Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

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.

Lyle Saxton
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and Development

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VOLUME IV — AHS SYSTEMS ANALYSIS

CHAPTER 4: AHS ENTRY/EXIT IMPLEMENTATION (TASK J)

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

Entry/exit is one of the major components of highway transportation service. Some might say it is the most important component since it ties directly to origin and destination (OD) pairs, as airline service is tied to city pairs and airport capacity.

Entry/exit capacity can dictate a freeway system capacity. As we increase the freeway cruise lane capacity, demand increase can overload the entry/exits. Local street volume in the vicinity will at some point reach capacity.

However, automation gives a new tool to deal with system overloads. The traffic controller can directly control sector speed and spacing. As we see in this chapter, the relationship between speed and "safe" capacity contains an optimum, much as manual traffic achieves today, only it is higher and peaks at a higher speed. The controller can choose to modify cruise speed, for increased capacity near an entrance region, to provide more space in the lane for a temporary increase in entry flow. Up to the capacity of the entry procedure, the need for queues or entry lane slowdowns can be eliminated.

Entry/exit concept definitions are closely tied to our RSC definitions. In I2, there is a shared or dedicated lane from the manual lanes to the AHS cruise lane. In I3, this transition lane is a dedicated lane and it can originate from a local street. In I2 the lane is not dedicated to AHS vehicles exclusively when participation[1] is not high enough to warrant. In I1 the cruise lane is not dedicated for the same reason.

Because low participation is associated with the early years of AHS deployment, the RSCs and their corresponding entry/exit concepts have an evolutionary interpretation. Entry/exit is also tied to the RSC communication aspect. As discussed in this chapter, the entry/exit procedures we envision involve predominantly the vehicle/vehicle (VV) communications link and C1 concepts in I1, the roadside/vehicle (RV) communications link and the VV link in I3, and a less complex RV link in I2, with a fully utilized VV link.

We feel confident that we can achieve higher vehicle densities with automation. However, if this brings higher person-miles traveled by attracting more and longer personal trips, real increases in travel efficiency are questionable. If, through various measures, we can keep vehicle-miles traveled VMT unchanged and, in addition, the total flow in all cruising lanes is not changed, then maximum flows at entry/exits are not changed and existing ramps and local streets are not overloaded. The benefits to the individual user are shorter and more reliable trip time, assuming that cruising lane congestion was the problem in the first place. If, indeed, entry/exit capacity is a problem, it seems that, short of building more concrete infrastructure, aspects of Intelligent Transportation Systems (ITS) other than vehicle

[1] "Participation" is defined as the automated cruising and accessing (or egressing) traffic flow ratioed to the total traffic flow. In general, this fraction could be higher than market penetration.

automation must be emphasized to solve congestion problems. There are concepts such as alternate routing and departure time specification, recognizing that everyone cannot use the same portion of concrete at the same time. This line of thinking leads us to examine rearrangement of flow from manual to automated in addition to producing high automated flows.

Finally, it seems reasonable to anticipate, with the increasing presence of automated vehicles, an "automation" mind set beginning to dominate all driver behavior. Perceiving automated vehicles to be a benefit to the manual vehicles in terms of decreased congestion and trip time, manual drivers would develop the cooperation and approval needed to share the road with automated drivers. In what follows, the entry/exit techniques can easily be foiled by irresponsible or uncooperative manual drivers. If our transportation systems and ourselves behave intelligently, we will all get to our destinations on time.

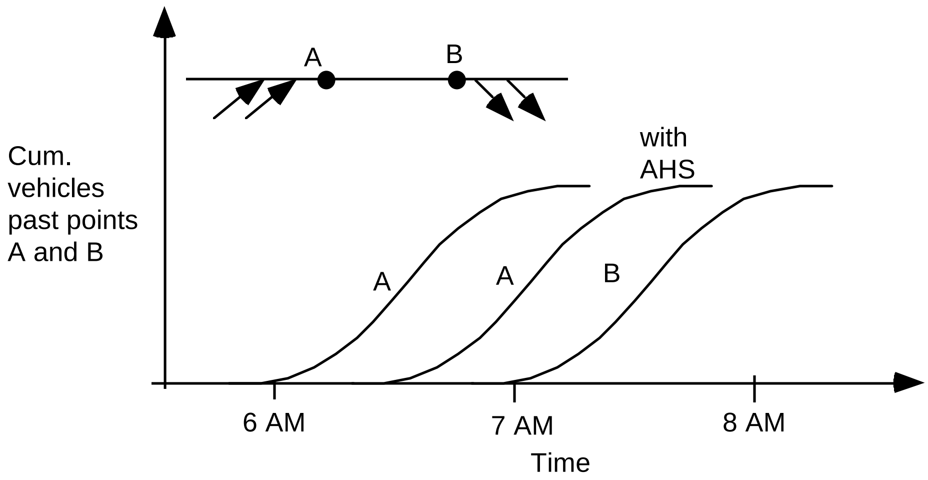
1.2 OBJECTIVE

The objective is to identify and analyze design parameters of entry/exit which have major impact on generating, maintaining, and dissipating the flows desired in automated lanes.

1.3 TECHNICAL APPROACH

We looked at scenarios that assume an advanced traffic management system (ATMS) is in place. Since we do not necessarily increase VMT and vehicle flow rates, we do not overload the entry and exit ramps; neither do we overload the transition lanes. If a locality demands additional entry/exit flow at a particular ramp, we assume another ramp lane will be built and/or the city streets will be altered.

This assumption attributes stop-and-go driving to cruise lane undercapacity. The figure below illustrates the benefit we hope to obtain. It plots cumulative traffic counts at A and B in a simple model of a freeway with rush hour traffic originating in Section A and leaving in Section B. Rush hour starts at about 6 a.m. because it takes an hour to get to Section B only 30 miles away. Using automation, the vehicles can move closer together and move smoothly at normal speed. The trip now takes 30 minutes and rush hour starts later. Note that the flows are the same. They occur later except at B where we assume the OD pairs have the same desired time at destination. Another way to look at it is to say that vehicles, sit in their garages a half hour longer instead of sitting on the freeway.



AHS TRIP TIME BENEFITS

Analyses show that we can get higher lane flow with AHS than with manual driving. Where the entry/exit capacity and the local streets can allow, this might be the choice of ATMS. Such an example is a bridge or tunnel bottleneck, where cruise and entry/exit capacity upstream and downstream are adequate, but traffic backs up from the bottleneck.

At given speed and weather conditions, how close can we space automated vehicles safely? The answer depends not only on cruise speed but also on entry/exit or ingress/egress to an AHS cruising stream. Our analysis provides a framework for determining how much space is available to add more vehicles. This analysis, used maximum braking distance, collision severity, maximum relative collision speed DV for elastic bumper behavior, deceleration system time delay, VV link time delay, the number of collisions and DVs of those collisions for a given deceleration of the vehicle ahead, the vehicle masses, and the vehicle lengths as input parameters in addition to speed.

Although not part of this task, we also consider that due to control limitations there will be a minimum allowed gap between vehicles for lane changes, mainly affecting the access maneuver.

Given a way to define the relationship of flow capacity (or vehicle density) and lane speed, we now proceed to the next step which is to define how we will utilize the empty space to add more vehicles to the stream. The concept of space distribution is introduced and we make the point that the merging of two flows with the spaces in one matching the vehicles in the other minimizes flow disturbances. Through a simple manual spacing strategy and a regular space distribution in the AHS lane approaching an ingress point, the final vernier adjustment is straightforward with minimal flow disturbance. Rudimentary flow analysis, with participation as a parameter, was undertaken. It leads to the definition of a reasonable boundary between the highest participation for which we still benefit by having manual vehicles in the AHS operating lane and the lowest participation appropriate for I2.

Topics related to I3 were studied. The concept of a dedicated entry ramp directly from the local streets allows a "collector" lane to be postulated that can run at high volume because it is automated. The final stage of this entry method is the merging of two automated streams at cruise velocity. This same high-speed merge appears in the interface of two AHS highways.

The use of space manipulation and entry vernier adjustments is shown to be rather primitive in I1C1, more sophisticated in I2C2 and highly refined in I3.

1.4 CONCLUSIONS/KEY FINDINGS

1) Entry/exits are key to AHS practicality since they dictate maximum flows throughout the system, are a big cost driver, and are a primary impact on the community.

2) Participation is key to entry/exit design and indeed drives overall design. It is reasonable to estimate that participation will be significantly higher than market penetration. However, AHS entry/exits feasible for low participation are initially the most attractive.

3) Entry/exit spacing is an important design criterion in the urban environment. Long Island Expressway data shows that the average OD pairing in that region involves only a few miles of freeway use. Yet, AHS conceptually is concerned with longer freeway segments.

4) The different access/egress techniques associated with the different RSCs may well all find application on a single AHS because the specific design requirements of each freeway, street and traffic situation dictate the best technique.

5) One of the highest infrastructure impacts assigned to entry/exit requirements is the merging of two AHS streams starting at right angles. This is due to the large radii required if speed is maintained and infrequent high-speed left lane exits in existing highway geometries.

6) AHS traffic controllers, according to derived capacity-versus-speed estimates applicable to automated vehicles, will have the ability to provide a tradeoff between velocity and capacity to accommodate substantial volume variations.

7) Single-lane access/egress <u>automated</u> flow is upper-bounded by single <u>manual</u> lane capacity.

8) Single manual freeway lane capacity as defined by field data varies from 1800 vph at 60 mph (Level of Service C) to 2000 vph at 30 mph (Level of Service E). Below 30 mph the maximum flow decreases and the Level of Service is F (Reference 1). Field measurements higher than 2100 vph (over 15 minutes) have been recorded but at LOS F.

9. Single automated lane capacity is 9600 vph at 52 mph based on detailed analysis of a moderate safety policy allowing a few minor collisions in rare instances. At speeds of 40 to 60 mph the capacity is maintained at 8800 vph and above. Outside of this speed range, capacity decreases rapidly but is maintained at 5500 vph and above for the speed range 28 to 80 mph.

10. For the mishap scenario assumed, the probability of injury requiring hospitalization is twice as high at 60 mph with 3 foot gap as with 19 foot gap

and there are 13 collisions at 60 mph as opposed to 2 collisions. The additional number of parties involved, much higher total property damage potential, and access/egress protocol complication lead us to favor the higher gap sizes. Grouping of vehicles to obtain the desired safety becomes unnecessary until the speed exceeds 60 to 70 mph.

11. For the mishap scenario assumed, a slippery pavement reduces capacity to 5100 vph peak at 20 to 25 mph. This is an issue because today's manual speeds are typically higher and changing weather conditions require contingency traffic control.

12. Using a less drastic mishap scenario increases the speed for maximum capacity but does not change the maximum significantly.

13. Changing bumper/body design in the direction of greater energy absorption than assumed (5 mph bumper) does not change results significantly. More elasticity causes more problems at the smaller gap sizes.

14. Heavy vehicles would require more space for equivalent safety. Adopting a no-collision policy requires about a factor of six at 60 mph. This translates to a large decrement in lane capacity for a small percentage of heavy vehicle flow. Hence we conclude that design to accommodate heavy vehicles may be optimized if they are automated in an I1 concept sense (mixed manual and automated flow) but do not use the exclusive lanes of the I2 and I3 concepts except where the heavy vehicle percentage justifies a lane dedicated to those vehicles.

15. The I1 concept (shared lane on a shared freeway with unmodified manual entry/exits) applies to early versions of AHS when participation will be low. It also applies to mature designs for four-lane interstates in rural areas giving manual vehicles a chance to pass. Access/egress is envisioned as manually performed using collision avoidance devices as aids. It can take place at any location at the driver's discretion.

16. I1 benefits in terms of increased flow rates are predicted. However the analysis is conservatively restricted to reduced trip time with no change in flow rate by equating speed to manual speed/flow conditions in the right lane. Benefits in I1 can be increased for a given participation by using communication to pair with another automated vehicle in the left lane. By not increasing overall flow, we can avoid any design change to entry/exits which would move away from the I1 concept of low infrastructure impact.

17. Detailed analysis of I1 suggests that participation as low as five percent can increase a congested 4000 vph two-lane manual traffic from 30 to 40 mph. Fifteen percent can increase the speed to 55 to 58 mph.

18. If the I1 concept is implemented on a six-lane freeway it can easily evolve into an I2 format where the left lane is exclusive.

19. The I2 concept (exclusive left lane, shared or exclusive middle lane at access/egress points, manual right lane, unmodified manual entry/exits) allows

synchronized access and quasi-synchronized egress. The I2 concept starts to make sense for participation higher than .45 and when flows at or higher than 6000 vph for each direction of a six-lane freeway can be serviced by existing manual entry/exits.

20. Access in I2 could be synchronized by a simple timing system facilitated by space regularization in the automated lane.

21. Manual vehicles in the transition lane need only hold the speed specified for the access/egress region but they must act cooperatively in doing so to avoid causing some automated vehicle to miss access or egress. The flow of manual vehicles in the middle lane must be limited by ATMS to about 1500 vph and preferably would be much lower. Operations in the middle lane can be modeled after the left lane in I1.

22. In I2 with low acceleration/deceleration limits (for comfort and low emissions) and reasonable vehicle dynamics, analysis and simulation indicates access distance is about 1100 feet at 60 mph. Egress distance is about the same. With a 500 foot buffer between the total region is about 2700 feet at 60 mph.

23. When I2 participation has grown to numbers that allow an exclusive transition lane, special entry/exit provisions can be justified to build flows in the cruise lane up to the 9000 vph range of an I3 concept.

24. The I3 concept (exclusive cruise lane with exclusive transition or entry lane) allows maximum freedom to configure the entry/exit infrastructure and process and applies to conditions of very high participation.

25. I3 allows the infrastructure to support a third kind of entry/exit – the cruise speed merge/demerge (the other two being access/egress from manual freeway lanes and from local streets).

26. I3 access/egress from manual cruise lanes is similar to I2 without manual vehicles present. This would allow synchronization by manipulation of accessing vehicles rather than by creating gaps in the cruise lane at the proper places.

27. I3 access from local streets allows safer low speed automation system engagement and disengagement. Once again, a timing procedures, in this application with a shaped acceleration profile, mechanized with a roadside data link and vehicle-to-vehicle link could be used with a closed-loop terminal guidance. The access distance is about 1100 feet for a cruise lane speed of 60 mph and it varies with speed in accordance with simple analysis of the access procedure up to 3300 feet at 120 mph.

28. I3 egress distance is about the same as the access distance using maximum braking deceleration no greater than the acceleration used for access. Queue length at the local street must be added and it is site-specific.

29. The new entry/exits designed for I3 should have curvature and possibly superelevation which limit side acceleration as a function of speed to

comfortable values. This conclusion applies as to cruise speed merge/demerges as well as local street ramps.

30. The I3 single-lane ramps would be limited to the 1200 to 1600 vph manual source flow capacity. To service greater demand, a collector lane can be used. Four single-ramp stages could build a flow of 4800 to 6400 vph for merging with the cruise lane (which must be running at a low v/c at the time) in a distance of roughly 6000 feet.

31. The I3 access/egress process and particularly the cruise speed merge/demerge of large flows would require ATMS supervision and control to prevent system overloads.

1.5 RECOMMENDATIONS

1. The relationship of collision velocity to injury severity at speeds less than 10 fps should be more fully defined for AHS-equipped vehicles as part of the lane capacity definition for access design.

2. Safety policy should be examined to define what would be acceptable to AHS designers, to users and to insurance companies. The role of a barrier between an automated lane and the manual lanes sharing the same roadbed in the I2 concept would be part of the mishap scenario definition as part of this policy. The presence of a barrier in the I2 concept allows access/egress only in specific places.

3. Access/egress operations and procedures should be tested, first through modeling and simulation but then on the test track to obtain reliable data.

4. The I1 concept is forecast to relieve a congested freeway with low participation. This prediction should be studied through simulation and then operationally tested.

5. The AHS/ATMS interface for access/egress regions and for entry/exits should be studied. The AHS potential benefit to ATMS on a regional basis using realistic conditions at these locations needs to be modeled as part of this study.

6. AHS operation in weather conditions affecting surface friction should be researched. Cruise speed, safety policy, lateral control, braking capability, speed for engagement and disengagement of automation, effects of grades and curves, presence of articulated vehicles, etc. all impact the entry/exit and access/egress operations.

7. The minimum space into which an automated vehicle can be safely maneuvered should be defined on the basis of realistic control capabilities and reasonable wind gusts, roadbed unevenness and other disturbances.

2.0 INTRODUCTION

2.1 DESCRIPTION

Much of the emphasis in AHS research has been placed on how to control vehicles automatically to follow a lane centerline and maintain a safe distance from the vehicle ahead. At the other end of the scale whole urban road networks have been simulated to show the benefits of obtaining high lane capacities. Meanwhile the entry/exit conditions at these high flow rates, until recently, have been largely neglected.

This chapter presents research which considers how large flows in one lane can be generated and dissipated. Since vehicle flow involves individual origin-destination (OD) pairs at various parking places and a section of freeway including the entry/exits is not an origin or destination it is therefore in equilibrium when flow is conserved i.e. the flow out equals the flow in. At this equilibrium condition, the speed is an MOE of great importance to the user.

Consider that today's freeway equilibrium capacity at 60 mph is about 1850 vph per lane and that we might safely place three to five lanes of traffic on one automated lane at the same speed. The user is satisfied, but the potential to overload existing entry/exits is great. New entry/exits are expensive and involve difficult social and political issues. Therefore this chapter concentrates on what can be done with the automation potential for high lane density to eliminate stop-and-go traffic-up to the existing entry/exit capacity. We do not necessarily assume that entry/exit flows will increase. At section equilibrium the freeway flows can either be the same as before or be redistributed to handle bottlenecks.

How can we offer an improved freeway cruising performance (a much improved trip time with high reliability) without attracting more traffic? This chapter offers some thoughts on the use of automated traffic streams in a regional advanced traffic control system. For this is the key to intelligent use of highway capacities. It makes little sense to allow traffic to choke in the cruising lanes when we presume to be able to control speed and spacing. It also makes little sense to allow traffic to overload entry/exits but the issues here are much more complex.

2.2 PURPOSE

Our research focus is on starting to relate entry/exit considerations to automated lane performance. Since the two are directly tied together by virtue of flow conservation, we have reached the point in system design where we should be able to conceptualize machine-like behavior through the region of lane access/egress.

How this access/egress could take place in the three generically different RSC infrastructure concepts is a research goal. It is insufficient to examine an AHS lane with only dedicated entry and exit from local streets (I3), since it is difficult to imagine such facilities being constructed for just a small market penetration. The I2 concept of access/egress from manual lanes sharing the same roadbed is worthy of careful consideration. Also I1 cannot be discarded out of hand (automated and manual traffic sharing the same lane). In this research we study the I1 concept as a method for reaping some of the benefits of automation and communication when the participation fraction (fraction of vehicles intending to use their automated capability for a particular road segment) is still quite low (less than 25 percent).

It is our purpose to analytically explore ways to define access and egress capacities in these three RSC scenarios. Our methods will stop short of realistic computer simulations involving several miles of freeway. This is not to say that such simulations are unnecessary but rather that they are a step beyond the scope of this precursor study. They need to be guided by analytical derivations and conjecture that are the results of assumptions with high face validity.

2.3 OVERALL APPROACH

The capacity of an automated lane is determined by defining a safety policy and deriving the implications of that policy using basic vehicle kinetics and some simplifying but non-restrictive assumptions. The underlying premise is that the rear-end collision relative velocities at impact determine the incident severity in terms of property damage and criticality of injury).

The capacity of a manual cruising lane is reviewed from existing references (References 1 and 2). The entry/exit manual ramp capacity is stated and the typical local street capacities that are frequently the determinants of ramp operating levels are reviewed.

Given these various capacities, feasible steady-state operating conditions for I1, I2 and I3 access/egress scenarios are defined and analyzed. Necessary assumptions regarding the behavior of manual drivers in I1 and I2 situations are exposed. The important relationship of automated lane capacity to lane speed is discussed with the ultimate objective that Advanced Traffic Management Systems (ATMS) can regulate traffic flow using this new tool, trading trip time for capacity.

2.4 GUIDING ASSUMPTIONS

2.4.1 VEHICLE MASS AND SIZE

We assume that the freeway traffic of importance to automated lane access/egress consists of single vehicle equivalents (SVEs) of roughly the same grade climbing acceleration, cruise speed and braking performance. This assumption will be modified for a section on the influence of mass on safety gap. This assumption does not exclude transit or commercial vehicles but it does set the larger and more massive vehicles aside for special examination.

Several factors influencing lane capacity, lane/ramp geometry, lines of sight, construction cost, road maintenance and basic highway utility are at issue here.

Large, massive vehicles reduce roadbed capacity by requiring more space laterally and reduce lane capacity per vehicle by requiring larger spaces between vehicles for equivalent safety. One can question this assertion by looking at capacity per pound but then the discussion rapidly broadens to cost per pound from origin to destination, use of other transportation modes, and a host of other subjects away from the basic automated highway goal which is improved utility of existing rubber tired roadbeds. We assume that our goal in entry/exit is to achieve maximum lane capacity in terms of SVE-size vehicles regardless of what or how much they carry.

Ramp grades, curvatures, super elevation and design speeds are all affected by large vehicle design. In an I3 scenario these factors would all show up on the negative side. In I1 and I2 the entry/exists remain unchanged. The I3 concept of freeway-to-freeway interchange at cruise speed would be influenced adversely by a tractor-trailer presence.

Lines of sight become important in situational awareness across adjacent lanes and could affect communication system design. Disparate physical size could be a factor in collision safety because bumpers might not be aligned.

The cost of constructing and maintaining a roadbed to handle the heavy trucks is higher. Pavement wears faster and becomes tracked because of heavy vehicle traffic. This would be an even more important factor at automated traffic densities. Lateral control may require special features to deal with tracking.

Since introduction of automated traffic on a freeway should improve the Level of Service for all vehicles, the heavy truck traffic should be a beneficiary regardless of which lane is used. The intercity freeways are likely to be configured as I1 where congestion is not prevalent and thus not designed for an exclusive AHS lane. I3 could involve an exclusive heavy-vehicle lane in certain sections of an urban setting where there is enough of this traffic to justify exclusivity. The I2 situation is the most interesting since maximizing freeway utility for the typical mix of SVEs and heavy vehicles may very well argue in favor of trucks staying in the then uncongested manual lanes.

2.4.2 VEHICLE DYNAMICS

The vehicles are assumed to be moving at essentially constant acceleration/deceleration or at constant speed. Turning dynamics have been simplified to constant radius turns. Braking dynamics are reduced to a simple time delay. The maximum longitudinal and lateral g loads are restrained to what today's passengers would judge to be familiar and comfortable.

2.4.3 STUDY PARAMETERS

Participation fraction is the major parameter of the study. The cruising speed and vehicle spacing are next in interest. Braking deceleration and deceleration of a vehicle ahead which has experienced some mishap are important parameters affecting the derivation of lane capacity.

2.4.4 SITUATIONAL AWARENESS

We assume that data links, collision avoidance equipment and/or other vehicle detection devices will be present to allow the automated vehicle computer to distinguish sudden changes in gap due to vehicle deceleration/acceleration from vehicles entering or leaving the lane. Conditions in the adjacent lanes are assumed to be known well enough to permit safe lane changes. Gap creation to allow access or egress is analyzed.

2.4.5 TRAFFIC CONTROL IN THE MANUAL SYSTEM

After due consideration, we conclude that it would be very difficult to physically prevent deliberate disruption of an automated system by a manual vehicle. However, we should be able to design access/egress so that it will be easy for the manual driver to avoid a disruption. In I2 manual drivers might be in the transition lane. But they are instructed not to join the automated lane and to maintain speed, perhaps with intelligent cruise control so that vehicles intending to access the automated lane can maintain position next to the intended empty space. It could be a traffic violation to disrupt an automated entry/exit and the enforcement might be quite reliable through television surveillance. If the automated traffic is viewed as a boon to the manual traffic on that freeway, the manual drivers might naturally tend to be at least tolerant of if not cooperative with procedures in the vicinity of access/egress regions.

To this we add the assumed presence of an ATMS functioning throughout the corridor or beltway. Reference 3 reports a design of the flow control function of the IVHS, looking at the control of the vehicle stream based on aggregate traffic variables. It examines the use of lane change to deal with lane-blocking incidents. This could be a use of the otherwise essentially empty breakdown lane we advocate for malfunction management. The authors conclude with the statement that "we believe roadside intelligence to be a crucial part of any IVHS that seeks to increase throughput significantly".

The ATMS would work to avoid flows that exceed capacities and might contain such advanced features as adaptive trip guidance and trip sequencing. Automated highway might have some success without ATMS but its success would be considerably enhanced with ATMS. The automated traveler would then not only have a reliable and short trip time but also have a high probability of access to the automated lane where and approximately when it was planned. It seems unreasonable to design an automated lane that could be inaccessible because everyone wanted to use it at once.

3.0 RESEARCH ACTIVITY

3.1 ACCESS/EGRESS GENERAL ANALYSIS

Given an AHS lane cruise speed, is there space to add more vehicles? If so, how many? The access flow comes from an adjacent lane where the vehicles are initially under manual control in I1 and I2 or under auto control in I3. The speed in the vicinity of the lane-change would reasonably be the same as the AHS lane speed. Given the speed and the space available, the access flow upper bound is determined.

Likewise in I1 and I2 the egress lane-change would reasonably occur at constant speed to a lane where maximum flow is determined by manual control constraints. Continued auto control after the lane change in I3 allows large flow at the egress point which would eventually be broken down into low-speed manual streams that are constrained by the local street configuration and traffic control.

After the access or egress lane change maneuver, another lane change might be planned. A short region of density higher than the normal maximum could be part of the general access/egress design. However, this design philosophy seems unsupportable. Since the maximum density is dictated by safety concerns, the existence of a region of higher density is unjustifiable as a steady state design condition even though it may be short compared with the section length.

We then conclude that AHS access/egress capacity is upper-bounded by the single AHS lane capacity and lower-bounded by the single manual lane capacity, both determined by the section speed of the AHS lane. Within these bounds constraints are dictated by the access/egress configuration or RSC. In I3, the entire lane can egress into another lane that eventually becomes a second AHS lane on a crossing freeway. Access to an I3 lane could be constructed from a number of manual collector lanes that are auto-merged to form a flow equal to the entire single-lane AHS flow capacity.

In I2, the adjacent lane is manual up to a point and automatic after that point for those vehicles desiring access. The access capacity is then the manual single lane capacity. The I1 access capability in the right lane is equal to the manual capability of today's right hand lane. The left lane in I1, as we will describe later, can operate smoothly at higher densities than today's left lane. Since left lane access and egress can happen anywhere in I1, the concept of a specific access or egress section capacity is not applicable.

3.2 MANUAL LANE CAPACITY AND LEVEL OF SERVICE

According to Reference 1, a maximum stable flow on modern freeways is about 2000 vph under ideal conditions. These conditions are obtained in good weather on high-speed, divided highways with 12 foot lanes, at least 6 foot shoulders and:

- Level, straight roadway
- Passenger cars only
- Drivers who are regular users of such freeways

From Reference 2 we have Table 4-1 which we interpret as follows: If you want to operate the facility at Level of Service E or better, you supply the lane at or below

TABLE 4-1 LEVELS OF SERVICE FOR BASIC FREEWAY SECTIONS*

Level of Service	Flow Condition	*v/c* Limit	Service Volume (veh/hr)	Speed (miles/hr)	Density (Veh/mile/lane)
A	Free	0.35	700	≥ 60	≤ 12
B	Stable	0.54	1100	≥ 57	≤ 20
C	Stable	0.77	1550	≥ 54	≤ 30
D	High density	0.93	1850	≥ 46	≤ 40
E	Near capacity	1.00	2000	≥ 30	≤ 67
F	Breakdown	Unstable		< 30	> 67

*Assuming ideal conditions and 70-mile per hour design speed.
Source: Reference 2.

2000 vph. Then the speed will be 30 mph or more and the lane density will be 67 vpm or less. Likewise for LOS D or better, flow does not exceed 1850 vph etc.

Are these LOS descriptions consistent with measured field data given in Reference 1, replotted here as Figure 4-1? The field data was obtained by observing freeway flow for a statistically sensible time (fifteen minutes is mentioned on page 251 of Reference 1) and recording the average speed and spacing. If the speed is less than the speed limit, and conditions are otherwise ideal, we conclude that the average spacing will be at a minimum for that speed. This headway (front bumper to front bumper) should be within the field data band on Figure 4-1. Superimposing the inequalities of Table 4-1 we find the field data was gathered under LOS E and F conditions. If we want to avoid stop-and-go driving at LOS E, we must reduce vehicle density as the speed increases, limiting the flow to 2000 vph or less. This gives a minimum distance headway of 156 feet at 60 mph. Extrapolation of the Reference 1 field data plot indicates this headway is at the bottom edge of the band. The speed is near (if not past) the speed limit so the LOS might easily be D with a little reduction of the 2000 vph by increasing the average space between cars. Table 4-1 suggests that a flow of 1800 vph giving a density of 30 vpm at 60 mph would be Level of Service D. A replot of Figure 4-1 as Figure 4-2 emphasizes that manual drivers can exceed 2000 vph, but it would probably be unstable and LOS F.

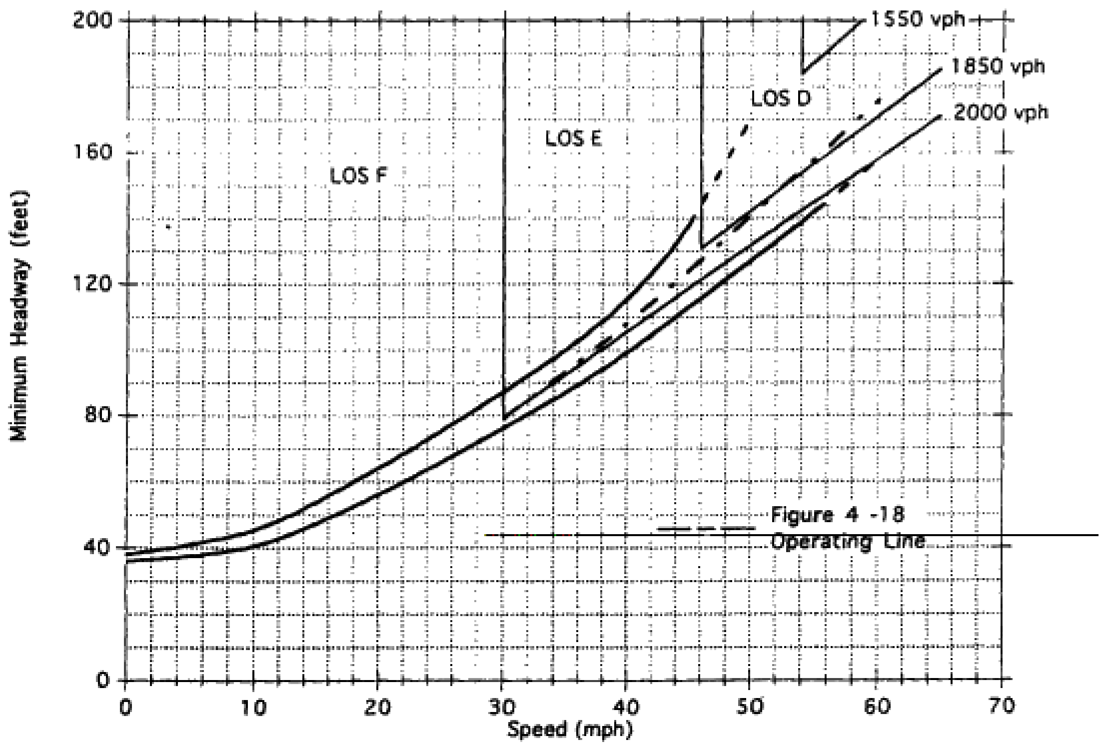


FIGURE 4-1 MINIMUM MANUAL HEADWAY FIELD DATA (AFTER REF. 1, PAGE 165)

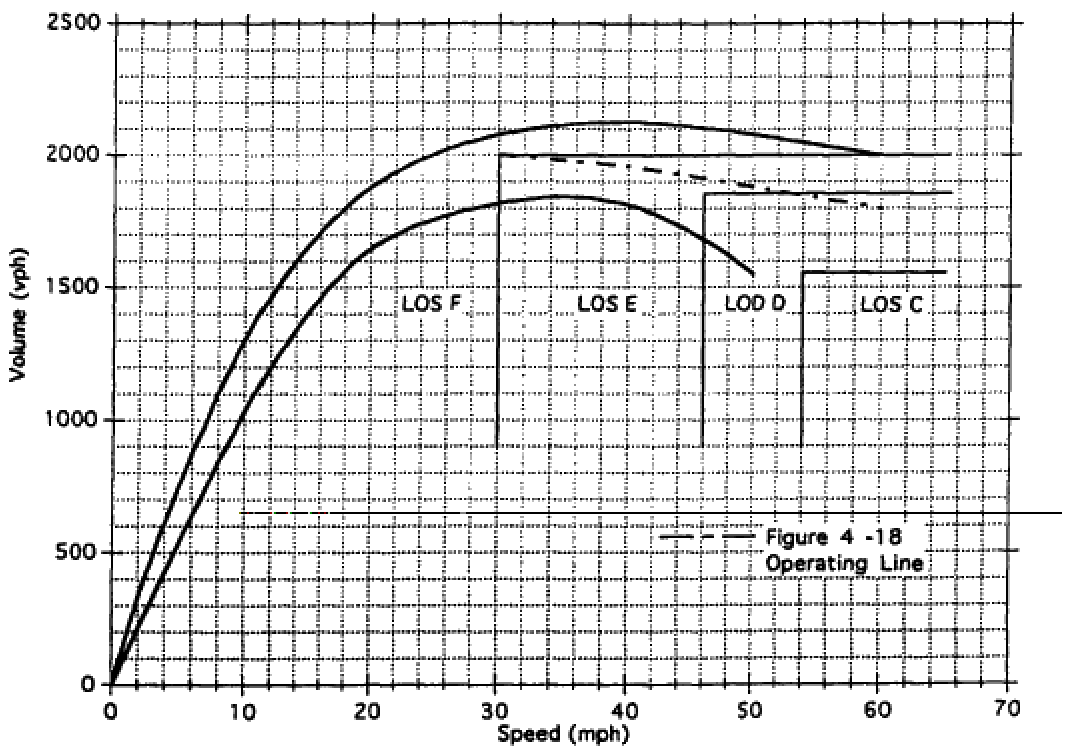


FIGURE 4-2 MANUAL FLOW FIELD DATA (REPLOT OF FIGURE 4-1)

Many urban commuters of the nineties would regard a five car-length gap at 50 mph as relaxed driving. Many would move into such a gap from an adjacent lane. However evidence is that such lane densities will be unstable at 50 mph and the average lane speed will fall off until both lanes will run at the same speed.

The LOS D maximum of 1850 vph drops down to the range 1750 to 1800 vph if the lane is used for entry/exit (Reference 1 page 256) merging and diverging. This is important for estimating capacities in I1 and I2 which use a manual cruising lane for all vehicles to enter and leave the freeway. We will also use this flow range as the capacity of a transition lane in I2.

Manual exit or entry ramp flow capacity is limited by its curvature and the capacity of the local street network or the receiving cruising lane of the freeway. Since most freeway ramp curvatures can be driven at 25 mph, the capacity of the ramp itself is, from Figure 4-2, 1750 to 2010 vph. This capacity as an exit could be supported by a single freeway lane but the implied assumption that practically every vehicle in that cruising freeway lane would be exiting would be satisfied only for special cases. The real difficulty in quoting such a capacity for exit is the dispersing capacity of the local network at that location. A conventional "T" signalized intersection would have difficulty supporting such a flow. All vehicles coming off the freeway would conflict with the local traffic. The maximum flow suggested in Reference 1, page 270 is 1400 vph. Looking at the entry situation, the capacity of a single ramp lane is probably dictated by the capacity of the receiving cruising lane minus the existing through traffic in that lane. If the lane is already carrying 1800 vph at 50 mph, the most traffic that could be handled by the on-ramp is about 200 vph without deteriorating to LOS F.

3.3 SINGLE AUTOMATED LANE CAPACITY

3.3.1 BACKGROUND

During the summer of 1994, PATH demonstrated automated longitudinal vehicle performance with three vehicles in trail behind a lead vehicle (Reference 4). Test drivers steered the vehicles and performed malfunction management. A data link communicated lead vehicle velocity and acceleration to the following vehicles which were maintaining the nominal 13 foot gap with radar detection on each vehicle. Deceleration was controlled by throttle only, since automatic braking was not yet provided. The vehicles followed velocity profiles between 45 and 65 mph with accelerations between .03 and .07 g's and deceleration's of .01 to .03 g's as indicated in Figure 1 of Reference 4. Through the eight-mile closed HOV section of I-15 typical deviations in gap were .8 to 2.3 feet around the 13 foot nominal as indicated in Figure 2 of Reference 4.

This demonstration represents the current state of experimental results which will ultimately yield a practical minimum gap size specification as a function of speed and road condition.

Speculation and analysis is available in the literature as to what this will be. Reference 5 uses 3600 vph at 60 mph which, for an average 17 foot vehicle, is an average gap of 71 feet. Reference 6 points out that very small gaps, such as 3 feet, could be much safer than the equivalent uniform gap size that is considered when the requirement to entirely avoid collisions (the "brick" wall criterion) is dropped. A doubling or tripling of present capacity is speculated for platoons of many vehicles separated by 3 feet with platoons separated by a "no-collision" gap policy.

The "brick wall" criterion at 60 mph gives a gap of 120 to 172 feet for .7 to 1.0g maximum braking on dry pavement which is a flow of about 1700 to 2300 vph - not much improvement over today's manual driving. The very short headways of Reference 6 are suggested as a way to minimize the relative velocity (ΔV) of the first collision in the string. However, as we see in this section, and elsewhere (Reference 7) there are many collisions in the string of vehicles adding to the total cost and the ΔV of the first collision is not necessarily the highest. Also the behavior of an automated lateral control after a minor collision (applying yawing moment and side forces as well as deceleration and pitching moment to the vehicle) has yet to be examined in detail. If railroad cars in collision are an example of what could happen, these low ΔV collisions bear further examination.

Reference 8 takes the approach that the following vehicle should not collide with the lead vehicle as long as the lead vehicle does not exceed a specified maximum deceleration level. Then a "load factor" of .8 is applied to the result, giving a maximum capacity of 1900 vph to 2400 depending on AHS technology maturity. The maximum occurs at about 55 mph. The author compares these numbers not with 1850 vph, the LOS D maximum value, but with 1160 vph or LOS B, and then derives lane cost per vph benefits. When an extra lane for breakdown and room for a possible barrier is factored into this analysis, it is clear that capacities of 1900 to 2400 will not be enough to justify AHS.

Reference 9 summarizes the methodology of Reference 7 for determining AHS capacity based on the specific case of multivariable collisions resulting from emergency braking of a long line of vehicles. This methodology is followed in this section to the extent that a collision model is proposed and analyzed, an accident severity measure is selected and a sensitivity analysis is started. The author mentions a "maximum theoretical capacity of 3600 vph" for a uniform-spacing policy, diminished to 2900 to 3200 to account for access/egress. Very short gaps are not favored because of concerns with possible negative psychological aspects and difficulties of access/egress.

The uniform headway policy is a convenient way to view capacity and access/egress. Reference 10 develops this policy further in what is called a quasi-synchronous approach whereby vehicles operate autonomously in a vehicle follower mode away from access/egress points and in a synchronous mode for access/egress. In either mode, the uniformity of minimum gap size determined by specific-case collision methodology readily allows computation of the available excess space in the lane and leads to simple ways to arrange that space so that vehicles can enter with minimum delay.

Platooning can in theory achieve lane flows in excess of 9000 vph. However, when access/egress protocols are superimposed, the actual flows achieved in simulation are more like 5500 vph (Reference 11). This leads to the recommendations to open up only small gaps to let vehicles in and out of platoons and to look for ways to minimize upstream disturbances caused by the split maneuver to allow access. Reference 12 introduces the concept of lateral flow (i.e. vehicles changing lanes) and asserts that longitudinal flow capacity without reference to lateral flow is misleading. The work reported here is fully compatible with this point of view.

3.3.2 SAFETY SCENARIO AND COLLISION MODEL

The scenario we choose is a mishap in a string of vehicles with various masses and lengths all moving at a constant velocity. The gaps among them are not necessarily the same but since we are interested in lane capacity we will make them all the same for our analysis, i.e. no empty spaces. Likewise we will say, except for a sensitivity calculation, that the vehicle masses are the same. It turns out that the maximum collision velocity, which is a major parameter of interest, does not depend on vehicle length.

The mishap can be any of a number of events, all of low probability, which would cause one of the vehicles to suddenly decelerate at a level higher than the vehicles behind can achieve through emergency braking. The deceleration is sensed by the vehicle accelerometer and communicated over the vehicle-to-vehicle data link to the vehicles behind after an assumed communication frame time. All following vehicles for which it matters receive the signal and begin braking simultaneously. The braking system, suspension and tires act to eventually produce a steady-state deceleration of each vehicle. The time delay for this sequence to take place is another parameter in the analysis.

If the first following vehicle collides with the mishap vehicle, the collision can be almost perfectly elastic if the relative velocity is low enough and the bumpers are so designed. It is essentially inelastic if the ΔV is high enough. Reference 7 uses inelastic collisions in its model. Reference 13 uses a realistic bumper/body model with a combination of elastic and energy absorbing qualities. In our analysis we have simplified the calculations by describing the collisions as perfectly elastic below and perfectly inelastic above a given ΔV.

The mishap could be caused by hitting another vehicle or any object causing failures of wheels or axles. It could be caused by tire or steering mechanism failure causing loss of directional control and rollover. Other causes of directional control loss such as an oil or gravel spill are conceivable. An incident in adjacent manual lanes could cause a vehicle to disrupt the automated lane. In many such examples, the resulting deceleration has roughly the value of the sliding friction of steel on concrete or asphalt or about 1g. Considering a constant deceleration of 1g, a vehicle is brought to rest from 60 mph in about 120 feet. The parabolic time history bringing the mishap vehicle to rest in 120 feet is used as the representative event for calculating the severity of resulting collisions with it and among the vehicles behind.

Other mishap time histories could be used to define lane capacity with some justification. The disrupting vehicle from another lane with no forward velocity component combines with the vehicle hitting it to form a higher mass moving much slower. The two-vehicle mass slides along with an initial velocity reduced by the momentum exchange and a deceleration of somewhat less than 1g. The disrupting vehicle could be an AHS vehicle that has hit a bridge abutment and become a stationary object in the lane. Likewise a less restrictive criterion could be justified (for example, a vehicle with locked brakes at .8g followed by vehicles using maximum operational braking at .6g). This criterion would yield higher AHS design capacity values than those we calculate.

System design would make all of these mishap scenarios quite rare. One could make the argument that none of them have a probability high enough to justify use as the design AHS condition. Then control system lateral/longitudinal interaction, longitudinal wind gusts, control system bandwidth limitations due to passenger comfort boundaries, and other such normal operating limitations would determine AHS capacity. However, it seems reasonable to use emergency conditions that the public is aware could happen.

We have chosen the more conservative approach of the 1g deceleration and the .7 g emergency braking capability. The probability of fatality can be designed to be quite low for persons not involved in the original mishap. We also will choose a minimum gap which limits the number of such collisions to <u>two</u> so that property damage and legal involvement is limited.

The velocity profile for capacity definition is shown in Figure 4-3. The vehicle suffering the mishap decelerates along line 1, 2. After time τ, which is the sum of a communications time delay and a braking time lag, the vehicles behind start to decelerate at maximum braking. At time $\tau + \Delta t_C$ the first vehicle is struck by the second vehicle in the string. The momentum exchange for an elastic collision gives:

$$\dot{x}_1(0+) = \dot{x}_1(0-) + \frac{2m_2}{m_1 + m_2}\left[\dot{x}_2(0-) - \dot{x}_1(0-)\right] \quad (4\text{-}1)$$

$$\dot{x}_2(0+) = \dot{x}_2(0-) + \frac{2m_1}{m_1 + m_2}\left[\dot{x}_2(0-) - \dot{x}_1(0-)\right] \quad (4\text{-}2)$$

where 0+ is the instant after collision and 0- is the instant before collision. The momentum exchange for an inelastic collision gives:

$$\dot{x}_1(0+) = \dot{x}_2(0+) = \dot{x}_{1,2}(0+) = \dot{x}_1(0-) + \frac{m_2}{m_1 + m_2}\left[\dot{x}_2(0-) - \dot{x}_1(0-)\right] \quad (4\text{-}3)$$

where $\dot{x}_{1,2}$ is the common velocity of the two vehicles.

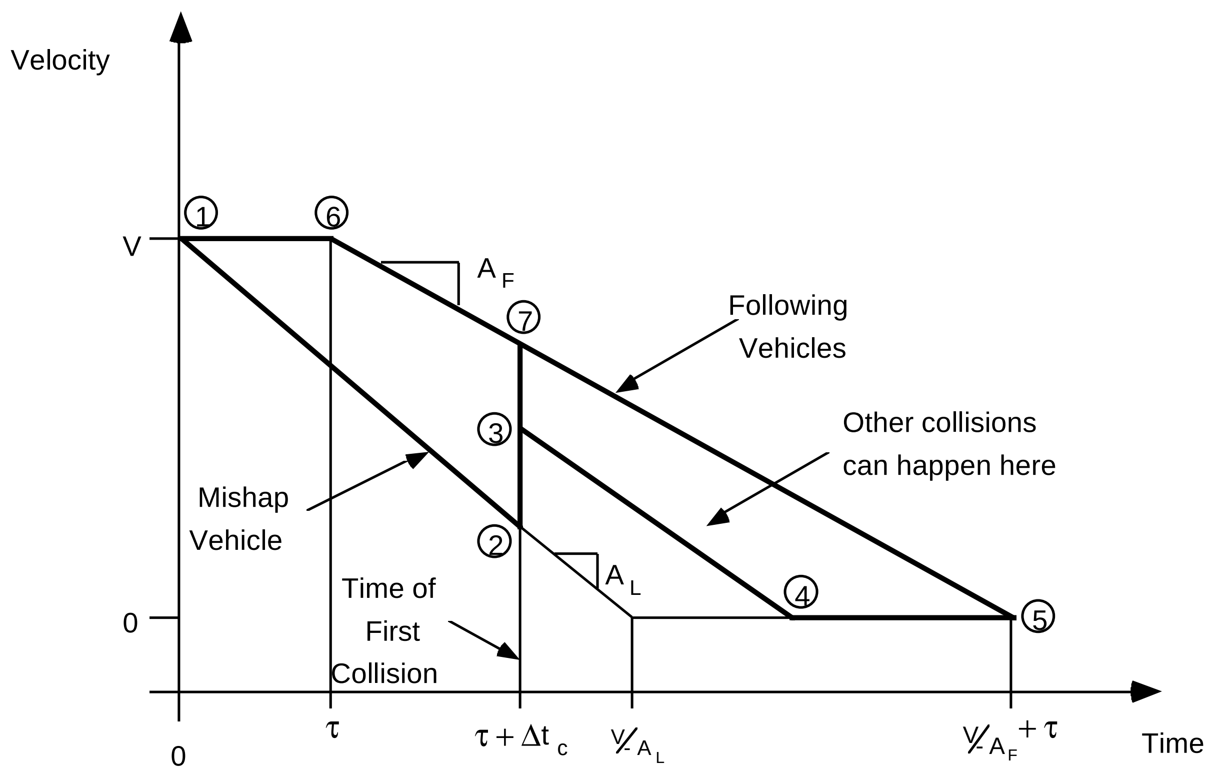


FIGURE 4-3 MISHAP SCENARIO FOR DEFINING AHS CAPACITY

By assumption, an elastic collision does not damage the second vehicle enough to cause higher deceleration and it continues at maximum braking deceleration. The first vehicle continues at the mishap deceleration giving,

$$\ddot{x}_1(0+) = \ddot{x}_1(0-) \tag{4-4}$$

$$\ddot{x}_2(0+) = \ddot{x}_2(0-) \tag{4-5}$$

By considering the inelastic collision as resulting in the two vehicles continuing with one mass restrained by the mishap sliding coefficient of maximum braking (μ_2), we obtain,

$$\ddot{x}_{1,2}(0+) = \left(\frac{m_1 m_1 + m_2 m_2}{m_1 + m_2}\right) g \tag{4-6}$$

In Figure 4-3, the colliding vehicles proceed along line 3, 4. If the gap between vehicles is less than the single-collision value, a second collision between vehicle 3 and the composite vehicle 1,2 happens. As gap is reduced, more collisions happen. Referring to Figure 4-4 we can see that, for the parameter values illustrated, there are thirteen collisions at 3 feet gap size. This drops rapidly as gap is increased. At 13 to

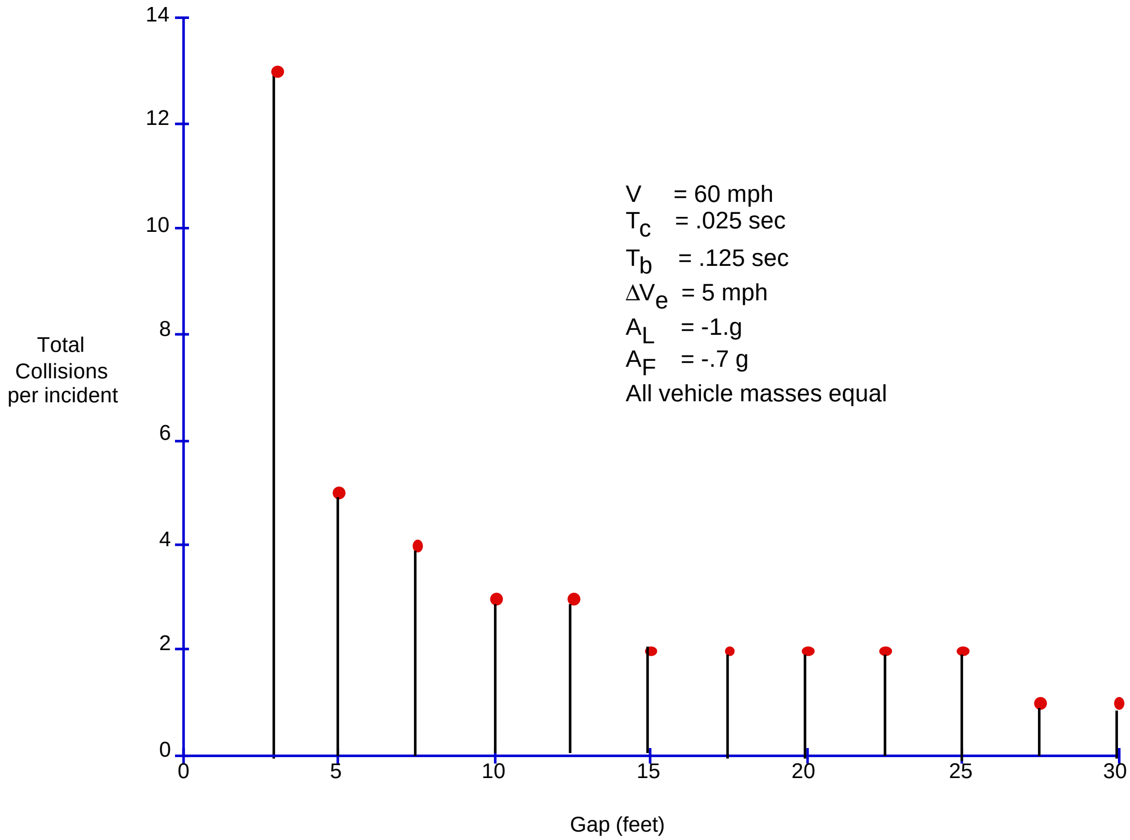


FIGURE 4-4 NUMBER OF COLLISIONS VS. GAP SIZE

15 feet the number drops to two and at 25 to 27 feet it drops to one. Figure 4-5 illustrates a typical distribution of ΔVs across the large number occurring at very short headways. It makes the point that the most severe collision is not necessarily the first. In Figure 4-5 it is the third. (In terms of Section 3.3.3 analysis, the most severe in terms of ΔV_c is the second, followed by the ninth.) These results were obtained using a Calspan program “Velfdei,” described in Reference 15, that was developed for the Entry/Exit PSA task.

Figure 4-6 plots this maximum ΔV as a function of gap size showing the typical increase with gap size until the greatest ΔV_{max} is reached. Then the curve rapidly descends to zero at the gap size where vehicle "two" comes to rest just before colliding with vehicle "one". The general character of this curve for the case where only one collision occurs is evident from Figure 4-3 where the maximum ΔV_{max} versus time occurs at time $V/-A_L$. For the gap size where $\tau + \Delta t_C = V/-A_L$ and only one collision occurs or the maximum ΔV collision is the first one, the maximum ΔV_{max} and associated gap are

$$\left(\Delta V_{max}\right)_{max} = V\left(1 - \frac{A_F}{A_L}\right) - A_F \tau \qquad (4\text{-}7)$$

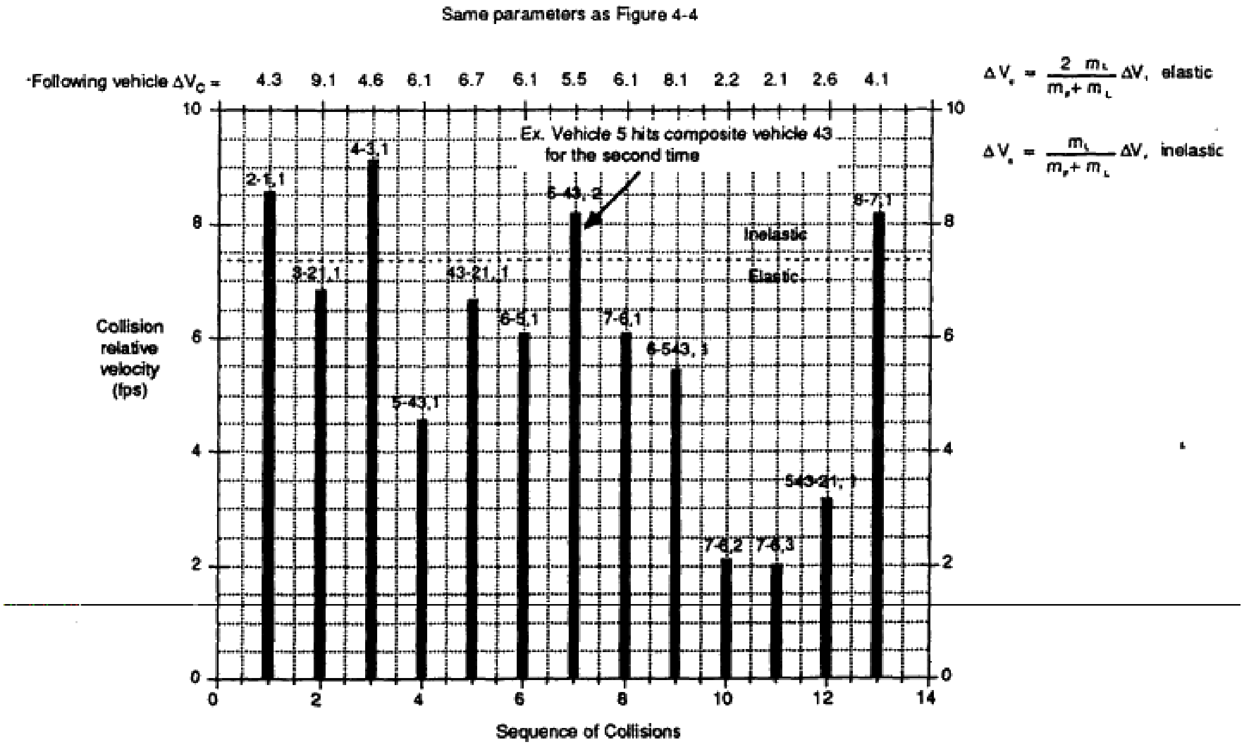


FIGURE 4-5 SEQUENCE OF COLLISION VELOCITIES FOR GAP = 3 FEET IN FIGURE 4-4

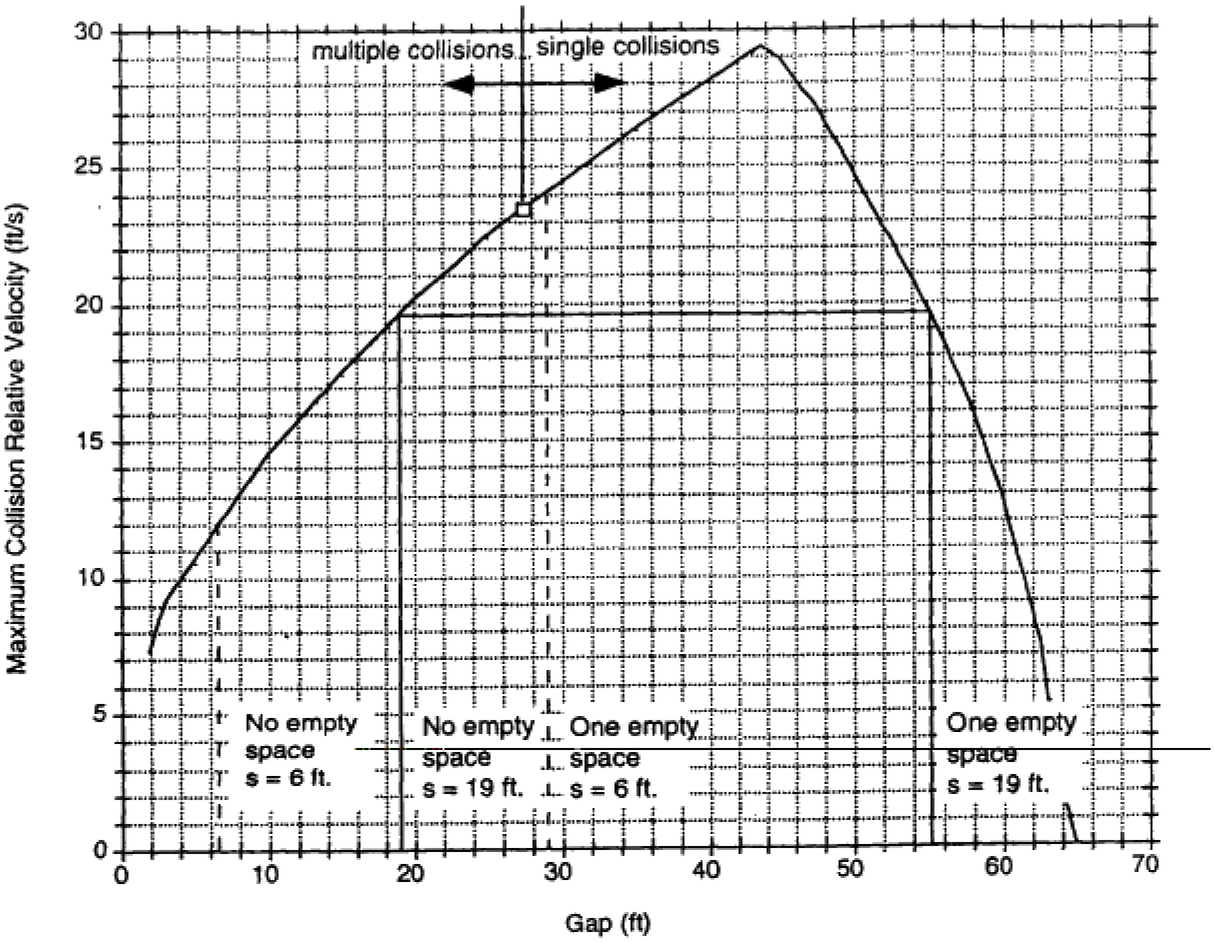


FIGURE 4-6 ΔV_{MAX} VS. GAP

$$s_{crit} = \frac{V^2}{2(-A_L)} - \frac{1}{2}(-A_F)\left(\frac{V}{-A_L} - \tau\right)^2 \qquad (4\text{-}8)$$

$$\text{with } \tau = \tau_b + \tau_c \leq \frac{V}{-A_L} \qquad (4\text{-}9)$$

The minimum gap size for no collision is

$$s_{NC} = \left(\frac{A_F - A_L}{2A_F A_L}\right)V^2 + V\tau \qquad (4\text{-}10)$$

Notice that for conditions where there is only one collision or the maximum ΔV collision is the first one, the relationship between ΔV_{max} and gap size is independent of vehicle mass. This is not true for the small gap sizes where there is more than one collision. Also when the lane velocity is low so that $V/-A_L$ is smaller than τ, equations (4-7) and (4-8) are not correct. Also, curves like Figure 4-6 are not dependent on vehicle lengths as long as the gaps between vehicles are equal.

An important gap size for access/egress consideration is the empty space gap which is 2s+l, where l is the average vehicle length. Figure 4-6 illustrates two instances of a single empty space – one where the gap is 6 feet and one where the gap is 19 feet.

The 6 foot gap gives an empty space value of 29 feet for a 17 foot vehicle length. At 29 feet, for the parameters given in Figure 4-6, the relative velocity of the first collision, ΔV_1,

$$\Delta V_1 = \frac{2(A_F - A_L)\, s'}{\left[2(A_F - A_L)\, s' + A_L^2\tau^2\right]^{1/2} - A_L\tau} - A_L\tau \qquad (4\text{-}11)$$

$$\text{where } s' = s + \frac{A_L\tau^2}{2} \qquad (4\text{-}12)$$

$$\text{and } \frac{1}{2}(A_F - A_L)\tau^2 \leq s \leq s_{CRIT}, \qquad (4\text{-}13)$$

has a value of 24 fps (the value of ΔV_{max} for s = 29 ft, since the point is to the right of the single-collision gap size of 27 feet). This is ΔV_{max} as well because the following vehicles at 6 feet spacing cause the remaining ΔVs to be much lower.

The equation describing ΔV_1 for gaps larger than s_{CRIT} is

$$\Delta V_1 = \left(\Delta V_{max_{max}}^2 + 2A_F s''\right)^{1/2} \quad (4\text{-}14)$$

where

$$s'' = s - \frac{1}{2} A_F \tau^2 - \frac{A_F}{A_L} V\tau - \frac{1}{2}\left(A_F - A_L\right)\frac{V^2}{A_L^2} \quad (4\text{-}15)$$

$$s_{CRIT} \le s \le s_{NC}$$

The 19 foot gap gives an empty space gap of 55 feet. At this gap size the ΔV_{max} is the same as it is at 19 feet. This nice property allows all vehicles in the lane to have equal or less collision severity potential whether there is an empty space ahead or not. With more than one space ahead empty there will be less collision severity potential. We define this gap as the safety gap.

Safety gap is a function of the mishap scenario parameters. The baseline choice for the parameters is the subject of the next section. By assuming dry pavement condition and uniform bumper design, we have velocity left as a parameter for ATMS to vary to maximize capacity in the vicinity of access/egress sections by slowing vehicles and spacing them closer together.

3.3.3 ACCIDENT SEVERITY MODEL

Using the approach of Reference 14 we can relate ΔV to the Abbreviated Injury Scale (AIS). The data from this report Volume V, Chapter 2, can also be used to construct a probability of injury metric.

First, it is important to note that the delta-V in both these sources is the overall change in a single vehicle's velocity during the collision. This is a function of the relative masses, the ΔV just prior to collision, the degree to which energy is absorbed by the bumpers/bodies and the degree to which energy is distributed to other motions like vehicle rotations. We will call this single-vehicle change in velocity ΔV_c.

To make a simple, first-order model of accident severity and relate that to AHS safety policy and capacity we set vehicle masses equal and compute the collisions as purely inelastic or purely elastic depending on ΔV_e. The general case is given by equations (4-1) - (4-6). When equal masses collide inelastically then $\Delta V_c = \frac{1}{2}\Delta V$ for both colliding vehicles. The lead vehicle increases velocity by ΔV_c; the following vehicle decreases velocity by ΔV_c.

The third vehicle, colliding inelastically with the composite of the two vehicles ahead, decreases velocity by $\Delta V_c = \frac{2}{3}\Delta V$; the leading composite vehicles increase velocity by $\Delta V_c = \frac{1}{3}\Delta V$.

If the collisions between equal masses are elastic, then $\Delta V_c = \Delta V$. For most cases we consider in this chapter, the maximum ΔV is inelastic and it is the first collision, making $\Delta V_c = \frac{1}{2}\Delta V$ for looking at probability of injury.

The probability metric for occupants of the following vehicle developed in Reference 14 is:

$$\text{Prob (fatality)} = (.70)(\Delta V_c - 10.8)^{3.2}\ 10^{-6} \quad \text{(4-15a)}$$

$$\text{Prob (AIS} \geq 3) = 1.04(\Delta V_c - 10.8)^{1.5}\ 10^{-3} \quad \text{(4-15b)}$$

$$\text{Prob (AIS} \geq 2) = .81\ (\Delta V_c)^{1.7} 10^{-3} \quad \text{(4-15c)}$$

$$\text{Prob (AIS} \geq 1) = 1 - e^{-f(\Delta V_c)}, f(\Delta V_c) = .47\ \frac{\Delta V_c}{10.8} + .029\left(\frac{\Delta V_c}{10.8}\right)^3 \quad \text{(4-15d)}$$

for 10.8 ² ΔV_c ² 50 fps

The AIS code descriptions are given in Table 2-15 of Vol. V, Ch. 2. Data at low velocities is sparse. Hence the cutoff of 10.8 fps. However, data in Vol. V, Ch. 2 does exist down to 6 mph or 8.8 fps to compare with eq. (4-15 c and d) below 10.8 fps.

If we apply this to the ΔV_{max} for 19 foot gap in Figure 4-6, we have $\Delta V_{c\ max}$ = 9.8 fps and thus

Prob (fatality) = small
Prob (AIS $\geq$ 3) = small
Prob (AIS $\geq$ 2) = .04
Prob (AIS $\geq$ 1) = .36

for the second vehicle in line.

For m collisions in the same incident, we have

$$\text{Prob (AIS} \geq k) = 1 - \prod_{i=1}^{m} \left[1 - \text{Prob}(\text{AIS} \geq k)_i\right] \quad \text{(4-16)}$$

where Prob (AIS $\geq$ k)$_i$ is computed for each collision.

Thus for the second collision at 15.6 fps (between the third vehicle and the two vehicles ahead) $\Delta V_c = \frac{2}{3}(15.6) = 10.4$ fps and Prob (AIS $\geq$ 1) = .39, Prob (AIS $\geq$ 2) = .04

For the incident,
Prob (AIS $\geq$ 1) = 1 - (1 - .36) (1- .39) = .61
Prob. (AIS $\geq$2) = 1 - (1 - .04) (1 - .04) = .08
Prob. (AIS $\geq$3) = small
Prob. (fatality) = small

Note that although ΔV is smaller for the second collision, ΔV_c is higher and therefore that collision is more serious.

Since we are dealing with a rare event, systems designers may accept these probabilities of injury, particularly since the chance of very serious injury is small.

When we apply this accident severity model to the data of Figure 4-5, Prob (AIS $\geq$ 2) = .17 which is twice the value of .08 for the 19 foot gap.

3.3.4 SAFETY POLICY AND CAPACITY

Next we consider a Safety Policy that will lead to safety gap and thus capacity as a function of the collision parameters and other safety concerns. Our policy takes into consideration the following factors:

a. Assumed deceleration of the mishap vehicle and assumed maximum braking deceleration as influenced by surface conditions, average tire wear, etc.

b. Assumed vehicle design for low velocity collision and passenger restraint systems.

c. Probability of serious injury and cost of vehicle damage.

d. Number of collisions (influencing number of parties involved and time to clear the incident).

e. Minimum gap necessary for reliable lane change during normal operation.

f. Influence of reserving an empty space(s) ahead for vehicles accessing the lane.

g. Assumed mix of vehicle masses.

It is by no means the only possible safety policy and certainly is not claimed to be the best. It does take items a) through g) into account in a rational way. The resulting dry pavement capacity-versus velocity relationship is shown in Figure 4-9, with the basic data from Figure 4-7. The factors a) through g) are satisfied as follows:

a. Covered by assuming a 1g mishap deceleration and a .7g emergency braking capability for the affected following vehicles.

b. Covered by the assumed 5 mph bumper and all-passenger restraint systems.

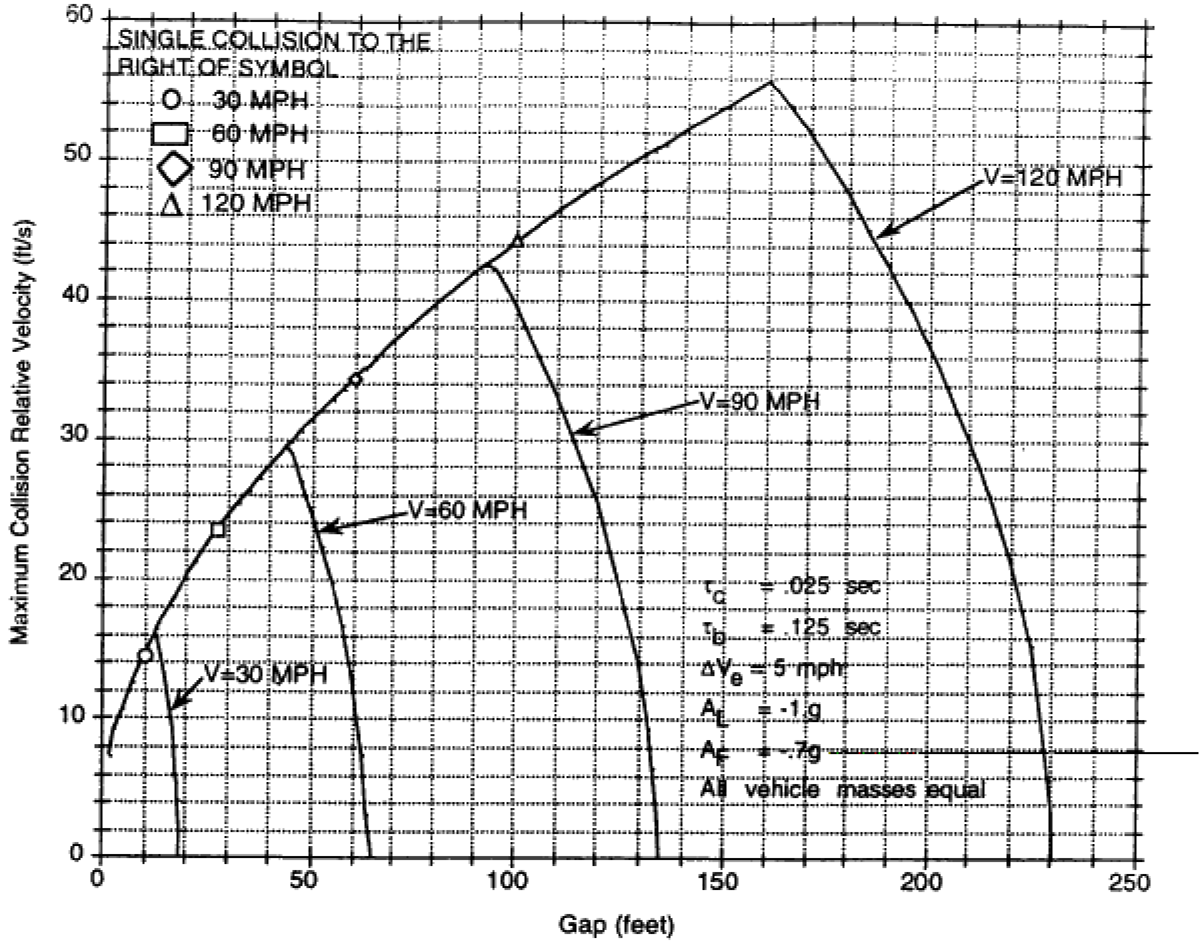


FIGURE 4-7 ΔV_{MAX} VS. GAP WITH WARNING V

c. Covered by limited $\Delta V_{c_{max}}$ to less than 10 fps. (Δv_{max} ² 20 fps)

d. Covered by limiting the number of collisions (beyond what might have happened to the mishap vehicle) to two.

e. Covered by taking 37 feet as the minimum maneuvering gap, giving 10 feet forward and aft around a 17 foot vehicle. (This number is based on current Calspan projections in Chapter 3 of this volume.)

f. Covered by the policy of equal safety for one empty space ahead and increased safety for more than one empty space.

g. The resulting capacity curve is drawn for a lane of vehicles of less than or equal to a given limiting mass ratio, heaviest to lightest. (For Figure 4-7 the mass ratio is 1).

Figure 4-9 is constructed directly from Figure 4-7, from crossplots and from computation details giving number of collisions.

Directly from Figure 4-7 we can crossplot a line of ΔV_{max} = 20 fps and a line of ΔV_{max} = 20 fps for a single empty space ahead versus gap. These are shown in Figure 4-8, along with the two-collision boundary.

Above 60 mph there is no longer a gap that will satisfy f). We can move vehicles ahead to fill empty gaps ahead created by egressing vehicles. This would create theoretical capacities above the maximum of 9600 vph at 52 mph. This could continue until reaching the two-collision curve once again with 10600 vph at 73 mph. The capacity curve would then continue to 8800 vph at 120 mph with a maximum of 10,800 vph at 80 mph. However, this operation would be impractical because no spaces are available to allow access. To keep $\Delta V \leq 20$ fps for uniform gaps and arbitrary empty space distribution, the capacity drops down to 4400 vph at 60 mph and continues to decrease to 2800 vph at 120 mph – too low to be considered for AHS application. Thus, we examined small groups.

Various small groups can be suggested to deal with velocities above 60 mph. One is shown on Figure 4-9. It creates groups of three separated by 19 feet and then preserving an empty space large enough to prevent a third collision. The formula for capacity becomes

$$q = 4\frac{5280\ V_{mph}}{2s + 4l + 2s_1} \qquad (4\text{-}17)$$

where s_1 is s_{NC} for the speed considered or is the gap for ΔV_{max} = 20 fps which is larger than s_{CRIT}. When vehicles "1" or "3" leave the lane, there is no decrease in safety for the remaining two vehicles. A vehicle can be added at these vacant positions without safety decrease. When vehicle "2" leaves, vehicle "3" should move up to take its place to avoid the hazard in holding a 55 foot space. The space available is thus reserved in the "3" position.

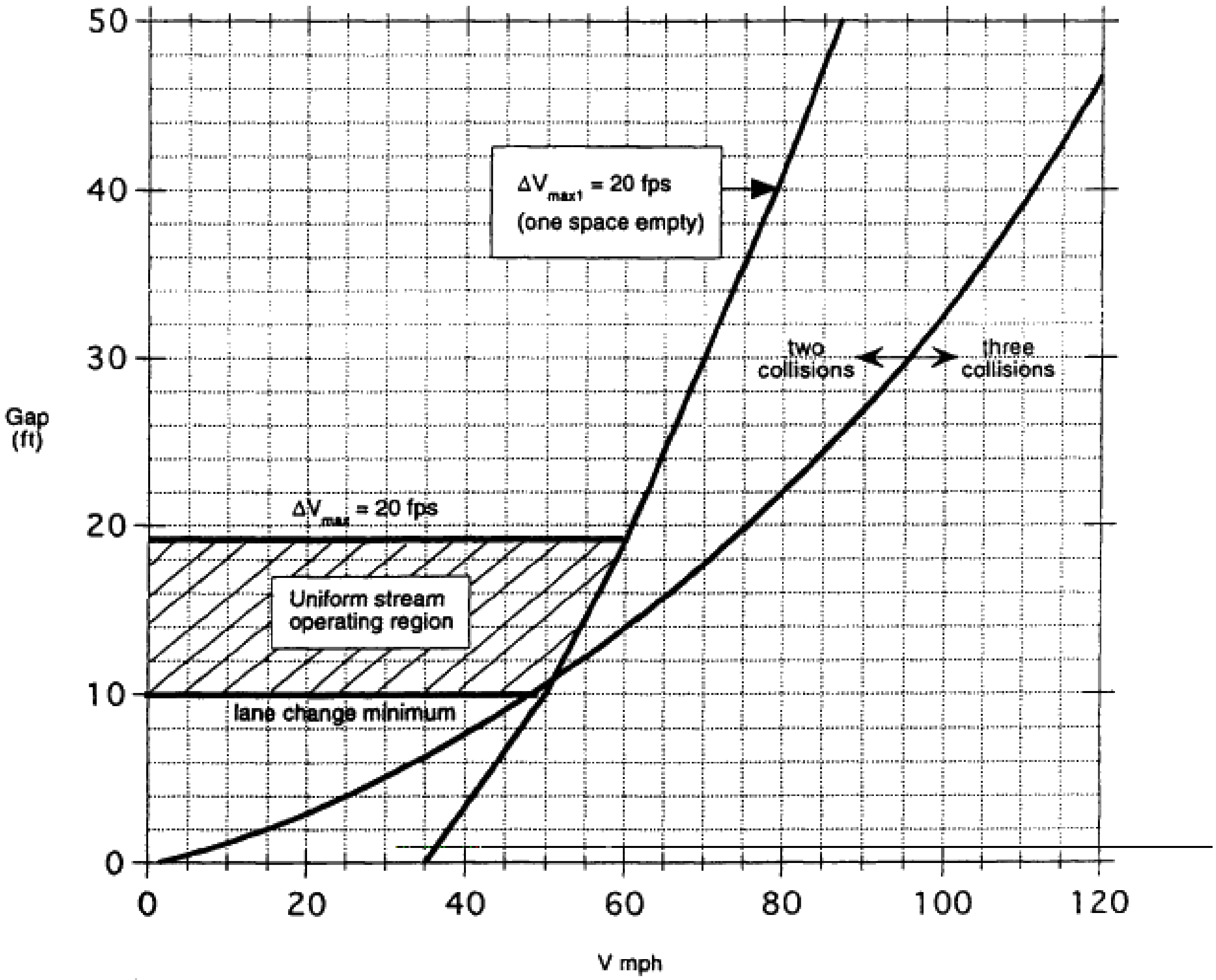


FIGURE 4-8 VARIOUS BOUNDARIES FROM FIGURE 4-7

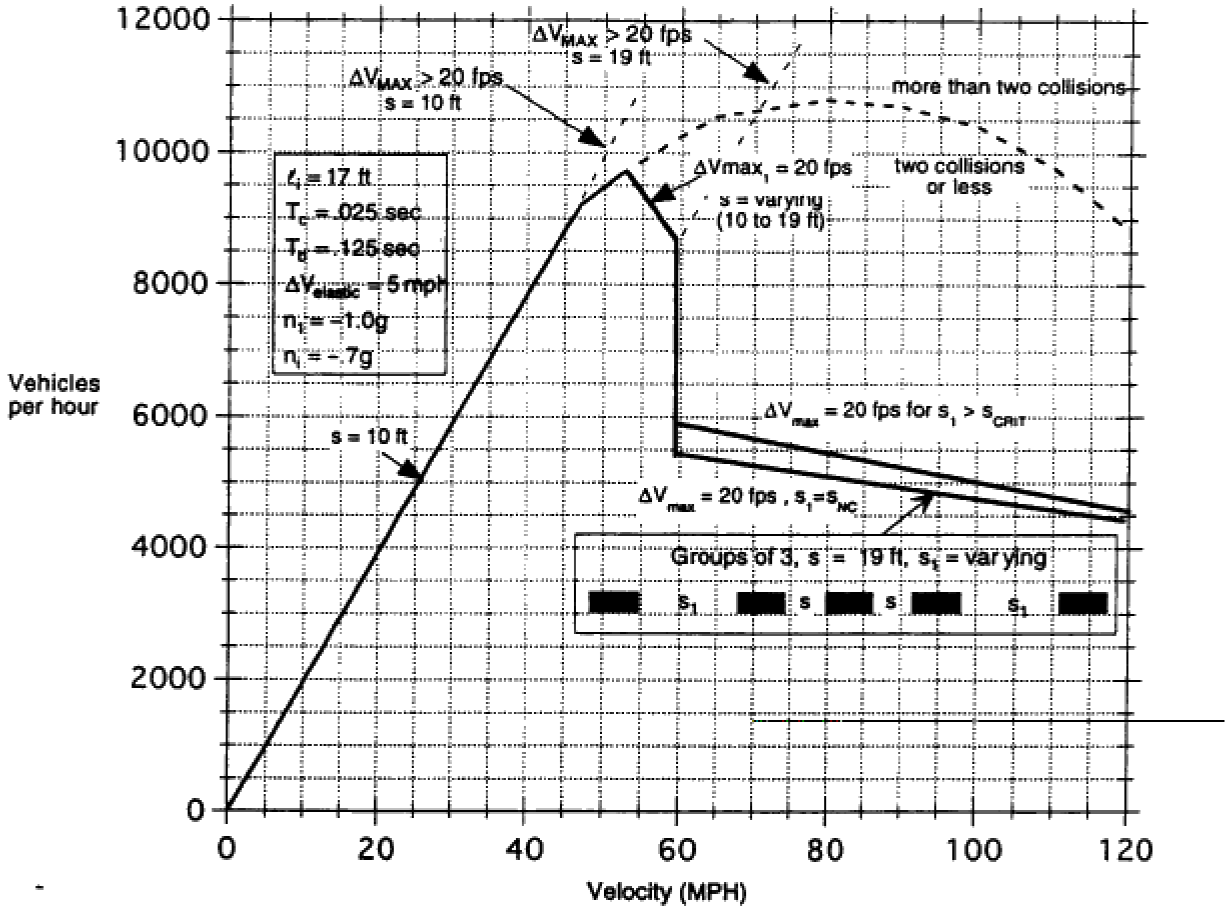


FIGURE 4-9 DRY PAVEMENT CAPACITY VS. VELOCITY FOR SAFETY POLICY OF 3.3.4

Notice that if groups are larger than three, there are three or more collisions if vehicle "1" has the mishap, violating condition (d) of our safety policy. Also groups of two always satisfy our safety policy regardless of which vehicle leaves but the resulting capacity is lower. Therefore a group size of three is appealing.

In summary, the safety policy of this section together with assumptions of dry pavement (n_i = -.7g braking capability), nearly equal vehicle masses, quick communications and braking initiation and essentially inelastic collisions leads to a maximum AHS lane capacity of about 9600 vph at 52 mph. Access and egress up to a large fraction of this analytical design limit are discussed in Sections 3.5 and 3.6.

3.3.5 SENSITIVITY ANALYSIS

3.3.5.1 MAXIMUM BRAKING DECELERATION

Calspan has data from maximum effort braking on dry pavement obtained from police cars equipped with ABS brakes. The deceleration data shows an initial peak at .86 to .99g followed by a decrease to the .72 to .89 g level. The acceleration peaks again at the former level near the vehicle stopping point and then drops quickly to zero. Data from Reference 1 shows braking decelerations with good tires at .75 g's. With poor tires this drops to the .4 to .6g level. Based on this data and what other researchers have assumed, we have assumed .7g for the numerical calculations presented above.

For wet pavement the Reference 1 data varies from .27 to .40. To illustrate what wet pavement would do to capacity we assumed a level of .3g keeping the 1.0 g deceleration for the mishap vehicle. This assumes the metal-on-pavement sliding friction value is not changed much with wet payment or the mishap vehicle has hit something massive and decelerated to a stop in a distance equivalent to a 1g deceleration. The basic data is contained in Figure 4-10.

The double collision boundary points (not shown), which are to the left of the single collision points, are at much larger gaps than in Figure 4-7. The gap for ΔV_{max} less than 20 fps at 60 mph is less than 9 feet or greater than 271 feet. The safety gap is about 9 feet with the nice property of all empty space distributions giving ΔV_{max} less than 20 fps at a speed of 25 mph. The capacity is 5080 vph which is probably near the maximum for the safety policy of 3.3.4. This raises an issue for lane operations above this flow on dry pavement when precipitation commences. The optimum speed of 20 to 25 mph is far below what most people drive on wet pavement. This is also an issue. An AHS for dry climates only? Can better tire or pavement designs be developed for wet conditions?

3.3.5.2 ONSET TIME FOR MAXIMUM BRAKING

Braking of following vehicles starts to occur when the communication arrives that a vehicle ahead is decelerating at a value exceeding some threshold. The communication time we have assumed is .025 seconds or a data frame rate of 40 htz. We have also assumed that all relevant vehicles receive the signal to brake in the same frame. This time is then added to the series of events in each vehicle that finally

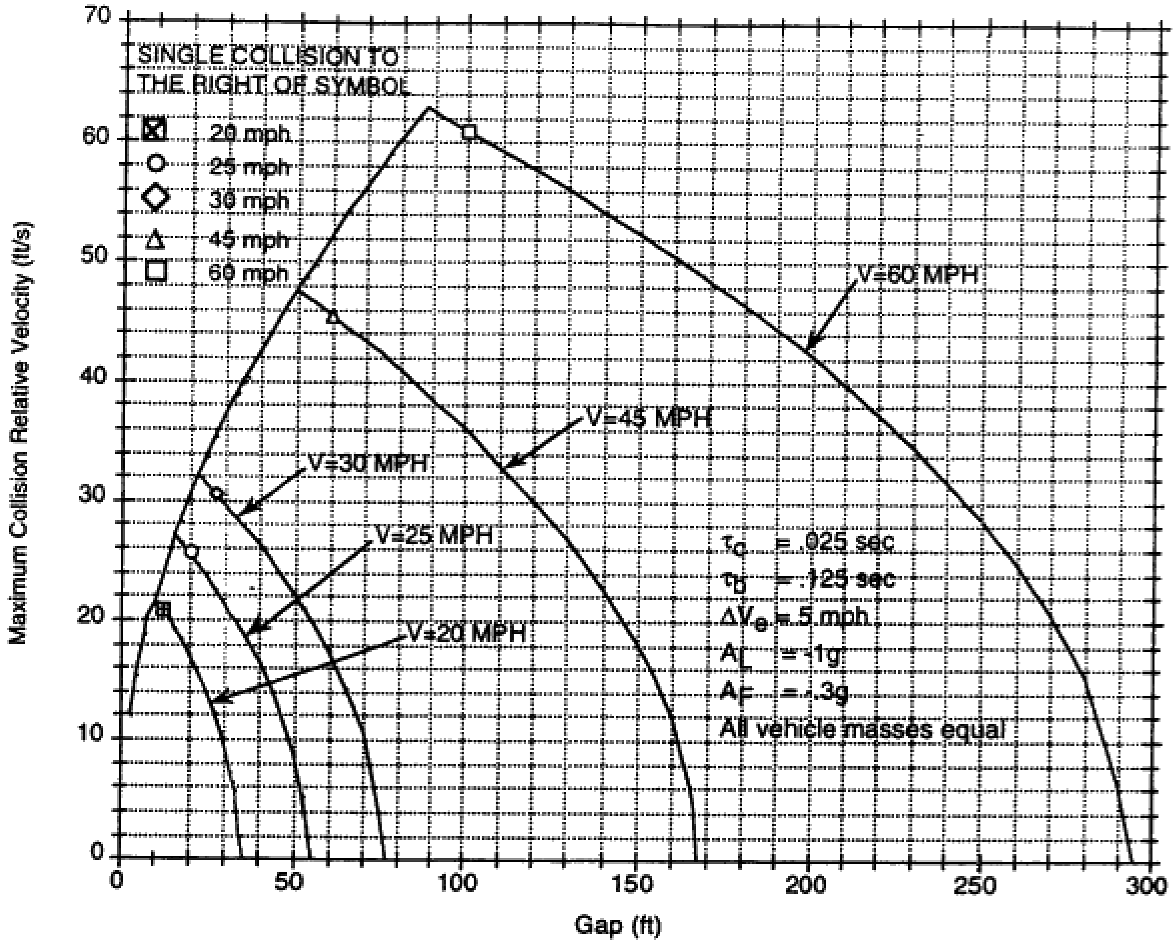


FIGURE 4-10 ΔV_{MAX} VS. GAP, WET PAVEMENT

ends with maximum braking deceleration of the vehicle's center of gravity. This series includes the braking actuator time constant, the pressure buildup in the braking disks at the wheel, the tire deflection, and the suspension deflection. Informal data at Calspan indicates this series to take a minimum of .150 seconds. We have assumed .125 seconds based on the advent of optimized, variable suspensions and tire designs for rapid reaction to braking. But we also have data that indicates rise times as high as .400 seconds. Although instrumentation time lags may have contributed to this high number, we are concerned about the .125 second assumption. Figure 4-11 shows what the collision curves look like for braking time delay of .200 seconds and communications at 20 htz. The combined effect of τ_b and τ_c into the parameter τ in equations (4-7) to 4-12) also show what increasing τ does to the collision curves and thus to capacity. Figure 4-11 shows that the safety gap is slightly reduced and the single and double collision gap limits are also reduced. The maximum speed for all-space safety is reduced from 60 mph. This all indicates a lower maximum capacity although not a drastic reduction.

3.3.5.3 MISHAP VEHICLE SCENARIO

As one would expect and as equations (4-7) to (4-12) indicate, lowering the mishap vehicle deceleration decreases ΔV_{max} at a given gap size. The design scenario might be allowed to be not as extreme as a -1g deceleration. Using a .9g deceleration as from a hardover braking failure, for example, might be substituted for the collision scenario. Figure 4-12 shows the effect on the collision curves. The safety gap moves up to 30 feet and the maximum speed for all-space safety is increased to roughly 80 mph. The capacity at optimum speed stays in the region of 9000 vph.

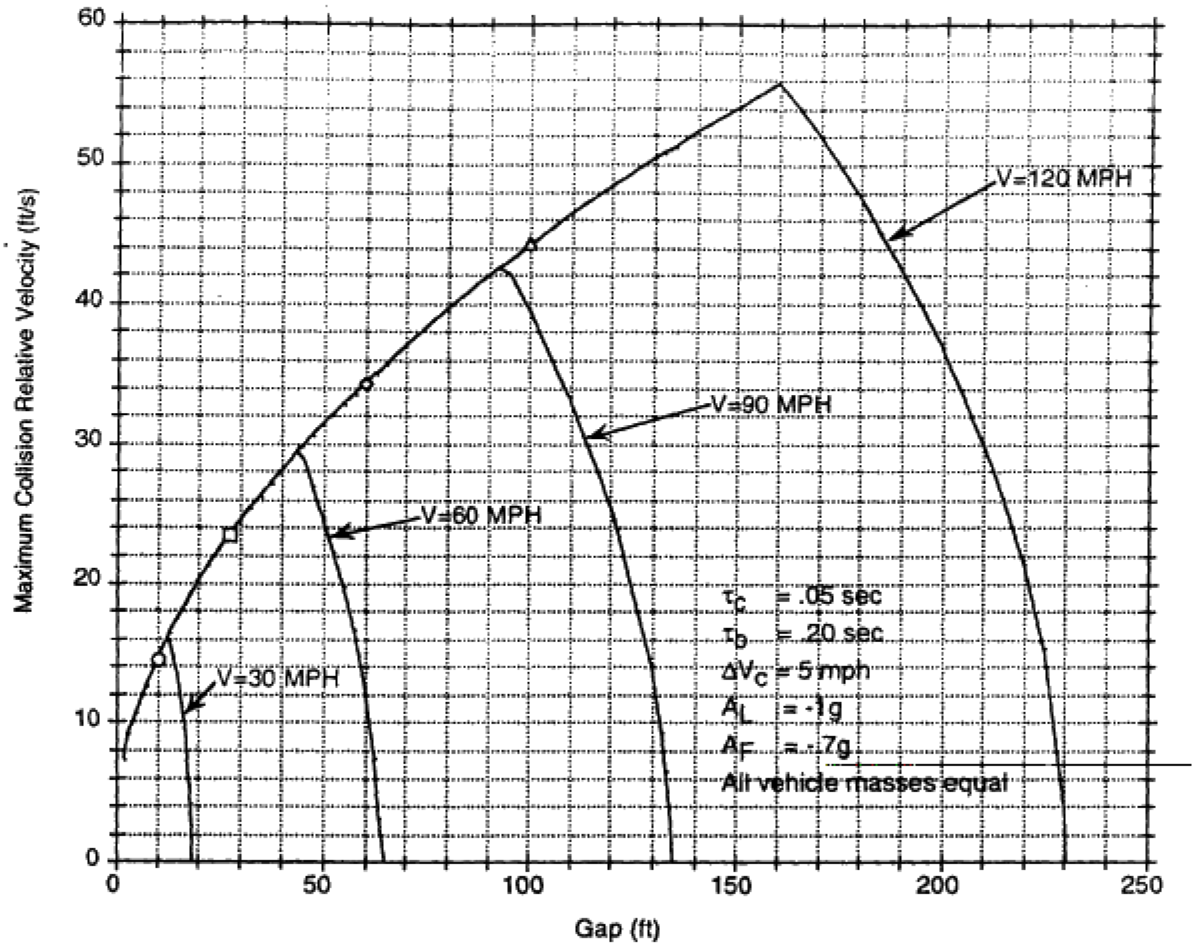


FIGURE 4-11 ΔV_{MAX} VS. GAP, LARGER BRAKING DELAY

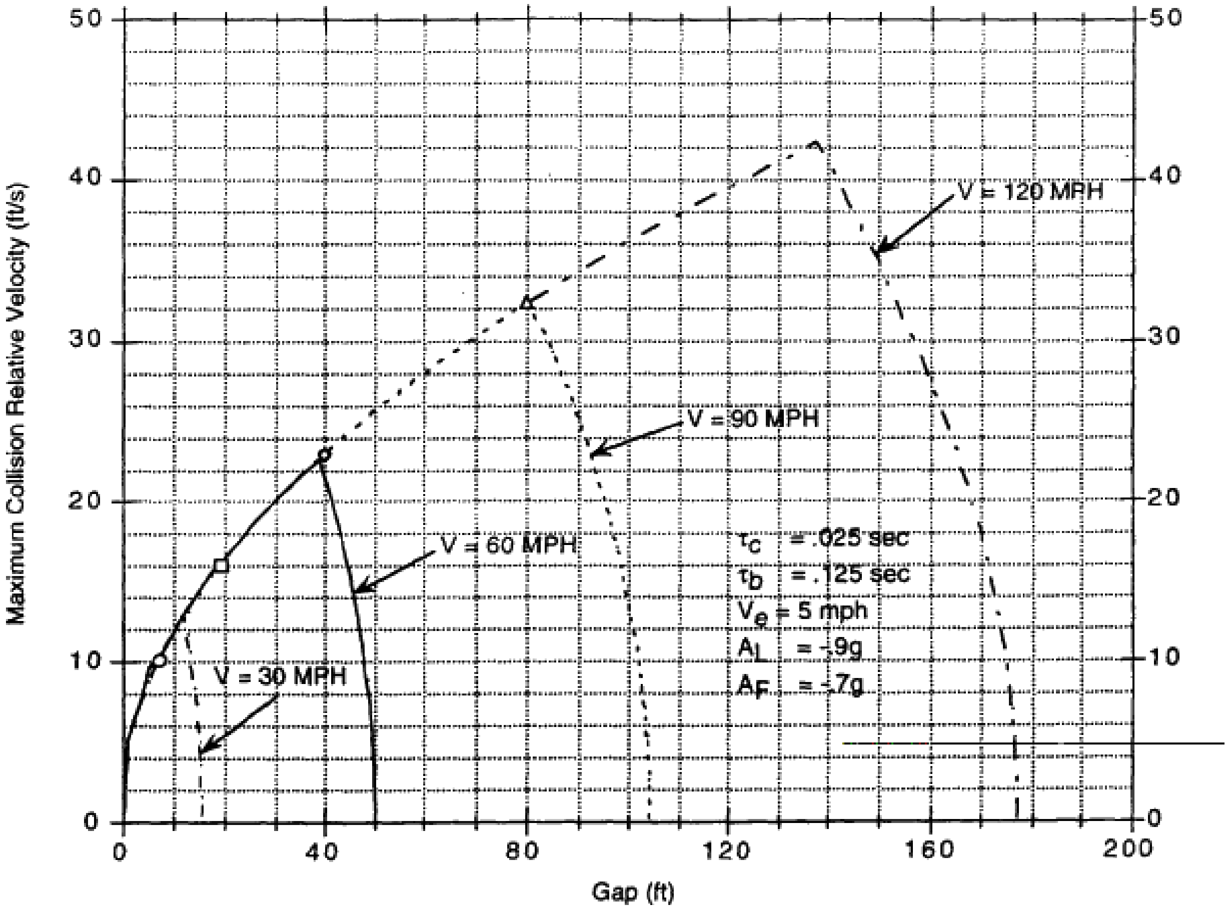


FIGURE 4-12 ΔV_{MAX} VS. GAP, SMALLER MISHAP VEHICLE DECELERATION

3.3.5.4 BUMPER DESIGN

The bumper/body could be designed to retain elasticity to collision speeds higher than 5 mph. Results with V_e = 15 mph, not shown here, indicate more collisions of higher ΔV's. This is particularly true at smaller gaps. This is definitely not a desirable design for AHS vehicles. Results with gaps of 10 feet or more and V_e = 0 mph all collisions inelastic are very similar to the V_e = 5 mph results since the collisions are inelastic at the speeds of interest. Thus some elasticity, desirable to deal with small mishaps, is acceptable for AHS vehicles.

3.3.5.5 MASS RATIO

If AHS vehicles are of different masses, the collision curve to the right of the new single-collision point is not affected. The reason is that the mass ratio affects the momentum exchange which changes the time histories only after collision. The curve to the left of the single-collision point changes drastically and the single collision point itself changes. Figure 4-13 and 4-14 are the 60 mph collision curves for mass ratios of 5 to 1 and 20 to 1. The second collision becomes worse than the first when the vehicle ahead is the heavier vehicle. For a mass ratio of 5, at 60 mph the gap for ΔV_{max} = 20 fps drops from 19 feet to 10 feet where five collisions occur. If the mass ratio is 20, we must run at 3 foot gap with 17 collisions to have ΔV_{max} = 20 fps.

We have said that SVEs, which includes pickups, buses, panel trucks etc., are permitted as part of passenger car AHS lanes. These have a substantial fraction μ of 5 to 1 mass ratio vehicles still with about the same vehicle length. To avoid decrease in safety, assume one empty space behind each of the heavier vehicles. We would then compute nominal capacity as

$$q = \frac{5280V}{s+l}\left(\frac{1}{1+m}\right) \qquad (4\text{-}18)$$

For example. a fraction of .2 would give 83% percent of the nominal capacity with mass ratio of unity for all vehicles.

For the large trucks that are 20 to 30 times more massive than passenger cars, we will adopt a no-collision policy. Using equation (4-10) to define the gap for no-collision, we plot Figure 4-15.

Based on data for dry pavement in Figure 10 of Reference 16, choose a large truck braking capability as .55g at 60 mph. If the vehicle ahead decelerates at 1.0 g, as we have assumed for the small vehicle capacity analysis, Figure 4-15 then specifies 111 feet as the minimum gap for no collision. With a vehicle length of 65 feet, the space for one truck is 176 feet. This compares with the small vehicle space of 36 feet based on previous analysis at 60 mph.

If we consider the safe gap to follow a massive vehicle at 60 mph to be 55 feet (from Figures 4-11 or 4-14 for ΔV_{max} = 20 fps) the total space taken by a large truck at 60 mph is 231 ft compared with 235 feet for six passenger cars (Figure 14-16) or an equivalence factor of six.

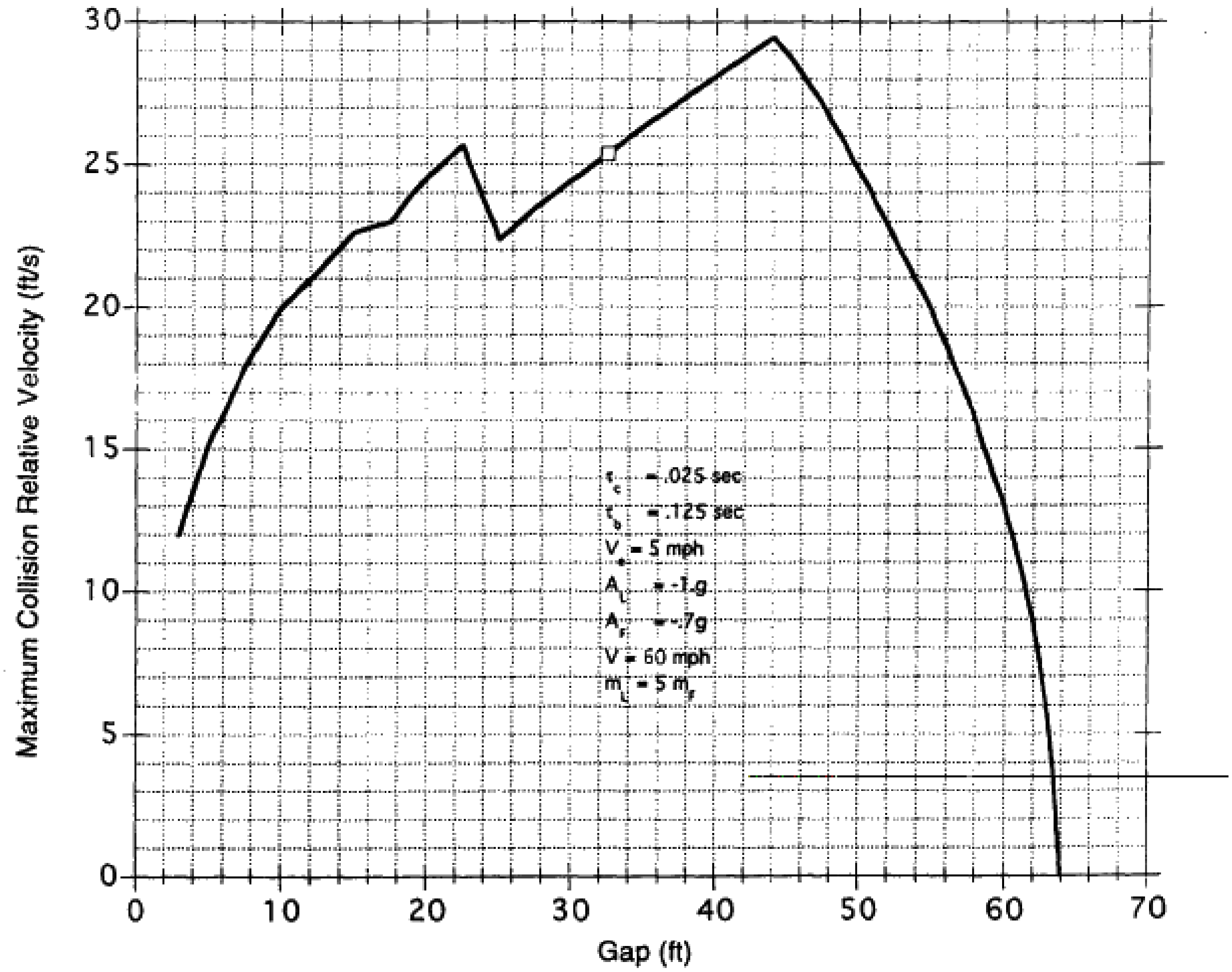


FIGURE 4-13 COLLISION CURVE WITH V = 60 MPH FOR MASS OF LEAD VEHICLE EQUAL TO 5 TIMES FOLLOWING VEHICLES

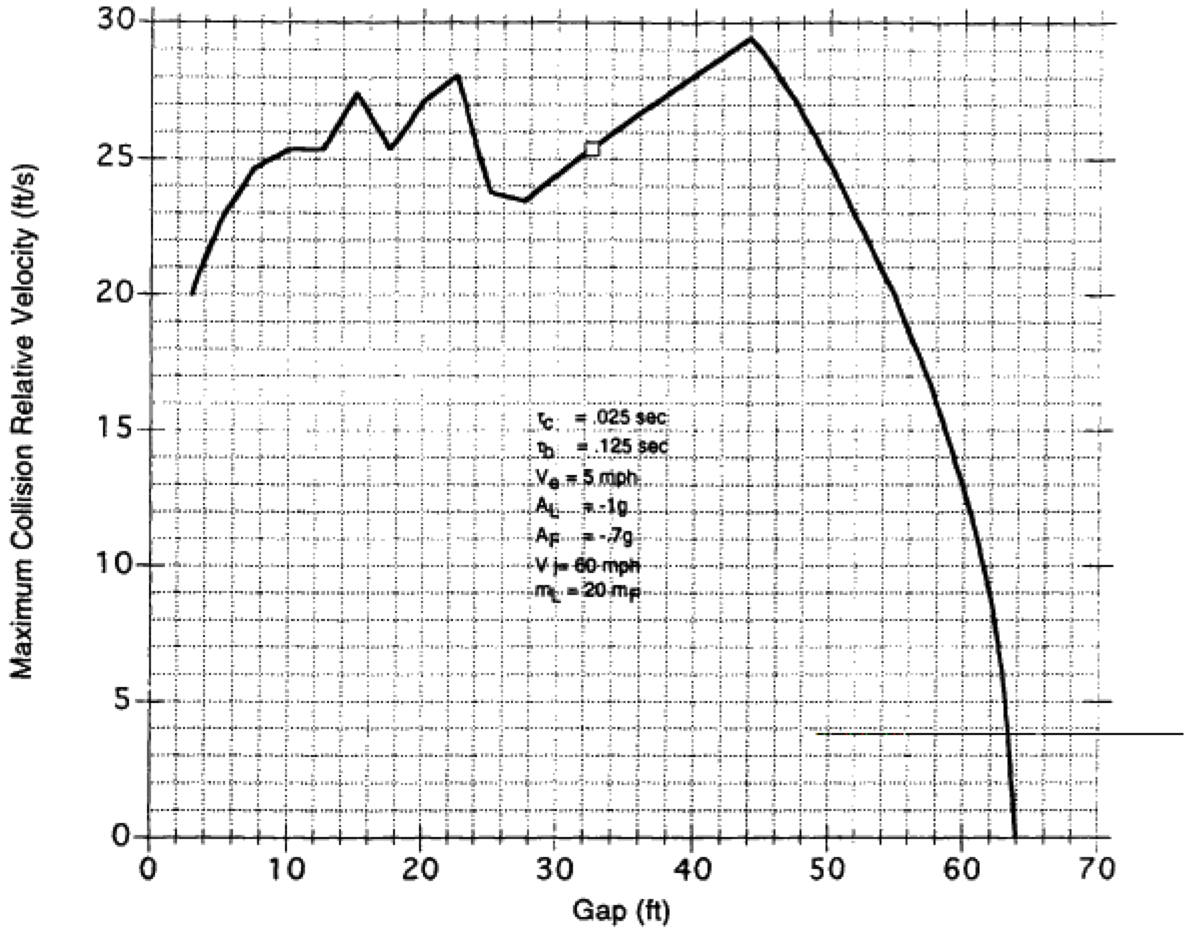


FIGURE 4-14 COLLISION CURVE WITH V = 60 MPH FOR MASS OF LEAD VEHICLE EQUAL TO 20 TIMES FOLLOWING VEHICLES

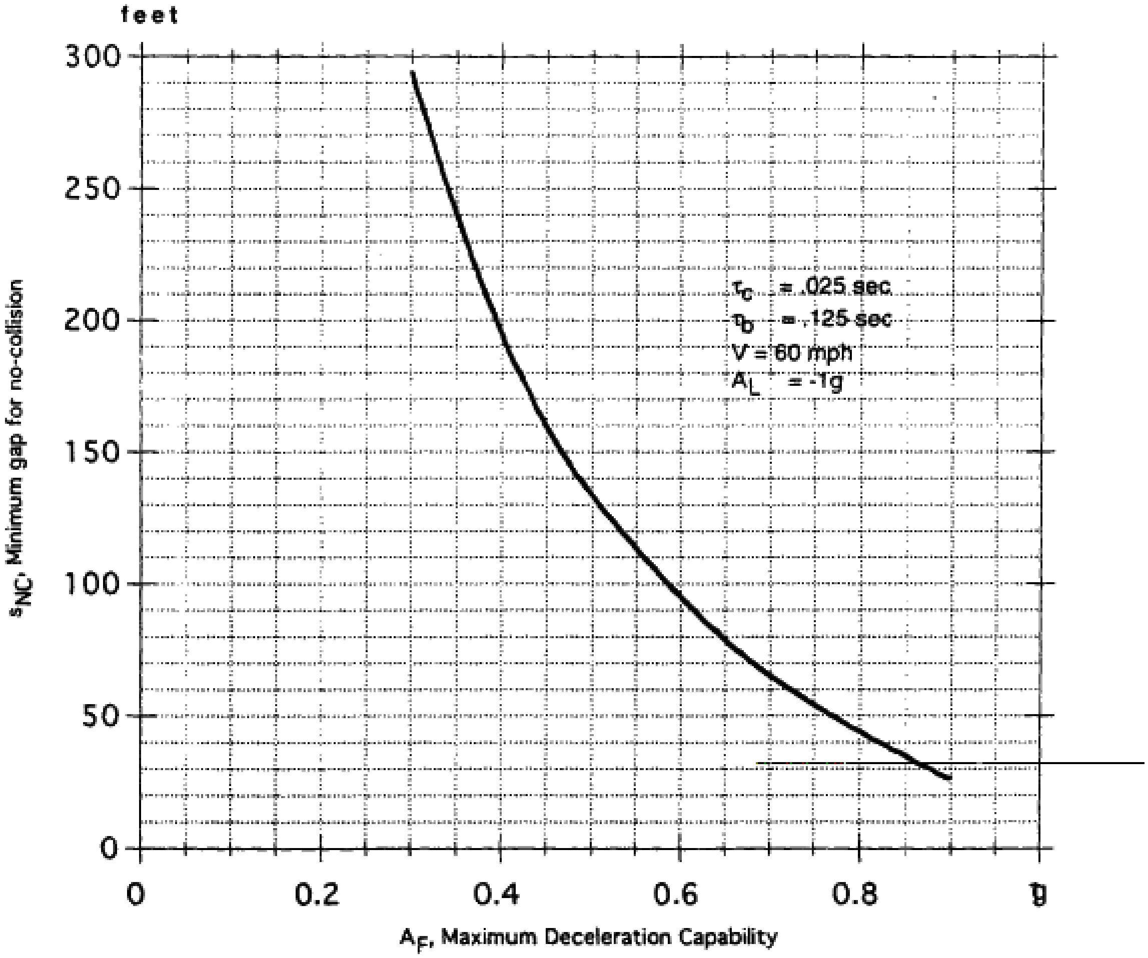


FIGURE 4-15 NO-COLLISION CAPABILITY

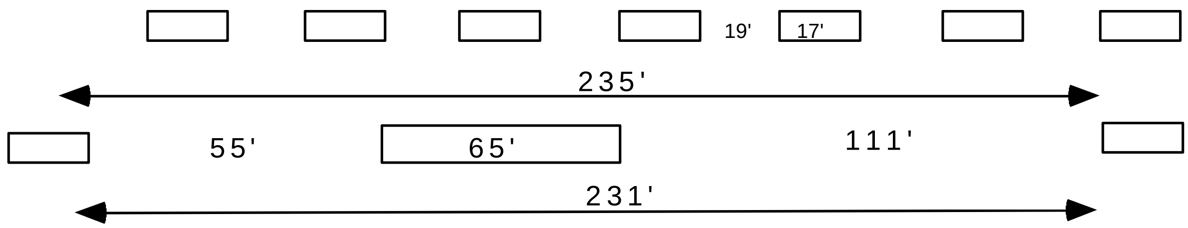


FIGURE 4-16 LARGE TRUCK CAPACITY EQUIVALENCE AT 60 MPH

Consider a congested three-lane manual flow of 6,000 vph, 8 percent of which are large trucks. The truck flow of 480 vph is equivalent to 2,880 vph of small vehicles -- not insignificant when designing an AHS with a theoretical capacity of 9,000 vph per lane.

What does this mean for an AHS lane reserved for large trucks? Can the scenario above be helped by a dedicated truck lane? With a space of 176 feet, these 480 trucks per hour only fill part of a dedicated lane since its capacity is 5280 x 60 ÷ 176 or 1,800 vph. Meanwhile, the remaining 5,520 vph are obliged to be content with only two manual lanes, an impossible result even with the absence of trucks in those two lanes.

On the other hand, if the small vehicles are given the AHS lane, the 5,520 vph flow is within the 9,000 theoretical capacity, while the 480 vph truck flow is occupying two lanes that could, with a two-second gap, handle a 1,300 vph manual truck flow in each lane.

3.4 ACCESS/EGRESS AND BENEFITS FOR THE I1 CONCEPT

3.4.1 GENERAL CONSIDERATIONS

The I1 concept is a shared lane on a shared freeway. It applies to early versions of AHS but it is also the concept for mature AHS designs that fits long sections of four-lane interstate highways in rural settings (implying lower traffic demand). With many vehicles operated manually on these highways for the foreseeable future and the use of the left lane for passing a necessity for this manual traffic, I1 is the primary concept to consider.

Other researchers have studied the concept of shared lanes. Reference 17 suggests ideas that are carried forth in this section such as automated vehicles running at close headways behind other automated vehicles and at more moderate but still less than manual headways when following a manual vehicle. Reference 17 goes on to develop the idea of using very close gaps when demand warrants (spontaneous platooning). The assumptions of participation and number of lanes are not explicitly stated but it is clear that low participation fits the concept. The conclusions are that “compared to a segregated approach, introduction of automation using an autonomous, heterogeneous approach will provide visible benefits in early stages of evolution”. The authors note that the benefits extend to the manual vehicles as well, so there is an issue regarding incentive to purchase automation equipment. We suggest a differential toll to deal with this issue.

Reference 18 is not as optimistic about I1 and moves away to an I2 concept with a dedicated transition lane, pointing out that the maximum flow must be high in the AHS lane to justify reserving the transition lane for automated vehicles.

The scenario for I1, in Reference 18, does not use lane change to support the flow in the AHS lane. Rather, it assumes that a flow of equipped and unequipped vehicles arrives at a point downstream of which an equipped vehicle engages automation and then operates at close gap to another automated vehicle if there is one ahead. Flow benefits are calculated based on (4-19). Since a manual flow feeds this process, the flow benefit is tenuous.

Using a completely random distribution of equipped vehicles, Reference 18 shows a Beta distribution of groups to result for the probability p_n of a group of size n given a general participation in the left lane of p. For a congested condition where there is always a vehicle ahead within detection range the formula is

$$p_n = n(1-p)^2 p^{n-1} \tag{4-19}$$

for the probability that, given an automated vehicle in the lane, there will be n-1 vehicles grouped with it. This formula will be used in our subsequent analysis.

The emphasis here is to maintain the freeway entry/exit flows unchanged thus not requiring the expensive modification to that infrastructure and not changing city street flow demands. The benefits then are measured in lower trip time, lower emissions, and lower driver stress. The implied assumption is that the cruise lanes are operating at capacity and thus are running at lower speed. Figure 4-17 illustrates the benefit we hope to obtain. It plots cumulative traffic counts at A and B in a simple model of a freeway with rush hour traffic originating in Section A and leaving in Section B. Rush hour starts at about 6 a.m. because it takes an hour to get to Section B only 30 miles away. Using automation, the vehicles can move closer together and move smoothly at normal speed. The trip now takes 30 minutes and rush hour starts later. Note that the flows are the same. They occur later except at B where we assume the OD pairs have the same desired time at destination. Another way to look at it is to say that vehicles sit in their garages a half hour longer instead of moving slowly on the freeway.

The shared-lane concept for I1 is not an informal use of autonomous intelligent cruise control (AICC) but a structured application of communicative intelligent cruise control (CICC) with compatible manual traffic intermingled.

We designate the entire freeway in this region as an AHS with manual vehicle operation allowed. Manual drivers will be fully aware of the operation although it should require little special action on their part.

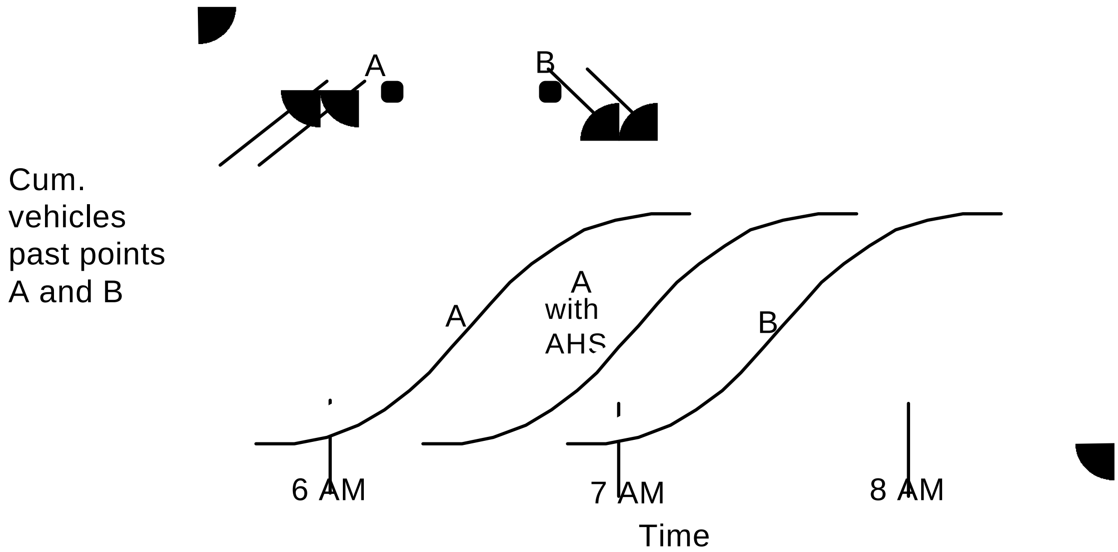
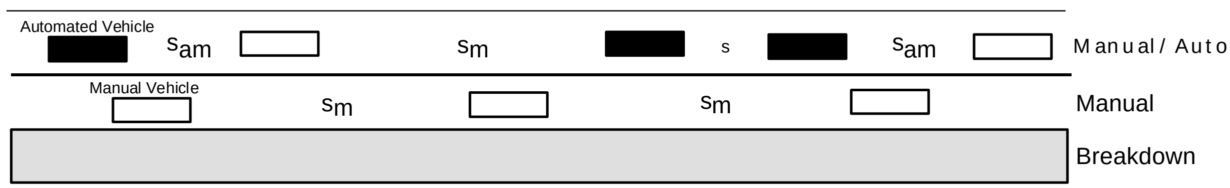


FIGURE 4-17 AHS TRIP TIME BENEFITS

3.4.2 OPERATIONS

The diagram below shows schematically the arrangement of an AHS traffic flow in I1.



The operation is detailed by the following:

1. This is an existing highway using little construction or modification and little centralized communication.

2. Drivers can only engage automation while in the automated lane (left lane).

3. Vehicles can access/egress the left lane at any time and place along the highway.

4. The driver of an automated vehicle is responsible for lane change decisions and maneuvers. Lane changes are executed manually.

5. Automated and many manual vehicles are equipped with a forward and sideways vehicle detection/proximity system that is assumed to be active even if automation is not engaged. The system warns the driver when the vehicle is following too closely or when a lane change maneuver cannot safely be executed.

6. The system will attempt to detect a vehicle in the same lane. If a vehicle is found, the system will close to the required gap between the vehicles. If no vehicle is found nearby, the vehicle will maintain the speed limit or will slowly increase speed to the speed limit for the surface conditions.

7. The automated vehicle will reduce speed if a slower vehicle is detected or if a vehicle suddenly appears directly ahead. Thus, the velocity for automated vehicles will be dictated by the manual vehicles up to the speed limit for surface conditions.

8. Automated vehicles communicate with each other. Consecutive automated vehicles transmit acceleration and velocity information.

9. Manual vehicles are, as usual, responsible for maintaining a safe gap.

10. Drivers are subject to periodic alertness tests originating within the vehicle. Failure to pass tests will result in slowly bringing the vehicle to rest in the left lane.

3.4.3 ACCESS AND EGRESS STRATEGY

An automated vehicle in the right lane transmits a signal to vehicles in the left lane that it desires to enter the left lane. The driver is responsible for transmitting signal. If an automated vehicle is found abreast or somewhat ahead in the left lane, it creates a gap by slightly decelerating to allow the vehicle to enter the automated lane. A manual vehicle in the right lane should not maneuver into the empty space. This improves the probability that two or more automated vehicles will group in the AHS/manual lane and operate at smaller gap. Once a gap is created, the driver will enter the left lane. The vehicle's sideways -looking vehicle detection system will discourage this maneuver if it is not safe to change lanes. The driver engages automation in the left lane. If no automated vehicles are detected close by, the driver enters the left lane at the next opportunity. Manual drivers should be willing to allow access since the benefit of automation in the left lane will extend to everyone.

When the driver plans to leave the left lane, the driver will disengage automation and perform the lane change at the next opportunity.

3.4.4 ANALYSIS

As suggested in Section 3.4.1 we apply the I1 to the congested four-lane freeway moving below design speed. The freeway is congested because there are not enough lanes. The entry/exits and city streets are not the problem. Using the data of Figure 4-1 we select a characteristic line to describe how this congested flow velocity increases as the vehicle density decreases. It represents an averaging of the field data with an end point of two-second spacing at 60 mph. A 1.5 second spacing could have been chosen but we opt for a more relaxed AHS. Using a vehicle length, L, of 17 feet we then have an empirically derived function $s_m(V)$ that relates manual gap and thus flow with speed.

Since the two lanes we examine are contiguous and vehicles can move freely between them we conclude that steady state traffic without incident will move at the same velocity in each lane. We start at 30 mph with 2000 vph in each lane and no vehicle automation. Given the participation, what will this new steady state velocity be?

As the number of equipped vehicles grows, the strategy of 3.4.2 increases the flow in the left lane because each automated vehicle takes less space than a manual vehicle. If it groups with another automated vehicle, it takes even less space.

The total flow remains constant for the following reasons:

- We wish to evaluate the benefits for minimal infrastructure change before going on to higher flow conditions which would require freeway entry/exit modifications in many localities, and would impact street traffic.
- Since all freeway users would benefit, there might be a toll for manual vehicles to provide their fair share of the cost of improved service.
- We assume an advanced traffic management system would attempt to balance the AHS with alternate routes so that the AHS demand does not reduce LOS.
- By assuming flow unchanged but speed increasing, the VMT is unchanged and vehicle emissions decrease (trip time decrease more than balancing increase due to higher engine horsepower required).
- Increasing the number and changing the description of OD pairs serviced by the freeway would be the inevitable effect caused by introduction of the improved service of AHS unless improved traffic control is also introduced. However, these matters are treated elsewhere in these studies.

Stated analytically, we then have total flow, a specified constant, equal to the manual flow in the right lane plus the manual and automated traffic in the left lane or

$$q_d = q_m + q_{ma} + q_a \tag{4-20}$$

leading to

$$\frac{V}{q_{ma} + q_a} = \frac{V}{q_d - q_m} \tag{4-21}$$

which equates space per vehicle in the left lane to a known function of velocity. This relationship is illustrated in Figure 4-18. To relate this difference to participation we use 4-19 and sum over all groups to obtain

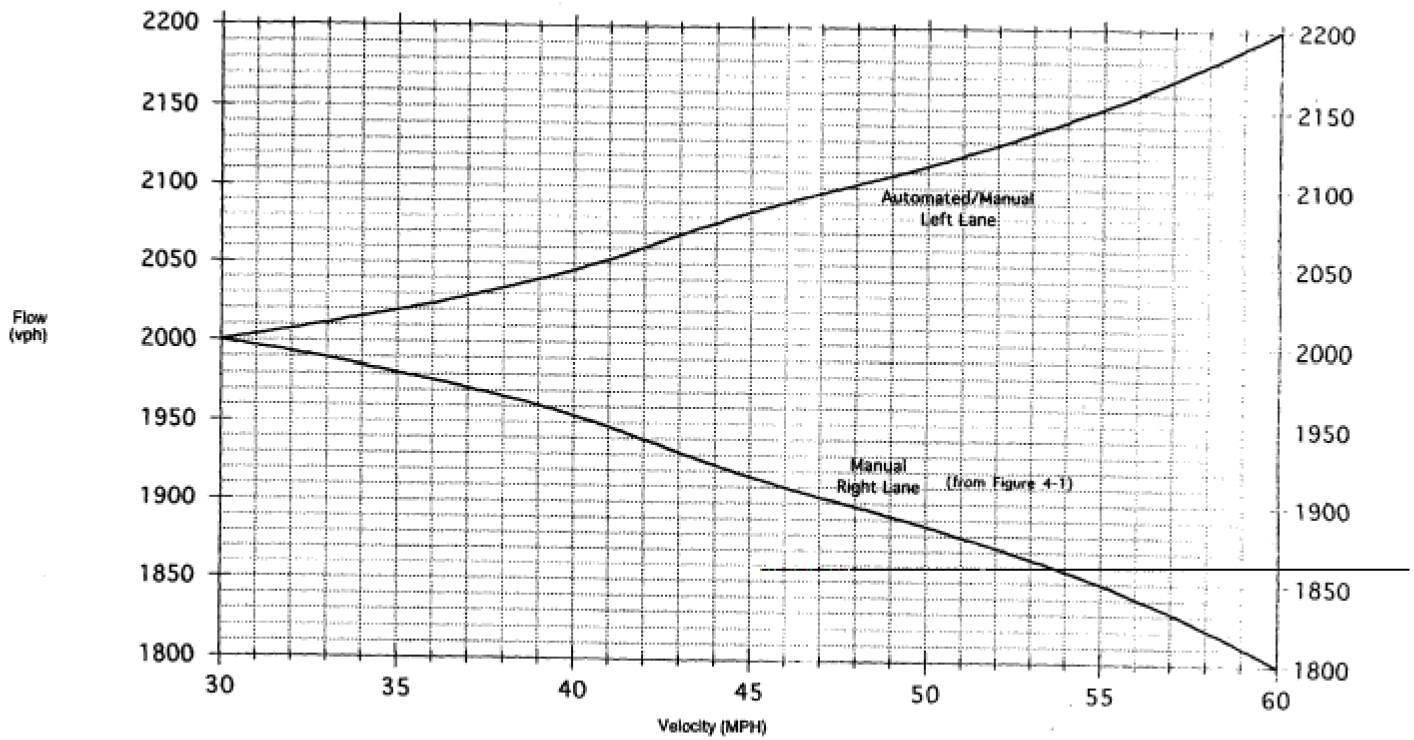


FIGURE 4-18 RIGHT LANE VS. LEFT LANE FLOW IN I1 WITH TOTAL FLOW = 4000 VPH

$$\left(s_{am}-s\right)p^2+\left(s_m-s_{am}\right)p-\left(s_m+L\right)=-\frac{V}{q_d-q_m} \qquad (4\text{-}22)$$

where s = gap for automated vehicle following another
s_m = gap for manual vehicle following any vehicle
s_{am} = gap for automated vehicle following manual vehicle

This conservative result discounts the strategy of communicating and grouping to say that the system will be no better than what would result by chance.

We use the results of 3.3.4 to relate s and s_{am} to velocity with s_m + L specified by velocity from Figure 4-1. The automated gap(s) made possible by quick braking system performance and communication between vehicle follows Figure 4-9. The automated following-manual gap (s_{am}) we take to be the no-collision gap (s_{NC}) given by equation 4-10 to be conservative but also to be more certain of safety acceptance by manual drivers. The time delay in 4-10 take to be .4 seconds to account for the lack of communication. (Reliably detecting range, range rate and possibly its derivative to maintain gap up to full deceleration requires adequate smoothing of data with suitable resolution).

We started out by asking at what equilibrium velocity will the freeway run for a given participation. The relationship is given by 4-22. But it is easier to, reverse the question and given V, to solve for p in closed form, obtaining

$$p=2\sigma\left(1-\frac{q_m}{q_d}\right)\left[\left(1+4\,p_{a_1}\sigma\right)^{1/2}-1\right]^{1/2} \qquad (4\text{-}23)$$

$$p_L=p\frac{1}{1-q_m/q_d}$$, the left lane participation, $$\frac{q_a}{q_a+q_{am}}$$

where $$\sigma=\frac{s_m-s_{am}}{s_{am}-s} \qquad (4\text{-}24)$$

and $$p_{a1}=\frac{1}{s_m-s_{am}}\left(s_m+L-\frac{V}{q_d-q_m}\right)$$, the participation in the (4-25)

left lane only,assuming no automated vehicles succeed in grouping. The result is plotted in Figure 4-19.

If we take some credit for our grouping strategy, we might compare this random result with the result if every automated vehicle found one, but only one, other automated vehicle. This produces

$$p_2=\frac{2}{2s_m-s_{am}-s}\left(1-\frac{q_m}{q_d}\right)\left(s_m+L-\frac{V}{q_d-q_m}\right) \qquad (4\text{-}26)$$

and the upper curve in Figure 4-19. The expected result should be better than random but not as good as all pairs would give because there would be many single automated vehicles in the left lane, and not many groups of three or more, particularly at these low participations.

Once the speed arrives at the speed limit, further increases in participation would produce a higher left lane density until the right lane became quite sparse. The analysis ceases to have meaning when $q_m = 0$, at V = 60 mph or from 4-23, p = .78. This places 3100 vph automated and 900 vph manual in the left lane and no traffic in the right lane. This I1 application is on two lanes in one direction. If it had been on three lanes we would now move the 900 vph manual over to the other lanes and have an I2.

3.4.5 SUMMARY AND CONCLUSIONS

I1 applies to early versions of AHS when participation will be low and also to four lane interstates in rural areas, giving manual vehicles a chance to pass. Other researchers have studied concepts similar to I1 as defined here but with mixed results. Benefits in terms of increased flow rates are forecast here. The emphasis here is to decrease trip time by increasing speed on a congested freeway. The OD pairs are not changed and VMT is not changed. Vehicles move smoothly at cruise speed for a reduced time, reducing emissions.

Access/egress is manually performed by a lane change using collision avoidance devices as aids. It can take place at any location at the driver’s discretion. Analysis suggests that participation as low as five percent can increase the cruising speed by ten mph. Fifteen percent can increase the speed to 55 to 58 mph. Benefits can be enhanced by using communication to locate and move in front of another automated vehicle in the AHS (left) lane.

If I1 is implemented on a six-lane freeway, it can easily evolve into an I2 format.

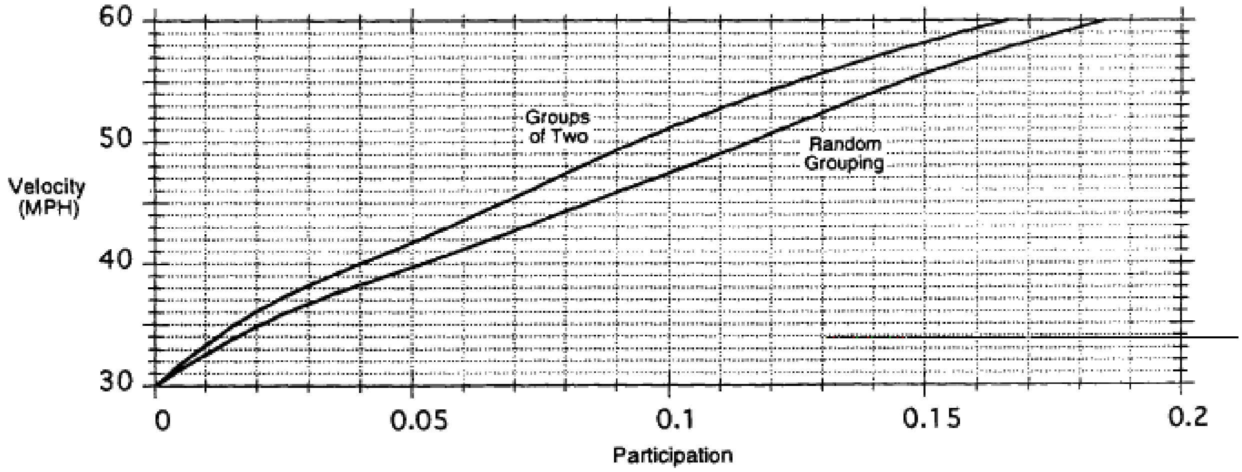


FIGURE 4-19 VELOCITY BENEFIT IN I1 AS A FUNCTION OF PARTICIPATION

3.5 ACCESS/EGRESS AND BENEFITS FOR THE I2 CONCEPT

3.5.1 GENERAL CONSIDERATIONS

The I2 concept is a dedicated cruise lane and a shared or, at high participation, a dedicated transition lane at access/egress points. As we have suggested at the end of Section 3.4 it can evolve from an I1 where the roadbed is three-lanes-wide in each direction with generous shoulders on both sides. It could also be added to an existing four-lane freeway provided enough right of way exists either into the median or to the side. Since the RSC assumes medium, not high, infrastructure impact and cost, we are careful to point out that the most cost effective application would involve minimum increase in the width of the paved portion and little or no entry/exit modification. The use of a barrier to the right of the AHS cruise lane and a breakdown lane to the left or right would be called medium infrastructure impact without adding any cruising lanes. In some sections of minimum right of way, this construction would be high impact.

In the past few years, several researchers have studied this concept. Reference 19 treats a concept similar to the one here except that the transition lane adds width to the roadbed at access/egress points. The FRESIM traffic model was used to describe individual autonomous vehicles moving in groups of one to twenty under automatic control. The method of access was to accelerate to the cruise lane speed coordinating to appear opposite a gap created in the automated lane and then to execute a lane change. Egress took place to an empty lane which led back to the manual lanes after a deceleration to 25 mph. The comparison of flow to the traditional six-lane freeway showed that high participation would be needed to justify loss of one lane each way to automated traffic. Also the weaving maneuvers caused slower velocities in the manual lanes.

Reference 20 investigates the critical matter of producing smooth flow by creating gaps in the automated flow and pursuing them in the transition lane. This mathematical analysis derives conditions required for a given situation at the beginning of the access zone to result in a successful merge. It allows acceleration in the transition lane which causes difficulty if the vehicle ahead does not accelerate because it is manual.

We have already mentioned that Reference 18 analyses an I2 with a dedicated transition lane. Access can occur anywhere but is assumed to only occur to join an existing group and to join at the end of the group. This restricts the flow and causes the access maneuvering to extend over a long distance. The maximum flow is restricted to the point where it does not justify a dedicated transition lane.

As in the analysis of I1 we will assume that freeway is initially congested and slow with excess entry/exit capacity but not enough cruise lane capacity. The benefit will be reduced trip time, reduced driver stress and reduced emissions. Having already implemented I1 and seen participation grow to the 40 percent range we have the situation in Figure 4-20. The far left lane is occupied by automated traffic only. The transition lane, which at this point still works like an I1 with access/egress at any point (no barrier), contains a relatively small flow of vehicles equipped for automation but

I1 Scenarios

p = 0	p = .18	p = .55
2000 vph manual	700 vph automated 1500 vph manual	2200 vph automated
2000 vph manual	1800 vph manual	1800 vph manual
→ 30 mph Initial Condition	→ 60 mph Velocity Reaches Limit	→ 60 mph Automated Lane Becomes Exclusive

I2 Derived from I1

p = 0	p = .45 (like p = .18 above)	p = .55
2000 vph manual	2000 vph automated	2400 vph
2000 vph manual	700 vph automated/manual 1500 vph manual	900 vph automated/manual 900 vph manual
2000 vph manual	1800 vph manual	1800 vph manual
→ 30 mph Initial Condition	→ 60 mph Early I2 Condition	→ 60 mph I2 with Localized Access/Egress

FIGURE 4-20 I2 EMERGES WITH INCREASED PARTICIPATION

either desiring access to the automated lane or egress to the right lane for an upcoming exit.

The next step to come with increased participation is to be able to transition higher automated flows. We can anticipate that to do this smoothly we will need to decrease the number of manual vehicles in the transition lane and become much more regimented in the ways the left lane is accessed. The access/egress can be restricted to specific regions and a barrier can be used elsewhere. Figure 4-20 indicates a suggested set of flows for p = .55, the same participation that I1 has for lane exclusivity.

At this point, we are ready to increase freeway cruising capacity beyond 6000 vph, if localities desire it. This would be possible until manual entry/exits, local streets or other facilities reach capacity. The analysis in Section 3.3 suggests that in good weather the far left lane could carry as much as 9600 vph.

3.5.2 OPERATIONS

Figure 4-21 shows schematically the arrangement of AHS traffic at an I2 access section. The transition lane services a mixture of manual and automated vehicles. It is similar to the automated lane of I1. In an early version there could be as many as 1500 vph (p = .45 from Figure 4-20) manually operated in the transition lane following the rules of I1 with the exception that automated vehicles would, upon entering the transition lane, not follow closer than one empty space behind another automated vehicle. This prevents the demand for consecutive empty spaces in the automated lane which would have its excess space distributed to appear at regular intervals (see Section 3.4.4.).

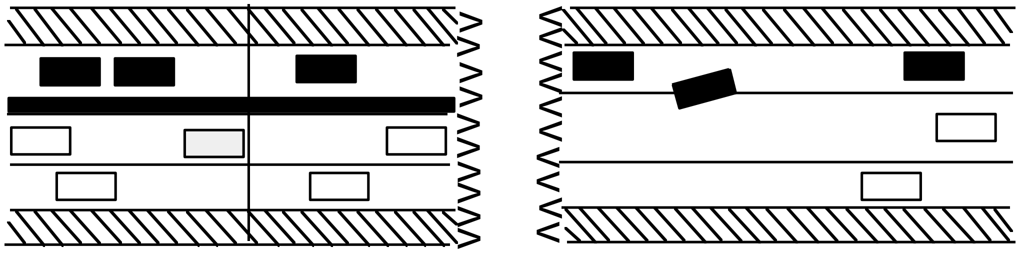


FIGURE 4-21 I2 ACCESS SCHEMATIC

The operation is detailed by the following:

1. This is an existing freeway with at least three lanes each direction which has been somewhat widened to include enough width for a breakdown lane to the left and a barrier (optional).

2. Automation is engaged in the transition lane.

3. Vehicles can access/egress the transition lane at any time except after the timing point and before the release point downstream of the access/egress region.

4. Lane changes between the manual and the transition lanes are executed by the driver as in I1. Lane changes between the transition and the automated lanes are automated.

5. Automated and many manual vehicles are equipped with a forward and sideways vehicle detection/proximity system that is assumed to be active even if automation is not engaged. The system warns the driver when following too closely or when a lane change maneuver cannot safely be executed.

6. In the transition lane the rules are the same as for I1 except for the empty space rule mentioned above. The automated vehicle's system will attempt to detect a vehicle in the lane and if one is found will move in front. The vehicle behind will close to the empty space gap. If no vehicle is detected ahead, the system will operate at the same speed as the automated lane.

7. The manual vehicles in the transition lane will engage cruise control or otherwise be operated to maintain speed. The transition lane and the automated lane will operate at the same speed in the region to facilitate access/egress. (Later versions of I2 might have no manual vehicles in the transition lane or no vehicles without at least CICC, Cooperative Intelligent Cruise Control, and thus be able to accelerate to a higher speed before access/egress.)

8. Automated vehicle communicate with each other. Consecutive automated vehicles transmit acceleration, velocity and coordination information.

9. Manual vehicles are, as usual, responsible for maintaining a safe gap.

10. After joining the automated left lane several normal modes are possible. These include speed hold, gap hold, lane change, speed increase, speed decrease, gap change, and space creation and space regularization. Abnormal modes include emergency lane change, emergency braking, normal braking to a stop and partial or full manual takeover (see Volume V, Chapter 1 on malfunction management).

11. Drivers in the automated mode are subject to periodic alertness tests which could originate within the vehicle. Failure to pass tests would result in the vehicle coming to rest in the breakdown lane (as opposed to the cruise lane in I1).

3.5.3 ACCESS AND EGRESS STRATEGIES

The suggested access/egress procedures are vehicle and driver centered to give the driver maximum awareness of automatic events and minimize dependence of system safety on software and data links. Transition lane capacity, dictated by manual capacity, would be about 1800 vph for LOS C or better. However, the I1 analysis indicates that a stable flow of 2200 vph at 60 mph can be obtained if $p = .18$ for the combined transition and manual lanes. This gives 700 vph automated and 1500 vph manual in the transition lane and 1800 vph in the manual lane (Figure 4-20). After the 700 vph access the cruise lane the transition lane can accept up to 700 vph egressing vehicles. The procedures are conducted at 55 to 60 mph to maximize cruise lane capacity. Minimizing transition lane speed changes also lowers emissions and is more comfortable. All maneuvers are smooth with low accelerations, much like a good manual driver, for maximum passenger comfort and driver acceptance.

If we had complete control of all vehicles in the transition lanes we could conduct the operation with great precision. The presence of manual vehicles driving at gaps chosen and controlled by those drivers means that procedures will not be guaranteed to work in normal operation. The alternative is, as in the case of a system failure, to continue on with access/egress postponed to the next such region downstream. As one can easily note, the uncooperative manual driver can disrupt the process. But as long as we have I2 of any sort, this will be the situation. Automated traffic law enforcement would be a powerful deterrent but also the fact that manual drivers would also enjoy many of the benefits should encourage cooperation.

3.5.3.1 ACCESS

Access is initiated by arrival of a transition vehicle at the timing point. If the driver does not desire access, the procedure can be nullified at any time up to initiation of the lane change. The vehicle automation system will already be engaged by the driver at some point upstream of the timing point. The automated sequence executed by the vehicle-to-vehicle (VV) communications link and individual vehicle computers is as follows:

1. Arrival of transition vehicle at the timing point sets a flag.

2. The next vehicle in the automated lane to reach the timing gate also sets a flag. Knowing the cruising speed, the distance between vehicles is known. Call this front-bumper-to-front-bumper distance the parameter d.

3. The transition vehicle executes a slide-back maneuver with parameter

$$\Delta d = d - n'(s + L) \qquad (4\text{-}27)$$

   where s is the current safety gap, L is the average length of vehicle, and n' is the next lowest integer below d/s + L and is less than n, the number of empty spaces currently held by the cruise vehicle's computer.

4. If n' = 0, the cruise lane vehicle slides back to create one space. This is the slide-back maneuver with parameter $\Delta d = s + L$ described below and is a simultaneous maneuver for consecutive automated vehicles in the cruise lane back to the next available empty space. The cruise lane vehicle's computer would then hold the space parameter $n'' = n + 1$ until reaching the access point.

5. Upon reaching the access point the transition vehicle changes lanes into the empty space with its computer holding speed or, if detecting a vehicle ahead, holding the required gap. If access fails, the transition vehicle continues on in the transition lane until reaching the next access region.

3.5.3.2 EGRESS

Egress is requested by the driver well upstream of the designated egress point. The request can be withdrawn by the driver or, in rare instances, by an ATMS communications link during conditions of egress overload. Again a timing point would be used. The event of the manual vehicle arriving at the timing point would be communicated to the egressing vehicle by a roadside beacon.

(a) Transition lane manual vehicle ahead, $d < s_{am} + L$

(b) Transition lane manual vehicle behind, $d < s_m + L$

(c) Transition lane automated vehicle ahead, $d < s + L$

(d) Transition lane automated vehicle behind, d < s + L

All of these conflicts could be resolved by sliding vehicles forward in the automated lane to fill spaces available due to the current volume-to-capacity ratio (v/c) or due to the vehicles egressing. No maneuvers need to propagate upstream in the automated lane. After a forward adjustment of 5L/2 in worst case (see Section 3.5.5.2) the lane change could be made.

No manual vehicle formal maneuvers are planned. However, adjustments in spacing as is normal in manual traffic would be required. Automated vehicles in the transition lane in an egress region would be rare if this region is immediately downstream of an access region. In any case, adjustments in (c) and (d) would be minor.

To avoid potential conflicts caused by consecutive egressing vehicles, these vehicles would be required to hold an empty space between. These vehicles would then be separated by at least 2S + L. If the empty space is filled by a vehicle accessing the lane, there is no difficulty created since that vehicle would not be immediately egressing.

The most demanding condition is (a) where the vehicle in the automated lane might be obliged to slide forward with parameter $\Delta d = s_m + L + d$. It would be preferable to slide back with parameter $\Delta d = S_{am} + L - d$, provided the maneuver does not propagate backward to an access region. A cooperative movement of the manual vehicle would ease condition (a).

3.5.4 SPACE REGULARIZATION

After leaving an access/egress region the empty spaces could be managed in many ways. In the arrangement with access first and egress second, the discussion above would favor moving up so that maximum space for sliding forward at the egress point could be provided. In the absence of a dominate requirement to move up, the vehicle computer could increment the value of n as vehicles leave ahead of it to hold relative position until well past the egress region. With all vehicles out of detection range it would hold the AHS commanded speed for the region.

With some distribution of spaces existing as vehicles move away from the region, we ask what would be a good policy to implement for the cruising region ahead. A regular distribution of space would appear to be optimum for entering the next access region, since the need for space at that point would be dictated by the random appearance of transition vehicles and a large number of spaces bunched together would result in many spaces going to waste at the next access region. This point is particularly clear as v/c approaches unity. With v/c = .91, a regular distribution of space would have one space for every ten vehicles. (For s + L = 19 + 17 = 36 feet this would give one space (2s +L) roughly every 415 feet or about 760 vph for the maximum permitted access flow at the next timing point.) If this space were not regularized there could be long stretches with no space to access, requiring many vehicles to slide back during the access maneuver.

Regular distribution could be achieved by a simple roadside counter and sector broadcast or by an extended VV link. Consider speed as constant in this regularization region except for minor changes to move up or slide back. By summing the values of n, which each computer puts on the VV data link, over a time long enough to obtain smooth results we obtain two integers, N_V and N_S, for the number of vehicles and the number of spaces. Regular distribution of spaces would require one or more spaces for every vehicle if $N_S \geq N_V$ or one or more vehicles for every space if $N_S \leq N_V$. Compute integers j_V and j_S by division with remainder, such that the regular pattern will be j_S spaces followed by j_V vehicles.

Case 1 $N_S \geq N_V$. Set $j_V = 1$ and compute j_S and k from

$$j_S = \frac{N_S + k}{N_V}, \ j_S \text{ and k integers} \qquad (4\text{-}28)$$

giving a regular pattern of j_S spaces ahead of each of N_V - k vehicles and k vehicles with j_S -1 spaces ahead.

Case 2 $N_S < N_V$. Set $j_S = 1$ and compute j_v and k from;

$$j_V = \frac{N_V + k}{N_S}, \ j_V \text{ and k integers} \qquad (4\text{-}29)$$

giving a regular pattern of one space ahead for each N_S - k group of j_V vehicles leaving k groups of j_V-1 vehicles each separated by one space.

Superimposed on this regular pattern would be the requirement for consecutive vehicles egressing at the next opportunity to carry an empty space between (see 3.5.3.2).

Example 1 With v/c = .5 we should measure N_S and N_V about equal. If (4-28) applies, we obtain a regular pattern of one space ahead of most vehicles with a few with two spaces. If (4-29) applies we have most vehicles with one space ahead and a few with no spaces ahead.

Example 2 With v/c = .8 we should obtain N_V/N_S about equal to .8/.2 or a pattern of 4 vehicles for every empty space with some groups of 3 for every empty space.

Example 3 With v/c = .3 we should obtain N_S/N_V about equal to .7/.3 or a pattern of 2 spaces for every vehicle with some vehicles with 3.

For low values of v/c all the spaces would not be useable at a single access region, since the flow of spaces would be well in excess of the maximum transition vehicle flow. Likewise for high v/c the access flow could exceed the flow of spaces and access would have to be postponed for some vehicles.

3.5.5 ANALYSIS

3.5.5.1 ACCESS DISTANCE

The lane length required to complete the access procedure was computed using simplified vehicle dynamics and realistic longitudinal acceleration/deceleration, velocity perturbation, and side acceleration limits. The vehicle was described in Laplace transform notation by

$$A_x = \frac{e^{-\tau_c s}}{\tau_x\, s+1} A_{x_c} \tag{4-30}$$

$$\dot{\psi} = \frac{e^{-t_c s}}{t_\psi\, s+1} \dot{\psi}_c \tag{4-31}$$

where A_{x_c} and ψ_c are the commanded longitudinal acceleration and yaw rate, respectively.

The kinematics were computed in simplified form as

$$\begin{aligned} \dot{x} &= V + \int A_x \\ A_y &\dot{=} V\,\dot{\psi} \\ \dot{y} &= V \int \dot{\psi} \end{aligned} \tag{4-32}$$

The limits chosen were

$$\begin{aligned} A_{x_{c_{max}}} &= .05\ g's \\ A_{x_{c_{min}}} &= .10\ g's \\ \left|A_{y_c}\right|_{max} &= .17\ g's \\ \left|\dot{x}\right|_{max} &= 9.0\ fps \end{aligned}$$

Transients for the slide-back maneuver and the lane change maneuver are shown in Figure 4-22 and 4-23. The slide back is illustrated for parameter Δd = 57 feet and is executed with pulses of -.1 and +.05 g. Longitudinal and lateral time constants were chosen at 1 second to be representative. The communication time was .1 seconds. The width, height and timing of the pulses are preprogrammed to achieve various Δd values within the constraints. The full velocity decrement is used in this case to minimize the time and therefore the distance used to complete the maneuver. The transition vehicle also executes a slide-back maneuver with Δd = 30 feet. The lane change maneuver is computed for a 12 foot lateral motion within the lateral acceleration constraint (equivalent to a yaw rate of .062 rps). The longitudinal maneuver uses about 11 seconds. The lane change uses about 4 seconds. The total of 15 seconds at the nominal speed of 60 mph uses 1320 feet.

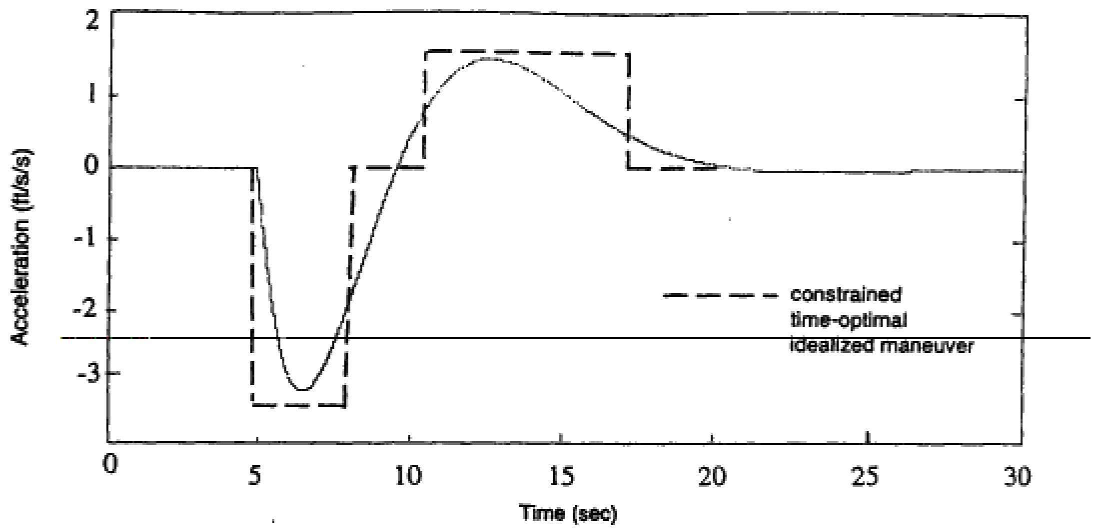


FIGURE 4-22A SLIDE-BACK ACCELERATION VS. TIME FOR ΔD = 57 FEET, V = 60 MPH

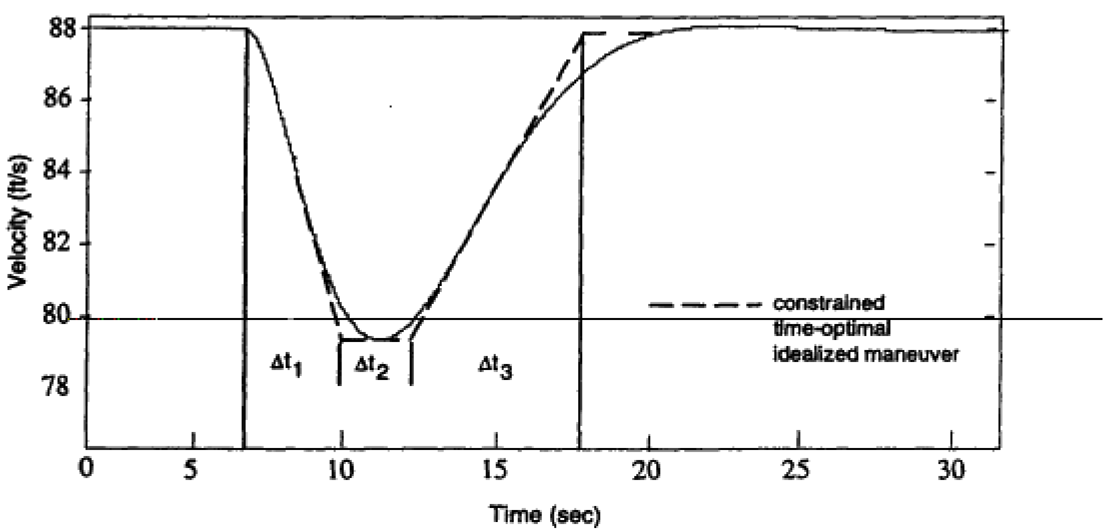


FIGURE 4-22B SLIDE-BACK VELOCITY PERTURBATION FOR ΔD = 57 FEET, V = 60 MPH

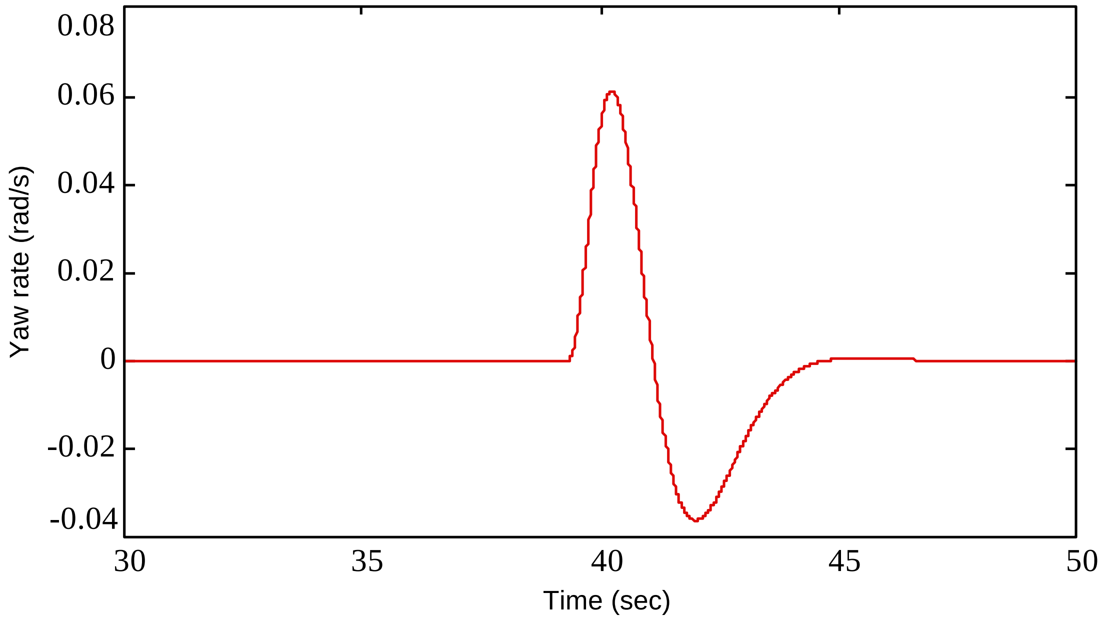


FIGURE 4-23A LANE-CHANGE YAW RATE FOR ACCESS

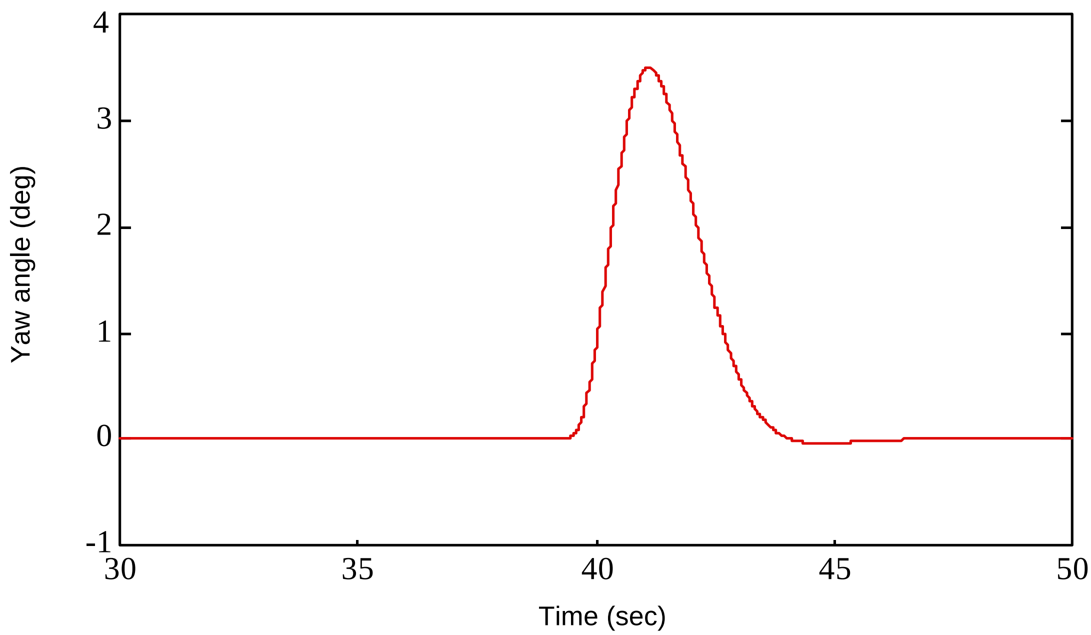


FIGURE 4-23B LANE-CHANGE YAW ANGLE FOR ACCESS

The time at the lower speed in Figure 4-22b is approximately given by

$$\Delta\tau_2 = \frac{\Delta\delta - \Delta' d}{\left|\dot{x}_{max}\right|} \qquad (4\text{-}33)$$

$$for\ \Delta d \geq \Delta' d = \frac{1}{2}\dot{x}_{max}{}^2 \left(\frac{1}{-A_{x_{c_{min}}}} + \frac{1}{A_{x_{c_{max}}}} \right) \qquad (4\text{-}34)$$

The total time is

$$\Delta t = \frac{\Delta d + \Delta' d}{\left|\dot{x}_{max}\right|} \qquad (4\text{-}35)$$

For Δd < Δ'd, there is no need to dwell at the lower speed and the deceleration/acceleration doublet widths can be smaller or the acceleration magnitudes can be reduced. For the numbers assumed above, Δ'd = 37.7 feet and Δt = 8.4 sec. which would use 739 feet of pavement. The process is illustrated in Figure 4-24.

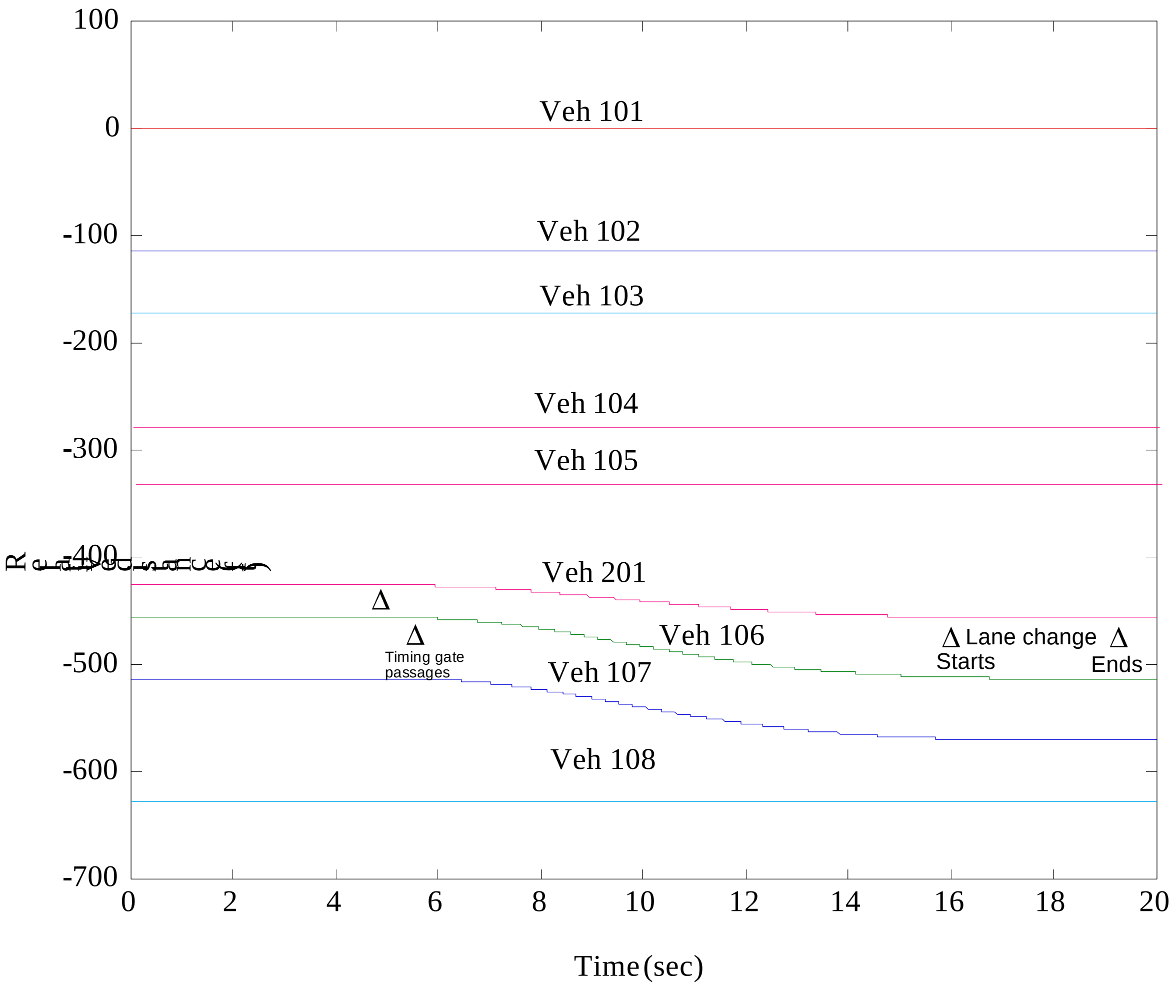


FIGURE 4-24 RELATIVE DISTANCE VS TIME FOR ACCESS V = 60 MPH

The preferred time involved to slide back Δd = 27 to 36 feet (gaps of 10 feet to 19 feet with a 17 foot vehicle, used in Section 3.3.4) may not turn out to vary greatly from 8.4 seconds.

In that event the distance for gap creation would be roughly proportional to cruise speed. The lane change constrained minimum time, Figure 4-25, is not greatly affected by forward velocity, causing this maneuver to also require a distance proportional to cruise speed. We then suggest the linear relationship shown in Figure 4-26 to define access distance for Δd = 36 feet (safety gap 19 feet).

3.5.5.2 EGRESS DISTANCE

We favor the egress region following rather than preceding the access region to have less flow in the transition lane. The automated vehicles desiring access will have departed the lane leaving a string of manual vehicles. The flow should not be greater than 1500 vph – the Service Level C for merging and diverging from Reference 1. For lane change, the automated vehicle would safely be at least a distance 2L ahead or behind the nearest manual vehicle as determined by arrivals at a timing point and the common cruising speed. If it is not in a safe zone, a relative distance adjustment must be made. The worst-case adjustment would then be 5L/2 or about 43 feet. Once the lane change is made, the automated vehicle, still under automatic control would continue the relative distance adjustment to follow the manual vehicle ahead no closer than s_{am} as in the I1 analysis. The adjustment, according to (4-34) would take about 9.2 seconds or 810 feet at 60 mph. The time for adjustment and a 4 second lane change gives a total of 1160 feet for egress at 60 mph. The variation with speed would be linear is indicated in Figure 4-27.

3.5.5.3 ACCESS/EGRESS FLOWS

The access/egress flow capacities in I2 depend on an I1-type left lane capacity as discussed in Section 3.4.2. With 1500 vph manual in the lane the maximum automated access flow would be 700 vph at 60 mph. With higher participation the flow of manual vehicles diminishes in the transition lane to the point where we have none at all. This would allow a transition flow as high as 5760 vph with one empty space between each automated vehicle (2s + L = 55 ft.) at 60 mph. Of course the automated lane would have to be running at no higher than v/c = 9600-5760/9600 = .4.

The maximum egress flow would also be 700 vph for 1500 vph manual in the transition lane. With fewer manual vehicles the egress capacity would increase but not higher than the capacity of the manual entry/exits servicing the freeway could handle. For 1500 vph in the right lane we would suggest that the center lane be limited to 1500 vph to maintain Service Level C or better for the automated vehicles, now manual, to weave to the right lane easily to make their exits.

3.5.5.4 ADDITIONAL TOPICS

3.5.5.4.1 Higher Speeds

If the automated lane is set to cruise at a speed higher than the 55 to 65 mph range which might be the manual lane speed, the transition vehicles must accelerate to the higher speed before the timing procedure starts (or a more sophisticated

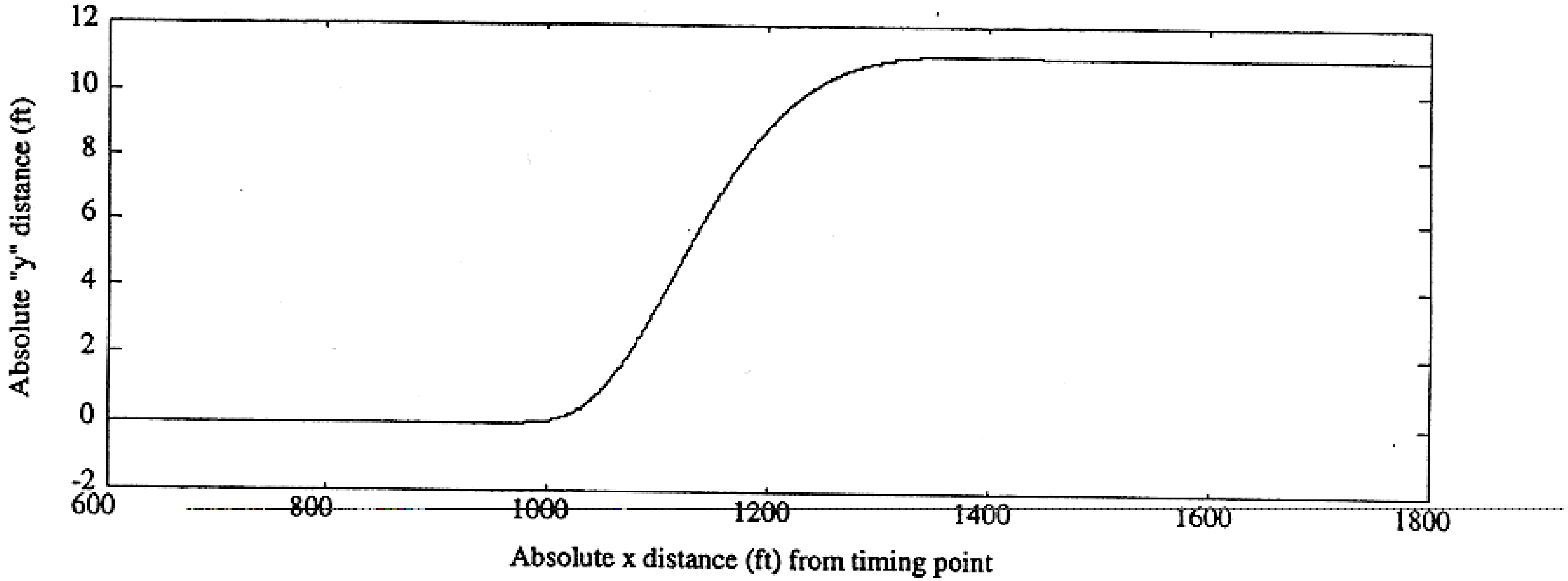


FIGURE 4-25 VEHICLE 201 LANE CHANGE TO ACCESS CRUISE LANE

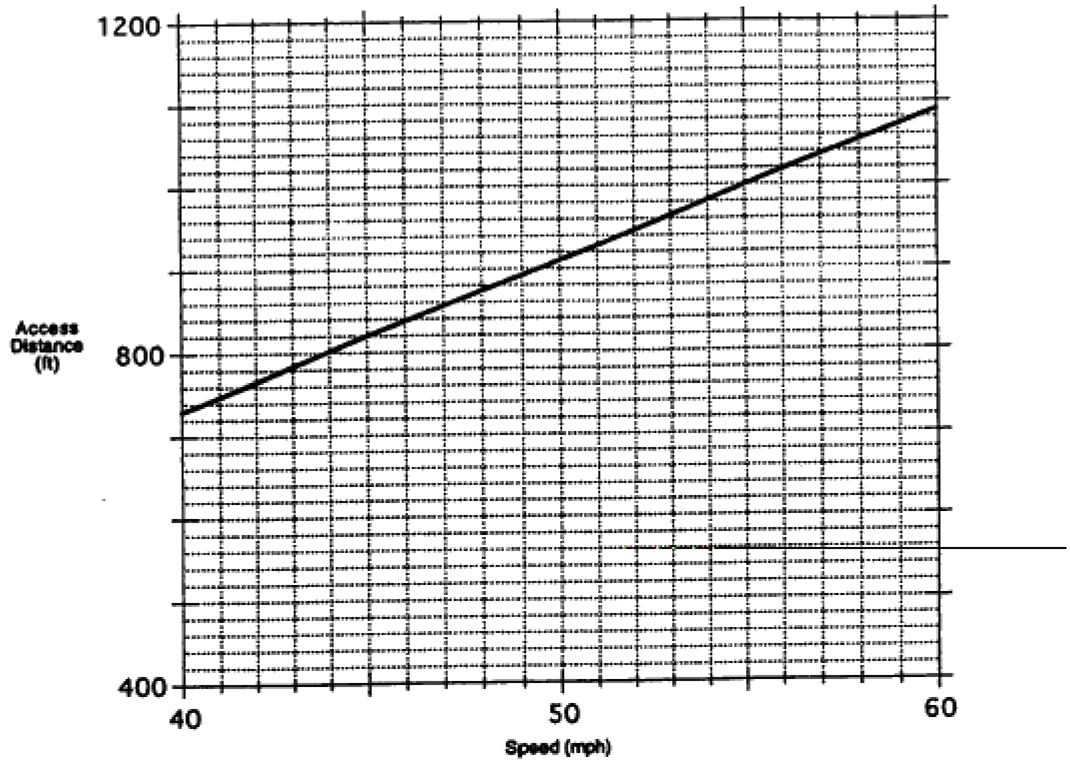


FIGURE 4-26 ACCESS DISTANCE IN I2 FOR SAFETY GAP OF 19 FEET

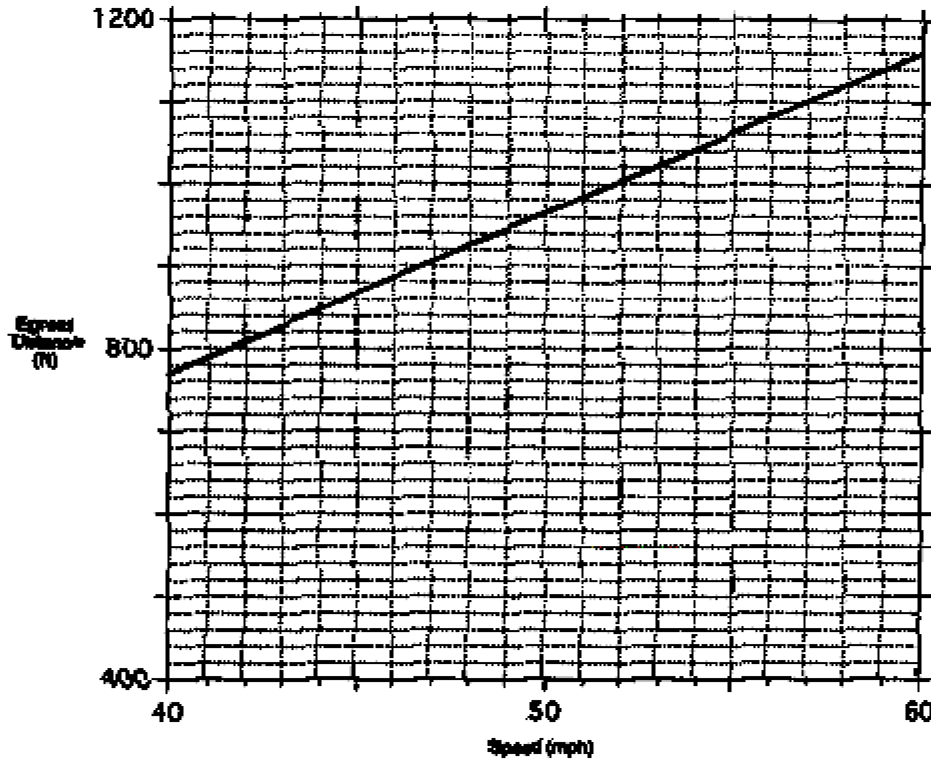


FIGURE 4-27   EGRESS DISTANCE IN I2

synchronization scheme must be used such as in I3). The distance of Figure 4-26 for 60 mph must be increased from 1100 feet to about 1700 feet for acceleration from 60 to 70 mph. This was computed with realistic dynamics and acceleration and jerk limits of .175 g and .1 g/sec, respectively.

Likewise after egress, the vehicle must be slowed to 60 mph for mixture with the manual traffic. This adds 500 feet to the egress distance.Using higher automated cruise speed than the manual lane speed in regions of access/egress probably means that manual vehicles would not be allowed in the transition lane. This implies a participation higher than .6 to .7.

The safety policy analysis indicates a maximum automated lane capacity around 55 to 60 mph. This would lead us to use speeds in that range through access/egress regions to maximize access flow.

Both of these considerations would lead us to avoid speeds higher than manual for the prevalent conditions.

3.5.5.4.2 Standing Start

If vehicles are required to stop or reduce speed in the transition lane prior to starting the synchronization procedure, the distance to the access point can be reduced to about 400 feet at 60 mph. However the flow would be limited to that of a toll gate and emissions would be increased. Users would probably not favor stopping on the freeway with manual traffic in the right lane moving at cruise speed. We also have no compelling reason to minimize distance unless a fourth lane is added to the region. Finally, the length of the queue must be added to the access distance. This distance may well nullify the advantage of stopping.

3.5.6 SUMMARY AND CONCLUSIONS

I2 can be conceived as an evolutionary development of I1 on six-lane freeways where there is a middle lane in each direction allowing synchronized access in specific access/egress regions and opportunities for manual vehicles to pass each other in other regions with the left lane exclusively devoted to automated traffic. Other researchers have recently examined variations on the transition lane concept but without manual vehicles allowed. The benefit beyond the decreased trip time of I1 is the potential for building higher than 6000 vph in each three-lane direction including the manual traffic. This could actually be accomplished only if the exiting manual entry/exits to the freeway and their access roads could accommodate the implied additional flow.

Access/egress could be synchronized by a simple timing system facilitated by space regularization in the automated lane. Manual vehicles in the transition lane need only hold the speed specified for the region but they must act cooperatively in doing so to avoid causing some automated vehicle to miss access or egress. The flow of manual vehicles in the transition lane must be limited to 1500 vph and would be preferable much lower.

With low accel/decel limits and reasonable vehicle dynamics the access distance is about 1100 feet at 60 mph. The egress distance is about the same. With a 500 foot buffer between, the total region is about 2700 feet at 60 mph. It is proportionally less at lower speed. Higher speeds are possible with an accel/decel portion when, at higher participation, manual vehicles can be restricted from the transition lane.

When participation grows to numbers that allow an exclusive transition lane, special entry/exit provisions can build flows up the 9000 vph range in an I3 concept.

3.6 ACCESS/EGRESS AND BENEFITS FOR THE I3 CONCEPT

3.6.1 GENERAL CONSIDERATIONS

The I3 concept is a dedicated lane(s) with dedicated access. As suggested in the last section, the flow per lane can approach the maximum capacity in Section 3.3.4 of 9600 vph. I3 is an AHS designer's ideal because there can be a high degree of control without having to deal with the uncertainties of manual traffic. The thought that all freeways would eventually become entirely automated is attractive as a long-term solution to the cost of building more highways to handle population growth.

Since participation is, by definition, 100 percent on I3 cruise and transition lanes, the concept fits either the very mature point in AHS development or a special situation where automated vehicles are attracted in large numbers even though market penetration is not high.

Much current and past research has assumed that I3 is the only AHS concept. This has been appropriate for early investigations into the concepts and technologies involved in automating the basic cruising and gap manipulation portion of driving. The PSA studies have moved beyond that point.

To illustrate how I3 can grow from an I2 situation, consider the flow progression in Figure 4-28. The 1500 vph flow of automated vehicles in the I2 transition lane for p = .75 is either intending to access or has completed egress and is intended to exit the freeway. Downstream of that exit the flow drops to 1500 vph for two lanes which is like a rural section of a conventional interstate. With the transition lane exclusively accessed and egressed in I3, the manual traffic is obliged to forego passing for the length of the access/egress region, which as we will see, can be short.

	I2 p = .55	I2 p = .75	I3 p = .86
Cruise Lane	2,400 vph automated	3,000 vph automated	7,200 vph automated
Transition Lane	900 vph auto/manual 900 vph manual	1,500 vph auto/manual	1,800 vph auto/manual
Manual Lane	1,800 vph manual	1,500 vph manual	1,500 vph manual
	6,000 vph total flow	6,000 vph total flow	10,500 vph total flow

FIGURE 4-28 I3 EMERGES FROM I2

3.6.2 OPERATIONS

Access can start at a local street at low speed as shown in Figure 4-29 or in a manual freeway lane at cruise speed. If access is from a manual freeway lane, the arrangement is the same as in Figure 4-21 with a barrier between the transition lane and the manual lane appearing at the access point. Emergencies in the access lane would be managed by moving to the manual breakdown lane if occurring before the access point or straight ahead into the empty extension of the access lane (Figure 4-30).

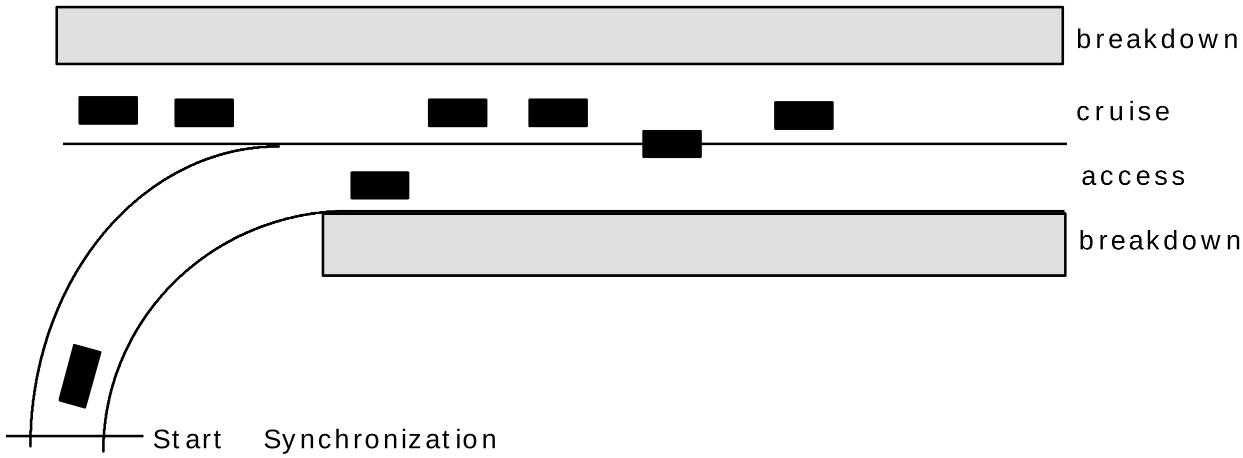


FIGURE 4-29 I3 EXTERNAL ACCESS

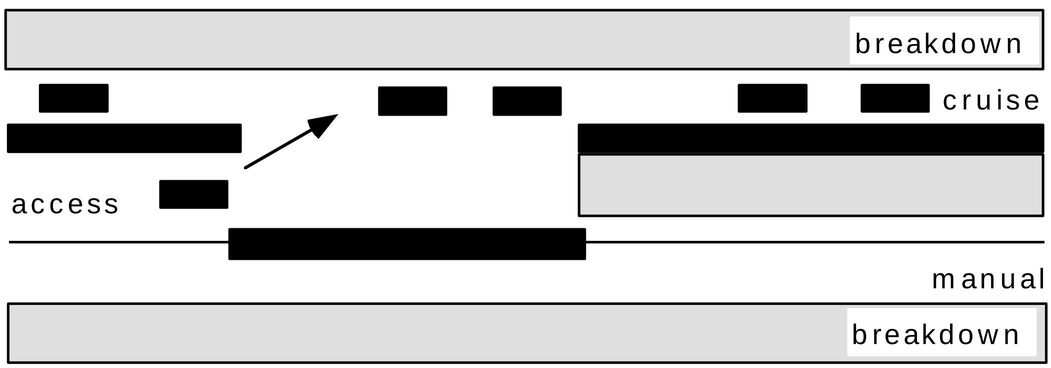


FIGURE 4-30 I3 ACCESS FROM MANUAL LANE

Egress is similar to access with the sequence ending at low speed at the local street or at manual cruise velocity in the manual freeway lanes.

The I3 concept allows a third kind of access/egress maneuvers which is a cruise speed merge/demerge. The requirement arises out the intersection of two AHSs. Occasionally this could be handled in an I2 application when the highway geometry already exists for left lane entry/exit but these segments are not always designed for cruise speed.

3.6.3 ACCESS AND EGRESS STRATEGIES

For access from manual lanes, the technique could be similar to I2 using VV link communication links. From low speed at the local street, variations in the acceleration profile can be used to control position relative to the intended space when at the access point. Low speed at the starting point allows automation to be engaged at low speed which has a safety advantage over cruise speed engagement.

Another improvement over the I2 procedure is that no sliding back is required in the automated lane because complete control is available in the access lane. The relative positions can be arranged to line up with the regularized spaces as they exist in the automated lane.

Both access and egress acceleration profiles must be constrained so the velocity in combination with the rate of lane curvature and super elevation does not exceed safe limits or maximum passenger comfort levels side acceleration as given by equation 4-32. Side acceleration is perhaps most constraining for the cruise speed merge/demerge procedure.

The strategy that seems most intuitively correct for cruise speed merge/demerge is to align vehicles and spaces by sliding the vehicles in the stream with $v/c < .5$ to align with the spaces available in the stream with $v/c > .5$. The sum of both v/c's cannot exceed unity on a per-lane basis. For that reason, AHS intersection geometry and control strategy must be designed with advanced traffic management in mind. It makes sense to operate at the speed for maximum flow capacity if extra capacity is needed. In the extreme, an overload would require vehicles to exit AHS and reenter at a point downstream of an exit from the target AHS lane where hopefully some space will have been provided by exiting vehicles.

In an advanced AHS traffic control system with complete route guidance, this situation would be prevented by knowing the link volumes in advance from the OD pairs and the routings cleared. The system would be operated at a safe margin from these critical situations.

Entries from the local street can be merged at the maximum capacity speed in a collector lane to form a flow greatly exceeding what could be achieved from a single-lane entry or low-speed plaza feeding a single lane at low speed. This collector flow would then be combined in a cruise speed merge maneuver with the main line.

Large exit flows could also be handled by splitting off an egress lane which would feed several local exits.

3.6.4 ANALYSIS

3.6.4.1 ACCESS DISTANCE

With an approach similar to the I2 analysis with simplified dynamics, the entry length from local street to AHS lane cruise was estimated. The longitudinal acceleration limit was taken to be .2g which restricts the analysis to SVEs or vehicles that can do 0 to 60 mph in 15.8 seconds or less. The side acceleration limit was taken to be .17g as in Section 3.5.5.1. Computation indicates (Figure 4-31) the vehicle has reached cruise velocity in about 17 seconds using about 700 feet of lane. Figure 4-31 starts from rest and uses 60 mph as the cruise speed. The lane change, we determined earlier, takes about 4 seconds. This adds about 350 more feet of lane or about 1050 feet to complete the access maneuver. This would increase with cruise speed as in Figure 4-32.

Idealization of this maneuver by neglecting system dynamics produces the dashed lines on Figure 4-31. The equations describing the maneuver give

$$x_{min} = \frac{v - v_o}{2} \Delta t_{min} + v_o \Delta t_{trim} \tag{4-36}$$

and

$$\Delta t_{min} = \frac{v - v_o}{A} + \frac{A}{J}, \quad v - v_o \geq \frac{A^2}{J} \tag{4-37}$$

where v_o and v are the initial and final velocities, and A and J are the acceleration and jerk limits. If we use the numbers of Figure 4-31 ($v = 88$ fps, $v_o = 0$, $A = 6.44$ fps^2, $J = 3.00$ fps^3) equation 4-36 and 4-37 gives access at 15.81 seconds and 695 feet. The more realistic system model in Figure 4-31 delivers the vehicle at 695 feet about a second later.

An open-loop, roadway-controlled dispatching system could deliver the vehicle at the entry point close to the time required using the procedure below. Also, more complex closed-loop procedures could be implemented using vehicle position information from the two vehicles on the main line and the entering vehicle. The data link volume requirement to implement the closed-loop system would be larger and we would judge it to be more costly to implement. The open-loop system would be combined with a vehicle-based, closed loop <u>terminal</u> guidance scheme to provide the necessary accuracy.

The access procedure with parameters as defined in Figure 4-33 is as follows:

1. The entering vehicle passes a timing point with measured v_o. This point is a known, fixed distance x_a from the starting point for changing to the cruise lane. We choose x_a so that

$$x_a > \frac{v^2}{2A} + \frac{vA}{2J} = X_{min} \text{ from 4-36 and 4-37)} \tag{4-38}$$

   This choice of x_a assures us that the required acceleration profile will not exceed limits A and J which give $x = x_{min}$ when $v_o = 0$. This point is near the local street so that v_o is low and

$$v_o < v - \frac{A^2}{J} \tag{4-39}$$

   as required for validity of 4-36 and 4-37.

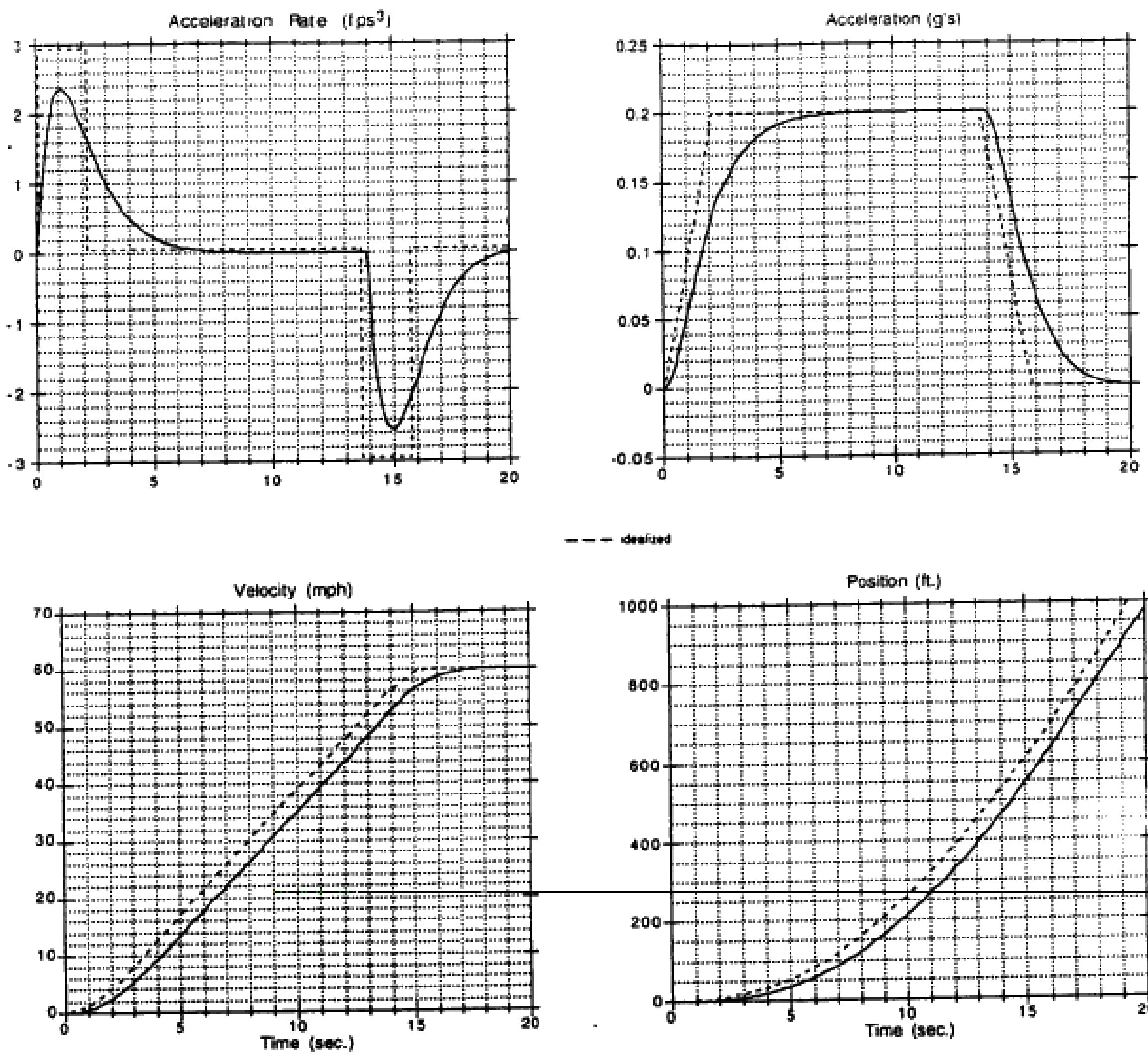


FIGURE 4-31 ACCELERATION TO CRUISE VELOCITY IN I3 ENTRY FROM LOCAL STREET

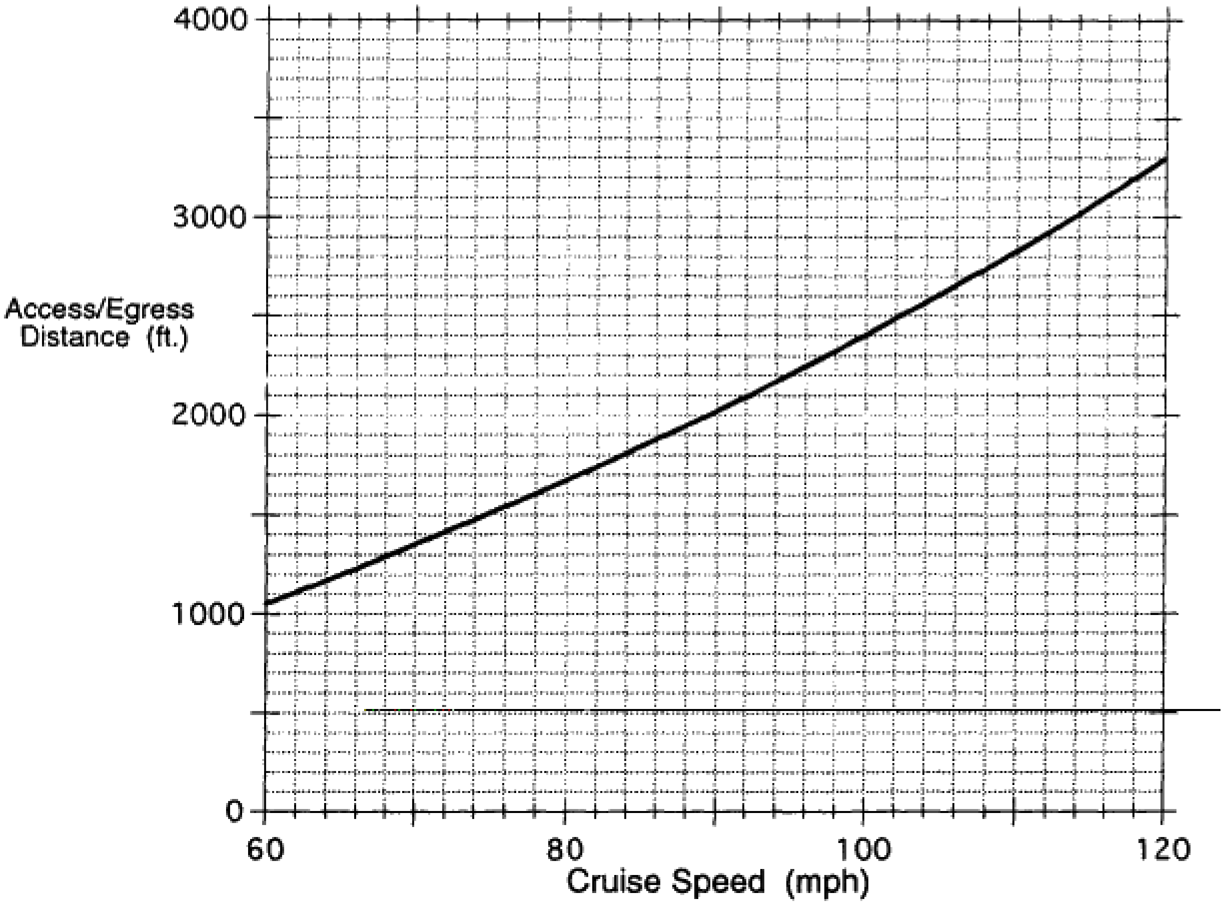


FIGURE 4-32 MINIMUM I3 ACCESS/EGRESS DISTANCE (A OR D = 6.44 FPS^2, |J| = 3.00 FPS^3

2. Calculate a nominal Δt from 4-36.

$$\Delta t_{nom} = \frac{2\, x_a}{v + 2\, v_o} + \tau_a \qquad (4\text{-}40)$$

where τ_a is a time delay to account for system dynamics.

3. Examine the cruise lane traffic and choose the empty space nearest upstream from the distance $v\Delta t_{nom}$ from the intended access point "a". This space is at distance Tv from point "a" as determined by roadway traffic data at t = 0.

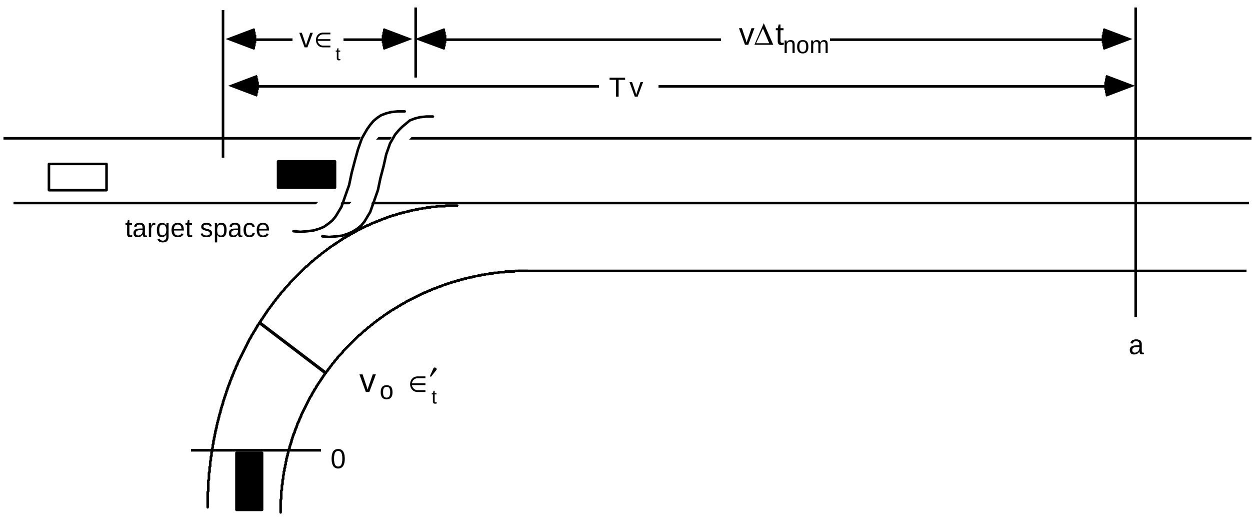


FIGURE 4-33 PARAMETER FOR I3 ACCESS USING OPEN-LOOP ROADWAY DATA LINK DISPATCH

4. Calculate $\in_t$ so that

$$\in_t = T - \Delta t_{nom} \qquad (4\text{-}41)$$

5. The entering vehicle holds velocity v_o for time $\in'_t$ and then accelerates on a profile similar to the one illustrated in Figure 4-31 with parameters A' and J',

$$J' = J \text{ by choice} \qquad (4\text{-}42)$$

$$\in'_t = \in_t \left(1 - \frac{2\, v_o}{v + 2\, v_o}\right)^{-1} \qquad (4\text{-}43)$$

$$\Delta t' = \frac{2\left(x_a - \in'_t\, v_o\right)}{v + 2\, v_o} \qquad (4\text{-}44)$$

$$A' = \frac{J\Delta t'}{2} - \left[\left(\frac{J\Delta t'}{2}\right)^2 - J'\left(v - v_o\right)\right]^{1/2} \qquad (4\text{-}45)$$

causing the vehicle to be at point "0" with velocity v at time T as desired.

An example of this procedure, using numbers from Figure 4-31 and an initial velocity of 10 fps, is worked out in the following steps.

Step 1. We fix x_a at 880 feet to be comfortably in excess of x_{min} = 696 feet.

Step 2. From 4-40 and τ_a = 1.0 seconds from Figure 4-31, Δt_{nom} = 17.30 seconds.

Step 3. Assume a very congested cruise lane with v/c = .9 so that there is only one space for every ten vehicles. Furthermore, assume that our entering vehicle has started the timing procedure just after a space available appears at distance $v\Delta t_{nom}$ which is 1522 feet. So we have to delay the acceleration maneuver to avoid disturbing cruise lane vehicles.

Step 4. If s + L = 36 ft as we have used in other analyses, the space is to be found (11) (36) = 396 feet further upstream or at 1918 feet. Then T = 21.8 sec and $\in_t = 4.5$ sec.

Step 5. The holding time at v_o is given by equation 4-43 as 5.52 seconds. The acceleration time by equation 4-44 is 15.28 seconds. The acceleration by equation 4-45 is 5.86 fps (less than .2g as required). The total time is 20.8 seconds without system delay. The delay time of 1.0 seconds places the vehicle at point "a" in 21.8 seconds with a velocity of 88 fps which is the space arrival time.

This procedure will not require a trailing vehicle to accelerate into the vehicle ahead because they are targeted for spaces which are trailing each other on the cruise lane.

3.6.4.2 EGRESS DISTANCE

Reversing the profile used to for access brings a vehicle to rest in about the same minimum distance as in Figure 4-32. The difference is the effect of system dynamics for braking as opposed to accelerating.

The procedure would be to initiate lane change at a timing point on the cruise lane and start deceleration at a second timing point. The vehicle's gap holding equipment would space vehicles accordingly. Since not all vehicles would be exiting, each vehicle's computer would, through the VV or the RV link, have to know how many empty spaces to hold after lane change. The holding number could then be modified to close ranks as the exit traffic management would require to manage queue length at the local street interface.

Queue length is not figured into Figure 4-32 because it is site- and situation-specific. Clearly, the line of slower-moving vehicles cannot extend back near the second timing point.

3.6.4.3 CURVATURE

Access/egress lane curvature is needed to produce the heading change required by site-specifics. A geometry was computed for the data of Figure 4-31 assuming a 90 degree change in heading is required while maintaining lateral acceleration equal to .17g after an initial short straight section. The initial curvature is dictated by the highest speed allowed at that point which we take to be the speed for the maximum acceleration profile from a standing start. In this example the speed is 19 fps and the distance of the straight section is 38 feet. The remainder of the geometry is obtained from the relation $\dot{} = .17\frac{57.3g}{V(t)}$ degrees per second and shown in Figure 4-34. Superelevation could also be used to make the curvature more comfortable and safer in slippery conditions.

For vehicles moving through the access procedure without stopping, the combination of initial speed, holding time, and required acceleration profile should not result in a speed at 38 feet in excess of 19 fps. If so, the side acceleration will exceed the comfortable limit. The computer can choose a smaller value of J´ in equation 4-42 to lower the speed at 38 feet but v_o must be less than 19 fps for this to work. In the example, which illustrated an extremely long $\in'_t$, there is no problem since v_o = 10 fps and $v_o \in'_t > 38$ feet. Another method to handle the requirement is to provide a profile increment based on vehicle dead reckoning or other distance information. It would correct a velocity/distance/time deviation required early in the profile.

In slippery weather conditions modified acceleration profiles can be used which hold a low velocity until past of section of large curvature. Under such conditions, the cruise lane would also be running under speed, possibly making the original profile suitable if simply sealed down.

The single-lane entrance from a local street is limited to manual low-speed flows in the range 1200 to 1600 (Reference 1). Two or more of these could be combined to build a large flow in a collector lane as stated earlier. The final entry flow would be dictated by the space available on the main line. For example, if the main line is running at v/c = .5 at the speed for maximum capacity, .5 (9600) or 4800 vph could be merged from the collector lane. This lane flow could be provided by four single-lane access stages of 1200 vph each.

The access procedure requires 15 to 20 seconds to complete. Therefore the collector lane flow must be known to the roadway data link about 1300 to 1900 feet upstream of each access point. Four access stages would then require three such lengths of collector lane (the first requires none but the access lane is about 1000 feet long). The collector lane is then 5000 to 7000 feet long.

An egress collector can be similar in design.

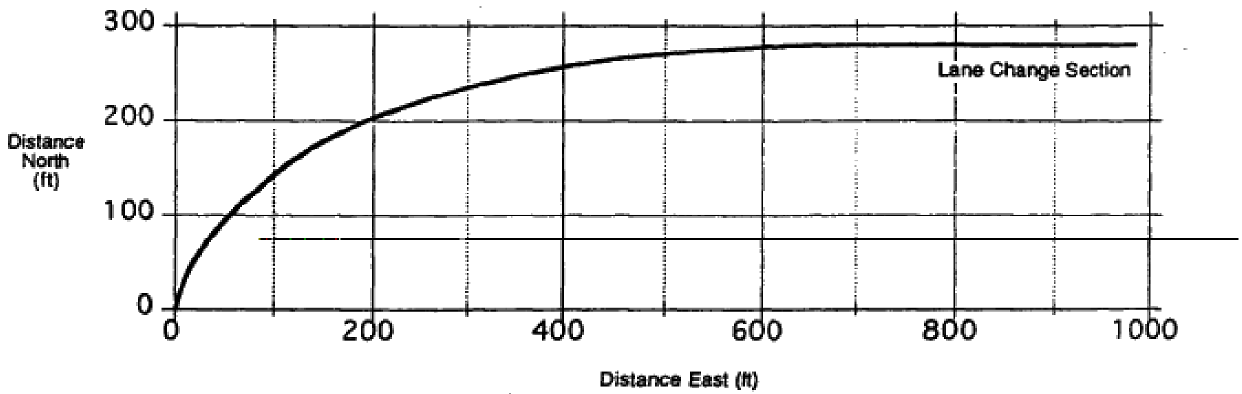


FIGURE 4-34 ACCESS LANE GEOMETRY FOR I3 CRUISE LANE SPEED 60 MPH (AN EXAMPLE FROM FIGURE 4-31 DATA)

The cruise-speed merge/demerge transition lane curvature is related to the speed which, in turn, affects the flow capacity. The maximum flow required is limited by v/c of the receiving lane. A common use of cruise-speed merge/demerge would be at right angle intersecting freeways. The interdependence of flows complicates traffic control. For example, if 50 percent of the westbound AHS traffic wants to transfer to the northbound lane of the intersecting AHS, we conceivably could have a flow as high as 4800 vph in the transition lane. From Figure 4-9, we could slow this traffic to 25 mph and still handle the flow. It would then accelerate to 60 mph for access to the northbound lane. That lane could receive the traffic only if it were running at 4800 vph or lower upstream of the merge. If we do not decelerate the entering stream the curvature without superelevation could be no greater than 3.6 degrees/sec at 60 mph or a circular arc of 1400 foot radius. The transition lane length is then 2200 feet for the 90 degree turn. A flyover would be required if the AHS exclusive lanes are built in the medians of two existing freeways.

The infrastructure complication involved in cruise-speed merge/demerge is a major reason why this access/egress is considered appropriate for the I3 concept but not for I2.

3.6.5 SUMMARY AND CONCLUSIONS

The I3 concept is exclusive entry and exit to an exclusive cruise lane. It is the designer's ideal since the maximum freedom is allowed to configure the entry/exit process and infrastructure. It fits applications where participation is very high and it is also the logical evolutionary end point for the I2 concept.

The access/egress process can originate from manual freeway lanes or from local streets depending on site-specific factors.

I3 also allows the infrastructure to support a third kind of entry/exit which is the cruise speed merge/demerge.

Access/egress from manual cruise lanes is similar to I2 without the constraint of dealing with manual vehicles in the transition lane. Sliding back in the cruise lane to create gaps would not be necessary since the automated vehicles in the transition lane can now be freely manipulated to synchronize entering vehicles with gaps regularized after the previous access/egress section.

If entry/exit is designed using ramps from the local streets, automation can be engaged and disengaged at low speed – a safer process. The curvature and superelevation of such ramps does need to be related to the speed profiles for occupant comfort and safety. To deal with the inherent flow limitation to – on single-lane ramps supplied by a manual soruce, collector lane running at cruise speed can be used. The flow can build to typical AHS cruise lane levels and merged with the main cruise lane. Four stages of entry ramps building a flow of 1200 to 1600 would require about 6000 feet with a single ramp taking about 1100 feet at 60 mph (Figure 4-32). The egress length is similar to the queue length at egress is site-specific but must be sufficient to prevent speed effects upstream of the start of deceleration.

The cruise merge/demerge of large flows would require ATMS supervision and control to prevent system overloads. Curvature and length such as required for interchanges for intersecting AHSs would typically require the new infrastructure that characterizes I3.

3.7 ROADWAY COMMUNICATIONS

3.7.1 EXTENDED DEFINITIONS OF C2 AND C3

In the discussion that follows, the "baseline C2 and C3 roadway communications links, roadway-to-vehicle (RV), would correspond to the "coordination layer" of Reference 21 with some aspects of the "link layer". The vehicle-to-vehicle (VV) link mentioned in this Chapter corresponds with the "regulation layer". However, the "alternate C3" takes over the regulation aspect.

The C2 description has the roadway controlling average speed, spacing and regularization in a sector. This would be accomplished through an RV data link broadcast to all vehicles in a sector, which might be four to six miles long between AHS lane access points. Along with speed and spacing we would assume directives could be given responding to potential overloads at the upcoming access/egress regions, incidents, weather-related slowdowns, etc. This form of traffic control is assumed to come from an ATMS which could be monitoring the VV link. The VV link is requesting access, requesting egress, changing lanes, sensing vehicles moving to the breakdown lane, performing an emergency stop, slowing in the lane, etc. Especially in an I3C2, the ATMS could also have its own independent surveillance sensors and equipment. In this case, incidents would also be detected independently. In addition, they can be detected by the drivers themselves using simplified automated messages to alert ATMS through the RV link.

By controlling average speed and/or spacing, ATMS can create more single lane capacity to deal with potential overloads. ATMS can also do a rudimentary form of access/egress demand control by using roadside or in-vehicle signing to request/direct drivers to avoid the situation by suggesting an alternate. This is the beginning of fully automated and controlled traffic management whereby all freeway trips and many urban arterial trips would proceed according to recommended routing and routing revisions. This concept moves into a C3 concept.

The concept of C3 is to have the roadway addressing individual vehicles. Two general ideas have been discussed. One assigns headway protection responsibility to the VV link using vehicle accelerometer and headway measurement data. The other assigns this responsibility to the roadway and eliminates the VV link and vehicle-based headway measurement. Since the latter concept is possible only in C3, it either replaces C1 and C2 technology at some point in time or it requires that C3 be implemented at the introduction of AHS (no I1C1 introduction). The former concept is quite prevalent in AHS thinking and has been termed the "Baseline C3". The latter is termed the "Alternative C3".

The individual vehicle control intended in "Baseline C3" allows the VV link to control rudimentary vehicle functions and uses the RV link, in addition to controlling average speed and spacing, to direct vehicles to reroute. Such directions could include changing lanes, latering entry/exit plans, special behavior associated with incidents, responding to individual vehicle requests for new routing. Entry/exit synchronization of vehicle position with slot position can be either an RV or a VV function.

The roadway functions intended in "Alternate C3" are all of the "Baseline C3" functions plus all of the rudimentary vehicle functions (longitudinal position within the slot, distribution of empty slots, synchronization and headway control/protection). The RV link accomplishes this through low-resolution (±2 ft.) sensing of absolute position. A smoother signal is provided to command a vehicle-based velocity control loop by using wheel pulse as the feedback signal compared with a vehicle-stored versus-time profile (point follower) or a roadway-stored position of the vehicle ahead (vehicle-follower). The feedback signal is updated for drift by using the data-linked absolute position signal. Since bandwidth and resolution are low, this version of C3 is not applicable to low gap sizes. A preliminary estimate of minimum gap size is 50 feet.

3.7.2 COMMENTS

1. In the point-follower mechanization, the so-called "string stability" mode stabilization is not a problem with the lack of a VV link. Each vehicle position is controlled by the clock and not coupled to the position of the vehicle ahead.

2. In "Alternative C3," deceleration to avoid rear end crashes would be delayed by 250 ms or so plus the data link and braking time delays – more than twice the vehicle-based time to acheive full deceleration.

3. "Baseline C3" distributes the data transmission load between the VV. link and the RV link. "Alternative C3" puts the load on the RV link and eliminates the VV link. Both concepts require a transmitter and receiver in every vehicle. "Baseline C3" continues to operate with a failed infrastructural receiver/transmitter, computer, etc. by falling back to C1 while "Alternative C3" must stop all vehicles or require an "open-loop" maneuver to the breakdown lane.

4. Concepts between these two C3's may have merit. For example, with gap sizes leading to at most two collisions, the VV link perhaps need not involve more than three vehicles. This may also be enough for vehicle access/egress coordination. With only three vehicles involved on each VV link and the RV link performing all functions except headway protection and access/egress, VV link could be simpler and more reliable. At the 19 foot gap size, a laser line-of-sight link for three vehicles requires a range of only 72 feet.

5. There is an RV link in C2 and in C3. How do we meaningfully separate the two? One way is to say that the RV link in C2 is a broadcast of the same data to all vehicles in the sector going, say, Westbound whereas in C3 the RV link can address single vehicles, like a cellular telephone system. Also in C2 the RV link can be one-way, requiring no vehicle response on that link. In C3, the RV link may be two-way.

4.0 CONCLUSIONS AND RECOMENDATIONS

4.1 CONCLUSIONS

1. Entry/exits are key to AHS practicality since they dictate maximum flows throughout the system, are a big cost driver, and are a primary impact on the community.

2. Participation is key to entry/exit design and indeed drives overall design. It is reasonable to estimate that participation will be significantly higher than market penetration. However, AHS entry/exits feasible for low participation are initially the most attractive.

3. Entry/exit spacing is an important design criterion in the urban environment. Long Island Expressway data shows that the average OD pairing in that region involves only a few miles of freeway use. Yet, AHS conceptually is concerned with longer freeway segments.

4. The different access/egress techniques associated with the different RSCs may well all find application on a single AHS because the specific design requirements of each freeway, street and traffic situation dictate the best technique.

5. One of the highest infrastructure impacts assigned to entry/exit requirements is the merging of two AHS steams starting at right angles. This is due to the large radii required if speed is maintained, and infrequent high-speed left lane exits in existing highway geometries.

6. AHS traffic controllers, according to derived capacity-versus-speed estimates applicable to automated vehicles, will have the ability to provide a tradeoff between velocity and capacity to accommodate substantial volume variations.

7. Single-lane access/egress <u>automated</u> flow is upper-bounded by single <u>manual</u> lane capacity.

8. Single manual freeway lane capacity as defined by field data varies from 1800 vph at 60 mph (Level of Service C) to 2000 vph at 30 mph (Level of Service E). Below 30 mph the maximum flow decreases and the Level of Service is F (Reference 1). Field measurements higher than 2100 vph (over 15 minutes) have been recorded but at LOS F.

9. Single automated lane capacity is 9600 vph at 52 mph based on detailed analysis of a moderate safety policy allowing a few minor collisions in rare instances. At speeds of 40 to 60 mph the capacity is maintained at 8800 vph and above. Outside of this speed range, capacity decreases rapidly but is maintained at 5500 vph and above for the speed range 28 to 80 mph.

10. For the mishap scenario assumed, the probability of injury requiring hospitalization is twice as high at 60 mph with 3 foot gap as with 19 foot gap and there are 13 collisions at 60 mph as opposed to 2 collisions. The additional

number of parties involved, much higher total property damage potential, and access/egress protocol complication lead us to favor the higher gap sizes. Grouping of vehicles to obtain the desired safety becomes unnecessary until the speed exceeds 60 to 70 mph.

11. For the mishap scenario assumed, a slippery pavement reduces capacity to 5100 vph peak at 20 to 25 mph. This is an issue because today's manual speeds are typically higher and changing weather conditions require contingency traffic control.

12. Using a less drastic mishap scenario increases the speed for maximum capacity but does not change the maximum significantly.

13. Changing bumper/body design in the direction of greater energy absorption than assumed (5 mph bumper) does not change results significantly. More elasticity causes more problems at the smaller gap sizes.

14. Heavy vehicles would require more space for equivalent safety. Adopting a no-collision policy requires about a factor of six at 60 mph. This translates to a large decrement in lane capacity for a small percentage of heavy vehicle flow. Hence we conclude that design to accommodate heavy vehicles may be optimized if they are automated in an I1 concept sense (mixed manual and automated flow) but do not use the exclusive lanes of the I2 and I3 concepts except where the heavy vehicle percentage justifies a lane dedicated to those vehicles.

15. The I1 concept (shared lane on a shared freeway with unmodified manual entry/exits) applies to early versions of AHS when participation will be low. It also applies to mature designs for four-lane interstates in rural areas giving manual vehicles a chance to pass. Access/egress is envisioned as manually performed using collision avoidance devices as aids. It can take place at any location at the driver's discretion.

16. I1 benefits in terms of increased flow rates are predicted. However the analysis is conservatively restricted to reduced trip time with no change in flow rate by equating speed to manual speed/flow conditions in the right lane. Benefits in I1 can be increased for a given participation by using communication to pair with another automated vehicle in the left lane. By not increasing overall flow, we can avoid any design change to entry/exits which would move away from the I1 concept of low infrastructure impact.

17. Detailed analysis of I1 suggests that participation as low as five percent can increase a congested 4000 vph two-lane manual traffic from 30 to 40 mph. Fifteen percent can increase the speed to 55 to 58 mph.

18. If the I1 concept is implemented on a six-lane freeway it can easily evolve into an I2 format where the left lane is exclusive.

19. The I2 concept (exclusive left lane, shared or exclusive middle lane at access/egress points, manual right lane, unmodified manual entry/exits) allows synchronized access and quasi-synchronized egress. The I2 concept starts to

make sense for participation higher than .45 and when flows at or higher than 6000 vph for each direction of a six-lane freeway can be serviced by existing manual entry/exits.

20. Access in I2 could be synchronized by a simple timing system facilitated by space regularization in the automated lane.

21. Manual vehicles in the transition lane need only hold the speed specified for the access/egress region but they must act cooperatively in doing so to avoid causing some automated vehicle to miss access or egress. The flow of manual vehicles in the middle lane must be limited by ATMS to about 1500 vph and preferably would be much lower. Operations in the middle lane can be modeled after the left lane in I1.

22. In I2 with low acceleration/deceleration limits (for comfort and low emissions) and reasonable vehicle dynamics, analysis and simulation indicates access distance is about 1100 feet at 60 mph. Egress distance is about the same. With a 500 foot buffer between the total region is about 2700 feet at 60 mph.

23. When I2 participation has grown to numbers that allow an exclusive transition lane, special entry/exit provisions can be justified to build flows in the cruise lane up to the 9000 vph range of an I3 concept.

24. The I3 concept (exclusive cruise lane with exclusive transition or entry lane) allows maximum freedom to configure the entry/exit infrastructure and process and applies to conditions of very high participation.

25. I3 allows the infrastructure to support a third kind of entry/exit – the cruise speed merge/demerge (the other two being access/egress from manual freeway lanes and from local streets).

26. I3 access/egress from manual cruise lanes is similar to I2 without manual vehicles present. This would allow synchronization by manipulation of accessing vehicles rather than by creating gaps in the cruise lane at the proper places.

27. I3 access from local streets allows safer low speed automation system engagement and disengagement. Once again, a timing procedures, in this application with a shaped acceleration profile, mechanized with a roadside data link and vehicle-to-vehicle link could be used with a closed-loop terminal guidance. The access distance is about 1100 feet for a cruise lane speed of 60 mph and it varies with speed in accordance with simple analysis of the access procedure up to 3300 feet at 120 mph.

28. I3 egress distance is about the same as the access distance using maximum braking deceleration no greater than the acceleration used for access. Queue length at the local street must be added and it is site-specific.

29. The new entry/exits designed for I3 should have curvature and possibly superelevation which limit side acceleration as a function of speed to

comfortable values. This conclusion applies as to cruise speed merge/demerges as well as local street ramps.

30. The I3 single-lane ramps would be limited to the 1200 to 1600 vph manual source flow capacity. To service greater demand, a collector lane can be used. Four single-ramp stages could build a flow of 4800 to 6400 vph for merging with the cruise lane (which must be running at a low v/c at the time) in a distance of roughly 6000 feet.

31. The I3 access/egress process and particularly the cruise speed merge/demerge of large flows would require ATMS supervision and control to prevent system overloads.

4.2 RECOMMENDATIONS

1. The relationship of collision velocity to injury severity at speeds less than 10 fps should be more fully defined for AHS-equipped vehicles as part of the lane capacity definition for access design.

2. Safety policy should be examined to define what would be acceptable to AHS designers, to users and to insurance companies. The role of a barrier between an automated lane and the manual lanes sharing the same roadbed in the I2 concept would be part of the mishap scenario definition as part of this policy. The presence of a barrier in the I2 concept allows access/egress only in specific places.

3. Access/egress operations and procedures should be tested, first through modeling and simulation but then on the test track to obtain reliable data.

4. The I1 concept is forecast to relieve a congested freeway with low participation. This prediction should be studied through simulation and then operationally tested.

5. The AHS/ATMS interface for access/egress regions and for entry/exits should be studied. The AHS potential benefit to ATMS on a regional basis using realistic conditions at these locations needs to be modeled as part of this study.

6. AHS operation in weather conditions affecting surface friction cruise should be researched. Cruise speed, safety policy, lateral control, braking capability, speed for engagement and disengagement of automation, effects of grades and curves, presence of articulated vehicles, etc. all impact the entry/exit and access/egress operations.

7. The minimum space into which an automated vehicle can be safely maneuvered should be defined on the basis of realistic control capabilities and reasonable wind gusts, roadbed unevenness and other disturbances.

Issues and risks are summarized in Table 4-2.

TABLE 4-2 ENTRY/EXIT ISSUES AND RISKS

#	Issue/Risk Description	Comments	RSC Impact	Discussed
1	Can practical AHS designs be realized that combine heavy vehicles with SVEs in the lane?	Analysis and study of the many sub-issues would suggest other solutions be examined	I2, I3	2.4.1, 3.5.5.5
2	How do AHS development planners deal with low participation?	Analysis suggests I1 and I2 concepts be seriously studied.	I3	3.4.1, 3.5.1, 3.6.1
3	Will collision avoidance and other situational awareness capability be in place before AHS?	AHS may require its development and refinement	I1, I2	2.4.4
4	Will ATMS regulation of certain OD pairs, routing and scheduling be in place before AHS?	Most benefits of AHS seem interdependent on ATMS	All	2.4.5
5	Can AHS successfully deal with decreasing surface friction and lower maximum braking deceleration?	Lane capacity decreases drastically with decreasing surface friction. Lateral control is also affected.	All	3.3.5.1
6	Can the use of the I1 concept to relieve congestion avoid attracting new traffic and destroying the benefit?	Rush hour pricing and advanced traffic management may be successful.	I1, I2	3.4.4
7	Would manual drivers tolerate automated vehicles trailing them at a smaller gap than normal for manual traffic?	Manual drivers need to embrace I1 as a mutually beneficial concept.	I1, I2	3.4.4

TABLE 4-2 ENTRY/EXIT ISSUES AND RISKS (continued)

#	Issue/Risk Description	Comments	RSC Impact	Discussed
8	When manual vehicles benefit in trip time and stress relief what is the incentive to purchase automation?	The increased Level of Service justifies a toll for manual vehicles. Prestige, lower stress and better use of travel time may also provide incentive.	I1, I2	3.4.4
9	How would manual flow in the I2 transition lane be limited to 1500 vph?	Traffic management can use lights to select lane and control overall flow.	I2	3.5.5.3
10	What if a manual vehicle in the I2 transition lane is uncooperative in egress regions?	Could be a ticketable offense.	I2	3.5.3, 3.5.5.2
11	Must I2 lane speed be equal to manual speed in access/egress regions? What happens in slippery weather?	The answer appears to be yes unless, with higher participation, manual vehicles are absent from the transition lane. AHS cruise lane speed can be increased away from access/egress regions.	I2	3.5.2
12	How is egress queue length in I3 controlled to not disrupt the cruise lane?	When an exit is projected to run near capacity, ATMS could delay entry to AHS or change exit by negotiation with the driver (See #4).	I3	3.6.4.2

APPENDIX A QUEUING AT AHS ENTRY LOCATIONS

Two types of point follower longitudinal control systems were described in Task D. For convenience, these descriptions are provided below.

A.1 Point Follower (Type 1)

The AHS mainline flow consists of a set of slots moving at a constant velocity (Figure 4-A1). The slots are large enough to contain a vehicle and its intervehicle spacing. The velocity may be changed from time to time by a control function. A set of control rules is provided for vehicle response under emergency conditions.

A.2 Point Follower (Type 2)

The AHS mainline flow consists of a series of slots which contain closely spaced platoons (Figure 4-A2). There is a fixed distance (for each mainline speed) between slots. Once a vehicle is in a slot it will not leave the slot until it leaves the AHS or changes lanes. There may be several vehicle positions spaced at short headways within the slot. A vehicle may move to a new vehicle position within the slot to facilitate merging and demerging. It should be noted that when slots are sized for platoons of up to three vehicles, no constraints are imposed on slot entry by the vehicle AHS entry or exit points. A set of control rules is provided for vehicle response under emergency conditions.

For vehicles to merge at entry points using either RSC I2 or I3 ramp configurations, the merging vehicle must be in a ramp or auxiliary lane position which is adjacent to a mainline slot which has no vehicle. The merging vehicle's speed must also be equal to the slot speed.

By appropriately adjusting the merging vehicle's speed on the AHS entry ramp or on the auxiliary lane, some of the entering vehicles will be able to achieve the appropriate position and velocity at the required merge time. When volume to capacity ratios on the AHS begin to exceed 0.5, the probability that the vehicle desiring entry has the appropriate combination of velocity and position which allows AHS entry within a reasonable distance decreases rapidly.

One strategy to insure successful merges is to stop such vehicles for a short time period until an appropriate AHS mainline gap is available. The vehicle will be released (under automatic control) from its hold position and the entire merge will be performed automatically.

A.3 Comparison and Conclusions

The queue delay time and storage requirements for both a Type 1 and Type 2 point follower were developed. The queuing relationships are described in Appendix B. Figures 4-A3, 4-A4, and 4-A5, provide examples of the median delay experienced as a function of the volume to capacity ratio upstream of the merge location. When used in conjunction with the I3 infrastructure concept, the point follower (Types 1 and 2) provide the following deployment features:

- If the ramp entry rates are kept below the mainline capacity level, vehicle merge is assured. For the range of ramp volumes which will actually be experienced, the median ramp delays are short, even at mainline capacity. Ramp storage space is modest, requiring storage for only a few vehicles.

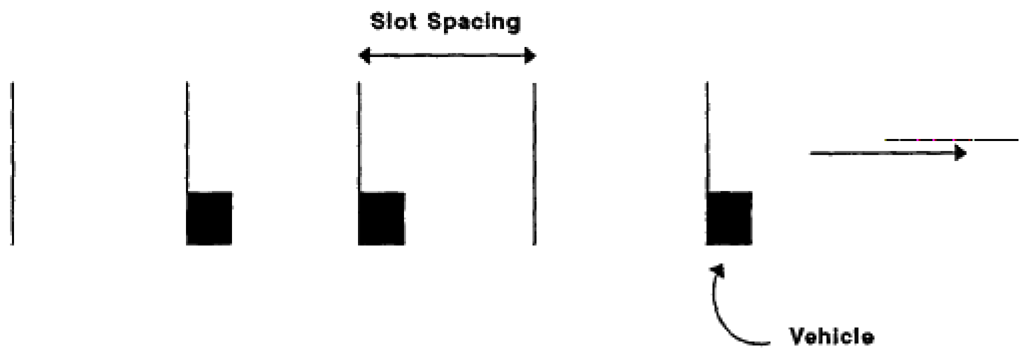
- The AHS mainline maintains an approximately constant speed. Thus longitudinal maneuvering is minimal and a good ride quality is assured.

- Because vehicle merge is assured (for the no malfunction case), a minimal distance merge lane which parallels the AHS lane is required. It is also possible to accomplish the merge without grade separation using an AHS ramp accessed from the left lane of the general freeway lanes. A ramp length of under 1000 feet will probably suffice. The I3/point follower configuration requires no extended or continuous transition lane.

- Using the concept of a three vehicle position slot for the Type 2 configuration, a vehicle can enter a slot containing an open vehicle position at any ramp destined for any other ramp without the platoon splitting maneuvers (and the consequent mainline turbulence) experienced in the PATH model of Reference 11.

- For approximately the same intraplatoon and interplatoon spacing used by PATH (Reference 11) a capacity of 4526 vehicles/hr is obtained for the Type 1 configuration and 7603 vehicles/hr is obtained for Type 2. The two configurations may, in fact represent an evolutionary development approach. Higher capacities are available with slots with more than 3 vehicle positions, however, this will require more complex vehicle platoon assignments at the entry ramp. It may increase the median ramp waiting time and vehicle storage space required.

- Many of the same entry and merge advantages might be obtained with a control configuration which is not, strictly speaking a point follower, but which retains station keeping characteristics in the neighborhood of the entry ramp once appropriate entry gaps are established on the mainline prior to the entry ramp area. As with the point followers, the entry ramp would be automated and the merge strictly controlled.



- •Slot spacing determined by infrastructure
- •Each slot has explicit position vs time relationship
- •Vehicle must control to slot position
- •Vehicle may or may not occupy slot

FIGURE 4-A1 TYPE 1 POINT FOLLOWER

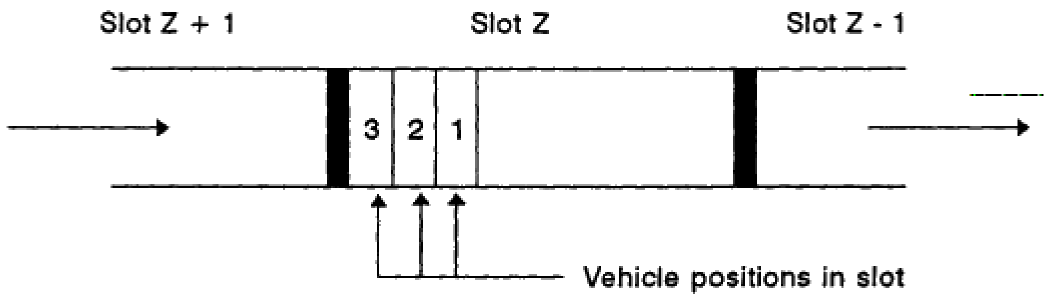


FIGURE 4-A2 TYPE 2 POINT FOLLOWER WITH THREE VEHICLE POSITIONS

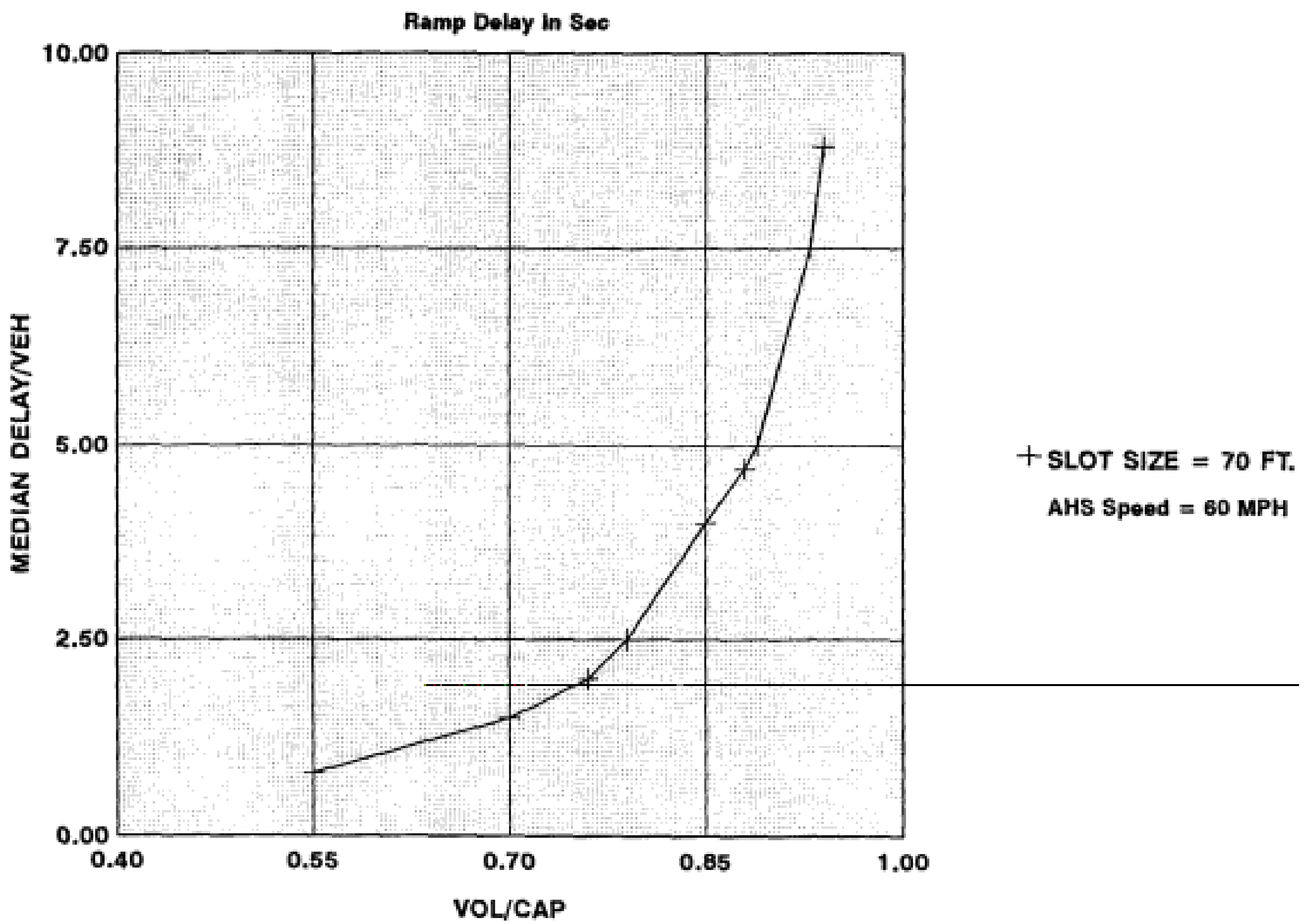


FIGURE 4-A3 RAMP DELAY FOR TYPE 1 POINT FOLLOWER

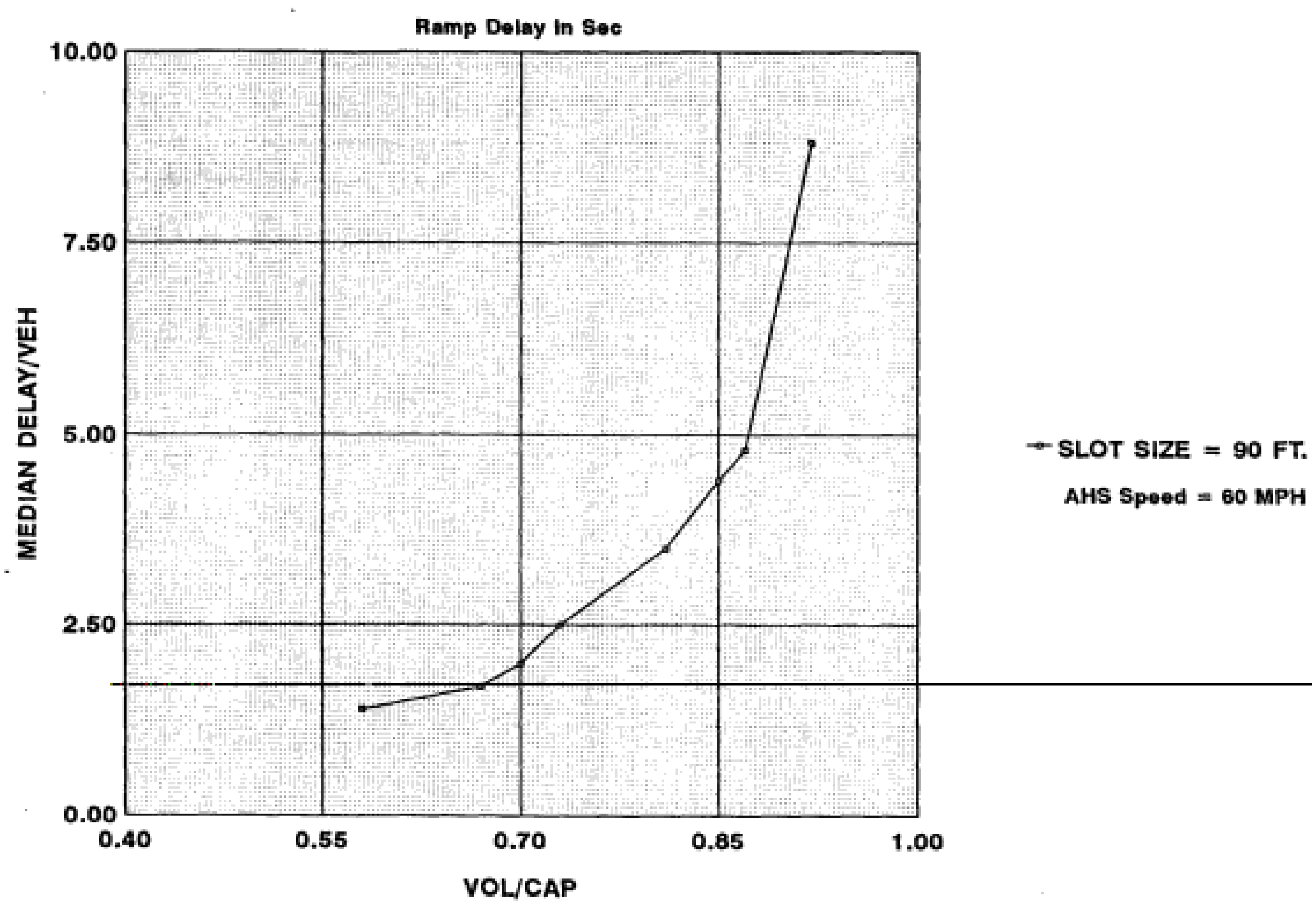


FIGURE 4-A4 RAMP DELAY FOR TYPE 1 POINT FOLLOWER

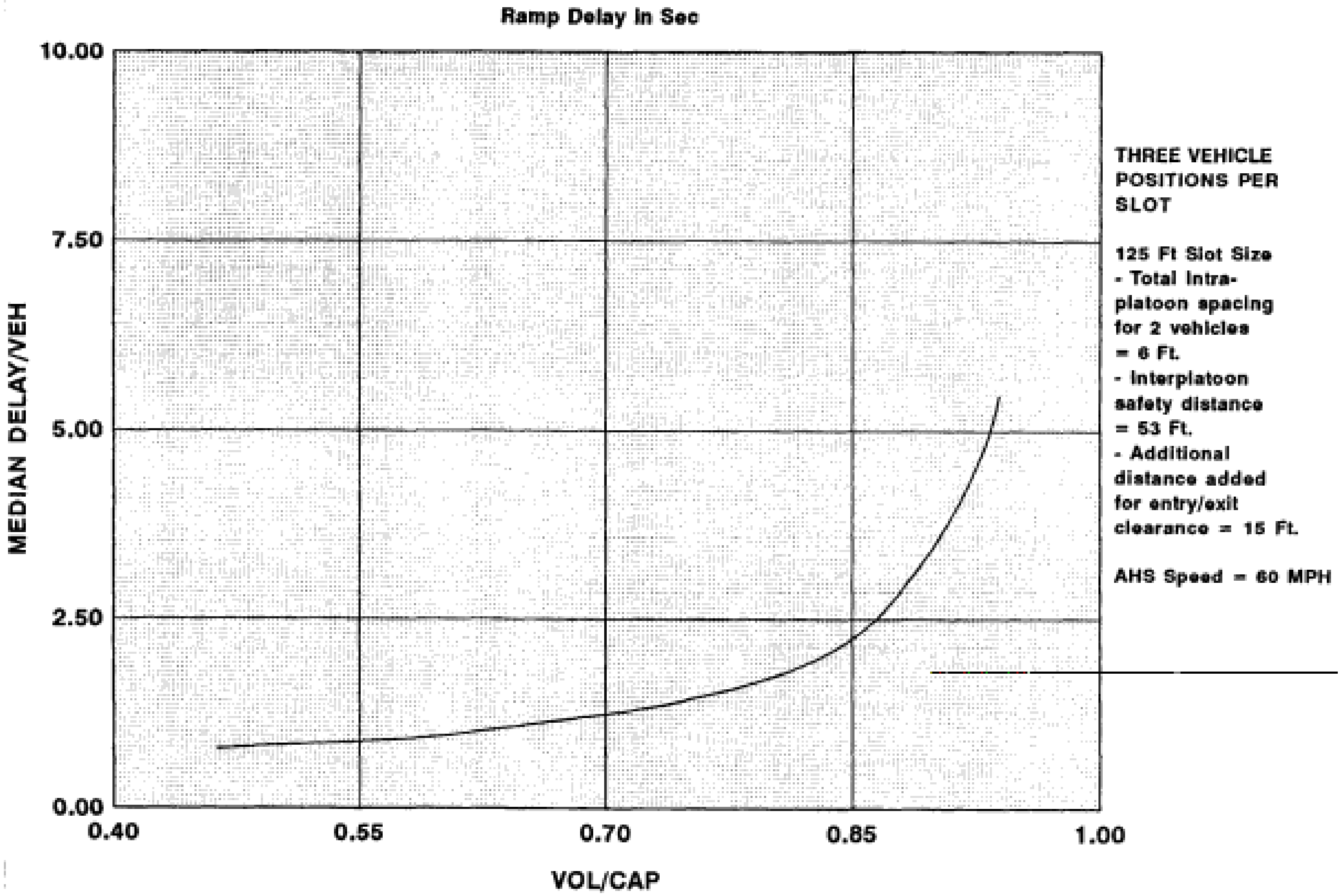


FIGURE 4-A5 RAMP DELAY FOR TYPE 2 POINT FOLLOWER

APPENDIX B QUEUING RELATIONSHIPS AT AHS ENTRY LOCATIONS

Appendix A discusses the possible need to queue vehicles prior to AHS entry for RSCs I2 and I3 configurations. Examples of merging delays were also provided. This appendix provides the queue formation relationships which were used to develop the examples. Figure 4-B1 develops the relationships for the Type 1 point follower and Figure 4-B2 provides the relationships for the Type 2 point follower.

FIGURE 4-B1 (SHEET 1 OF 2)
TYPE 1 POINT FOLLOWER ENTRY RAMP QUEUE RELATIONSHIPS

Let	L	=	Slot Size
	S	=	AHS Mainline Speed
	C	=	AHS Mainline Capacity
	M(N)	=	Mainline Volume in Section N
	E(N)	=	Volume at Entry Ramp N
	R(N)	=	Volume to Capacity ratio of Section N

$$C = \frac{S}{L} \text{ slots/sec and vehicles/sec}$$

$$R(N) = \frac{M(N)}{C}$$

Constraint $E(N) \leq C * (1 - R(N))$

To successfully merge, a merging vehicle must meet an available slot at the merge point of the AHS mainline and ramp. The passage time from the start of the automated AHS ramp section until the merge is assumed to be a well defined constant. The probability of a vehicle on-ramp N encountering a vacant slot is:

$$1 - R(N)$$

The number of slot passages for a 50 percent probability of encountering an empty slot (A) is defined by the following expression:

$$0.5 = R^A(N)$$

$$A = \text{in}\,(0.5)/\text{in}\,R(N)$$

FIGURE 4-B1 (SHEET 2 OF 2)

Similarly, the number of slot passages for a 95 percent probability of encountering an empty slot (B) is given by:

$$B = \text{in}\,(0.05)/\text{in}\,R(N)$$

The median time which a vehicle must wait at the ramp entry for a slot is approximately:

$$\text{Median Delay }(N) = \frac{A\,(N)}{C}$$

The median queue is approximately:

$$\text{Median queue }(N) = E\,(N) * \text{Median Delay }(N)$$

Similarly, the delay time and queue length which will not be exceeded for 95 percent of the ramp vehicles is:

$$95\%\text{ delay }(N) = \frac{B\,(N)}{C}$$

$$95\%\text{ queue }(N) = E\,(N) * \text{Median Delay }(N)$$

FIGURE 4-B2 (SHEET 1 OF 2)
TYPE 2 POINT FOLLOWER MATHEMATICAL RELATIONSHIPS

Let	L	=	Slot Size
	S	=	AHS Mainline Speed
	C	=	AHS Mainline Capacity (slots/sec)
	CPH	=	AHS Vehicle Capacity (vehicles/hr)
	M(N)	=	Mainline Volume in Section N (vehicles/hr)
	E(N)	=	Volume at entry ramp N (vehicles/hr)
	R(N)	=	Volume to capacity ratio of Section N

$$C = \frac{S}{L} \text{ slots/sec}$$

$$CPH = 3 * 3600 * C$$

$$R(N) = M(N)/CPH$$

Constraint: $E(N) \leq CPH * (1 - R(N))$

The probability of a candidate ramp vehicle encountering at lest one vacant position in a slot is:

$$1 - R^3(N)$$

The probability of encountering no open vehicle positions in D slots is:

$$p = (R^3(N))^D = R^{3D}(N)$$

To get a 50 percent probability of encountering at least one vehicle position:

$$D = \text{in } (0.5)/3 \text{ in } R(N)$$

FIGURE 4-B2 (SHEET 2 OF 2)

Similarly, the number of slot passages for a 95 percent probability of encountering an empty slot (B) is given by:

F = in (0.05) in (3*R(N))

The median time which a vehicle must wait at the ramp entry for a slot is approximately:

Median delay (N) = D(N)/C

The median queue is approximately:

Median queue (N) = E(N) * Median Delay (N)

Similarly, the delay time and queue length which will not be exceeded for 95 percent of the ramp vehicles is:

$$95\% \text{ delay } (N) = \frac{F(N)}{C}$$

95% queue (N) = E (N) * 95% delay (N)

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