment, the impacts of the check-in procedure to the entry facility are relatively minor. However, if the procedures must occur on site (at the entry to the AHS) and require specialized equipment to perform the testing, then the entry facilities must be able to store vehicles waiting to undergo testing, and perform the required testing within the entry facility.

For on-site testing, the entry's spatial requirements will depend upon whether or not the vehicles must come to a stop during testing and the rate at which vehicles are processed. Service rate is the rate at which vehicles can be processed for check-in. Dimensionally, service rate is expressed in vehicles per hour (veh/hr). Service rate is a function of the check-in tests that must be performed on site and the method by which this testing is performed. If vehicles must physically stop for testing, then the service rate depends upon the cycle time for the process that consists of: testing the stopped vehicle, driving the tested vehicle out of the testing bay, bringing another vehicle into the bay, and preparing the vehicle to be tested. Thus as cycle time increases, the service rate decreases.

If the vehicle does not have to stop for testing, then service rate is a standard capacity calculation. The service rate is directly proportional to the vehicle velocity through the check-in facility and inversely proportional to the headway length, the distance between similar locations on succeeding vehicles. Thus the service rate does not depend on the check-in time. The entry facility must however be of sufficient length to include the check-in length which is equal to the product of the check-in time and the travel speed. For this study, it is assumed that once the vehicle enters the testing mode, the system controls the vehicle. The headway distance for vehicles during testing provides adequate space for the system to react and stop a following vehicle to avoid a collision with the vehicle in front of it. For this analysis, the distance is calculated assuming a 7.6 m vehicle length, a 2 sec reaction delay, and a deceleration rate of 0.2 g. The deceleration rate is representative of values possible on wet pavement.

Table 1 provides check-in length, headway length, and service rates for a selection of check-in times ranging from 10 to 40 sec and vehicle velocities from 15 to 90 km/h. It is seen that in general slower vehicle velocities allow both shorter check-in lengths and higher service rates. However, associated with the low vehicle velocity is the need to provide acceleration lanes between the check-in facility and the AHS freeway. As the vehicle accelerates to the AHS cruise velocity, the simplistic headway length, as here calculated, implies decreasing capacity. The AHS freeway would operate under different headway policies, such as those for platoon operations, to attain the required higher capacities.

Table 1. Check-In Service Rate And Length Determination

Check-In Time (sec)	Vehicle Velocity (km/h)	Check-In Length (m)	Headway Length (m)	Service Rate (veh/hr)
10	15	41.7	20.36	737
10	30	83.3	41.97	715
10	45	125.0	72.44	621
10	60	166.7	111.76	537
10	75	208.3	159.93	469
10	90	250.0	216.96	415
20	15	83.3	20.36	737
20	30	166.7	41.97	715
20	45	250.0	72.44	621
20	60	333.3	111.76	537
20	75	416.7	159.93	469
20	90	500.0	216.96	415
30	15	125.0	20.36	737
30	30	250.0	41.97	715
30	45	375.0	72.44	621

30	60	500.0	111.76	537
30	75	625.0	159.93	469
30	90	750.0	216.96	415
40	15	166.7	20.36	737
40	30	333.3	41.97	715
40	45	500.0	72.44	621
40	60	666.7	111.76	537
40	75	833.3	159.93	469
40	90	1000.0	216.96	415

Elements Of Facility Design

The physical and operational elements that enter into the design of a functional AHS entry facility are discussed below.

Demand Of The System

The number of vehicles desiring to use the AHS and the number of available entry points will also affect the check-in facility configuration. The number of vehicles desiring entry to the AHS is termed "demand." The rate at which they approach the check-in facility is the arrival rate. If the arrival rate at the facility is larger than the check-in service rate, the vehicles will form queues while waiting to enter the check-in area. The size of the queue that forms is a function of the disparity between the service and arrival rates. Large queue lengths result in undesirable operational conditions at the facility and the surrounding street network that feeds the facility.

Merging Onto AHS Lane

The third main factor affecting the check-in facility size is the manner in which vehicles are added to the AHS lane(s) after a successful check-in. If vehicles are added immediately after the check-in process is completed, then the only requirement of the facility is to provide enough ramp distance to accelerate to AHS operating speeds. This would require that the system have enough reserve capacity on the AHS lane to accommodate ramp traffic without a delayed departure from the check-in station. Gaps in the AHS lane can be provided without serious operational degradation. Our analysis is based on the assumption that, in a platoon based system, platoons would be formed only in the AHS lane, not on the entry ramp.

However, the check-in facility size drastically differs if, after a successful check-in, vehicles must be stored or held prior to authorization to merge into the AHS lane. If, for example, vehicles in a platoon based system were required to form small platoons at the check-in facility and then merge onto the AHS as a unit, additional time and space would be required to form the merging platoon. This is more critical if the AHS is operating near or at capacity.

Providing a gap for a small platoon under congested conditions will require more time than for individual vehicles.

Forming queues on the AHS ramp would significantly increase the length of the ramp or the storage area just prior to the ramp, especially for single lane entry ramps. Multi-lane storage (queues) could be accommodated if the release of vehicles is staggered by queue lane.

A staggered release from a multi-lane check-in facility should be considered even if there is no delay required prior to merging onto the AHS lane. If the release of vehicles at multi-station facilities were done at a rate equal to the inverse of the facility's service rate divided by the number of stations or check-in lanes, the long ramp transitions down to a single lane ramp would not be required. Vehicles would automatically fall in directly behind the preceding vehicle and accelerate to AHS operating speed. In this manner, the ramp length required is only a function of distance required to accelerate to operating speeds. This staggered release approach would also allow the formation of mini-platoons on the ramp prior to merging.

Vehicle Characteristics

The type of vehicle that will be using the AHS freeway will also have an impact on the entry configuration. RSC 1 and RSC 2 provide for passenger cars and light trucks as the AHS vehicle. RSC 2 provides for high performance vehicles. A high performance vehicle may be able to accelerate, brake, and corner at higher rates than today's vehicles. However, most of today's passenger vehicles can outperform American Association of State Highway and Transportation Officials (AASHTO) ramp design standards, which are based on a combination of human factors and vehicle performance criteria. Because few drivers routinely brake, accelerate, or corner at anywhere near the limits of their vehicles, it is not felt appropriate to assume that a future high performance AHS will operate outside the levels perceived as comfortable by today's drivers.

Although not part of RSC 1 and RSC 2, heavy trucks and transit vehicles will have significantly greater spatial requirements than passenger cars due to their acceleration and deceleration characteristics. Since trucks and buses are physically bigger and require greater turning radius, the physical requirements of the entry facility will also be larger than those for passenger cars. AHS presents a special design issue at the merge point of an entry facility. On a conventional freeway, entry ramps are designed so that passenger cars can accelerate to a speed within 8 km/h of the mainline design speed. Buses and trucks, which take two and three times, respectively, the distance to accelerate to the mainline design speed, are not designed for separately. Instead, the assumption is made that vehicles upstream of the merge point will change lanes as trucks and buses enter.

By contrast, on an AHS the speed of merging and mainline traffic has to be the same. The large performance differentials among trucks, buses, and passenger vehicles may dictate segregated facilities or may make a high performance transit vehicle desirable. These issues are covered in detail in the Activity F – Commercial and Transit AHS Analysis in task 6, Interface Requirements.

Vehicle sensing and communication equipment may also pose geometric limitations on the entry facility. While undergoing testing, the vehicle will be under system control. If there are limitations on the range or spread of the equipment, then limitations on the geometry of the facility will also be imposed. Maximum horizontal and vehicle curvature, physical spacing of the testing equipment, etc., will affect the facility spatial needs. Mixed traffic (automated and non-automated) will be present. It is assumed that non-automated vehicles may occasionally breach the systems intended to keep them away from the check-in facility. It is also assumed that the occasional automated but non-functional vehicle will fail the check-in process and have to continue under manual control to a point where it can return to the non-automated traffic stream.

Length Requirements For Dedicated Check-In Facilities

Check-in facility length for dedicated AHS is defined as the distance a vehicle must traverse from the point that it leaves the local street network to the point that it enters the AHS lane. The facility length is a function of the demand at the facility, the service rate at which vehicles are processed, the actual check-in process and the operating speed of the AHS lane. These variables establish the individual segment lengths of the facility shown in figure 1 for on-site check-in and figure 2 for off-site check-in.

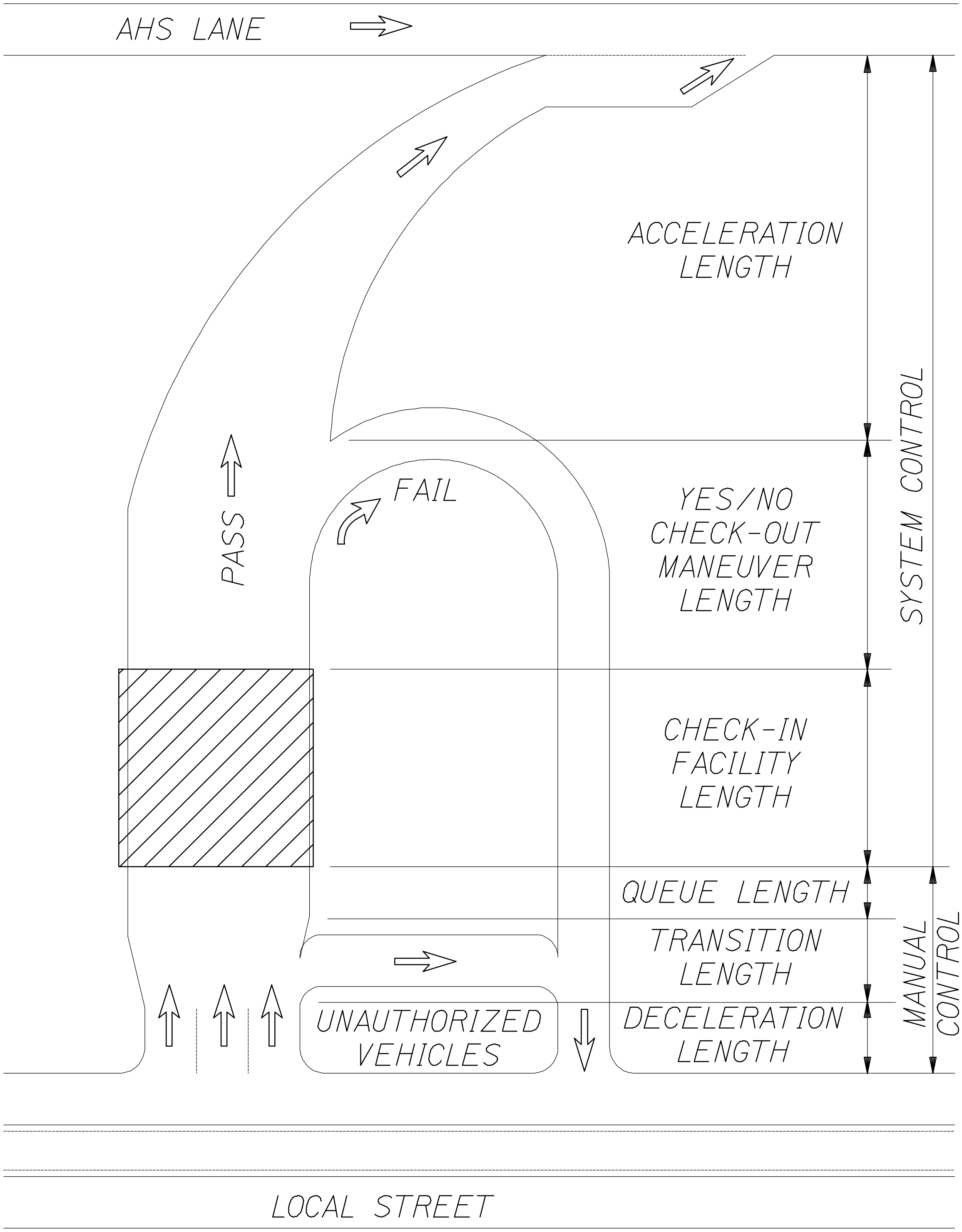

Figure 1. On-Site Check-In Length Components

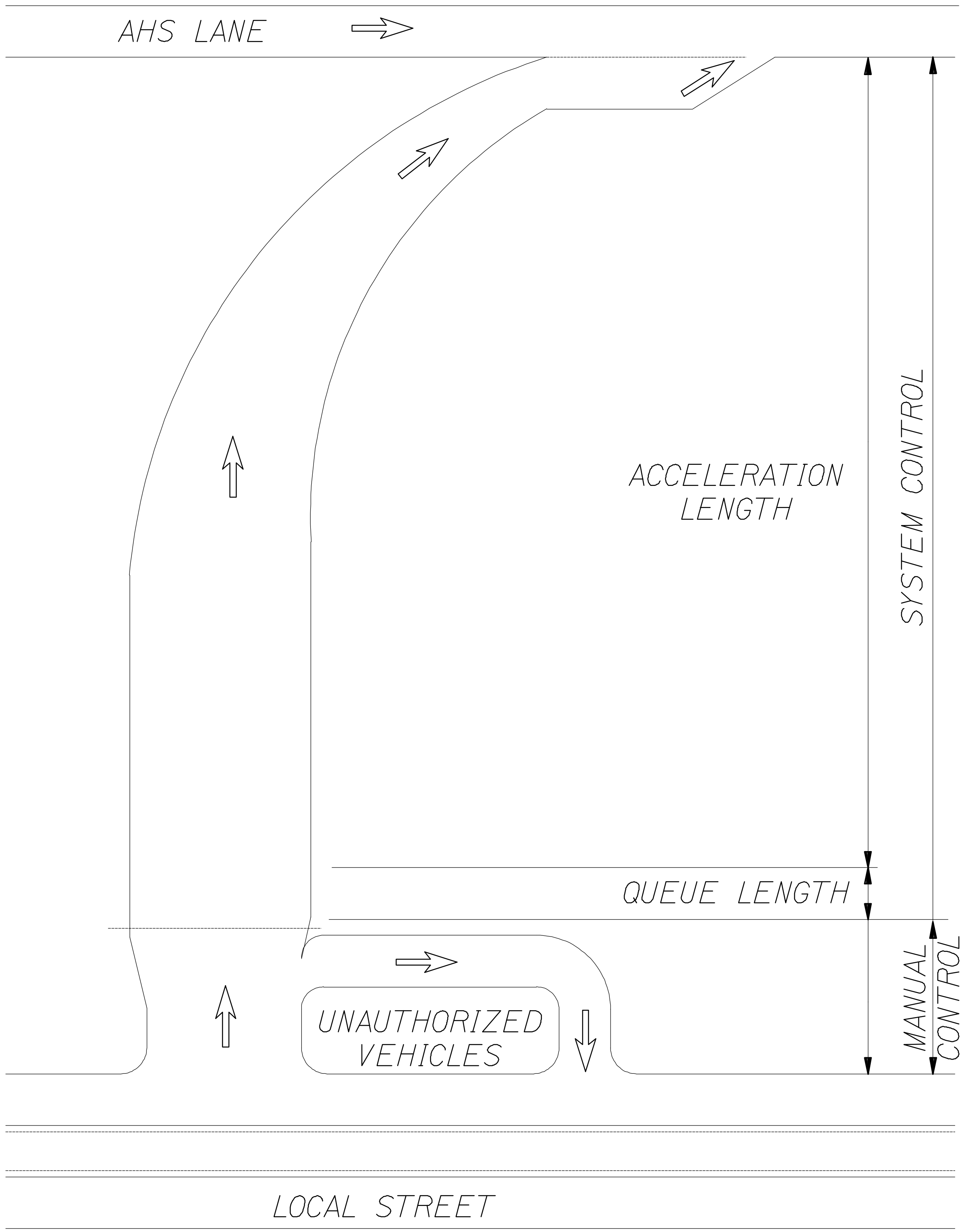

Figure 2. Off-Site Check-In Length Components

The facility length requirements can be segmented into the following portions:

- Deceleration Length – length required to reduce the vehicles entry speed to zero speed at the back of queue.

- Transition Length – The distance required to widen from the number of entry lanes provided at the local street to the number of lanes required for check-in demand. Since the vehicle will still be under manual control, a transition rate of 14:1 is assumed. (One meter of widening per 14 meters traveled.)

- Queue Length – The length required to store vehicle prior to the actual testing of the vehicle. Length is calculated by multiplying the number of queued vehicles per lane by 7.6 meters.

- Check-In Facility Length – The length requirement of the testing equipment. This varies considerably for check-in facilities where vehicles are not required to stop for check-in testing. Facility length is then based on travel speed and check-in duration. Figure 3 provides facility lengths for combinations of check-in duration's and vehicle speed during testing. In cases where vehicles must stop for the AHS testing, a set distance may be established for check-in facility length.

- Pass/Fail Maneuver Length – A set distance must be provided to return vehicles that do not pass the check-in testing to the local street. Since this maneuver will occur under system control, the length requirement will be based on the equipment operating constraints with regard to geometry.

- Acceleration Length – The distance required to bring vehicles that pass check-in testing up to the operating speed of the AHS. This distance also includes any pre-merging queuing or platoon for reaction distance required prior to the acceleration.

Given the variable nature of the individual component lengths of check-in facilities, overall facility length is also highly variable. However, if the check-in process must occur off of local streets, AHS entry ramp configurations will require more space and adjacent land than conventional freeway ramps, especially for dedicated AHS facilities. Figures 4 through 6 provide conceptual configurations for dedicated entry facilities.

Figure 4 represents an entry facility with a small on-site check-in duration where vehicles do not stop for testing. This represents a minimal length for an AHS entry facility. Service rates for check-in would be high. Figure 5 represents an entry facility with lower service rates, higher check-in duration and vehicles must stop for testing. The size requirements for this entry are much larger than those shown on figure 4. Figure 6 provides another entry configuration that could be considered for dedicated AHS freeways. Regardless of the configuration implemented, the entry facility must provide for the various segment lengths shown in figure 1. They must also provide a means for removing unauthorized vehicles from the queue prior to the check-in testing. All entry configurations reflect the system taking control of the vehicle once the entry testing begins.

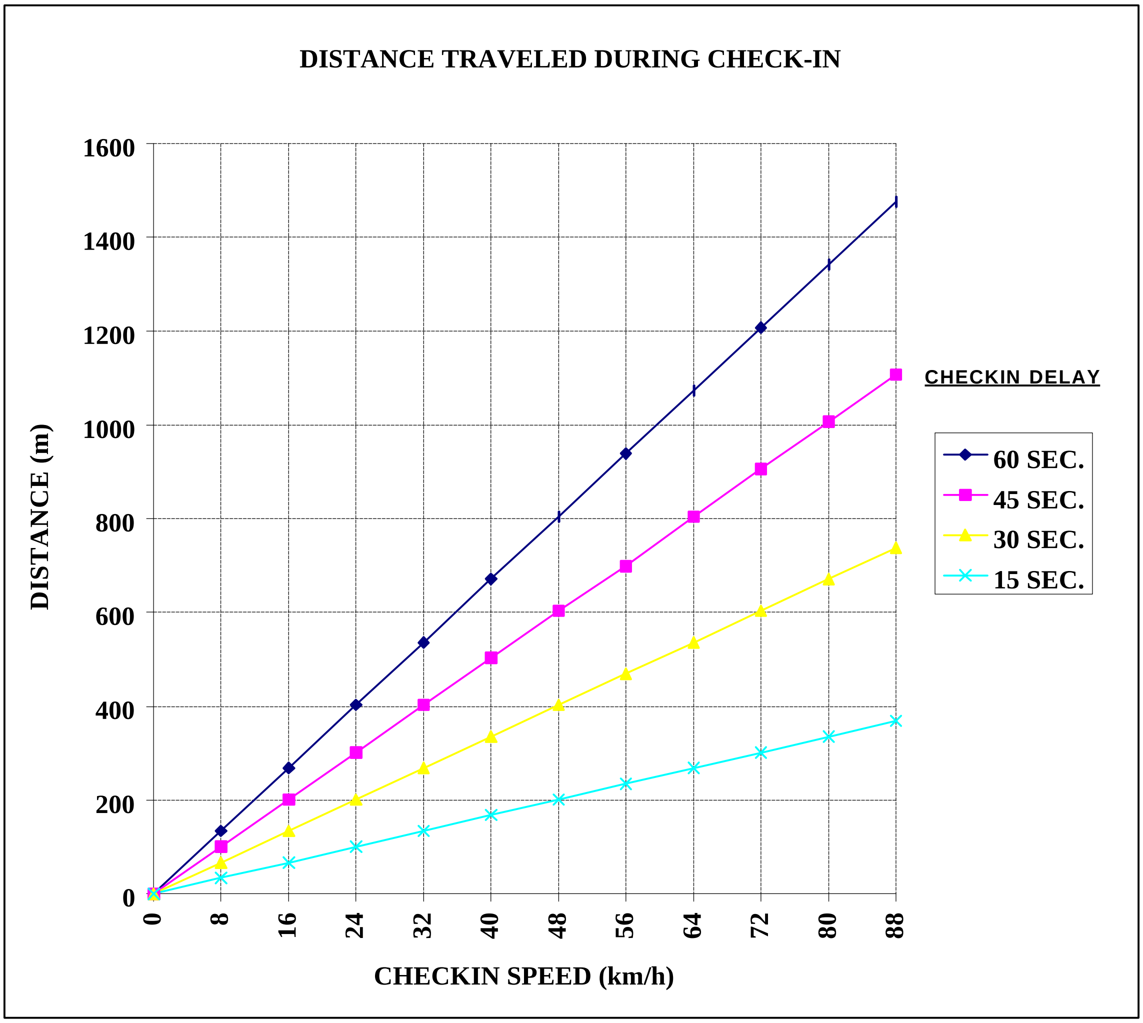

Figure 3. On-Site Check-In Length For No-Stop Testing

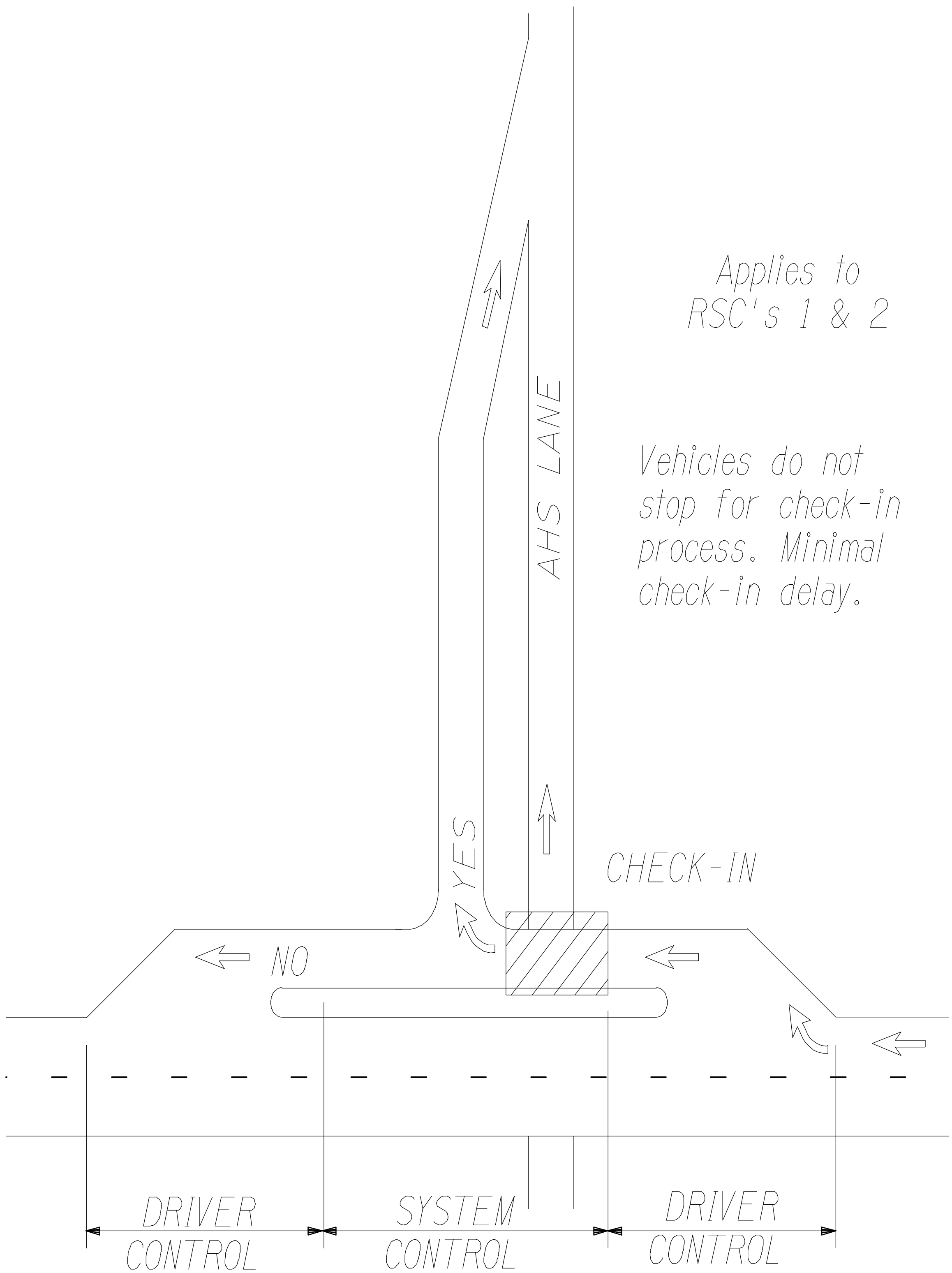

Figure 4. Slip Ramp Design For A Dedicated AHS Entry

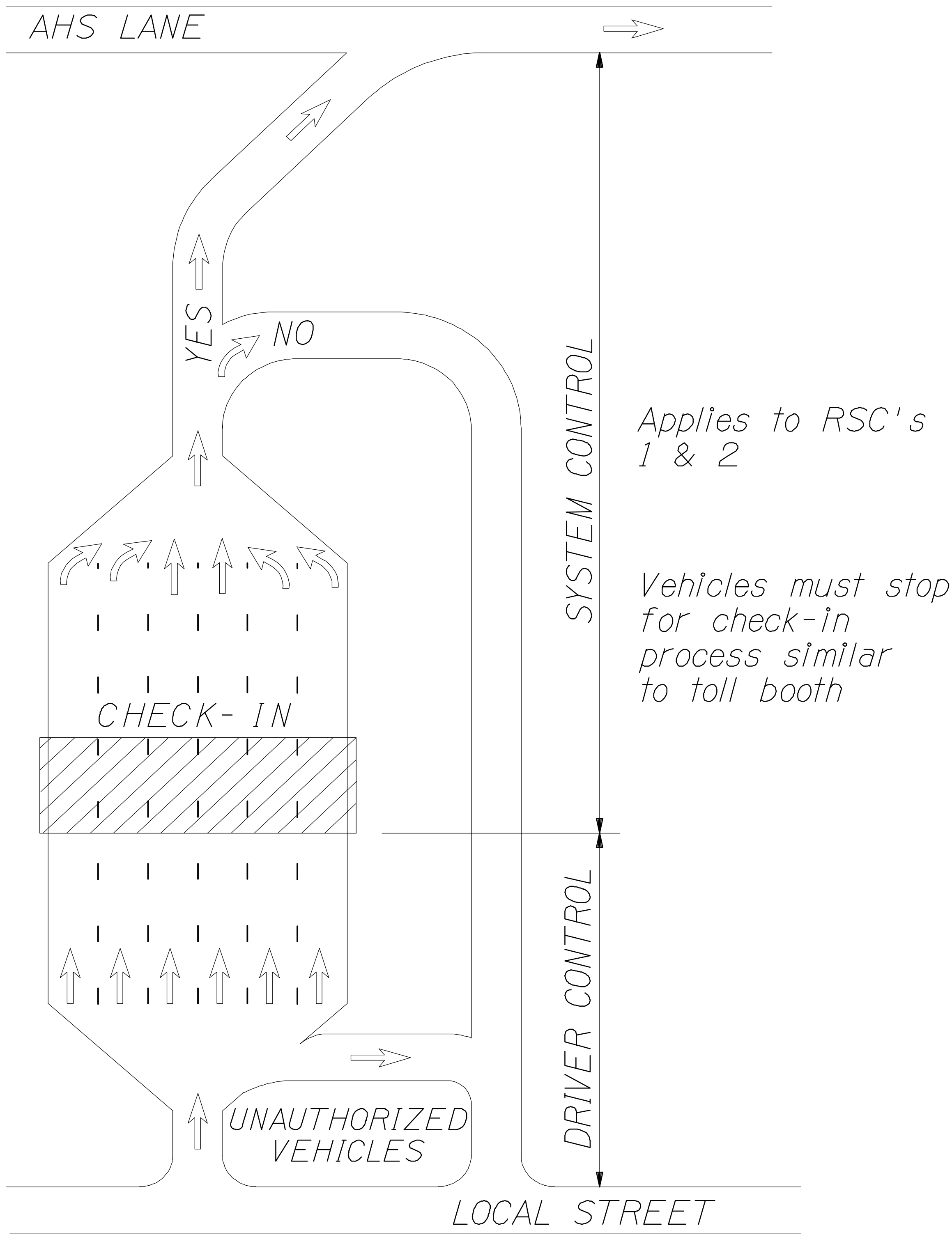

Figure 5. Dedicated AHS Entry With On-Site Testing While Stopped

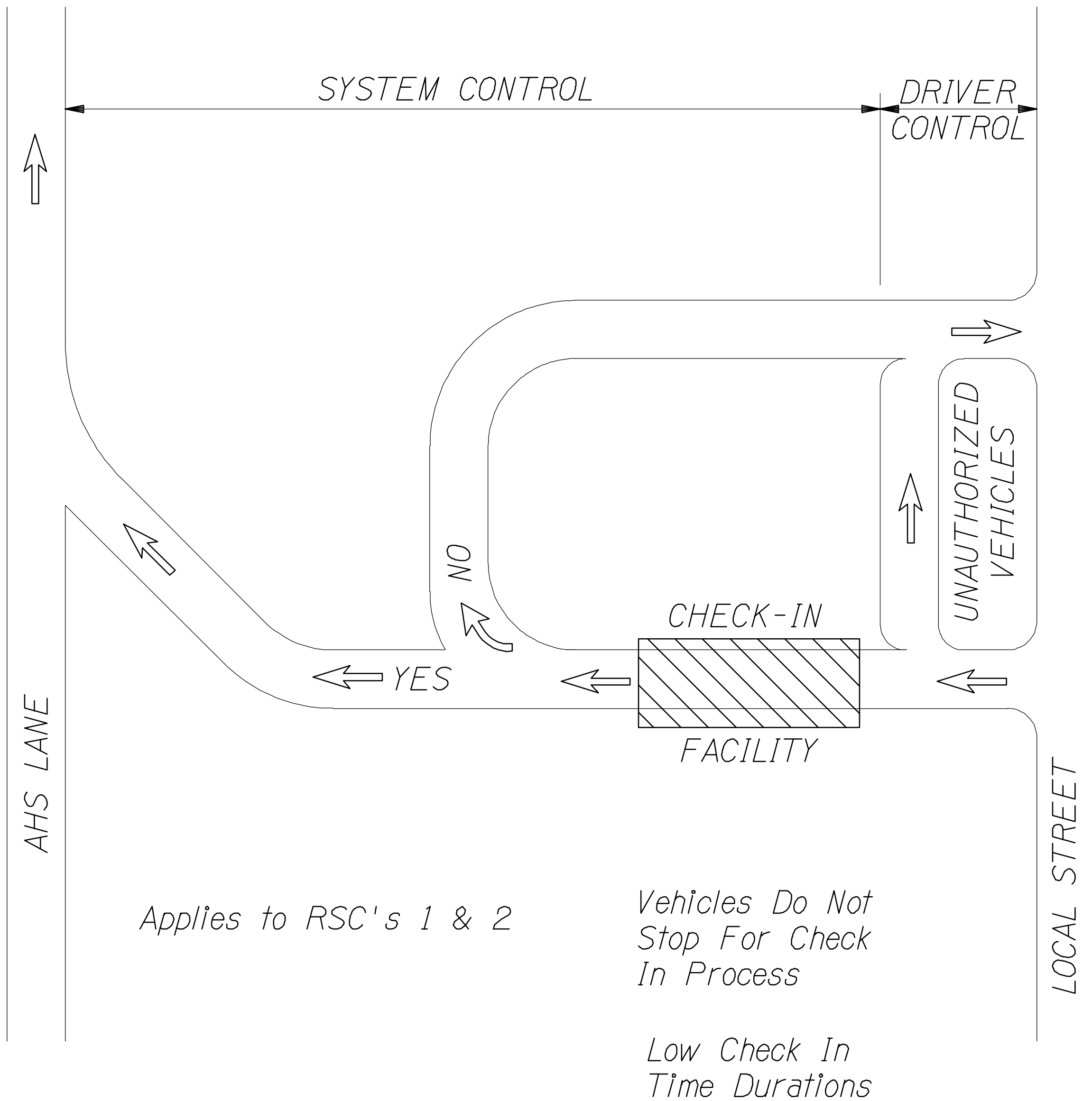

Figure 6. Dedicated AHS Entry With On-The-Fly Check-In Testing

Non-Dedicated Facilities

Entry onto a non-dedicated AHS freeway differs in the sense that AHS and non-AHS vehicles are mixed and use the same on ramps and off ramps. AHS traffic may use the conventional mainline lanes to weave to the AHS lanes. There is no separation, physical or electronic, between AHS and non-AHS lanes. RSC 3 is a non-dedicated facility.

Although entry to the AHS freeway will most likely be from conventional freeway ramps, this does not preclude the use of an off-site testing facility for AHS. For instance, if actually applying the brakes is a required test condition, then an off-site location to perform this test would be required. There may be other tests that mandate a testing facility. Spacing and location of these facilities may be easier to do than for dedicated facilities, since they will not be required to be located directly at the entry ramp.

In this case, the size of the testing facility will be dependent on the service rate of the facility, and the demand at the particular location. Since entering the freeway is through conventional means, the ramp operation is no longer a factor. The driver will enter the conventional freeway and maneuver to AHS lane(s).

Figures 7 through 9 present conceptual entry configurations to a non-dedicated AHS freeway. The main issues to be addressed by the entry procedure are:

- Providing an entry facility and procedure that can accommodate unauthorized entry by non-equipped or malfunctioning vehicles.
- Provide the ability for vehicles to reach AHS operating speeds without adversely affecting either AHS or conventional freeway operation.
- Provide an area where vehicles can be tested either off-site or on-site without adversely affecting either the AHS and non-AHS freeway operations.
- Check-in equipment/system that can perform testing in a non-confined environment.

The actual size of the on-site check-in facility, a check-in lane of buffer lane, is highly dependent on the duration of testing and the AHS operating conditions. AHS operation refers to whether it is a platoon based system or not, the capacity of the AHS, the volume to capacity ratio the AHS operates at, and the AHS operating speed. RSC 3 is a non-platoon based system and therefore eliminates the requirements of merging platoons onto the AHS. Therefore the AHS need only provide gaps large enough for a single vehicle plus the required safe following distance.

The ability to provide gaps in the AHS mainline, without impeding AHS operation, is dependent on how congested the AHS is. The more congested the AHS lane, the longer it may take to provide a gap for a merging vehicle. Also a merging vehicle must be able to reach the operating speed of the AHS. This is more important when there exists a large speed differential between the AHS lane and the buffer lane or conventional freeway lane(s).

These factors only become relevant if the buffer lane is not continuous. If, however, entry to the AHS lane is to be restricted to select areas along the freeway, then check-in lengths for buffer or check-in lanes will have to be estimated and designed for.

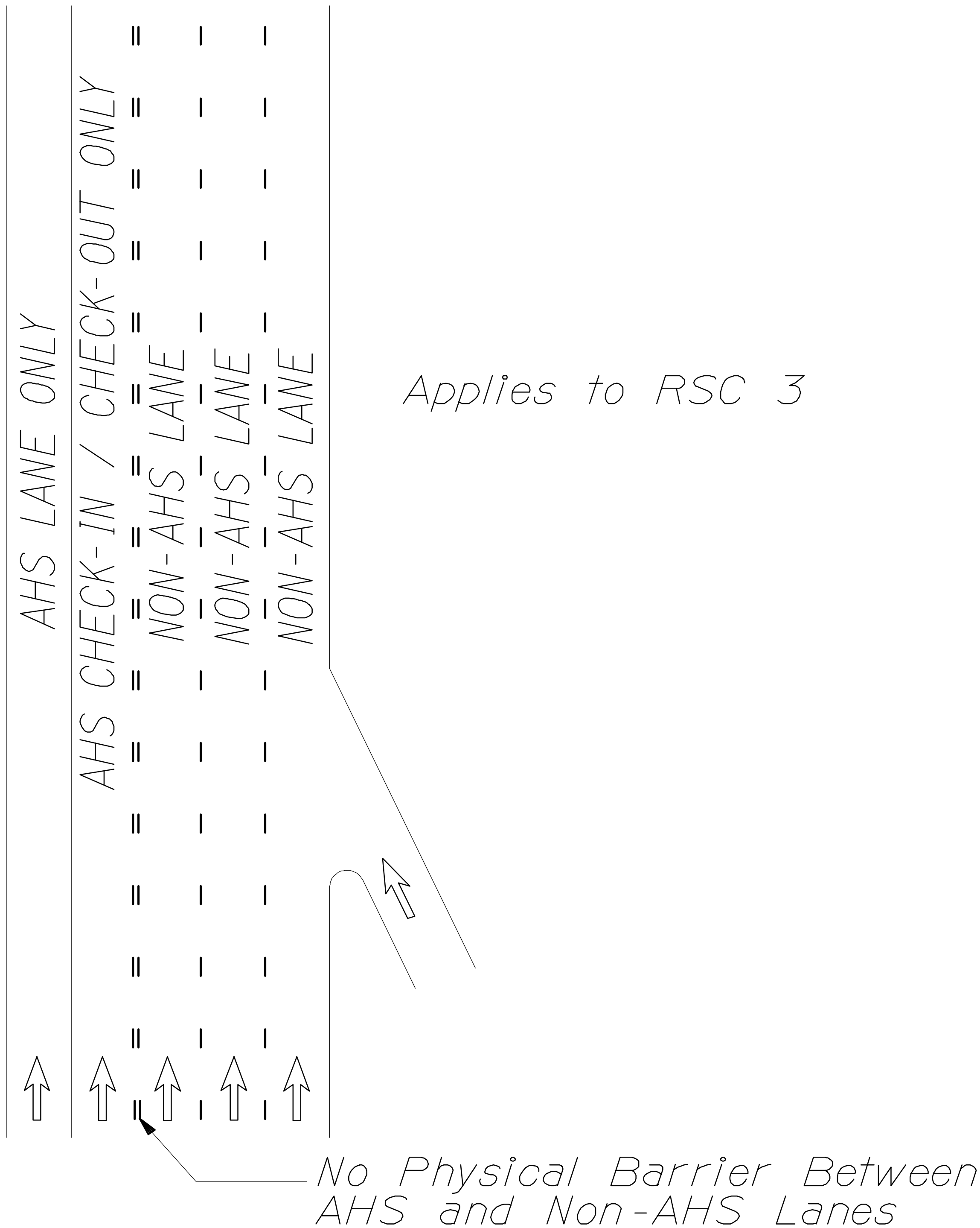

Figure 7. Non-Dedicated AHS Entry Utilizing A Transition Lane

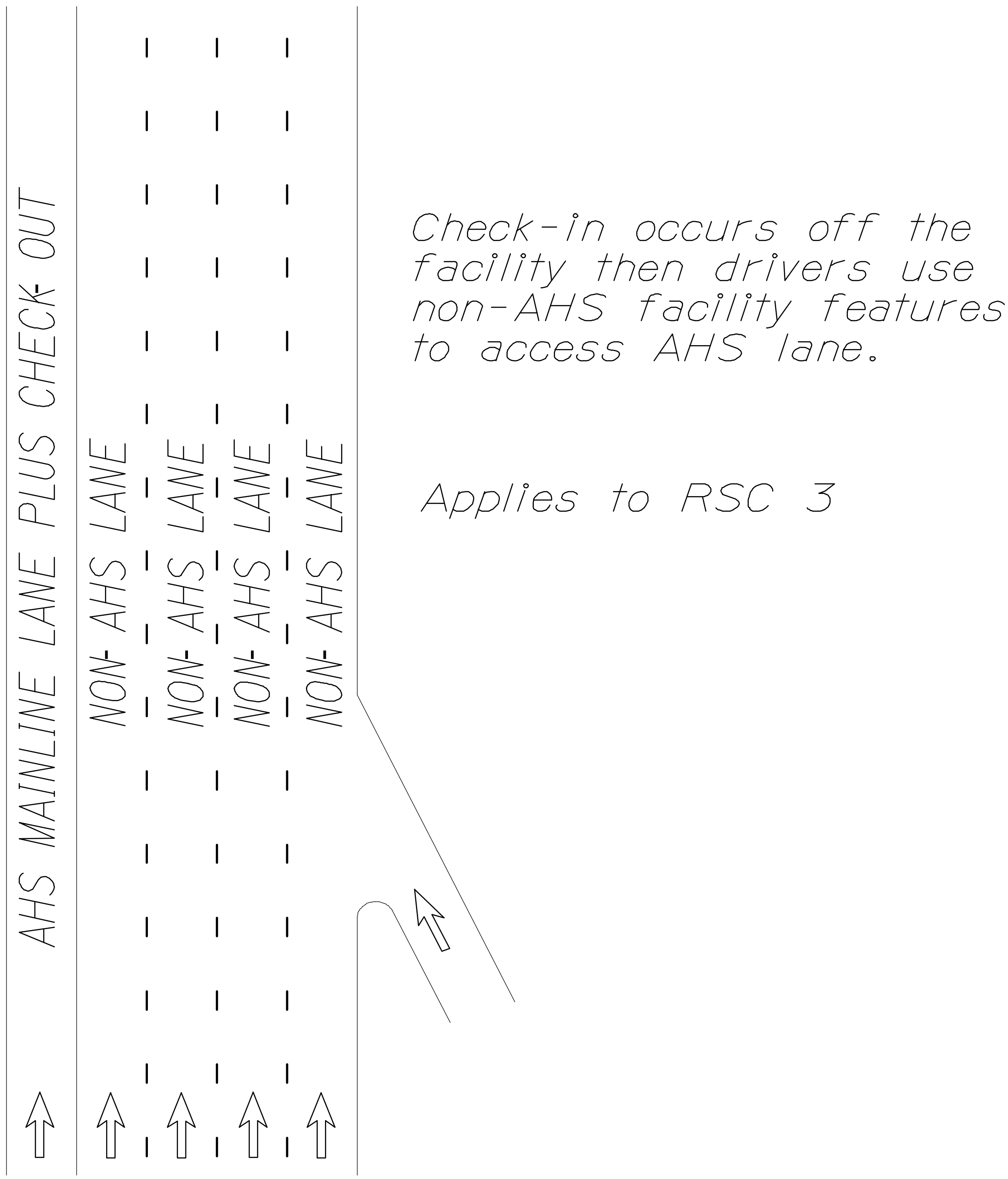

Figure 8. Non-Dedicated AHS Entry With Check-In Testing Off-Site

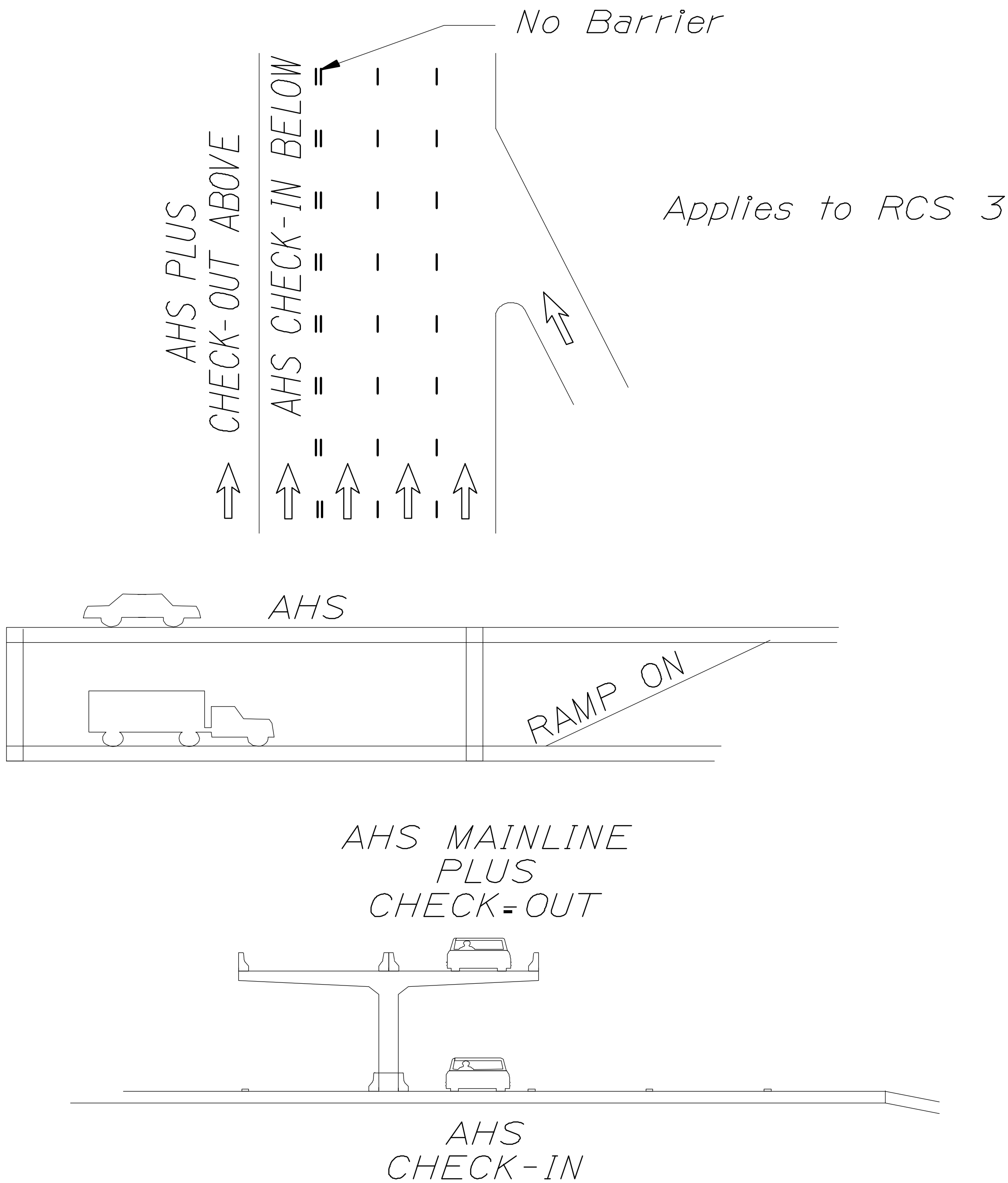

Figure 9. AHS Lane Elevated Above Freeway With Non-Dedicated Entry And Exit

Exit Strategies

As was the case for entry strategies, exit strategies will differ for dedicated versus non-dedicated facilities. Dedicated AHS freeways will have AHS vehicles separated from non-

AHS vehicles for the exiting process, while non-dedicated facilities will allow the two types to mix. The exiting process or “check-out” is a process to assure that both vehicle and driver ready for the return of normal control of the vehicle to the driver. The check-out process for non-dedicated facilities will have to occur far enough in advance of the desired exit so once control of the vehicle has returned to the driver, he has time to negotiate conventional freeway traffic and make his exit.

Dedicated AHS Facilities

Exit from a dedicated facility is envisioned to have all of the same attributes as an entry facility. Space will be required for vehicles to decelerate from AHS operating speed, queue for the testing process, house the testing equipment, allow for storage of vehicles or drivers that do not check-out and an area to convert from system control to normal control.

The actual size of the facility will be dependent on the number of vehicles desiring to leave the AHS, the spacing between exit facilities, the duration of the check-out testing and the anticipated check-out failure rate than can be expected. An exit facility must be able to store vehicles that do not pass the check-out process. The spatial requirements for the storage of these vehicles can be estimated if failure rates for AHS vehicles could be estimated. An alternative to providing a storage facility at the exit is the use of the AHS breakdown lane for failed vehicle storage. This may be a viable alternative if response times are short and usage is infrequent. Undesirable features of this alternative include dealing with disabled drivers or vehicles adjacent to high speed AHS through traffic. Issues related to shoulder usage are covered in more detail in Activity H – AHS Roadway Deployment Analysis.

Figure 10 provides a conceptual representation of an AHS exit facility for a dedicated system. The configuration reflects high service rates and low testing duration’s under no-stop conditions. Figure 11 reflects lower service rates and higher check-in testing durations. Provisions for queuing vehicles are required.

Both of the configurations shown provide a holding area for vehicles or driver that fail the check-out procedure. The size of these holding areas will significantly increase the size of the AHS exit facility. Placement of this type of facility in an urban environment will be extensively difficult and expensive.

Dedicated exit facility length requirements can be segmented into the following portions:

- Deceleration Length – length required to reduce the vehicles speed from AHS operating conditions to zero speed at the back of the queue.

- Transition Length – The distance required to widen from the single lane ramp to the lanes required for check-out demand.

- Queue Length – The length required to store vehicles prior to the actual testing of vehicles (for on-site check-out). Length is calculated by multiplying the number of queued vehicles by 7.6 meters.

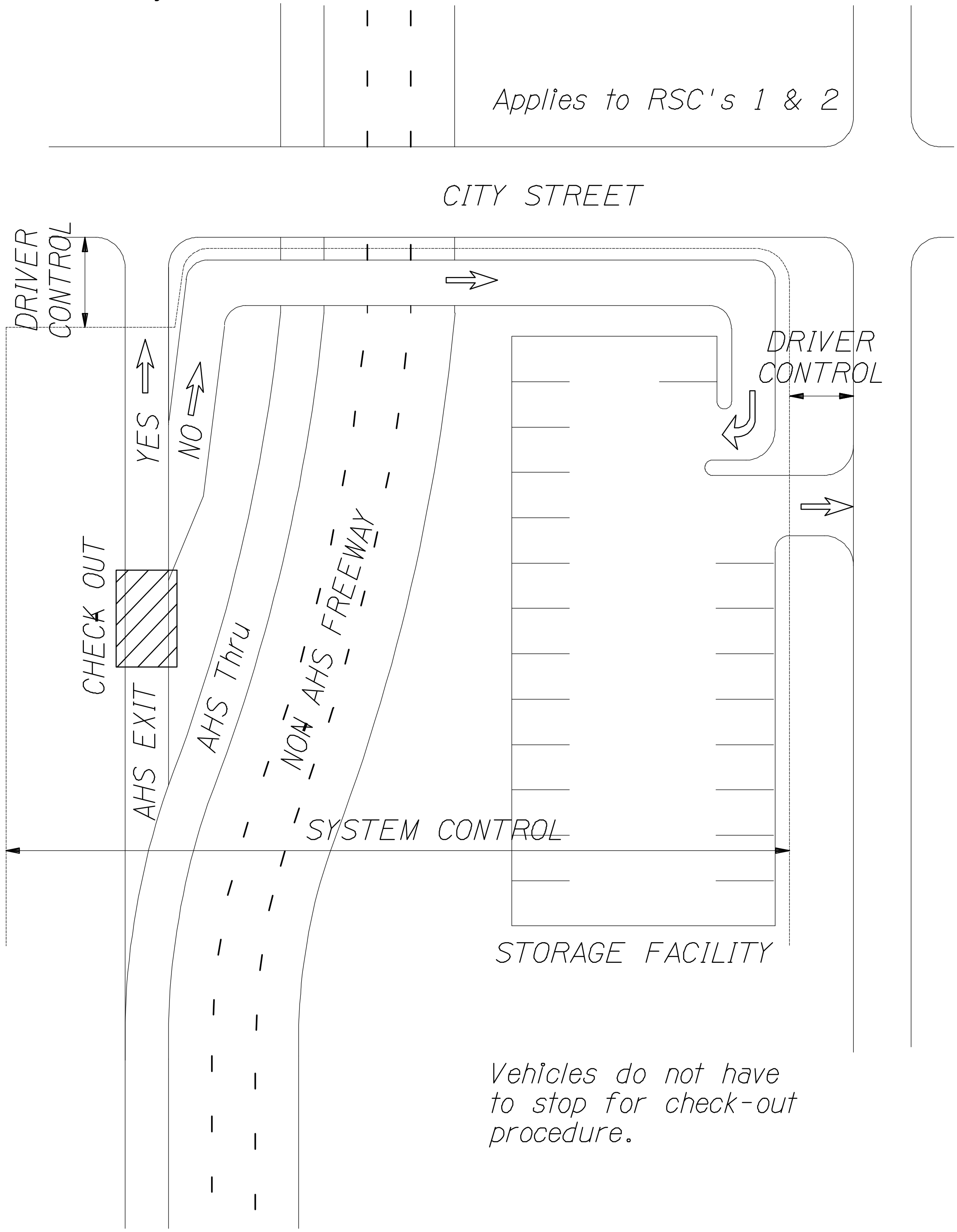

Figure 10. Dedicated AHS Exit With Minor Check-Out Testing

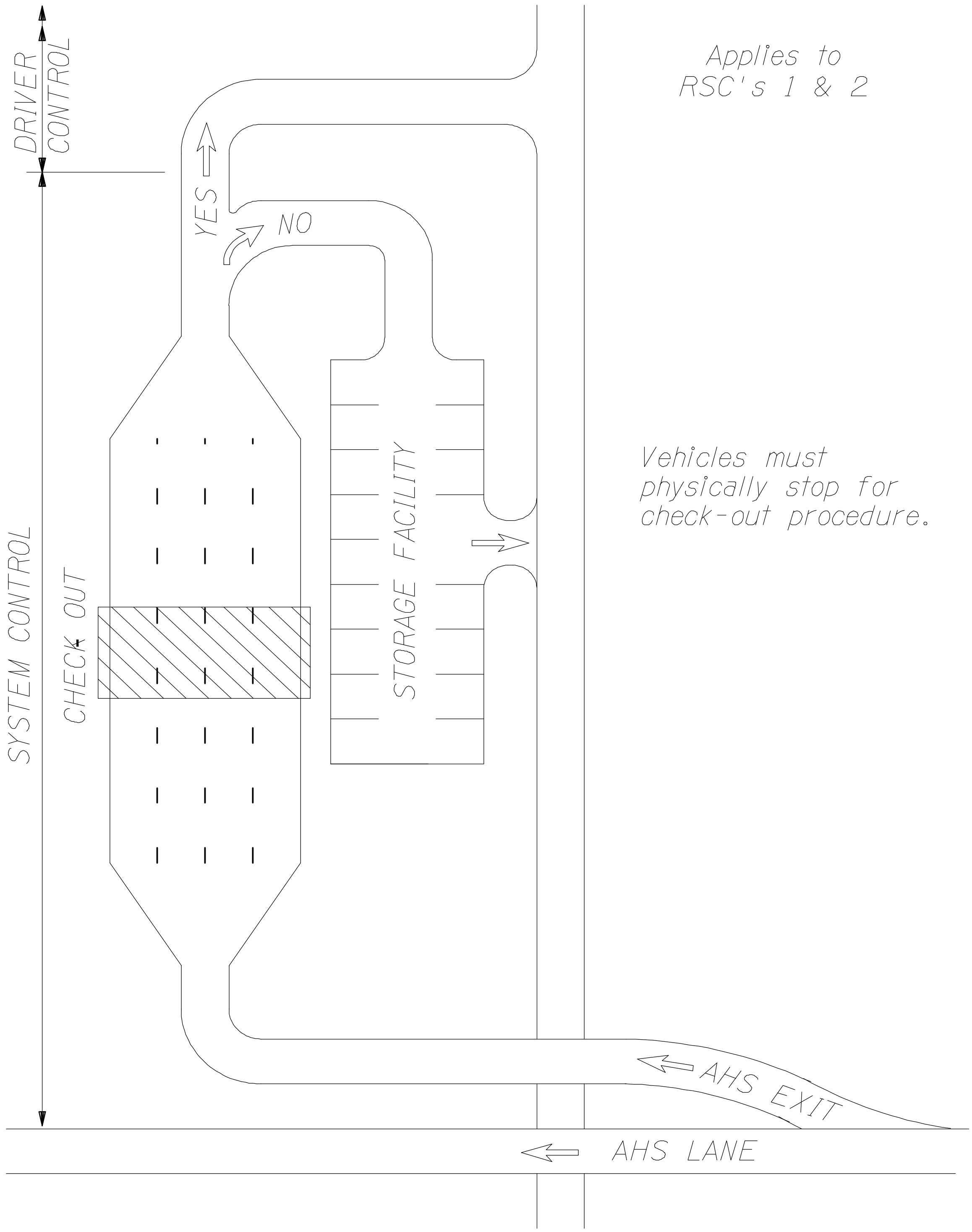

Figure 11. Dedicated AHS Exit With On-Site Check-Out Testing

For off-site check-out, the queue length will be a function of delay experienced where the ramp intersects the local street. For signalized junctions, AHS and local traffic volumes, the ratio of green time provided to the AHS ramp traffic to the whole signal cycle length (G/C ratio) and
intersection geometry all factor into how much delay is imposed on the vehicles. The average number of queued vehicles is determined by the following:[1]

$$n = q(R/2 + d) \quad (1)$$

Where: q = Approach flow, veh/sec.
R = Red time, seconds.
d = Average individual delay imposed on that movement.

Queue length is then calculated by multiplying the average number of queued vehicles by 7.6 meters.

- Check-Out Facility Length – The length requirement of the testing equipment. Figure 3 applies for rolling tests during check-out. (only for on-site check-out facilities).

- Pass/Fail Maneuver Length – A set distance provided to take vehicles to a holding area if they fail the check-out testing (only for on-site check-out facilities).

- Queue Length – For on-site check-out facilities, a second queuing area would be required for vehicles that pass check-out and experience delay trying to enter the local street system. The length is calculated using the same procedure discussed previously.

As with check-in, check-out lengths are highly variable due to the variability of the components. The key item to be considered , however is the queue that will develop due to delay experienced by AHS vehicles entering the local street system.

Non-Dedicated AHS Facilities

Exit from a non-dedicated exit facility has many of the same issues as non-dedicated entry:

- Providing an exit facility and procedure that can accommodate unauthorized entry by non equipped or malfunctioning vehicles.

- Provide for differential in operating speeds between the AHS lane(s) and the conventional freeway lanes and the ability of drivers to find gaps in congested areas.

- Provide an area where vehicles can be tested off-site or on-site without adversely affecting either AHS or non-AHS freeway operations.

The actual length of the on-site check-out facility, buffer zone, etc., is dependent on the duration of the testing, the AHS and non AHS volumes at the check-out points and the operating speeds of the AHS during the check-out. The queue length that develops for vehicles waiting to check-out and vehicles waiting for an acceptable gap in the non-AHS traffic for their merge maneuver is the critical item. Under congested freeway conditions and no constraints on demand, extremely large queues could develop with no way to service them. Some form of demand management would be required under this scenario. Demand management techniques are discussed later in this report.

Limited Access AHS

A limited access AHS would utilize an entry/exit configuration that allows access to the AHS lane from select collection points. These collection points would be located to handle traffic traveling from the urban fringe to the central business district (CBD) areas. Drivers would utilize AHS for longer trips only in this postulated system.

The facility configuration within the urban fringe areas could be on the freeway itself so that vehicles could enter the AHS lane at operating speeds. Provisions for vehicles that fail "on-the-fly" check-in testing would be provided prior to the point where the system takes control of the vehicles. Figure 12 presents this entry/exit configuration.

The facility configuration within the CBD would be an exclusive interchange configuration for AHS traffic only. The CBD entry/exit facility could be directly to a park and ride facility, or bus terminal facility. Figure 13 presents a concept for the CBD AHS entry/exit facility.

There are a number of benefits to a limited access AHS facility. The two major benefits from this type of entry/exit configuration are that:

- It supports AHS heavy vehicles and transit use.

- It provides the potential for a reversible AHS lane.

Vehicles enter the AHS from the urban fringe area at operating speed. The long ramp transition required for heavy vehicles and buses to reach operating speed is not required. Since access is limited to the AHS lane, the formation and operating of platoons is unimpeded and does not have to compete with ramp traffic.

Since the AHS terminates at the CBD, entry from this facility is also heavy vehicle and transit friendly. Buses and trucks enter from the first CBD ramps and reach operating speed without competing with other AHS traffic. Cars would enter the AHS far enough down stream of the bus/truck entrance so that the heavy vehicles have adequate room to reach operating speeds.

The limit access AHS freeway configuration also provides for the potential of a reversible AHS lane. The lane would operate in towards the CBD during the morning and out towards the suburbs during the evening. Since there is a limited number of entry/exit points along the AHS, ramp operation and configuration could allow for this type of operation.

This would allow for great savings in the construction of an AHS facility in just the reduction of infrastructure and right-of-way costs. Imports to the surrounding non-AHS facilities would be considerably less since most of the new infrastructure construction is either in the CBD area which is less affected by infrastructure changes or on the fringe of the urban area which is less developed, more rural in nature, and land is still available for infrastructure improvements. It eliminates trying to solve the problem, “How do we fit AHS into this existing corridor without rebuilding everything?” The AHS facility would handle the future growth of the area while the existing conventional freeway handles the existing distance trips.

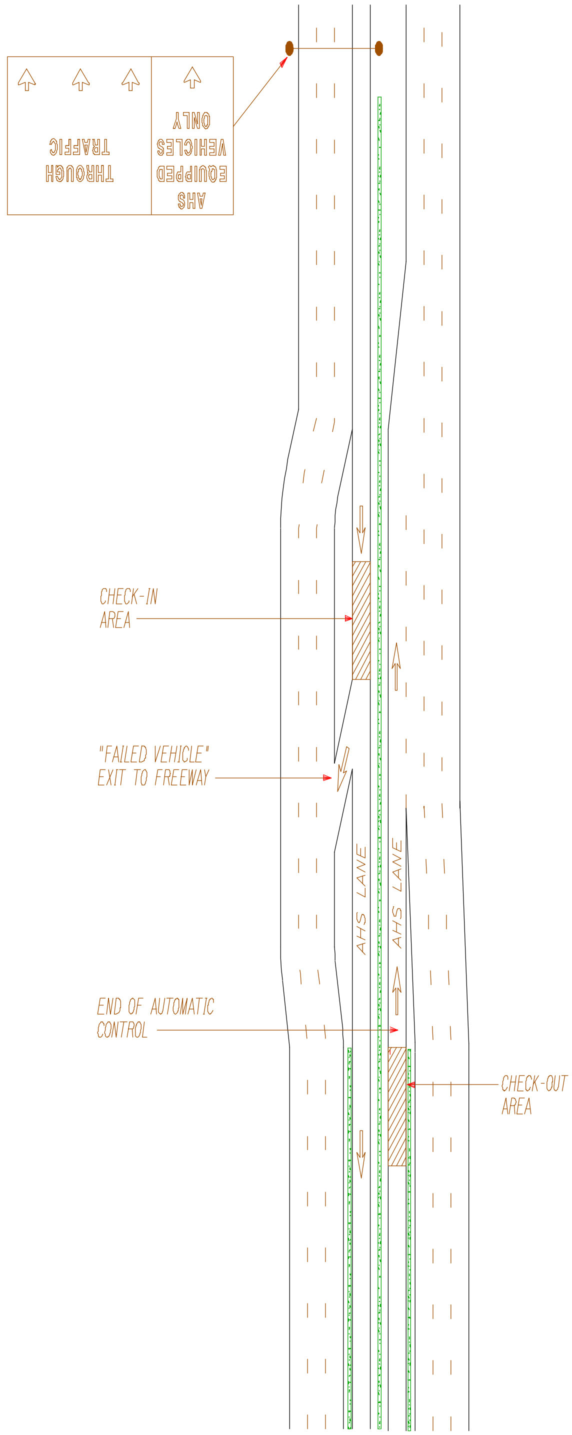

Figure 12. Limited Access AHS Entry/Exit At The Urban Fringe

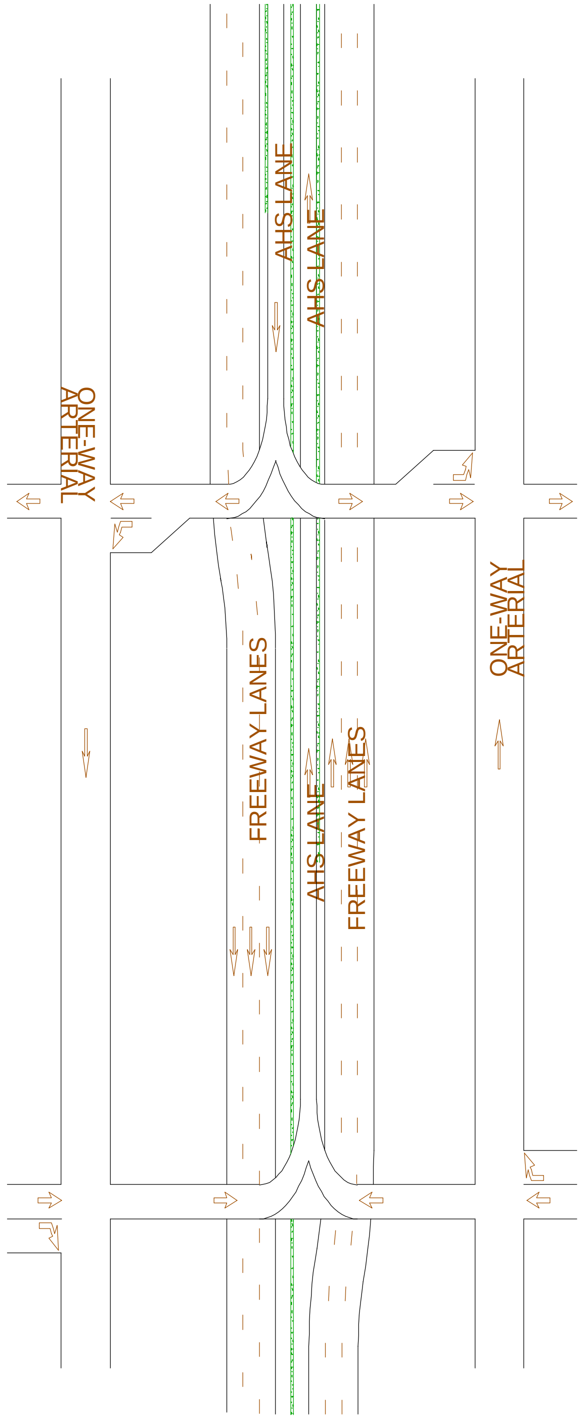

Figure 13. Limited Access AHS Entry/Exit In The CBD

Task 2. Define Measures Of Effectiveness For Entry/Exit Strategies

This task defines Measures of Effectiveness (MOE) for AHS entry/exit strategies. In order to effectively analyze the performance of entry/exit strategies, MOE's to be used for evaluation must be carefully selected to reflect the specific performance requirements. MOE's are derived from the design goals of the system being developed. For example, if a system's goal is to increase highway safety, then accident rates would be a primary MOE.

For AHS entry/exit strategies, a number of MOE's exist. Two classical measures, system throughput and delay, are certainly applicable. Other typical MOE's, such as error rate and system availability also apply. In addition, MOE's specific to the entry/exit strategies, such as the spacing of entry and exit points, will be discussed. The MOE's for entry/exit are summarized in the following table and ranked in relative order of priority, with one being most important.

Entry/Exit Rate

The entry/exit rate MOE measures the throughput allowed by the specific entry/exit strategy. This measure is important because the entry/exit strategy must allow a sufficient number of vehicles to enter the AHS to support the lane capacity of the AHS. Similarly, each AHS exit station must support a sufficient number of vehicles in order to prevent diversion of vehicles to non-AHS lanes for exit. This MOE is ranked sixth because reliability, safety and latency are considered more important than throughput.

Entry/Exit Delay

The entry delay is a measure of the amount of time that each vehicle must wait at an entry station before it is allowed on the automated highway. The exit delay is a measure of the amount of time that a vehicle must wait at an exit station before it is allowed off of the automated portion of the highway. These measures are important because delays at either the entry or exit stations will increase overall travel time and corridor performance. Excessive delays could cause the overall travel time on the automated highway to approach that of the non-automated highway. When this occurs, there will be little incentive to travel on the automated highway. Even relatively short delays could cause AHS to be viewed negatively by motorists waiting in line to enter the AHS while the non-AHS lanes are moving. This MOE is ranked second because entry and exit from the automated lines must not significantly increase the overall travel time relative to non-AHS to gain acceptance.

Operator Interface Complexity

The potential for errors caused by the complexity of operator actions and responses which are required to enter or exit the automated highways is an MOE. The user interface must be designed to provide a straightforward manner for entering and receiving information. The typical operator

Table 2. Measures Of Effectiveness Description And Ranking Matrix

MOE	Description	Ranking	Justification
Entry/Exit Rate	Measure of the throughput of the entry and exit strategies.	6	The entry and exit design must allow sufficient throughput. (Related to Utilization)
Entry/Exit Delay	Measure of the latency or delay when entering or exiting the AHS.	2	Entry and exit design must minimize delays or AHS lanes will not be used.
Operator Interface Complexity	Measure of the operator errors caused by complexity of the man-machine interface.	8	The operator interface must be simple enough to allow error free inputs even while driving.
False Entry Rate	Measure of the number of non-capable vehicles allowed to enter the AHS.	1 (tie)	Non-capable vehicles on AHS lanes will cause a safety hazard.
False Entry Rejection Rate	Measure of the number of capable vehicles not allowed to enter the AHS.	10	The design should allow all vehicles which are properly equipped to enter the AHS.
False Exit Rate	Measure of the number of non-capable vehicles allowed to exit the AHS.	1 (tie)	Vehicles incorrectly allowed to go to manual mode will cause a safety hazard.
False Exit Rejection Rate	Measure of the number of capable vehicles not allowed to exit the AHS.	9	The design should allow all vehicles capable of manual operation to exit the AHS.
System Availability	Measure of the percent of time that any entry or exit station is operating.	5	The entry and exit design must provide sufficient system availability.
Location of AHS Entry & Exit Points	Measure of the distance that AHS vehicles must travel on non-AHS portion of the roadway.	7	The spacing of entry and exit points must allow a high percentage of the travel to be on the automated portion of the highway.
Utilization	Measure of the percent of capacity that the entry/exit stations allow on the AHS.	4	The design of entry and exit points must allow the AHS lanes to reach capacity.
Queue Length	Number of vehicles that must wait to enter or exit AHS	2	Is a function of entry/exit delay.

should be able to correctly enter the proper information all of the time. A poorly designed system will be perceived as confusing by the operator, causing him to either put in incorrect information or not enough information to allow the vehicle to enter the AHS. This MOE is ranked relatively low at eighth, since safety, reliability and overall travel time are considered more important issues than the operator interface.

False Entry Rate

The rate at which the entry strategy incorrectly accepts vehicles which should not pass entry criteria is another measure of effectiveness. Accepting a vehicle onto the automated highway when that vehicle is either not equipped properly or has a failed AHS component could lead to a hazardous condition. The ideal entry strategy would set entry criteria such that a vehicle could not erroneously enter the AHS. This MOE is ranked first, along with the false exit rate MOE, since failure to prevent an improperly equipped vehicle from entering the AHS is a hazardous condition.

False Entry Rejection Rate

Closely associated with the false entry rate is the rate at which the entry criteria rejects vehicles which should be allowed to enter the automated highway. False entry rejection could occur if the entry criteria is set in such a way that vehicles which should be allowed to enter would occasionally be denied access to AHS. This MOE is ranked tenth since it is primarily a nuisance if a properly equipped vehicle is rejected.

False Exit Rate

The rate at which the exit strategy incorrectly allows vehicles to exit the automated lanes is an MOE. The exit criteria must be defined so that when control is given back to the driver, both the driver and the vehicle are able to safely convert to manual control. If either the driver or the vehicle is not capable of manual control and the exit strategy allows manual control to occur, a hazardous condition could exist. This MOE is ranked first, along with the false entry rate MOE, since failure to prevent a vehicle which is incapable of safe manual operation from exiting the AHS is a hazardous condition.

False Exit Rejection Rate

This MOE is the rate at which vehicles which should be allowed to exit the AHS are incorrectly rejected by the exit strategy. These vehicles would be diverted to an area where they can be safely brought to a halt. If the exit criteria is made strict enough to prevent a false exit rate, a non-zero false exit rejection rate may occur. This MOE is ranked ninth since it is mainly an inconvenience if a vehicle capable of manual control is diverted to a holding area.

System Availability

This MOE is a measure of the amount of time that any entry or exit station is inoperative, due to either preventive or corrective maintenance. The specification of the AHS entry and exit stations should include reliability requirements that prevent excessive down time. This is typically accomplished by redundancy or by use of highly reliable subsystems, or through a combination of the two. This MOE is ranked fifth since MOEs related to safety, travel time, and capacity are considered more important.

Location Of AHS Entry And Exit Points

The distance than an AHS user must travel both before entering the automated highway and after leaving automated highway is an MOE. Note that this is not a measure of the density of entry and exit points, but rather a measure of the distance traveled on the non-AHS portion of the highway by each AHS user. This MOE is ranked seventh since some degree of non-AHS travel is expected on automated highways and factors such as the cost and space required by entry/exit facilities tend to reduce priority of this MOE.

Utilization

The percent utilization of the AHS allowed by the entry and exit stations is an MOE. This measure is the difference between the theoretical utilization (i.e. overall capacity) and the actual utilization. The entry and exit stations should be designed such that the full capacity of the system can be achieved. Criteria such as the rate at which vehicles can enter or exit at any station and the spacing of entry and exit points could affect the utilization of the system. The AHS must provide entry/exit spacing and entry/exit rates across the system that allow sufficient cars access to the system to reach capacity. This MOE is ranked fourth since the system design of entry/exit strategy must not prevent the system from reaching capacity.

Queue Length

The number of vehicles that must wait to proceed onto or off of the AHS lane. Queue length is a function of delay associated with the entry or exit procedure. Queue length is calculated by the average number of vehicles queued multiplied by 7.6 meters. The entry and exit facility must provide ample room for the anticipated queues so that the ramp volume does not impede either AHS or conventional freeway and local street operation. This MOE is ranked second since it is closely tied with entry/exit delay.

Task 3. Analyze AHS Entry/Exit Strategies

The analysis of AHS entry/exit strategies concentrated on dedicated facilities. Other AHS contractors have investigated the use of transition lanes and non-dedicated facilities. Operational analyses were performed for three main areas:

- On-site check-in or check-out facilities.
- Interchange location and spacing.
- Ramp terminal analyses for off-site check-in and check-out.

The analysis procedures used to evaluate AHS entry/exit strategies utilized results obtained from the modeling of AHS presented in the Activity I – Impact of AHS on Surrounding Non-AHS Roadways report.

The freeway corridor entry simulation model, FREQ10PE, was used to model a dedicated AHS facility. The model was used to analyze on- and off-ramp queuing, ramp merging, weaving, and travel times. Measures of effectiveness were analyzed including travel time, delay, queue lengths, fuel consumption and vehicle emissions. The effects of varying the access points to the AHS, arrival rates, and service rates were investigated.

On-Site Check-In Entry Analysis

On-site check-in facilities that impose a check-in duration or delay are seen to have similar operating characteristics as toll plazas. Both have an associated service rate to perform a function prior to proceeding onto the freeway facility.

Recent research on toll plazas suggests that stable operation can generally be expected if the average queue length at a toll gate does not exceed three vehicles.[2] It also concludes that average queue lengths of more than 10 vehicles represent a rather unstable and undesirable operation. Measures of effectiveness used to assess toll plaza operations are average queue length and average time spent in the system (average vehicle delay). In this report the peak hour of traffic demand is used for analysis of queue lengths. Queue lengths reported are those that are predicted by the various models within or at the end of the peak hour.

Lin and Su [2] have proposed a subjective operational classification in the form of Level of Service (LOS) ranking that can be used in the planning of toll plazas. The following table provides the LOS criteria selected:

Table 3. Level Of Service Criteria For Toll Plaza Operation

LOS	Average Queue Length (vehicles)	Average Time In System (sec/veh)
A	≤ 1	≤ 15
B	$1 < L \leq 2$	$15 < T \leq 30$
C	$2 < L \leq 3$	$30 < T \leq 45$
D	$3 < L \leq 6$	$45 < T \leq 60$
E	$6 < L \leq 10$	$60 < T \leq 80$
F	> 10	> 80

Although LOS is a subjective characteristic that is a function of human perception, it can provide a means for sizing AHS entry facilities as well, since drivers' perception of how long they must wait prior to entering the AHS will greatly affect the market absorption or desirability of AHS. Drivers in large urban areas, where congestion is more common, may accept longer delays than those in small urban areas because drivers will perceive a better operation than on a conventional freeway. Therefore, LOS could also be used to evaluate and size the AHS entry check-in facilities.

Demand at check-in facilities is a function of desirability and the frequency of check-in facilities. The latter has been termed interface point spacing. The demand at each check-in facility for a 25 km long AHS freeway will be different if vehicles are allowed on every 1.6 km versus being allowed on every 5 km. As AHS entry points become further apart, the demand at each facility will increase provided the desirability to use AHS remains constant. As demand increases so does the size of the check-in facility. Table 4 shows the relationship between demand and service rate in the form of average queue length and average time in the system. Both measures of effectiveness were determined using dQueue, a dynamic queuing analysis program that simulates operations at toll facilities.[3] Number of stations listed in the table refers to the number of check-in lanes available for processing at the facility. As shown in table 4, as demand increases, the number of stations required to process the vehicles under stable operational conditions increases.

The lowest service rate used in this analysis was 240 vehicles per hour. This equates to one vehicle processed every 15 seconds. Although the actual check-in process may require more than 15 seconds per car, it is believed that some of the testing will occur off-site prior to the vehicle reaching the check-in facility. If actual service rates for AHS check-in are lower than 240 veh/hr, the size of the facility required for processing and storage of vehicles becomes extremely large even at lower demands. For example, at a service rate of 144 veh/hr and a demand of 500 veh/hr, a three station check-in facility would be required and the average time in the system per vehicle would be approximately 112 seconds. Referring back to the LOS criteria, this operation would equate to a LOS of F.

Table 4. Queue Lengths Associated With AHS Check-In.

Service Rate (veh/hr)	Demand (veh/hr)	Number of Stations	Average Queue Length (veh)	Average Delay (sec/veh)
240	500	1	104	1,563
240	500	2	8	123
240	500	3	1	13
240	750	2	71	1,069
240	750	3	10	157
240	750	4	1	15
240	1,000	2	137	2,052
240	1,000	3	55	830
240	1,000	4	10	154
240	1,000	5	1	17
240	1,500	3	134	2,012
240	1,500	4	77	1,148
240	1,500	5	37	560
240	1,500	6	7	111
240	1,500	7	1	19
360	500	1	66	660
360	500	2	1	11
360	1,000	2	65	645
360	1,000	3	1	15
360	1,500	3	69	694
360	1,500	4	5	50
360	2,000	4	34	341
360	2,000	5	1	11
720	500	1	2	11
720	1,000	1	135	673
720	1,000	2	2	8
720	1,500	2	15	76
720	1,500	3	1	7
720	2,000	2	66	329
720	2,000	3	2	9
720	2,500	3	1	4

Check-in length was calculated for a dedicated AHS entry facility with the following characteristics:

- A 15 second check-in duration and vehicles stop for testing (service rate = 240 veh/hr).
- Acceleration rate that allows vehicles to go from 30 to 100 km/h in a distance of 380 m.
- Acceleration from 0 to 30 km/h occurs in the pass/fail area (see figure 1).
- Deceleration length of 80 m (from 65 to 0 km/h).
- Arbitrary selection of fixed length segments:
  - Check-in equipment – 30 m.
  - Pass/fail maneuver length – 30 m.
  - Vehicle length – 7.6 m.
  - One lane transition length – 55 m.

Demand and the number of stations (lanes performing check-in testing) varied to show the effect on total check-in length. Measures of effectiveness were also obtained from this analysis.

Figure 14 shows the average delay associated with queues for a certain demand and number of check-in stations. Figure 15 provides the average number of vehicles in the queues. Total entry facility lengths were calculated by combining the parameter lengths previously mentioned. The facility lengths shown in figure 16 assume that there is no delay imposed on vehicles after they have successfully checked-in and start their acceleration to AHS speed, i.e. there is no delay in merging onto the AHS. The lengths given in figure 16 reflects a lineal distance required for the facility and does not reflect the actual physical layout. These values are for passenger cars only.

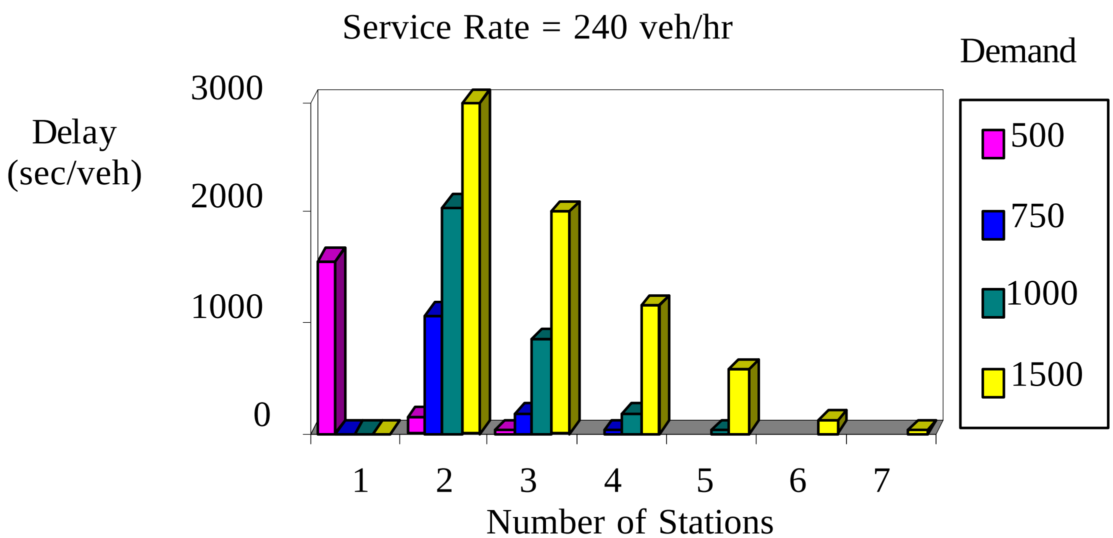

Figure 14. Average Delay For Queued Vehicles Entering AHS With On-Site Check-In

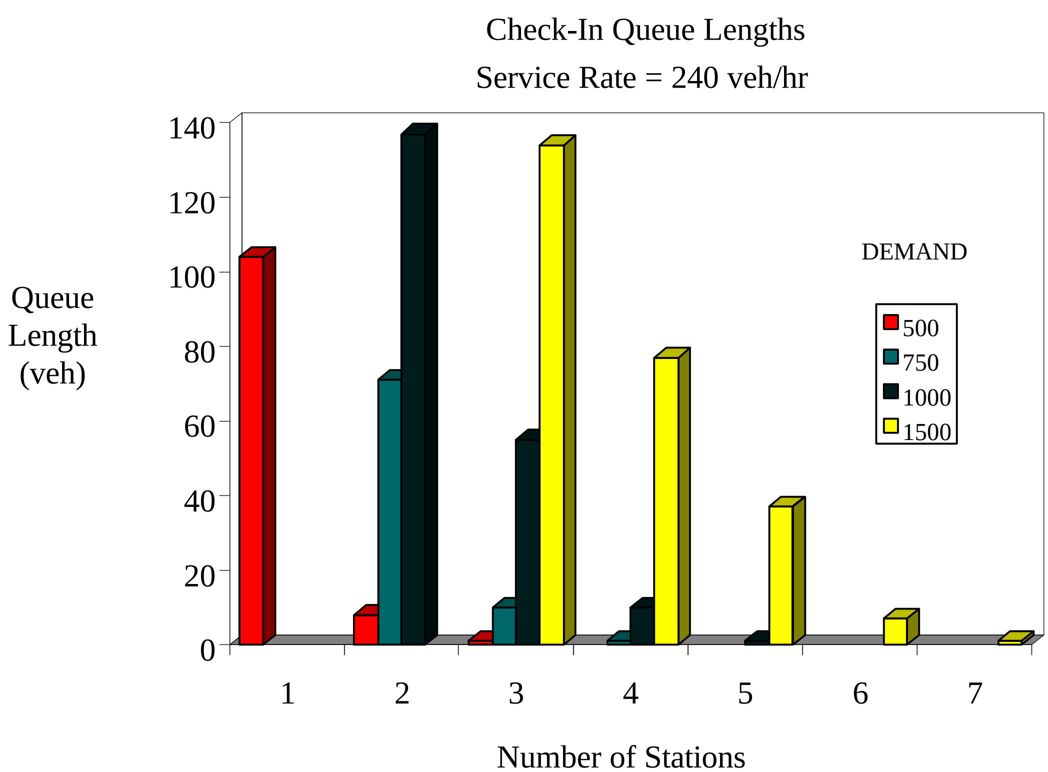

Figure 15. Average Queue Lengths At AHS Entry With On-Site Check-In

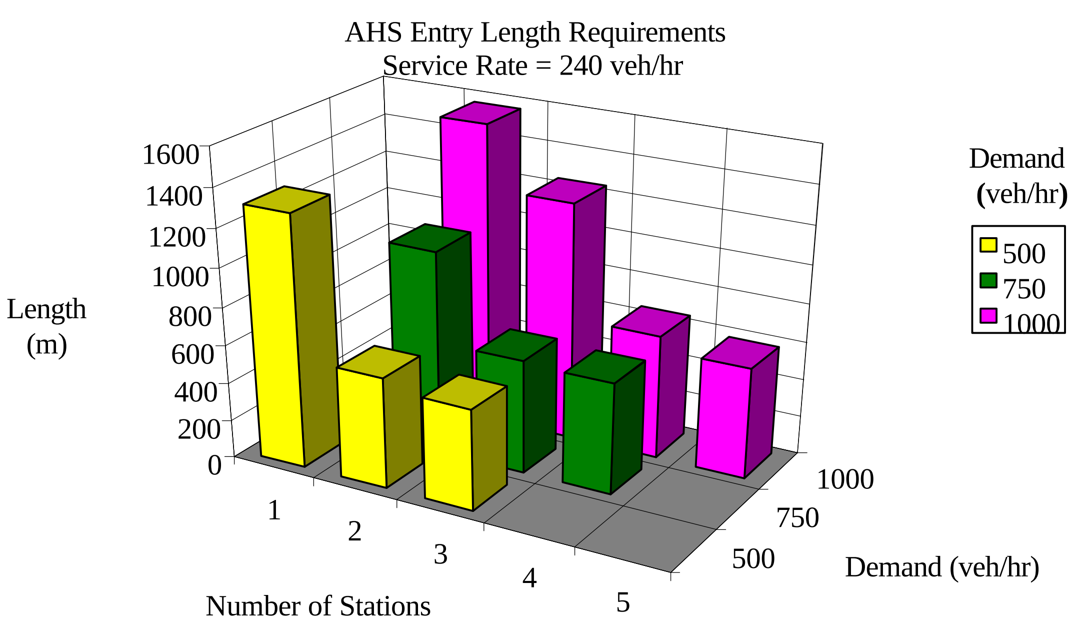

Figure 16. Estimated AHS Entry Length For On-Site Check-In

In order to determine the impacts different check-in operations have on facility length, the same parameter estimations were made for facility operation that does not require vehicles to stop for testing. For this operation it was assumed that more than one vehicle can undergo testing at the same time. A 15 second check-in duration was chosen so a comparison of check-in facility lengths between a stop and no-stop operation could be made.

This operation provides the following characteristics:

- A 15 second check-in duration and vehicles do not stop, assume a 30 km/h testing speed allowing a service rate = 720 veh/hr (in close agreement with table1).
- Acceleration rate that allows vehicles to go from 30 to 100 km/h in a distance of 380 m.
- Deceleration length of 80 m (from 65 to 0 km/h).
- AHS operating speed of 100 km/h.
- Fixed length segments as follows:
    - ∗ Check-in length – 135 m. Assumes AASHTO braking distance between vehicles.
    - ∗ Transition length per lane– 55 m. (lanes are tapered out over a distance of 55 m).
    - ∗ Pass/fail maneuver length – 30 m.
    - ∗ Vehicle length – 7.6 m.

Figure 17 shows the total entry facility length required for the two check-in operational procedures given a check-in demand of 1,000 vehicles per hour. A comparison of facility lengths are given for varying number of stations.

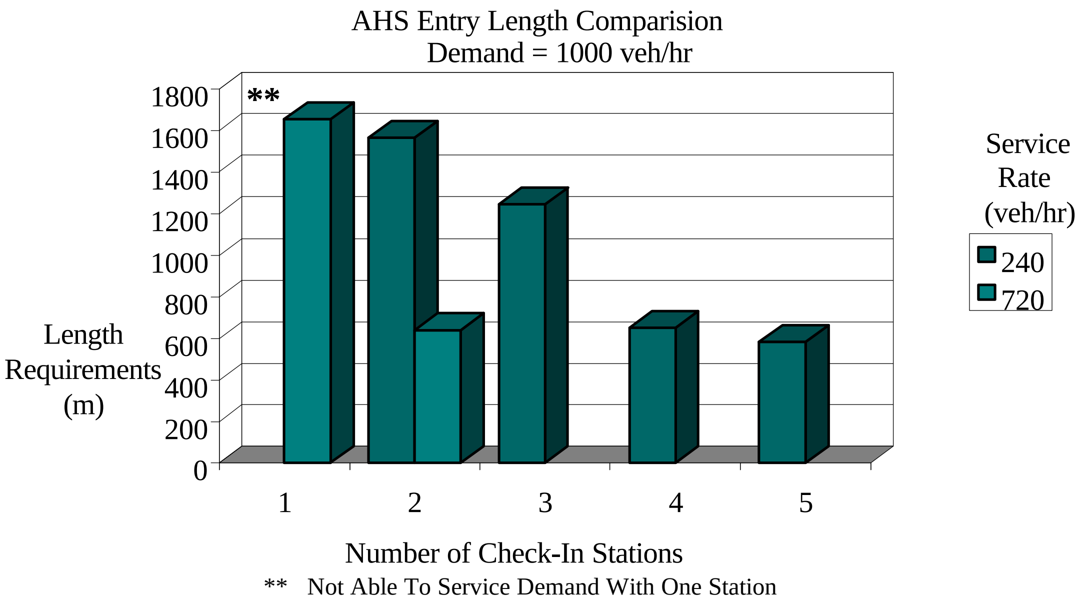

Figure 17. AHS Entry Length Requirements For Two Check-In Procedures

Figure 17 illustrates the trade-off between service rate and number of check-in stations provided. For a one station entry facility, a no-stop testing procedure requires approximately 1600 meters in total length. A stop condition for testing (service rate 240 veh/hr) cannot process demand of 1,000 veh/hr. The queue that would form would be so large that a system failure would occur.

However, if the entry facility can afford the spatial requirements to accommodate five check-in stations, then the total facility length required for a stop condition for testing is less than for a no-stop procedure. Figures 18 and 19 provide a comparison of two measures of effectiveness, average queue length and average vehicle delay respectively. Both show the same trade-off comparison.

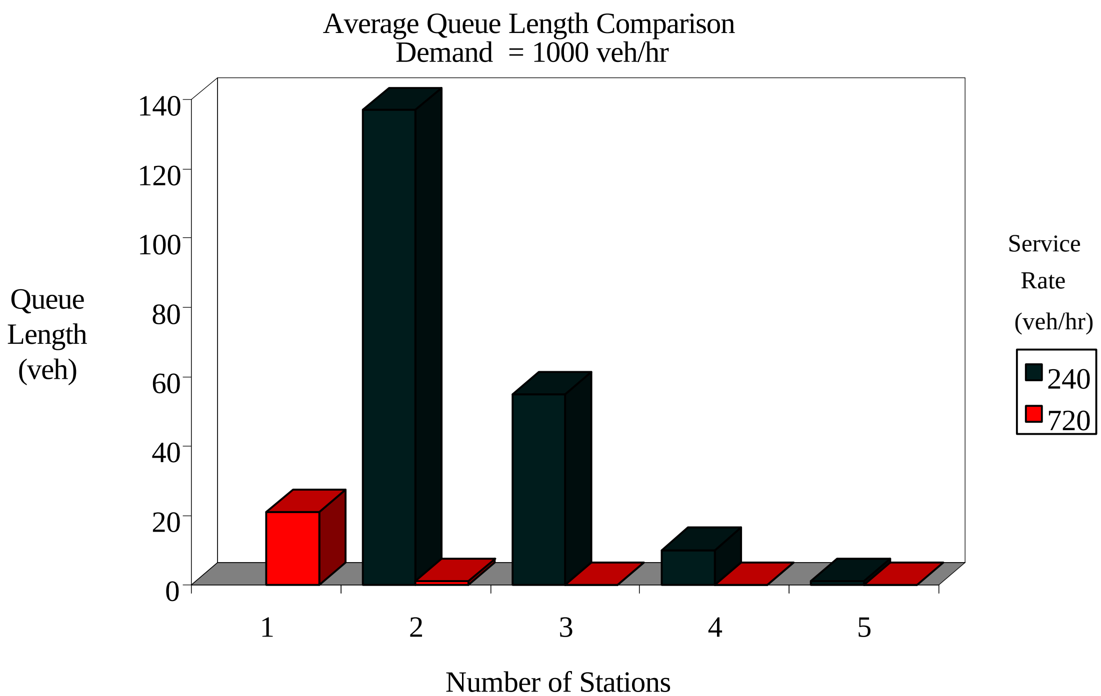

Figure 18. Average Queue Lengths For Two Service Rates

Stop condition testing, that equates to lower service rates, can perform equally with higher service rate testing procedures provided enough testing stations can be located at the facility. Only when the demand becomes very large (1,800 veh/hr) do inequalities arise. Figure 20 presents the number of stations required for various service and demand rates. Adding more check-in stations at an entry facility is an issue of cost, available space, and compatibility with system functions. If AHS vehicles will be subjected to any noticeable check-in duration during testing, a trade-off analysis will be required when selecting the preferred entry operation for use at a particular location. If the AHS compatibility limits the number of stations allowed per entry facility, then the service rate provided must accommodate the demand within these limitations. Under the modeling scenarios conducted in Activity I – Impact of AHS on Surrounding Non-AHS Roadways, ramp volumes of 2,000 to 2,900 veh/hr can be expected for AHS ramps at a market penetration rate of 40 percent and 1.6 km interchange spacing. Therefore, at a check-in service rate of 360 veh/hr, each check-in facility would require five to seven stations to handle the demand with acceptable vehicle delays and queue lengths.

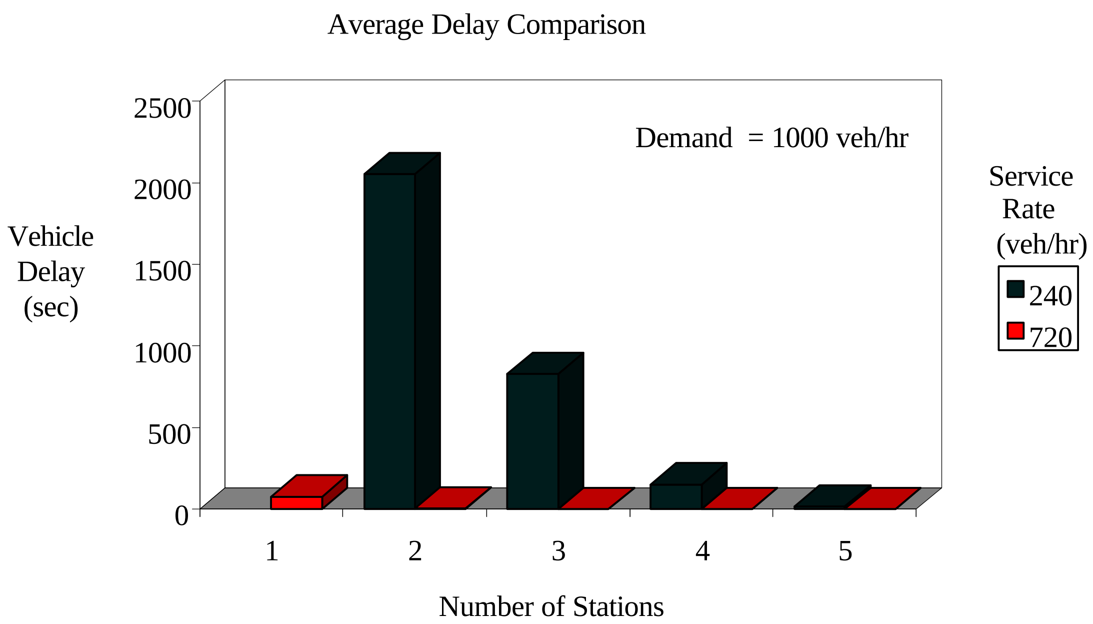

Figure 19. Average Vehicle Delay For Two Service Rates

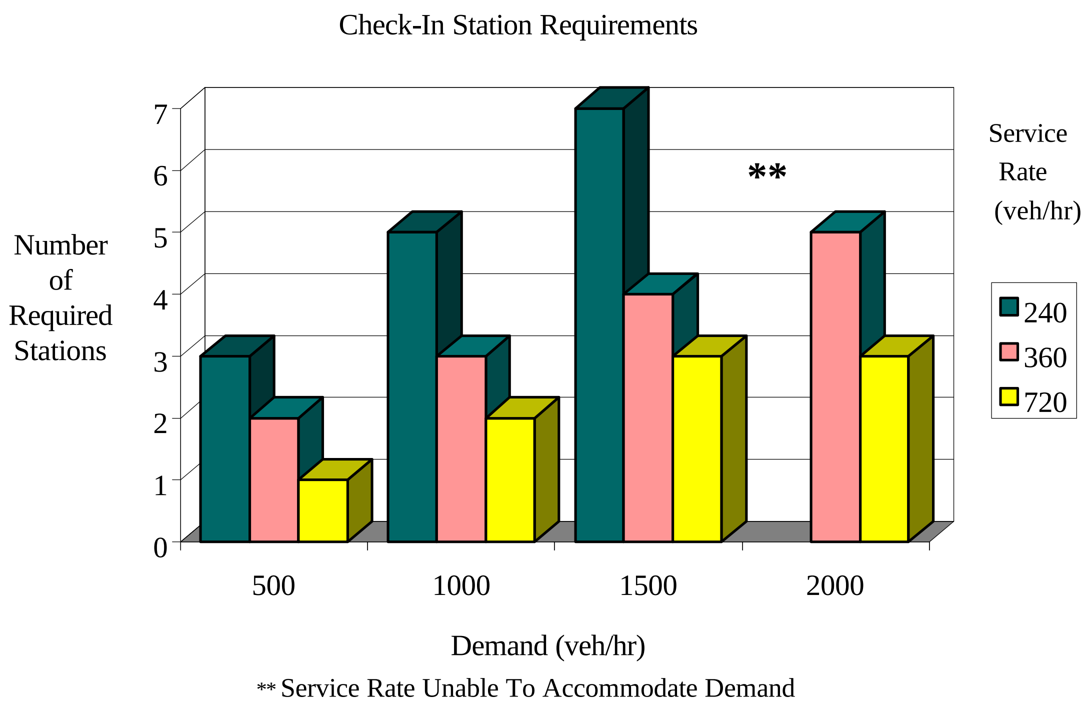

Figure 20. Check-In Station Requirements At AHS Entry

It is important to state that these comparisons were for a 15 second check-in duration and a demand of 1,000 veh/hr. Due to the lower check-in speed utilized for the no-stop condition, spatial requirements for check-in testing are feasible. If the check-in speed was 90 km/h, then approximately 400 meters is needed for a 15 second no-stop check-in test (see figure 3). Yet, the service rate obtainable for this condition is still 720 veh/hr, assuming AASHTO braking distance is provided between cars under system control. From figure 20, a demand of 1,500 veh/hr will require three check-in stations for a service rate of 720 veh/hr. In this case, a check-in speed of 90 km/h has larger spatial requirements since each check-in lane must extend to approximately 400 meters, versus the 135 meters required for a 32 km/h check-in speed.

However, in an urban setting, it will be extremely difficult to obtain the space required for these testing stations. The space requirements for dynamic testing make on-site check-in infeasible. Work performed for Activity B – Automated Check-In and Activity C – Automated Check-Out show that on-site check-in/check-out are not required for AHS to be feasible. “On-the-fly” check-in and check-out will be required at the entry and exit points of the AHS, but the time requirements are in the millisecond range.

Based on the modeling of AHS presented in the Activity I – Impact of AHS on Surrounding Non-AHS Roadways report, AHS ramp volumes exceeding 1,500 vehicles per hour can be expected at low market penetration rates and 1.6 kilometer interchange spacing. Applying the criteria discussed previously to these ramp volumes would require entry facilities with three to five check-in stations every 1.6 kilometer. The cost to obtain the land and construct and maintain the facilities will be enormous, in most urban settings. Other research shows that vehicle check-in and check-out can occur off site and eliminate these costs. It is therefore concluded that the design of entry and exit facilities should exclude on-site- check-in and on-site check-out capabilities.

Although the analyses for on-site check-out exit facility would incorporate the same procedures and parameters as done for on-site check-in entry facilities, the actual analyses were not performed due to the conclusions drawn from the on-site check-in analysis.

Interchange Location

The scenario of placing a dedicated AHS ramp(s) within an existing conventional freeway corridor has primarily two options for AHS interchange locations; at the same location as the conventional freeway interchange or at separate locations.

In an urban setting, most conventional freeway interchanges are signalized at the ramp/cross street conjunction. Adding dedicated entry/exit ramps for AHS at the same location would cause poor cross street and ramp operations due to the proximity of ramp signals (AHS and conventional freeway) and the need to provide for all intersection movements. Under heavy ramp volumes, cross street operation would suffer causing severe delays and long queues to form. Ramp operation would degrade and cause queues to form on both the AHS and conventional freeway ramps.

Typical minimum spacing between conventional freeway interchanges is 1.6 kilometers to allow for ramp movements onto and off of the freeway. One way to avoid the operational problems associated with combining both the AHS and conventional freeway ramps at the same cross street is to separate the two. AHS entry/exit ramps would be offset to the cross street located midway (approximately 0.81 kilometers) between the principal arterial streets and conventional freeway interchanges. Separating the two facilities can only work if the AHS is a dedicated facility with separate entry and exit ramps. Figure 21 depicts this possible interchange configuration. An AHS slip ramp configuration with a left-handed entry and exit ramp configuration would provide the best operational conditions at the cross street since the ramp configuration allows for a single point signalization phasing. This configuration corresponds to a no delay check-in or check-out procedure.

The staggering of AHS and conventional freeway interchanges also separates the circulation patterns of each on the surrounding street network. This may be of benefit in handling large AHS ramp volumes. The collector street located midway between the arterial streets which provide access to the conventional freeway typically do not cross the freeway and dead end at facilities right-of-way limits. Therefore, no cross traffic presently using these collector roads.

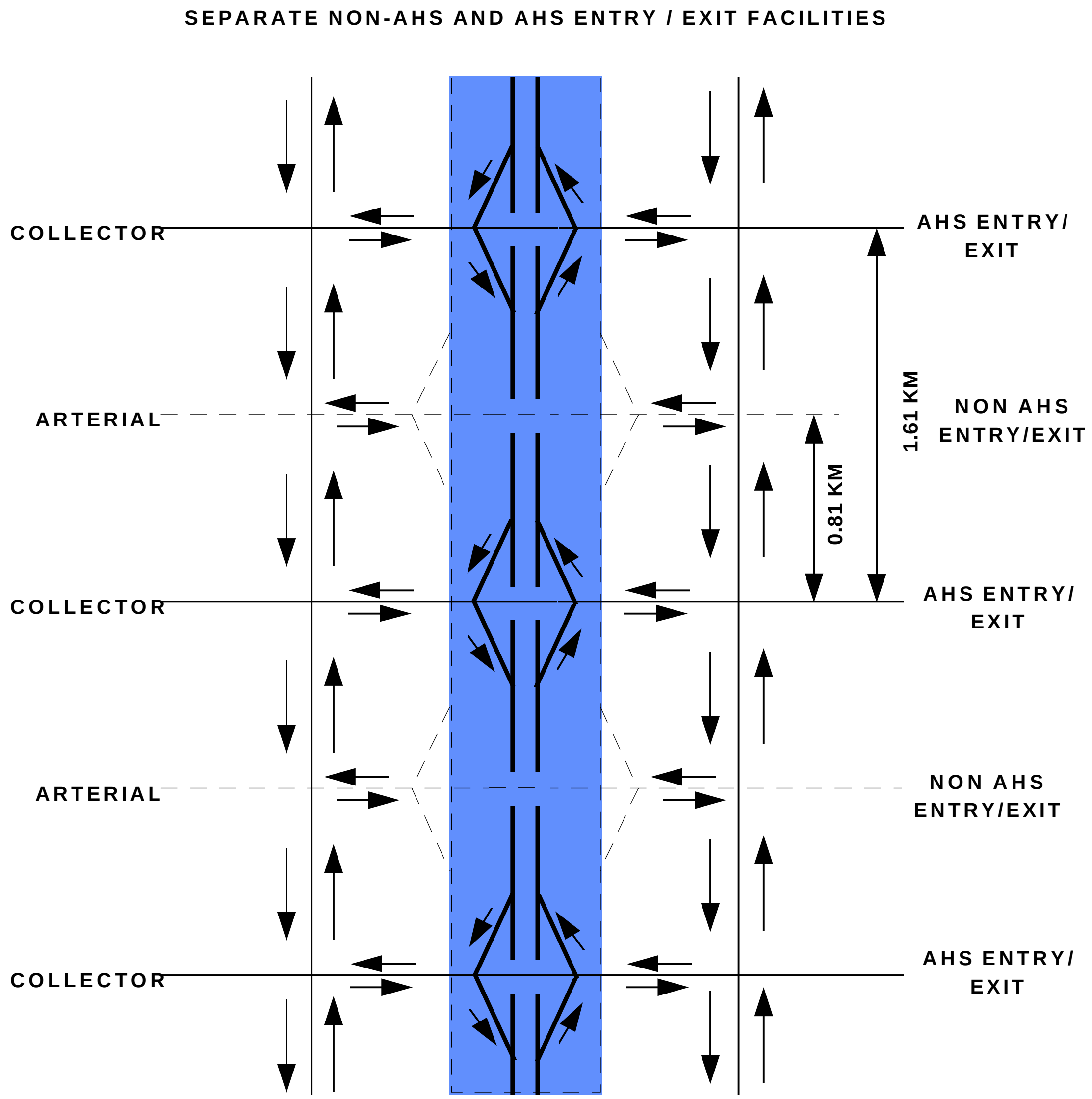

Figure 21. AHS Entry/Exit Separate From Conventional Interchanges

Construction of the AHS interchange from the collector road should be configured so no through traffic movement is allowed and therefore is limited to AHS traffic only at the interchange. This would maintain the same circulation patterns as present which would keep the non-AHS traffic to a minimum on these roadways. Since the AHS freeway and the conventional freeway are separate and their ramps enter from different sides of the freeway, the 0.8 kilometer spacing is can be accommodated.

The ability to separate AHS and conventional freeway traffic, both throughout and their entry and exit maneuvers provides an advantage in operating the two systems in the same corridor. The major disadvantages is the cost of constructing new interchanges for AHS entry and exit and the effects on the collector roads which presently carry minor traffic volumes. At higher market penetration rates, larger AHS volumes could exceed the capacity of the existing collector roadways. The collector streets may be required to be upgraded to arterial street classification (operational and physically) to accommodate the heavy AHS volumes.

Interchange Spacing

One strategy to limit the financial constraint of the proposed AHS interchange location and configuration is to limit the number of locations where AHS entry and exit can occur. Increasing the AHS interchange spacing would reduce construction costs and impacts on the collector streets to which they connect.

The urban corridor was modeled to compare the operational features of a 1.6 km spacing and a 4.8 km spacing of dedicated AHS interchanges. The analysis and resulting operational impacts were found to be a function of market penetration. The Activity I report presents the operational analyses using the FREQ model. The analyses showed that even at lower market penetration rates (30 percent of all vehicles equipped for AHS), that same AHS ramp volumes at the 4.8 kilometer spacing exceed 4,000 veh/hr. The results are consistent with expectations. As the number of entry and exit points to AHS are reduced, the hourly volume at the remaining points increases as long as the market penetration remains constant.

An interesting result of the interchange spacing analysis is the effect of interchange spacing on the overall corridor performance. Corridor performance decreases at an approximate market penetration rate of 40 percent due to the excessive ramp delay associated with the larger AHS interchange spacing. Ramp capacity is governed by geometry and the signalized ramp terminal point. AHS ramps are constrained by the same factors affecting conventional freeway ramps. Ramp capacity of a conventional freeway is approximately 1,500 veh/hr per lane. If demand exceeds the operational capacity of the ramps, then the whole corridor operational effectiveness diminishes even though the AHS lane is operating at two to three times the capacity of a conventional freeway lane.

The conclusion drawn from this analysis is that the AHS entry and exit operations govern the extent of corridor improvements that are achievable with AHS implementation. AHS entry and exit design must account for large ramp volumes. For urban areas, AHS ramp designs must be able to provide for a minimum of 2,000 veh/hr per lane.

Ramp Terminal Analysis

The modeling analysis and the interchange spacing analysis revealed that the AHS ramp terminal points, where the AHS ramps connect to the local street network will be the choke point for AHS. The capacity of these intersection points are governed by conventional traffic operations. This will be more critical in urban areas than in rural areas simply because rural areas have less vehicle traffic, rarely provide for pedestrian movements, and are typically unsignalized intersections. Therefore the emphasis of study was applied to urban interchange locations.

The constraints facing AHS ramp traffic consist of the following:

- Typically signalized terminal points.
- Signal phasing that must accommodate pedestrian movements.
- Interconnection with other signals along the cross street.
- Large cross street volume.
- Conflicting turning movements.
- Limited storage area for turning traffic.

The AHS slip ramp entry/exit configuration favors a typical signalized intersection at the cross street. For urban areas, its operation will be constrained by the items listed above. Figure 22 provides a schematic of a AHS slip ramp configuration at the local cross street. This configuration is termed a dual direction entry/exit configuration since both AHS entry and exit maneuvers in both directions of travel occur at one interface point.

Signalized intersection operation is evaluated in terms of capacity and LOS. Capacity analysis of signalized intersections results in the computation of volume to capacity ratios (V/C) for individual movements and a composite V/C ratio for the sum of the critical movements or lane groups. LOS is based on the average stopped delay per vehicle for various movements within the intersection.

Table 5 provides the LOS criteria used for signalized intersections as established by the Highway Capacity Manual. For most local agencies, an intersection LOS of D or above is acceptable for a urban signalized intersection. Intersection operation is greatly affected by turning movement volumes and their opposing volume that conflicts with their movement, the type of signal phasing utilized, the cycle length of the signal, and the street geometry provided. Under typical signalized operation, an intersection can accommodate approximately a 3,000 to 3,500 total veh/hr (sum of total approach volume) depending on the number of approach lanes provided and the left turning volume while maintaining a LOS of D.

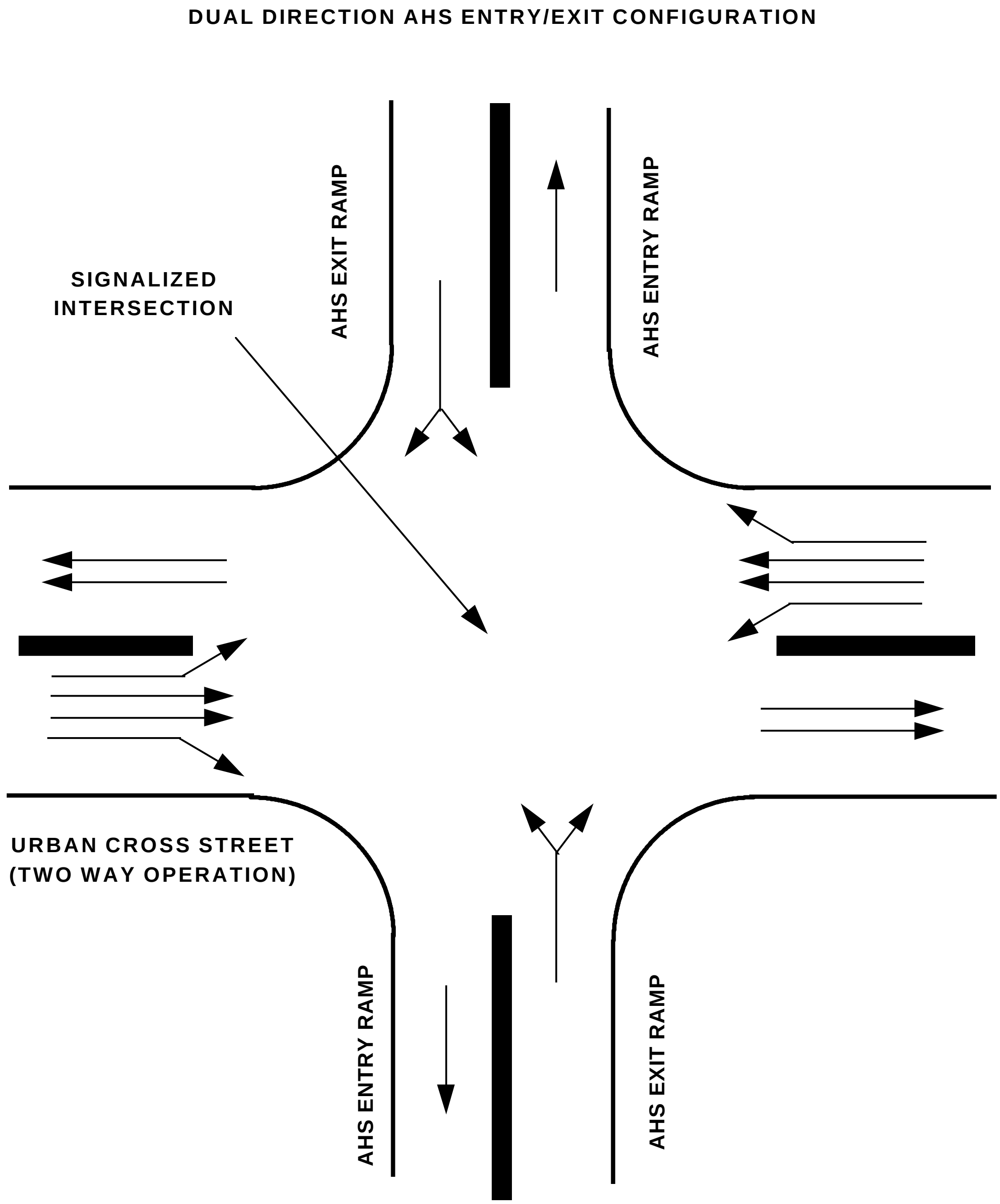

Figure 22. Dual Direction AHS Entry/Exit Ramp Terminal Intersection With Cross Street

Table 5. Level Of Service Criteria For Signalized Intersections

Level Of Service	Stopped Delay Per Vehicle (Sec)
A	$\leq$ 5.0
B	5.1 to 15.0
C	15.1 to 25.0
D	25.1 to 40.0
E	40.1 to 60.0
F	> 60.0

The modeling analysis showed that just one ramp of AHS may have a demand of 2,000 to 2,900 veh/hr at a market penetration rate of 40 percent with 1.6 km spacing of interchanges. AHS ramp volumes of this magnitude will not be able to be accommodated.

under a typical signalized intersection configuration. Long delays and queue lengths would be experienced on all approaches to the intersection.

For AHS to operate at its full potential, a means of handling large AHS ramp volumes, without sacrificing cross street operation must be developed. This is accomplished by eliminating conflicting movements at the ramp intersection with the local cross street and increasing the potential for free flow movement through the intersection.

One method to eliminate conflicting movements at the ramp terminal point is to stagger AHS entry/exit facilities by direction of flow. Figure 23 provides a schematic of this concept. This operation assumes that AHS and conventional freeway interchanges are already staggered. This staggered arrangement of entry/exit facilities by directional flow results in eliminating conflicting left turns from AHS ramps, but still requires signalization of the ramp terminal point, eliminating the potential for free flow operation. As discussed earlier, the collector road located between the conventional freeway interchanges typically does not cross the freeway and therefore does not presently provide for through movements. This can be used to AHS advantage if locating the AHS entry/exit facilities at the collector road. No local street traffic or through movement is allowed within the freeway right-of-way at these locations. Only AHS traffic is allowed to use the cross street within the vicinity of the AHS interchange. This would eliminate through movements at the ramp terminals which would allow more green time to the turning movements, thereby improving ramp operations.

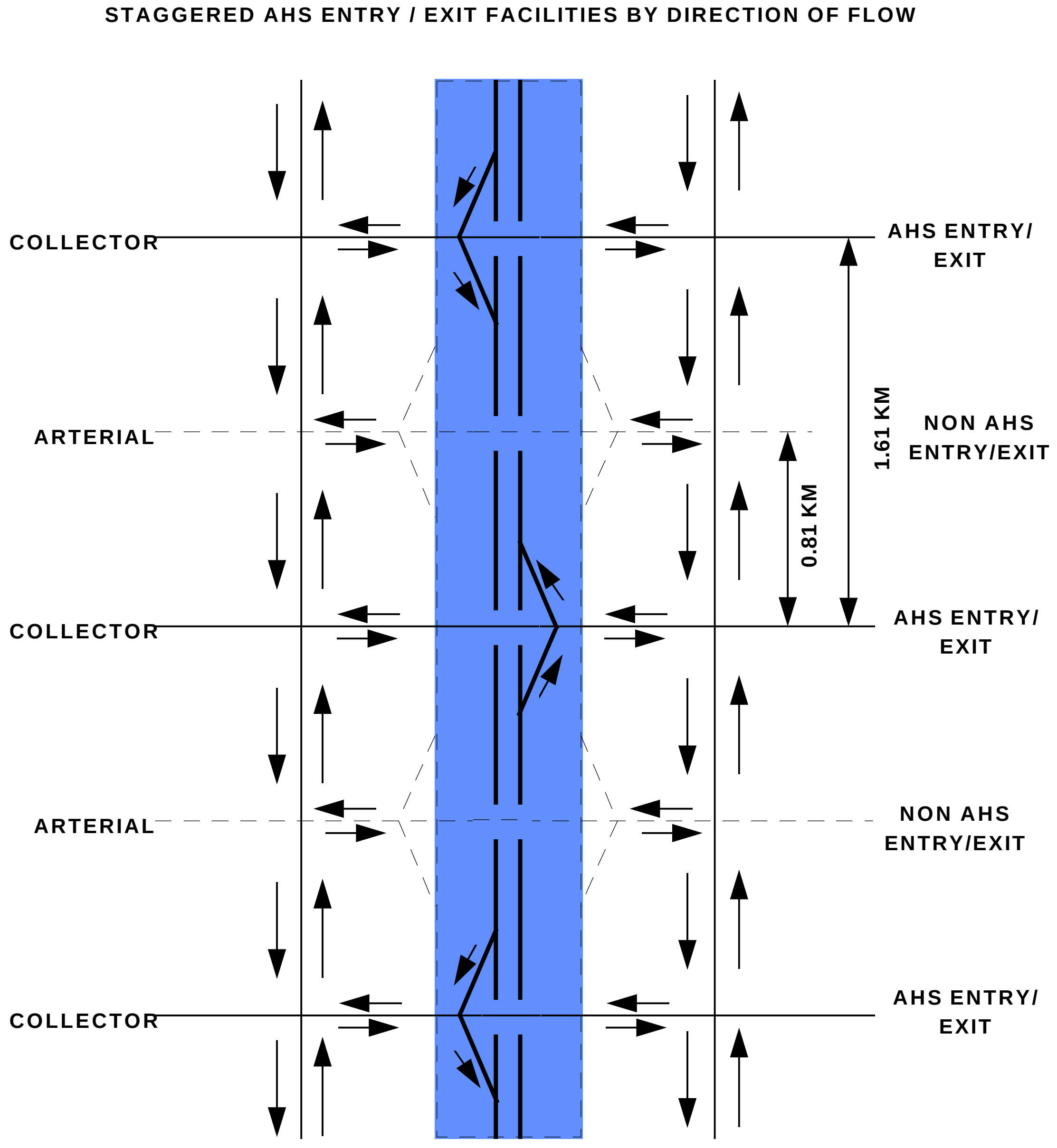

Figure 23. AHS Entry And Exit Staggered By Direction Of Travel

Eliminating the traffic signal at the ramp terminal would greatly improve operation if conflicting turning movements to and from the ramp can be eliminated. This can be accomplished by separating the AHS entry operation from the AHS exit operation and implementing one-way operation on the local cross street within the vicinity of the ramp. Figure 24 provides a schematic of the this type of operation. This operation would provide for both directions of travel at the same cross street, but solely for either AHS entry or AHS exit. The spacing between AHS entry or exit facilities would be approximately 3.2 km.

One-way operation on the intersecting cross street would be away from the AHS ramps if it was an exit facility and towards the AHS ramps if it were an entry facility. There would be no through movement on the cross street for AHS or local traffic. Figures 25 and 26 provide a schematic of ramp terminal intersections for AHS entry and exit respectively under this scenario. This configuration allows the ramp terminal points to be unsignalized and provide free flow movements without conflict to and from the ramp. This type of operation can accommodate large ramp volumes. Recent traffic counts performed for a location in Phoenix, Arizona where a freeway terminated into a local arterial roadway by means of a free flow 90 degree right-turn revealed hourly volumes of 2,300 veh/hr per lane at approximately 32 km/h operating speeds. All conflicting volumes on the arterial roadway had to be eliminated so that capacity was a function of roadway geometry (turning radius) and vehicle headway.

This particular freeway termination is similar to the proposed AHS entry/exit configurations. Therefore, hourly flow rates of 2,300 veh/hr per lane (single lane ramp) should be achievable especially if speeds and headway around the turns are system controlled. Control would then be returned to the driver after the car has made the turn and is traveling on the cross street, i.e. transition back to the manual mode on surface streets.

However, these large ramp volumes must be integrated into the local street network without degrading operation. The dispersing of AHS exit volume or the collection of AHS entry volume will require modifications to the local street network, at least in the vicinity of the AHS corridor. A method that could be utilized that would not require major geometric changes to the local street system is the implementation of one-way street operation. This would be accomplished by converting the closest local streets parallel to the freeway to one-way operation. The resulting intersection of the AHS interchange cross street with these roads would be signalized in an urban setting. However, the intersection of the one-way pairs allows a simple two-phase signal operation. Extreme flexibility in the allocation of green time to each phase to accommodate approach demand volumes is possible. This configuration is similar to a freeway that has parallel one-way frontage roads. Figures 27 and 28 show the individual AHS entry and exit configurations under this scenario.

STAGGERED AHS ENTRY AND EXIT FACILITIES

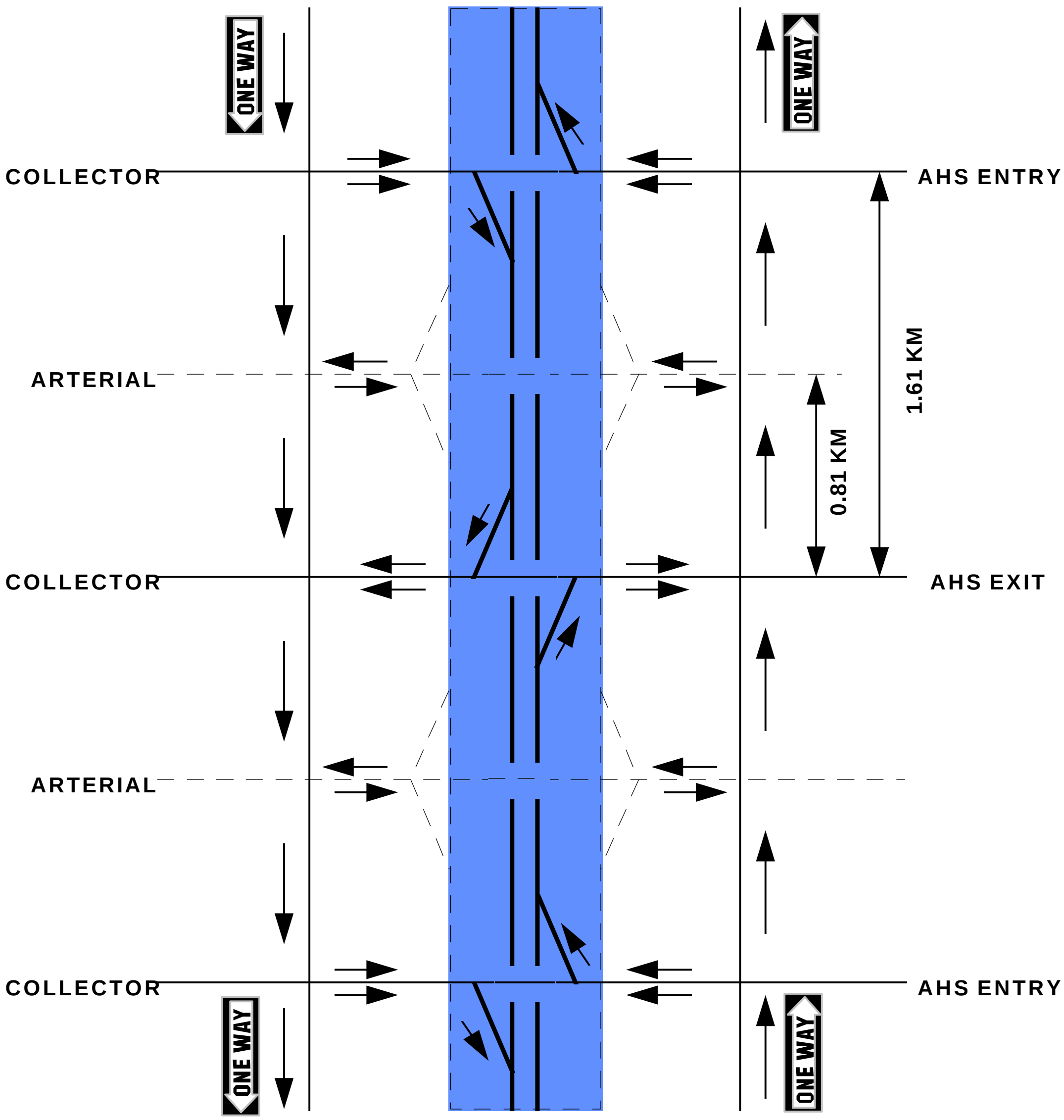

Figure 24. AHS Entry And Exit Are Separated And Staggered

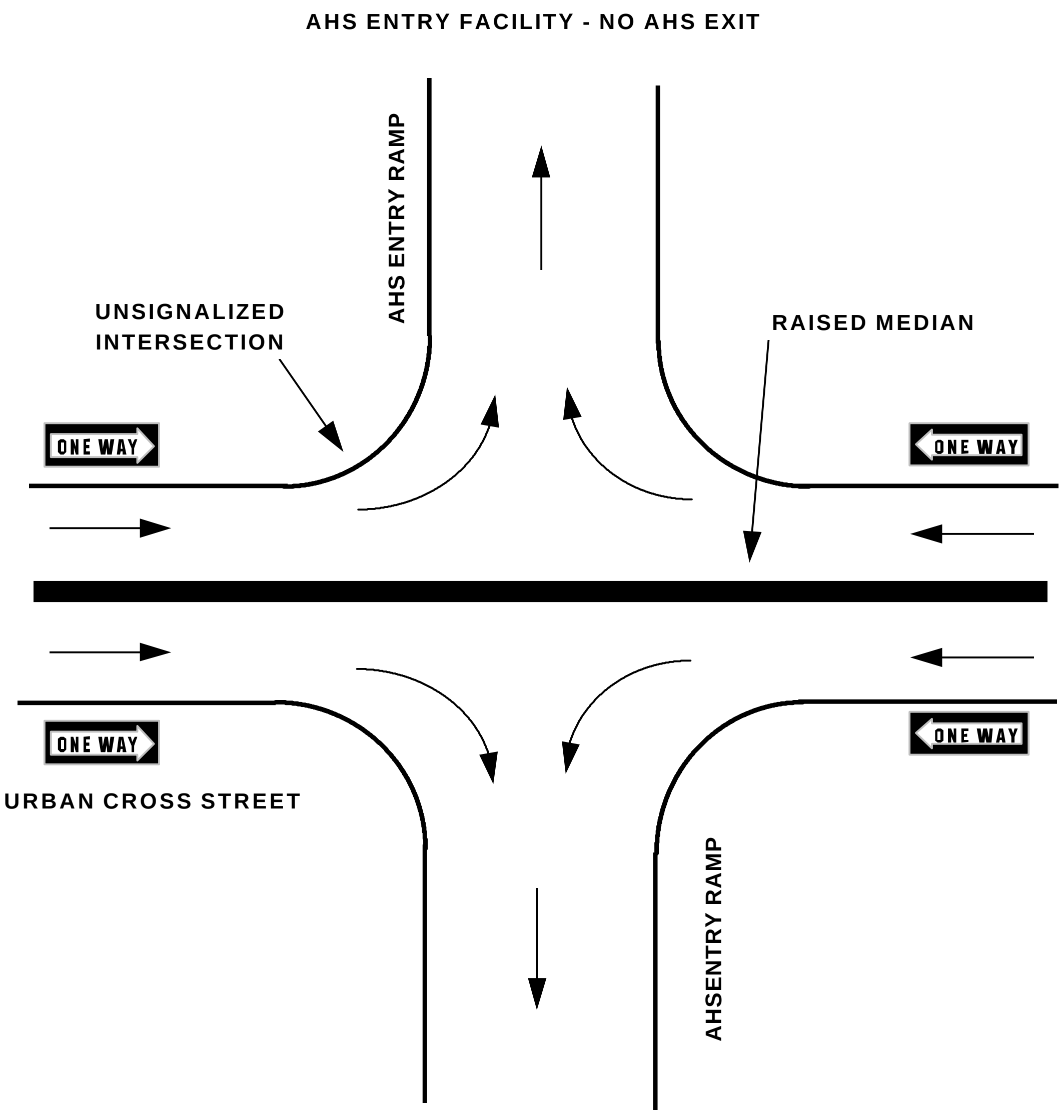

Figure 25. Free Flow AHS Entry Utilizing One-Way Operation On Cross Street

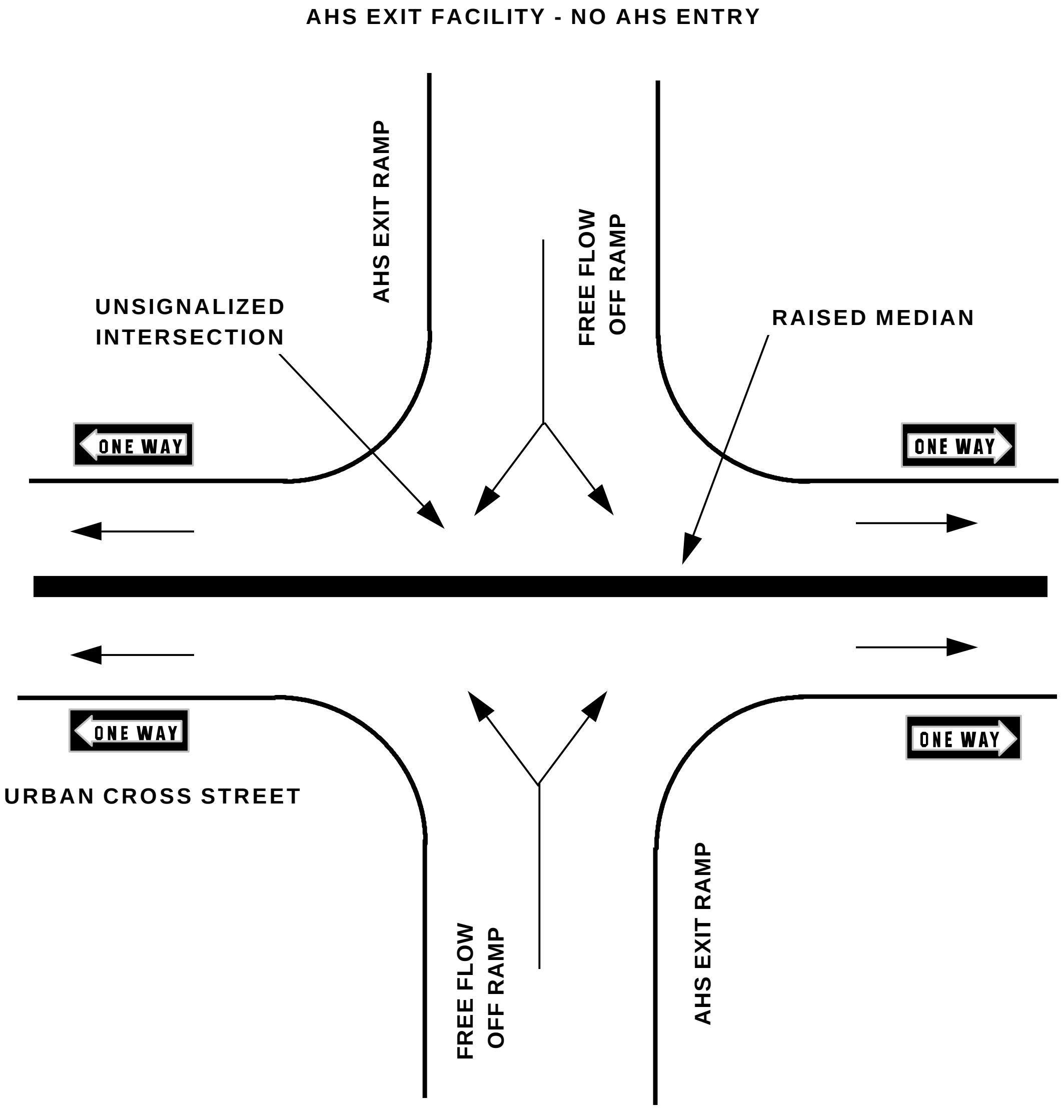

Figure 26. Free Flow AHS Exit Utilizing One-Way Operation On Cross Street

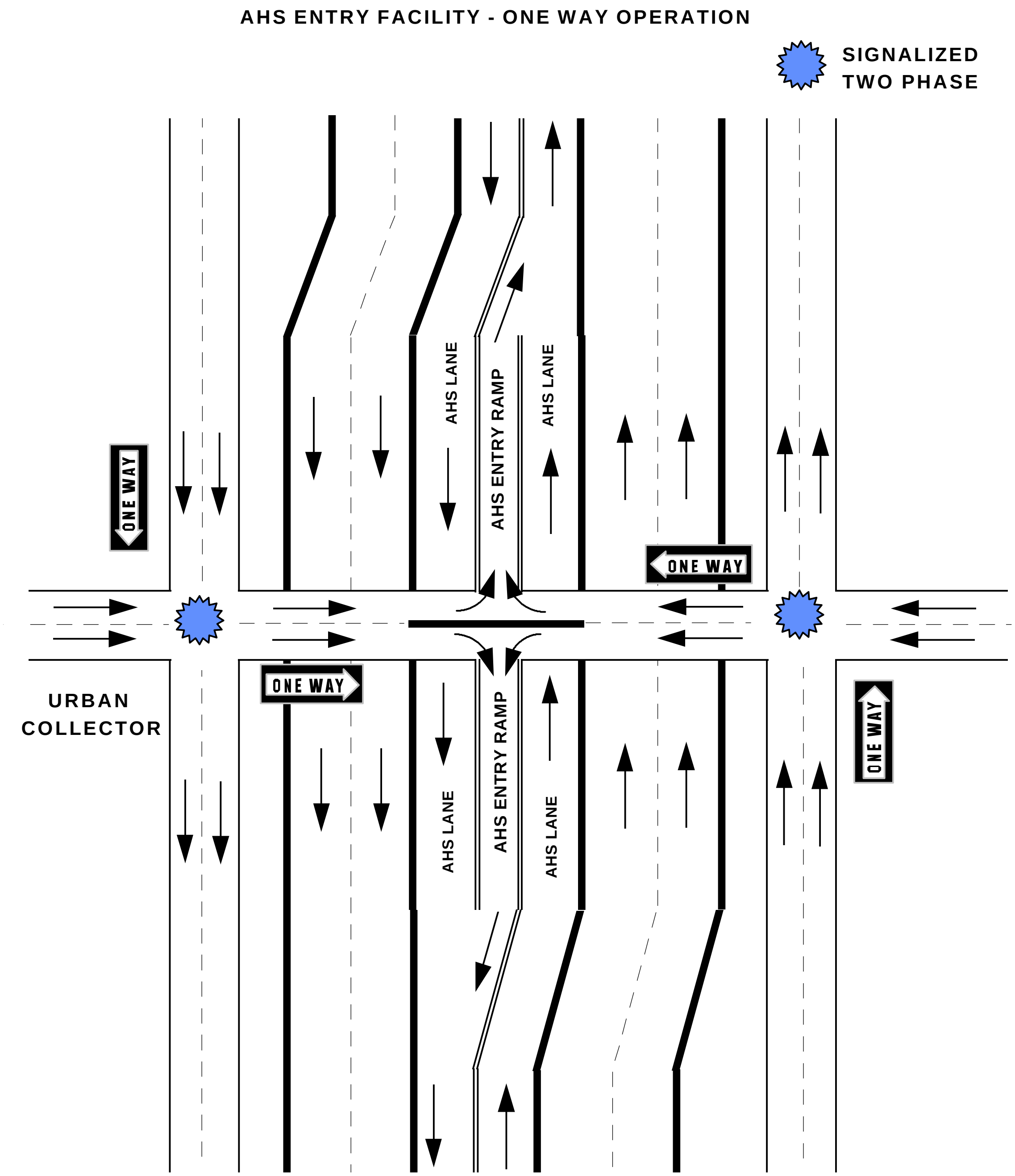

Figure 27. Free Flow AHS Entry With One-Way Operation On Paralleling Roadways

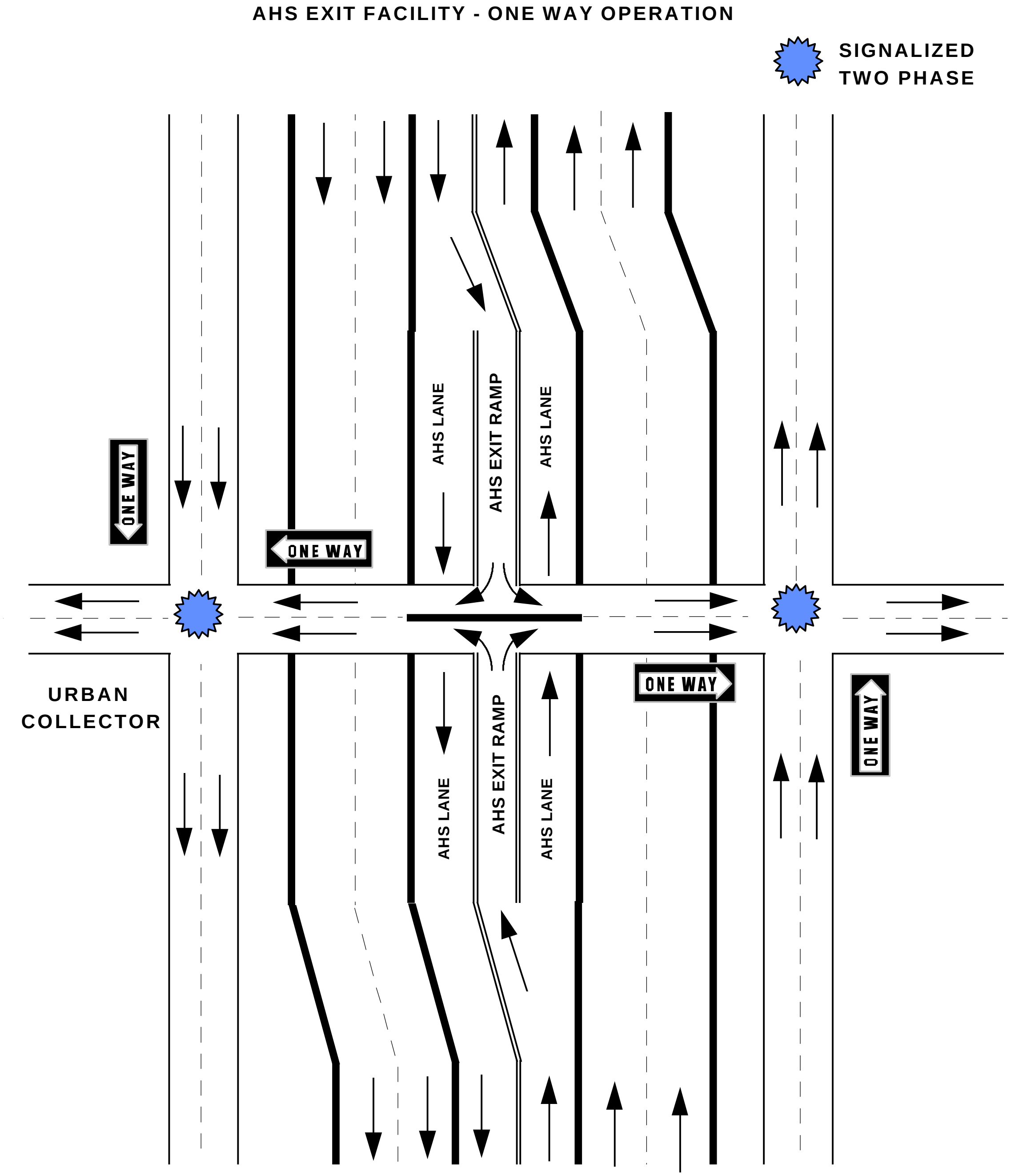

Figure 28. Free Flow AHS Exit With One-Way Operation On Paralleling Roadways

In utilizing this one-way operation, the intersection is capable of handling approximately 5,400 veh/hr and still operate at a LOS of D. Figure 29 represents the closest signalized intersection from the AHS exit ramps on the cross street. With one-way operation the intersection is capable of handling 4,400 veh/hr exiting from the AHS ramps and maintain a very acceptable LOS operation. Large turning movements of 2,200 veh/hr can be accommodated with relatively minor geometric changes to the local streets. Under these conditions it was determined that the average queue lengths that would develop for the AHS exit traffic would be 20 vehicles and 28 vehicles for through and left-turn traffic respectively. Since two lanes are provided for each movement, approximately 110 m. of storage per lane would be required, which is a very short separation distance between AHS ramps and the parallel roadway.

Implementing this one-way operation will help disperse or collect large AHS ramp volumes. The extent of how far the one-way system will be required to extend from the freeway will be a factor of the AHS ramp volumes and circulation patterns and local traffic volumes. Studies of the existing traffic patterns will be a design requirement for the location of AHS entry and exit facilities.

The main advantages of this entry/exit configuration are:

- Completely separate AHS and conventional freeway traffic.
- Can accommodate large ramp volumes at acceptable LOS operation.
- Minimum geometric impacts to local streets.
- Minimizes new structure widths for AHS entry/exit facilities.
- Provides area off of the ramps to switch from manual to automatic control.
- Provides adequate storage for queued vehicles without backup onto AHS lane.

The major disadvantages of this entry/exit configuration are:

- New structures and ramps required for each AHS entry/exit facility.
- Operations of local streets will change.
- Access to properties close to AHS facilities may require modification.
- Potential for land use changes near AHS interchanges are higher.
- Cost of implementation.

Demand Management

The unqualified success scenario (high market penetration) leads to situations, verified by modeling, where demand will exceed capacity. This is especially true at entry/exit points. Demand management is proposed as a viable solution to this possibility. In this case, demand management involves means to reduce peak demands on the system by redistributing the trips over time or by rerouting over less congested routes. These two demand management approaches are considered superior to accommodation of non-managed demand through extensive construction, or to building facilities to store queued vehicles.

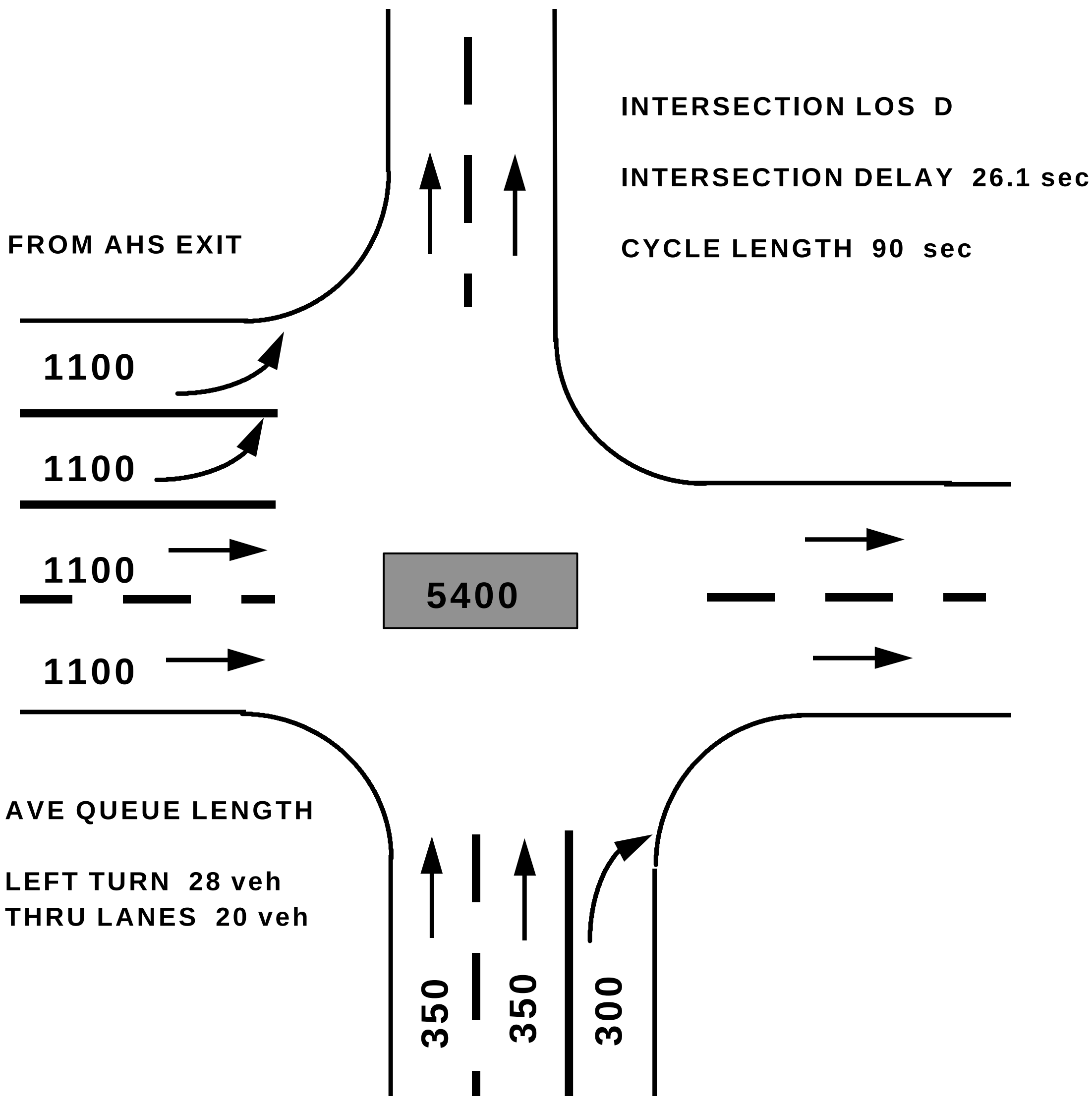

Figure 29. Signalized Intersection Of AHS Exit Ramp and One-Way Cross Street
(Approach Volumes In Units Of Veh/hr)

Another transportation mode, aviation, already has in place a demand management system that is analogous to AHS. Airports with severe regional air space limitations, for example Los Angeles International Airport (LAX), cannot put incoming traffic into holding patterns due to air space limitations. Furthermore, this practice is expensive to the airlines and ultimately to passengers. Demand management is practiced by not allowing traffic from "close" airports (Phoenix or Portland, for example) to be given clearance to take off until there is air space capacity at LAX for the plane based on its expected time of arrival. Longer haul planes (east coast, Trans-Pacific, etc.) are accommodated by en-route speed adjustments as needed to ensure landings without holding patterns near the destination.

Similar operating conditions could be imposed on AHS, with intra-city vehicle arrival times controlled by speed adjustments and shorter trips controlled by pre-trip travel planning.

Intelligent Transportation Systems (ITS) has several user services that can be utilized to accomplish effective demand management. Table 6 is the complete list of ITS user services.

Table 6. Intelligent Transportation Systems' User Services.

Travel and Traffic Management	**Commercial Vehicle Operations**
• Pre-Trip Travel Information	• Commercial Vehicle Electronic Clearance
• En-Route Driver Information	• Automated Roadside Safety Inspection
• Traveler Services Information	• Commercial Vehicle Administrative Processes
• Route Guidance	• On-Board Safety Monitoring
• Ride Matching & Reservation	• Commercial Fleet Management
• Incident Management	• Hazardous Material Incident Notification
• Travel Demand Management	**Electronic Payment**
• Traffic Control	• Electronic Payment Services
Public Transportation Management	**Advanced Vehicle Safety Systems**
• En-Route Transit Information	• Longitudinal Collision Avoidance
• Public Transportation Management	• Lateral Collision Avoidance
• Personalized Public Transit	• Intersection Collision Avoidance
• Public Travel Security	• Vision Enhancement for Crash Avoidance
Emergency Management	• Safety Readiness
• Emergency Vehicle Management	• Pre-Crash Restraint Deployment
• Emergency Notification & Personal Security	• Pre-Crash Automated Vehicle Operation

Of these services, the following subset are believed to have application in AHS demand management:

Traffic and Traffic Management

- Pre-Trip Travel Information.
- En-Route Driver Information.
- Traffic Control.

Public Transportation Management

- En-Route Transit Information.
- Public Transportation Management.

Commercial Vehicle Operations

- Commercial Vehicle Electronic Clearance.
- Commercial Fleet Management.

Pre-Trip and En-Route Travel Information can provide AHS drivers with information on expected delays and alternative routes (AHS and conventional). This information can be provided before the driver begins his trip or during his trip to the AHS entry point. In the case of pre-trip planning, drivers can apply for a time slot during which he would be guaranteed AHS access. Depending on access point design, en-route users could elect to wait in a queue or to take an alternative route.

Traffic Control can optimize operating conditions near entry/exit points to reduce the likelihood of non-AHS related congestion and delay, and to ensure (in coordination with Pre-Trip and En-Route Travel Information) that AHS entry/exit points to not generate queues that influence the surrounding traffic flow.

En-Route Transit Information and Public Transportation Management would be available to AHS transit operators and passengers to help make effective transfer decisions and itinerary modifications. Preferably, transit vehicles and AHS high occupancy vehicle (HOV) traffic would have priority over single occupant vehicle (SOV) AHS traffic. Such priorities would be provided by the system in a way that would not impact previously approved clearances for AHS entry by any class of vehicle.

Commercial vehicles could also utilize and benefit from pre-trip travel information and en-route guidance. Long haul, point to point users would typically benefit from pre-trip guidance. It may be feasible to “sell” clearances in advance to allow carriers to guarantee delivery schedules. It is conceivable that AHS lanes could be reserved for trucks only at certain times of day during which intense truck activity could take place. These hours would typically be the late night or early morning hours when total traffic is relatively light and light vehicle traffic would benefit from having most truck traffic on a separated facility.

Delivery or multiple stop commercial vehicle operations (taxis, courier services, shuttle services, etc.) could optimize their travel through the use of en-route guidance. This guidance would provide seamless travel planning for each segment (both AHS and non-AHS) of the total day's deliveries and pick-ups.

Demand can also be managed in the actual design of the AHS. The number of short trips on the AHS can be reduced by increasing entry/exit point spacing. Short trips are eliminated if total trip travel time is greater due to added AHS segment. However, there are some drawbacks to this method. Increased access point spacing concentrates remaining AHS trips onto fewer entry/exit points, exceeding their capacity. This was demonstrated in the modeling conducted on the hypothetical urban freeway as discussed in the Interchange Spacing section of task 3 of this activity report.

Implications of interchange spacing can be partly mitigated by partial interchanges. It could be found that demand and capacity could be balanced by having less access points than egress points. This access management scheme has the added benefit of mitigating some of the design problems and costs associated with the need for a close speed match between AHS mainline and merging vehicles, especially where trucks and transit vehicles are concerned.

If the AHS facility is a toll way, toll-related demand management means are available. Higher per-kilometer tolls can be charged to discourage short trips. Congestion pricing can be used to discourage peak hour trips. SOV vehicles can be penalized by higher tolls. Various combinations of these toll-related management techniques can be used based on the specific needs of an individual corridor.

CONCLUSIONS

Entry and exit to and from the AHS lane can occur under two scenarios; through dedicated facilities or non-dedicated facilities. Dedicated facilities provide direct ramp access to and from the AHS lane. Non-dedicated facility utilizes the existing conventional freeway interchange and enters or exits the AHS lane by weaving across conventional freeway lanes and entering from a transition lane. The focus of the work conducted for this report was on dedicated AHS entry/exit facilities in an urban setting.

Issues

The work performed resulted in identifying main issues associated with AHS entry and exit strategies. These main issues are:

- On-site check-in and check-out procedures should be limited to “on-the-fly” procedures that do not delay the AHS vehicles. Even with minor check-in or check-out durations, sizable queues of vehicles will form, large delays will be imposed to the entry and exit procedures, and the size of the facilities including the length of the ramps will exceed practical and realistic design parameters.

- For the corridor studied, market penetration rates of 40 percent will cause AHS ramp demands as high as 2,900 vehicles per lane (if unrestrained demand is assumed) which would cause the signalized ramp terminal to fail operationally. Current capacity of a ramp under urban settings is approximately 1,500 veh/hr per lane. AHS ramp volumes of this magnitude will not only affect AHS operation, but will affect the local street network operation as well.

- At approximately 40 percent AHS market penetration, ramp delay affects overall corridor performance and diminishes the benefits achievable by increasing through capacity on the freeway by the AHS lanes. Entry and exit facilities will determine how well AHS operates and dictate the benefits achievable by AHS implementation.

- Increasing the spacing between AHS entry and exit facilities causes ramp demand volumes to increase. Ramp delay increases significantly and overall corridor performance degrades significantly.

- Dedicated entry and exit capacities are governed by where and how they interconnect with the local street system. These capacities can be increased by separating AHS and conventional freeway interchange, separating AHS entry and exit procedures from the same location, and eliminating conflicting movements at the ramp terminals. Providing for free flow movement at these points could increase ramp capacities to 2,300 veh/hr per lane.

- Measures of effectiveness used to analyze AHS entry/exit configurations are divided into safety and operational categories. Safety related MOE's have the highest priority because they relate to failures of the system that could cause accidents. The two operational MOE's with the highest priorities are vehicle delay and queue length.

- Entry and exit volumes must be collected and dispersed by the local street network. Operational and geometric changes to local streets will be required even at lower market penetration rates. Implementing one-way streets is one method that will limit physical widening of existing roadways locally.

- AHS design and implementation will require a collective effort between the FHWA, State and local governments to assure a balanced system results.

- The cost of providing dedicated AHS entry and exit facilities will most likely be considerably higher than non-dedicated facilities due to structure costs of the new interchanges. A slip ramp configuration would best suit dedicated AHS facilities. This would allow complete separation of the conventional and AHS freeway operations and minimize construction costs.

- Demand management is a viable mechanism to help avoid over loading AHS entry and exit facilities by limiting demand to match the capacity of these facilities.

Future Research Needs

It is suggested that portions of the work conducted under this study be continued and investigated in the second phase of AHS development and prior to determining a preferred entry exit strategy.

The research conducted on interchange spacing of AHS facilities was limited to 1.6 km and 4.8 km spacing. Longer spacing between facilities should be investigated that accounts for actual origin-destination of trips and how this affects market penetration and ramp volumes of AHS. The effects of eliminating short trips on AHS should be documented.

Modeling of the limited access AHS concept should be conducted with this modeling accounting for heavy vehicle and transit use.

The actual procedure for entering and exiting the AHS lane needs to be defined and quantified to ascertain the impacts on entry and exit design. Will vehicles enter and exit AHS as single units or mini platoons? Will cars be required to stop to wait for a gap in AHS mainline traffic prior to entry? This will have a profound effect on entry facility size, especially at higher market penetration rates.

The effects of reducing the conventional freeway capacity (through reduction in lanes converted to AHS) on non-dedicated entry and exit strategies needs to be quantified. In dense urban areas already experiencing congestion, the reduction in the number of lanes will add to the problems. Weaving, merging, and ramp operations should be quantified and compared to a dedicated entry/exit facility design.

REFERENCES

1. A. A. Carter Jr., Transportation and Traffic Engineering Handbook, 2nd Edition, Chapter 16, p. 502.

2. F. -B. Lin and C. -W. Su, "Level-of-Service Analysis of Toll Plazas on Freeway Main Lines," Journal of Transportation Engineering, Vol. 20, No. 2, April 1994, pp. 246-263.

3. Florida Department of Transportation, "dQueue: A Toll Facility Simulation System," October 1990.

4. Transportation Research Board, "Highway Capacity Manual," Special Report 209, 1985.

5. American Association of State Highway and Transportation Officials (AASHTO), A Policy on Geometric Design of Highways and Streets, Washington, D. C., 1990.