Automated Highway System Merging Control
Part III: Evaluation

by

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ABSTRACT

The Automated Highway System (AHS) is not designed as a stand-alone transportation facility. Drivers will by necessity need to drive from their origins to the AHS entrance, and from the AHS exit to their final destinations. Therefore, the AHS will need to be integrated with other facilities in the transportation system. Interfaces create much of the congestion for today's transportation systems. Likewise, AHS interfaces may cause a similar problem, due to either AHS interactions with conventional systems or internal limitations from AHS merging capabilities. If these problems exist, either the AHS or the conventional road network cannot function properly.

Clearly not enough is known about the automated merging process to determine what conditions would lead to congestion at interface points. The current macroscopic techniques assume parameters that are not applicable to an AHS, and no detailed AHS merging models have been developed and validated. This paper addresses the AHS interface problem by presenting a microscopic simulation model for one scenario of the automated merging maneuver.

The results from this model show that for low flows and conventional highway speeds (55 mph), a one lane AHS merging section with a dedicated automated entrance ramp behaves with much of the same characteristics as a two lane section of conventional highway with or without fixed time ramp metering. However, when the conventional freeway begins to "break down" near its capacity, the AHS, in this model, continues to perform with little delay. These results seem to be reasonable. Because the merging maneuver from a single on ramp should have little effect on AHS mainline operations, if the control and communication methods used in this paper are applied. However, this paper does not show the effect of operations where several on and off ramps are used, neither does it show the interaction between these ramps. It also should be noted that the model presented in this paper is simplified in that it does not account for variances in acceleration or deceleration rates or vehicle types.

INTRODUCTION

The potential for bottlenecking to occur at Automated Highway System (AHS) interfaces, causing spill-back onto the AHS mainline, and a stoppage of AHS flow is a serious problem that has not been adequately addressed in the literature. If this situation occurs, all throughput gains from an AHS may be negated, greatly limiting feasible AHS benefits. This bottlenecking has the potential to occur in at least two places. One place is at the junction between two crossing automated highways. Control at an AHS interchange involves many dynamic processes that have to be coordinated in time and space in order to be successful. The limitations of this process will greatly affect the performance of an AHS. The second place bottlenecking could occur is at interfaces with local arterial or conventional highways. As shown in Ran et al (*1*) and Castillo et al (*2*), when AHS flows end at a common destination such as a Central Business District (CBD) or dense residential area, the AHS may fail due to the insufficient capacity for these areas to absorb increased off-ramp flows. If either of these failures exist, spill-back of congestion could occur on the AHS, creating a queue of traffic that would paralyze flow. The capacity of the AHS then would be limited not by its mainline capacity, but by the absorption capacity at its interface points.

Completed Work

Several authors have completed preliminary studies into the question of how an AHS interface would affect the AHS and conventional systems. The most extensive work has been completed by Hall et al (*3*), who has produced a macroscopic merging simulator for AHS on-ramps. This work is useful to analyze the group of merging strategies where vehicles would stop before completing the merging maneuver, such as stopped check-in operations. However, the model does not account for merging strategies where vehicles do not stop prior to executing the merging task, such as "on-the-fly" check-in operations, highway-to-highway interchanges, and where transition lanes meet mainline lanes. Some preliminary work has also been done by Ran et al (*4*). This paper, however, was of a theoretical nature and did not provide the detail of a working model useful in analysis.

Study Scenarios -- "On The Fly" Check-in and AHS Interchange with Dedicated Ramps

AHS "on the fly" check-in will occur in the context of an interface with an arterial or conventional
highway, where the entrance is not metered. This scenario is shown in Figure 1. Note that the traffic enters and merges from the right, but it is also possible that the traffic could merge or diverge from the left hand side. These alternate designs could prove to be beneficial for cost and right-of-way construction requirements, but are not explicitly discussed or modeled in this paper.

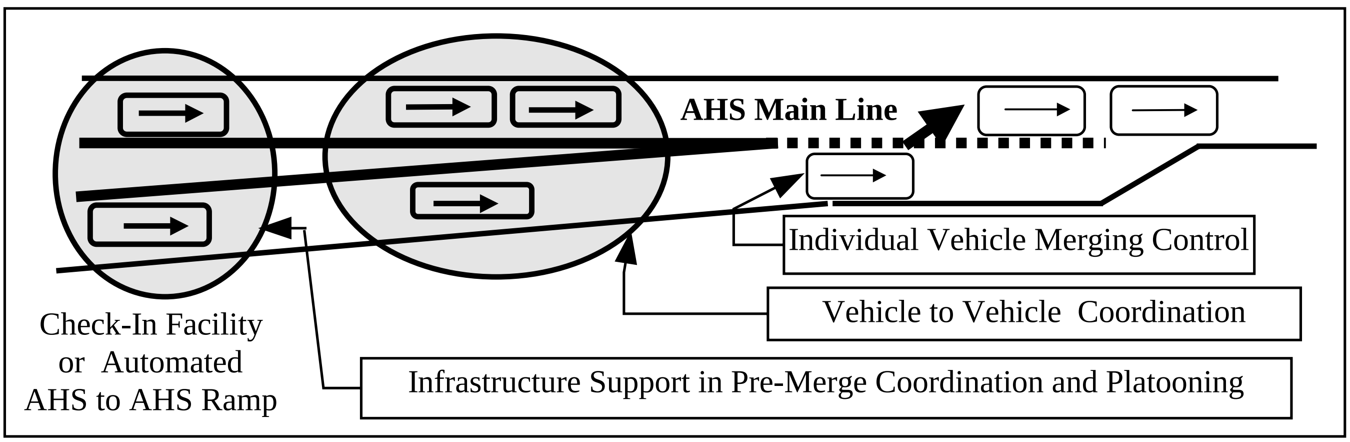

Figure 1. "On the fly" Check-in and AHS to AHS Interchange with Dedicated Ramps

Merging Process

The dedicated lane merging process consists of three main areas, infrastructure support, vehicle-to-vehicle communication and cooperation, and individual vehicle merging control, which are shown in Figure 1. The highest form of control in this system is the infrastructure support, and the lowest form of control is the individual vehicle control. Merging operations can take place with the following options: 1) individual vehicle control, 2) both individual vehicle control and vehicle-to-vehicle communication and cooperation, 3) individual vehicle control and infrastructure support, or 4) individual vehicle control combined with both vehicle to vehicle communication and cooperation and infrastructure support.

Infrastructure Support

Vehicle placement for merge preparation can take place by the use of infrastructure merge guidance systems. If so outfitted, the infrastructure may obtain vehicles' positions and speeds as they approach the merge point, use this information to analyze the traffic flow near the juncture, and issue restrictions on movement parameters or movement orders to vehicles in the merge area. The infrastructure can create, adjust gaps, or guide merging vehicles into existing gaps by issuing commands to vehicles or platoons to change speed, path, spacing, or platoon size. Also, merging vehicles may not be able to detect gaps in mainline traffic for various reasons, including roadway curvature, banking, slope, environmental conditions, elevation, and obstructions in the line of sight. However, the infrastructure's merge control system will have the capability to sense gaps and vehicle positions, and communicate this information to the vehicles on both automated mainline lanes and ramps.

Vehicle Cooperation

Once the vehicles have completed merge preparation, vehicle adjustments will take place through vehicle to vehicle communication and cooperation. As vehicles approach the merging juncture, they will ensure that if gaps were prearranged by the infrastructure, they are acceptable. If gaps were not prearranged by the infrastructure or if the gaps created by the infrastructure are inappropriate, vehicles will follow communication protocols and cooperate to either create acceptable gaps or adjust merging vehicles into existing gaps.

Merging Traffic

Once the vehicles are near the merge point, if infrastructure support and vehicle to vehicle communication and cooperation are in place, vehicles in both traffic streams should be coordinated with each other and be in correct position to merge. Once the vehicles are in position to merge, the merging vehicle will determine the appropriate changes it needs to make in its speed, path, and acceleration in order to ensure that it reaches its pre-specified gap at the right time, the right place, and with the appropriate speed.

Control and Communication Strategies Selected for the Simulation Model

A set of specific control and communication strategies were selected from the range of options, assuming an evaluation of the most promising merging control and communication strategies by selecting a model that would minimize mainline disruption and maximize of merging throughput. The following determinations were made on this intent.

Control Strategy

The control strategy which seems most advantageous to this definition of efficiency is the microscopic control with release to gaps, which are available from gap creation through gap consolidation. This strategy has a minimum effect on mainline vehicles in that it does not ever force mainline vehicles to slow, but it does provide an increased number of gaps to the merging vehicles.

Vehicle-to-Vehicle Communications

Vehicle-to-vehicle communications are required for the selected control strategy to work. An initial estimation shows that the most efficient vehicle-to-vehicle communication strategy is the infrastructure assisted vehicle-to-vehicle communications. Here, the infrastructure assists vehicle-to-vehicle communications by informing merging vehicles which mainline vehicles bound their desired gaps, and assists merging vehicle in opening communications with those mainline vehicles.

Infrastructure to Vehicle Communications

Some level of infrastructure control is required for the release to gap control strategy. The infrastructure instructed communication strategy provides this control through two methods. First, the infrastructure assigns merging vehicles to specific gaps based on each vehicle's length and acceptable acceleration. Second, once vehicles are assigned to gaps, the infrastructure does not allow the vehicle that bounds the upstream limit of that gap to accelerate until the merging vehicle has completed the merge. This second constraint ensures that the upstream vehicle does not eliminate the assigned gap before the merging vehicle is able to complete the merge.

Vehicle-to-Infrastructure Communications

Active vehicle-to-infrastructure communications are required to support infrastructure instructed communications because the infrastructure's assign gap protocol is constrained by vehicle acceleration rates which the merging vehicle must be able to communicate to the infrastructure.

MODEL DEVELOPMENT

A detailed description of the model used in this analysis is presented in "Automated Highway System Merging Control, Part 2: Model Development" of these proceedings. A brief description of the model follows.

Mainline Vehicle Parameter Update Cell

The mainline parameter update cell is the first cell in the system processor. The main sub-cells in the mainline vehicle parameter update cell are the intra-platoon following model, the platoon following model, and the platoon forming model.

Intra Platoon Following Model

The first sub-cell in the mainline parameter update cell is the intra-platoon following model. This model is used only in the case of platooning, whereby vehicles in the platoon follow each other at close range. The premise for this model is quite simple. For all platoon members behind the platoon leader, the model will assume user specified fixed time or fixed distance headway from lead vehicle. This model is based on the premise that low delta velocity collisions can be tolerated on an AHS, because they will produce limited damage to persons and property (*5*). It should be noted, however, that this premise is theoretical and has not been fully validated at this time.

Platoon Following Logic

The platoon following logic is based on the GM car following models developed in the late 1950's and early 1960's (*6*) and further refined by Ran et al in 1996 in the development of the AHS (*7*). This model is based on the premise that vehicle response should be a function of stimuli available and the sensitivity to that stimuli. Assume that a following vehicle is traveling at a higher velocity than its leader. The higher the following vehicle's speed, the greater the difference in the leader and follower's velocities, and the shorter their separation distance, the greater the following vehicle's deceleration rate. The platoon following logic works well at medium range for decelerating maneuvers. It does not work well at very close intra platoon headways or for "catch up" scenarios that are required to form platoons. Therefore, this model is only used at distances where a vehicle does not wish to join the platoon in front.

Platoon Forming Logic

The platoon forming logic sub cell, is the last of the major sub cells in the mainline vehicle parameter update cell. The premise of this sub cell is that the vehicle will accelerate at a user specified acceleration rate to a user specified catch up speed, and then decelerate at a user specified deceleration rate such that it "catches" the lead platoon at the user specified fixed time or space headway at the lead platoon's speed.

Merging Parameter Update Cell

The second major cell is the merging parameter update. The major sub cells in this cell are the platoon following model as described in the mainline update cell, the check for gap logic, the deceleration for metering logic, the gap adjustment logic, and the gap assignment logic.

Check for Gap Logic

The check for gap logic is the first sub cell in the merging parameter update cell. This sub cell checks the mainline to see if a gap is available for merging, and is based on the premise that if a vehicle travels at its initial velocity as long as possible and accelerates at the last possible moment to the mainline speed, it will intercept the furthest upstream gap that it can possibly merge into. Also, if a vehicle travels at its initial velocity as shortly as possible and accelerates at the first possible moment to the mainline speed, it will intercept the furthest downstream gap that it can possibly merge into. Any gap in this range is acceptable for the vehicle to merge into.

Gap Adjustment Logic

Once the range of possible gaps has been determined for a merging vehicle, and a specific gap has been assigned to that vehicle, the vehicle must adjust its acceleration rate so that it intercepts the correct gap at the correct time and at the correct speed. It does this by traveling at a constant velocity for a set distance, accelerating to the mainline velocity at a constant rate, and then traveling at the mainline velocity to the merging point. Note that the vehicle must arrive at the precise merging point at the right time and at the right speed.

Deceleration for Metering Logic

The deceleration for metering logic is the last sub cell in the merging parameter update cell. If no gap is available for the vehicle, it must stop in time such that when a gap does come available, it will be able to accelerate to the mainline speed. Note that vehicles do not have to come to a complete stop, but, as soon as they find a gap, they can begin adjusting to that gap. The deceleration for metering logic also defines the minimum ramp length that can be used for any given situation, which is a function of the merging vehicle's acceleration rate, the merging vehicle's initial speed, and the mainline speed. The ramp must be long enough such that a merging vehicle that can not find a gap can come to a complete stop on the ramp, and after finding a gap, accelerate to the mainline velocity and execute the merging maneuver.

MODEL VALIDATION

This section discusses the validation parameters. This validation used 12,000 time steps of 0.1 second for an overall simulation length of 1200 seconds (20 minutes). Also, the simulation scenario has a one lane two mile mainline and a two-thousand foot merging ramp intersecting the mid point of the mainline section. Geometric and flow parameters are shown in Table 1. Note that the only geometric parameters that can be changed in this model are mainline length upstream of the merge point, ramp length, and mainline length downstream of the merge point.

Table 1. Geometric Section Parameters

Section	Length (ft)	Flow (vph)
Mainline Upstream of Merge Point	5280	4197
Ramp	2000	2748
Mainline Downstream of Merge Point	5280	6945

Other geometric parameters such as grade and pavement type are assumed in the model and can not be changed by the user. Assumed grade is 0%, pavement condition is dry (max braking is 0.8 gs), and sections are assumed to be straight (no curves). Also, all vehicles are 20 feet long and have equal acceleration and deceleration capabilities as shown in Table 2.

Table 2. Acceleration Parameters

Desired Deceleration Rate	-9.5 fps^2	0.3 g

Maximum Deceleration Rate	$-25\ fps^2$	0.8 g
Desired Acceleration Rate	$6.5\ fps^2$	0.2 g
Maximum Acceleration Rate	$9.5\ fps^2$	0.3 g

Although not accounting for grade and differential acceleration and deceleration parameters is a significant simplification which makes this version unusable for safety analysis, it allows for initial control parameters and flow characteristics to be established and tested. These parameters, as shown in Table 3, resulted in a successful run with reasonable flows and speeds. Also, no accidents nor merge failures are encountered as long as adequate ramp lengths were provided.

Table 3. Model Results

Section	Average Speed (fps)	Initial Speed (fps)
Mainline Upstream of Merge Point	100	100
Ramp	89	75
Mainline Downstream of Merge Point	104	

Mainline Control Model

This section describes mainline component validation. As was shown previously, mainline vehicles are at all times in one of the following categories: intra platoon following, inter platoon following, platoon forming, or zero acceleration (for vehicles immediately upstream of a gap that has been assigned to a merging vehicle.)

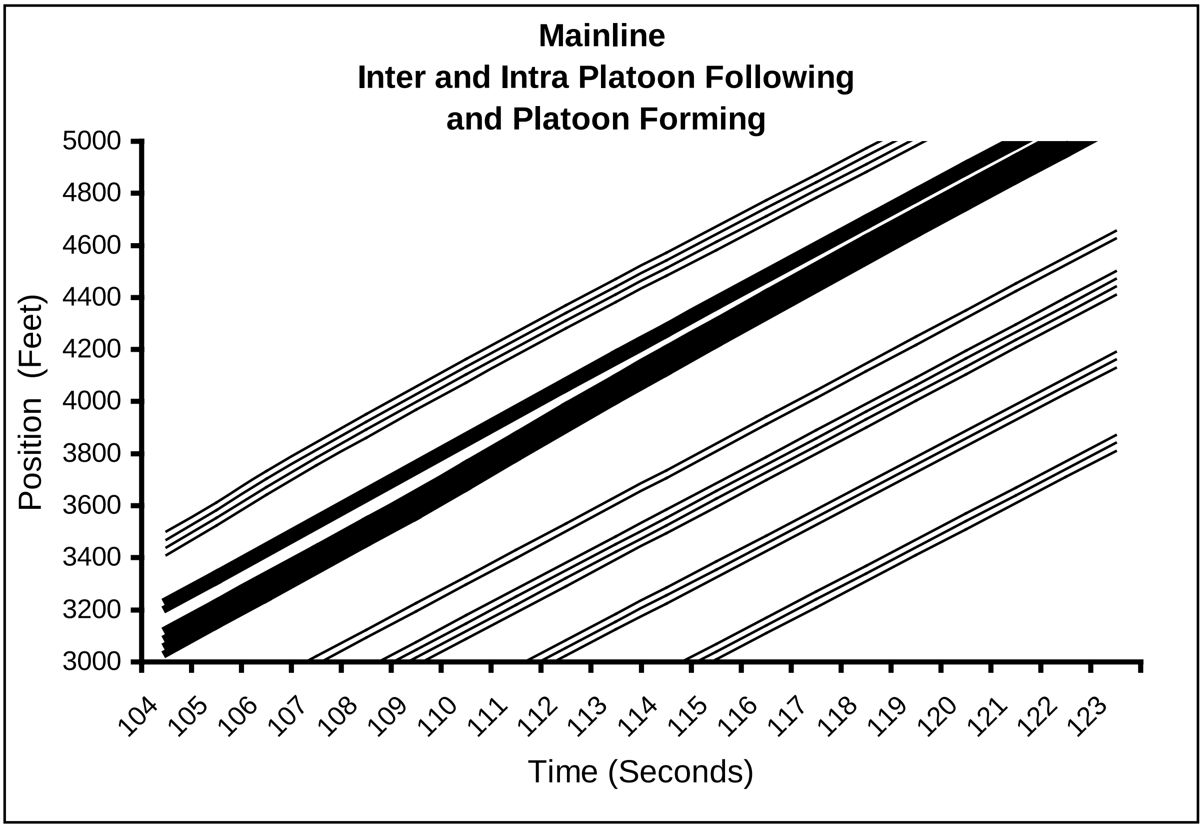

Figure 2. Mainline Control Validation

Intra Platoon Following Sub-Model

Intra platoon following is used for all mainline vehicles that are not platoon leaders or independent vehicles. The intra-platoon following sub-model control strategy for simply requires vehicles to follow their leader at a spacing of 30 feet, which requires a 10 feet separation between vehicles. Two examples of vehicles under the intra vehicle control are shown in Figures 2 and 3. Both figures show the successful implementation of intra platoon following in that vehicles maintain constant 30 foot headways.

Inter Platoon Following Sub-Model

The inter platoon control model governs vehicle acceleration on the basis of vehicle velocity and differential position and speed between the follower and leader. Figure 2 shows that following vehicles do follow its leading vehicle at an acceptable distance (about 100 feet in this case). Although not discernible from the figure, the followers do respond to slight acceleration changes of the leader (on the order of -2 to 2 fps^2). Although small, these changes in speed do show that the following vehicles do react to their leader's speed changes. Response to larger acceleration rates are not shown, because the smooth operation of the mainline did not result in large acceleration or deceleration rates on the mainline. It is important to note that this validation did not test the inter platoon following control under extreme or emergency circumstances. Because the intent of this study is to establish initial control and flow characteristics, and not to conduct a safety analysis, this omission is acceptable.

Platoon Forming Sub-Model

The platoon forming control logic applies to mainline vehicles where the leader has a non-negative acceleration, the sum of the leader and follower platoon length does not exceed the maximum platoon length, the gap immediately upstream of the following vehicle has not been assigned to a merging vehicle, and the distance between the follower and the leader does not exceed the maximum threshold. Figure 2 shows one instance of this maneuver. In addition, Figure 3 illustrates the results of this maneuver where the initial speed of both vehicles was 100 fps at a spacing of 90 feet, the maximum platoon size was 20 vehicles, the maximum speed on the mainline was 120 fps, and the maximum separation distance to form platoons is 120 feet. Note that intra platoon following is also shown in this figure.

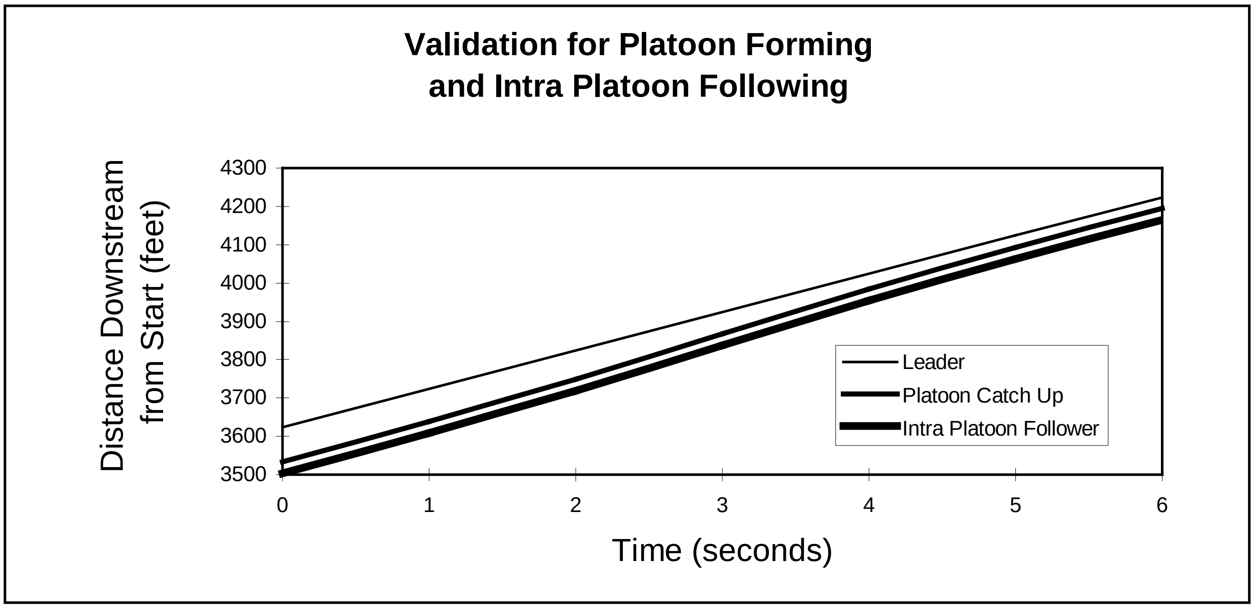

Figure 3. Platoon Forming and Intra Platoon Following Validation

Once the logic allowed the follower to begin the platoon forming maneuver, the follower accelerated at 6.5 fps^2 for the time period 0.2 seconds to 3.1seconds, which resulted in a speed increase from 100 fps to 120 fps. The follower then maintained a constant speed of 120 fps for the time period 3.1 seconds to 3.4 seconds, during which time the model logic determined that the critical deceleration point had been reached. Then, the follower decelerated at -10 fps^2 for the time period of 3.4 seconds to 5.4 seconds, which resulted in a speed drop from 120 fps to 100 fps during which time the follower had “caught up” with the lead platoon at the leader’s velocity at a 10 foot spacing.

Merging Control Model

This section will describe the ramp flow validation. Merging vehicles are at all times in one of the following categories: decelerating for metering, adjusting to gap, braking to avoid collision, or platoon following where the vehicle's leader does not have an assigned gap. The results are shown in Figure 4 and discussed in the following.

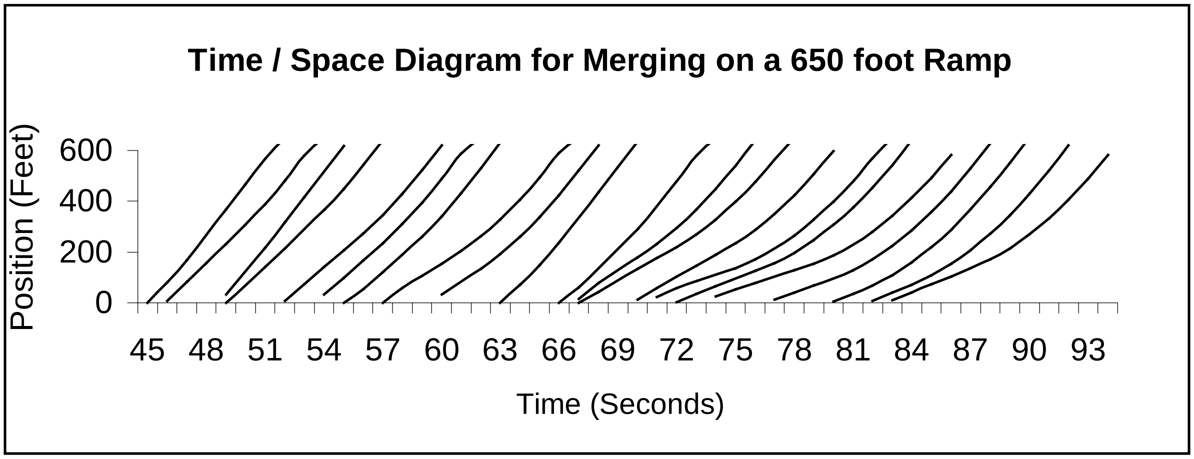

Figure 4. Merging Control Validation

Deceleration for Metering Sub-Model

The deceleration for metering control logic applies to merging vehicles that have not been assigned a gap.

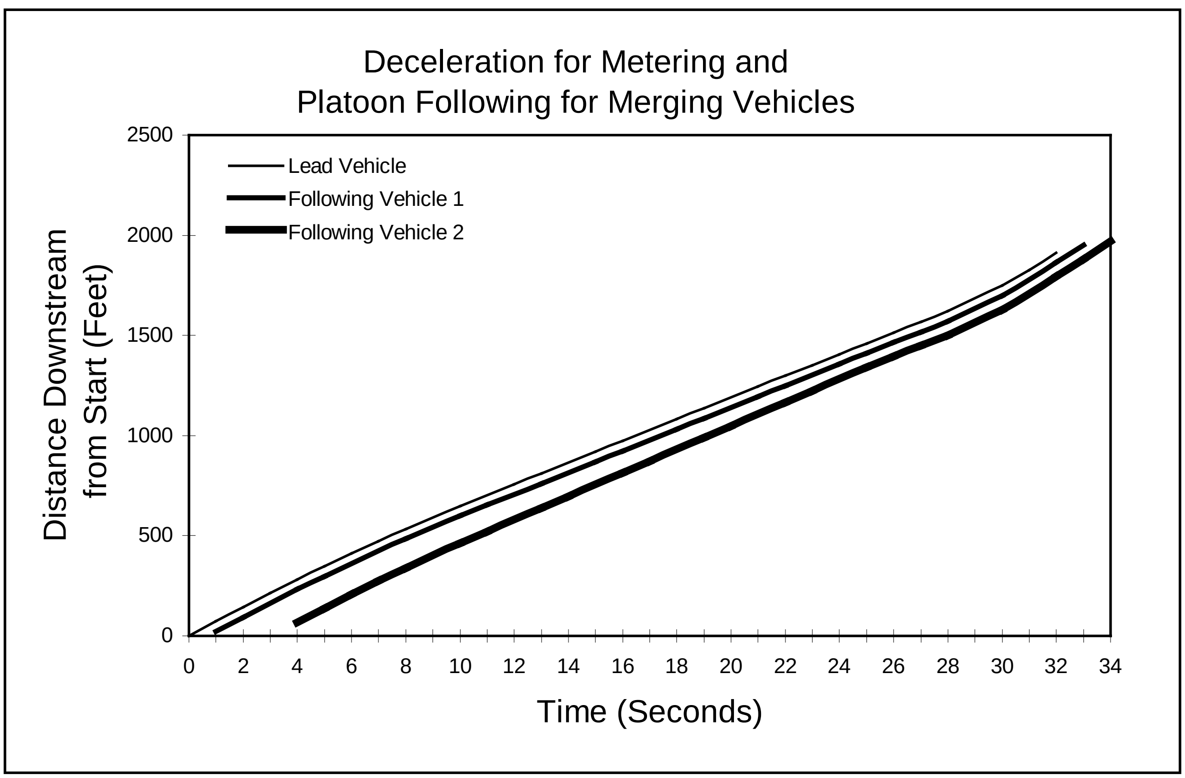

Figure 5. Deceleration for Metering and Platoon Following for Merging Validation

Those vehicles that do not have a gap can stop, wait for a gap, and accelerate to the mainline speed when a gap appears. This maneuver ensures that all merging vehicles will receive gaps. Figure 5 illustrates the results of this maneuver where the initial speed of the merging vehicle is 75 fps. As can be seen from the figure, the "lead vehicle" did not have a gap for the initial 10.8 seconds. The "lead vehicle's" leader (not shown) also did not have a gap for the first 0.3 seconds. Thus, the "lead vehicle" decelerated under platoon following rules in the initial 22 feet to 73 fps. Also shown are two following vehicles that operated under platoon following rules for the initial 10.8 seconds. Once the "lead vehicle's" leader received a gap, the "lead vehicle" decelerated under deceleration for metering rules at -1.87 fps^2 from 0.3 seconds to 10.8 seconds from a speed of 73 fps to 54 fps. This deceleration rate is appropriate because if the vehicle would not have found a gap, it would have stopped at 1447 feet downstream from the start of the ramp. This would have allowed the merging vehicle to accelerate to the mainline speed of 100 fps in the remaining 553 feet of ramp at the acceleration rate of 9.5 fps^2, once a gap would have come available. As can be seen from Figure 4, however, the vehicle did not stop, but did find a gap at 10.8 seconds and performed the gap adjustment maneuver.

Platoon Following Where Leader Does Not Have Gap

If a merging vehicle's leader is not assigned a gap, the merging vehicle will operate in the platoon following mode. Platoon following on the merging ramp is in place so that a vehicle can not be assigned a gap that is downstream of its leader's gap. Also, ramp platoon following assures that the infrastructure will not take a gap away from one vehicle so that it can reassign that gap to downstream merging vehicle whose gap options are more limited. Figure 4 illustrates several instances of ramp platoon following. Furthermore, Figure 5 illustrates the results of this maneuver in detail as the lead vehicle did not have a gap assigned during the period of 0.3 to 10.8 seconds, and the two following vehicles operated under platoon following rules. The figure shows the vehicles keeping a reasonable distance and adjusting to their leader's movements during this period.

Gap Adjustment Sub-Model

The gap adjustment logic applies to merging vehicles once they have been assigned a gap. It operates under the premise that vehicles will maintain a constant initial speed, accelerate at a constant rate to the mainline velocity, then travel at the mainline speed until the merge point. Figure 6 illustrates the results of this maneuver where the initial speed of the merging vehicle is 75 fps, the final merge speed is 100 fps, and the acceleration rate is 9.5 fps^2.

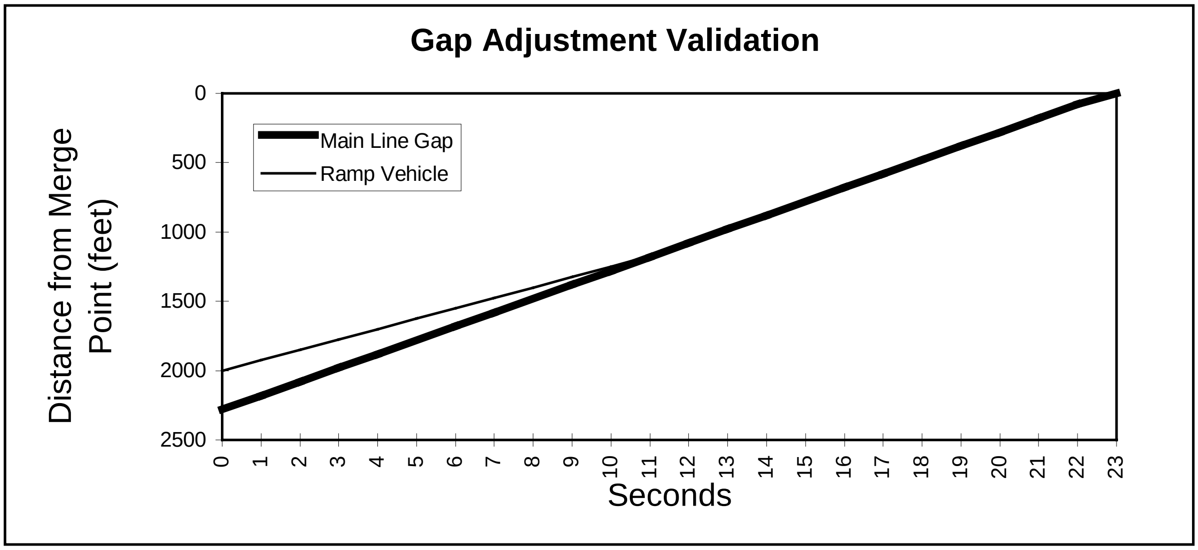

Figure 6. Gap Adjustment Validation

The merging vehicle in this case maintains a constant initial speed for time period from 0 seconds to 10.2 seconds, and accelerates at 9.5 fps^2 from 10.2 seconds through 12.8 seconds, which results in a speed change from 75 fps to 100 fps. Also shown in the diagram is the mainline gap that the vehicle adjusts to, which travels at a constant 100 fps. As shown in the figure, the merging vehicle does complete a successful merge as it intercepts the gap at the correct time, speed, and position.

MERGING EVALUATION

This chapter evaluates the effectiveness of the AHS merging control model by comparing its output to that of the same scenario generated in the Corridor Simulation Model (CORSIM) (*8*) (*9*), which is provided by the Federal Highway Administration (FHWA). This evaluation compares the average speeds of mainline and merging vehicles under a range of flow conditions for the conventional driving, two second fixed headway metering, and AHS control cases. The conventional driving and ramp metering cases are simulated and evaluated by using the CORSIM and the AHS case is evaluated by using the AHS merging simulator. The pertinent and significant similarities and differences of these two models are discussed in this section.

Evaluation Procedure

Results from the evaluation runs are reported in percent speed reduction, which is calculated for each segment based on Equation (1).

$$\% \text{ Delay} = \frac{(\text{Free-flow Travel Time} - \text{Segment Average Travel Time})}{\text{Free-flow Travel Time}} \qquad (1)$$

The intent of the evaluation is to determine if the model output is reasonable when compared to conventional systems, and to make an initial determination whether automated merging could be successful on an AHS. The level of detail in this merging model is not sufficient so that these results can provide a basis for an AHS merging safety analysis. Rather, these are initial results that should be used to determine if the model presented in this paper should be expanded to a higher degree of fidelity (i.e. incorporate differential acceleration and braking characteristics, differential roadway grades, communication delay, jerk, etc.) such that it provides output that can be used in more extensive AHS merging evaluation.

Time Steps and Simulation Duration

All AHS simulations use 12,000 steps, which is equivalent to a simulation length of 1200 seconds (20 minutes) with 0.1 seconds per time step. All CORSIM runs use 1200 time steps for 1200 seconds (20 minutes) with 1 second per time step.

Geometry

The AHS simulations use a one lane, 10,000 foot, AHS mainline, along with a 1000 foot automated merging ramp intersecting the mid point of the mainline section. The CORSIM evaluations use a two lane, 10,000 foot, conventional mainline, along with a one lane, 1000 foot conventional merging ramp which also intersecting the mid point of the mainline. CORSIM runs also incorporate a 2000 foot acceleration lane into the mainline downstream of the merge point, as shown in Figure 9. All sections are straight and all grades are 0%. The metering point for the CORSIM ramp metering case occurs at the midpoint of the ramp.

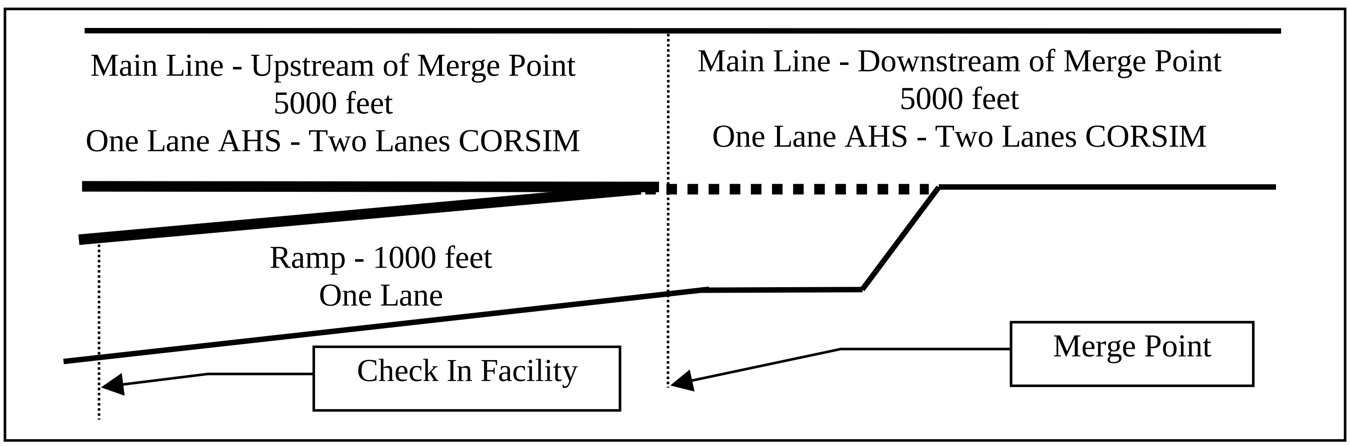

Figure 9. Evaluation Parameters

Acceleration and Deceleration Parameters and Traffic Types

For the AHS model, all vehicles are 20 feet long and have equal acceleration and deceleration capabilities as shown in Table 2. For the CORSIM evaluation, no trucks were used, and FRESIM default values were used for all passenger vehicle acceleration, deceleration, vehicle length, driver type, and car following sensitivity factors (*9*) as summarized in Table 4.

Table 4. Default CORSIM Passenger Vehicle Parameters (*9*)

Parameter	High Performance	Low Performance
Percent of the Fleet	75	25
Length (feet)	19	17
Maximum Deceleration (fps^2)	15	15
Maximum Jerk (fps^3)	7	7

Mainline Flow Upstream of the Merge Point

The mainline segment upstream of the merge are affected by the merge through shock-waves, which slow traffic upstream of a bottleneck.

1000 VPH Mainline

As shown in Figure 10, low mainline flows of 1000 vph have little effect on the mainline segment upstream of the merge point for conventional traffic (1% - 2% delay), ramp metered traffic (1% - 2% delay), or AHS traffic (0.0% to 0.5% delay). The fluctuations in the delay curves in this figure are most likely due to the randomness between runs in both the CORSIM and AHS Merging Control Models, and are not significant.

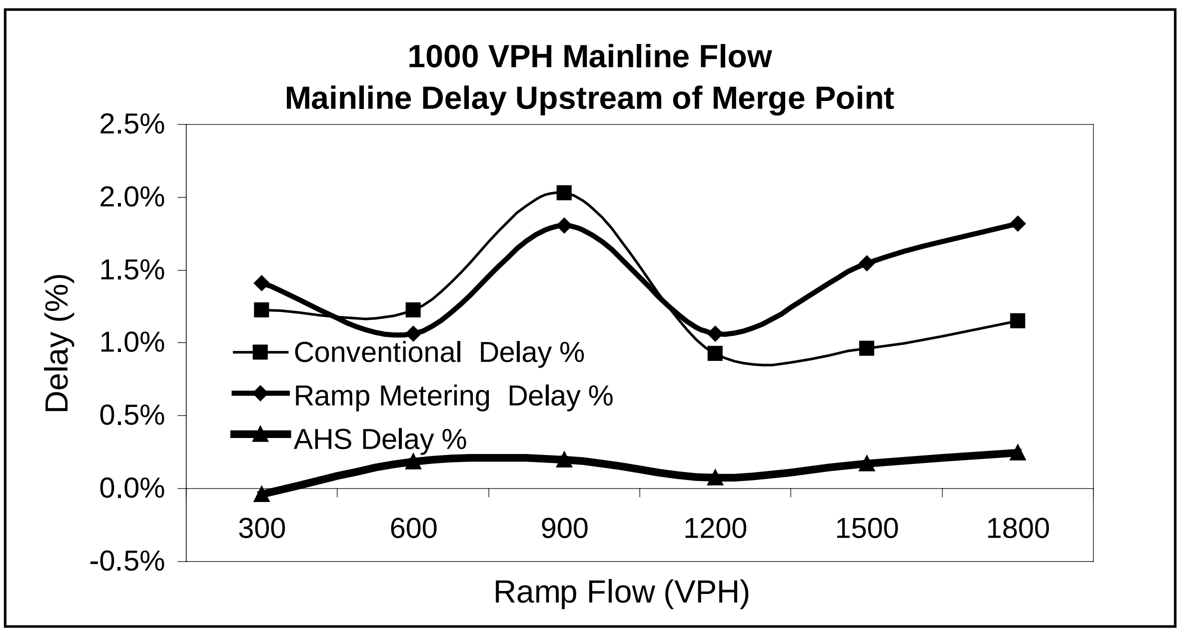

Figure 10. Mainline Delay Upstream of Merge Point with 1000 VPH Mainline Flow

4000 VPH Mainline

As shown in Figure 11, mainline flows of 4000 vph have a significant effect for conventional traffic and ramp metered traffic (up to 80% delay) while having little impact on AHS traffic (less than 1% delay).

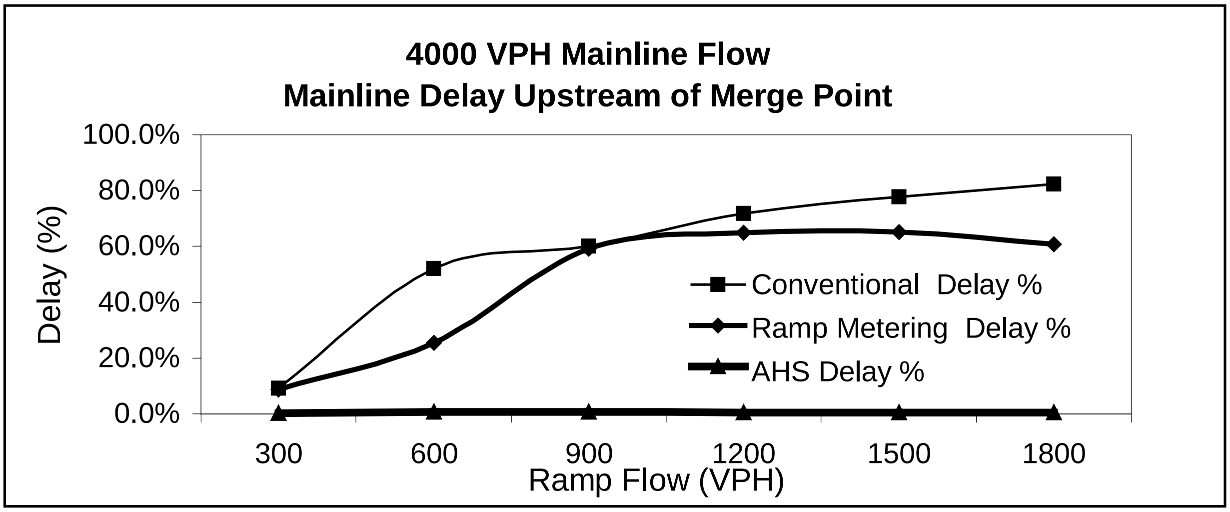

Figure 11. Mainline Delay Upstream of Merge Point with 4000 VPH Mainline Flow

5500 VPH Mainline

Mainline flows of 5500 vph were not evaluated in the CORSIM model for the conventional or ramp metered cases because the capacity of a conventional two - lane highway is only 4000 - 5000 vph. However, as shown in Figure 12, mainline flows of 5500 vph continue to have little effect on the mainline segment upstream of the merge point for AHS traffic (less than 1% delay).

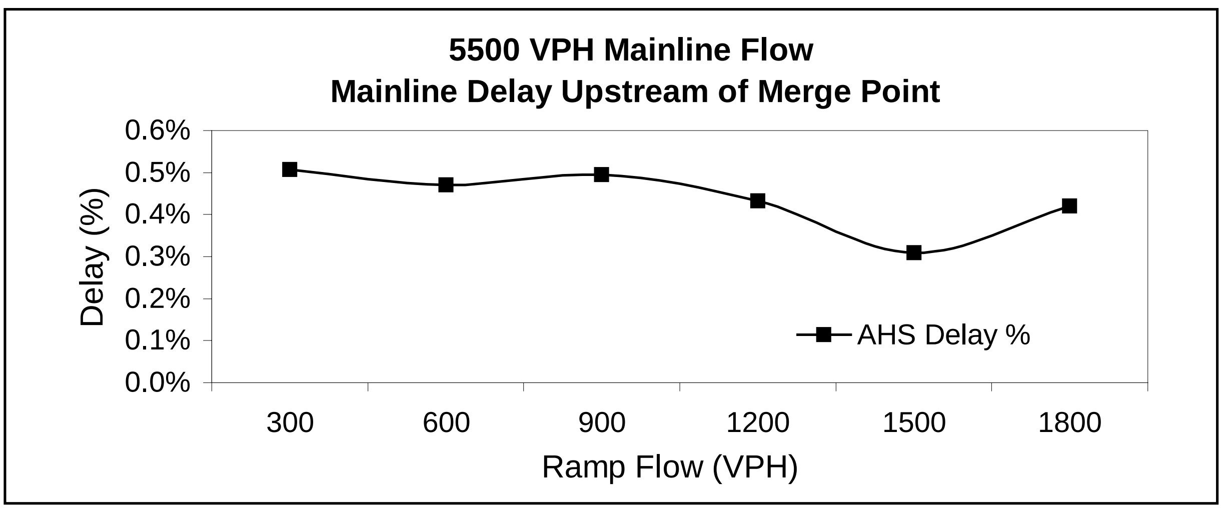

Figure 12. Mainline Delay Upstream of Merge Point with 5500 VPH Mainline Flow

Mainline Flow Downstream of the Merge Point

Delay incurred downstream of the merge point is due to the addition of merging vehicles to the traffic stream. The addition of vehicles at the merge point will tend to increase the density of the traffic stream and, in conventional systems, lower traffic speed. In the AHS model, this is not the case because increased density does not lower speed. Rather, because the mainline is not required to create gaps for merging vehicles, the mainline traffic stream maintains a desired speed. In fact, because the merging vehicles will form with mainline platoons, the downstream AHS speeds actually tend to increase.

<u>1000 VPH Mainline</u>

As shown in Figure 13, low mainline flows of 1000 vph has little effect on the mainline segment downstream of the merge point for conventional traffic and ramp metered traffic (2% to 6% delay) or AHS traffic (-1% to -5% delay). The negative delay incurred for the AHS traffic is the result of platoon forming after the merge point, where merged vehicles are accelerating to join the platoon in front of them.

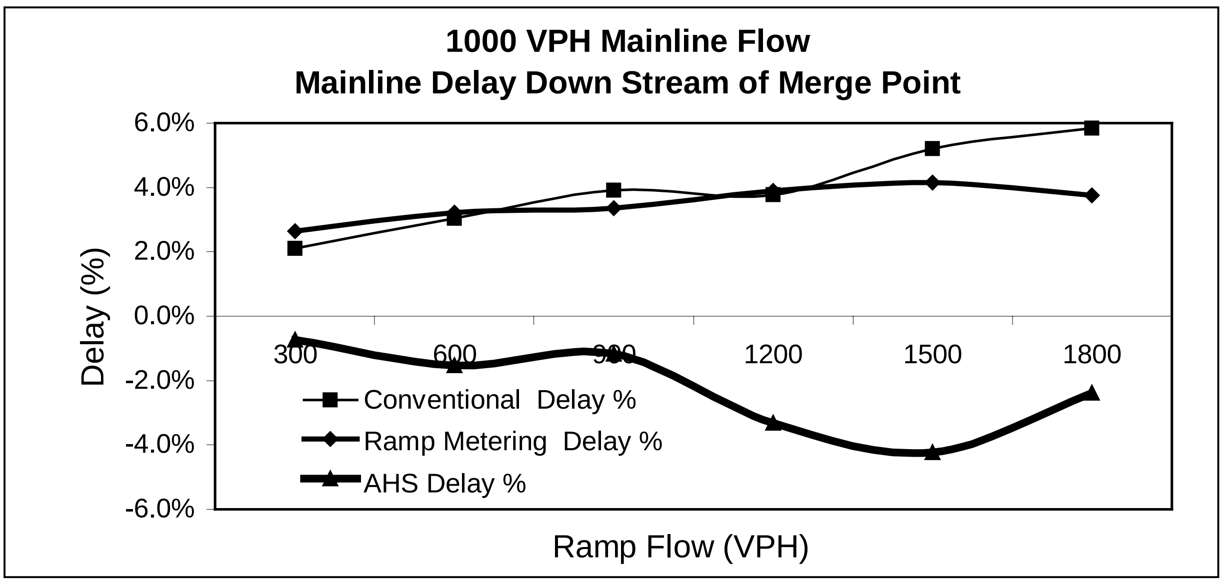

Figure 13. Mainline Delay Downstream of Merge Point with 1000 VPH Mainline Flow

<u>4000 VPH Mainline</u>

As shown in Figure 14, low mainline flows of 4000 vph has a significant effect on the conventional traffic and ramp metered traffic (10 % to 35 % delay), and again, has little effect on AHS traffic (0% to -5% delay).

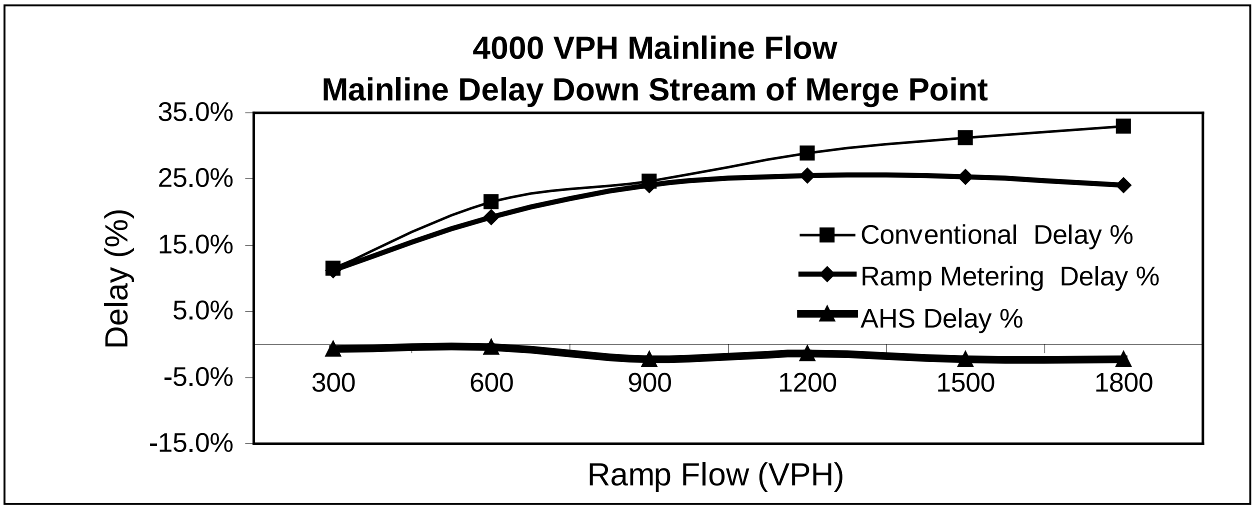

Figure 14. Mainline Delay Downstream of Merge Point 4000 VPH Mainline Flow

<u>5500 VPH Mainline</u>

Mainline flows of 5500 vph were not evaluated in the CORSIM model for the conventional or ramp metered cases because the capacity of a conventional two-lane highway is only 4000 - 5000 vph. However, as shown in Figure 15, mainline flows of 5500 vph continue to have little effect on the AHS traffic (0 % to -2.5 % delay).

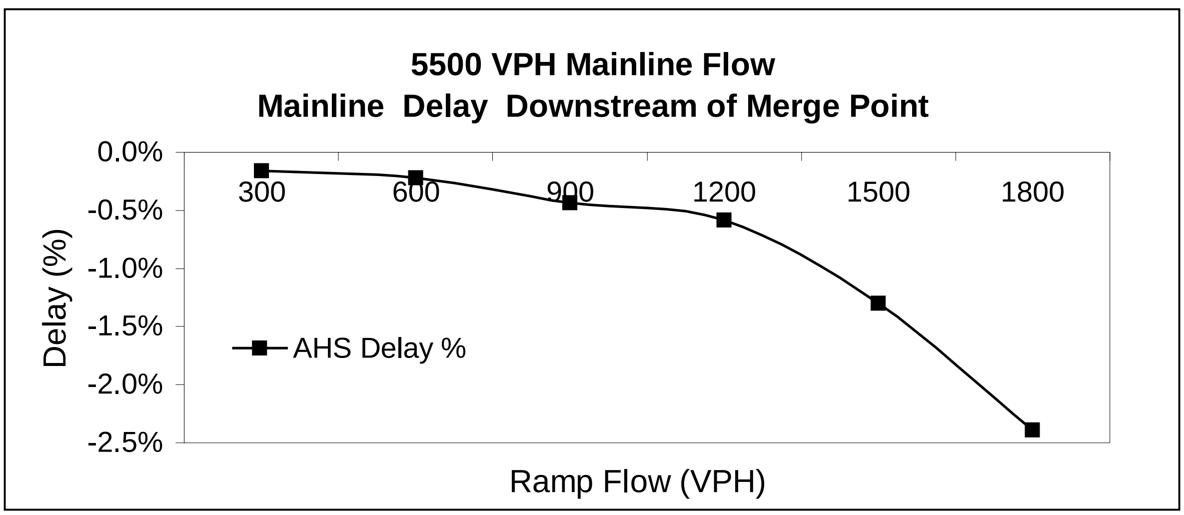

Figure 15. Mainline Delay Downstream of Merge Point with 5500 VPH Mainline Flow

Ramp Flow

For the conventional and AHS cases, delay incurred on the ramp is due to the merging vehicles that are unable to find gaps. Ramp metering causes delay for the CORSIM ramp metering case.

VPH Mainline

As shown in Figure 16, low mainline flows of 1000 vph has little effect on the ramp for conventional and AHS traffic and ramp metered traffic (0% to 5% delay). However, ramp metered traffic is delayed by 40 % to 60% because they must stop for the ramp meters whether or not a gap exists.

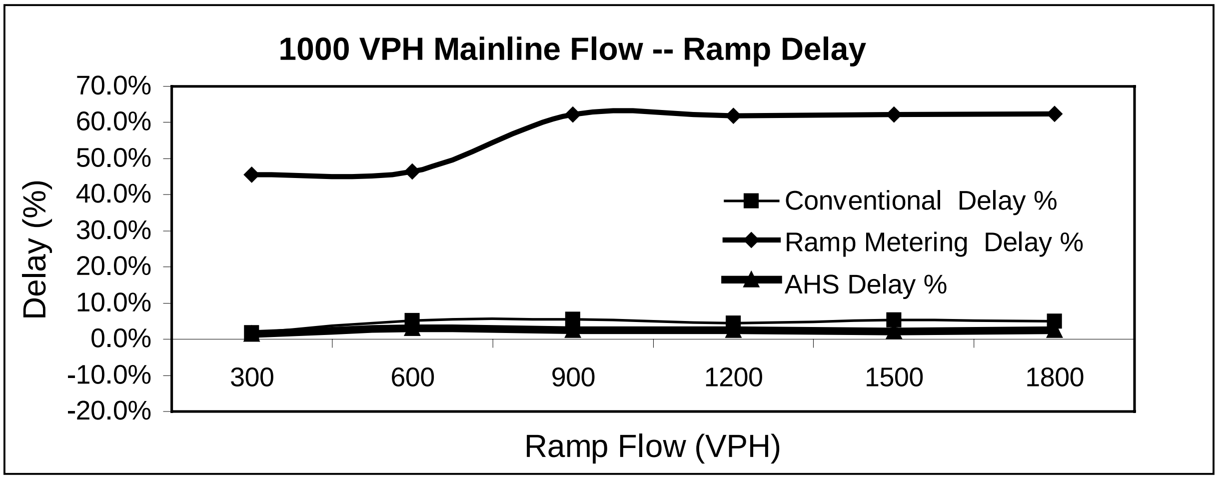

Figure 16. Ramp Delay with 1000 VPH Mainline Flow

4000 VPH Mainline

As shown in Figure 17, high mainline flows of 4000 vph has little effect on the ramp for conventional, AHS traffic and ramp metered traffic (0% to 6% delay) up to a ramp flow of about 1500 vph. The delay for conventional traffic increases sharply, up to 40%. However, the AHS ramp traffic maintains a low delay of 6%. Ramp metered traffic maintains 40 % to 60% delay.

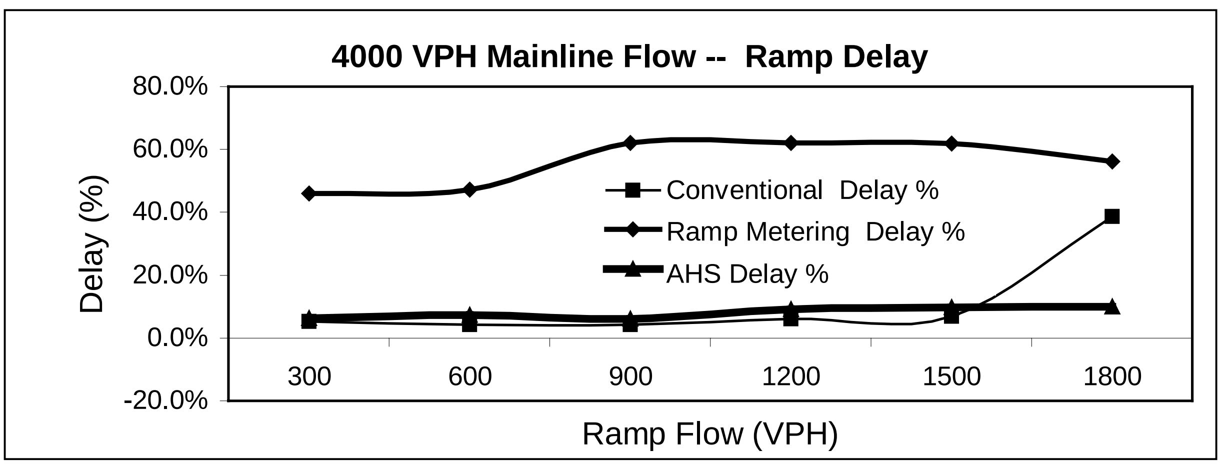

Figure 17. Ramp Delay with 4000 VPH Mainline Flow

5500 VPH Mainline

As shown in Figure 18, high mainline flows of 5500 vph continue to have little effect on the AHS ramp traffic (7 % to 13 % delay).

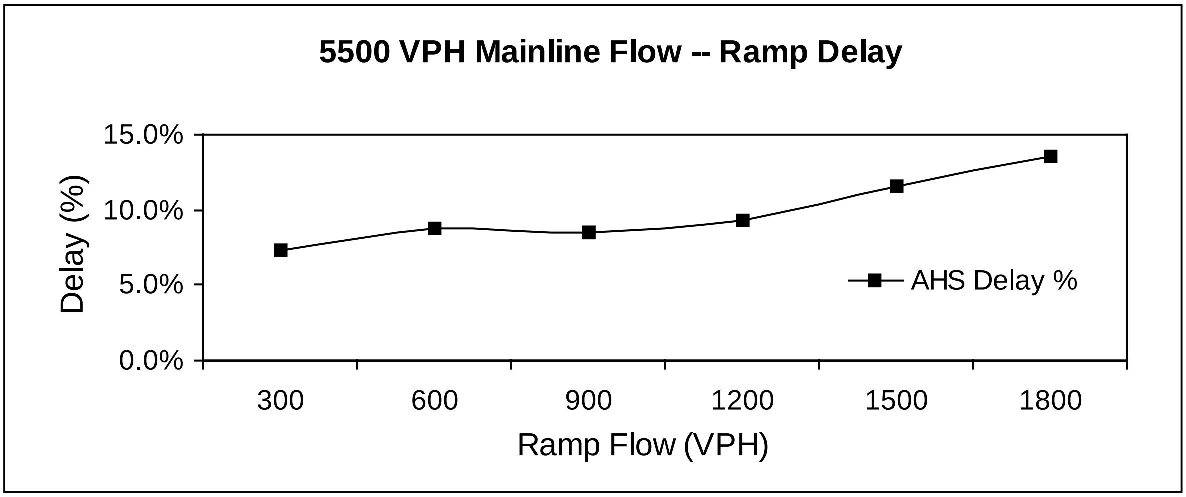

Figure 18. Ramp Delay with 5500 VPH Mainline Flow

CONCLUSIONS

The preceding sections show that for low flows and conventional highway speeds (55 mph), a one lane AHS merging section with a dedicated automated entrance ramp behaves with much of the same characteristics as a two lane section of conventional highway with or without fixed time ramp metering. However, when the conventional freeway begins to "break down" near its capacity, the AHS, in this model, continues to perform with little delay.

The results also seem to show that the merging maneuver from a single on ramp should have little effect on AHS mainline operations, if the control and communication methods used in this paper are applied. However, this paper does not show the effect of merging operations where several on and off ramps are used, and it does not show the interaction of these ramps with each other. However, because the mainline traffic takes precedence over merging traffic, it will most likely be the case that multiple merging points will not have a significant adverse effect on mainline operations, as long as total mainline capacity is not exceeded. This, however, should be the focus of future studies.

Also, it should be noted that the merging control scenario presented in this paper represents a simplified model of reality. Different scenarios and control and communication strategies could be created in the model by changing the sub-models to represent various assumptions. Furthermore, factors such as differential braking, communication time delay, and failure analysis need to be added to give the model a higher degree of fidelity.

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