

Toward an Intelligent Automotive System

Jason Sherwin

Georgia Institute of Technology, Atlanta, GA, 30332-0150

ABSTRACT

The introduction of intelligent systems into the current automotive system is a difficult problem due to both the current infrastructural rigidity and the cultural mistrust of intelligent systems, among other considerations. With such issues in mind, an introductory technology was hypothesized to begin the transition toward an intelligent automotive system, for which the selection of such a technology was based upon its ability to address the aforementioned issues. Due to the complexity of local traffic dynamics, the relatively simpler scenario of highway traffic was studied, for which each car's motion is most dominantly impeded only by the presence of other cars; thus within this scenario, the top-level characteristics of the automotive system were analyzed as the selected technology was infused in varying amounts. Furthermore, by looking at the early stages and the long-term limits of the infusion, assessing the technology's effects on both the traffic flow and the environment in multiple simulation scenarios was possible.

KEYWORDS

Adaptive & Communicative Automobile (ACA), Intelligent System (IS), Figure of Merit (FOM), Design of Experiments (DoE), Doppler Shift, Swarm Theory

1. INTRODUCTION

The idea of having automobiles drive themselves is not new. As the demands for automotive travel have increased, researchers have proposed and analyzed ways to alleviate the detriments of the high-density travel that cripple the mobility of drivers across the world, especially in population-dense metropolises. In addition to the adverse mobility effects, high-density automotive travel also has an observable effect on the environment because the cars' engines are operating at speeds well

below those of optimum fuel efficiency (which are typically 40-60 miles/hr). Because the current automotive traffic system is highly dependent on the actions of the humans controlling the automobiles, previous studies have been undertaken to understand how the infusion of computer-based technology would mitigate the detrimental effects of high-density travel. For example, a study that investigated how an intelligent cruise control would benefit the current automotive traffic system (Ioannou & Chein, 1993) concluded that completely infusing such a technology into the traffic system would augment the overall safety and mobility of the population's agents. Yet, today no widespread intelligent cruise control is in use, although its predecessor ('adaptive cruise control') appears in some luxury car models as an option. Nearly simultaneously, another study investigated the dynamics of the traffic system once the lane-change maneuvers of intelligent vehicles in highway traffic were considered (Chee & Tomizuka, 1994), showing that in a completely automated traffic system, a smooth lane change is possible. Yet, once again, there is little to no use of such automation in the current traffic system.

In both studies, the automation/intelligence of the automobiles depends on their ability both to sense the relative velocities/positions of their neighbors and to maintain a course towards the desired destination, while avoiding a collision. Yet, for intelligent systems (IS) to be successfully integrated into the current automotive system, the automated vehicles must coexist during an indefinite transition period with the manual ones already in use; thus not all vehicles will be able to sense the relative velocities and positions of their neighbors during this transition period, an effect that neither of the aforementioned studies (Ioannou & Chein, 1993; Chee & Tomizuka, 1994) considered, because for both scenarios a complete infrastructural overhaul is required. Therefore, it is necessary to show that it is possible to make a gradual evolution to an intelligent automotive system, while not upsetting the infrastructure already in place for the current one.

With this constraint in mind, I hypothesized the IS to be particular to each car, so that it is completely independent of any infrastructure imbedded either in the road or alongside it. A technology making this possible is one that uses the Doppler Shift of an electromagnetic source to calculate another object's relative speeds and, when integrated over time, positions in time.

Although the consideration of other technologies could augment the scope of the automation, the ubiquitous scenario of highway traffic was chosen as the focus of this study to develop a paradigm for more complex ones. Furthermore, the case of

highway traffic is a logical choice for this IS technology because the dynamics of local traffic flow are susceptible to other variables (e.g., pedestrians, bicyclists, etc.), for which technologies based on the Doppler Shift are not robust. Even though the narrowing to this scenario appears to be a limitation to the study, the effects on efficiency and traffic flow were found to be readily apparent; furthermore, this IS technology can coexist within the current automotive traffic system, so it could pave the way for future IS technologies that might be robust enough for local traffic flow.

As an illustrative case study, the population and traffic statistics of Atlanta, Georgia, with the fourth worst traffic in the United States of America (US)¹ were chosen to study the effects of the gradual infusion of the IS into the current automotive system. Because of its poor traffic conditions, Atlanta would provide a suitable staging for a technology to mitigate traffic congestion.

2. ADAPTIVE AND COMMUNICATIVE AUTOMOBILE CONCEPT

As the Introduction hinted, the basis of the IS was using the Doppler Shift to track the relative velocities and positions of other vehicles in the traffic flow. However, as mentioned above, I wanted the technology to be easily integrated into the current automotive system. As all driving today has a human in-the-loop, it was necessary to allow the technology to be able to transition between human control and automated control. In other words, the automobile must be allowed to adapt at the will of the driver either to dense highway travel, for which automation is more beneficial, or to local travel, for which a human must provide sufficient control. Once the automated driving has taken over in dense highway traffic, several layers of communication are necessary to ensure an effective group velocity of the traffic flow: driver-to-driver, vehicle-to-vehicle and intra-vehicle communication.

Beginning with the driver-to-driver communication, each driver must have a way of communicating the need for IS activation to his immediate neighbors. Today, the only forms of communication readily used by unacquainted drivers for alleviating traffic problems are the unrefined blare of a car horn or the unpleasant gestures and shouts that can result from a miscommunication of one's intended direction. Succinctly, the information flow of each driver's intention is stagnated from the rest of the population because of both insufficient channels of expression and the necessary media through which to reach consensus. Thus a simple way to

communicate a desire of each driver for his immediate neighbors to engage their IS was hypothesized in this study.²

Next, vehicle-to-vehicle communication is important because of the need to communicate the relative positions and velocities from which a decision can be made about how to adjust the steering and acceleration (or deceleration) for a safe commute; this communication would rely on the aforementioned use of the Doppler Shift.

Finally, intra-vehicle communication is necessary to enact the decision about the vehicle's course that is made possible by the information of the relative velocities and positions. Specifically, I hypothesized a mechanism by which the information of a vehicle's neighbors' relative positions and velocities is transferred both to the steering wheel and to the gas/brake pedals, so that each vehicle with the intelligent system has the ability to follow its immediate neighbor in front of it.³ Thus, the vehicles have been assumed to possess an adaptive and communicative ability, for which I shall henceforth refer to a vehicle with such intelligent systems as an Adaptive & Communicative Automobile (ACA).

3. MODELING & SIMULATION: SETUP AND LOGIC STRUCTURE

3.1 Modeling Considerations

Before developing the modeling environment, it was necessary to consider three phases of IS interaction to which the driver of each ACA would be exposed: the transition to the IS, the deactivation of the IS, and of course the phase during which the IS is active. Firstly, I hypothesize in this report that the transition to IS engagement would behave in a similar manner to any animal group, the ideas of whose collective decision-making abilities are understood by swarm theory (Couzin, Krause et al, 2005). As the driver of each ACA is allowed to communicate through 'social' interactions with its local neighbors (assuming they are ACAs as well), via the aforementioned driver-to-driver communication, the dynamics of animal groups may apply because of the high-density mode of travel that is particular to a congested highway—similar to a school of fish or a trail of ants. Concerning the actual IS engagement, each ACA is subject to a simple local rule that requires it to follow its immediate neighbor at some velocity-dependent distance.⁴ Thus in a similar manner as the transition to the IS engagement, the actual IS engagement also relies on the simple local rules of swarm theory that, when considered for agents of a larger

population, result in a decision-making group. Finally, once a certain threshold distance is passed, i.e. one for which an accurate Doppler Shift calculation of a neighbors' position and velocity is not possible, the IS must be deactivated so that the human retains control of the car.⁵ In this study, however, I modeled only the transition to and the engagement of the IS since these are the crucial steps by which traffic is eliminated; thus the deactivation of the IS is left for future study if necessary.

3.2 Modeling Overview

The modeling environment comprises two main sections: the data particular to Atlanta's freeways, and the calculation of the congestion alleviation allowed by the infusion of the ACAs into the traffic population. Following the N^2 -diagram technique, Figure 1 shows the modeling environment for the ACA simulations, where each modeling component along the diagonal is a different data set or calculation used in this study. The data particular to Atlanta's freeways are contained in all modeling components of the figure except for 'ACA_Infused_Traffic_Model', which is the calculation script that simulates the congestion alleviation.

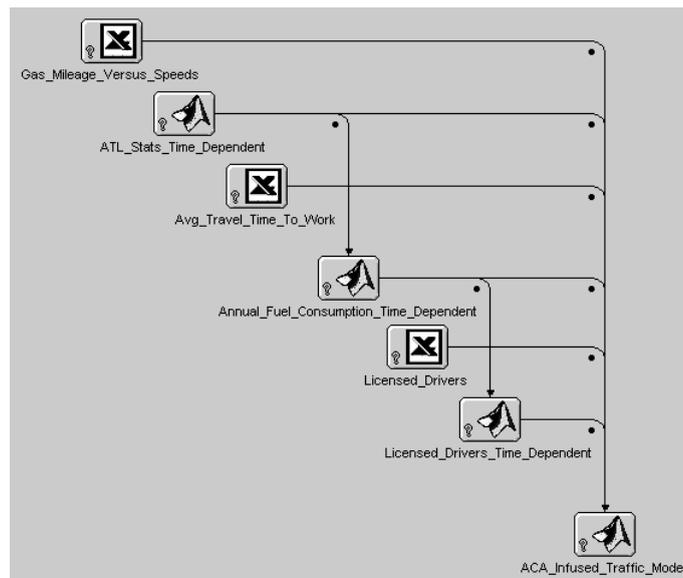


Fig. 1: Modeling environment

3.3 Atlanta Freeway Simulation Overview

From the data sets and data-dependent regression calculations contained in all modeling components excluding the 'ACA_Infused_Traffic_Model', the following information is included in the modeling environment: a vehicle's fuel efficiency relationship to its velocity, the average travel times of Atlanta drivers on congested freeways and other traffic population characteristics particular to the city that are required for the planned calculations. It is important to realize that, even though the example of this paper has been Atlanta, this calculation can be done for any other major city in the U.S., whose highway traffic suffers from periods of congestion.⁶

3.3.1 *Gas_Mileage_Versus_Speeds*. This modeling component contains a regression of how fuel efficiency varies with velocity⁷ for two different vehicle types: sub-compact and midsize vehicles. These datasets were then used to make second-order polynomial curve-fits for each of the vehicle types, both of which had R^2 values of approximately 0.91.

In this study, the generic sub-compact and midsize efficiencies were used because of the public availability of the data used to generate the regressions of how efficiency varies with speed. However, the underlying principle of a peak efficiency that depends on velocity universally applies to any air-breathing engine, so the calculation can be carried out for any engine for which such data exist.

3.3.2 *ATL_Stats_Time_Dependent*. This modeling component contains time-dependent regressions—valid from 1996-2003—of the data particular to Atlanta's traffic: the number of average freeway daily vehicle miles traveled per driver, the city population and the annual delay per person.⁸

3.3.3 *Avg_Travel_Time_To_Work*. This modeling component is simply an Excel spreadsheet of average travel times to work in 2002 for the cities with the longest average commute to work.⁹ Since the effects of an increased amount of ACAs on Atlanta's traffic is being modeled, the data particular to Atlanta has been extracted from this data file, though the same calculation could have been done for any other city in the U.S. with similar traffic problems (e.g., New York or Chicago).

3.3.4 *Annual_Fuel_Consumption_Time_Dependent*. This modeling component is also a polynomial regression of a time-dependent trend, as was 'ATL_Stats_Time_Dependent'; it is a regression of the annual fuel consumption of the nation's passenger vehicles from 1996-2004.¹⁰

Licensed Drivers, Vehicle Registrations, and Resident Population

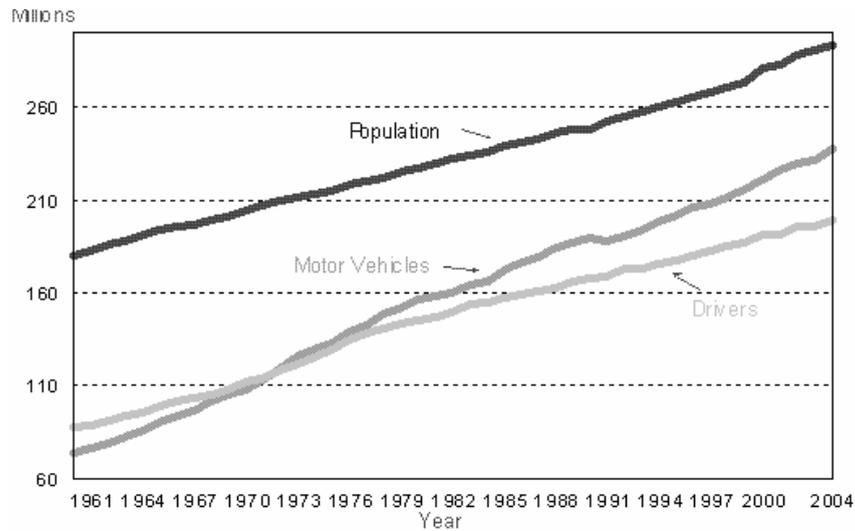


Fig. 2: U.S. Department of Transportation statistics. Figure and data available at: <http://www.fhwa.dot.gov/policy/ohim/hs04/htm/dlchrt.htm>

3.3.5 *Licensed_Drivers* and *Licensed_Drivers_Time_Dependent*. These two modeling components encapsulate the data shown in Figure 2. Noticing that the rate of population increase is nearly the same as the rate of drivers increase in the U.S., a ratio of drivers to population was extracted from this data and then used in tandem with the city population of Atlanta (from the aforementioned ‘ATL_Stats_Time_Dependent’) to get the total number of drivers in Atlanta.

Of course, such a deduction assumes that the ratio of drivers to population for the entire country applies to Atlanta, but as Atlanta is a major metropolitan area this is a likely lower bound to the actual possible value. Finally, the time-dependent data for the number of motor vehicles in the U.S. shall be used later to track the effects of infusing a technology into a growing population of vehicles.

3.3.6 *ACA_Infused_Traffic_Model*. With the data and regressions included in the aforementioned components, it was then possible to calculate the effects of distributing ACAs in the Atlanta traffic population. The actual component in which the ACA infusion calculations take place can be divided into three sections: the creation of the vehicles’ relative distances and absolute velocities in congestion¹¹, the swarm-theory-inspired propagation of IS engagement if a particular probability

density of vehicles are ACAs, and finally the calculations concerning fuel-efficiency and other performance-dependent Figures of Merit (FOMs).

The first section of this component creates a population of vehicles in dense traffic in one lane. Without considering lane changes (a possible aim of future study), the effect of ACA infusion was first developed for one lane of traffic with the current traffic system in mind. For example, if such a technology were to exist then in the transition period there could be a special lane—in the U.S. the High-Occupancy Vehicle (H.O.V.) lane common on most metropolitan freeways is a likely candidate—whose dynamics would closely resemble those that are calculated here. Although many theoretical models exist to capture the non-linear behavior of dense traffic flow (Helbing & Treiber, 1998; Klar & Wegener, 1997; Chandler, Herman & Montroll, 1958; Newell, 2000; Safonov et al, 2002; an overview is given by Brackstone & McDonald, 2000), it is assumed for simplicity that the distribution of cars within the one-lane population is random.¹² Because many theoretical models use gas kinetic theory as a starting point (especially several of the ones that have been cited here), the random distribution in space of the gas molecules is analogous to that of the vehicles on the road. Additionally, because this is a systems-level study assessing the effects of technology infusion, an approximation for the degradation of velocity was made, so that the velocity is assumed to drop by a linear factor related to how many vehicles populate the lane. Once again, even though more elaborate approaches exist for calculating the oscillatory effects of traffic population (e.g., the ‘slinky effect’ due to response lag of each driver (Pipes 1952)), it would not matter for the purposes of technology evaluation, as long as the traffic models used before and after infusion are the same. Overall, this part of the calculation creates a population of $N = 300$ vehicles, which amounts to about 1 mile of traffic propagated upstream from cruise conditions, where the velocity of the lead vehicle is near the maximum of a particular aforementioned fuel-efficiency regression.

The second section of this component is where the IS engagement occurs, if possible. Within the time of 700s, it is hypothesized that every 10s, on average, a driver will consider whether to relinquish control of the car to the IS. This ‘consideration’ process though is dependent, not only on whether or not the vehicle is an ACA but also on whether the upstream local neighbors to the vehicle communicate their desire that the driver’s IS be activated. It is via the communication of this desire for IS engagement that the swarm theory effects of decision-making animal groups are first felt. Of course, if the vehicle is not an ACA

then it is incapable of both IS engagement and IS communication with its neighbors; thus the issue of whether or not it is an ACA depends on the probability density of vehicles on the road with ACA capability. Even though work has been done on the local effects of a complete population of ACA-type cars and their effects within a population of manually-controlled vehicles (Bose & Ioannou 2001), the effects on system-level performance metrics remain unknown; thus, these figures of merit (FOMs) were tracked as a function of ACA probability density in various situations. Therefore it is crucial to evaluate the percentage of vehicles on the road with ACA capability as a function of time.

In this study, two scenarios of ACA infusion were studied: infusion through new vehicles and infusion into all vehicles. Whereas the second scenario will be discussed later, the first scenario merits a description presently. Using an extrapolation to 2007 for the total number of vehicles in the U.S. (Figure 2) and the number of new vehicles sold in 2007¹³, a probability density for the amount of new vehicles in the nation-averaged vehicle population was calculated. It was assumed due to a lack of sufficient data that the ratio holds for perturbations within ten years of the data point, but because the ratio is on the order of $1e-2$ there is little effect that other years' values would contribute; thus an average probability density of ACAs was calculated specifically incorporating the rate at which new vehicles are fed into the population. Furthermore, because data exists for each major automobile-makers' sales between 2006-07, it was possible to calculate the effects if only one or a few automobile-makers were to develop their vehicles with this capability. Therefore, the economics of the automobile market could be taken into account as well. Even though no specific makers' data were used in this study, the effects on system-level FOMs is shown later for sales percentages comparable to those of actual automobile-makers.

The pertinence of the ACA probability density, whether in new or all vehicles, arises in the agent-based modeling of the traffic flow subjected to ACA infusion. A series of three logic gates, or consideration processes, for each agent comprises the medium through which IS engagement is made possible. With the probability density of ACAs calculated, these three logic gates encountered at each time step for each agent can now be addressed. The first consideration process of the driver of the i^{th} car addressed the following questions:

1. Do I desire to relinquish control of the vehicle to the IS?

2. Is this vehicle an ACA?

The answers to these questions are addressed by the use of probabilistic analysis. As there are no ways to directly model the behavior of each individual driver, it is assumed that the response to the first question would be randomly 'true' or 'false', for a sufficiently large number of drivers (e.g., $N = 300$). Thus a random number is generated for each vehicle at this first logic gate and then compared in size to another randomly generated number. By a comparison test, the first question whose answer could allow IS engagement is answered either 'true' or 'false'. However, there is an additional question whose answer is an obviously more stringent condition for IS engagement: whether or not the car possesses the ability, i.e. whether or not it is an ACA. It is in this step that the probability density of new vehicles emerges in tandem with that of the automobile-makers' decisions to produce such vehicles. Thus, in a similar manner as the first question of this logic gate, another randomly-generated number is compared with the product of these two probability densities, i.e. the probability densities of all new vehicles and of ACA vehicles, with a non-homogeneity factor¹⁴. As this product is on the order of $1e-4$ for most major automobile-makers' market shares (e.g., $\sim 25\%$), this is the most stringent criterion for IS engagement. Nevertheless, within approximately 20 years of ACA infusion, this condition becomes less stringent than the driver-dependent one, due to the increased number of ACAs saturating the population; this is because in the limit of ACA infusion, i.e. when 'new car' effects are irrelevant, there is a greater probability that a given vehicle from the population is an ACA.

The next consideration process for the i^{th} car incorporates the swarm theory phenomenon that would take hold amongst the drivers in the traffic population, just as it would for any other group of socially interacting animals. Thus, the second logic gate to which the driver of the i^{th} car is subjected at each time step addressed the following questions:

1. Does my immediate neighbor behind me desire that I relinquish control of my car to the IS?
2. Is this vehicle an ACA?

Whereas the second question is subject to the same stringency as it had been for the previous consideration process, the first question behaves slightly differently than its predecessor. While a similar comparison of randomly-generated numbers is

done to answer the first question, due to the ‘peer pressure’ of the i^{th} vehicle’s neighbor (i.e. the $(i-1)^{\text{th}}$ vehicle’s driver), there is a higher probability on average¹⁵ that human social dynamics will guide the decision of the i^{th} vehicle’s driver to relinquish control of his car. Of course, if the i^{th} vehicle is not an ACA, then the social dynamics of its aft neighbor are irrelevant to the traffic dynamics at that moment.

Nevertheless, over time the recurrence of ineptitude at such an opportunity for mobile/economic efficiency would surely be incorporated into that driver’s future decisions concerning vehicle purchase. Even though this study did not aim to address this issue quantitatively, the high stress emotions of drivers in traffic situations (Galovski & Blanchard, 2002; Hennessy & Wiesenthal, 1997) can lead to an enhancement of the memory (Hamann, 2001; Reisberg & Heuer, 1992; Metcalfe & Jacobs, 2000) of being unable to engage an IS when one’s neighbors (and possibly one’s self) desire it; therefore with a sufficient passing of time, this memory could manifest itself as the purchase of an ACA-type vehicle. The recurrence of such a process could exponentially add to the number of ACAs in the population until all the vehicles had the hypothesized IS capability. Even though the dynamics of this transition from initial to complete ACA infusion are too difficult to predict quantitatively because of the complex market and social forces guiding the details, I show in this study that it is possible to assess the system-level effects at the endpoints of this domain, i.e. the initial decade of infusion when the probability density of ACAs is low, and the timeframe of nearly complete infusion of ACAs when the probability density readily approaches 1.

The final logic gate for the i^{th} car was used to incorporate the same idea of swarm theory as the previous one had been. The only difference is that the probability of the driver of the i^{th} vehicle to relinquish control is augmented once again because of the communicated desire of the neighbor behind its immediate one, i.e. the driver of the $(i-2)^{\text{nd}}$ vehicle. Even though the communication of information does not have to be limited to the two immediate neighbors aft of the i^{th} vehicle, it is assumed in this study that these two vehicles define the ‘locality’ of the i^{th} vehicle’s neighbors, thus any communication between it and its neighbors is restricted in this sense as it would be in any group of translating animals. Thus, if either of these two logic gates is completely satisfied then the i^{th} vehicle activates its IS.

The third and final section to ‘ACA_Infused_Traffic_Model’ is devoted to the calculation of the performance FOMs affected by the ACA infusion into the

population. In this section, the regressions of the velocity-dependent efficiencies of the midsize and sub-compact vehicles' data were used to assess the environmental impacts of ACA infusion in varying amounts to the population. Additionally, this section uses the data on Atlanta freeway congestion and the national driver-to-resident ratio to determine an Atlanta driver's average daily distance of congested highway travel. With this information, the question that is asked of every agent in the population is whether or not it was able to complete the 9-11km of average daily distance of congested highway travel in the simulated frame of time (700s); this distance in this amount of time amounts to an average speed of approximately 30 miles/hr, which is the speed limit of most local roads in the U.S. and is well below the normal speeds of freeways. Therefore such an average speed is an extremely reasonable, if not excessively modest, expectation of freeway travel velocity without neighbor impedance. Additionally, the travel time through this average daily distance is calculated to determine each agent's fuel costs, assuming a fixed value of gasoline price. In addition to the individual agent's performance calculations, population averages of efficiency and velocity were also calculated because in some cases the adverse effects of other time-dependent parameters usurped the beneficial effects of ACA infusion.

4. MODELING AND SIMULATION: RESULTS

With the modeling environment setup as described in the preceding section, I determined the effects of ACA infusion into a population of congested highway traffic. Even though a rudimentary model of the traffic before and during ACA infusion is used, there are important conclusions from the subsequent results because a comparison between system-level figures of merit (FOMs) before and after ACA infusion is still valid. This is true since the complications of more elaborate traffic models are actually attempts at modeling the multivariate problem of human behavior, whose presence is replaced in varying amounts by IS in the modeling environment used in this study.

To address the time-dependent and market-dependent nature of the problem, a series of several Designs of Experiments (DoEs) was used to investigate the design space of the vehicle population as ACAs were infused. Among others, the primary response variables that were tracked were population average fuel-efficiencies

(midsize and subcompact) and velocities, as well as individual agents' travel times and costs through the congested highway distance.

4.1 Design of Experiments #1: Gross Features

A 10-level full factorial experiment was first done both to understand the gross features of the modeling environment and to determine whether its predictions were intuitively what had been expected. With years taking on values between 1996 and 2003, i.e. the years for which sufficient data was obtainable to perform the calculations described above, and the probability density of new vehicles being ACAs varying on $[0,1]$, the results of the DoE are shown in Figure 3 for 2003 with the ACA market share as a parameter whose value appears next to each point.

Fig. 3: Sub-compact fuel efficiencies vs. number of IS non-activated vehicles

Assuming that ACAs had been introduced into the vehicle population beginning in 1996 with the parameterized market share serving as the probability density that a new vehicle is an ACA, it is no surprise that a population with no ACAs (bottom right corner of Figure 3) has the lowest average efficiency in 2003, in a total population of $N = 300$ cars all of which have a non-activated IS. Similarly, looking at a population for which all the new vehicles are ACAs (top left corner of Figure 3), it is no surprise that the average fuel efficiency is the highest for the greatest value of probability density of the 10 shown. Although the benefit in fuel efficiency is only

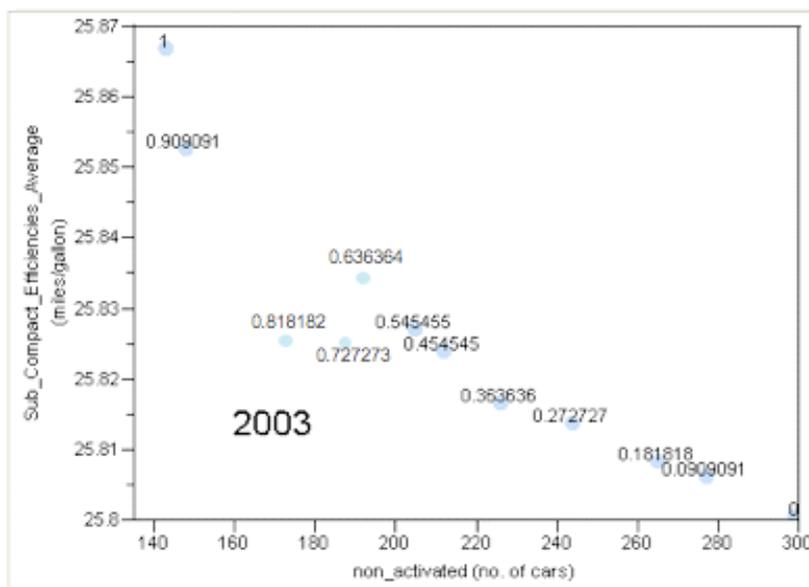


Fig. 3: Sub-compact fuel efficiencies vs. number of IS non-activated vehicles

one mile per gallon more than there otherwise would have been, it must be understood that the fuel efficiencies increase more dramatically as the number of non-activated vehicles goes to zero; this limit will be explored in a future discussion in which ‘new car’ effects shall be hypothesized to be irrelevant. Furthermore, one additional point of note is that the increase in fuel efficiency is not exactly monotonic with a decrease in the number of non-activated vehicles. This occurs because the probabilistic uncertainty of the agents’ decisions, i.e. whether to engage their IS (if possible), has been considered in the modeling because the decision-making of the drivers to engage their IS is subject to the random-number simulation described in the previous section describing ‘ACA_Infused_Traffic_Model’. Therefore, a particular value of the probability density that a new vehicle is an ACA is not bijective to a value of average efficiencies, average velocities, etc. because the probabilistic uncertainty of human behavior has been taken into account.

4.2 Design of Experiments #2: Accurate surrogate modeling and individual agents’ FOMs

Because a 10-level full factorial DoE generated insufficient data for accurate

response surface regressions, a 40-level full factorial DoE was performed. Although the use of the regression analysis is not pertinent to this paper, the fineness of the discretization of market share is pertinent to studying the economics of the infusion of ACAs, as most exemplified by the analysis of the fuel costs (US\$2007) vs. fuel efficiencies with ACA market share as a parameter between 1996 and 2003. Beginning with 1996, clearly there is little variation in an agent's fuel costs at such an early stage of ACA infusion into the population—independent of the ACA probability density; this calculation of fuel costs assumed that a distance (which is chosen as the average daily distance of freeway congestion) must be covered, as is the case for daily highway commuters. However, propagating forward to 2003, it is surprising to find that not only is there little variation around a particular cost of travel for different new ACA probability densities but also the average cost for all probability densities of ACA infusion is *higher* in 2003 than what it was in 1996.

Even though both facts seem to undercut the ability of ACAs to benefit environmental and economic conditions, both have explanations. Regarding the small variation of an agent's fuel costs as a function of average fuel efficiencies, there is little variation in the cost because of the small variation in the efficiencies between each population and its new vehicle ACA probability densities. Because a time-averaged gasoline price of \$2.50/gal (US\$2007) is assumed throughout the simulation from Department of Energy data¹⁶, a difference of 0.8 miles/gal only (the upper bound of increase in fuel efficiency from Figure 3) yields at most approximately a \$2.00 difference in cost for the distance traveled in congestion; thus the fuel costs' range of values exhibits its reduced variability because it is a function of the domain of new vehicle ACA probability densities. Regarding the increased fuel costs of the targeted agent, there is an external variable causing this effect whose presence has not yet been considered: as the average distance of congested freeway travel increases from 1999-2003, this variable is having a dominating effect on the agent's fuel costs. Although not shown in this report, the beginning of increasing fuel costs coincides exactly with the year during which the distances begin to grow.

Thus, a valuable lesson emerges from studying this apparent fault of ACA infusion: the awareness of time-dependent parameters is crucial to the success/failure of ACA infusion, as it is to any technology, because the apparent detriments to one FOM could be affected by time-dependent system-level influences. Of course, the awareness of such a coupling between the technology infusion and the evolving nature of the automotive system would not have been

known without the large-scale modeling capabilities used in this study.

4.3 Design of Experiments #3: Large Scale Limit of Implementation

As mentioned in the discussion of DoE #1 and other preceding sections, the limits of ACA infusion were also explored. In particular, the rate at which new vehicles with IS capability are infused is assumed irrelevant; rather, the varying probability density of ACAs is applied now to the entire population of vehicles. As Figure 4 clearly shows for 2003, just 7 years after large scale infusion, the average speed of the population increased by almost 4m/s ~ 9miles/hr as the ACA probability density went from 0 to 1.

Furthermore, next to each point of Figure 4 appears a number, which is actually the number of vehicles with a non-activated IS. As would be expected, the entire population ($N = 300$)¹⁷ is non-activated for an ACA probability density of 0, where the enumeration of non-activated vehicles has excluded the 1st vehicle whose IS engagement is irrelevant since its speed is unimpeded at ~ 22m/s. Likewise, the number of non-activated vehicles drops almost monotonically with the increase in ACA probability density, where the variation from monotonic behavior is attributed

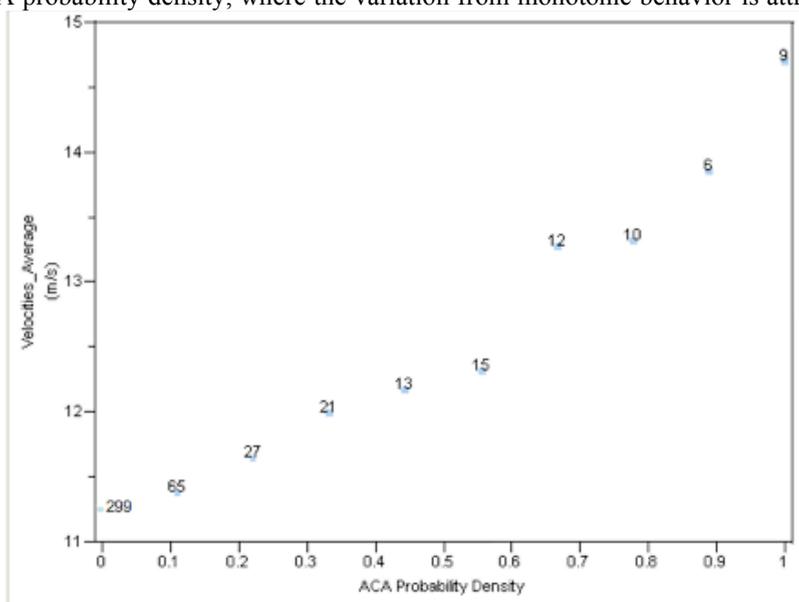


Fig. 5: Average population velocity vs. ACA probability density

to the probabilistic decision-making of the drivers about whether or not to engage

the IS. Thus, the limit of ACA infusion clearly shows a benefit for highway traffic flow, not only for an ACA probability density of 1 but also for lower values of this market- and technology-dependent parameter. I should emphasize though that the complexities of decision-based social dynamics are still present in this automation of the traffic flow: even when all vehicles in the traffic population are IS-capable, the average population velocity will still lag behind that of the lead car because of a small, yet effective, few agents who may exercise their own freewill at the expense of their neighbors' efficiency, and ultimately their own. Thus, on a level of societal impact, the infusion of ACAs to the traffic population introduces an intriguing balance of individual freewill with that of communal good.¹⁸

Finally, continuing the theme from before, I studied the environmental effects caused by the limit of ACA infusion. Recalling earlier that the environmental effects of ACA probability density of new vehicles had been examined (Figure 3), Figure 5 shows a similar trend except now the ACA probability densities apply to the whole population, rather than just to the new vehicles entering the population. In the same way

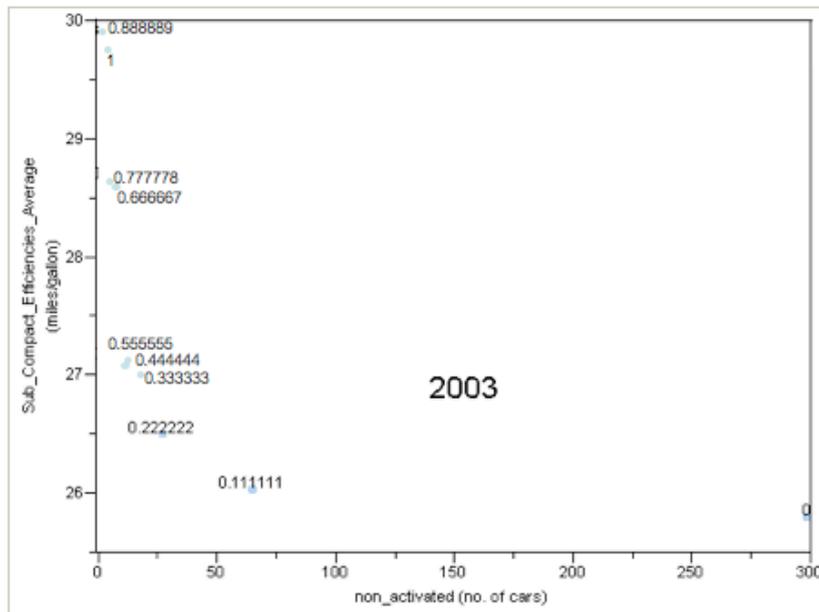


Fig. 6: Fuel Efficiency vs. Non-Activated IS vehicles

as in Figure 3, Figure 5 shows the value of sub-compact efficiency as a function of non-activated IS vehicles for the year 2003, where it is assumed as before that ACA

infusion began in 1996. Recalling the approximately apparent linearity of Figure 3 and its shallow slope, it is clear from the 'big picture' provided by Figure 5 that the shallow line of Figure 3 occupied the region for which the number of non-activated IS vehicles is between 140 and 300. Instead, on the entire domain of the number of non-activated IS vehicles, there is an approximate exponential decay of efficiency as a function of non-activated vehicles. As before, the numbers shown with the points in the figure correspond to the probability density of ACAs, yet whereas before these numbers pertained to new vehicles entering the population, in Figure 5 the probability density of ACAs applies to the entire population.

Just as Figure 3 has illustrated, probabilistic uncertainty is built into the modeling environment, thus there is similar variability around the decay function that would fit the data points shown in Figure 5. Clear though from this figure is that the infusion of ACAs into the traffic population would yield an increase of 4 miles/gallon on average for the traffic population seven years after infusion began, when compared with the case in which no infusion has occurred (bottom right corner of the figure).¹⁹

5. CONCLUSION

Although further extrapolations of this reasoning could lead to more quantitative justifications as to how ACA infusion would benefit both freeway traffic flow and the environment, those investigations are left for future study. Nevertheless, the system-level metrics of average population velocity and average population efficiency clearly exhibit themselves as valid FOMs for assessing the effects of implementing the IS capability hypothesized in this study within the current automotive system-of-systems. Not only is it possible to decrease automobile emissions by 20% in 7 years (Figure 5)²⁰ when considering large scale implementation but also it would be possible to increase the average speed on the freeways by 27% in congested traffic (Figure 4). Although the calculations of this study apply only to one lane of freeway traffic in a system that is closed off from the rest of the traffic flow, extrapolations of this study to the case of multiple lanes are quite possible although not performed in this study. Therefore, this study has shown that the infusion of an IS technology, which is controlled by the driver, could have beneficial effects on both the environment and the ubiquitous metropolitan freeway congestion. Whereas only mild improvements were shown when a varying amount

of new vehicles possessed the hypothesized IS technology, gross improvements were shown for varying amounts of all vehicles possessing said technology.

ACKNOWLEDGMENTS

Many thanks to the Aerospace Systems Design Laboratory at Georgia Institute of Technology for providing the software and encouragement to complete this study.

REFERENCES

- Bose, A. and Ioannou, P. 2001. Analysis of traffic flow with mixed manual and intelligent cruise control vehicles: theory and experiments, *California PATH Research Report*, UCB-ITS-PRR-2001-13.
- Brackstone, M. and McDonald, M. 1999. Car-following: a historical review. *Transportation Research Part F: Traffic Psychology and Behaviour*, **2**, 181-96.
- Chandler, P.E., Herman, R. and Montroll, E.W. 1958. Traffic dynamics: studies in car following, *Operations Research*, **6**, 165-84.
- Chee, W. and Tomizuka, M. 1994. Lane change maneuver of automobiles for the Intelligent Vehicle and Highway Systems (IVHS), *Proceedings of the 1994 American Control Conference*, 3586-7.
- Couzin, I.D., Krause, J., Franks, N. and Levin, S. 2005. Effective leadership and decision-making in animal groups on the move, *Nature*, **433**, 513-7.
- Galovski T. and Blanchard E.B. 2002. Psychological characteristics of aggressive drivers with and without intermittent explosive disorder. *Behavior Research and Therapy*, **40**, 1157-68.
- Hamann, S. 2001. Cognitive and neural mechanisms of emotional memory, *Trends in Cognitive Neurosciences*, **5**, 394-400.
- Helbing, D. and Treiber, M. 1998. Gas-kinetic-based traffic model explaining observed hysteretic phase transition, *Physical Review Letters*, **81**, 3042-6.
- Hennessy, D.A. and Wiesenthal, D.L. 1997. The relationship between traffic congestion, driver stress and direct versus indirect coping behaviours. *Ergonomics*, **40**, 348-61.
- Ioannou, P.A. and Chien, C.C. 1993. Autonomous intelligent cruise control, *IEEE Transactions on Vehicular Technology*, **42**, 657-72.
- Klar, A. and Wegener, R. 1997. Enskog-like kinetic models for vehicular traffic, *Journal of Statistical Physics*, **87**, 91-114.
- Metcalfe, J. and Jacobs, W.J. 2000. 'Hot' emotions in human recollection: toward a model of traumatic memory. In: *Memory, consciousness, and the brain: The Tallinn Conference*, edited by Tulving E, London-New York, Psychology Press, Taylor & Francis, 228-42.
- Newell, G.F. 2000. A simplified car-following theory: a lower order model, *Transportation Research Part B: Methodological*, **36**, 195-205.

- Pipes, L. 1952. An operational analysis of traffic dynamics, *Journal of Applied Physics*, **24**, 274-81.
- Reisberg, D. and Heuer, F. 1992. *Affect and accuracy in recall: studies of 'flashbulb' memories*, Cambridge, UK, Cambridge University Press.
- Safonov, L.A., Tomer, E., Strygin, V.V. and Ashkenazy, Y. 2002. Multifractal chaotic attractors in a system of delay-differential equations modeling road traffic. *Chaos*, **12**, 1006-14.

ENDNOTES

-
1. For more information, see: http://www.forbes.com/logistics/2006/02/06/worst-traffic-night-mares-cx_rm_0207traffic.html
 2. Possible enabling technologies for this would be similar to radio wave communication or cell phones (i.e. microwave-based communication devices).
 3. In fact, this is the ability that the Georgia Institute of Technology entrant to the DARPA Urban Grand Challenge has; this vehicle is called the Sting1.
 4. Even though the safety margin is not necessary with apt Doppler Shift sensors, there is a necessary distance that a car must travel when coming to a sudden stop because of loss of the 'no slip' condition between the wheel and the pavement. Although this necessary distance is not explicitly built into the modeling, the velocity dependence of the following distance emerges because of the chosen velocity of the unimpeded traffic sufficiently downstream of any congestion.
 5. This distance will depend, among other things, on what electromagnetic signature of the neighbor is used.
 6. Likewise, the same logic applies to metropolises around the world, however such data was not obtained in the course of the research that culminated in this study.
 7. Data available at: http://www.howstuffworks.com/framed.htm?parent=question477.htm&url=http://tqjunior.thinkquest.org/4116/Trip_Planning/speed.htm Even though the exact data are not necessarily representative of these types of vehicles, the trends and relative magnitudes of the relation are accurate enough for the intended calculation. Of course, more accurate modeling of this aspect of the calculation would be possible if the appropriate data were available. Nevertheless, the physical principles of the internal combustion engine would make it so that a more refined modeling of this aspect of the vehicle's performance would only mildly effect the possible environmental benefits (or detriments) of infusing IS into the automotive traffic system.
 8. Data available at: http://mobility.tamu.edu/ums/congestion_data/tables/atlanta.pdf
 9. Data available at: http://www.census.gov/Press-Release/www/releases/archives/american_community_survey_acs/001695.html
 10. Data available at: http://www.bts.gov/publications/national_transportation_statistics/html/table_04_05.html
 11. 'Absolute' velocities are meant to mean that they are relative to the reference frame of the road.
 12. Even though the effects of other types of traffic models have not been addressed in this study, I conjecture that the benefits/detriments of ACA infusion would be comparable; this is undoubtedly an area of possible study.
 13. Data available at: http://online.wsj.com/mdc/public/page/2_3024-carsales.html

-
14. This factor accounts for the observation that the vehicles that are ACAs can ‘exchange’ their ability with other vehicles in the population.
 15. Assumed to be 10%, though survey data could extract a more accurate number.
 16. Data available at: <http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp>
 17. Note that $N = 299$ appears on the figure because 299 vehicles are behind the leading vehicle, thus making 300 vehicles in total.
 18. Because of the emotional distress of impediment to a desired destination, however, drivers that incorporate past experiences into future vehicle purchase decisions would drive the effects of ACA infusion towards the benefit of the communal good.
 19. The key distinction between this result and earlier results is that ACAs are infused to already-existing vehicles as well as new vehicles. This could be a possible incentive for a new company to explore the feasibility of infusing such a technology on such a wide scale.
 20. This calculation is only for the sub-compact vehicle population. In fact, the mid-size population showed a 20% increase in fuel efficiency in only four years.