Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Activity Area J: AHS Entry/Exit Implementation

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FOREWORD

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

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

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

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

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and Development

NOTICE

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16. Abstract

The AHS entry and exit systems must be consistent with the AHS goals of safety, throughput, user comfort, and environmental impact. The systems must be designed to enable the vehicles and operators to safely enter and exit the roadway at rates that ensure that the AHS system's throughput objectives are met. The entry and exit areas must enable processing and deployment of the vehicles with minimal discomfort to the operator.

The requirements for entry and exit system design are influenced by the AHS concept. For example, a platooning concept may involve forming entire platoons in entry lanes prior to insertion into the roadway, while for the uniform headway spacing concept, vehicles may be released individually into the roadway. The infrastructure requirements also may differ substantially among AHS concepts. For example, longer and more entry lanes may be required to form platoons before entry to the roadway. With multivehicle pallets, the entry and exit lanes probably would have a much different design than concepts involving individual vehicles.

This task includes identifying measures of effectiveness (MOEs) for evaluating entry/exit strategies and land-use requirements for each RSC and will be closely tied to the AHS roadway deployment analysis (activity area H), automated check-in analysis (activity area B), and automated check-out analysis (activity area C). Thus, this work has a high priority similar to that of areas B, C, and H. We recommend that the performance of these activity areas be well coordinated.

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ACRONYMS/ABBREVIATIONS

AARP	American Association of Retired Persons
AASHTO	American Association of State Highway and Transportation Officials
ABS	Antilock Braking System
ADT	Average Daily Traffic
AE	Architectural Engineer
AHMCT	Advanced Highway Maintenance and Construction Technology Program
AHS	National Automated Highway System
AICC	Autonomous Intelligent Cruise Control
ANSI	American National Standards Institute
APTS	Automated Public Transportation System
ARPA	Advanced Research Project Agency
ARTS	Automated Rural Transportation System
ASTM	American Society for Testing Materials
ATIS	Automated Traffic Information System
ATMS	Advanced Traffic Management System
AVCS	Automatic Vehicle Control System
AVI	Automatic Vehicle Identification
AVLS	Automatic Vehicle Location System
BBS	Bulletin Board System
CASA	Computer and Automated System Association
CE	Civil Engineering
CI	Configuration Items
CVO	Commercial Vehicle Operation
DC	Direct Current
DCAA	Defense Contract Audit Agency
DOT	Department of Transportation
DVI	Driver Vehicle Interface
EPS	Electric Power Steering
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
FMEA	Failure Modes Effects Analyses
FMVSS	Federal Motor Vehicle Safety Standard
FOT	Field Operational Test

FREE-SIM	Freeway Simulation
FTA	Federal Transit Authority
FY	Fiscal Year
GIS	Geographic Information System
GPS	Global Positioning System
HOV	High Occupancy Vehicle
HW	Hardware
IAVD	International Association of Vehicle Dynamics
IEEE	Institute of Electrical and Electronic Engineers
IR	Infrared
IR&D	Independent Research and Development
ISO	International Standards Organization
ISTEA	Intermodal Surface Transportation Efficiency Act
IVHS	Intelligent Vehicle Highway Systems
MOE	Measure of Effectiveness
MOP	Measure of Performance
MPR	Mean Personal Rating
MTBCF	Mean-Time Between Critical Failure
MTBF	Mean-Time Between Failures
MVMT	Million Vehicle Miles Traveled
NADS	National Advanced Driving Simulator
NAHTSA	National Automotive Highway Transportation Society of America
NDS	National Driving Simulator
NES	National Energy Strategy
NHTSA	National Highway Traffic Safety Administration
NSC	National Safety Council
OEM	Original Equipment Manufacturer
PC	Personal Computer
PBMS	Performance Based Measurement System
PSA	Precursor Systems Analysis
QFD	Quality Function Deployment
R&D	Research and Development
SAE	Society of Automotive Engineers
TMC	Traffic Management Center
TRB	Transportation Research Board
TRAF-NET	Traffic Network Simulation
UL	Underwriters Laboratories

USG	United States Government
V&V	Validation and Verification
VMT	Vehicle Miles Traveled

EXECUTIVE SUMMARY

Objective and Scope

One of the greatest challenges facing the implementation of AHS is the ability to enter and exit the automated highway system (AHS) roadway effectively, safely, comfortably, and with minimal environmental impact. The primary objectives of the area J activities were to 1) identify strategies for entering and exiting an AHS roadway, 2) develop measures of effectiveness (MOEs) for evaluating these strategies, and 3) evaluate the team's selected set of representative system configurations (RSCs) with the aid of the special entry/exit MOEs developed. This work was coordinated with related concurrent work by other members of the program team—especially those involved in the roadway-related efforts for activity areas A, H, I, and K.

In many respects, entry and exit are “weak links” in an AHS system. For completely dedicated (AHS -only) systems, there are critical issues associated with land use and the influence on the surrounding roadways. For mixed use systems (even with dedicated AHS lanes), critical issues include converting medians and lanes previously used for non-AHS traffic. The feasibility of AHS depends in part on how effectively these and other issues can be resolved.

The scope of the area J activities was focused on entry/exit considerations for the program team's selected set of RSCs. The area J team members did, of course, participate in specialized area J meetings and teleconferences with area J members of other contractor teams.

Methodology

The following three-step approach was used in activity area J:

1. ***Development of Entry/Exit Strategies***—Strategies for entering and exiting vehicles were developed for each of six baseline RSCs defined by the Battelle team. The development of these strategies involved a) defining the “AHS experience” (i.e., the generic vehicle and system functions and decision points from the time a vehicle requests entry to the AHS to the time the vehicle is back on the surrounding non-AHS roadway); b) developing sets of assumptions and rules for entry and exit for each of the RSCs; and c) choreographing the vehicle and system functions for each of the RSCs.

2. ***Development of MOEs***—MOEs were developed to evaluate each of the entry and exit strategies. The MOEs were a combination of quantitative measures (e.g., distance and time required for entry) and qualitative measures (e.g., relative safety).

3. ***Evaluation of Strategies***—The MOEs were applied to each of the entry/exit strategies, from which an overall assessment of the viability of the strategies and the RSCs were made.

The basic entry/exit strategies considered were developed by defining functional requirements and infrastructural modifications necessary to transition a vehicle from the arterial roadway to the AHS lane and from the AHS lane to the arterial roadway. The functional requirements defined for each RSC then provided the framework for identifying the type of infrastructural changes needed to accommodate implementation of an AHS system. Four functional categories were identified which comprise the AHS entry/exit requirements common to each of the RSCs—i.e.:

- Fault mitigation.
- Lane merge maneuvers/transitions.
- Control transfer.
- ACI/ACO.

The specific elements of each of these functional categories were developed to satisfy the particular implementation requirements of each of the RSCs. The resulting entry/exit strategies were described in terms of their functional execution and roadway configurations.

Special MOEs were then developed for subsequent use in evaluating the viability of the various entry/exit implementation strategies for AHS s. Seven main MOEs were developed and defined as follows:

1. ***Minimal need for additional land***—A major constraint on implementing AHS is the cost of new entry and exit areas on the highway. Further, in congested urban areas (where AHS may have the greatest potential), the availability of additional land is very limited. A goal would be to retrofit existing entry and exit areas for AHS use.

2. ***Minimal need for additional facilities***—Additional facilities needed for entry and exit may include automated check-in and check-out (ACI and ACO, respectively) stations, loading and unloading areas for palletized vehicles, and traffic metering equipment. These facilities add cost to AHS implementation, and could pose reliability problems. A goal would be to minimize the need for additional facilities.

3. ***Minimal negative impact on adjacent roadways***—The entry and exit portions of the AHS must not create traffic flow problems on the adjacent streets to and from which the AHS vehicles are transferred.

4. ***Large improvement in potential capacity over comparable non-AHS roadway systems***—The entry and exit portions of the system must minimize any bottleneck effects that would restrict the throughput of the system.

5. ***Minimal disruption of non-AHS roadway traffic flow***—Metering of traffic to and from AHS lanes must not degrade the traffic flow on non-AHS lanes, and vice versa.

6. ***Ability to mitigate safety hazards***—The entry and exit areas must be designed to preclude and/or minimize safety hazards.

7. ***Low cost and complexity***—The overall cost for implementing entry and exit portions of the system should be minimized without compromising the four basic AHS goals of high safety, throughput, comfort, and environmental compatibility. Further, the entry and exit

systems should be made as simple as possible, which would reduce the cost to build, maintain and operate, and improve reliability.

Once the MOEs were developed, a six-point MOE rating scale was conceived and applied to assess the relative entry/exit merits of the program team's selected set of RSCs.

Results

A summary of key findings from the area J activities is provided below. Additional results and supporting information are supplied in the area J topical report.

Dedicated AHS

From a safety and performance standpoint, the most attractive entry/exit strategy involves dedicated AHS -only ramps that connect directly to dedicated AHS lanes, which in turn are separated from non-AHS lanes via barriers.

Transition Lanes

Entry and exit across non-AHS lanes must involve transition lanes. The transition lanes must be capable of performing vehicle check-in and/or check-out, rejecting vehicles, queuing vehicles (if the transition lane is not continuous) without interfering with surrounding traffic, and releasing vehicles from rest into the AHS lanes and out of the non-AHS lanes. The use of transition lanes would not require exclusive AHS ramps.

Without transition lanes, right-hand-side entry to and exit from inner AHS lanes would require that a) the vehicles are in manual control during some period while in the AHS lane, b) the vehicle entry speed is the non-AHS lane speed, and c) the vehicle exit speed must be reduced as needed to be consistent with the non-AHS lane into which it is exiting. Requirement a) is considered unsafe, requirements b) and c) could result in severe degradation in AHS lane throughput due to “wave action” between vehicles.

Barriers

As safety devices, barriers should be used wherever possible between AHS , transition, and non-AHS lanes. These should be positive barriers that physically prevent intrusion to and from the AHS lanes (e.g., the Jersey barrier). Barriers themselves could create a safety hazard at entry and exit areas, and should be designed and placed to mitigate end-on collisions.

Metering

Traffic metering should be implemented at several levels:

a. Pre-trip—users log-in trip requests to the system; the system in turn needs to evaluate the current and projected traffic conditions and approve or disapprove the request.

b. System Level—the flow of traffic on AHS and non-AHS lanes should be monitored and adjusted as needed to optimize throughput while not compromising comfort, safety, and environmental impact.

c. Local Level—systems similar to current ramp meters are needed to release vehicles onto and off of the AHS lanes based on availability of space.

Four-Lane Highways

The application of AHS in a four-lane highway scenario (i.e., two lanes in each direction with no additional lanes) may be based, at least initially, on AHS /IVHS systems such as "intelligent cruise control" and accident avoidance. Such a highway would require mixed traffic on the lanes, because without very high market penetration, dedicating two of four lanes to AHS -only would create considerable congestion on the non-AHS lanes. Thus, mixed traffic is a likely requirement for four-lane highways and introduces special safety and control considerations. The cost/benefit values of such an approach needs further evaluation. With regard to entry/exit, an immediate benefit is that no significant changes would be required in the physical layout of the entry and exit areas for this configuration.

Lane Widths and Ramp Geometry

Standard lane widths (typically 12 ft wide) should be used for AHS lanes that involve mixed commercial, transit, and automobile traffic. Smaller width lanes (e.g., 8 to 10 ft wide) should be considered only if use is restricted to specific "AHS class" vehicles. The geometry (lengths, curvatures) of existing ramps are based on current highway design speeds. Modifications to existing ramps should be considered if the operating speeds on the ramps are higher than the design speeds.

Pallets

The primary advantages of the pallet concept are a) automobiles do not have to be AHS equipped, therefore all automobiles are candidates for use on the AHS ; b) ACI/ACO during entry/exit requirements would be reduced substantially; and c) pallets could be designed to use more environmentally friendly fuels, to be more energy-efficient, more reliable, and more uniform than today's fleet of automobiles. Primary disadvantages include a) cost of the pallets; b) additional space, time, and facilities are needed for storage, loading, unloading and circulation; and c) a "pallet authority" must be in place for operating the system. Key entry/exit issues are where and how pallets are loaded, unloaded, and circulated throughout the AHS system while maintaining acceptable origin-to-destination travel times, good passenger comfort, and safety.

Surrounding Roadways

Surrounding roadways must be evaluated and modified as needed (e.g., by changes in traffic flow patterns, signaling, and AHS -only access) to assure that the flow of traffic to and from the AHS can be accommodated safely and with minimum impact on the AHS and surrounding roadways.

Spacing of Entry and Exit

To avoid unsafe weaving maneuvers, exit and entry should occur at different locations wherever possible.

Conversion of HOV Lanes

Conversion of high occupancy vehicle (HOV) lanes to AHS would provide an effective infrastructure for AHS operation. However, it is expected that the public would resist giving up HOV lanes (as well as any other lanes). An option would be to create an AHS system that is restricted to HOV traffic. From an entry/exit standpoint, the primary advantage of converting HOV lanes to AHS is that suitable dedicated entry and exit systems, and in many cases barriers, already exist.

Control Transfer

Except for the four-lane highway "intelligent cruise control" scenario, operation in AHS lanes must be restricted to vehicles under AHS control. Thus, transfer of control must occur prior to the vehicle entering the AHS lane and after the vehicle leaves the AHS lane.

Ranking the RSCs Based on Entry/Exit

The following are brief descriptions of the six RSCs and their associated entry/exit features for which MOE evaluations were conducted by the team:

> ***RSC 1—Smart Vehicle/Smart Highway with 6 Lanes (2 AHS Lanes)—***Mixed ramp traffic, transition lanes, no barriers. The entry/exit strategy for the RSC 1 requires an additional center lane to be used as an exclusive transition lane. There is a narrow buffer zone between the AHS lane and the transition lane. Traffic in the transition lane is operated in mixed manual and automated modes, but the automated mode of operation is used exclusively for executing merge maneuvers between the transition lane and the AHS lane.

> ***RSC 2A—Smart Vehicle/Average Highway with 6 Lanes (2 AHS Lanes)—***Mixed ramp traffic, no transition lanes, with barriers. The entry/exit strategy for RSC 2A uses the center lane as the transition segment which is operating in manual mode only. As in RSC 1 there is a narrow buffer zone between the AHS lane and the center lane. The transition segment is also the left lane or passing lane for manual traffic.

RSC 2B—Smart Vehicle/Average Highway with 6 Lanes (2 AHS Lanes)—Mixed ramp traffic, no transition lanes, without barriers. There are three entry exit strategies for this RSC: 1) right-handed entry/exit fly-over ramps, 2) left-handed entry/exit overpass ramps, and 3) left-handed entry/exit fly-over ramps. All three entry/exit strategies for RSC 2B use the ramp as the transition segment. ACI, ACO, control transfer, lane merge maneuvers and fault mitigation occurs on the access and egress ramps.

RSC 2C—Smart Vehicle/Average Highway with 5 Lanes (Reversible AHS Center Lane)— Exclusive ramp traffic, no transition lanes, barriers. The entry/exit strategy for RSC 2C is functionally identical to RSC 2B except provision is made for the roles of the entry and exit ramps to be reversed concurrent with AHS traffic direction changes. The direction changes are indicated by lighted directional arrows. One other distinction is that the right-hand and left-hand fly-over ramps are combined as illustrated in figure 13 for dual use as both entry and exit ramps.

RSC 3—Smart Pallet/Average Highway with 6 Lanes (2 AHS Lanes)—Exclusive ramp traffic, loading/unloading/recirculation facilities, no transition lanes, barriers. The strategy required for this RSC is unique from the others because it involves single-vehicle pallets. Thus, entry and exit must accommodate the loading and unloading of vehicles, and the circulation of pallets over the AHS system to meet user demands.

RSC 4—Smart Vehicle/Passive Highway with 4 Lanes (2 Mixed Traffic Lanes)—Mixed ramp traffic, no transition lanes, no barriers. This RSC is essentially the same as a manual roadway. However, provision is made for automated operation of a vehicle and mitigation of control transfer faults. Entry and exit ramps are identical to the ramp designs for conventional controlled access roadways. Fault mitigation for entry consists of simply continuing to operate the vehicle in the manual mode. Fault mitigation for exit consists of the AHS bringing the vehicle to rest on the right shoulder or in a park and hold area adjacent to the exit ramp. The former option has the advantage that only a small segment of the right shoulder needs to be AHS equipped. The park and hold option would require construction of a park and hold area adjacent to the exit ramp as well as equipping all of the exit ramps for AHS .

A comparative ranking of the RSCs with respect to these MOEs is provided in table 1. The following observations can be made from the table:

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Table 1. Comparative ranking of RSCs for entry/exit implementation.*

MOE	RSC #1 - Smart Vehicle - Smart Hwy - 6 Lanes/2 AHS - Mixed Ramp Traffic - Transition Lanes - No Barriers	RSC #2a - Smart Vehicle - Average Hwy - 6 Lanes/2 AHS - Mixed Ramp Traffic - No Transition Lanes - No Barriers	RSC #2b - Smart Vehicle - Average Hwy - 6 Lanes/2 AHS - Exclusive Ramps - No Transition Lanes - Barriers	RSC #2c - Smart Vehicle - Average Hwy - 5 Lanes/Reversible AHS Center Lane - Exclusive Ramps - No Transition Lanes - Barriers	RSC #3 - Smart Pallet - Average Hwy - 6 Lanes/2 AHS - Exclusive Ramps - No Transition Lanes - Barriers	RSC #4 - Smart Vehicle - Passive Hwy - 4 Lanes/2 Mixed AHS Lanes - Mixed Ramp Traffic - No Transition Lanes - No Barriers
Minimal need for additional land	4	3	5	2	6	1
Minimal need for additional facilities	4	3	5	2	6	1
Minimal impact on adjacent roadways	3	2	5	4	6	1
Large improvement in potential capacity	3	4	1	2	5	6
Minimal disruption of traffic flow	5	6	1	1	1	1
Improvement in safety	5	6	1	2	3	4
Low cost and complexity	5	3	4	2	6	1

- Rankings range from 1 to 6, with 1 representing the highest rank.

- Relatively high scores were assigned to RSC 2C and RSC 4. This is primarily because these concepts make maximum use of the existing highway infrastructure, require the least amount of additional land and facilities, and have relatively low-cost, low-complexity entry/exit concepts. The primary weakness in RSC 2C is the potential degradation of traffic flow on adjacent roadways. RSC 4 is relatively weak in the areas of improvements in capacity and safety.

- RSC 2B received average to high scores. Because it involves the use of exclusive, direct-access ramps and barriers between AHS and non-AHS lanes, it offers high levels of safety and potential capacity improvement, along with virtually no disruption of non-AHS traffic flow on the roadway. Tradeoffs for these benefits are the significant cost and land requirements for new ramp construction.

- Average to low scores were assigned to RSC 1 and RSC 2A, primarily because of safety concerns associated with mixed ramp traffic, along with the absence of physical barriers. Further, RSC 1 would require the development of a network of transition lanes, which in turn could require significant additional land and complex metering schemes.

- The overall lowest scores were assigned to RSC 2C (the pallet concept). Although pallets provide potentially high capacity on the AHS roadway, the overall throughput could be degraded substantially because of the requirements for loading and unloading. Further, the development of efficient loading and unloading schemes could be very costly and complex. Salient benefits are the potential for a high level of safety, 100 percent immediate accessibility by conventional vehicles, and virtually no disruption of adjacent non-AHS roadway traffic.

INTRODUCTION

One of the greatest challenges facing the implementation of automated highway system (AHS) is the development of effective strategies to enter and exit the AHS roadway safely, comfortably, and with minimal environmental impact. In some respects, entry and exit are “weak links” in an AHS system. If effective entry and exit strategies cannot be achieved, the AHS will fail.

Myriad issues confront the development of AHS entry and exit strategies. The development of completely dedicated (AHS -only) entry/exit systems is challenged by the cost and shortage of available undeveloped land and the potential for significant disruption of surrounding roadways. For mixed use systems (even with dedicated AHS lanes), a critical issue is the safety of moving vehicles into and out of non-AHS traffic and the impact of converting medians and lanes previously used for non-AHS traffic. The feasibility of AHS depends in part on how effectively these and other issues can be resolved.

Relationship to Other AHS /PSA Activity Areas

All of the activity areas covered in the FHWA's precursor systems analyses (PSA) program are interrelated. Thus, evaluations of entry/exit implementation must recognize the requirements associated with other aspects of AHS , such as institutional issues, safety issues, malfunction management, and roadway design. Those activity areas that are particularly strongly related to AHS entry/exit implementation include areas A, H, I, and K from the standpoint of ramp and transition lane requirements; areas B and C from the standpoint of check-in and check-out requirements; and area D from the standpoint of control transfer requirements.

Objectives and Scope

The objectives of this study were 1) to identify and discuss various strategies for implementing AHS entry and exit, 2) to identify measures of effectiveness (MOEs) for evaluating and optimizing various entry/exit strategies, and 3) to analyze various strategies and land use requirements for the representative system configurations (RSCs) in conjunction with activity area H, roadway deployment analysis.

The scope of the study was defined by the following basic assumptions:

1. AHS entry consists of all activities from a vehicle's request to enter to the completion of the vehicle maneuver into the AHS lane and control transfer to the AHS system.

2. AHS exit consists of all activities from a vehicle's request to exit the AHS lane to the vehicle leaving the exit ramp and entering the adjacent roadway.
3. New construction is limited to modifications and retrofits to existing highway systems. Completely new roadway construction is not considered.

4. An AHS environment ranges from urban to rural.

5. Use of the AHS is restricted to vehicles with roughly similar design and performance characteristics (e.g., a class of existing automobiles). Commercial and transit vehicles—which typically are bigger and accelerate more slowly than automobiles—are not considered.

A comprehensive description of all assumptions used in the study is provided in the baseline assumptions section of this report.

Technical Approach

The following three-step approach was used in activity area J:

1. ***Development of Entry/Exit Strategies***—Strategies for entering and exiting vehicles were developed for each of six baseline RSCs. The development of these strategies involved a) defining the "AHS experience," i.e., the generic vehicle and system functions and decision points from the time a vehicle requests entry to the AHS to the time the vehicle is back on the surrounding non-AHS roadway; b) developing sets of assumptions and rules for entry and exit for each of the RSCs; and c) choreographing the vehicle and system functions for each of the RSCs.

2. ***Development of MOEs***—MOEs were developed to evaluate each of the entry and exit strategies. The MOEs were a combination of quantitative measures (e.g., distance and time required for entry) and qualitative measures (e.g., relative safety).

3. ***Evaluation of Strategies***—The MOEs were applied to each of the entry/exit strategies, from which an overall assessment of the viability of the strategies and the RSCs were made. Then, in conjunction with the work in area H, entry and exit configurations were developed for selected roadways.

Organization of Report

This report covers the activities, results, and conclusions of the study. Detailed functional definitions of AHS entry and exit are provided in the next section. Then, the baseline assumptions used in the study are described. The entry/exit strategies developed for each of six RSCs are presented in the next section. These entry/exit strategies are evaluated. Conclusions associated with the overall technical feasibility and critical issues for entry/exit are described in the last section.

DEFINITION OF AHS ENTRY AND EXIT

Description of AHS Entry and Exit Functions

The objective of AHS entry/exit is simply to transition a vehicle from the arterial roadway to the AHS lane and from the AHS lane to the arterial roadway. The complexity of entry/exit arises in the specific implementation strategies employed to accommodate safety and infrastructural issues associated with the particular RSC and roadway configuration.

The entry and exit functions were defined to provide a framework for developing implementation strategies and identifying any necessary modifications to the existing infrastructure.

The entry/exit can be described in general terms under four functional categories:

- Automated check-in and check-out (ACI/ACO).
- Lane merge maneuvers/transitions.
- Control transfer.
- Fault mitigation.

ACI/ACO

Automated check-in and check-out are defined as black-box functions that are transparent to both non-AHS and AHS traffic. Any vehicle diagnostics are assumed to be internal to the vehicle and performed "on the fly." ACI and ACO operations external to the vehicle consist of the set of communications operations given in table 2. This task was not funded to perform a precursor analysis of ACI and ACO so general assumptions about implementation details were necessary.

Table 2. ACI/ACO external-to-vehicle operations

Automated Check-In	Automated Check-Out
Communication of an entry request	Communication of an exit request
Communication of vehicle diagnostic report to AHS system controller	Communication of operator diagnostic report
Communication of a destination log-in request	Communication of system authorization to exit the AHS roadway
Communication of system authorization to enter the AHS roadway	Communication of a destination log-out request

The entry request notifies the AHS system of the vehicle entry location. The vehicle diagnostic report notifies the AHS system of the fitness of the vehicle for AHS operation. The destination log-in notifies the AHS system of the vehicle's intended travel plan enabling ACI to meter entry vehicles based upon roadway conditions such as congestion and serviceablity. Authorization to enter the AHS roadway is transmitted to the vehicle and operator and is contingent upon the vehicle diagnostic report and roadway conditions at both the point of entry and intended destination.

The exit request notifies the system that the vehicle is arriving at the intended destination. The operator diagnostic report consists of the result of a system or vehicle query of the operator to determine whether he is prepared to assume manual control.

Based on the operator's response and roadway conditions at the point of exit, the system authorizes the vehicle to exit. Upon exiting the AHS roadway, the vehicle communicates its arrival at the intended destination and a log-out of the vehicle from AHS system is executed.

While we have assumed that these elements of the ACI/ACO function are transparent to the infrastructure, they do have an impact on implementation of entry/exit strategies. For example, if the operator fails the diagnostic prior to return of manual control, the exit strategy must make provision for bringing the vehicle safely to rest without obstructing traffic flow in either the manual or AHS lanes.

Lane Maneuvers

The lane maneuver function defines acceleration and deceleration profiles within a lane to safely accomplish lane changes and merging of a vehicle when entering or exiting the AHS roadway. This functional element of AHS entry also defines the velocity profiles of the segment of AHS vehicles in the merge zone of the entry/exit vehicles. In those RSC/roadway configurations where metering may be required, this function includes definition of queuing strategies to facilitate metering requirements of AHS entry and exit.

Control Transfer

The objective of control transfer is to provide a safe transition of control of the vehicle from the operator to the AHS system (entry) and from the AHS system to the operator (exit). The control transfer function defines the process by which this transition is accomplished and the infrastructure requirements to facilitate its implementation. The difficulty in implementing a control transfer strategy is related to imposing the requirement that the vehicle be under AHS control when on the AHS roadway. Unless the AHS system has exclusive entry and exit ramps then mixed manual and automated modes of operation will have to occur during some interval of the process of merging from non-AHS to AHS lanes and vice versa. To accomplish this with a high assurance of safety, while minimizing the need for major modifications of roadway structures, is a major challenge for the development and implementation of entry/exit strategies.

Fault Mitigation

The fault mitigation function defines the infrastructure requirements for fail safe dispositioning of entry/exit malfunctions. The principal entry/exit malfunctions involve failures under the functional categories of ACI, ACO, and control transfer. Conditions may arise during the process of ACI, ACO and control transfer that may require the vehicle to remain either under manual or automated control. During the transitional phases necessary to change modes of operation, provision must be made for the entry or exit vehicle to remain under its existing control mode. The various fault conditions will thus lead to one of two actions; denied entry or denied exit. Potential malfunctions for each of these entry/exit functions are given in table 3.

Table 3. Malfunction conditions and actions for ACI, ACO, and control transfer functions.

Function	Automated Check-In	Automated Check-Out	Entry Control Transfer	Exit Control Transfer
Condition	Vehicle Status Failure	Operator Status Failure	Aborted Control Transfer from Operator to AHS	Aborted Control Transfer from AHS to Operator
	Traffic Status Failure	Traffic Status Failure		
	Roadway Status Failure	Roadway Status Failure		
Action	Denied Entry	Denied Exit	Denied Entry	Denied Exit

Critical Entry/Exit Parameters and Variables

The critical parameters for entry and exit are time (time to enter and exit) and land area (number of lanes, lane length, and lane width). The objective in the precursor analysis is to minimize both parameters constrained by appropriate margins of safety, vehicle performance limitations, and vehicle occupant comfort. The primary variables affecting these parameters are vehicle velocity, acceleration, and deceleration. These variables are also related to traffic congestion and design limits of the existing roadway but are treated as independent variables in this analysis.

BASELINE ASSUMPTIONS

An important step in the study was to develop a set of defendable assumptions upon which a meaningful assessment of entry/exit strategies could be performed. Assumptions were derived from the following sources:

·Assumptions specified in the RFP.

·Assumptions made in the PSA proposal.

·Guidance from FHWA and Mitre.

·Assumptions derived by other PSA investigators.

·Suggestions from the team's senior technical review panel.

·Assumptions derived by the task team based results of on-going analyses.

Entry/exit-related assumptions are described below in the following categories:

·Basic AHS Goals and System Definition.

·AHS -Related Infrastructure.

·Traffic Mix.

·Vehicle Control.

·ACI and ACO.

·Merging and Weaving.

Basic AHS Goals and System Definition

The RFP stated that the PSA studies must be consistent with a set of eight baseline assumptions. These are:

1. All vehicle types (automobiles, buses, trucks), although not necessarily intermixed, must be supported in the mature system. Initial deployment emphasis is expected to be on automobiles and vehicles with similar vehicle dynamics and operating characteristics.

2. The vehicle will contain instrumentation that will allow the AHS to control the vehicle when it operates on instrumented segments of the roadway.

3. Not all vehicles will be instrumented and not all roadways will be instrumented:

a. Instrumented vehicles will be able to operate on non-instrumented roadways.

b. Only instrumented vehicles will be allowed to operate on instrumented roadways. [This assumption was relaxed for this study; we considered the possibility of non-instrumented and instrumented vehicles travelling in common lanes for rural applications.]

c. Non-instrumented vehicles will be instrumentable on a retrofit basis.

4. Operation in a freeway as defined by the American Association of a State Highway and Transportation Officials (AASHTO) is assumed.

5. The AHS will perform better than today's roadways in all key areas including:

   a. *Safety*—The AHS will be significantly safer than today. In the absence of malfunctions, the system will be collision-free; and a malfunction management capability will exist that minimizes the number and severity of collisions that occur as a result of any system malfunctions.

   b. *Throughput*—There will be a significant increase in vehicles per hour per lane.

   c. *User comfort*—The ride will be smoother, with less strain on users and high trust in the system.

   d. *Environmental impact*—Fossil fuel consumption and emissions per vehicle mile will be less.

6. The AHS will be practical, affordable, desirable and user-friendly.

7. The AHS will operate in a wide range of weather conditions typical to that experienced in the continental U.S.

8. The AHS primary system control and guidance will rely on non-contact electronics-based technology as opposed to mechanical or physical contact techniques. The latter might be part of a backup system if the primary system should degrade or fail.

AHS -Related Infrastructure

The following assumptions were developed with regard to the AHS entry/exit infrastructure:

- Existing freeways may be converted or modified for AHS use; however, a new, AHS -only freeway system is *not* considered.

- A high priority is to avoid new construction and use existing infrastructure with minimal impact on existing and adjacent roadways, and with minimal land use.

·New ramp construction is for AHS vehicles only.

·Entry and exit ramps have features for handling malfunctioning and rejected vehicles.

·Entry and exit areas may include equipment and facilities for ACI, ACO, and traffic metering.

·Entry and exit areas may include transition lanes, which are AHS -only.

·Entry/exit facilities are required for pallet loading, unloading and storage/circulation.

·Conversion of existing HOV systems is considered.

Traffic Mix

The AHS vehicle characteristics and the manner in which AHS and non-AHS vehicles interact is critical to meeting the four basic performance goals of an AHS system. In this context, the following assumptions were defined:

·A four-lane highway (two lanes in each direction) cannot have exclusive AHS -only lanes.

·For right-hand entry with existing ramps, the vehicle operates in mixed traffic until it weaves into either the transition lane or the AHS lane.

·Initially, the AHS system will be used by passenger vehicles only.

Vehicle Control

The time and location at which control is transferred between the driver and the AHS system have a strong influence on AHS entry/exit operation. The following assumptions were made for vehicle control:

·With the exception of operation on a four-lane highway, the driver is in control of the vehicle whenever in mixed traffic.

·The vehicle is under system control whenever it is in an AHS -only lane.

·For mixed ramp traffic, the AHS vehicle is under driver control on the ramp.

·For AHS -only ramps that are connected directly to the AHS lane, control is transferred while on the ramps.

·Pallets are always under system control.

ACI and ACO

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It is critical from the standpoint of safety and efficiency that only AHS -qualified vehicles operate in AHS -only portions of the roadway. It is equally important that the driver and vehicle are qualified and prepared to resume operation under driver control when exiting. To this end, adequate facilities and procedures must be in place to perform check-in and check-out of the vehicles. The following assumptions were made with regard to ACI and ACO:

·For AHS -only ramps, ACI may occur before or during vehicle operation on the entry ramp, and during or after vehicle operation on the exit ramp.

·For mixed ramp traffic, ACI occurs before the vehicles are sorted (e.g., at the beginning of the transition lane).

·There may be ACI or ACO plazas which require the vehicle to stop or slow down.

·Pallet systems do not require ACI or ACO plazas.

·There will be no in-motion vehicle maneuverability tests during entry or exit. If necessary, maneuverability will be verified through a pre-certification inspection.

Merging and Weaving

Vehicle merging and weaving into and out of AHS and non-AHS traffic may present the most significant potential safety hazards of all AHS functions. These assumptions were used in the entry/exit analyses to address merging and weaving issues:

·The AHS system coordinates AHS roadway traffic with ramp traffic to enter and exit vehicles only when there is sufficient space.

·Weaving across non-AHS lanes is done under driver control.

·Platoons are formed and "un-formed" in the AHS lanes.

·There may be gates, signals, etc., for sorting and merging control during entry and exit.

·A vehicle may enter the AHS lane at less than nominal AHS speed, provided there is a safe distance between adjacent vehicles.

REPRESENTATIVE SYSTEM CONFIGURATIONS

For the purpose of this document, the research team considered four primary representative system configurations (RSCs). Detailed descriptions of these RSCs can be found in the AHS Precursor Systems Analyses Overview Report. Only the characteristics of these RSCs relative to the research in this activity area are contained herein.

In general terms, the RSCs can be summarized as follows:

Table 4. Representative system configurations.

RSC	Traveling Unit	Headway Policy	Vehicle Intelligence	Guideway Intelligence
1. Average Vehicle Smart Highway	Individual Vehicle	Uniform	Average	Active
2. Smart Vehicle Average Highway	Individual Vehicle	Platoon	Autonomous	Passive
3. Smart Pallet Average Highway	Pallet	Uniform	Autonomous	Passive
4. Smart Vehicle Passive Highway	Individual Vehicle	Independent	Autonomous	Passive
Note: [1]RSC 2 consists of three lane configuration variations, resulting in a total of six specific RSCs.				

Each RSC used in this research requires a specific definition of the associated roadway configuration. Three of the four primary RSCs (i.e., 1, 3, 4) were assigned only one roadway configuration, and one of the RSCs (i.e., 2) was assigned three different roadway configurations. The result is a total of six variations of the four primary RSCs, described by their *mainline*, *AHS access*, and *separation characteristics*.

Mainline

None of the RSCs investigated in this research effort involved a roadway which is completely AHS for all lanes, with no provisions for non-AHS vehicles. However, three distinctly different mainline roadway configurations were associated with the target RSCs and considered:

1. Two lanes in each direction, with the left lane in each direction serving mixed AHS and non-AHS traffic.

2. Three lanes in each direction with the left lane in each direction serving only AHS traffic.

3. Two lanes in each direction serving non-AHS traffic and a reversible lane between the non-AHS lanes serving only AHS traffic.

AHS Access

Access to the lane in which AHS is provided can involve a variety of entry/exit designs, some of which require maneuvering through non-AHS traffic to get to the AHS lane. Others simply provide direct access to the AHS lane via an exclusive ramp system.

For the sake of this research, entry and exit facilities were addressed only at a high level to determine compatibility with roadway design strategies. The main interest in entry/exit for this effort is simply to acknowledge whether a ramp system is on the left or right side of a lane set, spacing between terminals, and whether the ramp is intended for mixed or exclusive AHS flows. Other research teams have conducted detailed studies of entry/exit facilities (area J—Entry/Exit Analysis) and their deployment, and have documented those results in other reports.

The following AHS lane access components were considered germane to the RSCs in this research:

1. Mixed Ramps—AHS vehicle enters/exits the freeway facility by using the same ramp facilities as non-AHS vehicles. Special lanes may be provided for AHS vehicles on the ramps to facilitate check-in and check-out, but the AHS vehicle must maneuver through non-AHS lanes when traveling between the AHS lane and the ramp system.

2. Exclusive Ramps—All entry and exit points serving the AHS are provided by ramps intended exclusively for the use of AHS vehicles only and are physically located such that no maneuvers by AHS vehicles through non-AHS traffic are necessary to reach the AHS lane.

3. Transition Lane—Similar to the mixed ramp concept where AHS and non-AHS vehicles utilize the same ramps, but includes a transition lane located adjacent to the AHS lane. The transition lane is used for maneuvers into and out of the AHS lane. Traffic flow in the transition lane may be AHS only or mixed flow, and AHS vehicles must maneuver through non-AHS lanes and traffic to reach the AHS lane.

Lane Separation

The means by which separation of AHS and non-AHS traffic is accomplished is closely associated with how entry/exit may be accomplished. In terms of the RSCs considered for this research, the following two concepts were considered:

1. None—Separation of AHS and non-AHS traffic is accomplished by signing and striping only.

2. Barrier—Physical barrier used to separate AHS and non-AHS traffic streams along the length of the AHS lane.

Using these characteristics, the resulting six variations of the four primary RSCs are summarized as follows:

Table 5. Global RSC characteristics.

RSC	Mainline Roadway Configuration	AHS Lane Access			Lane Separation	
		Mixed	Exclusive Ramps	Transition Lanes	None	Barriers
1	3 Lanes each direction Exclusive AHS Lt. lane	X		X	X	
2A	3 Lanes each direction Exclusive AHS Lt. lane	X			X	
2B	3 Lanes each direction Exclusive AHS Lt. lane		X			X
2C	2 Non-AHS lanes each direction Reversible excl. AHS center lane		X			X
3	3 Lanes each direction Exclusive AHS Lt. lane		X			X
4	2 Lanes each direction Mixed traffic Lt. lane	X			X	

The graphics on the following sheets illustrate the general roadway configurations of the six variations of RSCs used in this research. The basic assumptions as to how each RSC would operate in summarized in table 7. Detailed descriptions of characteristics beyond the roadway deployment characteristics may be found in the AHS precursor systems analyses overview report.

Average Vehicle/Smart Highway/Dedicated Lane/Transitions

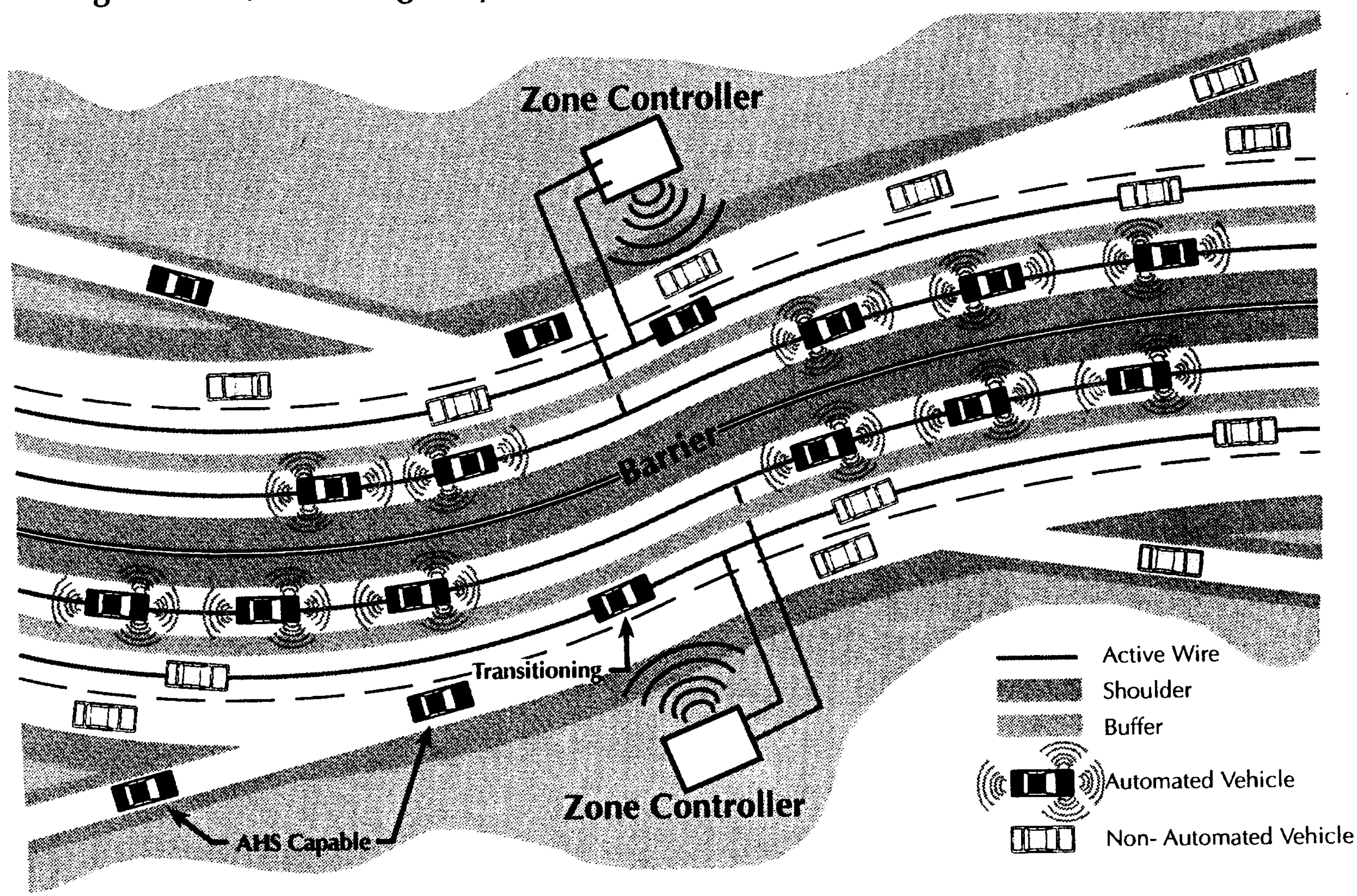


Figure 1. RSC 1.

Smart Vehicle/Average Highway/Dedicated Lane/Transition

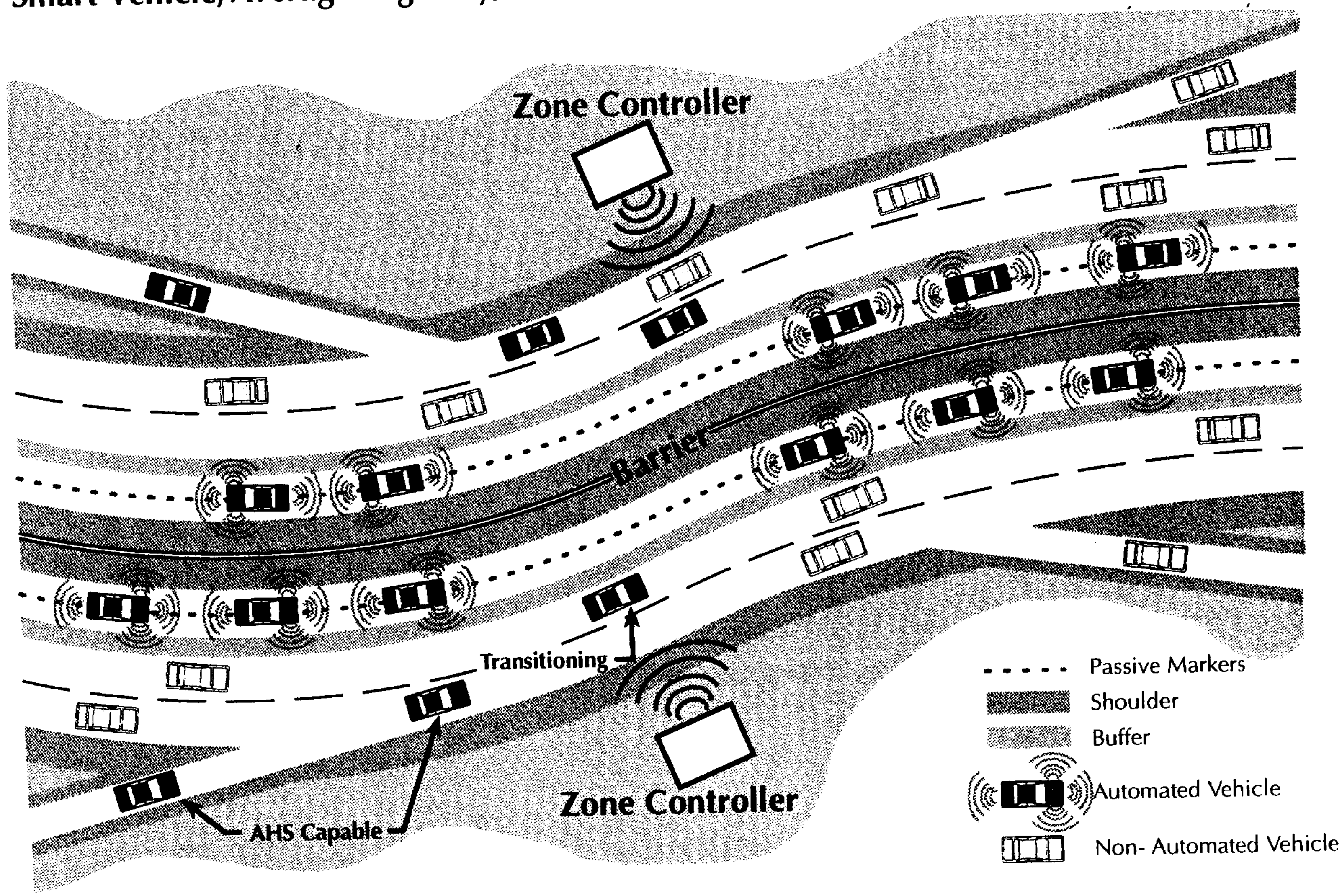


Figure 2. RSC 2A.

Smart Vehicle/Average Highway/Exclusive Lane/Ramps

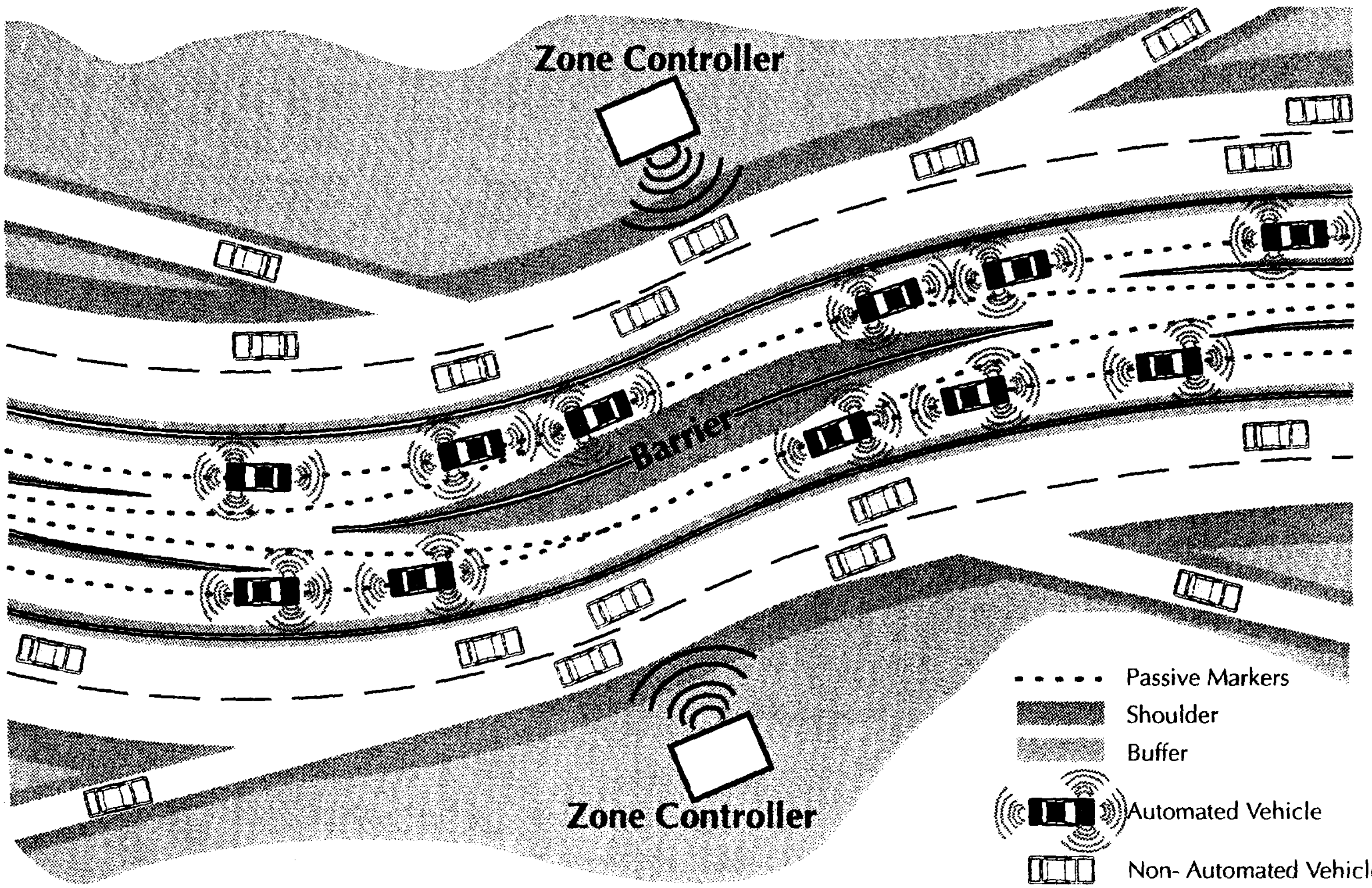


Figure 3. RSC 2B.

Smart Vehicle/Average Highway/Reversible Median

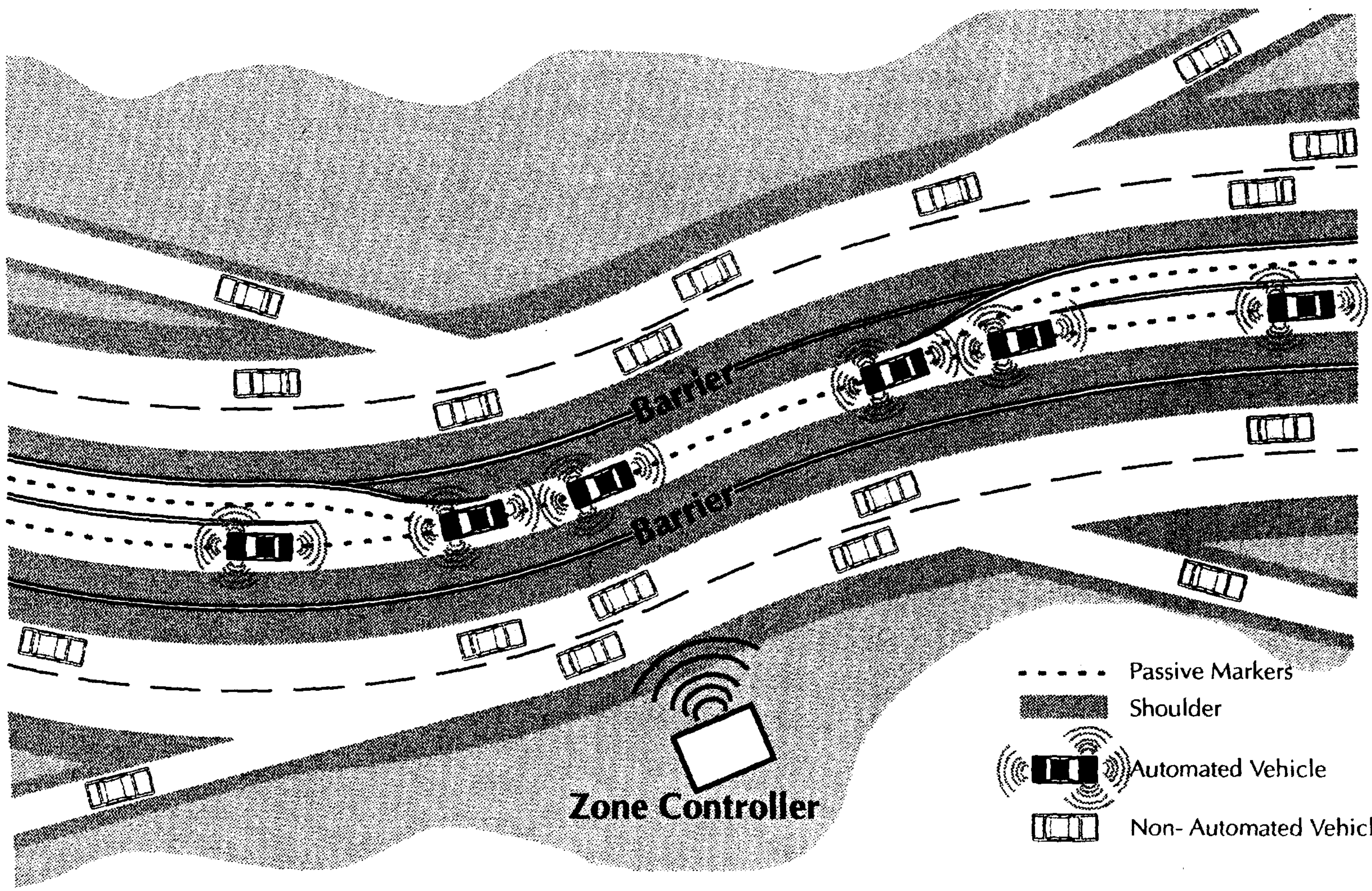


Figure 4. RSC 2C.

Smart Pallet/Average Highway/Exclusive Lane/Ramps

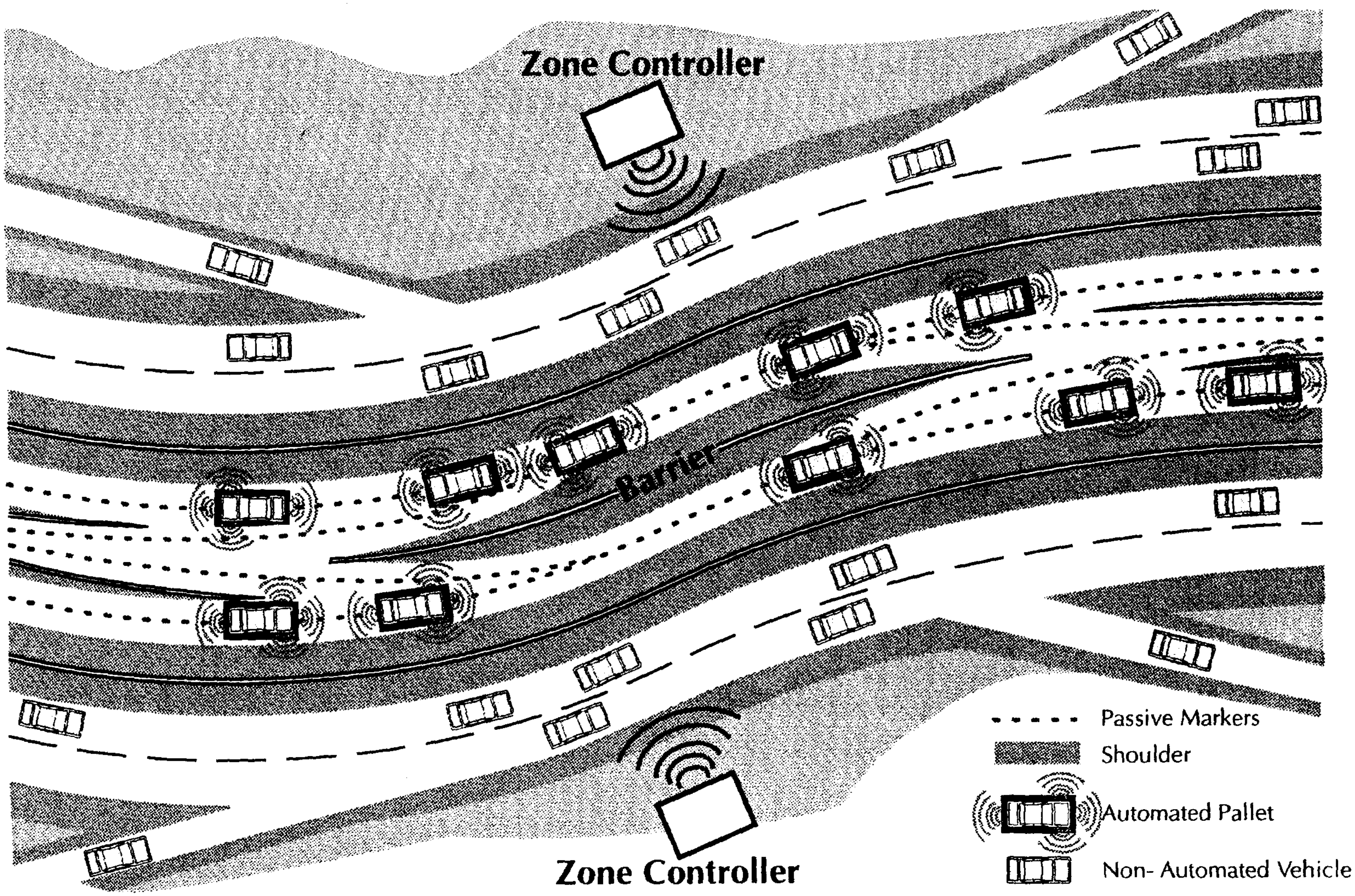


Figure 5. RSC 3.

Smart Vehicle/Dumb Highway/Two Lane Mixed

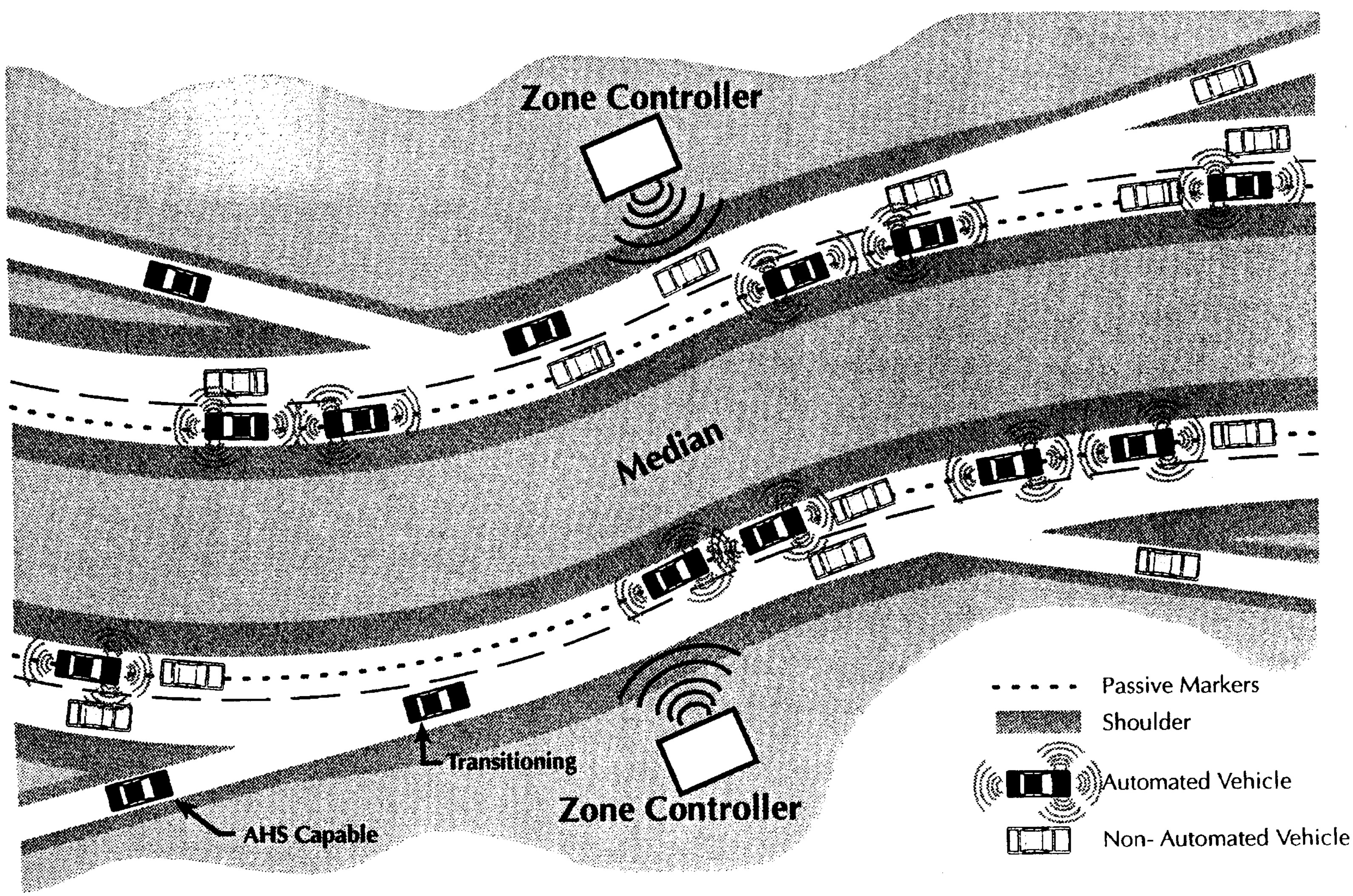


Figure 6. RSC 4.

Table 6. RSC assumptions.

Parameter	RSC 1	RSC 2	RSC 3	RSC 4
Vehicle Type	Individual Passenger Car	Individual Passenger Car	Single Car Pallet, Automatic Control Only	Individual Passenger Car
Headway Policy	Uniform	Platoon	Uniform	Independent
Vehicle Intelligence	Good	Smart	Smart	Very Smart
Roadway Intelligence	Good	Average	Average	Dumb
Lane Configuration	Mixed traffic on inside AHS lane with manual traffic on outside lane	Dedicated AHS lane(s) with transition lane and manual lane(s)	Dedicated reversible AHS lane with pullover space adjacent to AHS lane	All lanes mixed traffic
Barriers	None	None	Between AHS and Non-AHS Lanes Only	None
Entry/Exit Ramps	Current Type	Current Type	Current Types for Non-AHS Dedicated for AHS	Current Type
Transition to AHS	Where: In AHS lane When: At driver command after sector control OK How: Manual switch	Where: In Transition Lane When: At driver command after sector control OK How: Manual switch	Where: In Pallet Attach & Detach Area When: Upon link to pallet How: Automatic with link	Where: In AHS lane When: At driver command after sector control OK How: Manual switch
Check-Out of AHS Vehicle Systems	Combination of periodic certification and polling of internal sensors	Combination of periodic certification and polling of internal sensors	Pallets under control of central authority—Inspected before allowing on AHS	Combination of periodic certification and polling of internal sensors
Failure to Transition Results In:	Driver must continue under manual control	Driver must continue under manual control in transition lane or re-enter manual lane	Essentially cannot fail to transition unless driver refuses to enter destination	Driver must continue under manual control

DEVELOPMENT OF ENTRY/EXIT STRATEGIES

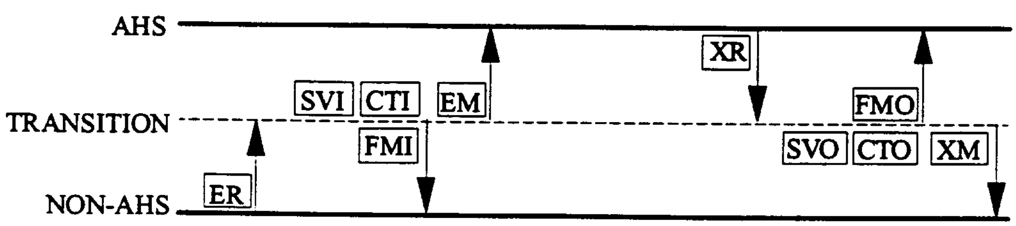
Rationale for Developing Strategies

The rationale for developing entry/exit strategies is to provide a set of criteria by which the measures of effectiveness of particular RSCs may be evaluated based on the distinctive elements of each implementation of the entry/exit functions. Developing entry strategies shows how the necessary functions to transfer a vehicle under manual control on a non-AHS roadway to an AHS roadway under automated control are implemented in each of the six baseline RSCs. Conversely, developing exit strategies shows how the necessary functions to transfer a vehicle on an AHS roadway under automated control to a non-AHS roadway under manual control are implemented.

The entry and exit strategies for each of the six baseline RSCs are based on the generalized functional implementation depicted in figure 7. This conceptualization represents entry and exit as a transitional interface between non-AHS operation to AHS operation. The elements of each entry/exit function common to the six RSCs are symbolically represented in their sequential execution as the vehicle is transferred from manual non-AHS operation to automated AHS control. The transitional nature of entry and exit is depicted by the location of the entry/exit operations along the transition line. The arrows represent the direction of the vehicle transition (i.e., non-AHS to AHS or AHS to non-AHS). Since entry and exit are the interface between both the functional and spatial aspects of AHS and non-AHS operation, the effectiveness of entry/exit strategies is critical to both the manual and automated modes of vehicle operation.

The sequential order of events for entry are as follows. An entry request (ER) is initiated by the vehicle operator on the non-AHS roadway. This request includes the operators intention to qualify for entry to AHS and the intended destination. A status verification (SVI) is performed which determines vehicle qualification for AHS operation. The status verification may also include AHS traffic and roadway status at both the point of entry and destination to provide metering for AHS capacity management. If the vehicle is granted authorization to enter the AHS roadway then the process of control transfer (CTI) from manual to AHS operation is initiated. If control transfer failed, or the vehicle did not qualify for entry (e.g., failed diagnostics, AHS roadway operating at capacity, etc.) then the fault mitigation (FMI) provides a safe transfer of the vehicle from this transitional stage of operation back to non-AHS operation. If the control transfer is accomplished then the entry maneuver (EM) is executed and the vehicle merges with the AHS traffic.

The sequential order of events for exit begins with an exit request as the vehicle approaches the intended destination. A status verification (SVO) is performed to establish that the operator is prepared to resume manual control of the vehicle. If the status verification qualifies the operator for manual operation then control transfer (CTO) occurs and AHS control is relinquished. The operator then executes the exit maneuver (XM) and merges the vehicle with non-AHS traffic. If the operator is not qualified by the status verification to resume manual control of the vehicle or control transfer otherwise fails then the vehicle enter the fault mitigation exit mode (FMO) whereby the vehicle either remains under AHS control. Under the fault mitigation mode the AHS



AUTOMATED CHECK-IN	ER: ENTRY REQUEST SVI: STATUS VERIFICATION IN
AUTOMATED CHECK-OUT	XR: EXIT REQUEST SVO: STATUS VERIFICATION OUT
CONTROL TRANSFER	CTI: CONTROL TRANSFER IN CTO: CONTROL TRANSFER OUT
LANE MANEUVERS	ELM: ENTRY LANE MANEUVER XLM: EXIT LANE MANEUVER
FAULT MITIGATION	FMI: FAULT MITIGATION IN FMO: FAULT MITIGATION OUT

Figure 7. Generalized functional implementation.

system navigates the vehicle to a safe holding area (e.g., emergency shoulder lane, parking lot, etc.) and brings the vehicle to rest.

The above functional descriptions defines entry and exit as used in this precursor analysis and provides the framework for the implementation strategies for each of the RSCs discussed in the section below.

Description of Entry/Exit Strategies for Each RSC

Entry/Exit Strategy for RSC 1

The entry/exit strategy for RSC 1 requires an additional center lane to be used as an exclusive transition lane. These transition lanes need not be continuous. There is a narrow buffer zone between the AHS lane and the transition lane. Traffic in the transition lane is operated in mixed manual and automated modes, but the automated mode of operation is used exclusively for executing merge maneuvers between the transition lane and the AHS lane. An implementation of this entry/exit strategy is illustrated in figure 8.

Entry. All of the AHS entry functions are executed in the transition lane. This is because the entering vehicle must access the AHS roadway through manual navigation of the vehicle from the ramp, and go across the manual right lane and center lane to the transition lane. Since the time and distance to make these two lane changes will be governed by congestion and other human factors, there is little advantage in beginning the AHS entry functions prior to the transition lane. After ACI is completed, the operator engages AHS control and is merged with AHS traffic. Since the transition lane consists of mixed traffic, conflicts between the required AHS entry speed and slower traffic speeds in the transition lane due to congestion can occur. Speed conflicts can be resolved by either denying access to the entry candidate vehicle, delaying the merge maneuver until a sufficiently large gap in AHS traffic permits safe entry at the lower transition lane speed, or downgrading the AHS speed of a segment of vehicles in the vicinity of the entering vehicle to permit the entry vehicle to safely merge. Fault mitigation upon entry simply consists of continued manual operation of the vehicle on the non-AHS roadway.

Exit. The exit strategy is similar to the entry process except the vehicle is merging from the AHS roadway into the transition lane. As with entry, the major difficulty with this strategy is the potential speed difference between traffic in the AHS lane and the manually operated traffic in the transition segment. The fault mitigation options for ACO are to either deny exit until a suitable open slot in the manual traffic occurs or to downgrade the operating speed of AHS traffic to facilitate the right hand merge of the exiting vehicle. Fault mitigation for aborted control transfer requires the vehicle to re-enter the AHS roadway and be navigated by the AHS system to a location where provision is made to bring the vehicle to rest in a holding area (left shoulder, or AHS parking area).

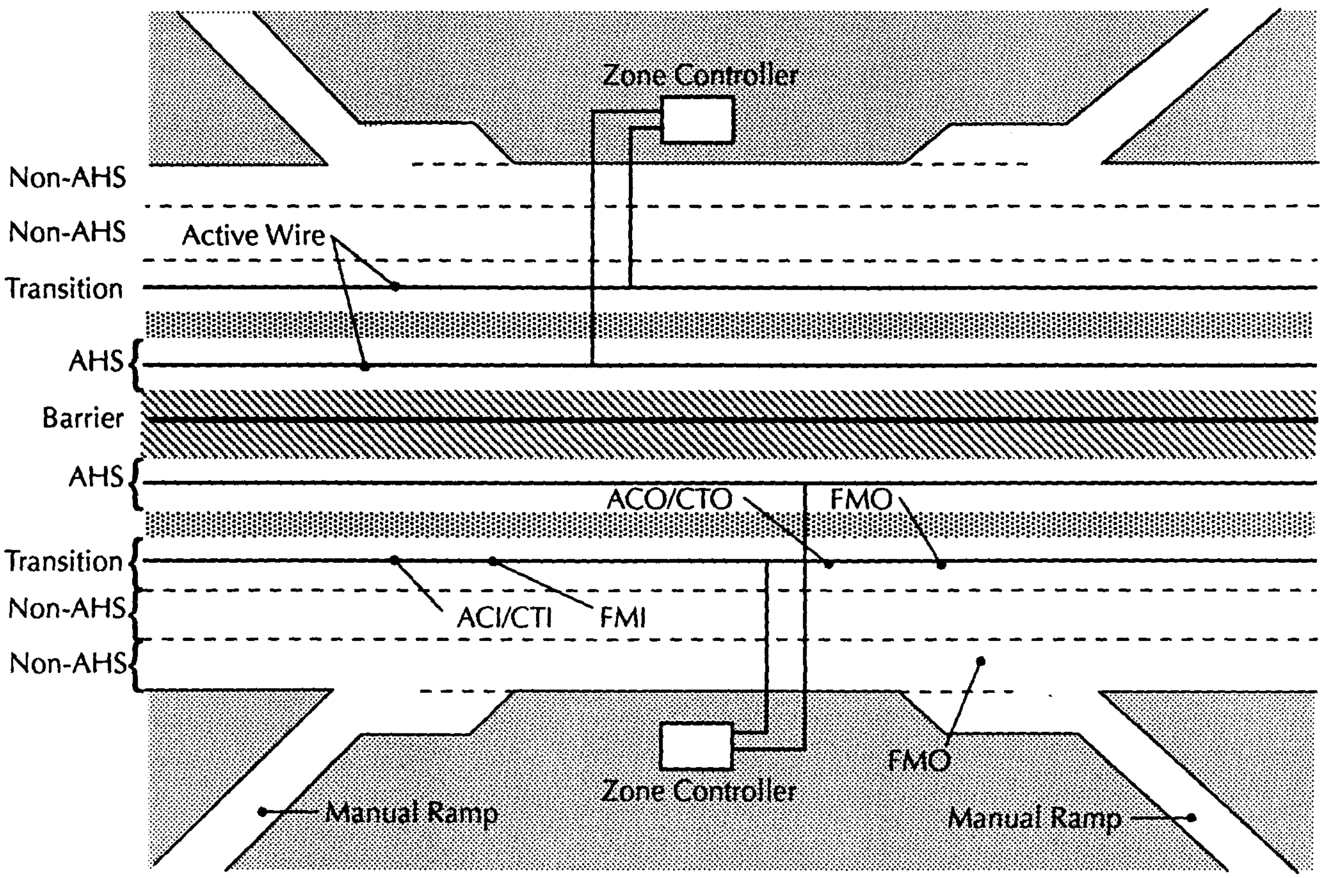


Figure 8. Entry/exit strategy for RSC 1.

Entry/Exit Strategy for RSC 2A

The entry/exit strategy for RSC 2A uses the center lane as the transition segment, which is operating in manual mode only. This implementation is shown in figure 9. As in RSC 1, there is a narrow buffer zone between the AHS lane and the center lane. The transition segment is also the left lane or passing lane for manual traffic.

Entry. The ACI functions are executed in the transition segment. The operator of the AHS vehicle is given authorization to enter the AHS roadway while manually operating the vehicle in the transition segment of the center lane. Entry into the AHS traffic is accomplished by a manually executed merge from the transition segment into the AHS roadway traffic. Control transfer occurs automatically once the vehicle has moved across the buffer zone between the center lane and AHS lane. As with the entry strategy for RSC 1, fault mitigation for conditions arising during ACI consists simply of continued manual operation of the vehicle on the non-AHS roadway. However, if an aborted control transfer occurs in RSC 2A, the vehicle will have already entered the AHS roadway. In this case the only fault mitigation option is for the operator to manually merge the vehicle back across the buffer zone into the transition lane. It is possible, however, for traffic conditions to have changed such that the right handed merge may no longer be possible. In this case, the operator must navigate the vehicle in the AHS lane until an opportunity to merge with the non-AHS traffic becomes available. This would require the AHS system operation to be temporarily degraded by maintaining a large headway between the manual vehicle and automated vehicles on the AHS lanes to safely accommodate the presence of the manually operated vehicle. Since the merges from the center lane are manual control transfer faults speed and slower traffic speeds in the transition segment due to congestion are likely to have a more severe effect than the same fault in RSC 1. As in the previous case, speed conflicts can be resolved by either denying access to the entry candidate vehicle, delaying the merge maneuver until a sufficiently large gap in AHS traffic permits safe entry at the lower transition segment speed, or downgrading AHS speed of a segment of vehicles in the vicinity of the entering vehicle to permit the entry vehicle to safely merge.

Exit. The exit strategy is similar to the entry process except the vehicle is merging from the AHS roadway into the transition segment of the center lane. Control transfer, as with entry, occurs on the AHS roadway. Thus the exit strategy for RSC 2A is identical to the exit strategy for RSC 1 except the merge maneuver is manually executed. Again, the major difficulty with this strategy is the potential speed difference between traffic in the AHS lane and manually operated traffic in the center lane. As with RSC 1, the options are to either deny exit until a suitable open slot in the manual traffic occurs or to downgrade the operating speed and headway of AHS traffic to facilitate the right hand merge of the exiting vehicle. Fault mitigation of conditions arising from an aborted control transfer consists of the vehicle remaining under AHS control. AHS navigates the vehicle to a location where provision is made to bring the vehicle to rest in an AHS holding area (left shoulder, or AHS parking area).

RSC 2A has one critical flaw that affects both the safety and throughput of the entry and exit strategies. The critical flaw is the imposed operation of non-AHS traffic in the transition segment. The functional purpose of a transition segment as defined previously under the section on lane maneuvers is threefold: 1) control transfer, 2) matching the speed of the entry/exit vehicle with the collateral traffic lane, and 3) longitudinal coordination of the entry/exit vehicle with the merge slot

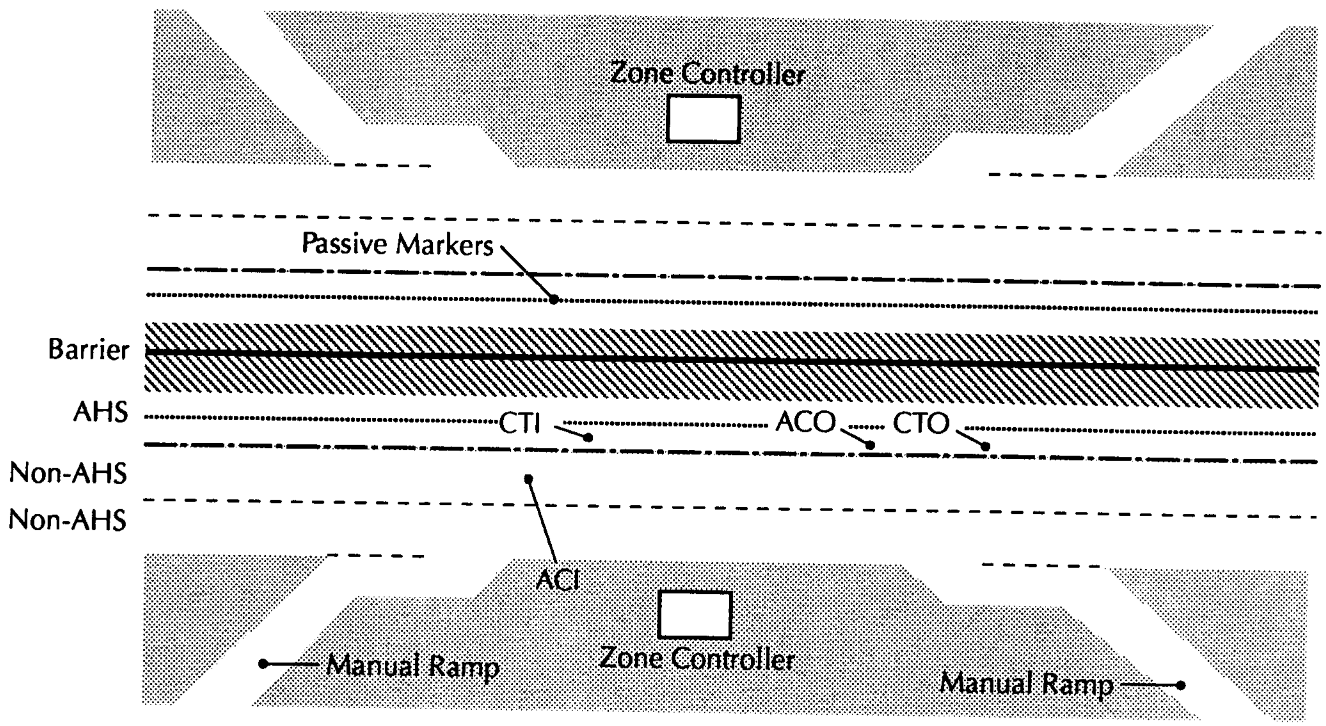


Figure 9. Entry/exit strategy for RSC 2A.

in the collateral traffic lane. In congested traffic conditions, a transition segment cannot fulfill the speed matching function and is severely limited in maneuverability options to provide longitudinal coordination of the entry/exit vehicle with a merge slot in the collateral lane. In order for the transition segment to fulfill its functional role, it is necessary that the lane be exclusively for entering or exiting AHS vehicles. This requires an additional lane to be constructed as in RSC 1. This can be accomplished without additional land use if the left or right shoulder can be modified to divert traffic laterally to provide space for the additional lane over a sufficient distance to accomplish the entry/exit functions.

Entry/Exit Strategy for RSC 2B

There are three entry exit strategies for this RSC:

- Right-handed entry/exit fly-over ramps
- Left-handed entry/exit overpass ramps
- Left-handed entry/exit fly-over ramps

All three entry/exit strategies for RSC 2B use the ramp as the transition segment. ACI, ACO, control transfer, lane merge maneuvers, and fault mitigation occur on the access and egress ramps.

Right-Handed Entry/Exit Fly-Over Ramps

An implementation of this entry/exit strategy is shown in figure 10.

Entry. All of the AHS entry functions are executed on the access ramp. The access ramp connects the arterial roadway directly to the AHS roadway and is divided into six segments. The access ramp is designed to provide egress of vehicles failing ACI or transfer of control from manual to automated mode. The egress lane removes a failed AHS vehicle from the ramp by allowing the vehicle to merge with either the arterial traffic or non-AHS collateral roadway. To accommodate the possible entry fault conditions, ACI and control transfer occurs on the segment of the ramp prior to the access ramp egress. If the vehicle is authorized for AHS entry by the ACI function, then AHS automated control is either engaged by the operator or the AHS controller. The AHS system then provides the longitudinal and lateral control of the vehicle necessary to merge the entry vehicle with the AHS roadway traffic.

Exit. The exit strategy is similar to the entry process. ACO and control transfer occur on the exit ramp prior to the fault mitigation egress adjacent to the ramp. Fault mitigation for aborted ACO or control transfer requires the vehicle to be navigated by the AHS system to a location where provision is made to bring the vehicle to rest in a holding area or egress lane (e.g., an AHS parking area adjacent to the exit ramp).

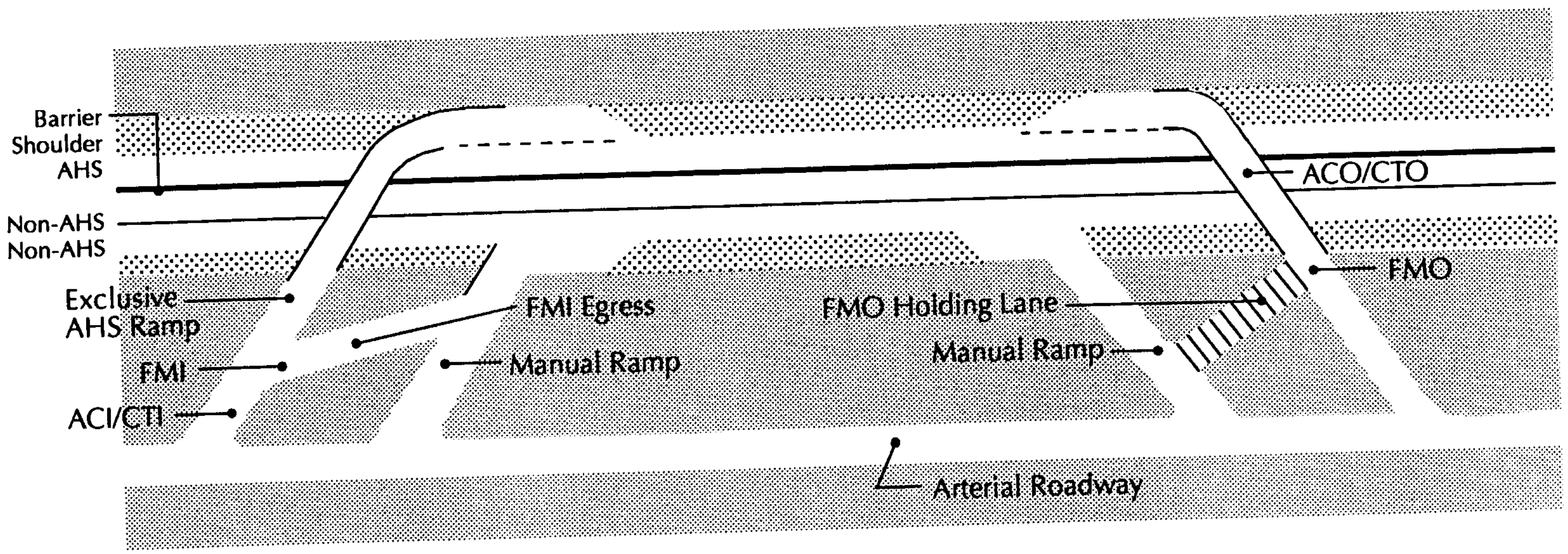


Figure 10. Entry/exit strategy for RSC 2B: right-handed fly-over ramps.

Left-Handed Entry/Exit Overpass Ramps

An implementation of this entry/exit strategy is shown in figure 11.

Entry. All of the AHS entry functions are executed on the overpass lanes connected to the access ramp. The overpass lanes connect the arterial roadway directly to the AHS access ramps. The overpass is designed to provide egress of vehicles failing ACI or transfer of control from manual to automated mode. The egress lane returns the failed AHS vehicle to the arterial traffic. To accommodate possible entry fault conditions, ACI and control transfer occurs on the segment of the ramp prior to the access ramp. If the vehicle is authorized for AHS entry by the ACI function, then AHS automated control is either engaged by the operator or the AHS controller. The AHS system then provides the longitudinal and lateral control of the vehicle necessary to merge the entry vehicle with the AHS roadway traffic.

Exit. The exit strategy is similar to the entry process. ACO and control transfer occur on the exit ramp prior to the fault mitigation egress adjacent to the ramp and overpass lane. Fault mitigation for aborted ACO or control transfer requires the vehicle to be navigated by the AHS system to the egress lane where provision is made to bring the vehicle to rest.

Left-Handed Entry/Exit Fly-Over Ramps

An implementation of this entry/exit strategy is shown in figure 12.

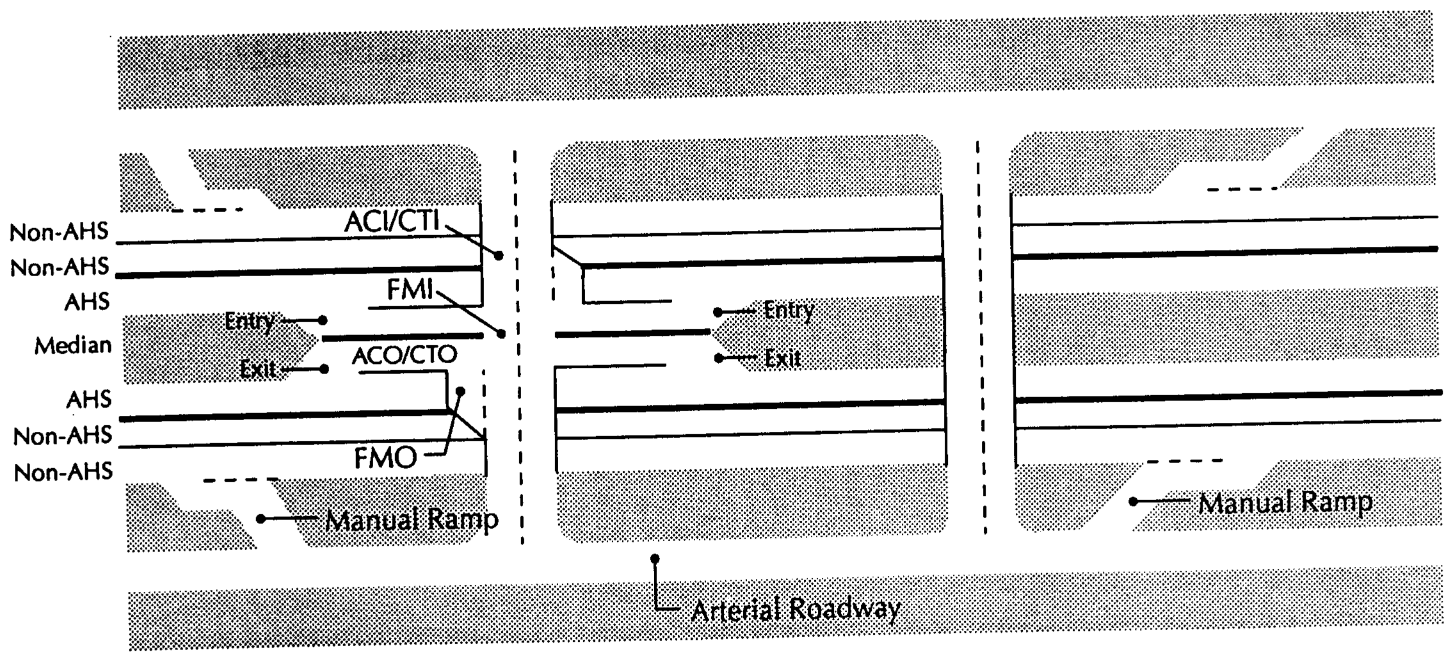


Figure 11. Entry/exit strategy for RSC 2B: left-handed overpass ramps.

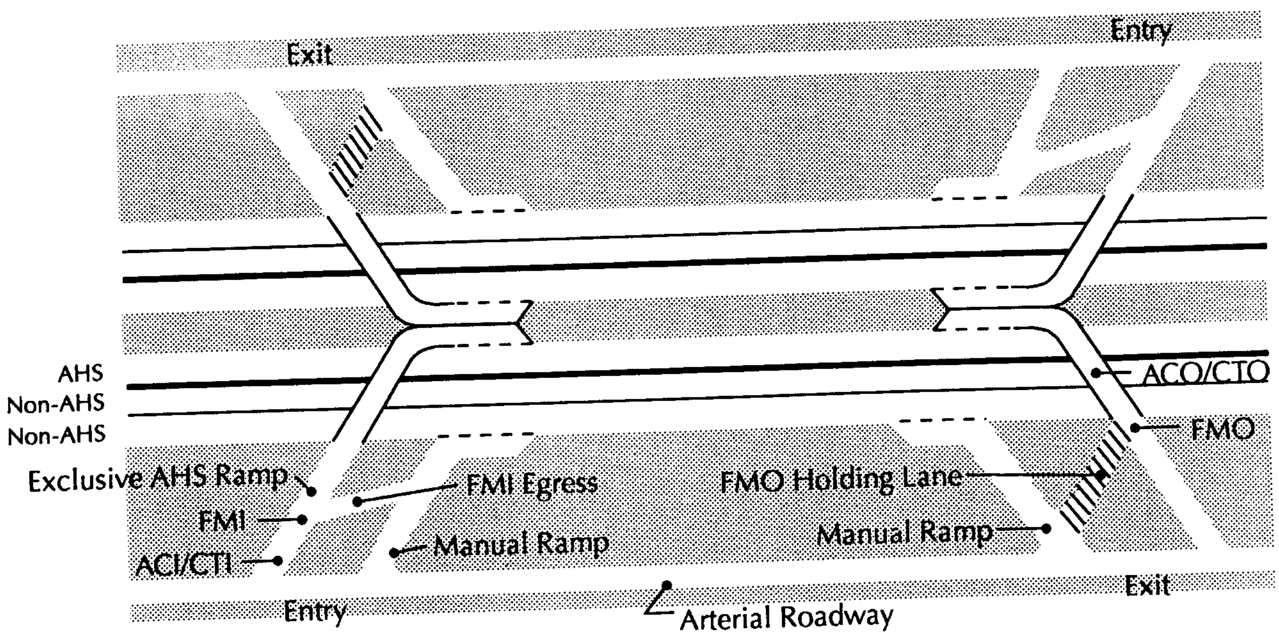


Figure 12. Entry/exit strategy for RSC 2B: left-handed fly-over ramps.

Entry. All of the AHS entry functions are executed on the access ramp. The access ramp connects the arterial roadway directly to the AHS roadway and is divided into six segments, as in the case for the right-handed entry/exit ramp. The access ramp is designed to provide egress of vehicles failing ACI or transfer of control from manual to automated mode. The egress lane removes the failed AHS vehicle from the ramp by allowing the vehicle to merge with traffic on the non-AHS collateral roadway. To accommodate possible entry fault conditions, ACI and control transfer occurs on the segment of the ramp prior to the access ramp egress. If the vehicle is authorized for AHS entry by the ACI function, then AHS automated control is either engaged by the operator or the AHS controller. The AHS system then provides the longitudinal and lateral control of the vehicle necessary to merge the entry vehicle with the AHS roadway traffic.

Exit. The exit strategy is similar to the entry process. ACO and control transfer occur on the exit ramp prior to the fault mitigation egress. Fault mitigation for aborted ACO or control transfer requires the vehicle to be navigated by the AHS system to the egress lane where the vehicle is brought to rest.

Entry/Exit Strategy for RSC 2C

The entry/exit strategy for RSC 2C is functionally identical to RSC 2B except provision is made for the roles of the entry and exit ramps to be reversed concurrent with the AHS traffic direction changes. The direction changes are indicated by lighted directional arrows. One other distinction is that the right-hand and left-hand fly-over ramps are combined, as illustrated in figure 13, for dual use as both entry and exit ramps.

Entry/Exit Strategy for RSC 3

The strategy required for this RSC is distinct from the others because it involves single-vehicle pallets. Thus, entry and exit must accommodate the loading and unloading of vehicles and the circulation of pallets over the AHS system to meet user demands.

Entry. Vehicles would enter via a left-side ramp to a loading area located in the roadway median area. Then, the vehicle would be loaded onto a single-vehicle pallet. The pallet, which is always under system control, enters the AHS lane directly via a left-side entry ramp. The palletized vehicle would travel on the exclusive AHS lane (separated from adjacent lanes with barriers) until exit is desired.

Exit. For exit, the pallet would pull over to an unloading area (also in the median area), where the vehicle would roll off the pallet and leave the system under driver control via a left-side exit ramp.

Storage/Distribution. Essentially, a pallet must be provided for every vehicle desiring use of the AHS . This poses a critical problem of storing and distributing the pallets around the AHS system. If stationary storage facilities were used, they would have to be of the order of typical downtown multistory parking garages (perhaps at each entry and exit location). However, the storage problem for the pallet concept could be minimized if the AHS lanes themselves were used to circulate

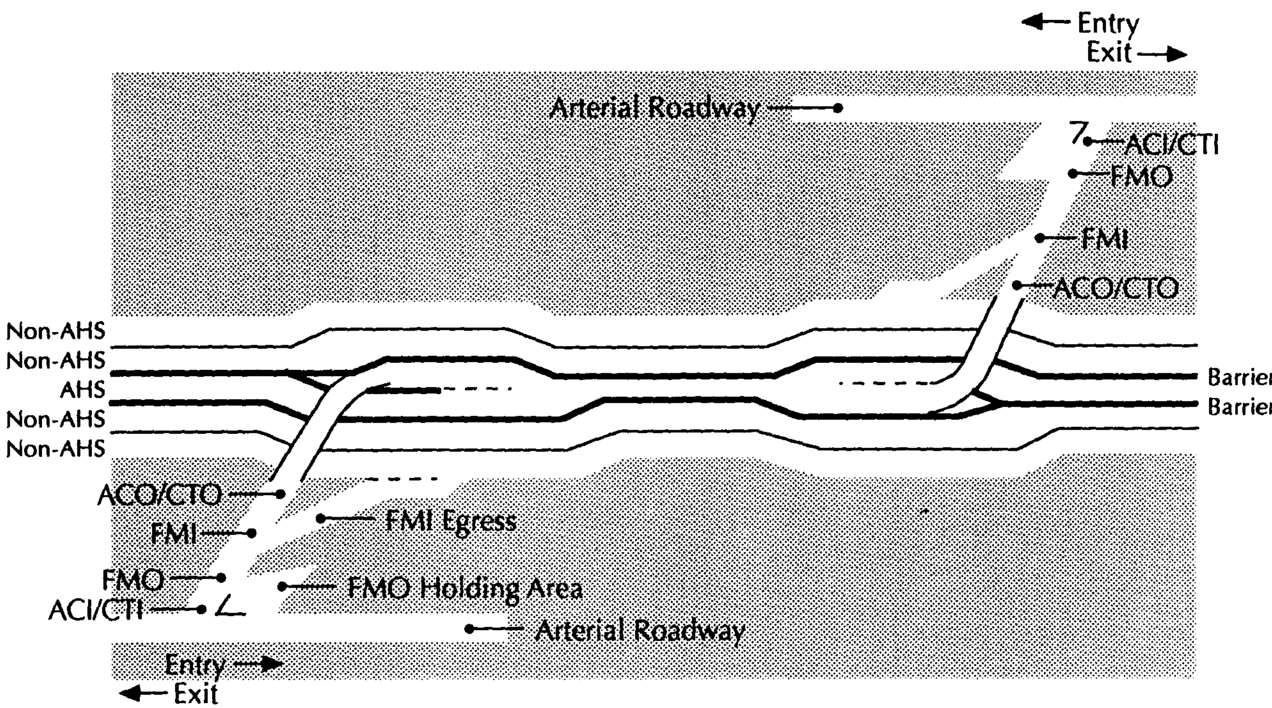


Figure 13. Entry/exit strategy for RSC 2C.

pallets throughout the system. Conceivably, such a distribution network could be modeled after transit bus systems.

Entry/Exit Strategy for RSC 4

The AHS entry/exit strategy for RSC 4 is the same as the entry and exit on a manual roadway except that provision is made for mitigation of control transfer faults. Implementation of this entry/exit strategy is illustrated in figure 14. Entry and exit ramps are identical to the ramp designs for conventional controlled access roadways. Fault mitigation for entry consists of simply continuing to operate the vehicle in the manual mode. Fault mitigation for exit consists of the AHS bringing the vehicle to rest on the right shoulder or in a park-and-hold area adjacent to the exit ramp. The former option has the advantage that only a small segment of the right shoulder needs to be AHS equipped. The park-and-hold option would require construction of a park-and-hold area adjacent to the exit ramp as well as equipping all of the exit ramps for AHS .

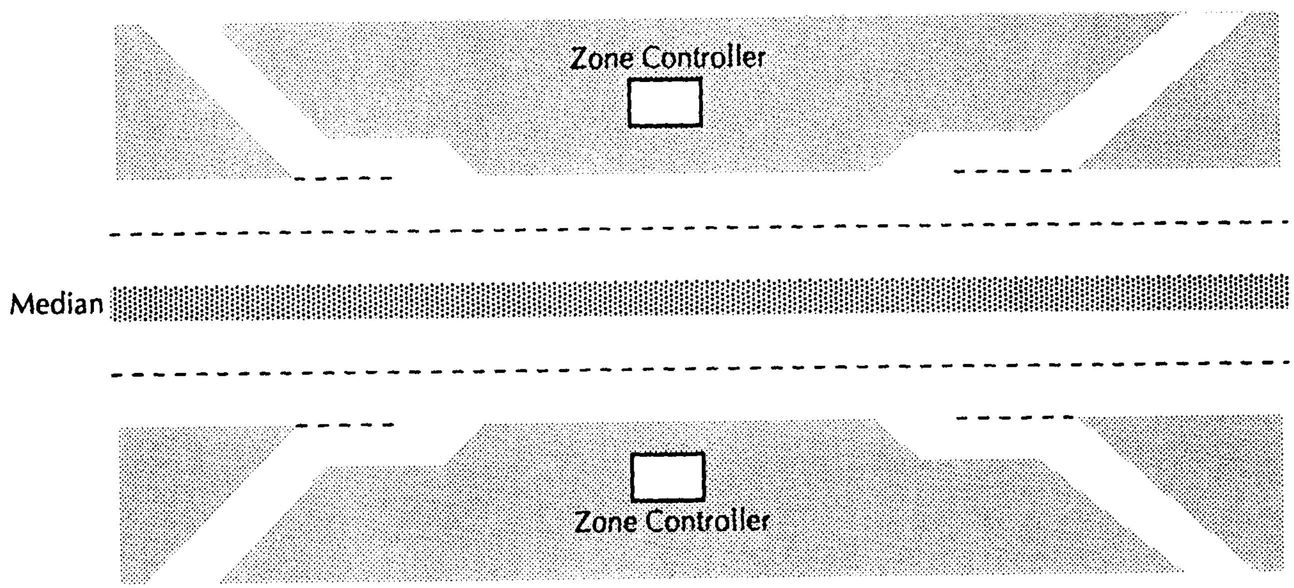


Figure 14. Entry/exit strategy for RSC 4.

DEVELOPMENT OF MEASURES OF EFFECTIVENESS

A set of seven MOEs were identified as effective measures of the viability of entry/exit implementation strategies for AHS . These were chosen to cover the four basic goals of safety, comfort, throughput, and environmental impact, while focusing on infrastructure considerations. The entry/exit strategies were compared and ranked for each of the MOEs, which are defined and discussed in the following sections.

MOE #1—Minimal Need for Additional Land

A major constraint on implementing AHS is the cost of new entry and exit areas on the highway. In congested urban areas (where AHS may have the greatest potential), the availability of additional land is limited. A goal is to retrofit existing entry and exit areas for AHS use wherever possible.

Entry/exit space is needed for a wide range of applications, including ACI, ACO, ramps, transition lanes, rejection lanes, barriers, pallet operations, emergency vehicle access, and malfunction management. Longitudinal distance is needed for accelerating and decelerating to the desired speeds for entry, exit and slot formation in the AHS lanes. If existing shoulders must be preserved, then the addition of a transition lane and/or physical barriers may require substantial road construction. If the AHS lanes are restricted to a certain class of passenger vehicles, then it may be possible to narrow the transition and AHS lanes and/or shoulders, thereby minimizing the amount of additional roadway that may be constructed. However, if the AHS lanes are not restricted to a vehicle class, then full lane widths (typically 12 feet long) would be needed to ensure adequate space.

MOE #2—Minimal Need for Additional Facilities

Additional facilities needed for entry and exit may include automated check-in and check-out (ACI and ACO, respectively) stations, loading and unloading areas for palletized vehicles, and traffic metering equipment. These facilities add cost to AHS implementation, and could pose reliability problems. A goal would be to minimize the need for additional facilities. This would reduce the cost of the AHS system and possibly increase its reliability.

New ramps and lanes constructed in the existing space envelop of the roadway system represent additional facilities. New lane construction in the median of an existing highway may require extensive modifications to overpasses with support structures located in the path of the AHS lane. New ramps for direct left-side entry and exit to an AHS lane would require some kind of grade separation to clear the non-AHS lanes. Examples include elevating the AHS lane in the vicinity of a new ramp constructed at surface street grade, and constructing a flyover ramp.

ACI and ACO facilities can be minimized by performing some of these functions “on the move,” and others via a periodic inspection/certification process.

MOE #3—Minimal Negative Impact on Adjacent Roadways and the Environment

The entry and exit portions of the AHS must not create traffic flow problems on the adjacent streets to and from which the AHS vehicles are transferred. The advantage of increased roadway capacity on may be offset by congestion caused by increased traffic on adjacent surface streets. ACI plazas and vehicle rejection lanes could exacerbate this problem by causing backups onto the surface streets due to long queues. This MOE also is related to environmental impact; the most prominent impact on adjacent roadways is traffic congestion, which in turn is manifested in increased emissions.

MOE #4—Great Improvement in Potential Capacity over Comparable Non-AHS Roadway Systems

The entry and exit portions of the system must minimize any bottleneck effects that would restrict the throughput of the system. It is important that capacity of the overall roadway system—both AHS and non-AHS —is improved. Achieving higher than normal capacity on the AHS lanes at the expense of lowering the capacity on the non-AHS lanes would be unacceptable if the total capacity is not improved over the system before AHS was deployed.

MOE #5—Minimal Disruption of Roadway Traffic Flow

Metering of traffic to and from AHS lanes must not degrade the traffic flow on non-AHS lanes, and vice versa. The inability to control non-AHS traffic flow and non-AHS vehicle behavior presents one of most significant hurdles for achieving high capacity and improved safety. Minimal disruption of the flow in non-AHS lanes would require entering AHS vehicles to move into the flow under driver control and enter the transition lane or AHS lane at the earliest opportunity. For highly congested non-AHS flow, it is conceivable that the entering AHS vehicle may not be able to enter the vehicle at the first available location, because the time required to weave would be substantial. Further, without transition lanes, AHS vehicles could enter the AHS lane at speeds much lower than the nominal operating speed, resulting in reduced throughput on the lane. The ability of the AHS to coordinate slot formation for an entering or exiting vehicle also could be compromised. This problem could be mitigated by ramp metering at the local (ramp) level, in which vehicles are released into the flow based on upstream traffic conditions. A more extreme method would involve slowing or stopping flow in the non-AHS lanes (via signalling) to provide opportunities for entering and exiting AHS vehicles to cross the non-AHS lanes quickly over a short distance.

MOE #6—Ability to Mitigate Safety Hazards

The entry and exit areas must be designed to preclude and/or minimize safety hazards. Although AHS safety has its own designated activity area, the salient safety implications of entry/exit strategies must be considered in their assessment. In fact, all entry/exit strategies must be passed through the “safety filter” before being considered as candidates for deployment. Key issues associated with AHS entry and exit safety are the need for barriers, transition lanes, traffic metering, and shoulders, and more generally, the safety of mixed traffic entry and exit.

MOE #7—Low Cost and Complexity

The overall cost for implementing entry and exit portions of the system should be minimized without compromising the four basic AHS goals of high safety, throughput, comfort and environmental compatibility. Further, the entry and exit systems should be made as simple as possible, which would reduce the cost to build, maintain and operate, and improve reliability. Primary low-cost strategies involve maximizing the use of the existing infrastructure and minimizing facilities requirements.

EVALUATION OF ENTRY/EXIT STRATEGIES

An assessment of the candidate entry and exit strategies is presented in this section.

The criteria used to evaluate the entry/exit strategies contain a number of qualitative categories. Determining the measures of effectiveness for these qualitative categories at the precursor analysis stage of this evaluation necessarily involved some subjectivity in the assessment process. The subjective elements of the evaluation are justified since the objective was to produce only a relative merit scales for comparing RSC strategies to their non-AHS counterparts.

RSC 1—Smart Vehicle/Smart Highway—Transition Lanes, No Barriers

In this RSC, vehicles enter a six-lane highway via a mixed traffic ramp. The AHS vehicle weaves across two non-AHS lanes to enter a transition lane. ACI and transfer of control to the system occur in the transition lane, and the system maneuvers the vehicle into the inner AHS lane. A uniform headway policy is used in the AHS lanes with nominal gaps of 10 m (33 ft). During exit, the system maneuvers the AHS vehicle into a transition lane, where ACO is performed and control is transferred to the driver. The driver then enters a non-AHS lane and either continues on the roadway or weaves across the lanes to exit. Physical barriers are not part of this RSC.

MOE #1—Minimal Need for Additional Land. RSC 1 would make maximum use of exiting ramps, but would require that existing roadways be modified to establish transition lanes at each entry and exit location. For entry, a transition lane must be long enough to perform ACI and accelerate a vehicle from rest to AHS speed. For exit, the transition lane must be long enough to decelerate from AHS speed to rest and perform ACO. Further, the transition lane network must be designed to queue a sufficient number of vehicles so that flow on the non-AHS lanes is not impeded and drivers are not discouraged from using the AHS .

Simple calculations were made to determine minimum transition lane lengths based on acceleration and deceleration level. These are shown in figure 15, and indicate that for minimal required vehicle acceleration capabilities of 0.1 G to 0.2 G, minimum transition lane distances of from about 950 feet to 1900 feet would be required if a vehicle starts from rest. Further, it would take from 17 seconds to 24 seconds to accelerate the vehicle over these distances. The transition lanes would need to be longer than the calculated values to accommodate vehicle queues, ACI and ACO processes, and vehicle rejection. Further, a much longer transition lane would be needed if a vehicle is required to stop and then accelerate to merge into the non-AHS lane. If entry and exit points are spaced on the order of the minimum required distance, then the result would be effectively a continuous transition lane.

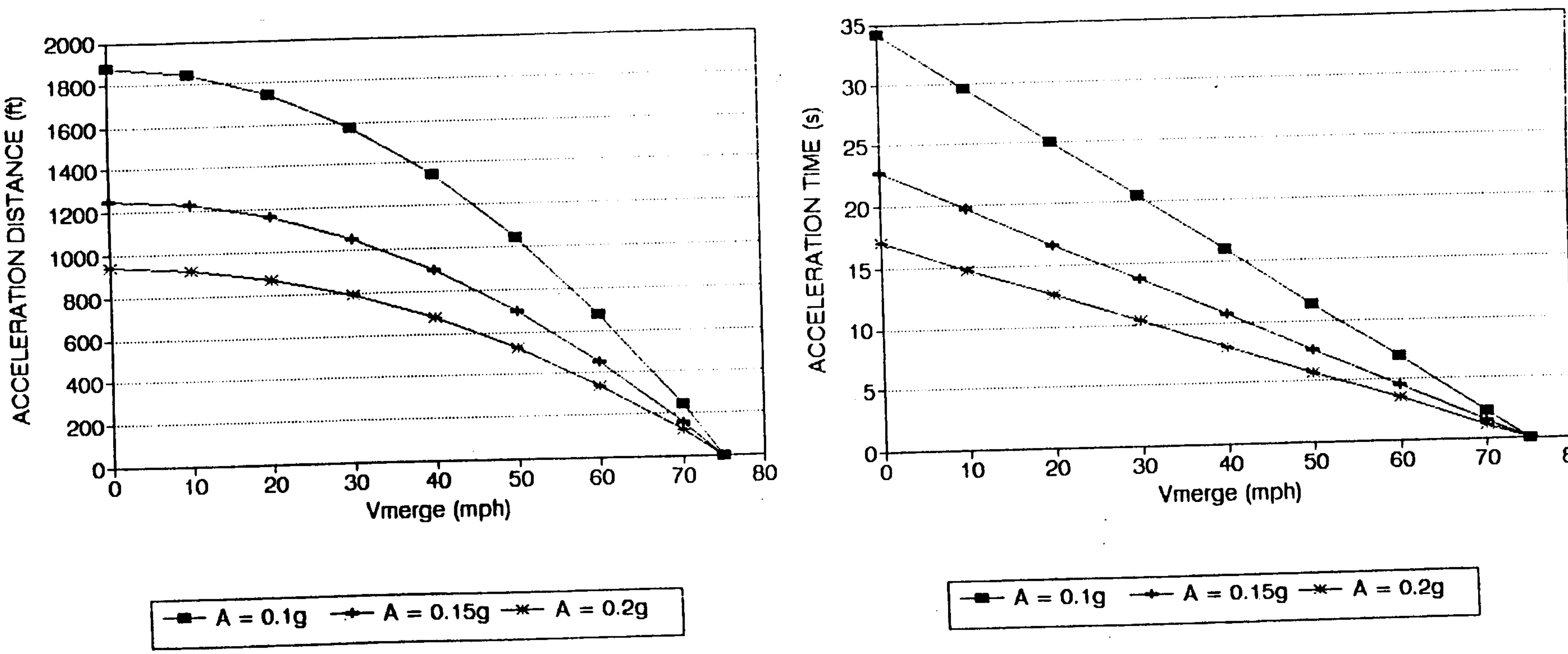


Figure 15. Distance and time required for entering vehicle to accelerate from an initial speed (Vmerge) to AHS speed (Vahs = 75 mph).

Results of work under the safety and roadway deployment analysis activity areas have indicated that shoulders next to the AHS lanes are highly desirable to provide space for malfunctioning vehicles, snow removal, emergency access, and to move around stalled vehicles in the AHS lane. Thus, widening of the existing roadway to accommodate transition lanes would be required, even if the existing shoulders and the AHS lane were made narrower. It would not be practical to make non-AHS lanes narrower, because the range of vehicles operating on the non-AHS roadway generally require the full lane width. Further, narrow AHS lanes would preclude some classes of vehicles (e.g., vans with trailers and extended mirrors, commercial vehicles with wide loads).

MOE #2—Minimal Need for Additional Facilities. An important facility required to deploy this entry/exit strategy is traffic metering in the transition lanes for ACI, ACO and release of vehicles into the traffic streams. This could take the form of signals or gates. Since it is assumed for this study that there will be no dynamic performance checks during ACI or ACO, the required facilities will have minimal impact on the infrastructure requirements.

MOE #3—Minimal Negative Impact on Adjacent Roadways and the Environment. Because this RSC will involved mixed traffic entry and exit, the impact of the AHS on adjacent roadways will be limited to the ability of the adjacent roadways to handle a potential increase in traffic at the entry and exit points. The effect of this RSC on backup on the ramps is not expected to be significant. A potential environmental effect related to entry and exit is increased emissions due to queues formed in the transition lanes.

MOE #4—Great Improvement in Potential Capacity over Comparable Non-AHS Roadway Systems. The entry/exit strategy for this RSC could limit the ability of the AHS to reach its full potential. Vehicles desiring to enter or exit the AHS would have to weave across two non-AHS lanes to reach the transition lane. If the non-AHS lanes are severely congested, then the time and distance required to complete entry and exit could be excessive, and the driver may decide not to enter if his perceived overall travel time is not significantly better than achievable on the non-AHS portion of the roadway.

MOE #5—Minimal Disruption of Roadway Traffic Flow. The entry strategy for this RSC would result in minimal disruption of traffic flow in the AHS lane if the transition lanes provide sufficient distance for the vehicle to enter at the prevailing AHS lane speed. An exception is if AHS lane traffic is adjusted to open a slot for an entering vehicle. As shown in figure 16, opening a slot for an entering vehicle could require adjustment of AHS traffic flow beginning several hundred feet upstream of entry point. Some disruption of non-AHS traffic flow could occur if the transition lane queue is filled and entry to the transition lane denied. A possible result in this case could be unsafe maneuvering of the vehicle desiring entry because of indecision or frustration in response to being denied entry. The exit strategy would not disrupt traffic flow on either the AHS or the non-AHS lanes if the transition lanes are sufficiently long for exiting vehicles to enter at AHS speed, decelerate, pass through ACO, queue, and accelerate to merge mto the

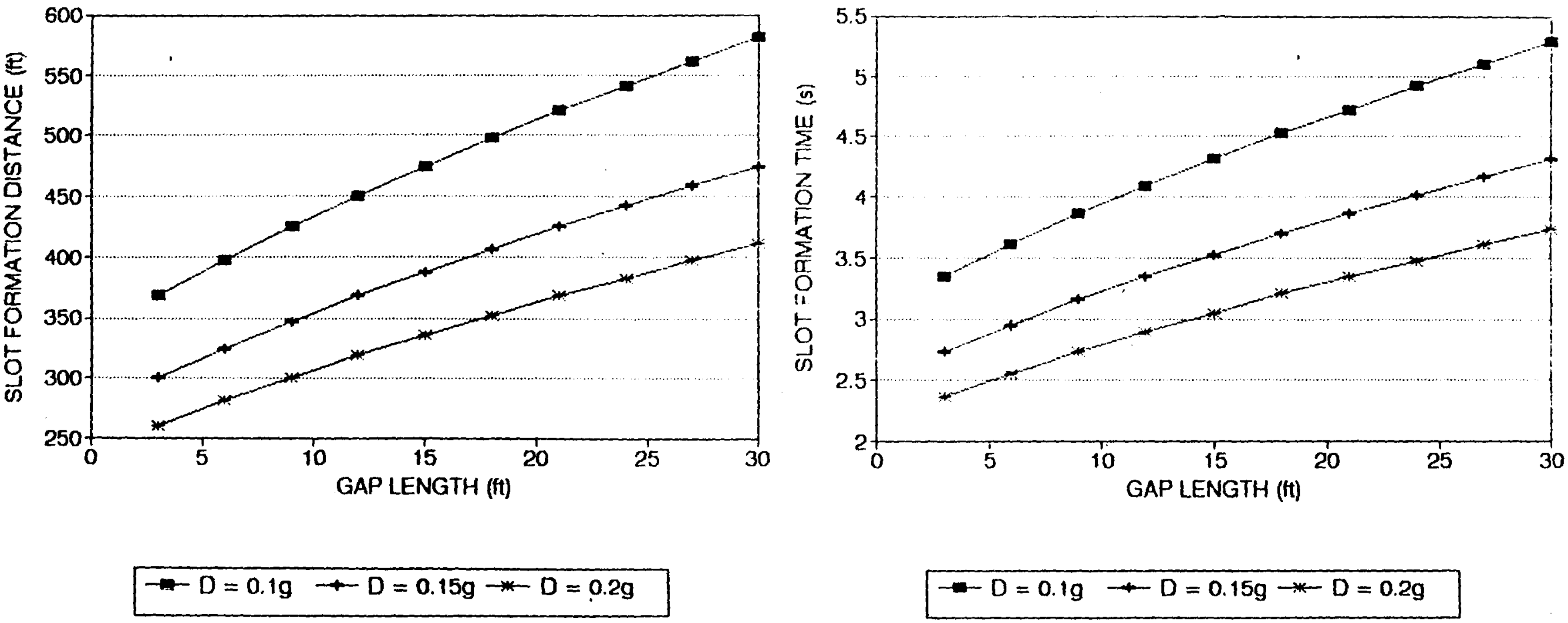


Figure 16. Distance and time required to form a slot in the AHS lane for a vehicle entering at AHS speed (Vahs = 75 mph).

non-AHS lane. Methods must be used to prevent backup of exiting vehicles onto the AHS lane. Release of vehicles into the non-AHS flow must be metered prevent unsafe merge conditions.

Another approach to entering and exiting vehicles for this RSC could involve metering traffic on the non-AHS roadways with signals, thus creating a sort of intersection through which vehicles can move quickly across the non-AHS lanes without the hazard of colliding with non-AHS vehicles. This approach may cause significant disruption of non-AHS traffic flow under light traffic conditions, but may have a negligible effect on capacity under severely congested conditions with optimal metering.

MOE #6-Ability to Mitigate Safety Hazards. A significant safety risk associated with this entry/exit strategy is possible collisions with non-AHS vehicles during weaving and merging. This risk can be mitigated with appropriate traffic metering and transition lane design.

MOE #7-Low Cost and Complexity. High cost items for implementation of this strategy include the construction of transition lanes and traffic metering to manage flow between the AilS, non-AilS, and transition lanes. However, existing ramps could be used at virtually no additional cost.

RSC 2A-Smart Vehicle/Average Highway-No Transition Lanes, No Barriers

In this RSC, the vehicle entry and exit strategy is similar to that for RSC 1, except that there are no transition lanes and a platooning-type headway policy (1 m gaps) is used on the AHS lanes. Consequently, a vehicle enters the AHS lane directly from a lane at an initial speed that is determined by the throughput on the non-AHS lane. Because there are no transition lanes, transfer of vehicle control must occur in the adjacent non-AHS lane. Under heavily congested conditions, the vehicle conceivably could enter the AHS lane at nearly zero speed.

MOE #1-Minimal Need for Additional Land. For this RSC, the additional land requirements are minimal because two existing lanes are converted to AHS, existing ramps are used, and no barriers or transition lanes are required.

MOE #2-Minimal Need for Additional Facilities. For reasons similar to those given for MOE #1, additional facilities requirements for RSC 2A are minimal.

MOE #3-Minimal Negative Impact on Adjacent Roadways and the Environment. The entry and exit strategies for RSC 2A would have a small negative effect on traffic flow on adjacent roadways because existing ramps are used without traffic metering. As with RSC 1, some degradation of traffic flow on adjacent roadways, along with an increase in emissions, could occur because the capacity of the overall roadway is improved.

MOE #4-Great Improvement in Potential Capacity over Comparable Non-AHS Roadway Systems. The entry and exit strategies could limit the potential throughput on the AHS lane because entering vehicles generally would be at less than nominal AHS lane speed. Consequently, the AHS system would have to provide a sufficiently large slot for the slower vehicle to enter. As shown in figure 17, the required safe distance between platoons to accept a slower entering vehicle increases rapidly with decreasing vehicle entry speed. For example, a safe distance of over 500 ft could be required to accept a vehicle entering a 75 mi/h AHS lane at 30 mi/h. If the AHS system is required to open a slot for a slow, entering vehicle, the "disruption distance" required to accomplish slot formation, vehicle entry, and resumption of "steady state" flow at nominal AHS lane speed can be quite large. For example, as shown in figure 18, this "disruption distance" for the 30 mi/h entering vehicle could be over one mile if the AHS controls speeds on the lane to no less than 90 percent of nominal.

MOE #5-Minimal Disruption of Roadway Traffic Flow. In addition to the effect on AHS throughput described above under MOE #4, this entry/exit strategy potentially could disrupt flow on both the AHS and non-AHS lanes, primarily because of the absence of transition lanes and barriers. Non-AHS vehicles could enter the AHS lanes (either intentionally or unintentionally), degrading throughput significantly. Further, vehicles desiring entry to the AHS lane could disrupt non-AHS traffic flow because of entry queues that may form. Exiting can disrupt AHS lane flow if the vehicle must be decelerated to reach a speed that is compatible with the non-AHS flow into which it desires entry. If the exiting vehicle is not decelerated in the AHS lane, then the non-AHS flow could be disrupted if the exiting vehicle speed much different than the prevailing non-AHS lane speed.

MOE #6-Ability to Mitigate Safety Hazards. Because of the absence of barriers and transition lanes, there exists the risk of collisions between vehicles in adjacent lanes. Although the encroachment of AHS vehicles into the non-AHS lane could be mitigated by highly-reliable control system design, the encroachment of none’s vehicles into the AHS lane is difficult to mitigate without barriers. Possible mitigation methods in this case are painted lines, low curbs, and strict enforcement.

MOE #7-Low Cost and Complexity. This RSC is relatively low-cost, because existing ramps are used, existing lanes are converted, and no barriers or transition lanes are required.

RSC 2B-Smart Vehicle/Average Highway-No Transition Lanes, Barriers

The entry and exit strategy for this RSC involves continuous physical barriers between the AHS and adjacent lanes. Thus, vehicles must enter and exit the AHS lanes directly on exclusive left-side ramps. ACI, ACO, and control transfer are accomplished on the ramps.

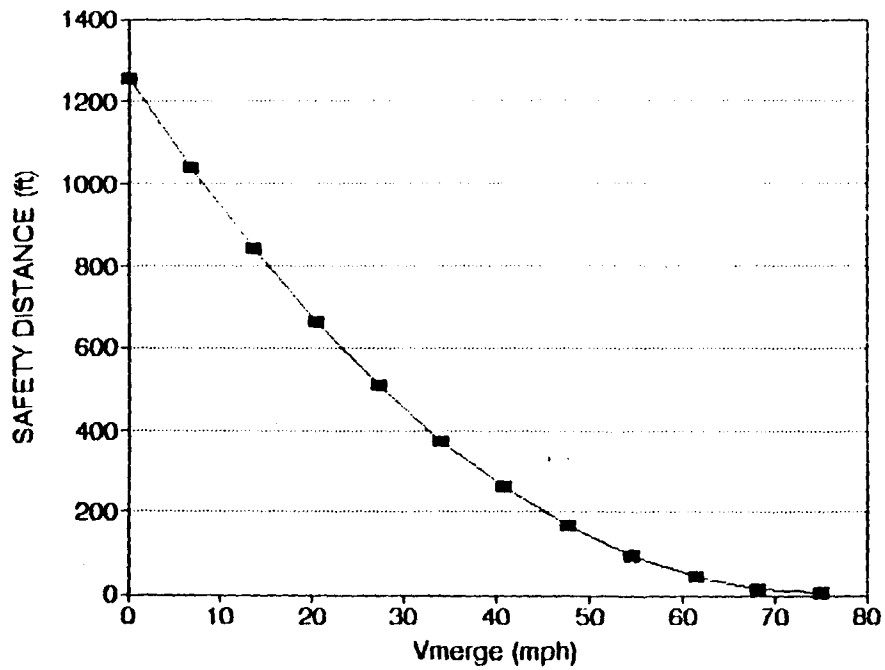


Figure 17. Minimum safe distance between platoons to enter a vehicle into AHS lane at less than AHS speed. (Vmerge < Vahs; Vahs = 75 mph, 0.15 G).

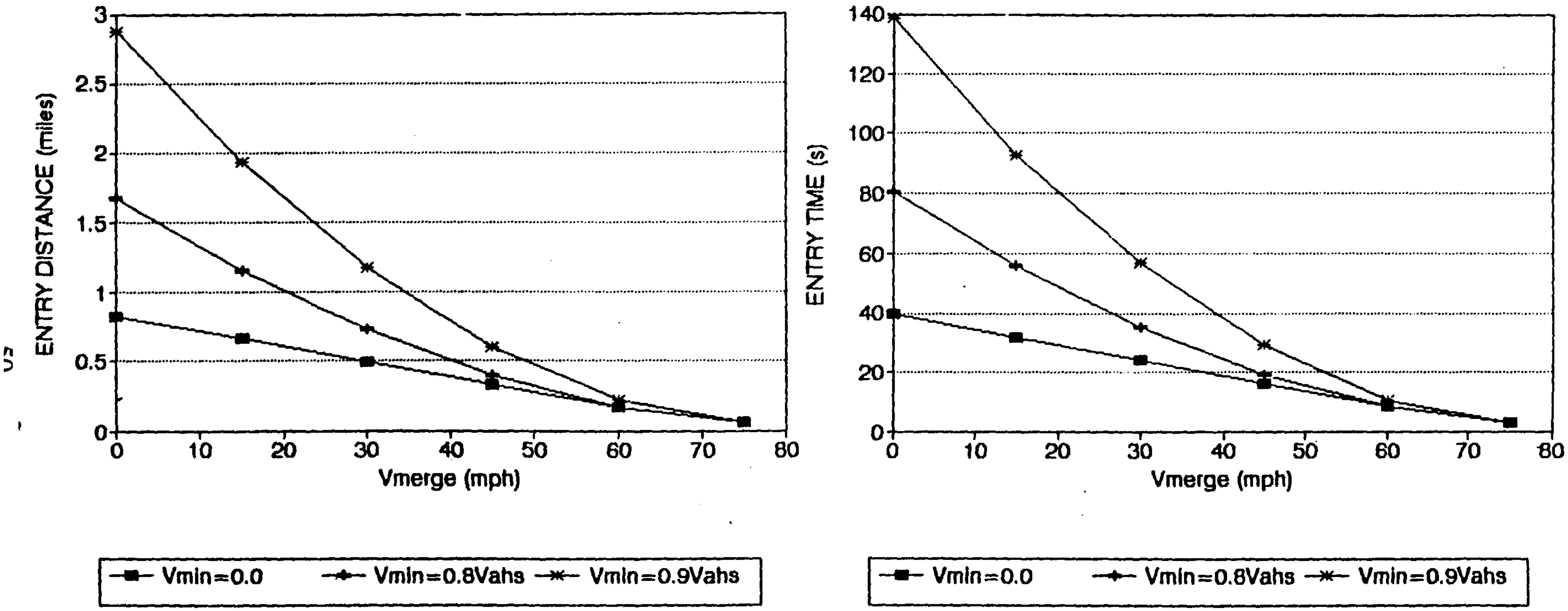


Figure 18. Distance and time required to a) form a slot, b) enter a vehicle at less than AHS speed, and c) accelerate entered vehicle to AHS speed. (Vahs = 75 mph, ± 0.15 G, Gap = 3 feet, Vmin = minimum allowable speed of platoon)

MOE #1-Minimal Need for Additional land. Significant additional land is required for left-side entry and exit ramps, because the majority of existing highway ramps are designed for right-side entry and exit. Land requirements could be reduced if maximum use is made of the median areas. Further, existing over-passes conceivably could be modified to accept ramps; however, significant engineering effort would be required to determine the feasibility of such modifications from a structural integrity standpoint. Alternatively, "flyovers" could be designed to enter vehicles via banked, high-curvature ramps.

MOE #2-Minimal Need for Additional Facilities. In addition to the requirements for ramps described above, facilities would be required to meter entry to and exit from the ramps and for ACI, ACO, control transfer, and vehicle rejection on the ramps.

MOE #3-Minimal Negative Impact on Adjacent Roadways and the Environment. Because of the requirements for new, exclusive ramps, traffic flow on adjacent roadways could be affected significantly. Traffic patterns on nearby surface streets may need to be redesigned significantly to route AHS vehicles to and from the AHS ramps efficiently. The environmental impact of this RSC is expected to be nearly neutral.

MOE #4-Great Improvement in Potential Capacity over Comparable Non-AHS Roadway Systems. Because AHS entry and exit is exclusive and the AHS lanes are physically separated from adjacent lanes, the entry and exit strategies should not limit the AHS from achieving its potential capacity.

MOE #5-Minimal Disruption of Roadway Traffic Flow. For the same reasons given under MOE #4, the entry/exit strategy for RSC 2B should could minimal disruption of traffic flow on AHS and non-AHS roadway lanes.

MOE #6-Ability to Mitigate Safety Hazards. Segregation of AHS and non-AHS traffic during entry and exit effectively mitigates the risk of encroachment. Other safety hazards could be mitigated through effective AHS system design.

MOE #7-Low Cost and Complexity. The high-cost items for this entry/exit strategy would be the cost for constructing ramps.

RSC 2C-Smart Vehicle/Average Highway With a Reversible MIS Lane

The entry/exit strategy for this RSC involves the vehicle entering directly onto the AHS lane via an exclusive AHS ramp. No transition lanes are used, and physical barriers are used to separate AHS and non-AHS lanes. The vehicle exits the AHS lane to the left directly onto an exclusive exit ramp. Transfer of control, ACI, and ACO occur on the ramps. The AHS lane is reversible (e.g., inbound to an urban center in the morning and outbound in the evening). Conversion of existing HOV systems is the basis for implementing this RSC.

MOE #1-Minimal Need for Additional land. Because this RSC involves conversion of existing HOV systems, existing ramps would be used. Thus, additional land requirements would be minimal.

MOE #2-Minimal Need for Additional Facilities. Facilities would be required to meter entry to and exit from the ramps, and for Ad, ACO, control transfer, and vehicle rejection on or next to the ramps.

MOE #3-Minimal Negative impact on Adjacent Roadways and the Environment. From an entry/exit standpoint, the conversion of HOV systems to AHS should be nearly transparent to the adjacent roadways and the environment. Adjacent roadways already would be designed to handle "exclusive" HOV traffic. However, an important issue is public reaction to losing an existing HOV system.

MOE #4-Great improvement in Potential Capacity over Comparable Non-AHS Roadway Systems. The entry/exit strategy would affect the potential capacity of the AHS system if the existing ramps were inadequate to meet the input and output demands of the system.

MOE #S-Minimal Disruption of Roadway traffic Flow. The entry/exit strategy is not expected to disrupt roadway traffic flow.

MOE #6-Ability to Mitigate Safety Hazards. Existing HOV mitigation methods are expected to be effective for the AHS application.

MOE #7-Low Cost and Complexity. The high-cost items for entry and exit would be associated with the ACI, ACO, and control transfer systems, and in adding vehicle rejection metering before the entrance ramps and at the end of the exit ramps.

RSC 3-Smart Pallet/Average Highway

In this RSC, vehicles would enter via a left-side ramp to a loading area located in the roadway median area. Then, the vehicle is loaded onto a single-vehicle pallet. The pallet, which is always under system control, enters the AHS lane directly via a left-side entry ramp. The palletized vehicle would travel on the exclusive AHS lane (separated from adjacent lanes with barriers) until exit is desired. For exit, the pallet would pull over to an unloading area (also in the median area), where the vehicle would roll off the pallet and leave the system under driver control via a left-side exit ramp. The storage problem for the pallet concept could be minimized if the AHS lanes themselves were used to circulate pallets throughout the system.

MOE #1-Minimal Need for Additional Land. Additional land requirements for this RSC would be associated with areas for loading, unloading and storage of pallets The land required to achieve these functions at a single site is potentially enormous when one considers that one vehicle-sized pallet is required for every vehicle desiring access to the AHS . For example, for 19 ft pallets moving at 55 mi/h with 1 ft gaps, the throughput is about 14,500 pallets per lane per hour. However, maximum use of medians for these functions would reduce the additional land requirements. The land requirements for providing left-side ramps are similar to those described for RSC 2B.

MOE #2-Minimal Need for Additional Facilities. The facilities requirements for the pallet concept are expected to be much greater than those for non-pallet concepts. As described above, extensive loading and unloading facilities would be required. To maximize throughput, these facilities must be automated for rapid (yet safe) loading and unloading of vehicles. One loading concept is to have a vehicle roll up onto a "loading dock," and come to a stop against blocks located on a platform attached to a pallet. When the vehicle is determined to be secured to the platform, the pallet would begin moving onto the AHS lane. ACI and ACO facilities may not be needed with this concept, because the pallets would be system-owned, maintained and operated.

MOE #3-Minimal Negative Impact on Adjacent Roadways and the Environment. The impact on adjacent roadways would be associated with hauling pallets to and from the system. Because the pallets are special vehicles, the potential exists to power them with energy-efficient, low emissions power sources (e.g., electric motors), which would have a net positive environmental impact.

MOE #4-Great Improvement in Potential Capacity over Comparable Non-AHS Roadway Systems. The pallets potentially could operate with extremely small gaps (1 m or less), and the potential throughput on the AHS lane could be superior to non-pallet AHS concepts. However, the time required for loading and unloading could degrade the overall trip time significantly.

MOE #4-Large Improvement in Potential Capacity over Comparable Non-AHS Roadway Systems. The pallets potentially could operate with extremely small gaps (1 m or less), and the potential throughput on the AHS lane could be superior to non-pallet AHS concepts. However, the time required for loading and unloading could degrade the overall trip time significantly.

MOE #5-Minimal Disruption of Roadway Traffic Flow. There would be virtually no disruption of traffic flow on the non-AHS lanes, because AHS and non-AHS traffic would be separated by physical lane barriers.

MOE #6-Ability to Mitigate Safety Hazards. Mitigation of potential safety hazards would be accomplished through the design of the pallet vehicles (e.g., vehicle tie-down, propulsion and guidance systems) and inter-pallet control strategies. Since the AHS lanes would be physically separated from adjacent lanes, the potential for lane intrusion would be minimal.

MOE #7-Low Cost and Complexity. There is a direct trade-off between the high cost and complexity associated with developing loading and unloading facilities and the low cost and simplicity associated with minimal requirements for vehicle-borne equipment.

RSC 4 - Smart Vehicle/Dumb Highway With Mixed Traffic

In this RSC, operation on a rural, four-lane highway is assumed, with mixed AHS and non-AHS traffic in the inner lanes. A vehicle enters the highway via a mixed traffic ramp under driver control. When AHS operation is desired, the driver enters the inner lane and control is transferred to the system. When non-AHS operation is desired, control is transferred to the driver in the inner lane. The driver may continue driving on the roadway or exit. ACI and ACO would occur on the move in the inner lane. No transition lanes or barriers are used in this RSC.

MOE #1-Minimal Need for Additional Land. Virtually no additional land would be needed for this RSC because existing ramps and lanes would be used.

MOE #2-Minimal Need for Additional Facilities. The need for additional infrastructure would be limited to that required for system-to-vehicle communications. If the vehicles were fully independent (e.g., using intelligent cruise control), then the requirements for additional facilities would be minimized.

MOE #3-Minimal Negative Impact on Adjacent Roadways and the Environment. This RSC would be nearly transparent to the existing system.

MOE #4-Great Improvement in Potential Capacity over Comparable Non-AHS Roadway Systems. The potential improvement in capacity over the existing roadway would be modest, because the AHS lanes would involve mixed AHS and non-AHS traffic. Thus, the throughput would be limited by that associated with the speeds and headways maintained by the uncontrollable non-AHS vehicles.

MOE #5-Minimal Disruption of Roadway Traffic Flow. There would be minimal disruption of traffic flow in all roadway lanes.

MOE #6-Ability to Mitigate Safety Hazards. The presence of non-AHS vehicles in the AHS lanes presents a significant potential safety hazard during control transfer. Mitigation methods for safety hazards during entry and exit for this RSC would be required to ensure that the lateral and longitudinal control systems are designed to prevent accident situations during control transfer.

MOE #7-Low Cost and Complexity. The cost and complexity associated with entry and exit for this RSC are minimal because vehicles enter and exit under driver control, and no barriers or new ramps are required.

Rankings of RSC Entry/Exit Strategies

A comparative ranking of the RSCs with respect to these MOEs is provided in table 7. The following observations can be made from the table:

- Relatively high scores were assigned to RSC 2C and RSC 4. This is primarily because these concepts make maximum use of the existing highway infrastructure, require the least amount of additional land and facilities, and have relatively low-cost, low-complexity entry/exit concepts. The primary weakness in RSC 2C is the potential degradation of traffic flow on adjacent roadways. RSC 4 is relatively weak in the areas of improvements in capacity and safety.

- RSC 2B received average to high scores. Because it involves the use of exclusive, direct-access ramps and barriers between AHS and non-AHS lanes, it offers high levels of safety and potential capacity improvement, along with virtually no disruption of non-AHS traffic flow on the roadway. Tradeoffs for these benefits are the significant cost and land requirements for new ramp construction.

- Average to low scores were assigned to RSC 1 and RSC 2A, primarily because of safety concerns associated with mixed ramp traffic along with the absence of physical barriers. Further, RSC 1 would require the development of a network of transition lanes, which in turn could require significant additional land and complex metering schemes.

- The overall lowest scores were assigned to RSC 2C (the pallet concept). Although pallets provide potentially high capacity on the AHS roadway, the overall throughput could be degraded substantially because of the requirements for loading and unloading. Further, the development of efficient loading and unloading schemes could be very costly and complex. Potential benefits are the potential for a high level of safety, and virtually no disruption of adjacent non-AHS roadway traffic.

Table 7. Comparative ranking of RSCs for entry/exit implementation.*

MOE	RSC #1 -Smart Vehicle -Smart Hwy -6 Lanes/2 AHS -Mixed Ramp Traffic -Transition Lanes -No Barriers	RSC #2A -Smart Vehicle -Average Hwy -6 Lanes/2 AHS -Mixed Ramp Traffic -No Transition Lanes -No Barriers	RSC #2B -Smart Vehicle -Average Hwy -6 Lanes/2 AHS -Exclusive Ramps -No Transition Lanes -Barriers	RSC #2C -Smart Vehicle -Average Hwy -5 Lanes/ Reversible AHS Center Lane -Exclusive Ramps -No Transition Lanes -Barriers	RSC #3 -Smart Pallet -Average Hwy -6 Lanes/2 AHS -Exclusive Ramps -No Transition Lanes -Barriers	RSC #4 -Smart Vehicle -Passive Hwy -4 Lanes/2 Mixed AHS Lanes -Mixed Ramp Traffic -No Transition Lanes -No Barriers
Minimal need for additional land	4	3	5	2	6	1
Minimal need for additional facilities	4	3	5	2	6	1
Minimal impact on adjacent roadways and environment	3	2	5	4	6	1
Great improvement in potential capacity	3	4	1	2	5	6
Minimal disruption of traffic flow	5	6	1	1	1	1
Improvement in safety	5	6	1	2	3	4
Low cost and complexity	5	3	4	2	6	1

* Rankings range from 1 to 6, with 1 representing the highest rank.

CONCLUSIONS

The following conclusions have been derived from the results of this study of AHS entry/exit implementation:

Dedicated MIS

From a safety and performance standpoint, the most attractive entry/exit strategy involves dedicated AilS-only ramps that connect directly to dedicated AHS lanes, which in turn are separated from non-AHS lanes via barriers.

Transition Lanes

Entry and exit across non-AHS lanes must involve transition lanes. The transition lanes must be capable of performing vehicle check in and/or check out, rejecting vehicles, queuing vehicles (if the transition lane is not continuous) without interfering with surrounding traffic, and releasing vehicles from rest into the AHS lanes and out of the non-AHS lanes. The use of transition lanes would not require exclusive AHS ramps.

Without transition lanes, right-hand-side entry to and exit from inner AHS lanes would require that a) the vehicles are in manual control during some period while in the AHS lane, b) the vehicle entry speed is the non-AHS lane speed and c) the vehicle exit speed is reduced as needed to be consistent with the non-AHS lane into which it is exiting. Requirement a) is considered unsafe, requirements b) and c) could result in severe degradation in AHS lane throughput due to "wave action" between vehicles.

Barriers

As safety devices, barriers should be used wherever possible between AHS , transition, and non-AHS lanes. These should be positive barriers that physically prevent intrusion to and from the AHS lanes (e.g., the Jersey barrier). Barriers themselves could create a safety hazard at entry and exit areas, and should be designed and placed to mitigate end-on collisions.

Metering

Traffic metering should be implemented at several levels:

- Pre-trip-users log-in trip requests to the system; the system in turn evaluates the current and projected traffic conditions and approves or disapproves the request.
- System level-the flow of traffic on AHS and non-AHS lanes are monitored and adjusted as needed to optimize throughput, while not compromising comfort, safety, and environmental impact.

- Local level-systems similar to current ramp meters release vehicles onto and off of the AHS lanes based on availability of space.

Four-Lane Highways

The application of AHS in a four-lane highway scenario (i.e., two lanes in each direction with no additional lanes) is limited to systems such as "intelligent cruise control." Such a highway would require mixed traffic on the lanes, because without very high market penetration, dedicating two of four lanes to AilS-only would create considerable congestion on the non-AHS lanes. Thus, mixed traffic must operate on the four-lane highway, which presents significant safety and control issues. Further, the cost of such a system may be significant to achieve rather modest gains in throughput and safety. No changes would be required in the physical layout of the entry and exit areas for this configuration.

Lane Widths and Ramp Geometry

Standard lane widths (typically 12 ft wide) should be used for AHS lanes that involve mixed commercial, transit, and automobile traffic. Smaller width lanes (e.g., 8 to 10 feet wide) should be considered only if use is restricted to specific "AHS class" vehicles. The geometry (lengths, curvatures) of existing ramps is based on current highway design speeds. Modifications to existing ramps should be considered if the operating speeds on the ramps are higher than the design speeds.

Pallets

The primary advantages of the pallet concept are a) automobiles do not have to be AHS equipped; b) ACI/ACO during entry/exit would be reduced substantially; and c) pallets could be designed to be more energy-efficient, more reliable, and more uniform than today's fleet of automobiles. Primary disadvantages include a) cost of the pallets; b) additional space, time, and facilities needed for storage, loading, unloading and circulation; and c) a "pallet authority,,, which must be in place for operating the system. Key entry/exit issues are where and how pallets are loaded, unloaded, and circulated throughout the AHS system while maintaining acceptable origin-to-destination travel times, good passenger comfort, and safety.

Surrounding Roadways

Surrounding roadways must be evaluated and modified as needed (e.g., by changes in traffic flow patterns, signaling, AilS-only access) to assure that the flow of traffic to and from the AHS can be accommodated safely and with minimum impact on the AHS and surrounding roadways.

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Spacing of Entry and Exit

To avoid unsafe weaving maneuvers, exit and entry should occur at different locations wherever possible.

Conversion of HOV Lanes

Conversion of HOV lanes to AHS would provide an effective infrastructure for AHS operation. However, it is expected that the public would resist giving up HOV lanes (as well as any other lanes). An option would be to create an AHS system that is restricted to HOV traffic. From an entry/exit standpoint, the primary advantage of converting HOV lanes to AHS is that suitable dedicated entry and exit systems and, in many cases, barriers already exist.

Control Transfer

Except for the four-lane highway, "intelligent cruise control" scenario, operation in AHS lanes must be restricted to vehicles under AHS control. Thus, transfer of control must occur prior to the vehicle entering the AHS lane and after the vehicle leaves the AHS lane.