Automated Highway Merging Protocols and their Effectiveness on Highway Operations and Vehicle Performance

by

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Introduction

Urban freeways in the modern era have become highly congested in every major city, especially in peak commute hours. With the outgrowth of population from city centers to suburbia, there has arisen an equally aggressive growth in demand on the corridors that link them. This increase in traffic volumes has long since surpassed the intended capacity and has led to the overall breakdown in the function of the original freeway system. The results of this dysfunction promote high congestion and highly unstable traffic flows. These, in turn, promote the increase of harmful emissions, fuel consumption rates, and travel time delays.

Because of our highway system's inability to meet emerging travel demand, the highway frequently operates in a "stop and go" state where vehicles accelerate and decelerate often. This constant change on the demands on the vehicle's engine creates a state of inefficient fuel usage which when aggregated to the total amount of vehicles on the road, represents an extraordinary waste of our fuel resources. (1) In a society where dependence on foreign oil is a necessary crutch , it is in our economic and political interest to maximize the use of our reserves to minimize this handicap. Reduction of highway congestion is essential to this end.

Unstable traffic flow also leads to great increases in the amount of emissions in our atmosphere. Because of the inefficient operating state of our engines in traffic congestion, the amount of emissions compared to free flow travel increase greatly. The results of this phenomenon are clear and widely known: poor air quality, increases in global warming, and unpredictable environment changes. Therefore, from a quality of life perspective, any reductions in the emissions that occur without detracting from the normal necessities of travel are not only favorable, but necessary to maintain the current status quo in the long term. Reductions in highway congestion are necessary to this end as well.

Highway congestion is also the cause of increased delays in travel time which are the most visible disadvantage of a dysfunctioning highway system. Average metropolitan travel times, can seem unimaginably long and if population growth patterns continue, the decreasing unused capacity levels can lead to even longer delays. Automobiles will become part-time residences because of the increasing portion of the day that the average individual will spend in congestion. As a result, significantly increasing freeway efficiency and pipeline capacity over marginal amounts are ideal methods to alleviate congestion and thus reduce travel time to acceptable levels in the long term.

The most direct plan of action for alleviating congestion would be to add marginal capacity by building more streets, lanes, or even freeways. However, this external approach to problem-solving is not feasible when considering the structural and financial constraints and complexities of central business district (CBD) construction. Government agencies are simply very hesitant to fund such large-scale projects because of limited funds and/or political agendas. Therefore, it is impossible to implement this approach over an adequate portion of the highway networks to achieve results favorable enough to justify the investment of capital and resources.

In addition, latent demand, which states that traffic volumes grow proportionately with marginal increases in capacity (5), also eliminates this measure as an effective alternative. For example, the construction of an additional lane will only alleviate congestion temporarily, but as time passes, it will attract more commuters, either from alternative corridors or modes of transport, which will eventually cause congestion to recur on a greater scale. As a result, this limited additional capacity provides only a temporary solution and only delays problems until traffic volumes once again grow to exceed system capacity. Therefore, this approach is too shortsighted to consider as an effective long term solution to the problem of congestion.

The expansion of public transit as both a means to reduce congestion by reducing automobile demand on highways and improve air quality by utilizing clean electrical power has also been considered in attempts to improve highway operations. However, its effectiveness in attracting enough ridership to accomplish this has proven to be infeasible. Despite attempts to improve and extend transit service, it simply cannot match the convenience nor performance of the automobile. In addition, in low density areas such as suburbs, transit is simply not cost-effective enough to justify the amount of capital needed to initiate and maintain service[1]. In short, transit is not a realistically effective means of reducing congestion and the problems that accompany it.

A wide range of other alternatives have also been implemented in an attempt to mitigate the effects of congestion on highways. Small scale ones such as telecommuting, ridesharing, and staggered work hours have had limited success, but are still hindered by their negative effects on the economy, convenience of the passenger, and necessary

[1] Federal Transit Administration,National Transit Summaries and Trends,May 1995

changes in lifestyle. They simply demand too many changes in the way in which one travels and lives. Other proposed large scale mitigations such as rezoning to distribute travel patterns are very costly and often hindered by opposing political agendas. In addition, it may take decades to reap any rewards which is simply impractical considering its modest effect on the reduction of congestion. Therefore, since these approaches are not sufficient, any alternative solution or mitigation to the problem of congestion that can possibly be implemented must be both extremely effective and representative of a long term solution or mitigation.

Abstract

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Merging areas of onramps to freeways are major sources of highway congestion. Frequently, the combination of mainline vehicles and merging vehicles exceed the capacity of the freeway segment immediately downstream. The resulting queue leads to a highly unstable mainline state in which delays, vehicle emissions levels, and fuel consumption rates are all characterized by values indicative of congestion.

Automated highway system merging protocols are designed to improve both merging processes and conditions downstream such that the above negative side effects of a congested freeway system are significantly reduced. However, it is important to identify as to what degree this reduction will occur as well as what intelligence level of automated system will bring about this level of improvement. These automated highway system intelligence levels, or concepts, will be analyzed to determine their level of effectiveness on congestion in the presence of varying degrees of traffic on a typical urban highway.

Traffic was simulated along Interstate 10 in Houston, Texas using microscopic automated highway modeling tools programmed in SHIFT. Data was generated on vehicle emissions, fuel consumption rates, level of service, and delay to estimate the effective of an AHS system. Several different intelligence levels of AHS were used in this process.

Average hydrocarbon emissions were reduced by the implementation of the Automated Highway System. In addition, fuel consumption rates were also decreased. Overall, as expected, vehicles experienced reduced travel times and superior highway operations. Their level of improvement was dependent upon their intelligence level where the most advanced, Cooperative Platooning, experienced no delay or reduced travel times, while the others showed significant, but lesser improvements over non-automated, or manual, conditions. All AHS scenarios demonstrated an ability to serve greater amounts of vehicles at superior highway conditions than these manual conditions.

1. Merge Description

1.1. Automated Highway System

1.1.1. System Description

The Automated Highway System, or AHS, is a system of greater highway operations control. It seeks to maximize freeway efficiency in maneuvering and travel conditions, while minimizing individual vehicle delay. The AHS technology is implemented for each vehicle such that automatic control is exercised by monitoring and dictating each longitudinal and lateral vehicle movement. Each vehicle action is regulated in the interests of both safety and performance. By having the vehicles under automated control, the efficiency of highway operations is greatly improved such that more vehicles can use the system at any given time with less delay.

AHS entails sensors on vehicles, which can sense other vehicles and obstacles that may be on the highway. In addition, AHS may also consist of infrastructure which aids the vehicle sensors in determining external vehicle speeds, gaps, and positions. It is this information which is essential in governing AHS control. Through AHS, vehicles identify a plan of action such as merging, exiting, or increasing speed. Each vehicle then uses sensors to identify its current environment constraints, such as nearby vehicles, and adjusts its acceleration and/or steering accordingly. All vehicle dynamics are regulated and reaction times are much faster than that of humans. Therefore, vehicles improve the efficiency at which they maneuver, thereby creating a superior system of highway operations by allowing vehicles to travel at free flow speeds at greatly decreased spacings than manual constraints allow.

The regulation created by AHS allows for improvement in highway conditions. According to AHS simulations, accelerations are significantly less sporadic and this greater stability decreases emissions that are the result of unstable engine states (2). AHS also enables vehicles to travel with lesser inter-vehicle spacings than normal highways can allow. Because sensors and on-board processors are able to identify, process, and react much more quickly than humans, the needed spacings in between vehicles to maintain safety are much less constrained. As a result, the critical density at which vehicles can travel a highway segment with little or no delay is greatly increased. In addition, the decreased inter-vehicle spacings cause fuel consumption rates to be reduced by reducing the aerodynamic drag associated with isolated longitudinal travel. Therefore, AHS, theoretically, is a system achieves a much improved level of safety and performance.

AHS implements actual merge protocols and gap aligning algorithms which serve to minimize the mainline congestion associated with merging. It is the intent of this system to maintain free flow travel speed on the highway even at merge junctions where usual shock waves are created. Therefore, the highway system may still enjoy the benefits of greater vehicle flow without experiencing the additional shock waves that would normally accompany such an increase. By eliminating these major causes of highway congestion, AHS seeks to improve emissions, fuel consumption, highway throughput operations, and travel times.

1.1.2. Merging Analysis

Many significant causes of mainline congestion lie in the interfaces between the designed free flow portion of a highway and its interface with transitions between transportation systems such as onramps and offramps. It is within these areas where most breakdowns in the normal flow states occur. As a result, beyond merge junctions at both metered and non-metered onramps, the increased in density contributes to shock waves that lead to both severe congestion and accidents. Though current strategies such as ramp metering seek to improve this situation by efficiently distributing vehicle flow into the highway, they are still unable to reduce the relative speed and minimum gap limitations that human drivers must obey to ensure a safe merging maneuver. In addition, metering and similar strategies are largely unsuccessful because they cannot improve the actual dynamics of the merging maneuver nor the aligning of themselves to gaps to achieve efficient merging at near free flow speeds. Therefore, both the merging capacity and conditions downstream are simply not adequate enough to reduce congestion.

1.2. AHS Merging Concepts

AHS was modeled within three ascending levels of automated intelligence scenarios: autonomous, cooperative, and cooperative platooning. In the autonomous case, vehicles on the mainline and ramp cannot sense each other nor align themselves to gaps until they are within both visual and sensing range of each other. Therefore, the time allowed for a vehicle to complete a merge is limited to the point where vehicles can visually interact. In the cooperative case, vehicles can sense each other before they are in sensor range utilizing advanced transportation infrastructure. Therefore, vehicles can begin to align to gaps sooner than the autonomous case and thus complete merge maneuvers in a shorter amount of time. Finally, in the cooperative platooning case, vehicles maneuver just as in the cooperative scenario except that once on the mainline, they form closely spaced platoons during longitudinal travel. More detailed descriptions of each concept follow.

1.2.1. Autonomous Intelligence

Autonomous merging intelligence is the most basic level of merging intelligence in SmartAHS. Each autonomous vehicle is independent and maneuvers according to its own agenda. Therefore, they are completely reactionary in the sense that they respond to changes in their immediate environment. Autonomous ramp vehicles wishing to merge do not sense vehicles on the mainline until they are beyond the **L_gap_visible_range** point which is defined as the point where vehicles on the ramp can begin to visually sense vehicles on the mainline. In the case of autonomous intelligence, the **L_gap_visible_range** is located at the point where vehicles begin to merge (See Figure 1). Therefore, vehicles begin to align themselves to gaps only when they reach the point of merging and mainline vehicles yield when appropriate. For speed, spatial, and acceleration profiles of typical autonomous vehicles within a merge area, see Figures 2, 3, and 4. A transition map of a typical autonomous vehicle is shown in Figure 5.

1.2.2. Cooperative

Cooperative merging intelligence is the next level of SmartAHS intelligence. Through the use of advanced infrastructure, the cooperative case allows vehicles to efficiently position themselves to gaps in the mainline traffic and thus improve merge operations. It does this by allowing vehicles to sense each other *before* they are in actual visual range. As a result, the **L_gap_visible_range** point is located 240 meters upstream of the point where vehicles can begin merging (See Figure 1). Therefore, vehicles begin to align themselves to gaps in the mainline traffic stream well before they reach the point of merging. As a result, when they do reach that point, they are much more likely to be already aligned with a gap in which to merge immediately. This is a more advanced automation strategy to the autonomous case because vehicles do not have use additional time to align to gaps when they could be using it to merge. For speed, spatial, and acceleration profiles of typical cooperative vehicles within a merge area, see Figures 2, 3, and 4. A transition map of a typical cooperative vehicle is shown in Figure 5.

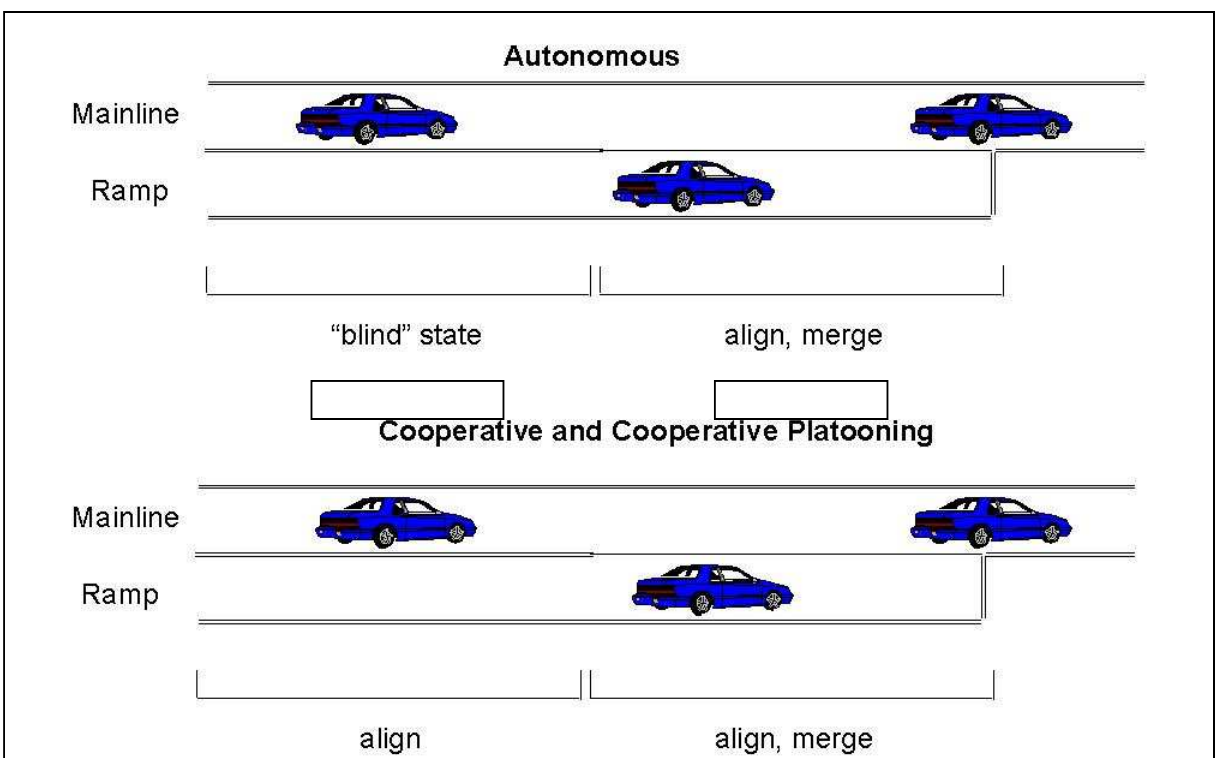


Figure 2

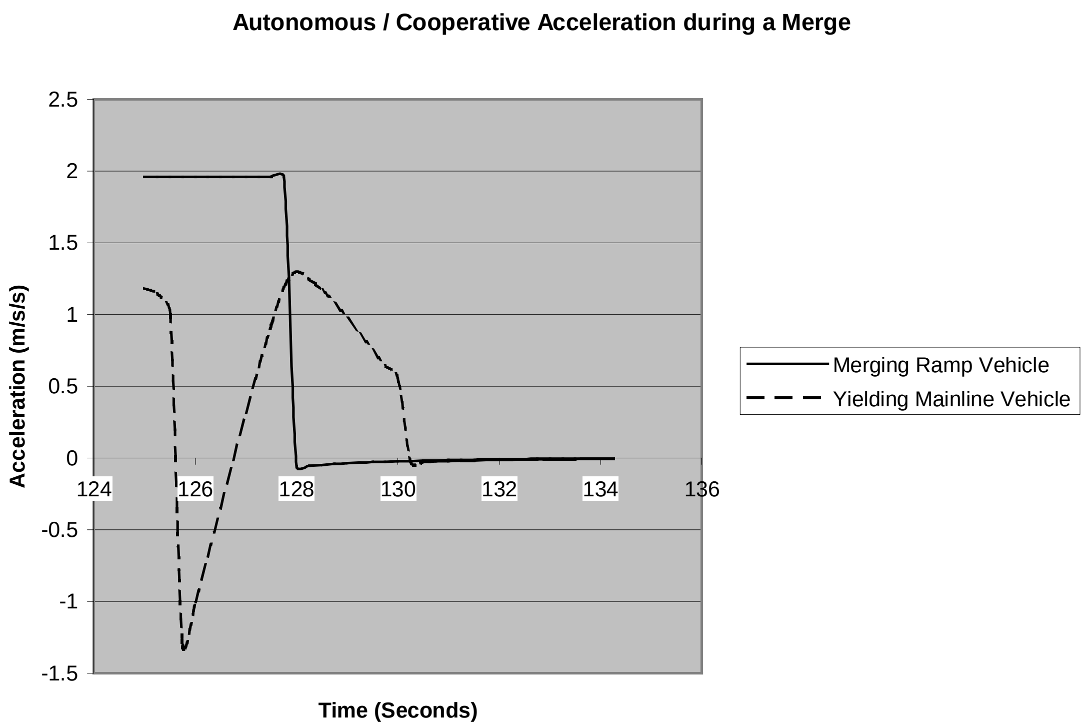

Autonomous / Cooperative Acceleration during a Merge
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
124
126
128
130
132
134
136
Acceleration (m/s/s)
Time (Seconds)
Merging Ramp Vehicle
Yielding Mainline Vehicle

Figure 3

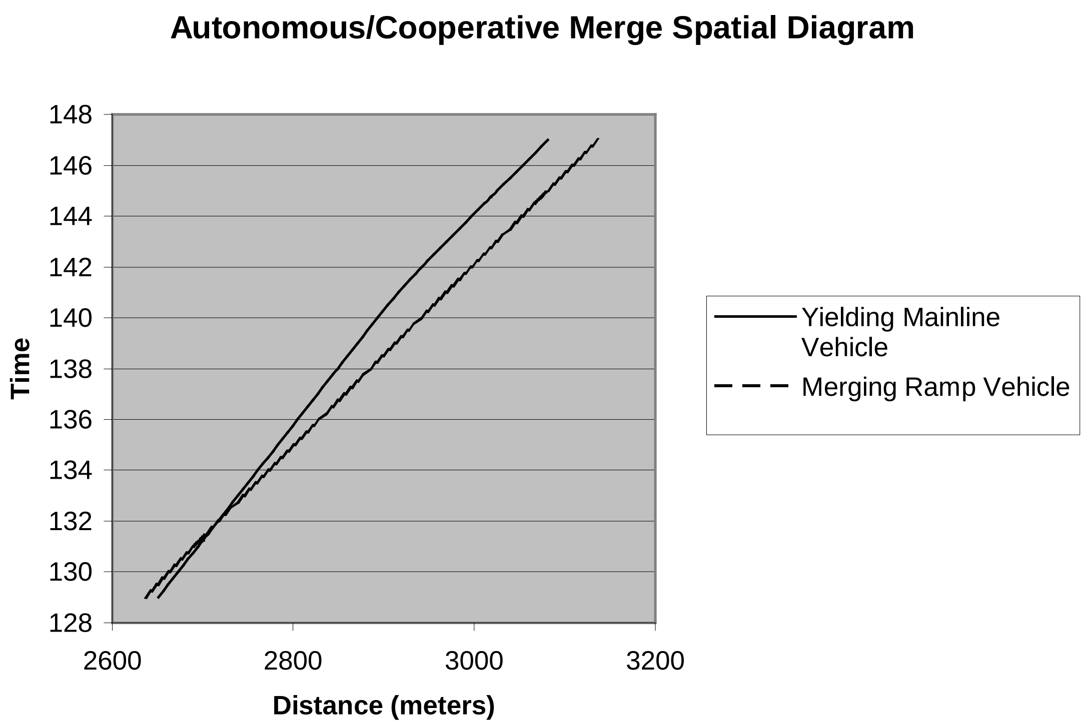
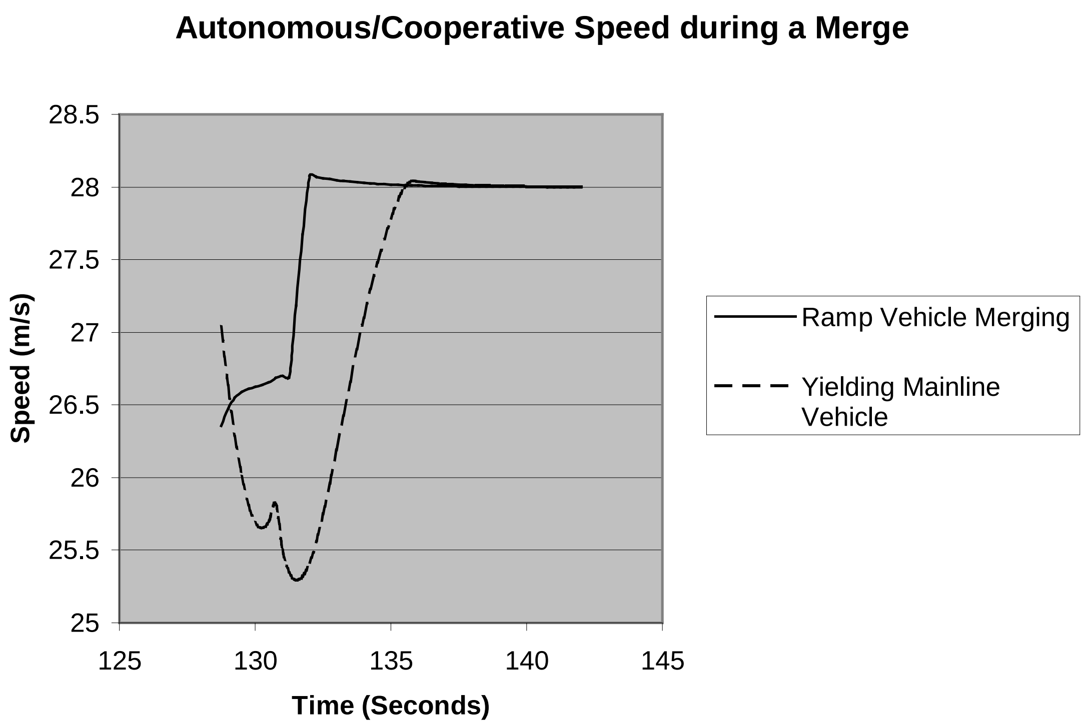

Autonomous/Cooperative Merge Spatial Diagram
148
146
144
142
140
138
136
134
132
130
128
Time
2600
2800
3000
3200
Distance (meters)
Yielding Mainline Vehicle
Merging Ramp Vehicle

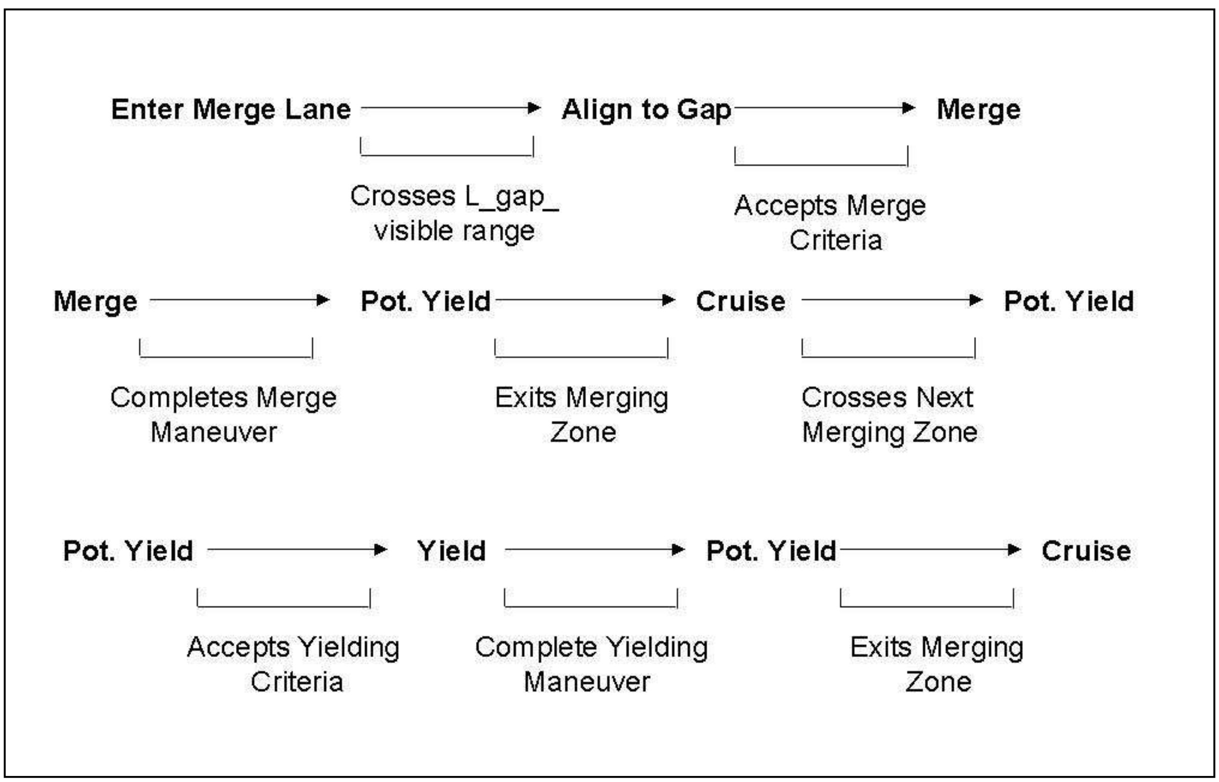
Figure 4


Autonomous/Cooperative Speed during a Merge
28.5
28
27.5
27
26.5
26
25.5
25
Speed (m/s)
125
130
135
140
145
Time (Seconds)
Ramp Vehicle Merging
Yielding Mainline Vehicle

1.2.3. Cooperative Platooning

Cooperative platooning is currently the highest level of SmartAHS merging intelligence. It works identically to the cooperative scenario except that after vehicles merge onto the mainline, they form closely spaced platoons and travel in unison. Platooning is a mechanism designed to allow vehicles to reduce their aerodynamic drag coefficient and thus improve fuel consumption efficiency. It also serves to maximize space usage on the mainline by grouping vehicles at a high density, while maintaining safe, yet free flow longitudinal speeds.

Figure 5



1.3. Performance Evaluation

1.3.1. Emissions

Hyrdrocarbon emissions from vehicles are an increasingly growing hazard where some studies have estimated it to account for 30% of urban pollution(3). As a result, it is crucial to control the amount of these emissions in our environment in an attempt to maximize air quality levels. The magnitude of these vehicle emissions is dependent upon the operating mode of the vehicle. For example, with respect to the total amount of emissions produced by a typical vehicle, steady state cruise speeds produce modest amounts of emissions, while changes in acceleration at high speeds produce significantly more (1). Therefore, maintaining constant speeds over long periods of time is very effective in reducing the emissions level of vehicle travel. AHS seeks to achieve this constant vehicle speed by implementing efficient merge protocols and yielding guidelines which are superior to manual driving behavior and thus maximize steady state travel time, while reducing emissions.

1.3.2. Fuel Consumption Rates

Vehicle fuel consumption rates are closely related to emissions whereas certain vehicle maneuvers increase or decrease the efficiency of fuel usage. The air to fuel ratio is the determining factor in this phenomenon. During engine start-up and warm-up, this ratio is usually large or *rich* which maximizes combustion stability (1). However, this factor is also induced into richness with hard accelerations especially at higher speeds. This event is often is referred to as enrichment and can also be attained when vehicles attempt to climb steep grades. Enrichment causes fuel consumption rates to increase greatly and also encourages additional amounts of hydrocarbon emissions. In fact, during times of enrichment, these emissions may be several magnitudes greater than normal conditions (2). As result, vehicle fuel consumption rates are minimized with the same actions and policies that decrease emission levels -- increases in steady state travel time and minimization of accelerations at high speeds. AHS attempts to control both of these through efficient merging protocols.

1.3.3. Level of Service

The level of service measure, or LOS, is a performance criteria used to qualify the operating states of freeways and signalized intersections. At a particular corridor or intersection, the level of service is measured by either its volume to capacity ratio, average delay per vehicle, or average speed throughout the segment. The calculation of it is dependent upon the closeness that traffic patterns are to the system's capacity. The freeway level of service remains relatively constant until a critical volume is reached. This critical point will vary with regard to the type of transportation system being considered. At this juncture, operations begin to break down, congestion emerges, and level of service measure begins to depict a system operating in congestion (See Figure 6). Therefore, at any volume levels below capacity, acceptable level of service, with respect to free flow speeds, is maintained.

To differentiate degrees of level of service, the following states are used to represent varying operational efficiency levels: (4)

“A” = When a system is operation in LOS “A”, free flowing traffic conditions prevail where vehicles are able to undertake and complete virtually any maneuver they choose

“B” = Traffic states become a little more constrained. Vehicles have somewhat less freedom than before, but are still able to travel freely.

“C” = Vehicles are noticeably limited in their choice of feasible maneuvers. Though they still travel at free flow speeds, desired movements such as lane changing and merging are significantly hindered and thus take greater time to initiate.

“D” = Vehicles restricted to speeds at or slightly below free flow speeds. Maneuvers are still limited.

“E” = Traffic volumes approach system capacity. Speeds decrease significantly from free flow speeds and maneuverability becomes almost impossible.

“F” = This state represents a complete system breakdown. “Stop and Go” traffic prevails where speeds drop to zero frequently. Vehicle maneuverability is almost completely infeasible.

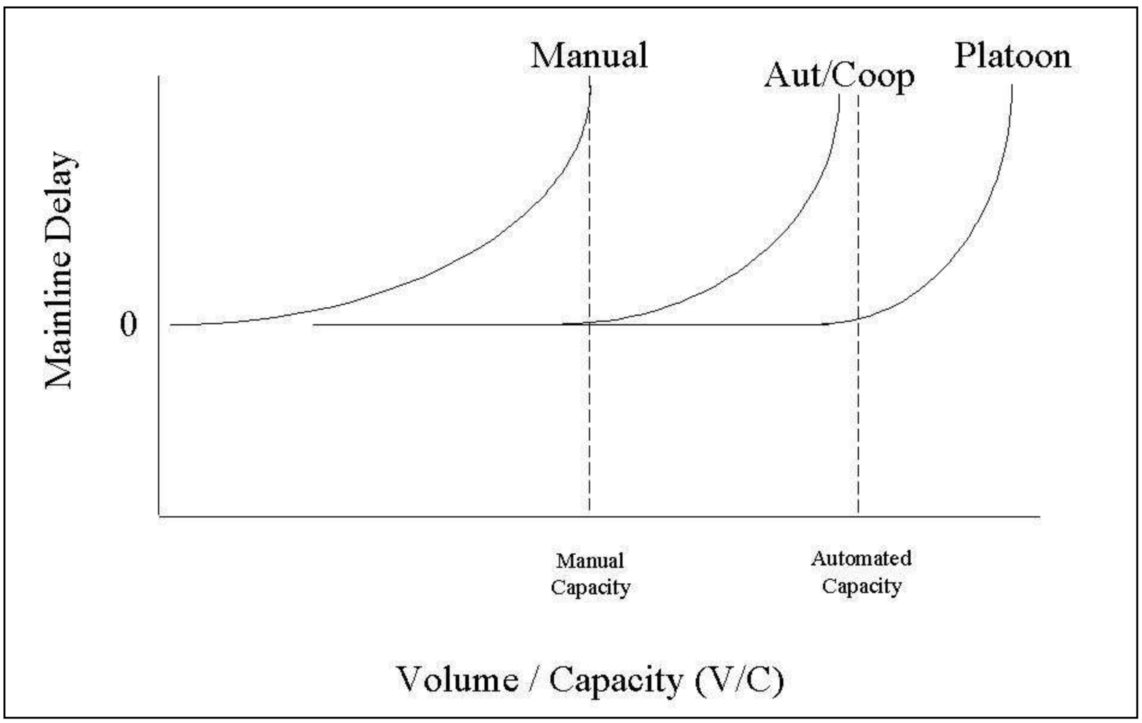
1.3.4. Delay

Delays in travel time caused by highway congestion are the most visible and distressing cost to the user. They frustrate drivers and illuminate the shortcomings of our highway system. More importantly, however, delays also aggravate other environmental and economic issues such as elevated fuel consumption rates and harmful emissions. Because of the importance of these issues, minimizing travel time delay is an integral concern of SmartAHS and thus all individual and system control methodologies are geared to this end.

Merging operations are typically a major cause of congestion that leads to travel time delays. Within bottlenecks and areas of merging, appropriate gaps, speeds, and positions are manually estimated. However, due to varying desired vehicle speeds and necessary overly cautious safety perceptions of humans, this process becomes too inefficient to achieve favorable highway traveling conditions. At low ramp and mainline flows, however, the current manual merging methods are adequate enough to enable travel without extraordinary delays. However, when the combination of ramp flows and mainline flows exceed the capacity of the merge junction, queues form and delays increase exponentially (See Figure 6). On many highways, the capacity of the system, is insufficient to handle the given demands of traffic, especially during the peak hour. As a result, SmartAHS seeks to maximize both the capacity and traveling conditions of merging areas by improving merging protocols and downstream highway operations.

Delay over the freeway portion of a vehicle trip can be categorized into two categories: ramp delay and mainline delay. The former consists of the time in addition to an otherwise free flow travel time that a vehicle takes to enter the ramp, traverse its length, and complete its merge maneuver onto the mainline. It also includes, if applicable, the time spent waiting to be released from a metering stop bar. Meanwhile, mainline delay is the additional time over free flow travel time that it takes to traverse the segment stretching from just before the merge junction queue to beyond the last point of merging.

Figure 6



Manual
Aut/Coop
Platoon
Mainline Delay
0
Manual
Capacity
Automated
Capacity
Volume / Capacity (V/C)

2. Simulation Description

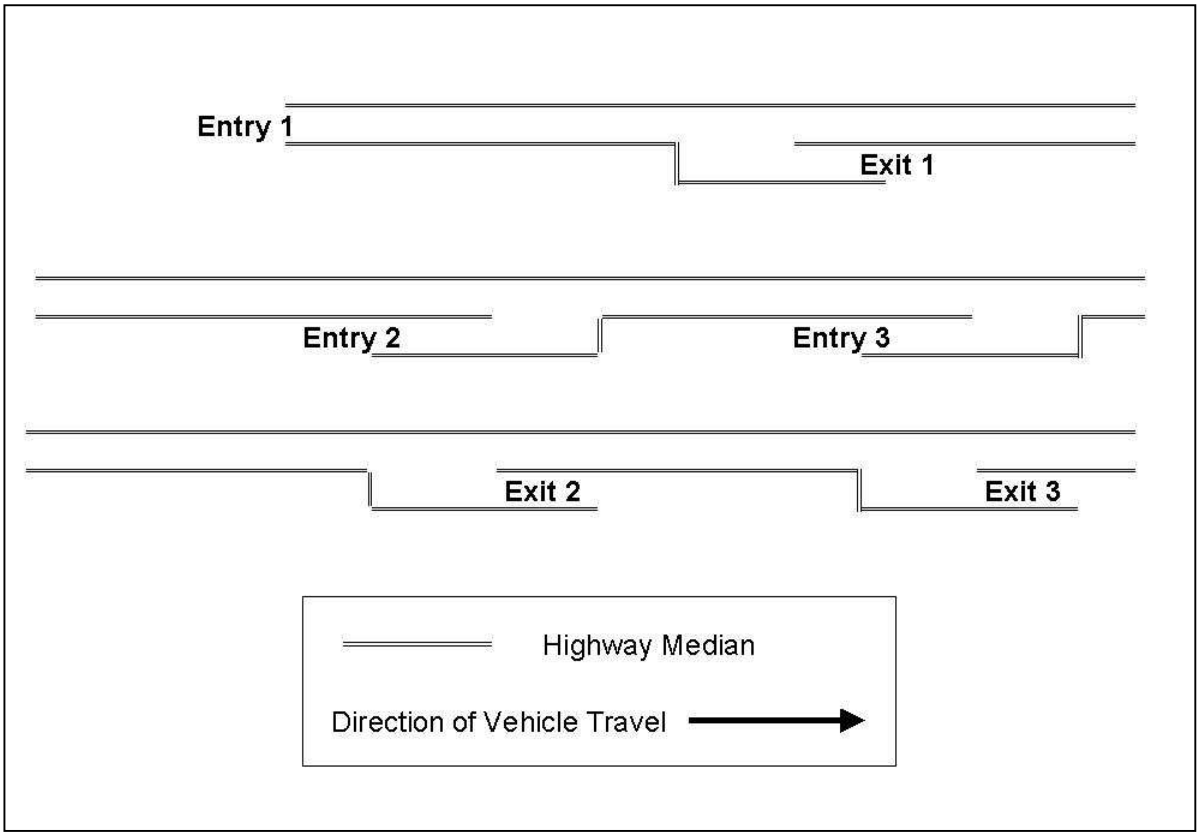
2.1. Simulation Parameters

2.1.1. Geometry and Demand Characteristics

The case study chosen for the simulation of AHS was the Katy Corridor, or Interstate 10, in Houston, Texas (See Figure 7a). This straight urban corridor has three entry and three exits points. It is approximately 10,000 meters in length and has lane widths of 4 meters. The highway portion, as depicted in the simulations, consists of one automated lane which begins at the first entry ramp. The remaining two entry ramps each are 480 meters in length where vehicles may merge in the latter 240 meter portion. It is also assumed that vehicles on the ramp and vehicles on the highway cannot "sense" each other directly until they can actually begin to merge.

The intent of selecting the Houston Katy Corridor was to represent the merging operations in a generic urban corridor. Therefore, the results of this study are comparable to corridors of similar environmental and geometric characteristics. Furthermore, the purpose of performing this study is to identify the expected benefits of AHS in a typical highway segment with respect to emission, fuel consumption, and highway performance characteristics.

Figure 7a



With respect to levels of traffic generated, two major demand scenarios were considered for the emissions and fuel consumption analysis: a low intensity case to represent off-peak hours and high intensity case to consider peak period vehicle interactions.[2] The vehicle flows are listed below:

Table 1 - Low Intensity Demand

Entry	Vehicles per Hour
1	1000
2	500
3	300

[2] Houston Metropolitan Transportation Authority

Table 2 - High Intensity Demand

Entry	Vehicles per Hour
1	2000
2	1000
3	1000

Also, four additional levels of demand were examined for the level of service and delay analysis. Each correspond to a given percentage increase over the low intensity case. The maximum demand scenario denotes the maximum dispersion rate of each ramp onto the mainline. In other words, it represents the greatest number of vehicles that a ramp can generate safely at ramp free flow speeds. The demand levels of each case are as follows:

Table 3a - 50% Increase

Entry	Vehicles per Hour
1	1500
2	750
3	750

Table 3b - 150% Increase

Entry	Vehicles per Hour
1	2500
2	1250
3	1250

Table 3c - 200% Increase

Entry	Vehicles per Hour
1	3000
2	1500
3	1500

Table 3d – Maximum Increase

Entry	Vehicles per Hour
1	3100
2	3100
3	3100

Note that the 100% case is equivalent to the high intensity scenario. In addition, each percentage increase in based upon an assumed 500 vehicle per hour parameter for merge junction 3 instead of the 300 vph value used in the low intensity case.

2.1.2. Analysis Tools and Simulation Parameters

The simulations were programmed in SHIFT, a new synchronous language developed at U.C. Berkeley. SHIFT specializes in representing dynamic systems of hybrid automata. It is an object-oriented forum whose components can be created, interconnected, and destroyed as the simulation matures. SHIFT gives rise to SmartAHS which is a modeling framework for representing an AHS. Together, both are used to simulate the AHS on the Katy Corridor and evaluate its effect on highway operations.

Each model was run using a 0.25 second integration step on a Sun Ultra Unix operating system. Since each simulation began with no vehicles on any ramps or lanes, it was run until equilibrium to gather data on highway operations. After this point, the simulation was run until the parameters for evaluating highway performance stabilized into long run averages. Finally, the results were collected and tabulated.

A SHIFT example of a transition between vehicle states, or operating modes, can be seen in Figure 7b. The conditions for intiating a merge maneuver are located in the “when” clause and correspond to the merging requirements stated later in this analysis.

2.1.3. Vehicle Acceleration

In an effort to minimize fuel consumption, each vehicle's acceleration, during every integration step, was calculated such that fuel enrichment was avoided. In addition, each acceleration is computed to first maintain safety and next to achieve AHS operating standards. The nominal values of these acceleration values are defined in by the following:

Table 4

Acceleration Type	Value Used
Hard Brake	-0.2 * g
Mild Brake	-0.1 * g
Hard Acceleration	0.2 * g
Mild Acceleration	0.05 * g
Resume Acceleration	0.01 * g

Figure 7b

Transition : From gap aligning state to Merging state

Code:

```
// The platoon is in a safe position for merging.
   align_to_gap -> first_half_merge {begin_merge}
    when rear_gxp(the_platoon) >= L_start_merge(junction)
        and side_lane_ratio > merge_ratio_threshold
           and yielding_ratio > merge_ratio_threshold
        and side_lane_rel_speed > - merge_rel_speed_threshold
        and yielding_rel_speed > - merge_rel_speed_threshold
    define {
         number d := rear_gxp(the_platoon) - L_start_merge(junction);
    }
    do {
         distance_to_begin_merge := d;

    },
```

2.2. Performance Evaluation Parameters

2.2.1. Emissions and Fuel Consumption Rates

Emissions are calculated using a microscopic emissions model developed by the College of Engineering-Center for Environmental Research and Technology at the University of California (CE-CERT). The methodology of this model to is to correctly represent the emissions of light duty vehicles, such as Buick LeSabres, according to their current operating mode (1). It is also used to estimate fuel consumption rates based on the same criteria.

Accelerations, speeds, and environmental conditions serve as inputs to the emissions model to estimate accurately automated conditions, while data collected empirically for the initial development of the model is used to estimated the baseline conditions of the manual case. Each automated scenario's results are evaluated upon their improvement from this manual baseline scenario to estimate the level of AHS effectiveness.

2.2.2. Level of Service on Katy Corridor

The level of service of SmartAHS can be calculated similarly, but with a few noticeable differences. First of all, through its superior system of merging and vehicle following protocols, it can allow normal freeway geometries to achieve greater pipeline capacities than before. As a result, higher flows can be achieved with a greater level of service because similar volumes are no longer near this improved capacity.

In addition, SmartAHS levels of service are estimated with a few different techniques as well. Since density has a lesser effect on AHS traffic than for manual volumes, it is not an accurate determinant of performance. Also, volume to capacity ratios in the manual and automated cases are do not correspond to similar LOS measures because some AHS scenarios do not deteriorate as rapidly at volumes near capacity. Instead, when volumes are less than capacity, AHS vehicles operate in ideal longitudinal travel conditions and thus enjoy an “A” level of service state. Alternatively, at volumes greater than capacity, it is intuitively clear that AHS conditions become unstable and LOS worsens. Therefore, any volume to capacity ratio greater than 1 in the automated case will, for the purpose of this analysis, be denoted as having a LOS of “F”.

Using the length of an automated vehicle and the assumed inter - platoon spacing of 10 meters, an adjusted capacity value was calculated for the automated case as follows:

$$\text{Automated Capacity} = 3600 / [(\text{Spacing} + \text{Vehicle Length}) / \text{Free Flow Speed}] = 6720\text{vph}$$

This value is calculated under the assumption that no vehicles are platooned. Therefore, it represents a “worst case” capacity for the Cooperative Platooning intelligence. However, it was used to calculate the level of service for automated highway segments.

The degrees of the level of service criteria for volume to capacity ratios along a segment of highway are listed in the following table.

Table 5 – Level of Service Thresholds

Level of Service	Manual	Aut / Coop	Coop Platooning
A	<= .272	<.9	< 1
B	> .272	-	-
C	> .436	-	-
D	> .655	-	-
E	> 829	-	-
F	> 1.00	> .9	> 1

Note that the critical threshold for the Automated and Cooperative cases is lower than that of the cooperative platooning. This is due to the fact that in these intelligence scenarios vehicles yield to merging vehicles, thus decreasing throughput, whereas vehicles in the cooperative platooning case do not. The highway conditions and levels of service will be evaluated according the above scale.

2.2.3. Delay on Katy Corridor

The Katy Corridor was divided into three major merge junctions for delay evaluation (See Figure 7c). Within two junctions, delay to mainline vehicles was calculated. Ramp delay was calculated in all merge junctions as well as total merge junction delay which is defined to be the delay through the defined merge junctions. Mainline delay was not calculated in merge junction 1 because the vehicles entering from the ramp represent the beginning of the automated lane. Therefore, the mainline delay is equivalent to the merge junction 1 delay. Lastly, the total average system delay was calculated as the delay to vehicles from when they enter the AHS to when they exit.

To normalize the delay values from vehicles with differing entry and/or exit points, percentage delay was used as a measure of AHS effectiveness. It is calculated as follows (7):

% Vehicle Delay = Vehicle Delay / free flow travel time

where vehicle delay = actual travel time - free flow travel time.

Manual delays were computed using expected actual travel times from the average speeds defined by each segment's volume to capacity ratio. These manual delays are only estimated for the low intensity case, yet it is intuitively clear that greater demand scenarios yield greater delay values.

In the interest of thoroughness, delay was evaluated as six demand levels. They are as follows:

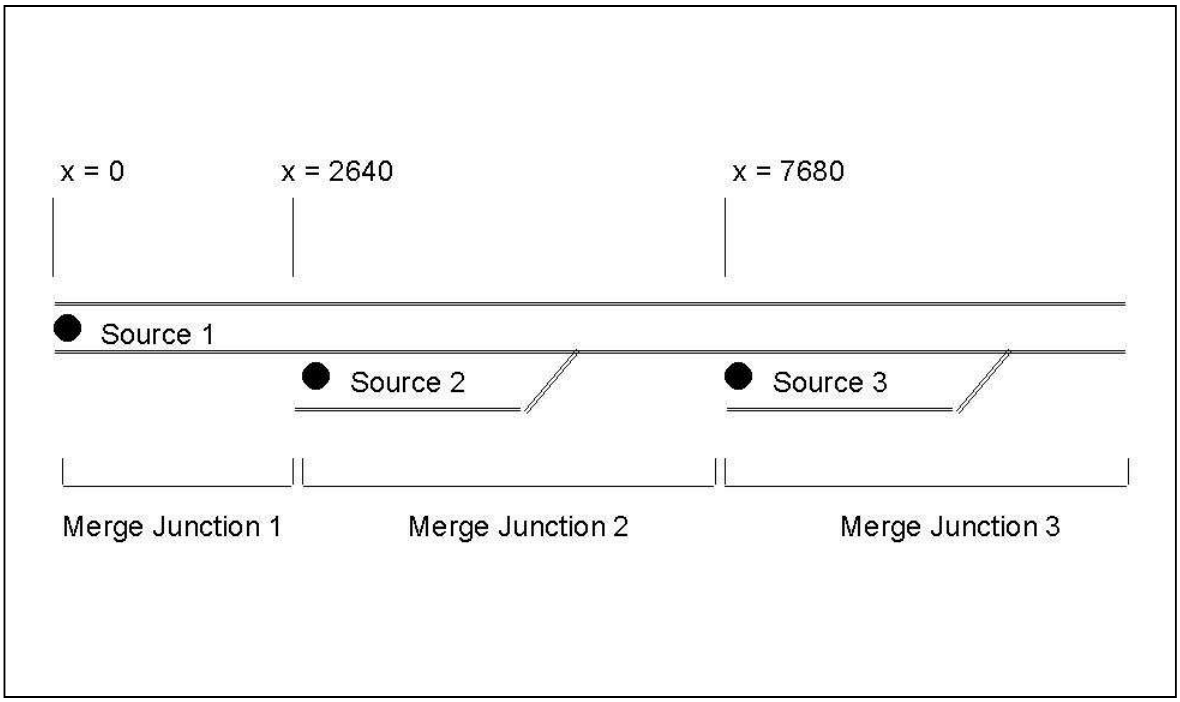
Table 6 – %Increased Demand Levels

% Increase	Merge-jxn 1(vph)	Merge-jxn 2(vph)	Merge-jxn 3(vph)
0% (Low Intensity)	1000	500	300
50%	1500	750	750
100% (High Intensity)	2000	1000	1000
150%	2500	1250	1250
200%	3000	1500	1500
Maximum	3100	3100	3100

Each of which are listed as their percentage increase over the low intensity case. Note that though merge junction 3 consists of 300 vehicles per hour in the low intensity case, its percentage increases in the subsequent scenarios are based on a 500 vehicle per hour low intensity count.

It is important to note that many demand levels analyzed are significantly greater than that which are present on current highways. This scope of consideration was undertaken to demonstrate the effectiveness level of AHS well above the current system volumes.

Figure 7c



3. **Merge Specifications**

3.1. Merge Controller

3.1.1. Dynamic Vehicle States

Each automated vehicle consists of a fixed length and width. A source located at the beginning of each entry ramp creates each vehicle according to a deterministic rate based on the demand characteristics of the particular demand scenario. Once a vehicle enters the ramp, it is in the **enter_merge_lane** state where it travels at a ramp nominal speed of 22 meters/second. When this vehicle crosses a point on the ramp where they can begin to sense vehicles on the mainline, it enters the **align_to_gap** state where it begins to align itself to a gap in the mainline stream of traffic by accelerating to a mainline nominal speed of 28 meters/second. This point of visual range is known as the **L_gap_visible_**range. Upon locating a gap, the vehicle will make slight adjustments in its speed to align perfectly to that gap. It will then transition into a **merge** state and merge when appropiate. In the next phase, the **cruise** state, if it is not at mainline nominal speed already, the vehicle will undergo further slight speed adjustments until it is. Upon reaching that speed, the vehicle will remain at that velocity until it is no longer safe to do so or it exits. When it reaches another merge junction, it enters a **potential_yield** state where it prepares to possibly yield to another merging vehicle in front in the adjacent merging lane. Finally, in the autonomous and cooperative scenarios, it actually yields to that vehicle in the **yield** state. When each of these vehicle enters a situation where they must halt for safety reasons, it enters a **stopped** state where their speed is zero. When they wish to resume after this state, they resume their former state in **resume** state. Each dynamic state defined above has their own respective **stopped** and **resume** state. For a detailed view on the transition between states, see Figure 8.

Figure 8

3.1.2. Vehicle Control Laws

To regulate movement throughout the corridor and maintain safety, vehicles maintain a pre-specified inter-vehicle time headway which corresponds to an inter-vehicle spacing of 10 meters. This inter-vehicle spacing is dependent upon the intelligence scenario being considered. They accomplish this by using their sensors to identify nearby vehicles, specifically ones directly in front and back in the same and adjacent lanes. Each nearby vehicle's position, speed, and distance from current vehicle is evaluated with respect to the current vehicle's similar attributes and an appropiate acceleration is computed in the interest of both safety and maintaining the desired headway.

Automated vehicles stay in the lateral center of the lane unless they merge into the mainline or exit out of it. If a collision should occur, the vehicles involved move to the emergency lane and exit the simulation. When a vehicle reaches its exit ramp, it merges into the adjacent exit lane and exits out of the simulation when it is in the center of the exit lane. When a ramp vehicle does not complete its merge by the time it reaches the end of the ramp, it "drops out" and exits the simulation.

It is also important to note at this time that the position and speed of the **same lane vehicle** is constantly being tracked in an effort to maintain ramp inter-vehicle spacing. If safety is compromised and the ramp vehicle violates this spacing, then appropiate decelerations are mandated. As a result, when merging and safety actions oppose each other, deceleration to maintain appropiate spacing take precedence. Therefore, the following merging protocol is applicable when safe following distance on the ramp is constantly maintained.

3.1.3. Merging Maneuver

Upon perfecting their alignment to an appropriate gap, ramp vehicles begin to consider the merge maneuver. By using their sensors to locate nearby vehicles, they identify other automated vehicles in which they will have to monitor before actually merging (See Figure 9) . The **same_lane_vehicle** is defined as the vehicle directly in front of the current vehicle in the same lane. The **side_lane_vehicle** is defined as the vehicle in front of the current vehicle in the adjacent lane. Also, the **yielding_vehicle** is seen as the vehicle in back of a ramp vehicle in the mainline. A 0.6 second headway between vehicles is assumed which represents a minimum desired inter-vehicle spacing of 16.8 meters. Using these pointers to other vehicles, the vehicle in the merge lane computes the relative time headway of both its **side_lane_vehicle** and **yielding_vehicle**. This relative time headway is defined as:

Relative time headway = distance from **side_lane_vehicle** / speed of **side_lane_vehicle**

Relative time headway = distance from **yielding_vehicle** / speed of **yielding_vehicle**

If the ratio of this relative time headway to our desired headway of 0.6 is greater than a pre-specified merge threshold, then the ramp vehicle further considers merging. Specifically, if

relative time headway / .6 > merge threshold,

then consider merging further. Otherwise, merging is not approved for this particular integration step. The merge threshold used for this simulation is 0.8.

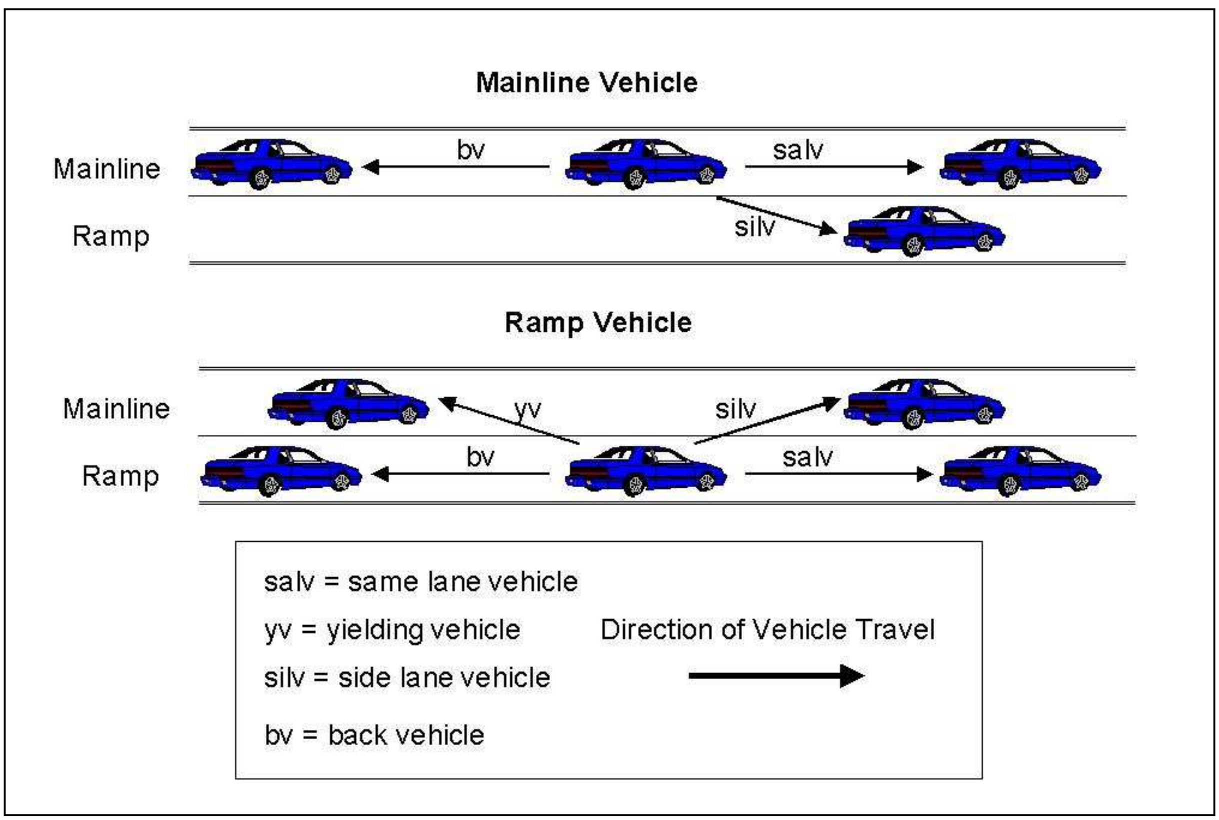
To finalize a merging approval, a ramp vehicle must consider the relative speeds of its **side_lane_vehicle** and **yielding_vehicle** with respect to its own speed. Relative speed between a ramp vehicle and it nearby vehicles is defined as follows:

Side lane relative speed = side lane vehicle speed - speed of ramp vehicle

Yielding relative speed = speed of ramp vehicle - yielding vehicle speed

If both side lane relative speed and yielding relative speed are greater than a pre-specified merge relative speed threshold, then a merge maneuver is approved and undertaken. The merge relative speed threshold used for this simulation is -4.

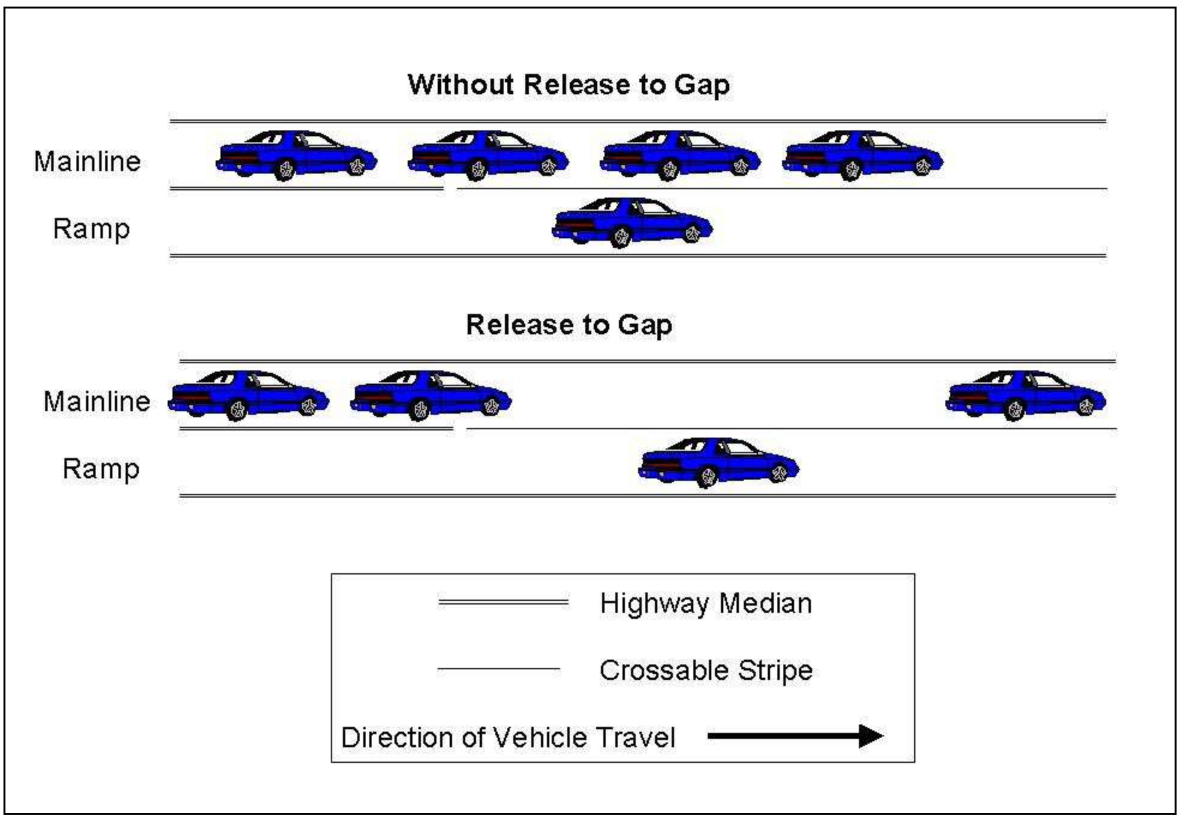
Figure 9



3.1.4. Release to Gap

Release to gap metering is a system of mainline feed control designed to maximize the efficiency and safety of merging operations. It requires infrastructure to identify and monitor possible merging gaps in the mainline traffic stream. It then releases vehicles from a metering stop bar such that at the point where they have accelerated to the mainline nominal speed and can first merge with mainline traffic, they are already aligned with a gap (See Figure 10).

Figure 10



Release to gap seeks to optimize gap aligning and thus allow for minimum and, in some cases, no yielding of mainline traffic due to merging vehicles. Because shock waves caused by yielding often lead to congestion and frequent vehicle collisions, this metering operation, in theory, is a great asset to both highway performance and safety. In addition, release to gap further ensures the presence of a merging gap in the mainline so merging operations are also more efficient. Finally, with less sporadic acclerations of vehicles in the merging area, smoother acceleration profiles prevail and thus both emissions and fuel consumption rates are reduced.

3.2. Cooperative Platooning Specifications

The cooperative platooning concept employs additional maneuvering to aid in the creation of groups of vehicles called platoons. Each vehicle in a platoon is either a follower or a platoon leader. Each platoon has exactly one platoon leader, which is always the frontmost vehicle in the platoon. In addition, a platoon may have none or several followers. The platoon leader governs the acceleration and most maneuvers of every other vehicle in the platoon. When a vehicle is a leader, it acts as platoon leader to itself and follows the same headway keeping laws that are exercised on the mainline. When a vehicle is a follower in a platoon or in a **follow** state, it simply adjusts its speed continuously to maintain the standard intra-platoon spacing of 2.5 meters from the vehicle in front of it.

When a platoon wishes to join a platoon in front of it, the leader of the back platoon, or joining platoon, communicates with the leader of the front platoon, or receiving platoon. A join maneuver of the joining platoon is approved and initiated only when the following conditions are satisfied:

1) The spacing between the joining platoon leader and the last vehicle in the receiving platoon is less than 60 meters

2) Both the joining platoon leader and the receiving platoon leader are not currently located in a merging area

3) The number of vehicles in the joining platoon + the number of vehicles in the receiving platoon does not exceed the maximum allowed platoon size of 8 vehicles

4) No platoons are currently in the process of joining the joining platoon

5) The receiving platoon is currently not in the process of joining another platoon

When a join is initiated, the joining platoon leader accelerates to a given speed and decelerates back down to the mainline nominal speed of 28 meters / second. The joining maneuver, or **join** state, is designed such that joining platoon leaders attain 28 meters / second just as they are at the desired intra-platoon spacing of 2.5 meters (See Figure 12). Via this joining maneuver, the gap between the joining platoon leader and the last vehicle in the receiving platoon decreases uniformly (See Figure 11). At the end of the joining sequence, the joining platoon leader and its followers become followers of the receiving platoon leader in a new aggregate platoon where all vehicles travel at the mainline nominal speed.

Figure 11

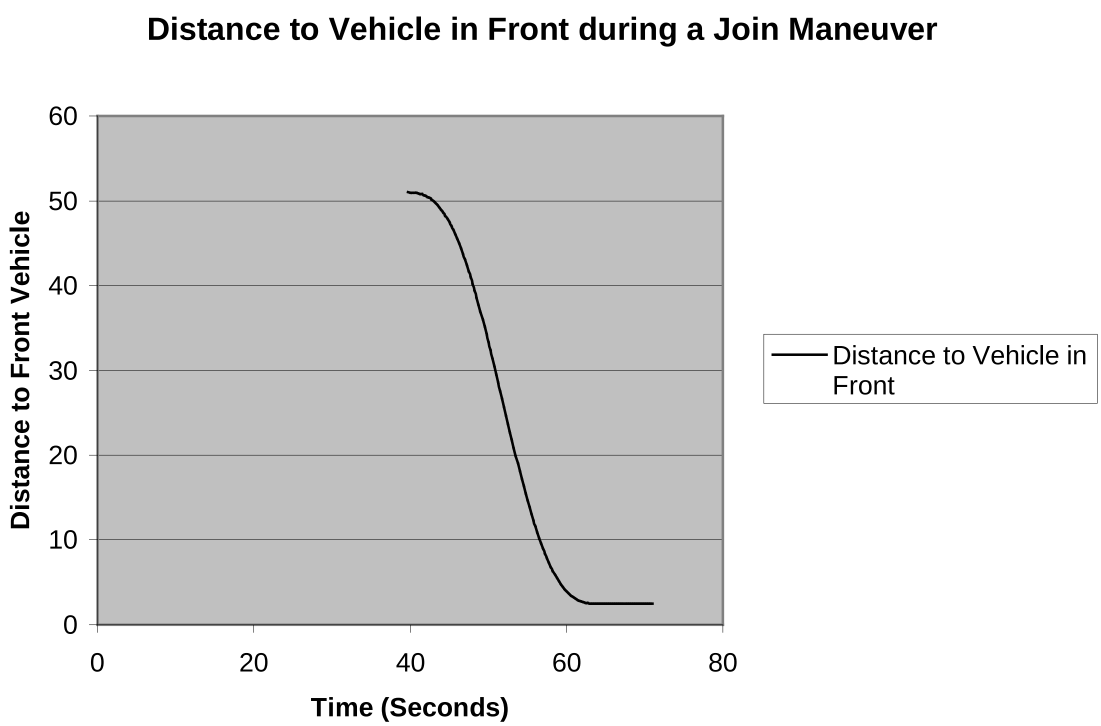
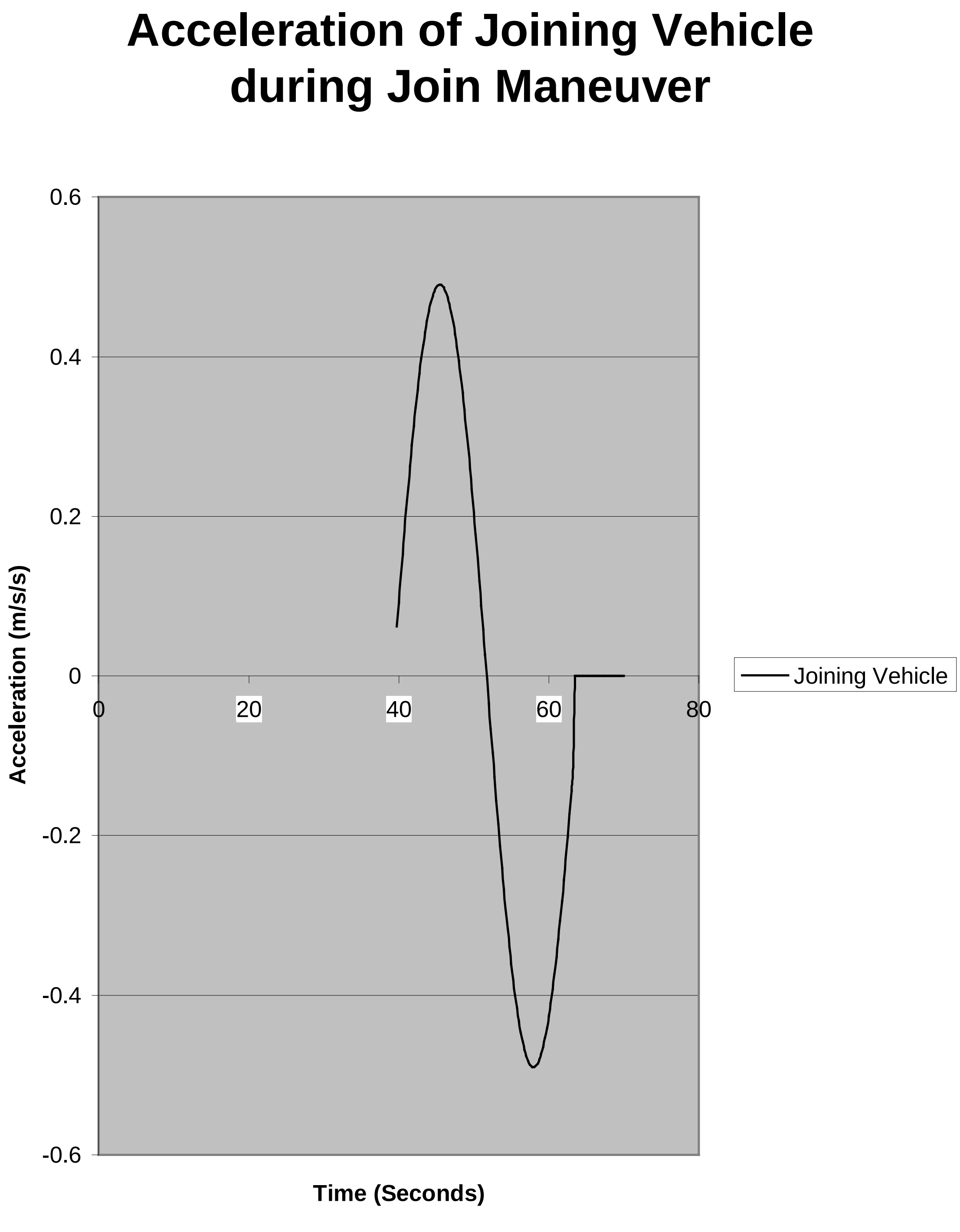

Distance to Vehicle in Front during a Join Maneuver
60
50
40
30
20
10
0
Distance to Front Vehicle
0
20
40
60
80
Time (Seconds)
Distance to Vehicle in Front

Figure 12


Acceleration of Joining Vehicle during Join Maneuver
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
20
40
60
80
Acceleration (m/s/s)
Time (Seconds)
Joining Vehicle

Sometimes, however, a join maneuver must be aborted for safety or highway performance reasons. In the event of a join abortion, joining platoon leaders return to a **cruise** state. Events during a joining maneuver that trigger a join abort command include:

1) The receiving platoon leader enters a merging area

2) The receiving platoon leader exits the highway before a join is completed

3) The last vehicle in the receiving platoon exits the highway before a join is completed

Though platoons move in unison, every vehicle within the platoon is not identical. Many vehicles have different desired exiting ramps which make it necessary to break up the platoon into individual vehicles. When a platoon leader reaches its exit ramp, it exits the mainline and appoints the next vehicle as the new platoon leader. Similarly, when the last vehicle in a platoon reaches its exit point, it simply breaks away and completes its exit maneuver without interrupting the flow of the platoon as whole. In either case, this process, takes place with little or no change in any vehicle speeds. However, when a vehicle in the middle of the platoon needs to exit, it simply breaks away laterally and completes an exit maneuver. At this time, the vehicles behind the exiting platoon initiate a join maneuver to close the newly formed gap within the platoon. They then reform the original platoon less the exiting vehicle. The profiles of such a maneuver are seen in Figure 13a – 13d.

Figure 13a

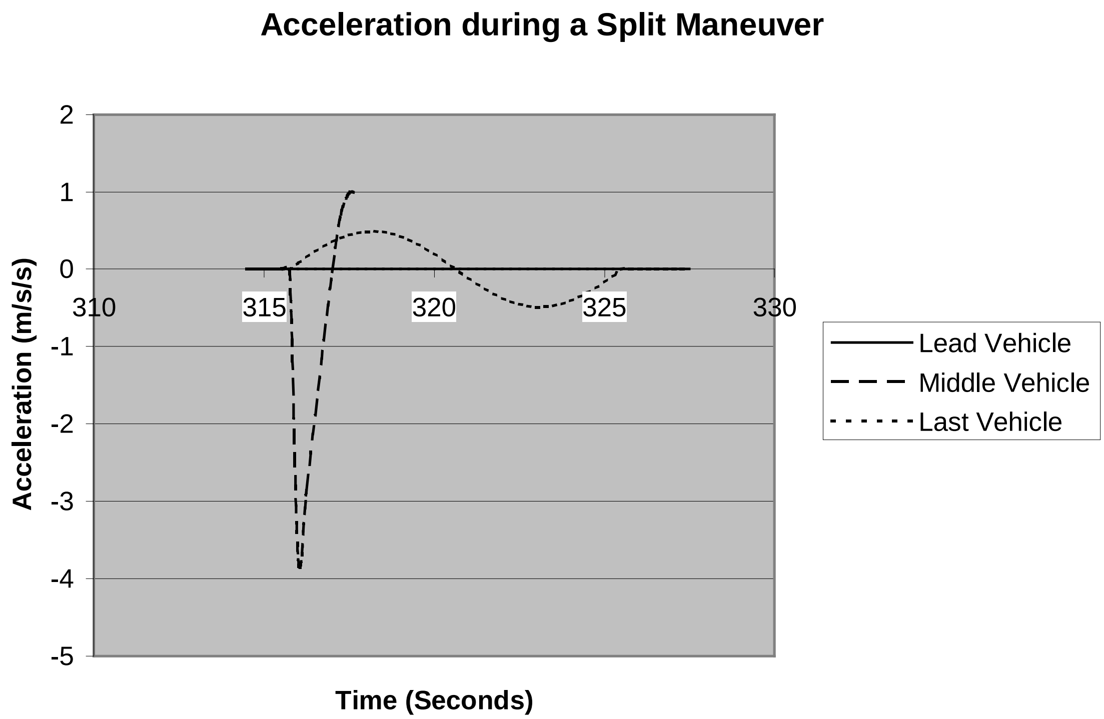

Acceleration during a Split Maneuver
2
1
0
-1
-2
-3
-4
-5
310
315
320
325
330
Acceleration (m/s/s)
Time (Seconds)
Lead Vehicle
Middle Vehicle
Last Vehicle

Figure 13b

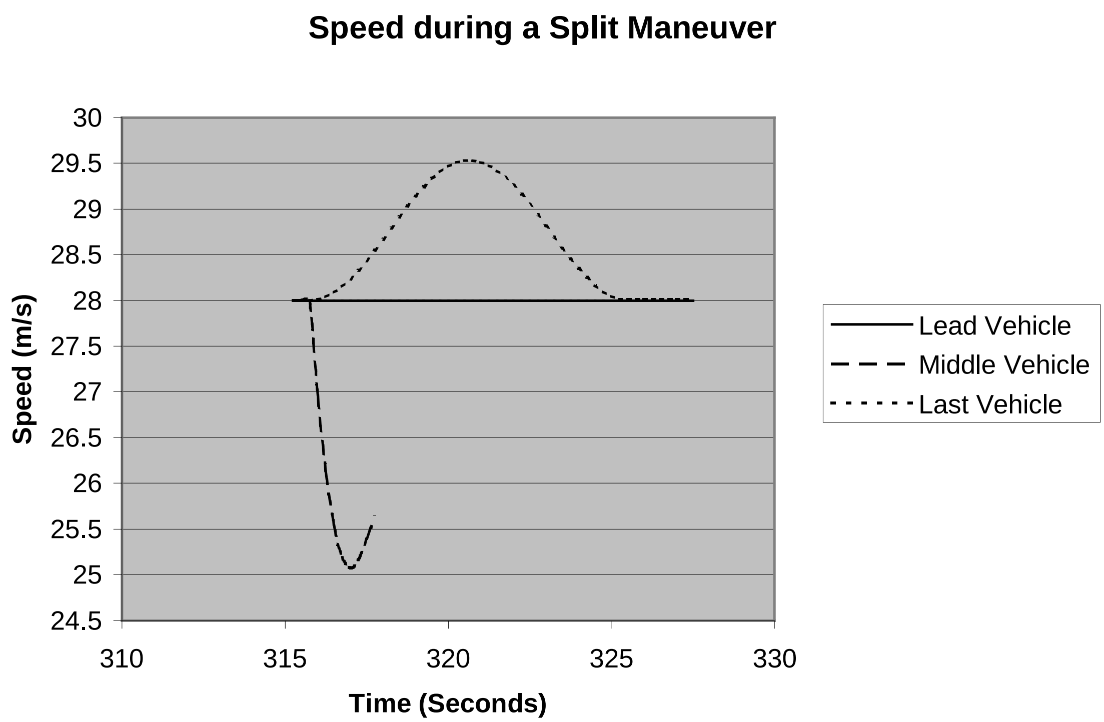

Speed during a Split Maneuver
30
29.5
29
28.5
28
27.5
27
26.5
26
25.5
25
24.5
Speed (m/s)
310
315
320
325
330
Time (Seconds)
Lead Vehicle
Middle Vehicle
Last Vehicle

Figure 13c

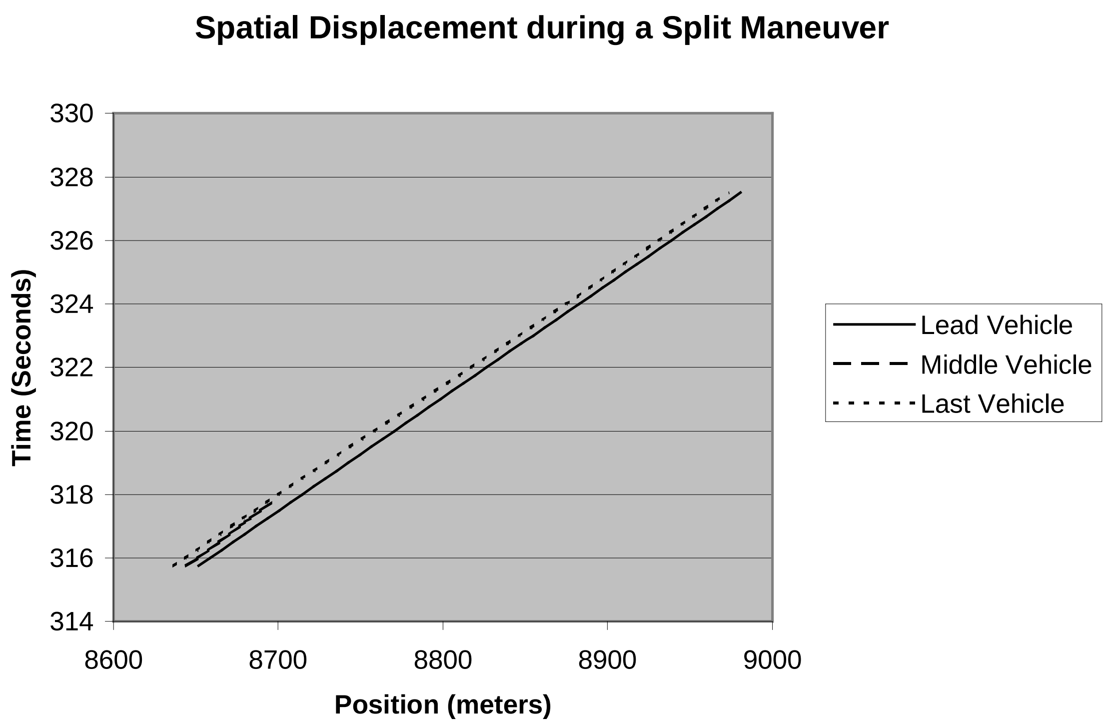
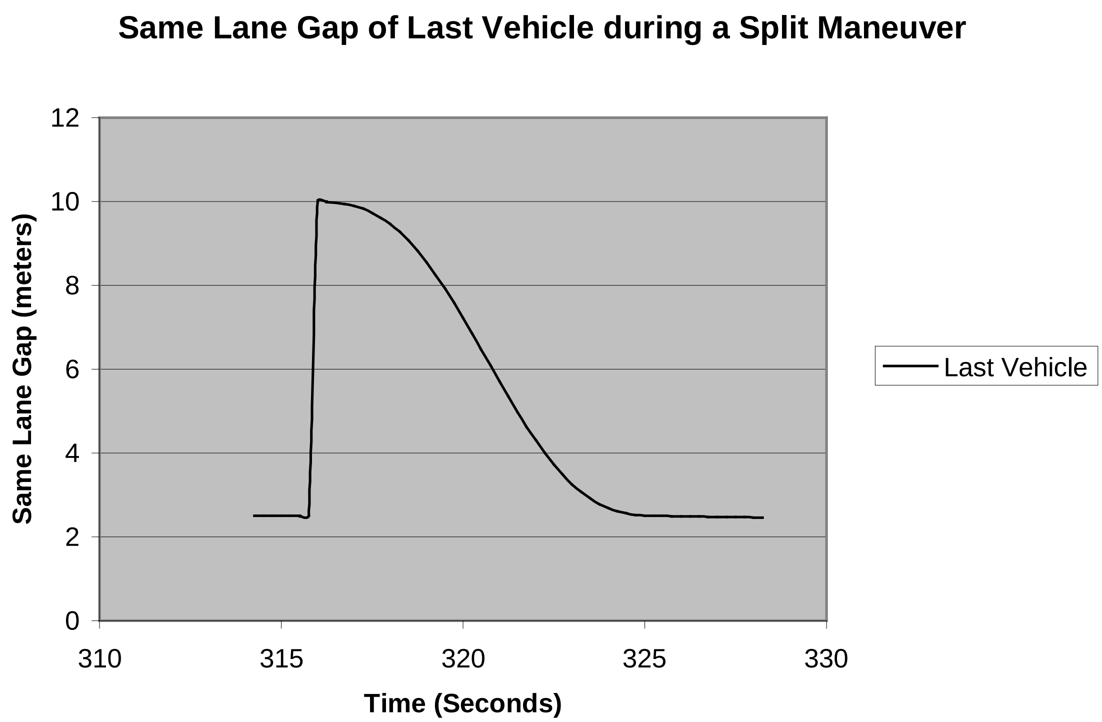

Spatial Displacement during a Split Maneuver
330
328
326
324
322
320
318
316
314
Time (Seconds)
8600
8700
8800
8900
9000
Position (meters)
Lead Vehicle
Middle Vehicle
Last Vehicle

Figure 13d


Same Lane Gap of Last Vehicle during a Split Maneuver
Same Lane Gap (meters)
12
10
8
6
4
2
0
310
315
320
325
330
Time (Seconds)
Last Vehicle

The compact intra-platoon spacing of 2.5 meters also allows greater vehicle density on the mainline and thus increases pipeline capacity. However, this compact spacing also creates a system of mainline traffic flow that is very sensitive to sudden decelerations. Since the inter-vehicle spacings within platoons are much less than the spacings in both the cooperative and autonomous scenarios, shock waves caused by mainline vehicle yielding to merging vehicles result in collisions much more frequently than in large inter-vehicle spacing environments. As a result, in the cooperative platooning scenario, vehicles on the mainline do not yield at all (Figures 14 and 15). Instead, release-to-gap metering strategies and merging vehicle speed adjustment to gaps are essential in ensuring the safety and success of merging maneuvers.

Figure 14

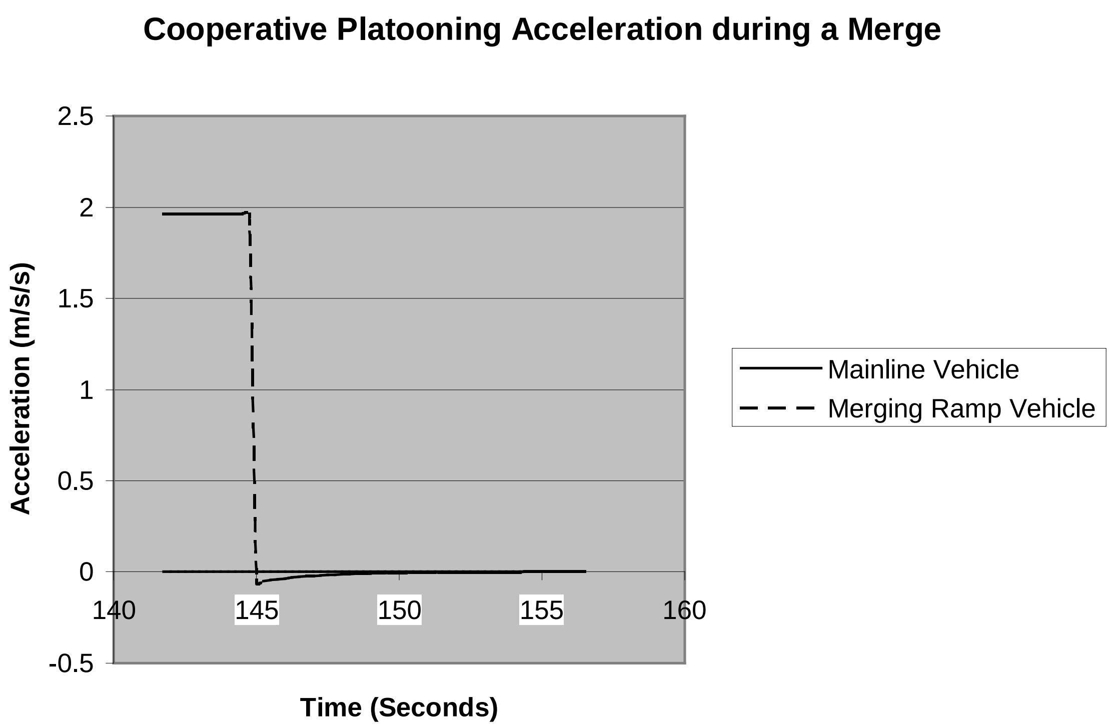
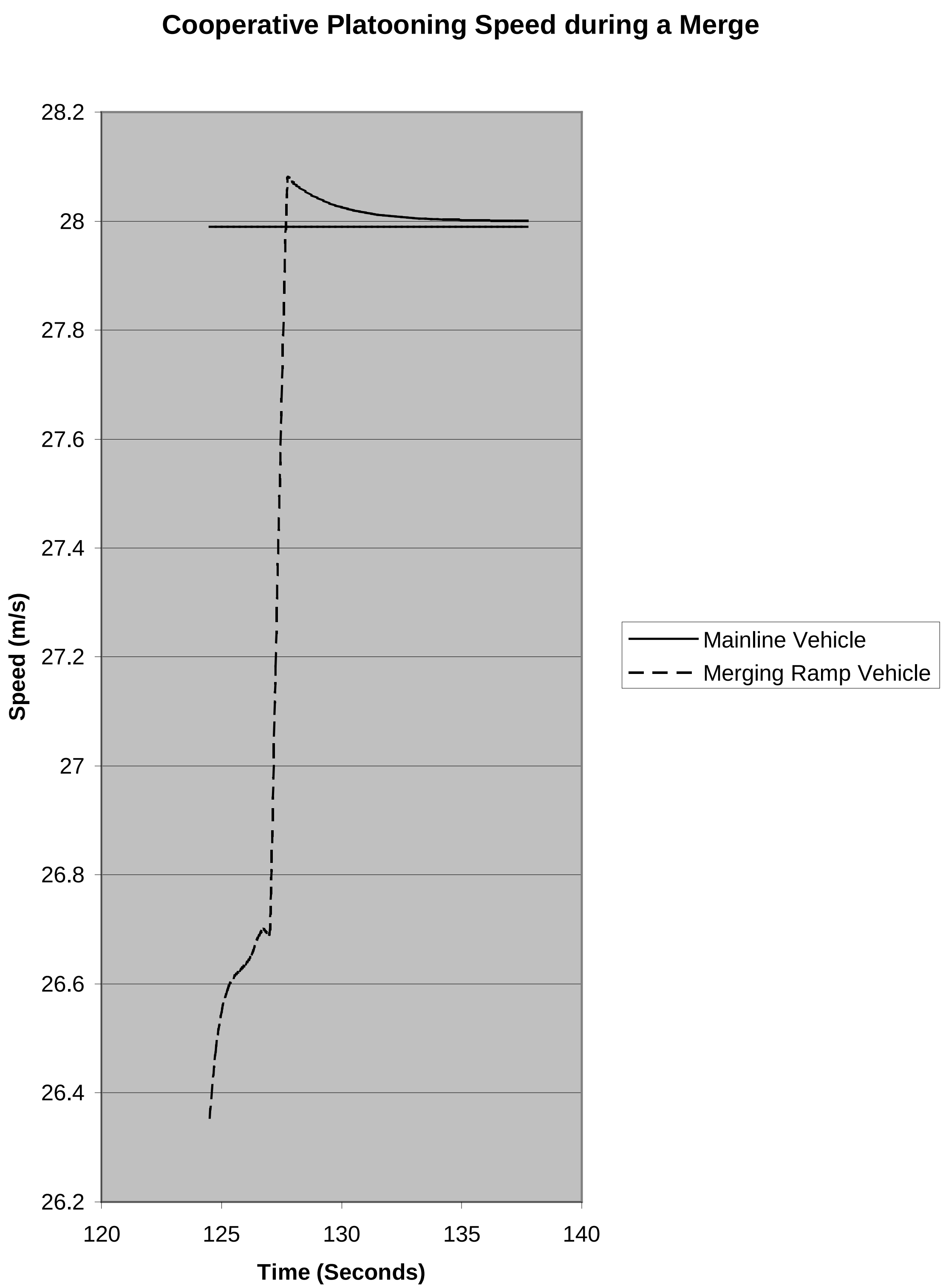

Cooperative Platooning Acceleration during a Merge
2.5
2
1.5
1
0.5
0
-0.5
140
145
150
155
160
Acceleration (m/s/s)
Time (Seconds)
Mainline Vehicle
Merging Ramp Vehicle

Figure 15


Cooperative Platooning Speed during a Merge
28.2
28
27.8
27.6
27.4
27.2
27
26.8
26.6
26.4
26.2
Speed (m/s)
120
125
130
135
140
Time (Seconds)
Mainline Vehicle
Merging Ramp Vehicle

4. Results

4.1. Emissions

4.1.1. Summary

The resulting emissions data is located in Figures 16a and 16b.

4.1.2. Comparative and Qualitative Analysis

Non-automated hydrocarbon emissions are estimated based upon level of service as a function of average vehicle speed. It is important to note that these emissions are greater at optimal level of service conditions (A-C) than at non–ideal conditions such as “D” or “F”. This is due to the vehicle engine’s increased sensitivity to emissions at higher speeds.

The HC emissions from the Autonomous and Cooperative intelligence scenarios were virtually identical and thus are combined into a single “AHS non-platoon” measure, whereas the results from the Cooperative Platooning intelligence concept are tabulated in an “AHS platoon” value. Due to smoother vehicle acceleration profiles, improvements of 33% and 43% for the non-platooned and platooned scenarios, respectively, were calculated in equivalent level of service conditions. However, only marginal advantages over the manual case were found in “D” conditions.

Figure 16a

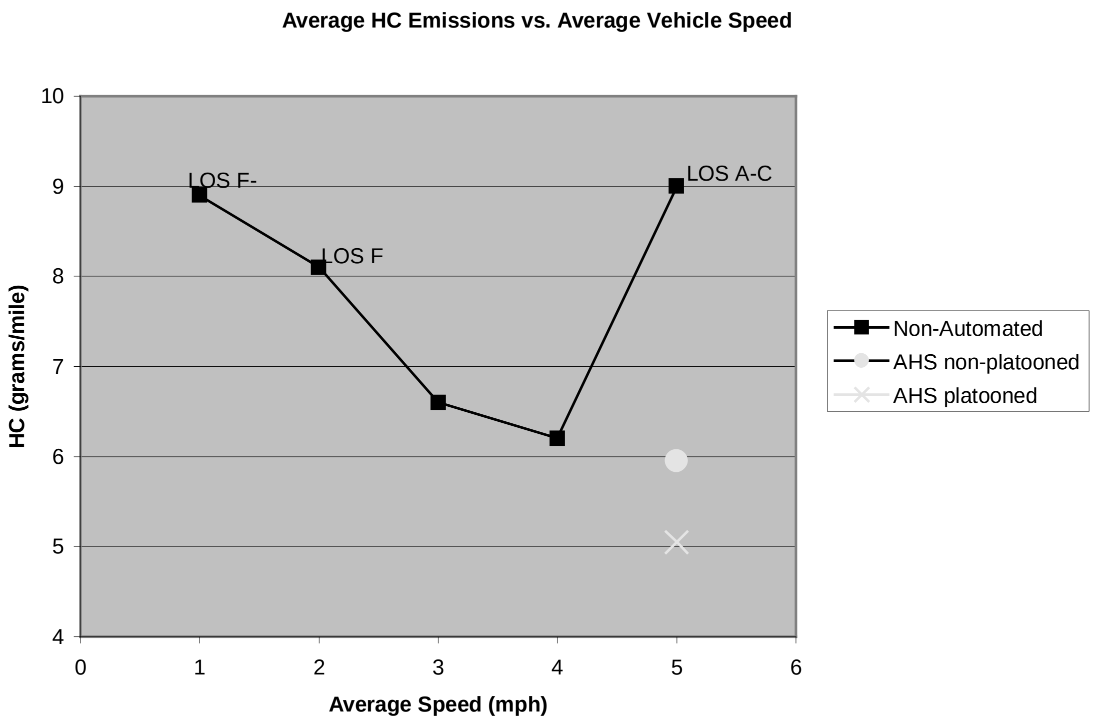
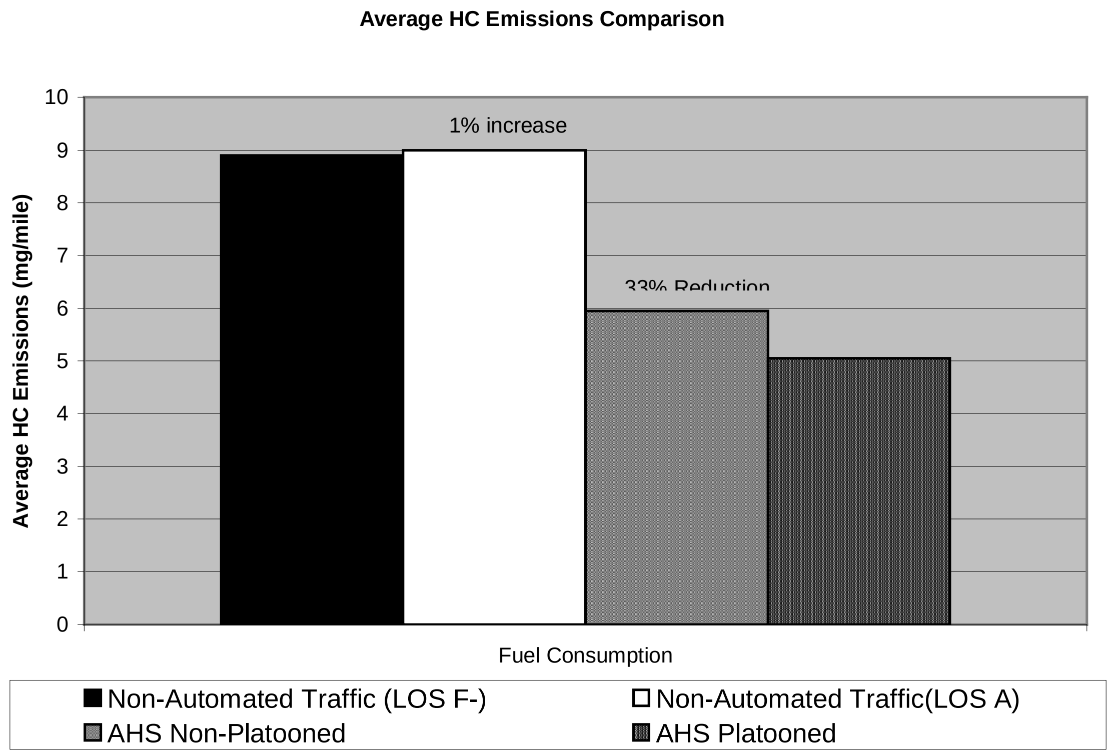

Average HC Emissions vs. Average Vehicle Speed
HC (grams/mile)
10
9
8
7
6
5
4
0
1
2
3
4
5
6
Average Speed (mph)
LOS F-
LOS F
LOS A-C
Non-Automated
AHS non-platooned
AHS platooned

Figure 16b



Average HC Emissions Comparison
10
9
8
7
6
5
4
3
2
1
0
Average HC Emissions (mg/mile)
1% increase
33% Reduction
Fuel Consumption
Non-Automated Traffic (LOS F-)
Non-Automated Traffic(LOS A)
AHS Non-Platooned
AHS Platooned

4.2. Fuel Consumption

4.2.1. Summary

See Figures 17a and 17b.

4.2.2. Comparative and Qualitative Analysis

Like hydrocarbon emissions, fuel consumption rates in the automated non-platoon scenario were 47% less than of manual rates in level of service “F” conditions. Platooned vehicles experienced even greater reductions of 51%, where the compact intra-platoon spacing reduces aerodynamic drag and thus induces efficient fuel usage behavior.

Figure 17a

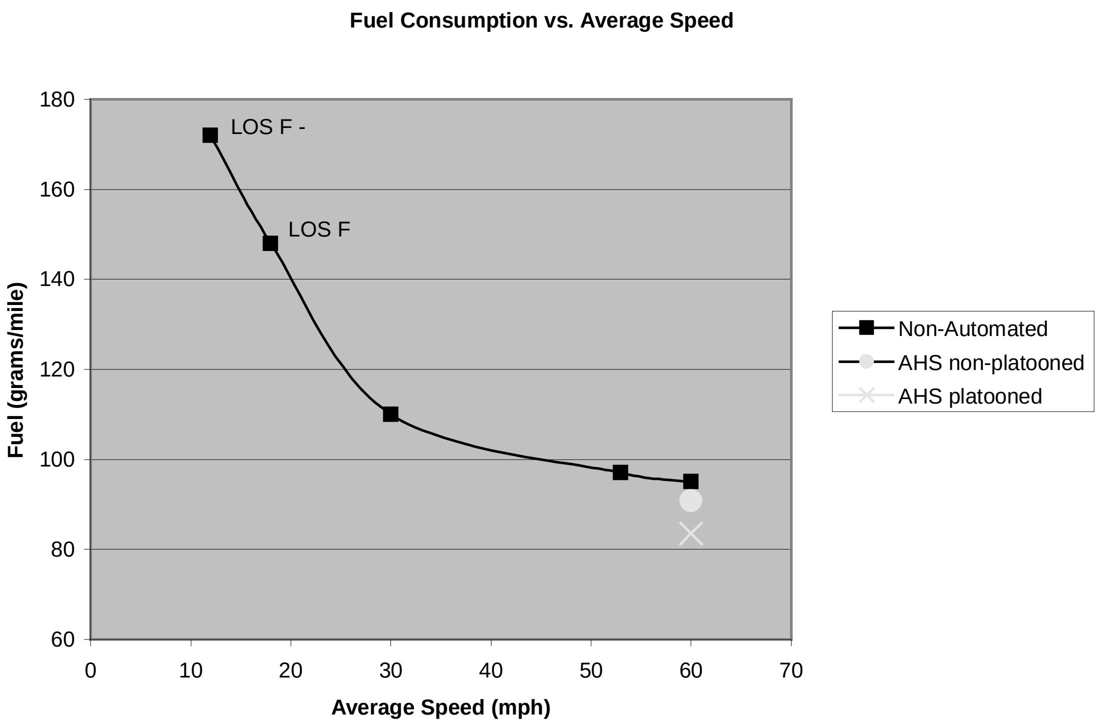
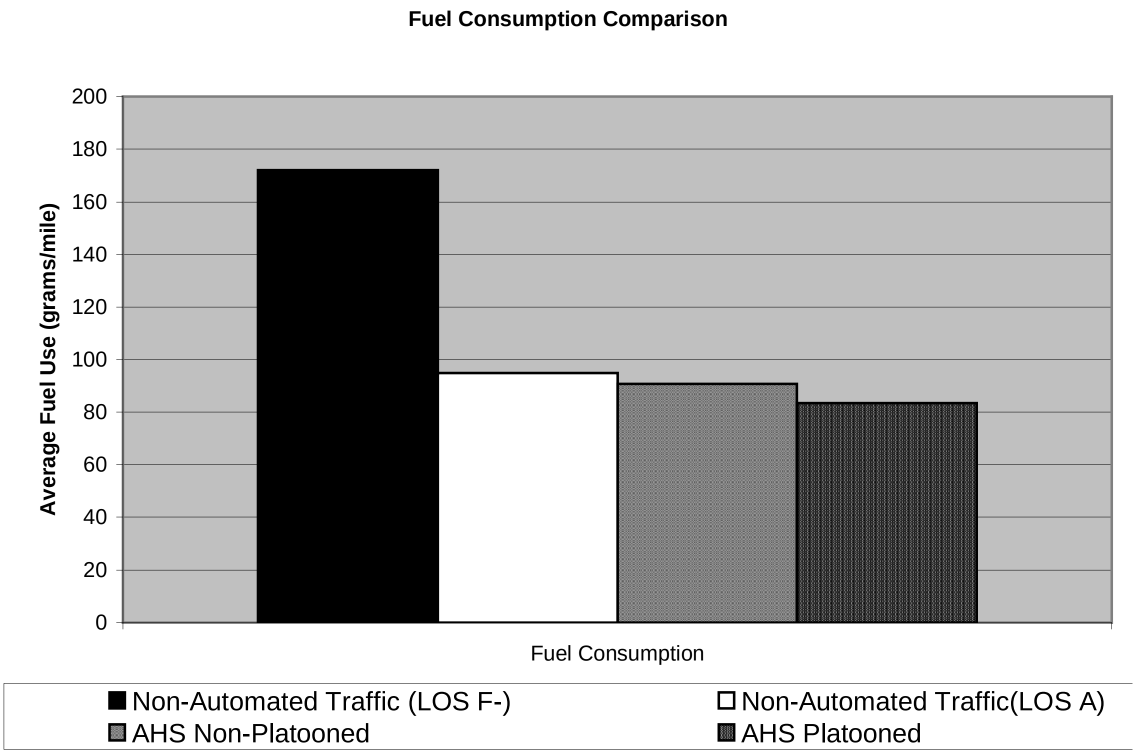

Fuel Consumption vs. Average Speed
180
160
140
120
100
80
60
0
10
20
30
40
50
60
70
Fuel (grams/mile)
Average Speed (mph)
LOS F -
LOS F
Non-Automated
AHS non-platooned
AHS platooned

Figure 17b



Fuel Consumption Comparison
Average Fuel Use (grams/mile)
200
180
160
140
120
100
80
60
40
20
0
Fuel Consumption
Non-Automated Traffic (LOS F-)
Non-Automated Traffic(LOS A)
AHS Non-Platooned
AHS Platooned

4.3. Level of Service

4.3.1. Summary

The levels of service of the mainline segment in each merge junction are listed below:

Table 7a – Manual Level of Service of Merge junctions

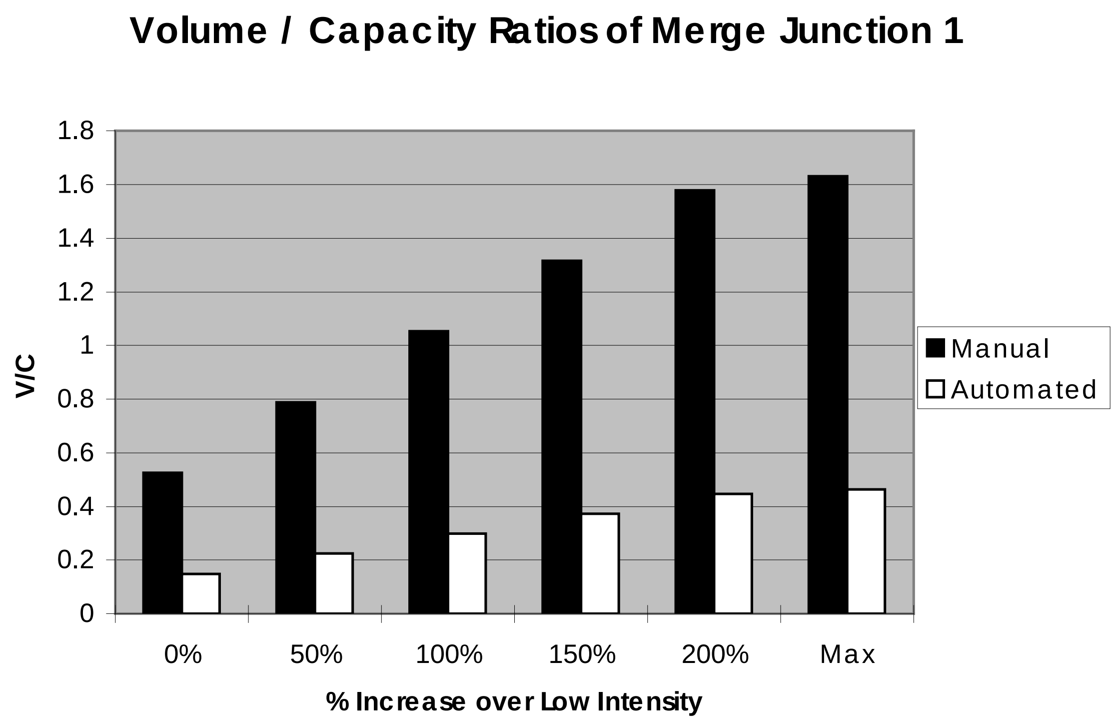
Manual	Merge Jxn 1	Merge Jxn 2	Merge Jxn 3
Low	C	D	E
50%	D	F	F
100%	F	F	F
150%	F	F	F
200%	F	F	F
Maximum	F	F	F

Table 7b – Automated level of Service of Merge Junctions

Automated	Merge Jxn 1	Merge Jxn 2	Merge-Jxn 3
Low	A	A	A
50%	A	A	A
100%	A	A	A
150%	A	A	A
200%	A	A	A
Maximum	A	A	F

The volume to capacity ratios of the mainline segments in each merge junction are listed in Figures 18a - 18c.

Figure 18a



Volume / Capacity Ratios of Merge Junction 1
V/C
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0%
50%
100%
150%
200%
Max
% Increase over Low Intensity
Manual
Automated

Figure 18b

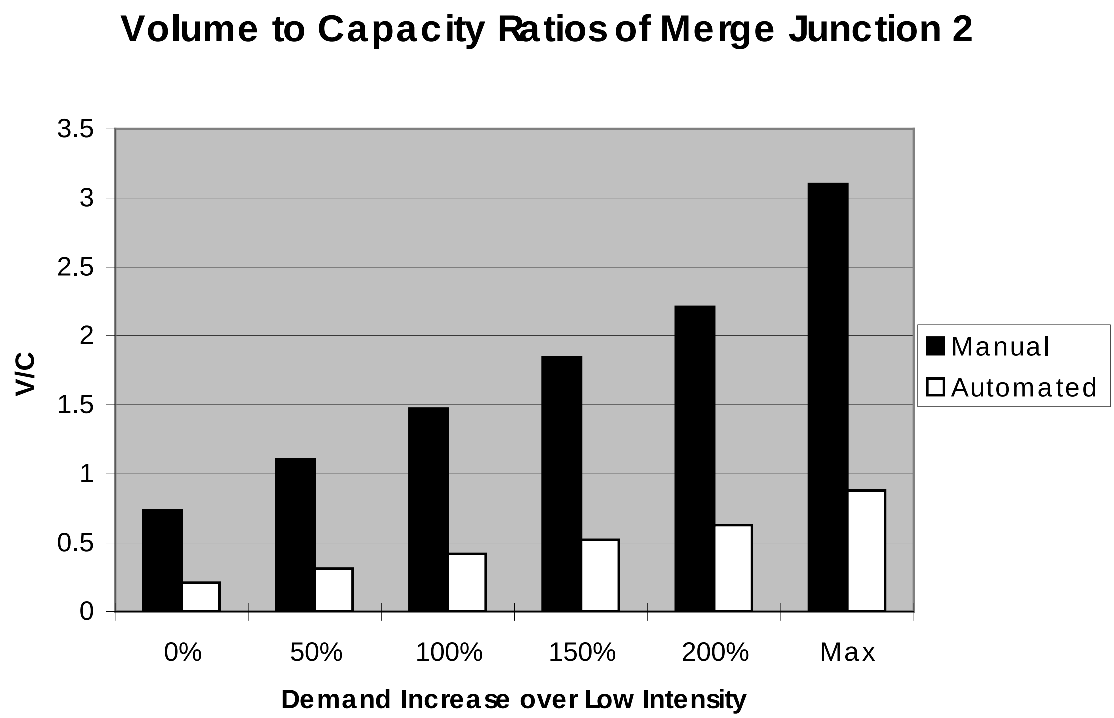
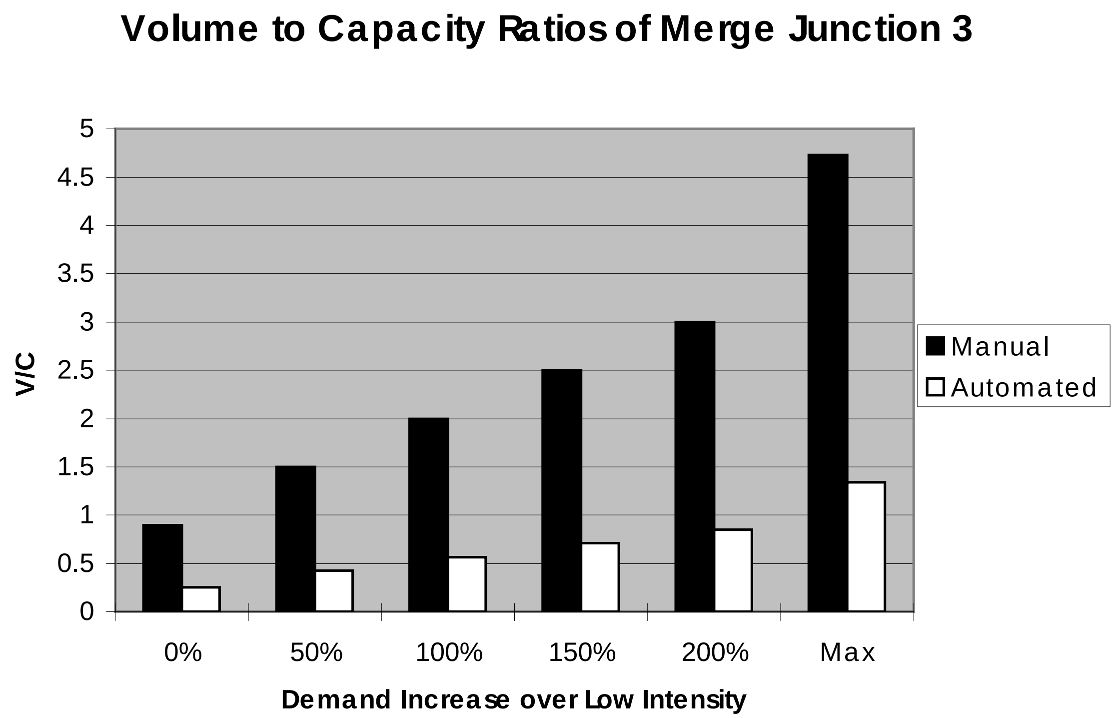

Volume to Capacity Ratios of Merge Junction 2
3.5
3
2.5
2
1.5
1
0.5
0
V/C
0%
50%
100%
150%
200%
Max
Demand Increase over Low Intensity
Manual
Automated

Figure 18c



Volume to Capacity Ratios of Merge Junction 3
V/C
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0%
50%
100%
150%
200%
Max
Demand Increase over Low Intensity
Manual
Automated

4.3.2. Comparative and Qualitative Analysis

As expected, the levels of service for the automated highway system were greatly improved over that of the manual case. The results show that AHS performs at optimal LOS even at demand levels over 200% greater than the low intensity case. Each mainline segment experienced a 72% improvement in their respective volume to capacity ratio. Therefore, it is clear that the increased capacity offered by AHS contributes to greatly superior highway operations.

4.4. Delay

4.4.1. Summary

Results are listed in Figures 19a – 19i. In these figure, the x-axis represents the various demand levels in ascending order. Therefore, "1-6" is indicative of the following respective cases: low intensity, 50% increase, 100% increase (also high intensity), 150% increase, 200% increase, and the maximum demand scenario. Percentage delay, represented in decimal form is shown on the y-axis.

4.4.2. Comparative and Qualitative Analysis

4.4.2.1. Mainline Delay

As seen from mainline delay figures, the Autonomous and Cooperative concepts experience comparable delays throughout the mainlines of each merge junction. However, the Cooperative Platooning concept consistently incurs less delay than both. This is due to the fact that platooning vehicles do not yield to merging vehicles whereas the other concepts in fact do. In addition, the negative delay values of the Cooperative Platooning can be attributed to the joining maneuvers initiated by vehicles to join platoons. Since vehicles must travel at speeds greater than normal free flow speed, actual travel times often are less than calculated free flow travel times causing less than zero delay values.

The Autonomous and Cooperative concepts show a slight reduction in mainline delay from the low intensity manual case on the mainline of merge junction 1, but a significantly greater improvement is evident on the mainline of merge junction 2. This reduction is maintained throughout all demand levels except the maximum case. The Cooperative Platooning concept shows respective 10% and 18% time savings on the mainlines of merge junctions 1 and 2 from the manual case in the low intensity scenario. It maintains this improvement throughout all demand levels.

4.4.2.2. Ramp and Merge Junction Delay

The delay values and patterns which are present in both ramp and total merge junction areas are virtually identical and thus their results are explained together. In all areas, the cooperative platooning concept performs with less delay than the autonomous and cooperative. In addition, it operates with negative delay at all ramps and demand levels expect ramp 1 in merge junction 1 where it operates at less than 2% delay. The cooperative concept consistently performs with less delay than that of the autonomous, but both maintain less than 10% delay in all demand levels except the maximum scenario.

4.4.2.3. Average Corridor Delay

The reductions in delay are consistent with the level of automated intelligence present in each scenario. As expected, the Cooperative Platooning concept perfomed with less delay (1%) than both the Cooperative (5%) and Autonomous (8%) concepts. The exception was in the maximum demand case where all concepts exhibited extraordinary delays.

Figure 19a

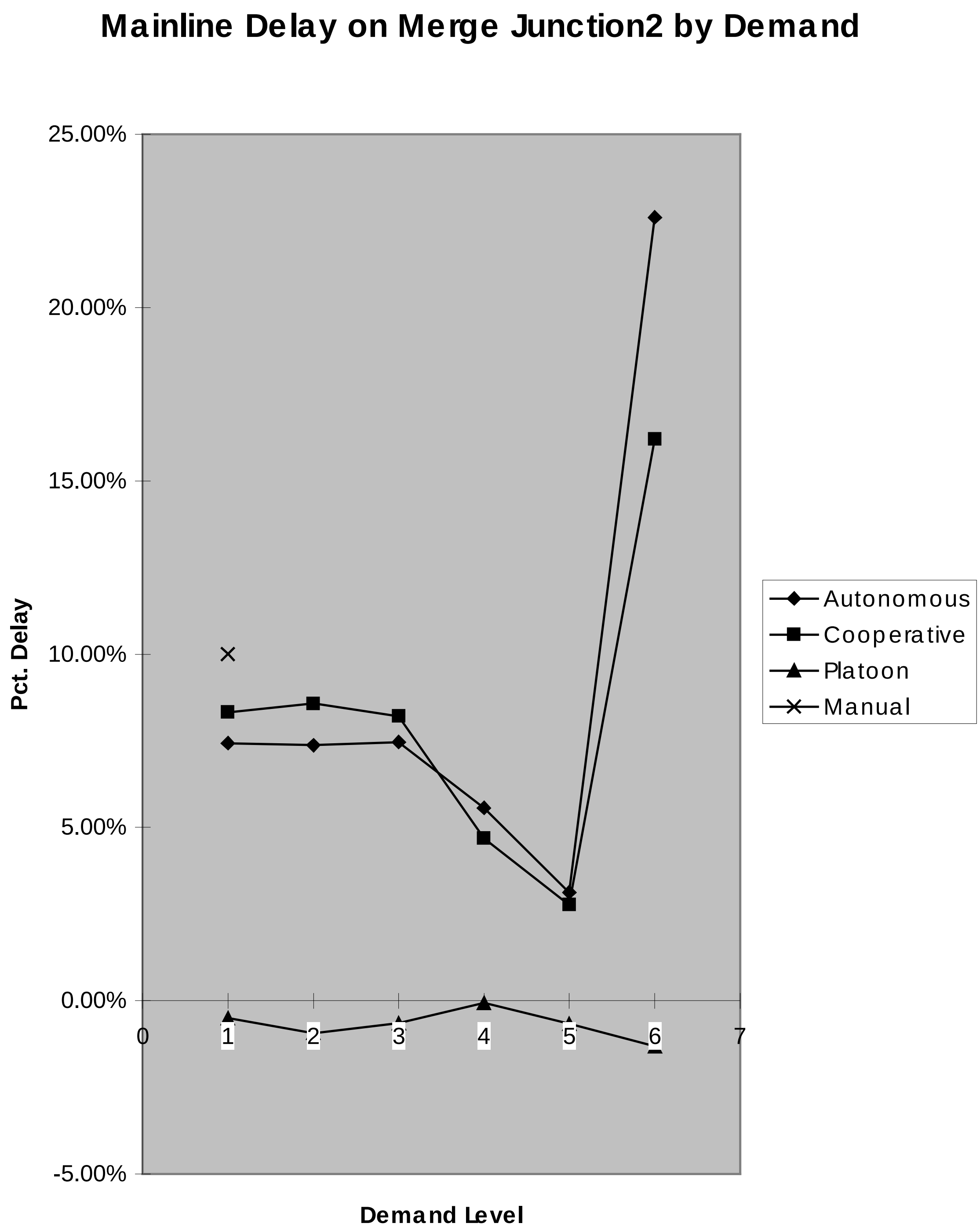

Mainline Delay on Merge Junction2 by Demand
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
-5.00%
Pct. Delay
0
1
2
3
4
5
6
7
Demand Level
Autonomous
Cooperative
Platoon
Manual

Figure 19b

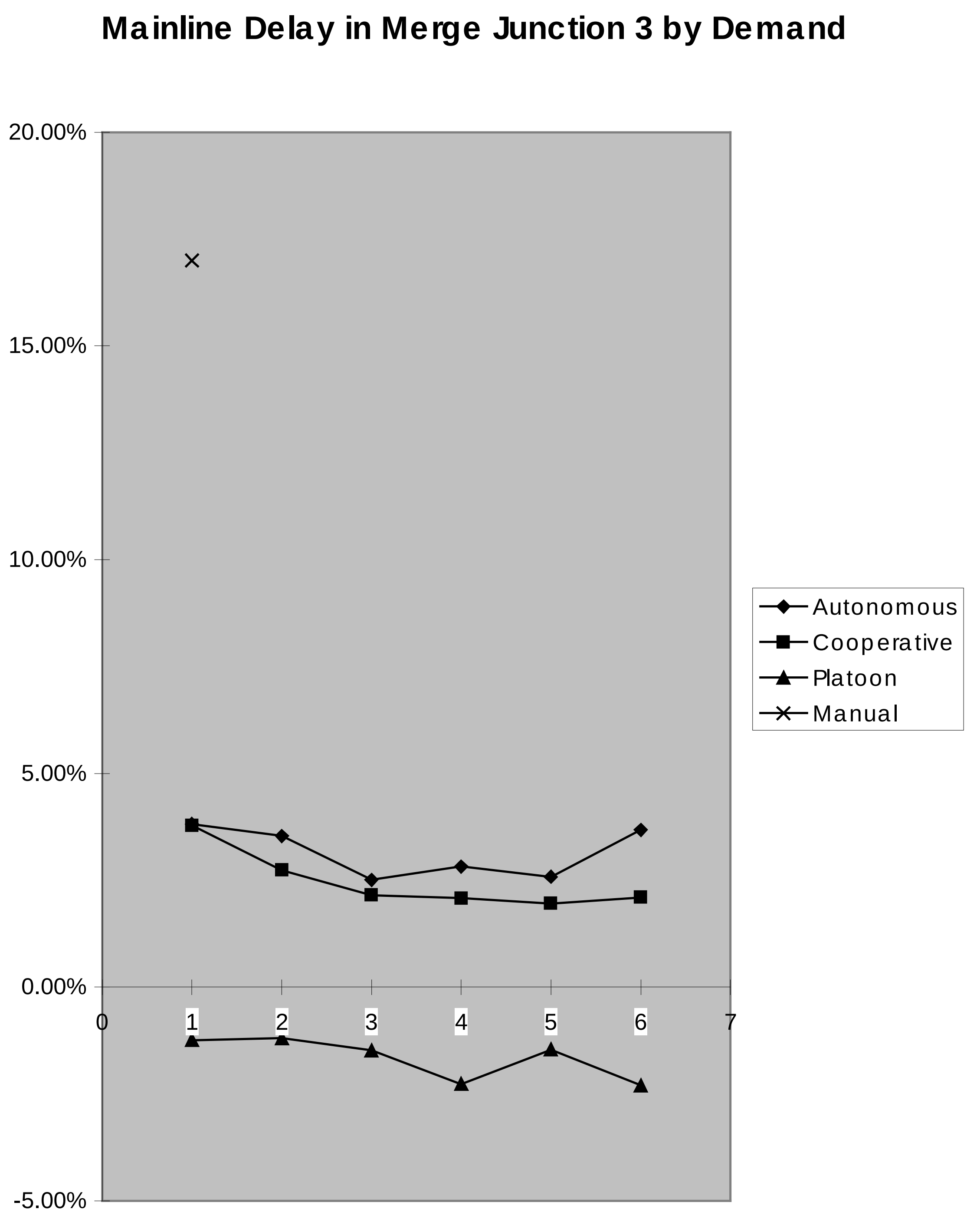

Mainline Delay in Merge Junction 3 by Demand
20.00%
15.00%
10.00%
5.00%
0.00%
-5.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon
Manual

Figure 19c

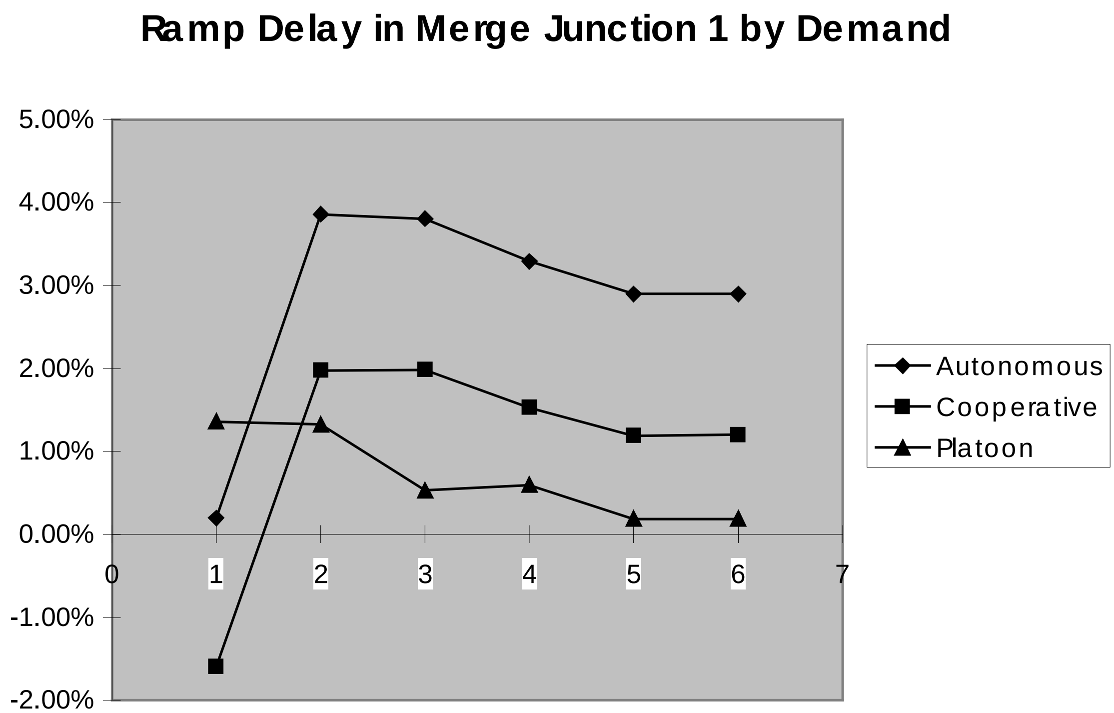

Ramp Delay in Merge Junction 1 by Demand
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon

Figure 19d

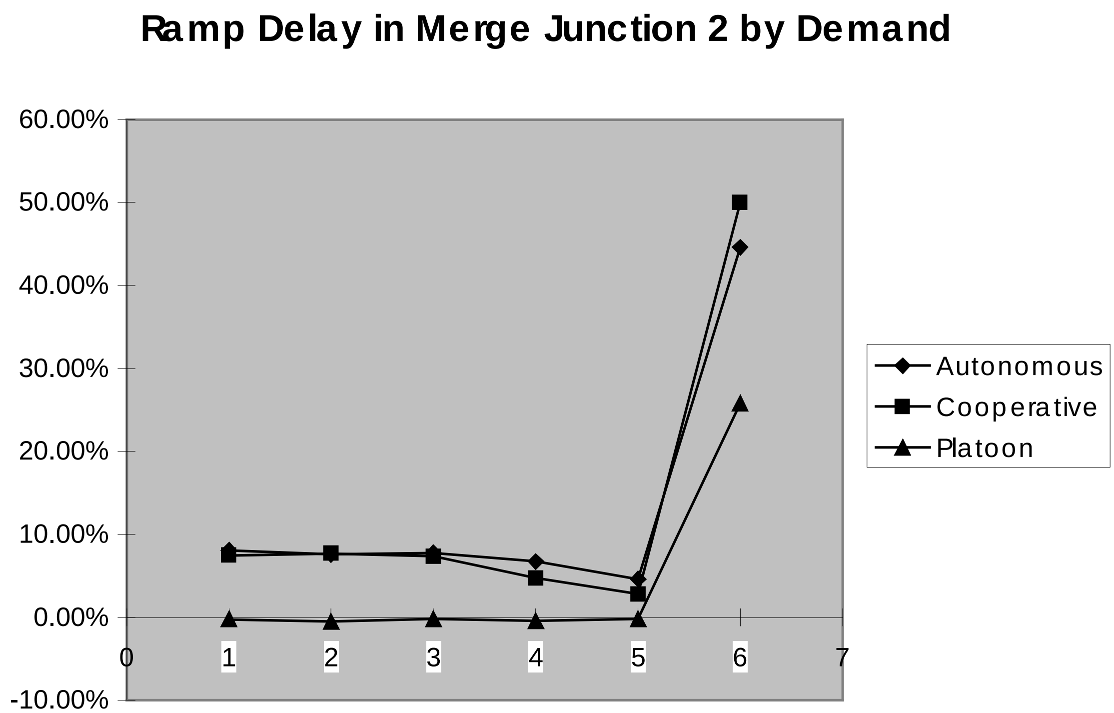
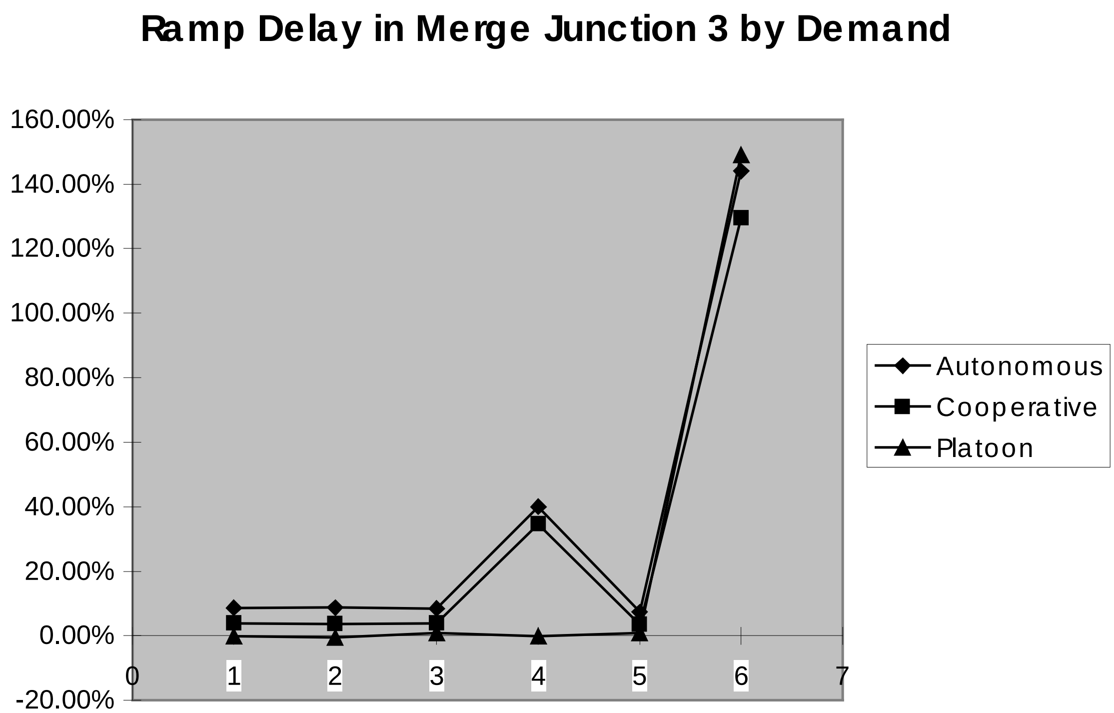

Ramp Delay in Merge Junction 2 by Demand
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
-10.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon

Figure 19e



Ramp Delay in Merge Junction 3 by Demand
160.00%
140.00%
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon

Figure 19f

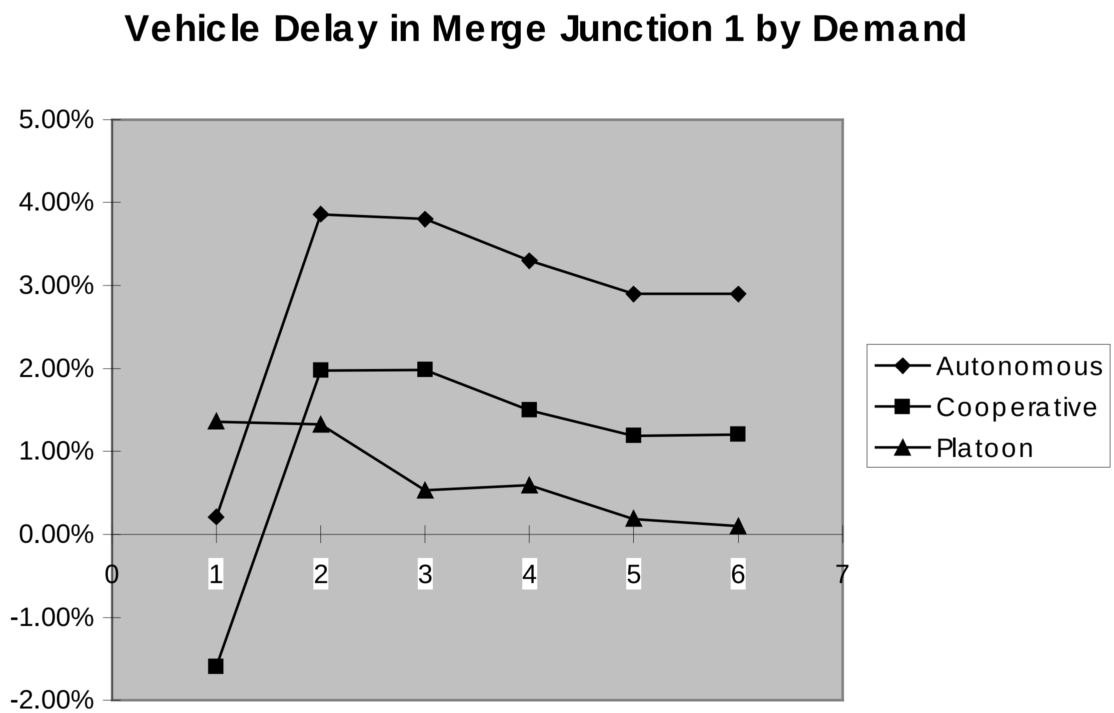

Vehicle Delay in Merge Junction 1 by Demand
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon

Figure 19g

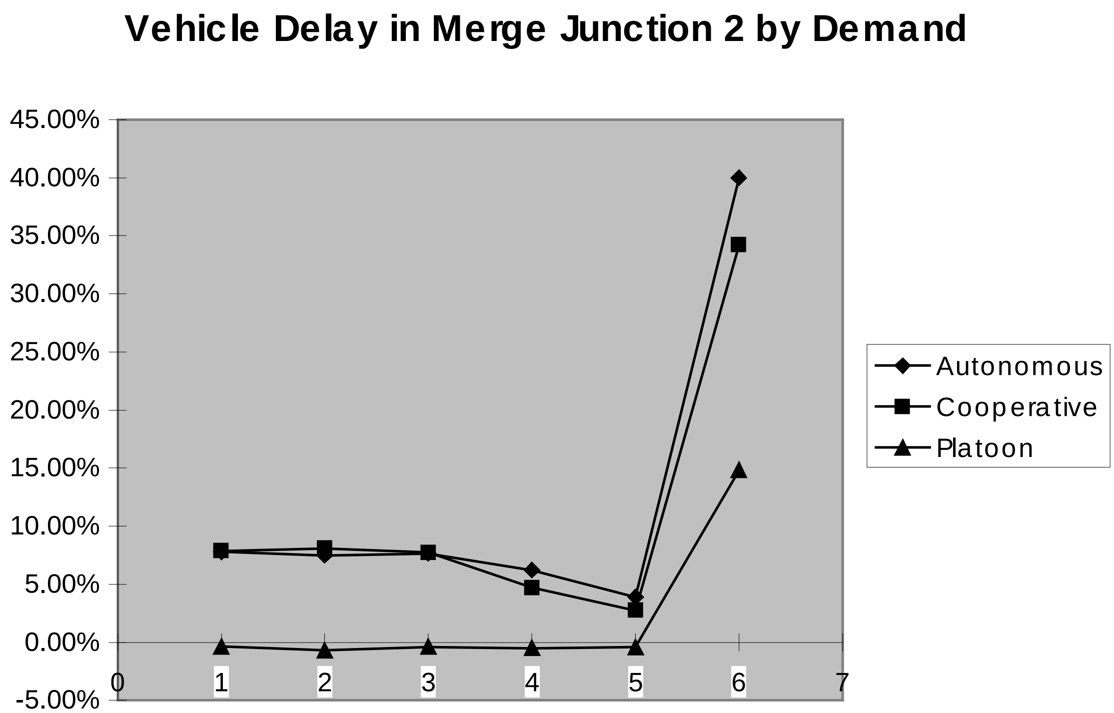

Vehicle Delay in Merge Junction 2 by Demand
45.00%
40.00%
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
-5.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon

Figure 19h

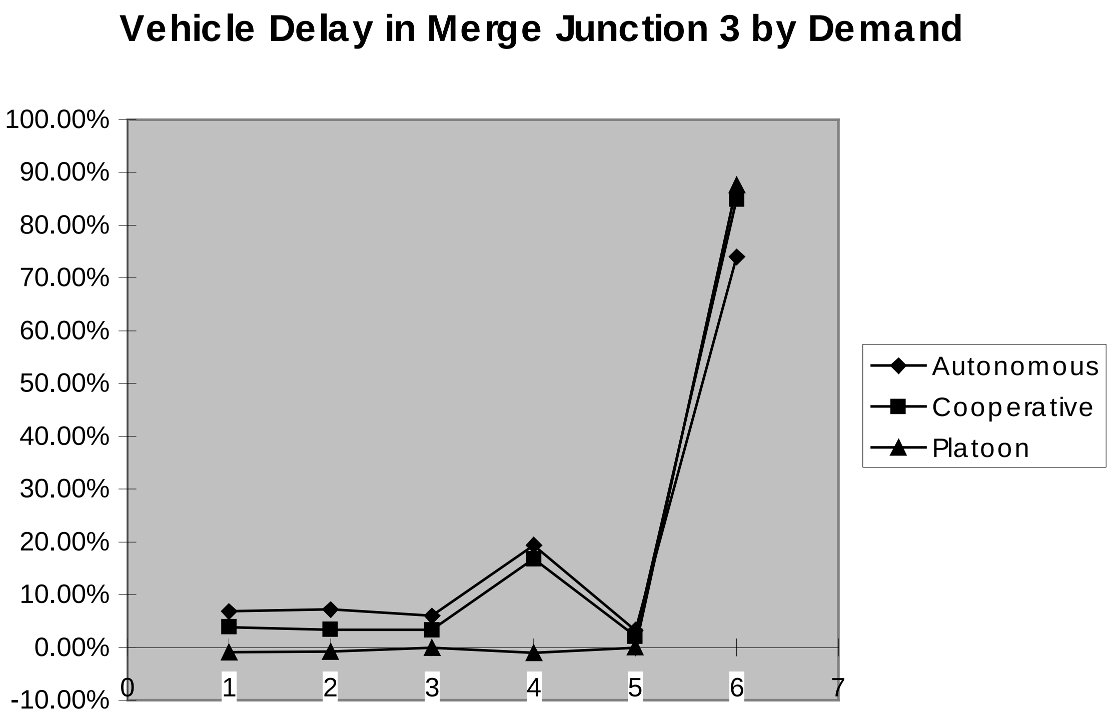
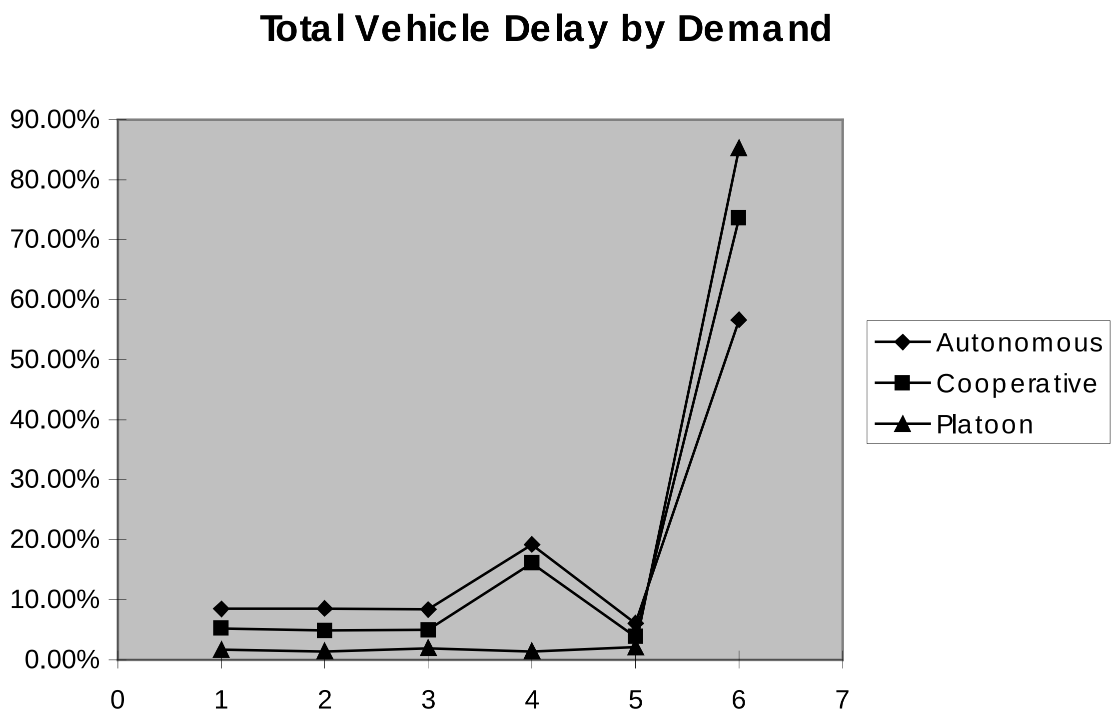

Vehicle Delay in Merge Junction 3 by Demand
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
-10.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon

Figure 19i


Total Vehicle Delay by Demand
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
0
1
2
3
4
5
6
7
Autonomous
Cooperative
Platoon

5. Conclusion

5.1. Emissions and Fuel Consumption

Fuel Consumption Rates achieved by both non-platooned and platooned Automated Highway Systems are slightly lower than manual free flow conditions, but significantly less than manual congested conditions. Since the Katy Corridor usually operates in the “F” level of service range in the peak hour, AHS merging protocols can represent a marked improvement in existing conditions.

Also, because of greater stability in vehicle speeds and especially accelerations, non-platooned AHS induces significant reductions in average vehicle emissions than all manual conditions. In addition, platooned vehicles show additional improvement over their non-platooned counterparts. Clearly, these platooned vehicles benefit from the aerodynamic drag reductions associated with close intra-platoon spacings such that the sensitivity usually encountered at higher speeds is neutralized.

5.2. Level of Service and Delay

At low intensity traffic volumes, AHS shows a significant advantage in highway level of service conditions and modest improvements in time savings or delay reduction. However, when volumes increase to levels beyond the ability of manual highways to serve efficiently, non-platooned systems continue to operate at stable conditions up to a 150% increase over baseline demand volumes. In addition, platooned vehicles traverse the mainline with negative or no delay at all demand levels up to the maximum allowed. Clearly, the merging protocols implemented in all AHS scenarios contribute to superior highway conditions.

6. References

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