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### Publication Date

2003

CALIFORNIA PATH PROGRAM  
INSTITUTE OF TRANSPORTATION STUDIES  
UNIVERSITY OF CALIFORNIA, BERKELEY

## **Evaluation of the ACC Vehicles in Mixed Traffic: Lane Change Effects and Sensitivity Analysis**

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**California PATH Research Report  
UCB-ITS-PRR-2003-3**

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

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Report for Task Order 4217

January 2003

ISSN 1055-1425

**EVALUATION OF THE ACC VEHICLES IN MIXED TRAFFIC: LANE  
CHANGE EFFECTS AND SENSITIVITY ANALYSIS<sup>1</sup>**

by

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<sup>1</sup> This work is supported by the California Department of Transportation through PATH of the University of California. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

# EVALUATION OF THE ACC VEHICLES IN MIXED TRAFFIC: LANE CHANGE EFFECTS AND SENSITIVITY ANALYSIS

by

Petros Ioannou and Margareta Stefanovic

## Abstract

Almost every automobile company is producing vehicles with Adaptive Cruise Control (ACC) systems that allow a vehicle to do automatic vehicle following in the same lane. The ACC system is designed for driver comfort and safety and to operate with manually driven vehicles. These characteristics of ACC were found to have beneficial effects on the environment and traffic flow characteristics [1, 2, 3] by acting as filters of a wide class of traffic disturbances. It has been argue that the smooth response of ACC vehicles to high acceleration disturbances or large position errors creates large gaps between the ACC vehicle and the vehicle ahead inviting cut –ins and therefore generating additional disturbances that would not have been created if the vehicles were all manually driven.

In this report we examine the effect of lane changes on the benefits suggested in [1,2,3] as well as the sensitivity of these benefits with respect to various variables such as ACC penetration, level of traffic disturbances etc. We demonstrate using theory, simulations and experiments that during lane changes, the smoothness of the ACC vehicle response attenuates the disturbances introduced by the cut –in or exiting vehicle in a way that is beneficial to the environment when compared with similar situations where the ACC vehicle is absent. We concluded that the higher number of possible cut-ins that may be present due to the higher gaps created during high accelerations maneuvers by the vehicle in front of the ACC vehicle, will not take away the benefits shown in the absence of such cut –ins when compared with the situation of similar maneuvers but with no cut-ins in the case of 100% manually driven vehicles.

**Keywords:** Adaptive Cruise Control vehicles, manually driven ('manual') vehicles, mixed traffic, vehicle following, lane change, air pollution, fuel consumption.

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## 1 Introduction

Recent advances in technology have propelled efforts to automate vehicles in order to achieve safe and efficient use of the current highway system. Fully automated vehicles that are able to operate autonomously in a highway environment are a long-term goal. On the other hand, partially or semi-automated vehicles designed to operate with current manually driven vehicles in today's highway traffic are seen as a more near term objective. Adaptive Cruise Control (ACC) systems developed during the last decade and recently produced and made available to users by every major automobile company is the first step towards that direction.

Considering the current penetration of products such as Anti-Lock Braking Systems (ABS), air bags and cruise control into the vehicle market, it is justifiable to expect that ACC systems that give vehicles the capability to follow the vehicle in front automatically in the same lane will penetrate the market in a similar fashion. A variety of different ACC control schemes have been designed for passenger cars during the last decade. Human factors and driver comfort considerations dictate that the response of the ACC vehicle to a leading vehicle maneuver or disturbance should be smooth. This smooth response of the ACC vehicle was suspected to have beneficial effects on traffic flow characteristics and the environment. Since the vehicle-highway system is one of the major contributors to air pollution in urban areas due to increasing vehicle miles traveled and congestion [8], the impact of the ACC vehicles on the environment as more of these vehicles penetrate the system is an important topic for investigation and it was first addressed in [3].

In [1-3] the effects of ACC vehicles operating together with manually driven vehicles in a mixed traffic situation are analyzed on the microscopic and macroscopic level using the fundamental diagram, space-time graphs and simulations. The results of the analysis that are demonstrated experimentally on the microscopic level indicate that ACC vehicles have a beneficial effect on traffic flow characteristics and positive effects on the environment due to their smoother response and more intelligent use of the throttle and brake in achieving desired driving tasks in situations involving high acceleration maneuvers.

The results of [1] developed using simulations and experiments show that a disturbance generated by vehicle during a high acceleration maneuver is attenuated when it reaches an ACC vehicle due to the fact that the ACC vehicle is designed to respond to such disturbances in a smooth way and with lower acceleration. While this characteristic of the ACC vehicle has beneficial effects on the environment and traffic flow characteristics in the same lane, the analysis and study of [1-3] does not include the effect of this ACC response to the vehicles in the neighboring lane. For example a rapidly accelerating vehicle in front of the ACC vehicle will create a large gap between the two vehicles since the ACC vehicle will follow such a vehicle with much lower acceleration due to human factors and driver comfort constraints. Such a large gap may invite vehicles from neighboring lanes to cut in. As a result additional disturbances will be created that have

not been taken into account in the work of [1-3]. Similarly lane exit may also generate disturbances. A vehicle ahead of ACC may change lanes for several reasons but one possible reason could be that the driver of such vehicle does not want to be followed by a vehicle driven by the computer. While this assumption may not be valid with the current ACC designs where relatively large minimum time headways are used, it may be valid in the case of future more advanced ACC systems with much smaller minimum time headways.

The purpose of this report is to first examine the sensitivity of earlier results obtained in [1] with respect to several variables such as level of disturbance, percent penetration of the ACC vehicles etc, and evaluate the effect of lane changes on traffic flow characteristics on the microscopic level and environment.

## **2 ACC vehicle behavior in mixed traffic**

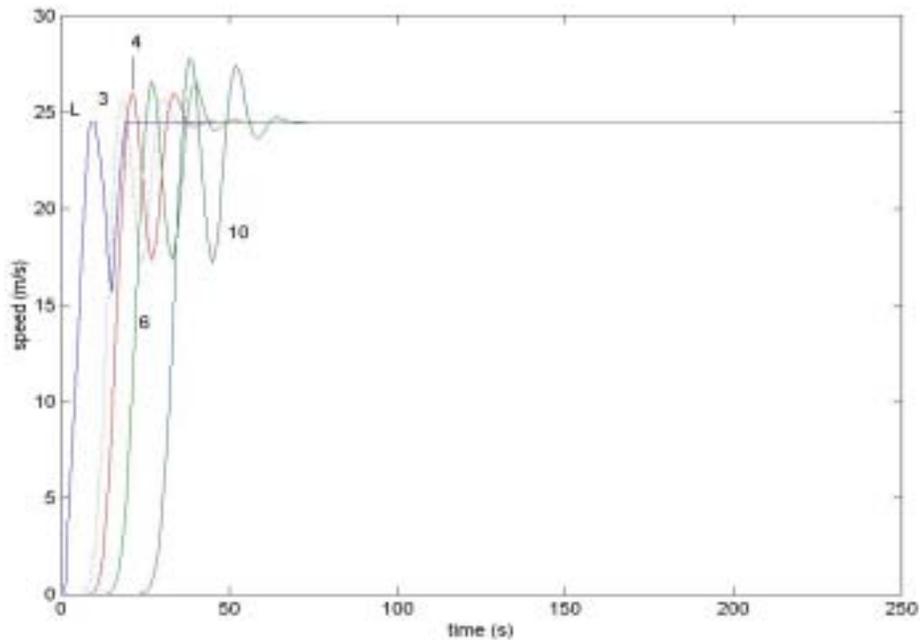
In [1,3] it was established using theory and experiments that ACC vehicles have beneficial effects on traffic flow characteristics and the environment especially during disturbances generated when the lead vehicle in front of the ACC vehicle exhibits high acceleration maneuvers. The emission model developed in [5,6] is used to calculate the benefits in terms of pollution benefits and fuel economy. The reason why the ACC vehicle response is so friendly to the environment is that ACC vehicles are designed to exhibit smooth response to changes in speed and acceleration mainly for human factors and driver comfort purposes. The results in [1] are demonstrated experimentally at Richmond Field and Crows Landing and they are found to be in close agreement with those predicted from theory and simulations using driver and ACC models. In [1] the ACC vehicle was always at a position close to the point where the disturbance was generated, followed by a number of human driven vehicles. The sensitivity of the benefits generated in [1] with respect to the position of the ACC vehicle in the string of a number of vehicles and to other variables is examined in this section.

### **2.1 High acceleration maneuvers**

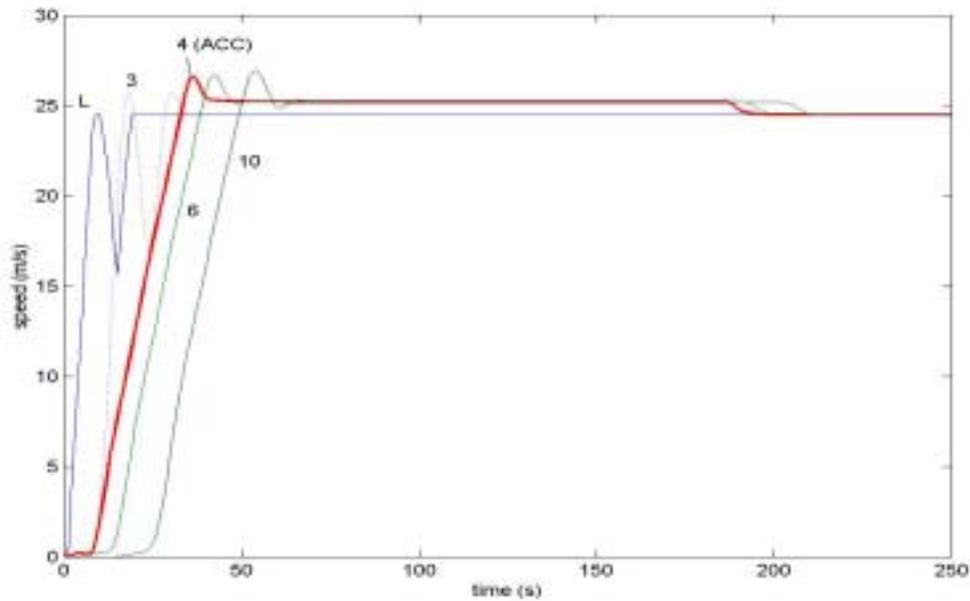
Let us consider a string of ten vehicles following one another in the same lane. Due to an accident that was just cleared, the lead vehicle begins to accelerate from 0 speed with acceleration  $0.35g$  to  $24.5$  m/s. The rest of the vehicles respond accordingly trying to follow the vehicle response of the vehicle right in front of them in an effort to maintain a small but comfortable intervehicle spacing. After reaching  $24.5$  m/s, the lead vehicle decelerates to  $14.5$  m/s at  $-0.3g$ , and finally accelerates back to  $24.5$  m/s at the acceleration rate of  $0.25g$ .

In order to examine the effect of these maneuvers on the environment and the difference between having an ACC vehicle present in the string of the 10 vehicles and not having one we use as in [1] the Pipes model [4] to model human drivers and the ACC model [7] to model the ACC vehicle. Figure 1 shows the speed responses of the various vehicles in the string of 10 when all vehicles are manually driven. As indicated in [1,3] the disturbance generated by the lead vehicle gets amplified and becomes more oscillatory as

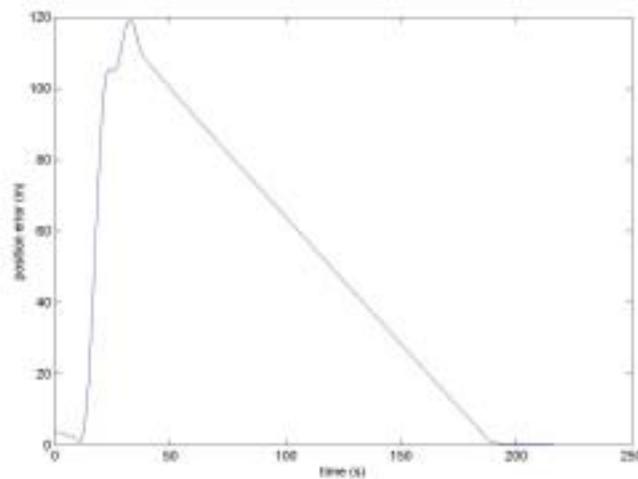
it travels upstream. This is a phenomenon often observed in today's traffic. In Figure 2 we assume that the 4<sup>th</sup> vehicle in the string of 10 is an ACC vehicle. It follows from Figure 2 that the ACC vehicle due its limited acceleration cannot follow the rapid oscillatory speed response of the vehicle in front but instead it acts as a filter presenting to the vehicles behind a smoother less oscillatory speed response to follow. The drawback of this ACC behavior is that the intervehicle spacing between the ACC vehicle and that in front becomes large for some time until the ACC vehicle catches up as shown in Figure 3. In some cases if the vehicle ahead of the ACC continues speeding with high acceleration the ACC vehicle may lose the target and switch to the cruise mode.



**Figure 1: High acceleration/deceleration maneuver initiated by the lead vehicle; Speed responses of the lead, 3<sup>rd</sup>, 4<sup>th</sup>, 6<sup>th</sup> and 10<sup>th</sup> vehicle in a string of 10 manually driven vehicles**



**Figure 2: High acceleration/deceleration maneuver initiated by the lead vehicle; Speed responses of the 1<sup>st</sup>, 3<sup>rd</sup>, 4<sup>th</sup>, 6<sup>th</sup> and 10<sup>th</sup> vehicle in a string of 10 vehicles of which the 4<sup>th</sup> is ACC and the rest are manually driven.**



**Figure 3: Large Position error for the ACC vehicle due to its limited acceleration**

As analyzed in [1], the above simulations show that the smooth response of the ACC vehicles have beneficial effects on the environment and fuel economy. Using the emissions model of [5,6] we compare the accumulative pollution levels and fuel economy for the case where the 10 vehicles are manually driven and when the 4<sup>th</sup> vehicle in the string of 10 is replaced with an ACC vehicle for the same lead vehicle maneuver. The results are summarized in table 1.

Table 1. Summary of benefits

	Percent benefits of mixed over manual traffic in high acceleration vehicle following
HC emission	38 %
CO emission	48 %
CO <sub>2</sub> emission	negligible
Fuel consumption	8 %

The above results are in agreement with those presented in [1]. In [1] the validity of the above results is demonstrated experimentally using 3 vehicles. Due to the short range of the ranging sensor, high accelerations were not possible as at such accelerations large gaps are created and the ACC vehicle loses the target forcing it to switch to the cruise mode. As a result these experiments are repeated with a longer range sensor as described in the following subsection.

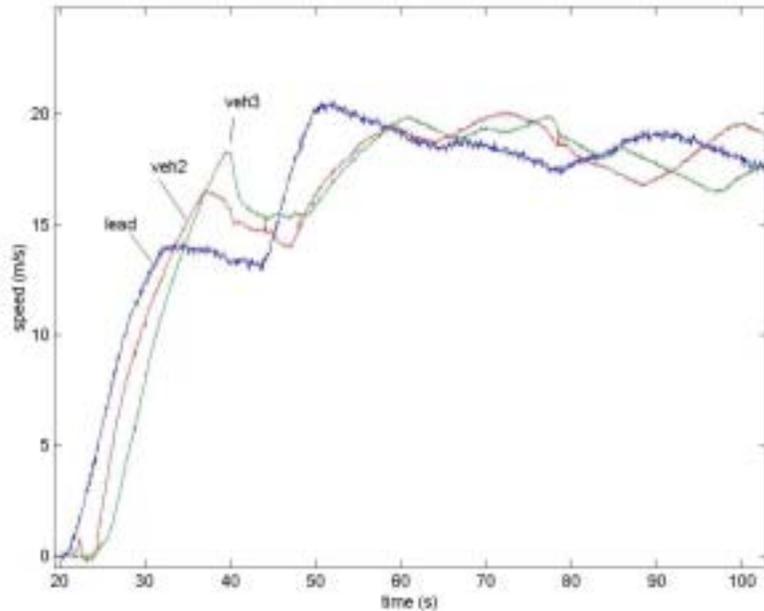
## 2.2 Experiments

Several runs of tests were performed at the Crows Landing test track with the aim of investigating the validity of the theoretical results. They consisted of two types of traffic – fully manual in which all vehicles were under manual control and mixed in which one of the vehicles was equipped with an ACC system and the rest were manually driven. Three vehicles were used for the experiments, with one changing to the ACC mode for the mixed traffic scenarios.

The ACC system was implemented on a Buick LeSabre experimental vehicle. The ACC controller used range and range rate measurements from the radar mounted at the front of the vehicle. The experimental vehicle had two radars installed: Doppler Eaton-Vorad EV300 radar, with more than 150m range and a non-Doppler Delco radar, with shorter range of ~50m. Most of the time, the radar reading used by the controller was that of EV-300. However, due to the fact that it is a Doppler type radar, when the relative velocity was less than 0.25 mph the radar range reading dropped to zero. One way of handling these radar dropouts was to use a weighted combination of the two radar readings when radar dropouts were suspected. Otherwise, only the EV300 radar range readings were used by the controller. The other two vehicles were also Buick LeSabre and they were equipped with data acquisition systems to record their speed and longitudinal acceleration.

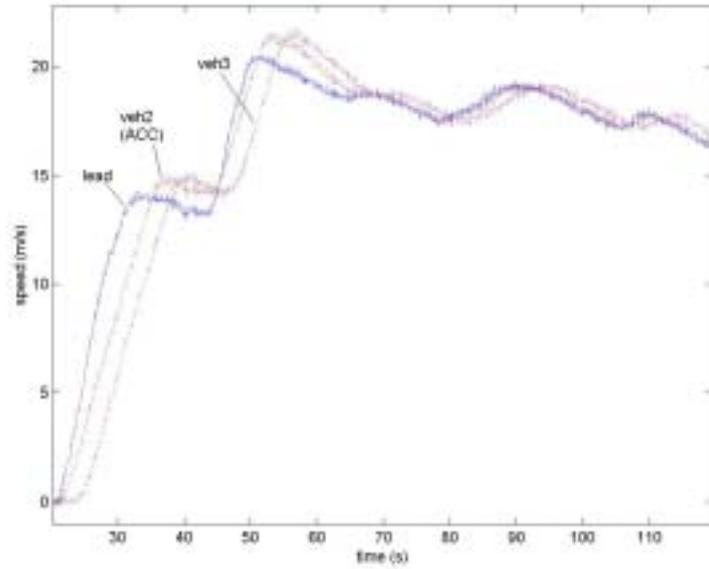
For manual traffic, all vehicles were operated manually. The driver of the lead vehicle was instructed to follow a given speed profile to the best of his/her abilities. The drivers of the following vehicles responded by following the vehicle ahead with a comfortable

headway. The vehicles were interchanged for different runs. Figure 4 shows the experimental results for one such run.



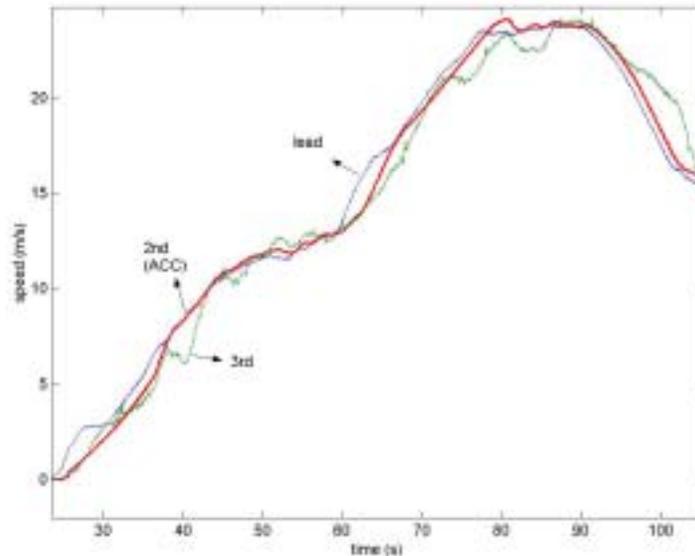
**Figure 4: Speed response of three manually driven vehicles during high acceleration maneuver: Experimental results**

For mixed traffic experiments, the ACC algorithm was implemented on the Buick LeSabre that was used along with the two other Buicks. A time headway of 1.0 sec was used by the ACC vehicle. The lead vehicle performed as closely as possible the same type of maneuvers as in the manual traffic. The ACC vehicle was placed as the second vehicle for the vehicle following runs. Figure 5 shows the responses of the three vehicles.



**Figure 5: Speed response in the mixed traffic during the high acceleration maneuver: 2<sup>nd</sup> vehicle is equipped with the ACC system. Experimental results.**

Since the ACC vehicle is limited in maximum acceleration it lags behind, but its response and that of the 3<sup>rd</sup> vehicle is much smoother than that in Figure 4 where all 3 vehicles were manually driven. Figure 6 shows the speed responses of the 3 vehicles for lower lead vehicle acceleration. It is clear that the ACC vehicle is able to track closely the lead vehicle speed.



**Figure 6: Speed responses for a low acceleration lead vehicle maneuver. Experimental results**

The speed responses in Figures 4 and 5 are fed into the emission model and the cumulative values of the emissions and fuel consumption were calculated. The percentage improvements caused by the presence of the ACC vehicle are calculated and summarized in Table 2. In order to validate the simulation results, obtained earlier and in the rest of the paper, the 3-vehicle experiment of Figures 1 and 2 is simulated using the mathematical models for the human drivers and the ACC system, and the benefits obtained are also presented in Table 2 for comparison purposes. It is clear that the simulations are more conservative in the estimate of the benefits than in the actual case. The same observation was made in [1].

Table 2. Summary of benefits

Benefits obtained in high acceleration maneuvers	Experimental results	Simulation results
CO emission benefits	12 %	6 %
HC emission benefits	6 %	5%
CO <sub>2</sub> emission benefits	Negligible	Negligible
NO <sub>x</sub> emission benefits	7 %	6 %
Fuel consumption benefits	Negligible	Negligible

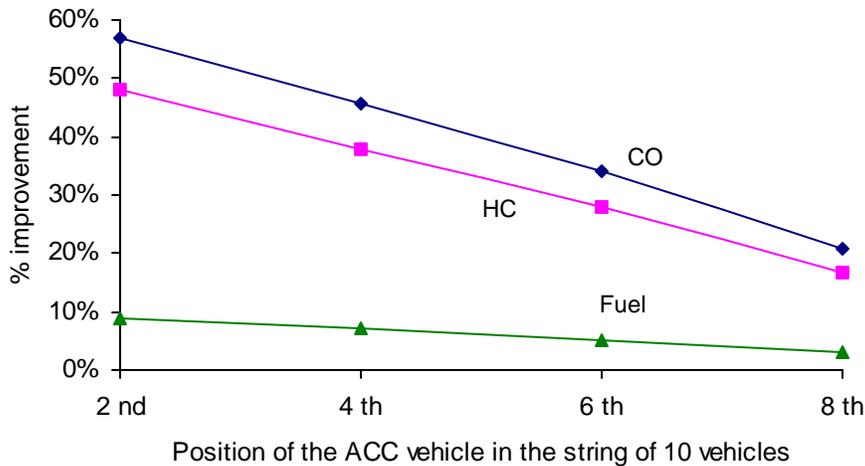
### 2.3 Sensitivity analysis

The results in [1] and in the previous section are obtained for a specific scenario that is likely to occur in an actual highway. The question that arises is how these benefits vary with respect to the 1) relative position of a (single) ACC vehicle in a string of manually driven vehicles; 2) acceleration and deceleration levels exhibited by the lead vehicle in the string, and 3) percent penetration of ACC vehicles in the mixed traffic.

#### 2.3.1 Sensitivity analysis with respect to the position of a single ACC vehicle in a string of manually driven vehicles

We consider a string of 10 vehicles following the leader in a single lane. The lead vehicle performs high acceleration and deceleration maneuvers as shown in Figure 1 (100% manual) and Figure 2 (mixed). The only difference is that the ACC vehicle in the case of Figure 2 is placed at different positions in the string of the 10 vehicles. In particular we consider a single ACC vehicle positioned 2<sup>nd</sup>, 4<sup>th</sup>, 6<sup>th</sup> and 8<sup>th</sup> place in the string. Environmental analyses for these three cases are carried out, and the percent improvements of mixed over manual traffic are calculated. Figure 7 shows the variation of the benefits as the position of the ACC is moved away from the point where the traffic disturbance is generated. It is obvious that the further away the ACC vehicle is from the

point of disturbance the less effect will have on the pollution levels and fuel economy of the vehicles in the string as the vehicles ahead of the ACC will perform as in the manual case. This indicates that the environmental benefits of ACC will improve with the penetration of ACC vehicles as more ACC vehicles are likely to be present close to the origin of the disturbance acting as filters of oscillatory high acceleration speed responses.

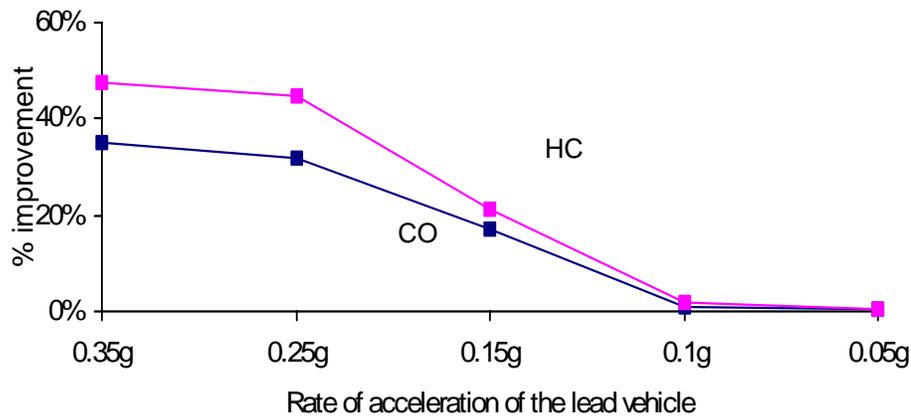


**Figure 7: Percent benefits in CO and HC emission and fuel consumption versus the position of the ACC vehicle in the string of 10 vehicles**

In Figure 7 the benefits in CO<sub>2</sub> and NO<sub>x</sub> were less than 5% and considered to be negligible.

### 2.3.2 Sensitivity analysis with respect to the acceleration of the lead vehicle

In this subsection we examine the environmental impact of manual vs. mixed traffic with respect to the aggressiveness of the lead vehicle maneuver for a 10% ACC participation. As before we consider a string of 10 vehicles where the 3<sup>rd</sup> vehicle is ACC and the rest are manually driven. The lead vehicle starts from rest, accelerates at the specified rate (0.35g, 0.25g, 0.15g, 0.1g, 0.05g) to 24 m/s, and keeps that speed for ~100 sec. The rest follow suit. The speed responses in the manual and mixed case are used together with the emission model to calculate the cumulative percent benefits shown in Figure 8.

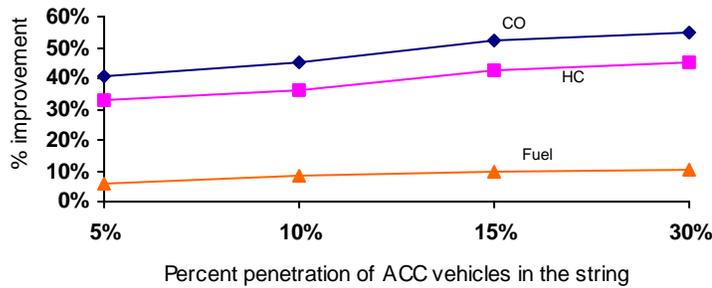


**Figure 8: Percent benefits in CO and HC emission vs. acceleration rate of lead vehicle maneuver**

The benefits for  $\text{NO}_x$ ,  $\text{CO}_2$  and fuel consumption were less than 5% and considered to be negligible. As expected the benefits decreased with the level of the lead vehicle acceleration. Since the ACC vehicle is allowed to generate up to .1g acceleration the benefits for lead vehicle accelerations close to .1g and below are negligible. That is for accelerations close to .1g and below the ACC vehicle follows exactly the maneuver in an effort to maintain accurate position as in this case driver comfort is not an issue. As pointed out in [1] in this case the ACC vehicle simply passes the disturbance upstream with high accuracy without any filtering or attenuation.

### 2.3.3 Sensitivity analysis with respect to the penetration of ACC vehicles

Since the ACC vehicles act as filters of disturbances that are due to high acceleration maneuvers the more ACC vehicles are present in a string of vehicles the more effective this filtering effect will be. We study the case where 5%, 10%, 15% and 30% of the vehicles are ACC vehicles. In particular we consider a string of 20 vehicles where 5% corresponds to the presence of 1 ACC vehicle, 10% to 2 ACC vehicles, 15% to 3 ACC vehicles and 30% to 6 ACC vehicles. The position of the ACC vehicles in the string of 20 is chosen randomly. Ten possible such positions are evaluated and the benefits obtained are averaged and presented in Figure 9. The evaluation was performed for the following maneuver: The lead vehicle accelerates from 0 to 24 m/s with acceleration .35g and keeps that speed for a duration of about 100 sec and the rest of the vehicles follow accordingly. The results shown in Figure 9 demonstrate that the benefits increase with a relatively small slope with the penetration of the ACC vehicles. As the penetration increases further the benefits level off. The results indicate that most of the benefits can be obtained even for low levels of penetration.



**Figure 9: Percent benefits in CO emission, HC emission and fuel consumption versus percent penetration of ACC vehicles**

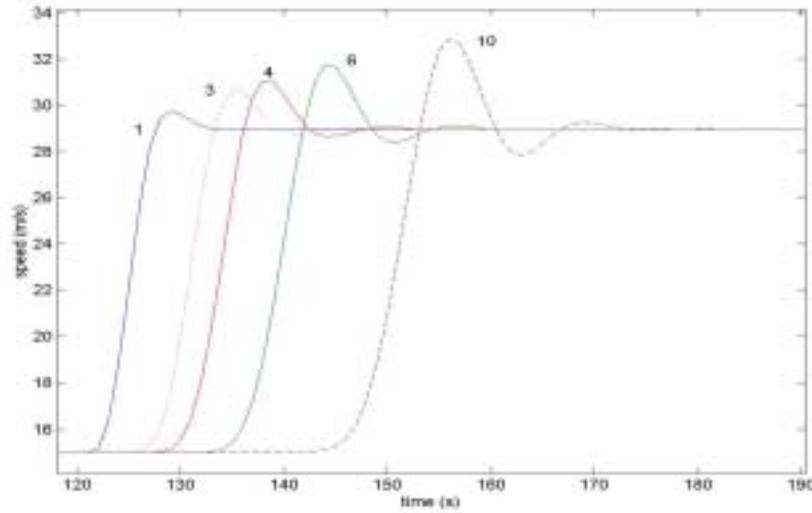
### 3 Lane Change Effects

As indicated before, the smooth response of the ACC vehicle may create large gaps in situations where the vehicle in front of the ACC vehicle speeds up with acceleration that is higher than the maximum allowed by the ACC system. One could argue that such large gaps may invite cut-ins from neighboring lanes, creating additional disturbances and negatively affecting the benefits established in [1] and in section 2 above. Another one could also make the argument that advanced ACC systems may use smaller time headways during vehicle following which may discourage lane changes and therefore reduce disturbances due to lane changing. In this section, we examine the effect of cut-ins on the benefits reported in the previous section when during high acceleration maneuvers large gaps are created that invite a cut-in from the neighboring lane. Furthermore, we examine the effect of vehicles exiting the lane on the benefits established in section 2. ACC vehicles may encourage such exits as with advanced forms of ACC where the time headway used may be small a driver may exit the lane in order to avoid being followed so close by a vehicle driven by a computer. In the following subsections we use simulations and experiments to evaluate the effects of cut-ins and exits.

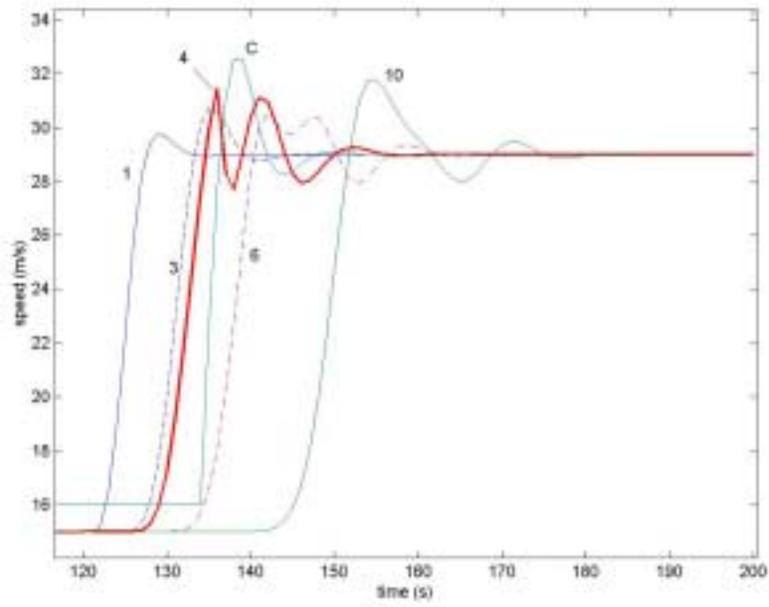
#### 3.1 Lane cut-ins: Simulations

Let us consider ten vehicles following each other in a single lane (lane 1), with the lead vehicle speeding with high acceleration. The increased inter-vehicle spacing between the ACC vehicle and the vehicle ahead invites a cut-in from the adjacent lane. For simplicity, assume that only one vehicle from the neighboring lane (lane 2) performs a cut-in. The vehicles in lane 1 are traveling at steady state speed of 15 m/sec (33.5 mph) when the lead vehicle accelerates at 0.35g to reach a speed of 29 m/s (65 mph), and the rest follow suit. The ACC vehicle at the 4<sup>th</sup> position in lane 1 responds smoothly and lags behind the vehicle in front creating a large gap. The manually driven vehicle in lane 2 that was initially traveling at somewhat higher steady state speed of 16 m/sec (35.8 mph) takes advantage of the large gap in the neighboring lane to cut in between the ACC vehicle and the vehicle ahead.

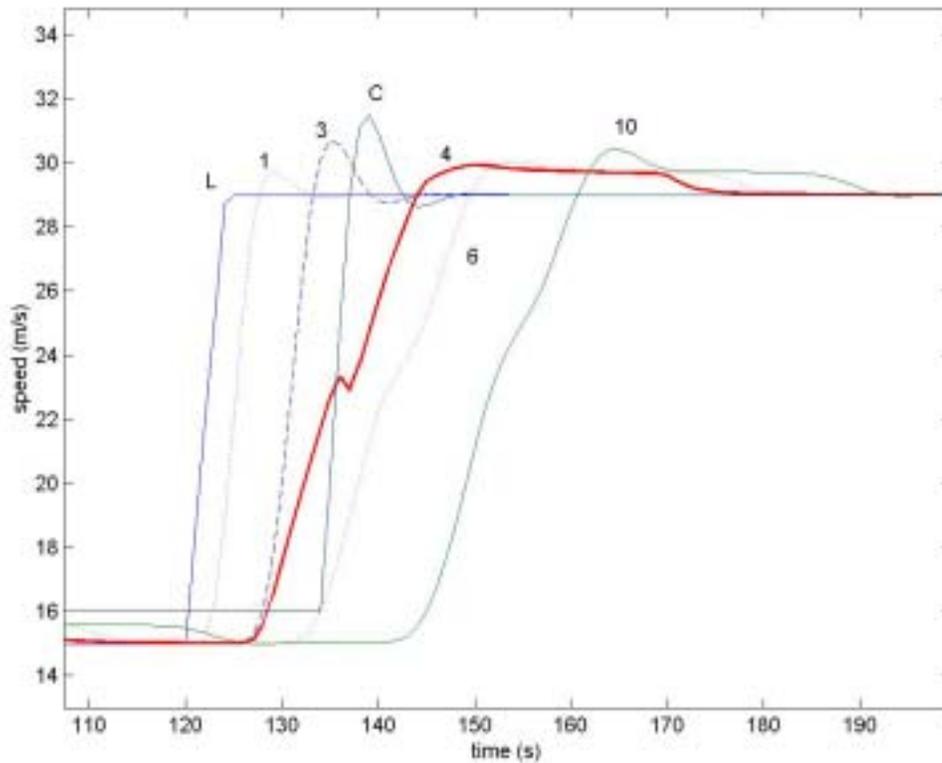
Let us now the same situation with the ACC vehicle replaced with a manually driven one. In this 100% manual case we have two possible scenarios. In scenario 1 the vehicle behind the accelerating lead vehicle follows the lead vehicle equally aggressively leaving no space for the vehicle in lane 2 to cut in so no cut in takes place. This scenario is simulated in Figure 10. In scenario 2 the vehicle behind the accelerating lead vehicle lags behind and the vehicle from the neighboring lane 2 manages to cut in. This scenario is shown in Figure 11.



**Figure 10: (Manual case) Speed responses of the vehicles at positions 1, 3, 4, 6 and 10 (no cut-in)**

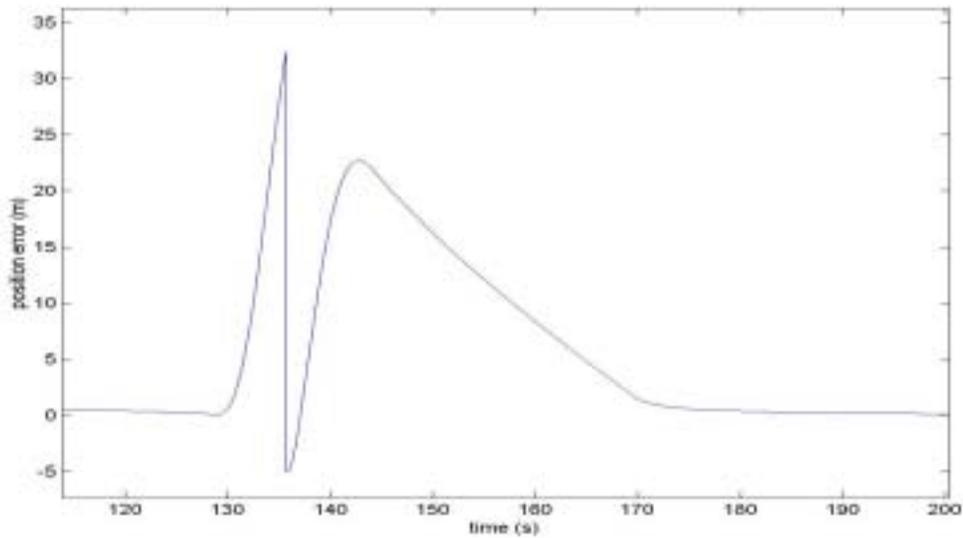


**Figure 11: (Manual case) Speed responses of the vehicles at positions 1, 3, 4, 6 and 10, as well as that of vehicle (C) from the adjacent lane and cuts-in in front of the 4<sup>th</sup> vehicle**



**Figure 12: Speed responses of the vehicles at position 1, 3, 4 (ACC), 6 and 10, as well as that of vehicle (C) from the adjacent lane that cuts-in in front of the ACC vehicle**

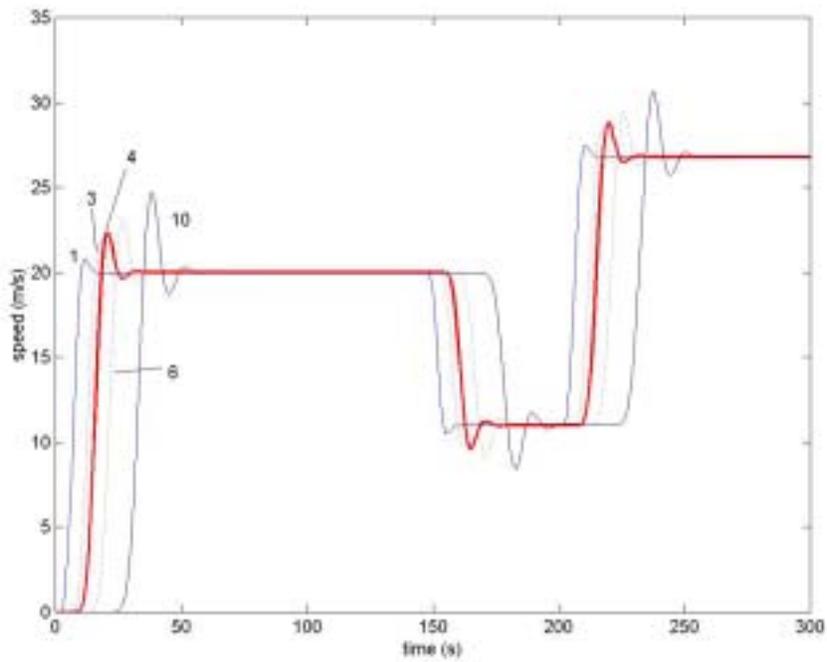
Figure 12 shows the speed responses of the mixed traffic in the cut-in situation: It is assumed that the neighboring lane vehicle cuts in immediately in front of the ACC vehicle, causing it to temporarily slow down, and then smoothly catch up with the new predecessor. Figure 13 shows the position error of the ACC vehicle as it responds to the lead vehicle maneuver and switches targets from the lead to the cut-in vehicle.



**Figure 13: Position error of the 4<sup>th</sup> (ACC) vehicle as it switches targets during the lane cut-in**

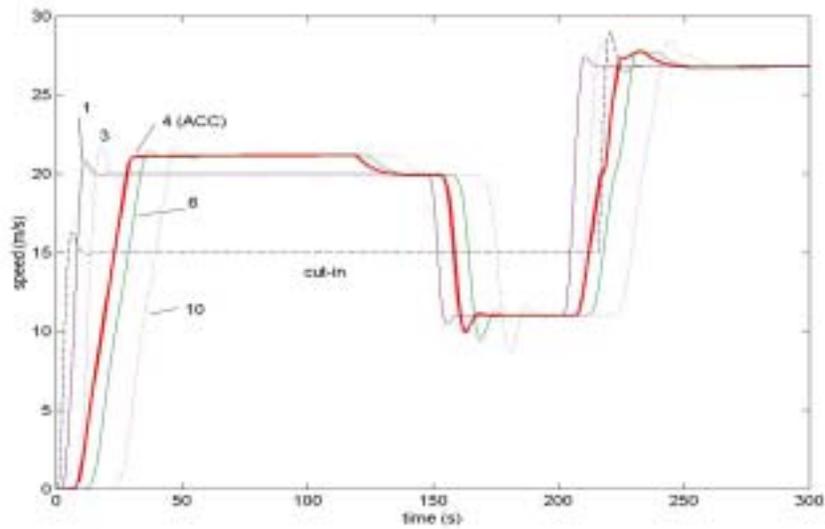
Comparing the responses in Figures 11 and 12 it is clear that the presence of the ACC vehicle attenuates the disturbance due to the lead vehicle acceleration and cut-in vehicle effect.

The following Figures show similar results for a different lead vehicle acceleration maneuver. In this case, the lead vehicle in a string of 10 vehicles accelerates from 0 m/s to 20 m/s at 0.35g, keeps that speed for 140 sec, then decelerates to 11 m/s (~25 mph) at -0.25g, maintains that speed level for 50 sec, and finally accelerates at 0.3g to 26.8 m/s (60 mph). Figure 14 shows the speed responses when all 10 vehicles are manually driven. The oscillatory response of the following vehicles and slinky effects are evident. Due to the tight vehicle following, it is assumed that no cut-in occurs by any vehicle from the adjacent lanes.

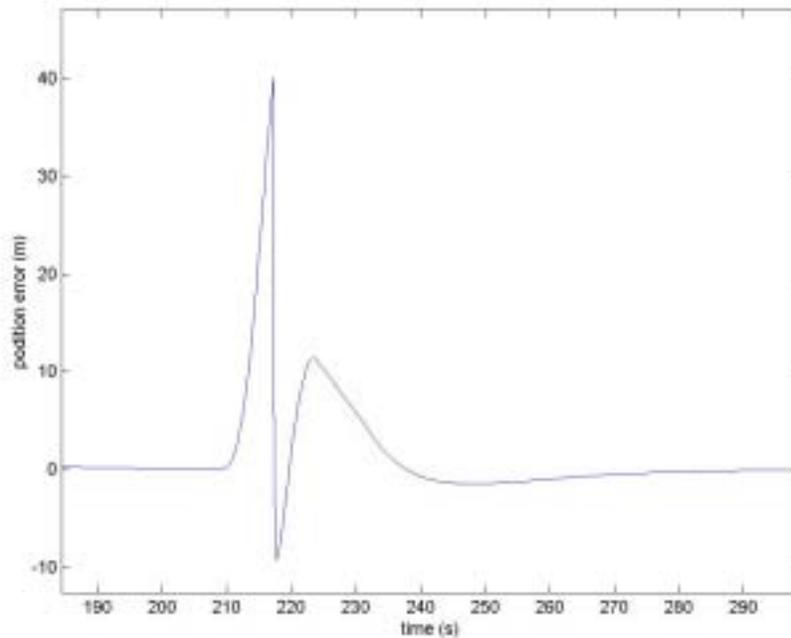


**Figure 14: Speed responses for 100% manual traffic**

Figure 15 shows the vehicle speed responses in the case where the 4<sup>th</sup> vehicle is an ACC vehicle. Due to the smooth response of the ACC vehicle, a large gap is created shown in the Figure 16 that encourages a vehicle in the adjacent lane that is moving at the steady state speed of 15 m/s to cut in at  $t = 217$  sec.



**Figure 15: Cut-in situation in mixed traffic: Speed responses of vehicles 1,3,4(ACC), 6, 10 and cutting-in vehicle C from adjacent lane versus time**



**Figure 16: Position error of the 4<sup>th</sup> (ACC) vehicle whose speed response is presented in Figure 15**

The above speed responses to the acceleration of the lead vehicle and cut-in vehicle disturbance are used with the emission model to calculate possible benefits that are due to the presence of the ACC vehicle in the string of vehicles in the following subsection.

### 3.2 Lane cut-ins: Environmental benefits

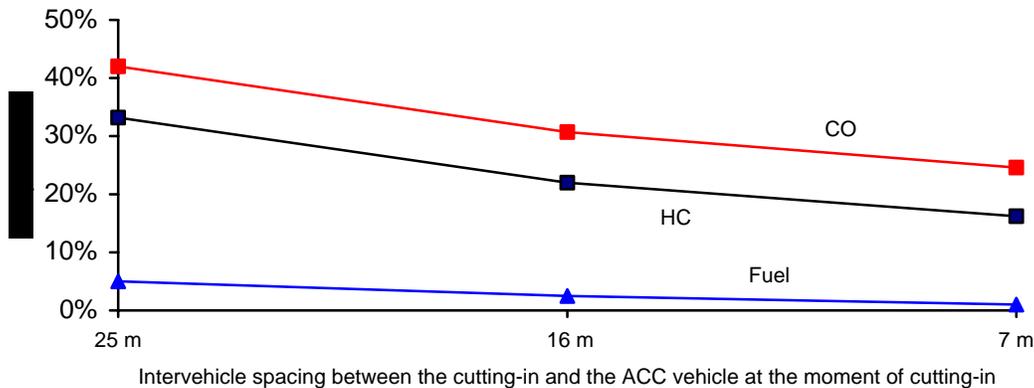
The speed responses in Figure 10 to 15 are used with the emissions model to calculate the percentage improvements obtained due to the presence of the ACC vehicle in the mixed over the manual traffic case. The results are summarized in Table 3:

Table 3: Summary of benefits

	Comparison of manual with a cut-in and mixed traffic (responses from Figure 11 and 12)	Comparison of manual with no cut-in and mixed traffic (responses from Figure 10 and 12)	Comparison of manual with no cut-in and mixed traffic (responses from Figure 14 and 15)
HC emission	23.8 %	24 %	30.2 %
CO emission	30.5 %	31 %	37.8 %
Fuel consumption	negligible	negligible	7.6 %

The results shown in Table 3 demonstrate that the cut-in invited by the ACC vehicle in a situation of high acceleration maneuvers that lead to large gaps will not take away the benefits calculated earlier in the absence of cut-ins.

The results in Table 3 are based on the assumption that the cut-in vehicle cuts in close to the ACC vehicle at about 7m causing the ACC vehicle to initially apply braking. The sensitivity of the results of Table 3 based on Figures 11 and 13 with respect to variations in the cut-in distance from the ACC vehicle are presented in Figure 17.



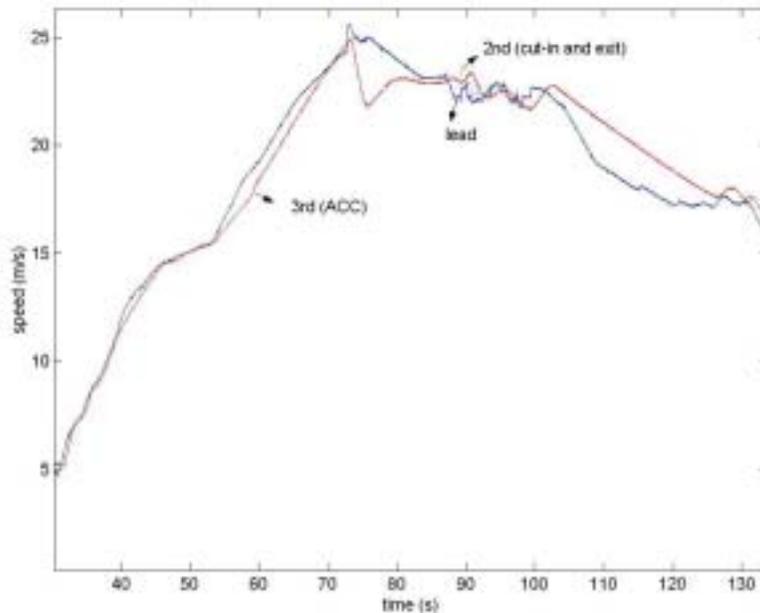
**Figure 17: Percent benefits in HC, CO emission and fuel consumption for lane cut-in situation in mixed traffic case vs. manual case without cut-ins, for three different cut-in distances between the neighboring-lane vehicle and the ACC vehicle**

Results for the comparative emission of CO<sub>2</sub> and NO<sub>x</sub> are not shown in Figure 17 as they are negligible. What we observe from the obtained results above is that the benefits in the

lane cut-in situations depend largely on the spacing at which the manual vehicle cuts in front of the ACC one. In the case of a ‘sharp’ cut-in, i.e. when the initial cut-in spacing is only 7m, the ACC vehicle activates its brake actuator, which means additional disturbances in its response. When the distance is larger the level of braking is less and the disturbance due to the cut-in is smaller.

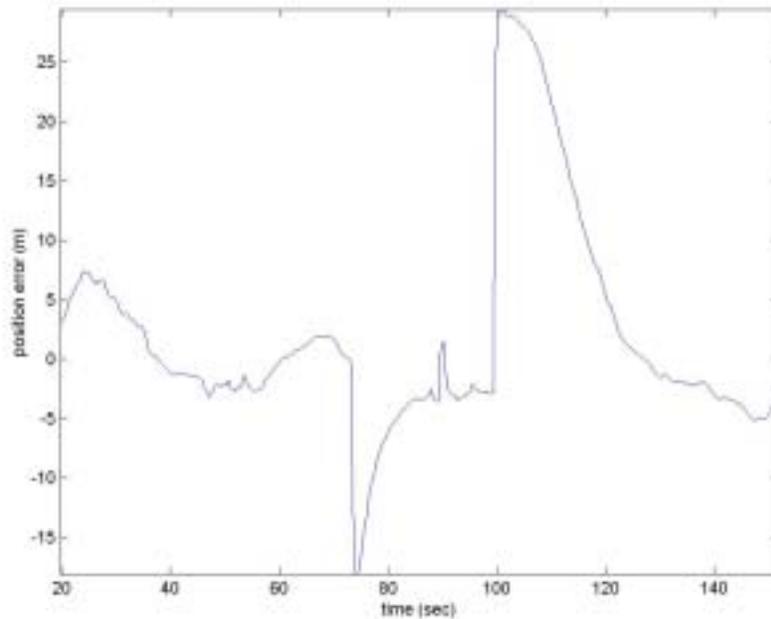
### 3.3 Lane cut-ins: Experiments

The behavior of the ACC vehicle during cut-in situations is tested at the testing facility at Crows Landing using one ACC vehicle and two manually driven vehicles. Several runs were conducted to evaluate the mixed traffic response during lane change situations. One of the typical runs that consisted of both lane change and lane exit, is shown in Figure 18.



**Figure 18: Speed response of two manually driven and one ACC vehicle during the scenario that includes both lane exiting and cut-in maneuver.**

As shown in Figure 18, the lead manual vehicle accelerates from 0 m/s to 15 m/s, keeps that speed for a short while, then rapidly accelerates to ~25 m/s. The ACC vehicle follows by accelerating smoothly, thus increasing the inter-vehicle distance between the two vehicles. The 3rd experimental vehicle, traveling in the adjacent lane, cuts in between the two vehicles at approximately  $t = 73$  sec. The ACC vehicle decelerates in order to maintain safe distance, then increases its speed to catch up with the target vehicle speed. At  $t = \sim 100$ s, the second vehicle leaves the lane, creating a large gap between the first and the third vehicle. Again, the ACC vehicle handles the disturbance in a smooth manner, eventually reducing the position error close to zero (see Figure 19).



**Figure 19: Position error of the ACC vehicle during cut-in and exiting**

The above experiment demonstrates experimentally the smooth response of the ACC vehicle to disturbances due to high acceleration maneuvers of the lead vehicle together with those due to cut-in and lane exit.

### 3.4 Lane exit: Simulations

Another type of abrupt traffic disturbance that may occur during vehicle following in a lane is due to a vehicle exiting the lane. This will create a gap that the vehicle behind will try to reduce by speeding up with all other vehicles in the string acting in a similar manner. In the case of a manual vehicle this could be done aggressively and in the case of an ACC vehicle the closing of the gap is done smoothly due to driver comfort and human factor constraints. We simulated and evaluated this scenario as follows:

We consider a string of 10 vehicles following a lead vehicle at steady state speed of 22.5 m/s (50 mph). At some point in time the 2<sup>nd</sup> vehicle exits the lane leaving a large gap between the 1<sup>st</sup> and 3<sup>rd</sup> vehicle. The 3<sup>rd</sup> manually driven vehicle that now becomes 2<sup>nd</sup>, speeds up to close the gap with an acceleration of about .15g. The vehicles behind follow suit trying to synchronize their speeds and maintain gaps that are comfortable for the individual drivers. We repeat the same experiment when the 3<sup>rd</sup> vehicle is an ACC that is designed to respond to such disturbance in a smooth manner. The results for the manual traffic case are shown in Figure 20. The results for the mixed traffic case are shown in Figure 21 with the corresponding position error shown in Figure 22. It is clear from these Figures that the presence of the ACC vehicle reduced the effect of the disturbance considerably.

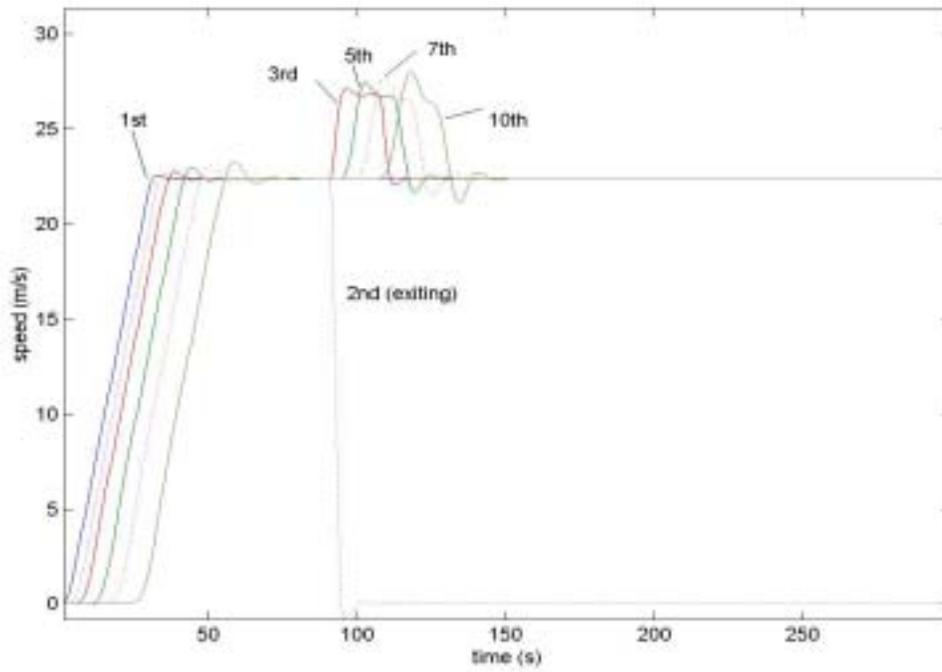
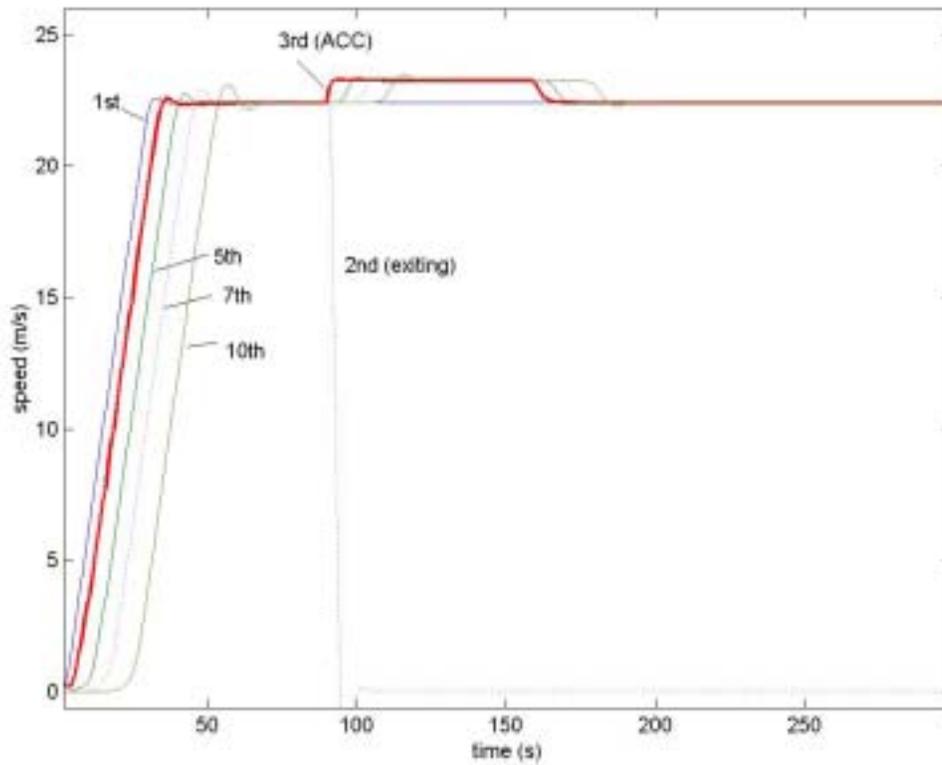
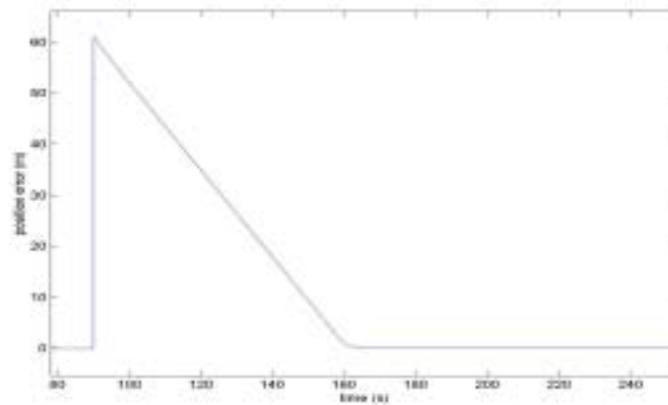


Figure 20: Lane exit scenario, manual traffic. Speed responses of 1<sup>st</sup>, exiting 2<sup>nd</sup>, 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup> and 10<sup>th</sup> vehicles versus time.



**Figure 21: Lane exit scenario, mixed traffic. Speed responses of 1<sup>st</sup>, exiting 2<sup>nd</sup>, 3<sup>rd</sup> (ACC), 5<sup>th</sup>, 7<sup>th</sup> and 10<sup>th</sup> vehicles versus time.**



**Figure 22: Position error of the 3<sup>rd</sup> (ACC) vehicle versus time**

In the following subsection we use the speed responses Figures 20, 21 and the emission model to calculate the effect of the ACC vehicle on the disturbance generated by the exit vehicle.

### 3.5 Lane exit: Environmental benefits

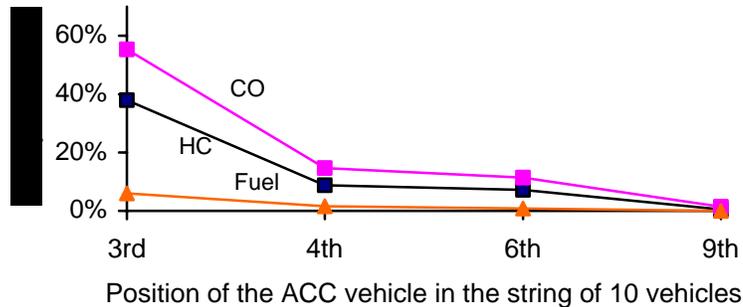
The following table shows the summarized benefits calculated for the mixed over manual traffic in the lane exit scenario described by Figures 20, 21 in section 3.4.

Table 4: Summary of benefits

	Percent benefits of mixed over manual traffic in lane exit scenario described by Figures 20, 21
HC emission	34 %
CO emission	49 %
CO <sub>2</sub> emission	5 %
NO <sub>x</sub> emission	negligible
Fuel consumption	5 %

The results in Table 4 demonstrate that the presence of the ACC vehicle will reduce the effect of disturbances due to lane exit by the immediate vehicle ahead of the ACC in a way that is beneficial to the environment.

The results of Table 4 are obtained for the scenario described in Figures 20, 21 with the ACC vehicle located in the 3<sup>rd</sup> position (right behind the exit vehicle). We repeated the above scenario with the ACC vehicle located in the 4<sup>th</sup>, 6<sup>th</sup> and 9<sup>th</sup> position in the string of 10 vehicles while retaining the lane exit to take place at the 2<sup>nd</sup> vehicle position. The results are presented in Figure 23.

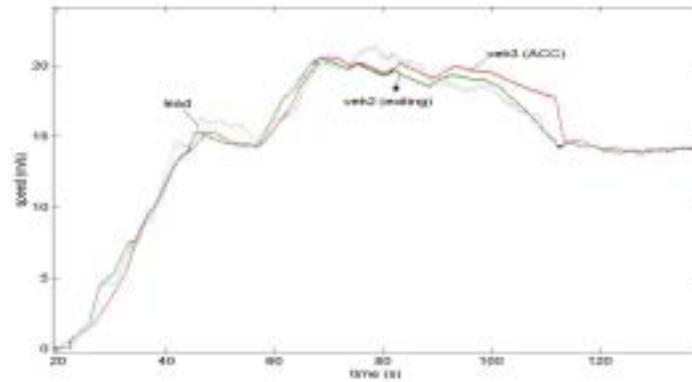


**Figure 23: Percent improvement in HC, CO emission and fuel consumption during a lane exit situation in mixed vs. manual traffic case where 2<sup>nd</sup> vehicle exits the lane versus the position of the ACC vehicle in the string of 10 vehicles**

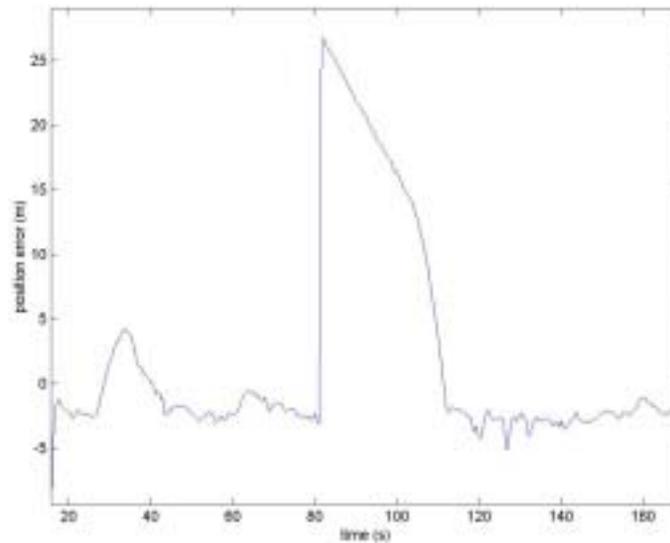
It is clear from Figure 23 that the benefits in emission and fuel consumption are drastically reduced when the position of the ACC vehicle is shifted from the 3<sup>rd</sup> place (immediately behind the exit vehicle) to the 4<sup>th</sup>, 6<sup>th</sup> and 9<sup>th</sup> position. The reason is that the manual vehicles ahead of the ACC vehicle undergo speed response oscillations that do not correspond to high acceleration so that the ACC vehicle provides little attenuation. Instead it passes these oscillations on to the vehicles upstream. This simulation demonstrates that a higher penetration of ACC will lead to more benefits in terms of emissions and fuel economy in the presence of disturbances due to lane exit.

### 3.6 Lane exit: Experiments

The behavior of the ACC vehicle during the lane exit of the vehicle ahead is tested using actual vehicles at the test facility in Crows Landing. Three vehicles were used, two of them manually driven and one ACC. Figure 24 shows one such run where the 2<sup>nd</sup> manually driven vehicle exits the string of the 3 vehicles at time  $t=81$  sec. The following ACC vehicle switches targets and closes in smoothly. Figure 25 shows the position error between the ACC vehicle and the vehicle in front. It increases almost instantaneously when the vehicle exits and the ACC vehicle switches targets but then it decreases smoothly to close to zero at steady state. The experimental results demonstrate the smoothness properties of the ACC vehicle during disturbances that arise because of vehicles exiting the lane which as analyzed in previous sections are responsible for the emissions and fuel economy benefits obtained when compared with the case where the ACC vehicle is replaced by a manually driven vehicle.



**Figure 24: Speed response of two manually driven and one ACC vehicle during lane exit maneuver. At ~81 sec, vehicle 2 exits the lane, and vehicle 3 (ACC) accelerates to catch up with the new predecessor**



**Figure 25: Position error versus time of the ACC vehicle in lane exit scenario**

## 4 Conclusion

In this report we examined, using simulations and experiments, the mixed manual/ACC traffic characteristics on the microscopic level during disturbances that may arise due to high acceleration maneuvers and lane changes. The effect of the ACC vehicles is evaluated from the environmental point of view using an emissions model. We have demonstrated that the smooth response of the ACC vehicles has a beneficial effect on the environment in the presence of disturbances that are due to high acceleration maneuvers, lane cut-ins and lane exiting. These benefits vary with the levels of the disturbance, the position of the ACC vehicle in the string of manually driven vehicles and the ACC vehicle penetration. Several sensitivity curves are developed that show the variation of the benefits with respect to the various variables.

## Acknowledgments

We wish to thank the UCB/PATH experimental group for their assistance in collecting the data and valuable discussions during the experiments performed at the Crows Landing in July 2002.

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