SIMULATION OF FLOW CONTROL ALGORITHM FOR MULTI-LANE AUTOMATED HIGHWAY SYSTEMS

By

DIEGO ORLANDO TERZANO

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2001

To my parents and sister

ACKNOWLEDGMENTS

First, I would like to extend my heartfelt appreciation to my advisor, Dr. Sherman Bai, for his support and encouragement during the development of this thesis. I would also like to thank Dr. Shen for taking the time to read and evaluate this thesis, as well as serving on my supervisory committee.

In addition, I would like to acknowledge the generosity of Gabriel Gomez and Dr. Mireille Broucke from the University of California, Berkeley, for dedicating time to provide the version of the SmartCAP simulator used in this study. Furthermore, gratitude is extended to John Haddon for his work on activity space requirements which provided valuable input for the development of this work.

Finally, I would like to thank my parents for their encouragement, guidance and support without which I probably would not have accomplished this work.

TABLE OF CONTENTS

page

APPENDICES

LIST OF TABLES

Table Page

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Science

SIMULATION OF FLOW CONTROL ALGORITHM FOR MULTI-LANE AUTOMATED HIGHWAY SYSTEMS

By

Diego Orlando Terzano

December 2001

Chairman: Dr. Sherman X. Bai
Major Department: Industrial and Systems Engineering

The increasing social and economic burden of highway congestion coupled with high construction costs and difficulties faced in expanding the current highway infrastructure triggered interest in recent years on alternate methods to increase highway capacity. Technological developments in control systems, sensor technologies, communications and data processing capabilities make it possible to automate the decision-making process and execution of driving maneuvers with greater accuracy, lower response time and higher safety than human controlled vehicles. The combination of advanced technologies, information sharing and use of analytical tools to safely increase traffic throughput epitomize the motivation behind the Automated Highway Systems (AHS) program under development. In this work, the activity based theory of traffic flow is applied to describe a link layer controller to ensure smooth traffic flow under conditions of high traffic volume. The design considers an hypothetical highway configuration of a multi-lane AHS architecture under scenarios of vehicle platoons and free agents (individual vehicles with constant safe headway under automatic control). In addition, the platoon size effect is studied along with two information sharing concepts for free agents operation. Simulation outputs are obtained using SmartCAP, a meso-scale fluid flow simulator capable of representing vehicular flow models with discrete activities in space and time. Finally, results using Matlab are presented and discussed.

CHAPTER 1
INTRODUCTION

1.1 Motivation

Highway congestion is imposing an intolerable burden on many urban and suburban areas. Because congestion occurs when the demand for travel exceeds highway capacity, alternatives for alleviating congestion concentrate on mix policies affecting demand and capacity depending on local circumstances and priorities (Varaiya, 1993). The traditional solution of constructing more highways or expand the current infrastructure to meet the growing demand is no longer possible in many urban areas. Furthermore, the expansion of public transportation cannot provide a cost-effective solution in areas facing dispersion of the workforce, and the vast majority of commuters continue to use private vehicles (Kourjanski et al., 1997a). It is estimated that by the year 2010 total roadway travel will be more than double relative to 1992. Moreover, the average speed of vehicles during peak hours is expected to drop to 11 mph by the year 2005 from 35 mph in 1995. The lost of productivity due to traffic congestion costs around $100 billion each year in the United States along with substantial personal frustration and some 2 billion gallons of wasted fuel by traffic congestion. Environmental issues are increasingly critical, with vehicle emissions in particular posing an ever-increasing problem to public health (Fenton, 1994). Alongside congestion and environmental issues, safety continues to be a prime concern. The National Highway Traffic Safety

Administration (NHTSA, 1998) estimates that a total of 6 million traffic accidents occur each year, in which about 41,000 people are killed and 3 million suffer injuries.

It is evident that the transportation sector which accounts for one-sixth of the GNP of the United States[1] needs to be improved in order to protect the environment, the people who use the transportation system and to ensure growth potential for the industry as whole. The nationwide estimates for vehicle miles traveled predict a growth of 2.5 percent per year until the year 2030 (Broucke and Varaiya, 1997b). Correspondingly, there is an inability to build or expand the infrastructure to account for the increased demand and usage estimates. In summary, private automobile travel is the main mode of travel in the United States, the demand is growing while productivity is declining. Furthermore, Fenton (1994) states that this phenomena arises, in part, from the lack of sufficient land for roadway construction and the high constructions costs, especially in congested areas. These developments led to Federal Highway Administration to conclude: “The highway transportation system is at a critical crossroads in its evolution and has started to plateau in its ability to provide significant new performance in its presence form” (as cited in Broucke and Varaiya, 1997b, p. 1584).

To address the aforementioned issues, the U.S government under the Intermodal Surface Transportation efficiency Act of 1991 initiated a comprehensive program to improve safety, enhance mobility, minimize environmental impact, save energy, and promote economic productivity in the transportation industry. This program is the Intelligent Transportation System (ITS), formerly called Intelligent Vehicles and Highway Systems (IVHS). The program tries to combine several modern technologies

---

[1] Forty percent of the transportation sector represents freight and the rest private automobiles. Public transportation is negligible in these aggregate figures.

and advances in sensors, communications and data processing to achieve its objectives. Currently there are two main threads of research:

1. The first consists on providing more reliable traffic information to drivers to help make better decisions regarding their route selection and consequently increase the throughput. Unfortunately, this approach is limited by humans reaction time and constraints the theoretical highway capacity to approximately 2,000 vehicles/hour/lane (Al-Deek and Kanafani, 1989).
2. The second area of research consists on automating the decision-making process for route selection and vehicle control. The principal motivation for this alternative is dramatic improvements in capacity, safety and energy efficiency. Over the last decade there have been many research papers justifying this claim (Shladover, 1991; Shladover et al., 1991; Varaiya, 1993). This initiative leads to the concept of Automated Highway Systems (AHS) and Partners for Advanced Transit and Highways (PATH) which in the early 90's proposed a specific control hierarchy for the highway automation project and currently leads the research efforts in this area.[2]

The developments and techniques explored in this research thesis deal with the second thread of research. The potential for improvement and the benefits it may bring to the transportation system are extraordinarily promising. Varaiya (1993) argues that it is certainly feasible that the benefits in capacity alone could quadruple the throughput over existing peak flows. In addition, one could also argue that AHS will be a safer way to travel since data suggest (Varaiya, 1993) that human error accounts for 90% of accidents

---

[2] More information on PATH and general AHS concepts is provided in Chapter 2.

(Hedrick et al., 1994). However, the planning and execution of an Advanced Highway System is a daunting task. It involves the integration of several technologies into the design of ‘intelligent’ vehicles and highways. The approaches taken to develop such infrastructure involve recognition, learning and trajectory planning in the face of diverse threads and obstacles.

To manage such a large-scale endeavor, several public and private organizations founded PATH (Partners for Advanced Transit and Highways) in 1989 with support from the California Department of Transportation (Caltrans) and established an organized AHS research program. The methodology generally used to tackle large-scale systems involves design, prototyping and finally deployment. Specifically, the design phase requires the specification of an overall architecture within which controllers can be designed to coordinate the system. Subsequently, the architecture design decomposes the control design problem into the control of sub-systems. In 1991, the PATH program developed a highway automation architecture (Shladover et al., 1991) to establish the sub-systems needed to develop a robust framework leading to a safe Automated Highway System. The first step of the decomposition process established the separation between roadside controllers and in-vehicle controllers. Further decomposition of the sub-systems led to a five layers architecture (refer to Chapter 2, section 2.3 for a description of each of the layer functions) that represents the main controllers responsible for safe execution of vehicle maneuvers, planning and coordination of activities and tactical decisions to improve traffic flow.

Jong-Kwon Lee and Ju-Jang Lee (1997) noted that most of the research efforts regarding an AHS architecture has been in control systems (longitudinal and lateral control) and particularly the lowest layers of the PATH hierarchy. Namely the planning, regulation and physical layers; mainly vehicle control systems (Hedrick et al., 1994; Varaiya, 1993; Hsu et al., 1991; Sheikholeslam and Desoer, 1990; Hessburg and Tomizuka, 1994). In contrast, there are relatively few works regarding the roadside components of the AHS architecture, especially the link layer controller (Rao and Varaiya, 1994; Broucke and Varaiya, 1996; Peng, 1997). As a result, this research thesis will explore the requirements, design and performance of a proposed methodology for traffic flow behavior on a multi-lane AHS setting.

Moreover, to facilitate the design, specification and evaluation of large-scale systems, and to provide cost-effective support for objective comparison of proposed alternatives, a simulation framework is needed. Consequently, in 1992 the ITS program developed a strategic plan (IVHS America, 1992). The plan identifies modeling and simulation as vital steps in realizing the proposed AHS initiative. The almost unpredictable behavior and complexities inherited in hybrid systems make analytical approaches impractical (or sometimes nearly impossible) for realistic scenarios with multiple-lanes and high traffic volume. To describe and execute performance evaluations consistently, the framework must allow the designers to use a specification that fits the domain and must represent dynamic interaction dependencies among components in the system. For this reason, the simulation granularity of highway traffic is divided into three main categories: macro, meso and micro-scale simulators.[3] To simulate the activity flow profile describing the behavior of the proposed link layer controller, SmartCAP (Broucke et al., 1996b), a meso-scale simulator was chosen. SmartCAP performs numerical

---

[3] See Chapter 2, section 2.6 for additional information on simulation granularity.

computations of the analytical activity flow model (Broucke and Varaiya, 1996), an extension of traditional traffic flow models. The simulator permits differentiation of discrete activities such as vehicle maneuvers and captures the impact on highway productivity (Deshpande et al., 1995). Each activity is characterized by the amount of highway *space* and *time* the vehicles use to perform a maneuver. These two parameters are essential to the concept of activity flow profile and are constantly used in the model to determine the aggregate delay or capacity loss incurred due to the activity performed by the vehicles under automated control.

1.2 The AHS Experience

Consider the following AHS hypothetical scenario. To drive a car over a two-lane highway under the AHS architecture, the driver first enters from an on-ramp on the outer-most lane and announce the destination. The announcement can be made by voice or on-board keyboard entry. The vehicle's on-board computer communicates the destination to the roadside computer. Then, the roadside computer evaluates the status of the section in which the vehicle intents to enter the AHS lanes based on aggregate variables such as flow and density and assigns a lane (1 or 2) that the vehicles should occupy for most of the trip. In addition, it tells the vehicle at what point along the assigned lane it should start maneuvering to make a lane change so that it can exit at the desired destination. In essence, according to AHS terminology the roadside controller assigns a *path* to the vehicle. The transition from automatic to manual control and vice-versa is not fully studied yet, however, at some point on the entrance ramp, the vehicle computer takes over longitudinal and lateral control. The computer will then try to keep a trajectory as close as the assigned path as possible keeping safety and ride comfort under prime consideration. At the off-ramp, the on-board computer will alert the driver to take control of the vehicle[4] (see Figure 1.1 for an AHS design layout).

In addition, during the vehicle's trip, there are additional maneuvers the vehicle will perform to increase the capacity of the highway. To do so, the vehicles will try to organize in clusters with small vehicle spacing called platoons (more information in Chapter 2). This activity requires coordination and communications between vehicles in order to be performed safely and comfortably for the driver and passengers. In summary, Hedrick et al. (1994) identifies three control tasks that must be performed for successful AHS operation:

1. To assign a path to each vehicle
2. To safely carry out maneuvers of platoon formation, stabilization and dissolution, lane change, entry and exit.
3. To implement the maneuvers in (2) via feedback laws (algorithms) that control each vehicle's throttle, braking and steering actuators.

The following figure (1.1) illustrates the main features of a conceptual AHS design.

The layout shows a transitional AHS architecture scheme with a three-lane manual driving and two-lane automatic driving design. The outermost three lanes represent a conventional highway while the two innermost lanes on each direction represent the proposed automated driving transportation medium. Vehicles with the necessary technologies to take advantage of automated driving will be able to join the AHS lanes to enjoy a faster, safer and cleaner way to travel. In (1), the vehicle waits for

---

[4] The entry and exit are far more complicated activities that the brief description given here. The entry procedure includes a "check-in" activity and vehicle coordination for merging into an adjacent lane. Likewise, the exit includes a "check-out" procedure and advance control techniques to ensure a safe transition to manual control. See Godbole et al. (1995) for more detailed information.

authorization to join the AHS lanes. The process consists on verifying the vehicle systems and waiting for an appropriate space slot for the vehicle to begin automatic driving. Once the vehicle has been granted access and the vehicle's on-board computer system has been evaluated for proper AHS operation, the vehicle (2) proceeds to enter the designated AHS lane. The vehicles already in automated driving mode can be designated as leaders or followers depending on their role in platoons or free agents in which case the vehicle does not belong to any platoon and it is traveling independently.[6] A platoon of four vehicles is shown in (3), a leader and 3 followers are traveling on lane 1 of the AHS. Finally, when a vehicles reaches its destination, the vehicles exits through the off-ramp (4) and resumes manual driving to complete the trip.

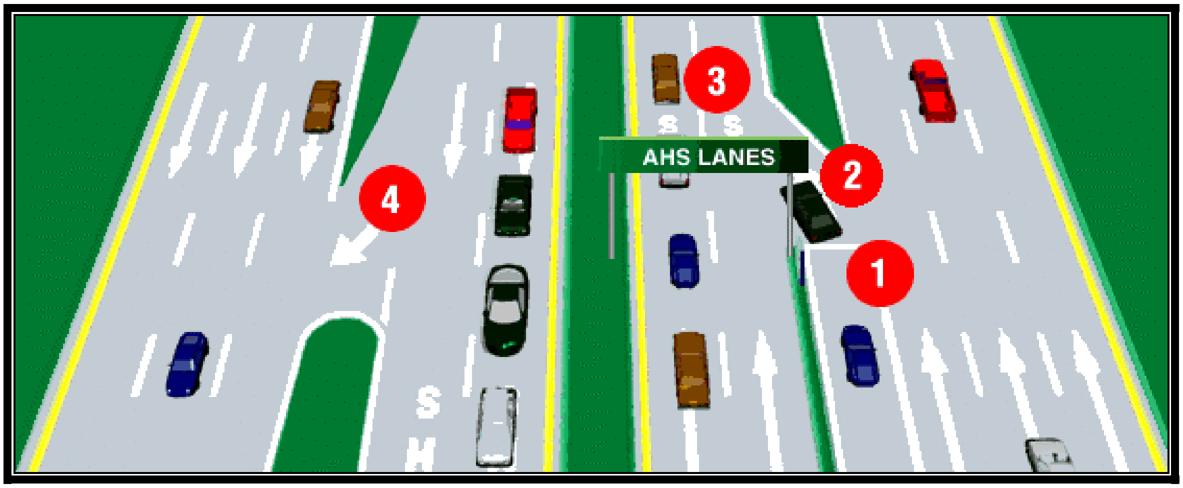

Figure 1.1: Two-lane AHS layout[5]

---

[5] Graphical depiction courtesy of Delco Electronics (1997)

[6] Chapter 2, section 2.4, provides more information regarding the definition and characteristics of this terminology.

1.3 Research Goals

This research is intended to be a preliminary study on the capabilities and performance of a flow control methodology according to the requirements of the link layer controller from the PATH architecture for AHS operation under scenarios of platoon formation and free agents on a multi-lane architecture, extending the nature of the single-lane scenarios presented in Haddon (1996). Performance evaluations are based on the system's ability to reach a steady state behavior, average speed, and the unmet demand due to insufficient time-space availability at the highway. Also, the platoon size effect will be analyzed to evaluate the impact on time-space availability for lane change maneuvers.

The vehicle flow model will be introduced based on the activity flow model developed by Broucke and Varaiya (1996). Performance evaluation and analysis will be carried out using the compatible simulation framework of SmartCAP meso-scale simulator. Finally, concluding remarks and future research topics will be identified.

In Chapters 3 and 4, the SmartCAP activity flow model in introduced and the implementation of the flow methodology explained. The model consists on conservation of vehicles, evolution of average velocities on highway sections, and physical constraints on the vehicle and highway. The vehicle conservation law extends standard traffic flow models by keeping track of activity flow as well. Secondly, the average velocity dynamics accounts for anticipation due to follower behavior on a platoon scenario, relaxation due to reference velocity-tracking control laws, and vehicle interactions due to speed variations between activities. Finally, constraints capture the vehicle's limitations on velocity and acceleration, the feasible and permitted sequence of activities, and the highway space-time limitations in which activities can take place (Deshpande, 1995).

1.4 Organization of Thesis

This thesis is organized as follows. Chapter 2 presents the basic concepts surrounding the AHS initiative. A brief history is introduced along with the current developments regarding flow control strategies for link layer controllers. The concept of platooning is also explored to demonstrate potential gains in capacity on the current highway infrastructure. Chapter 3 introduces the flow control methodology based on previous works by Rao and Varaiya (1994), Jong-Kwon Lee and Ju-Jang Lee (1997), and Broucke and Varaiya (1996 and 1997a). In Chapter 4 the SmartCAP (Broucke et al., 1996) meso-scale simulator is introduced. Details on the flow control implementation, simulator limitations and other characteristics are given. Special attention is given to the input parameters, activity plan, velocity plan and Traffic Management Control (TMC). Chapter 5 presents the simulation results on tested scenarios using Matlab (MathWorks, 1994). Finally, Chapter 6 offers some conclusions on the proposed flow control methodology and a discussion on future research areas.

CHAPTER 2
BACKGROUND LITERATURE

Before a flow control model for Automated Highway Systems (AHS) is presented, some background information is introduced. This chapter offers the basic concepts behinds AHS, the layered architecture designed for AHS control, proposals to increase highway capacity and a description about the issues surrounding the design of link layer controllers.

2.1 Brief History of AHS

The concept of Automated Highway Systems has its roots at the General Motors Pavilion during the 1939-40 World's Fair. During the Fair, the notion of vehicles that drive themselves while the driver comfortably relax and enjoy the ride was first introduced as a vision of the future of automobiles (Gardels, 1960). Years later, when the technology to make that vision possible matured, several initiatives began to surface around the world, starting in Europe and Japan. In the United States it was not until October 1986 when the California Department of Transportation (Caltrans) sponsored a conference to discuss the role of advanced vehicle-highway technologies in meeting the increasing demand for highway capacity and efficiency (Ioannou, 1997). The success of the event promoted research in Intelligent Vehicle-Highway System (IVHS) or as more recently called, Intelligent Transportation Systems (ITS).

Nowadays, the leading research body in the United States is PATH, Partners for Advanced Transit and Highway, composed by many public agencies, private organizations and universities. The University of California, Berkeley is at the core of the research efforts and is currently where most developments are taking place (see PATH[1] for updated research news). In addition, several other programs are active in North America, including Pathfinder, SMART Corridor (it is also the test site for Pathfinder), TravTel (Travel Technology) in Orlando, Florida, Free Agents at Carnegie Mellon University (CMU) (Thorpe et al., 1997), Advance in the Chicago area and GuideStar in the Minneapolis/Saint Paul area (Jurgen, 1991; Collier and Weiland, 1994). However, it was not until 1994 when the Department of Transportation established a national consortium to investigate alternative designs, develop and test prototype AHS technologies, named the National Automated Highway Systems Consortium (NAHSC).[2] A pinnacle demonstration took place in 1997 where several technologies were demonstrated in San Diego, California. An eight vehicle platoon-based system and more than 100 NAHSC engineers gave rides in automated vehicles to more than 1,700 people proving the success and stability of the technology. Unfortunately, for funding reasons, the consortium was dissolved in 1998 and currently, PATH with support from Caltrans continues NAHSC efforts to develop AHS technologies. Further information and more comprehensive historical reviews on AHS, IVHS/ITS and PATH can be found in Fenton and Mayhan (1991), Fenton (1994), Shladover et al. (1991) and Varaiya (1993).

---

[1] The Partners for Advanced Transit and Highway website is located at http://www.path.berkeley.edu/

[2] The core members of NAHSC were Bechtel, Caltrans, Carnegie Mellon University, Delco, General Motors, Hughes, Lockheed Martin, Parsons Brinckerhoff, PATH and the Federal Highway Administration.

2.2 AHS Components

In order to successfully deploy such a daunting endeavor like an AHS architecture, several aspects need to be resolved and an appropriate consensus level among researchers needs to be attained. Varaiya (1993) identified five aspects of Intelligent Transportation Systems (ITS), which constitute the main areas of debate about the appropriate form of 'intelligence'. The diversity of opinions comes from the difference in judgment about function, architecture, design, evolution and evaluation. Function constitutes the range of driving functions that should be automated, and the degree of automation. Architecture refers to the decomposition of these functions into control tasks and the assignment of those tasks to the ITS subsystem. Design addresses the division of intelligence between the vehicle and highway, and how the enabling technologies are to be combined to realize this architecture. The evolution of the system depends on the timing of system development and deployment, and the extent to which the architecture should accommodate new functions not included in earlier designs. Finally, evaluation measures the effectiveness, costs and benefits of different ITS proposals.

The evolutionary strategy for AHS deployment has been addressed is several research articles (Hall, 1991; Ioannou, 1997; Al-Ayat and Hall, 1994). Heinrich (1991) believes that the success of ITS in highly dependent upon the driver's acceptance and continued use of in-vehicle ITS equipment. He defines the consumers (car buyers) as conservative buyers regarding their preferences and what they look for as potential solutions for their needs. Furthermore, he argues that "the capability of IVHS infrastructure to provide timely and credible traffic advisories will play a key role in forming and more importantly maintaining the buyer's interest in IVHS." (as cited in Ioannou, 1997, p. 50).

In order to achieve fully automated travel in a multi-lane highway, as required to implement the control laws expressed in this research thesis, several modifications are required to the current highway infrastructure and vehicular technology. Hall (1991) provides a progression on the developments of highway infrastructure. He explores different versions of AHS architectures, including AHS without automated lane changes and with lane changes at reduced speeds. Later on, Hall (1995b) introduced a framework for an AHS evolutionary deployment strategy that includes three principal entities: the vehicle, driver and roadway/infrastructure. In order to successfully deploy an AHS strategy, the entities and its individual components must be able to work together to perform the basic driving behaviors on a highway, namely:

- Exiting/Entering: Split from current roadway and set a trajectory to merge into another roadway while transitioning from/to automatic driving.
- Lane maneuvering: Safely steer into the desired lane without conflicting with adjacent vehicles or disrupting traffic flow. Ideally, balance excess lane capacity by selecting most efficient lane of travel.
- Cruising: Accelerate or decelerate to maintain desired headway or avoid obstacles, steer to keep center of lane and maintain desired velocity.
- Path Selection: Choose the most efficient roadway path between the selected origin and destination (more information on section 2.5).

Using the proposed framework, table 2.1 presents a depiction of the current state of highway systems.

Table 2.1: Current State of Highway Systems

Conventional Vehicle Roadway			
	Capabilities		
	Vehicle	Driver	Roadway
Sensors		Vehicles/adjacent lanes Vehicles/same lane Obstacles Hazards Weather conditions Vehicle condition	Traffic condition
Intelligence		Lane keeping Lane maneuvering Lane choice Speed regulation Exiting/entering	
Memory		Rules of the road Driving skills	
Actuators	Hydraulic brake Conventional Throttle Hydraulic steering		
Communication	*To drivers* Vehicle warning lights	*To drivers* Turn signals	*To drivers* Traffic conditions (CMS, HAR)[3]

This scenario represents a conventional vehicle on a conventional highway where most of the intelligence resides on the driver, responsible for all of the driving tasks. Vehicle actuation is minimal and provides no automatic longitudinal control or steering. A more detailed evolutionary representation of the framework can be found in Hall (1995b).

The proposed evolutionary strategy refers to AHS2 as the ultimate step in vehicle/roadway intelligence. In this stage vehicles are capable of communicating to/from

---

[3] Congestion Management System (CMS) and Highway Advisory Radio (HAR), respectively.

vehicles in adjacent lanes, same lanes and roadway controller. They are able to make automated lane changes, have speed regulation and are equipped with a complete sensors array. The policies discussed here require an infrastructure that issues commands to vehicles based on global traffic conditions and therefore, an AHS2 architecture is required.[4]

Table 2.2 depicts the level of sophistication required for each entity on the proposed framework for an AHS architecture. There is an evident shift in 'intelligence' from human control to machine actuation. In order to achieve this state, several technologies need to be implemented on the vehicle and roadway. The vehicle needs an array of sensors to detect the range of the vehicle ahead, lane keeping and be able to detect wet road conditions. Technologies such as multi-beam millimeter radars, magnetic field sensors and vision-based sensors are being evaluated to accomplish those tasks.

Table 2.2: AHS Architecture

	AHS Vehicle in AHS Roadway		
	Capabilities		
	Vehicle		
	Machine	Human	Roadway
Sensors	Brake Engine Velocity, Acceleration, jerk Yaw angle Lane reference Distance (to leader) Vehicle condition	Unusual hazards	Roadway conditions Weather conditions Traffic conditions
Intelligence	Lane keeping, with close headway vehicle following	Exiting/entering (partial)	Speed regulation Entrance metering

---

[4] For the remaining of this research paper, AHS2 will be referred to as AHS for simplicity of notation.

	Capabilities		
	Vehicle		
	Machine	Human	Roadway
	Lane maneuvering Exiting/entering (partial)		System showdown Lane choice Lane change initiation
Memory		Rules of the road	Lane reference system
Actuators	Electronic brake Electronic Throttle Electronic steering		
Communication	*To Roadside* Vehicle condition *To drivers* Enter/exit commands Vehicle condition *To vehicles* Acceleration, velocity, jerk, location Lane change data	*To drivers* Enter/Exit requests Hazards	To drivers Permissions to enter Target speeds Enter/exit commands Roadway conditions Weather conditions

In addition, communications devices, actuators (brake, throttle and steering), sensor data processing and diagnostics systems will have to be integrated to provide the required abstraction level and limit the driver to simple monitoring tasks.[5] Moreover, computer interface designers and human factors engineers are responsible to present the proper information in a suitable manner to create the necessary awareness in the driver to effortlessly monitor the system status in real-time. Delco Electronics (1997) in conjunction with Carnegie Mellon University have developed a prototype for the user interface which includes a flat panel display with information regarding the mode of operation (manual or various degrees of automation, automatic steering and full

---

[5] Refer to Rockwell (1994) for a detailed description of the technological implementation.

automation), maneuver completion status, sensors and actuators status, distance and time to destination and gap (in ft.) to vehicle in front.

The experimental efforts to realize a fully functional and safe AHS architecture requires a diverse skills set, including control design, hardware, software and systems integration. Furthermore, as identified by PATH in 1989, sub-systems, analysis, and verification frameworks must be established to organize the research efforts and focus the necessary aptitudes in tackling specific problems. As a results (and a previously mentioned) the following control system hierarchy was created.

2.3 Control System Hierarchy

The PATH program has proposed a hierarchical control architecture for the development of an AHS system to realize the promise of increased capacity while enhancing safety (Shladover et al., 1991 and Varaiya, 1993). The automation strategy of the architecture is organized in a control hierarchy with several layers, figure 2.1 illustrates the interaction between these layers.

The lower three layers reside on the vehicle while the link and network layer reside on the roadside. Starting from the bottom, a brief description of each layer and its functions will be given.

The *physical layer* refers to the vehicle dynamics and comprises all the on-board controllers of the vehicle. These include the engine, transmission, brakes, steering and longitudinal guidance[6] controls, ranging sensors and communication devices. Its main

---

[6] Longitudinal guidance refers to the task of controlling the forward motion of the vehicle along a lane. Swaroop et al. (1994) provides extended information on guidance control.

function is to decouple[7] the longitudinal and lateral vehicle guidance control and to approximately linearize the physical layer dynamics (Hedrick et al., 1994 and Pham et al., 1994).

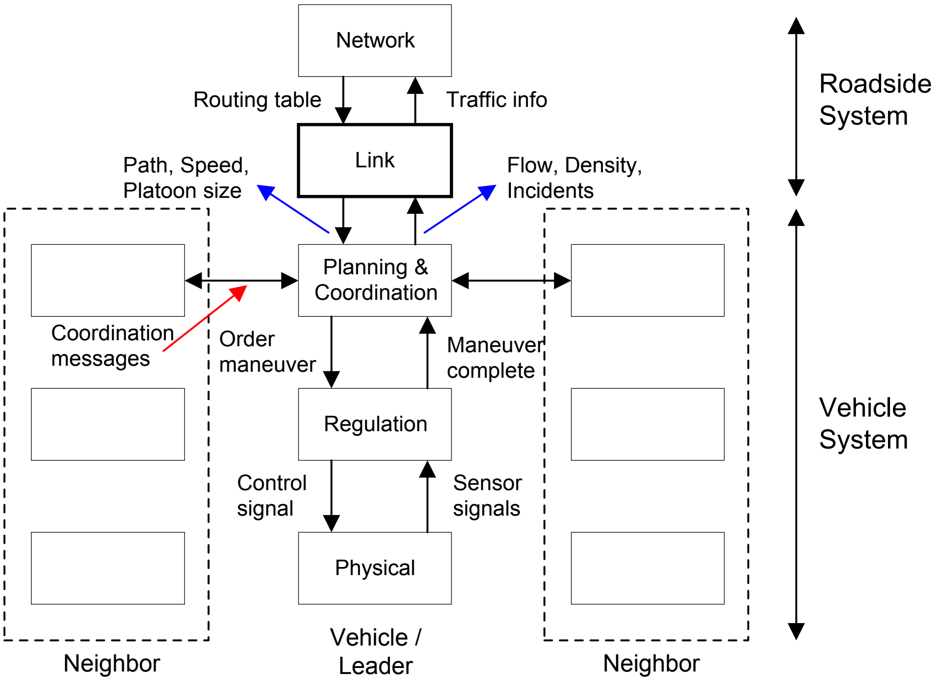

Figure 2.1: PATH Hierarchical Architecture

The *regulation layer* is responsible for the longitudinal and lateral guidance of the vehicle, and the execution of the maneuvers ordered by the coordination layer. There are two important longitudinal control tasks at this third level of hierarchy that it must accomplish. The first consists of maintaining a specified constant spacing from the

---

[7] Decoupling simplifies the design of the regulation layer (for heavy trucks, the models are coupled making the design more difficult).

preceding vehicle to a follower in a platoon (Swaroop, 1994). The second control task pertains to leaders of platoons and free agents equally. Its purpose is to safely and efficiently execute a maneuver instructed by the coordinated layer. These maneuvers are: regulating the platoon velocity to a desired value while keeping a safe distance from the preceding platoon (leader law), joining to the preceding platoon (join law), splitting a platoon (split law), and splitting from a platoon while maintaining safe distance from neighboring platoons in the adjacent lanes in order to change lanes (split to change lanes law) (Alvarez and Horowitz, 1999a, 1999b and Li et al., 1997). The lateral control tasks involve keeping the vehicle in its assigned lane or to change to an adjacent lane.[8] Finally, the regulation layer controls the entry and exit maneuvers to the portions of the highway under automated control (Godbole, 1995).

The *planning and coordination layer* task is to select the activity[9] that the vehicle should attempt or continue to execute according to its activity plan. This layer communicates periodically with the neighbors vehicle counterpart layer and supervises its commands to assure safety in the maneuvers that the vehicles will perform. In addition, there is communication with the link layer roadside controller to receive updated activity plans that will optimize traffic flow. This layer is crucial to the proper function and safety of vehicles under automatic control. For that purpose, this layer stores and updates all the vehicle's relevant information periodically to ensure that the vehicles systems are

---

[8] This task is called change lane maneuver. See O'Brien (1995) for more detailed information.

[9] An activity is defined as any of the vehicle's longitudinal and lateral tasks and maneuvers.

operating correctly. Some of the information includes the current state of the vehicle for verification (vehicle's identity[10]), current location, activity, and assigned activity plan.

The *link layer* is part of the roadside system controller and its purpose is to assign an activity plan to different sections in the highway that will maximize capacity while minimizing travel time and undesirable congestions. The link layer gathers information from the vehicles coordination layer and then broadcasts a specific activity plan for each vehicle type and section. At this level of the architecture hierarchy, the response of individual vehicles is no longer monitored. Instead, the state of the system is measured and described as *aggregated* space and time density profiles. Consequently, the link layer dynamics are described by density conservation flow models (Broucke and Varaiya, 1996, 1997a and Li et al., 1997). This concept will be further explored in chapters 3 and 4. In addition, a more detailed description of the link layer controller, current research and design issues is provided in section 2.4.

Finally, the last layer in the architecture hierarchy, *network layer*, controls the entering traffic and route traffic flow within the network of highway links that constitute the AHS. This layer main responsibility is to minimize the transient congestion by ensuring an efficient distribution of traffic across all possible routes given a particular origin-destination profile by the vehicles entering the highway system (Rao and Varaiya, 1994). An important characteristic about this layer is that the system is modeled as a capacitated graph. Eskafi (1996) provides a description about the modeling characteristics and simulation of this roadside control layer.

---

[10] It refers to the vehicle's serial identifier (i.e. license plate number), its type (bus, private car, emergency vehicle, etc.), origin and destination.

In summary, the network layer allocates the route vehicles should follow to reach their destination, the link layer assigns the path, platoon size and speed for each highway and vehicle type, the planning and coordination layer selects which maneuvers to execute in order to follow the assigned path safely in cooperation with neighbor vehicles finally the regulation layer implements the maneuver by means of the physical layer of the vehicle.

2.4 Platooning

A platoon is simply a cluster of vehicles traveling at close range (intra-platoon spacing of 1-2 meters). On the other hand, inter-platoon spacing is large, on the order of 60 meters (Varaiya, 1993). In the AHS architecture, platoons are the basic unit of automation, they hold the key to increase capacity on current highways. Estimates on the actual capacity increase range from factors of 2 to 6 over current peak capacities.[11] A platoon is divided in two parts, the *leader* or front vehicle and the *followers* which operate under coordinated behavior to performs any activity instructed by the roadside controller (see Figure 2.2 for a description of platoon characteristics).

In addition to platooning, other alternatives were evaluated by PATH to obtain larger traffic flow rates. Concepts like multi-vehicle pallets uniformly spaced and entrainment were deemed as alternatives. However, the use of multi-vehicle pallets was considered impractical and harmful to the environment by potential delays in both loading and unloading of vehicles (General Motors, 1982). The next alternative, entrainment, has similar properties to platooning, however, the mechanical coupling of vehicles could cause substantial delays at entry point due to vehicle sorting in search for

---

[11] Peak highway steady state capacities for manual driving range from 1800-2200 vehicles/lane/hour.

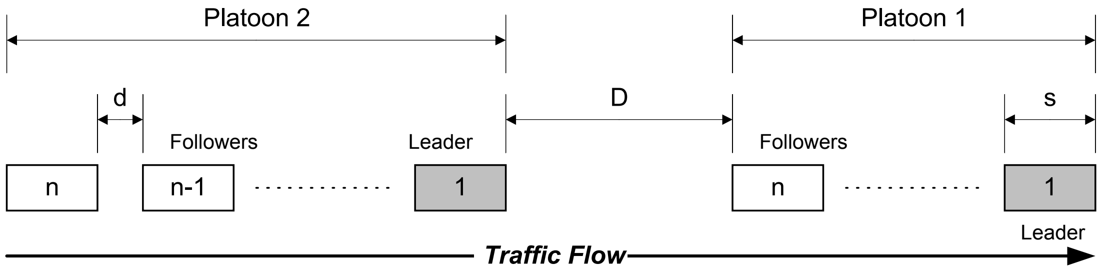

Figure 2.2: Platoon Characteristics.[12]

a common destination. In addition, some rider discomfort could occur from inadequate coupling and the psychological aspect of riding at very close inter-vehicular spacing eliminated entrainment as a viable option (Fenton, 1994). Conversely, these concerns, although similarly applicable to platoons, can be resolved by the extensive and coordinated use of control systems and communication technologies. Currently, platooning and uniform spacing vehicles are the most probable alternatives for deployment. The advantages in capacity, environmental cost and arguably safety that platooning may bring to the transportation network as a whole greatly overcomes the considerable requirements in infrastructure needs. From comparisons between equations (2.1), free agents and (2.2), platooning it is easily appreciated the flow, ϕ [vehicles/lane/hour] gains by operating in platoons over free agents or uniform-spaced vehicles.[13]

$$\phi(d) = 3600 \cdot \frac{v(d)}{d + s} \qquad (2.1)$$

---

[12] Where ‘d’ represents the inter-platoon spacing, ‘D’ = intra-platoon spacing, ‘s’ = vehicle length (uniform vehicle lengths across all highway sections is assumed) and ‘n’ is the number of vehicles per platoon.

[13] See Figure 2.2 for a full description of the terms used in the equations. Appendix A also offer a complete glossary of the terms used throughout this research paper.

$$\phi = 3600 \cdot \frac{v \cdot n}{n \cdot s + (n-1)d + D} \tag{2.2}$$

As the number of vehicles in the platoon increases and the inter-vehicle separation decreases, the flow increases significantly. If we take s = 5m, v = 20 m/s (~72 km/hr), D = 30m and d = 30m, with a 1 car platoon (n = 1, same as free agent) the flow approaches the current highway capacity of approximately 2050 vehicles/lane/hour. In contrast, with a fully functional platoon architecture the capabilities change dramatically. If for example, the inter-vehicle distance is taken as d = 2m, the intra-platoon distance is increased to D = 60m for safety and the number of vehicles in a platoon reaches n = 15, then the flow increases to approximately 6000 vehicles/lane/hour, an almost threefold increase in capacity.[14]

In order to form or dissolve the aforementioned platoons, there are some basic maneuvers and communications that the vehicles must be able to perform. The platoon maneuvers involve longitudinal and lateral control (see Figure 2.3). The control objective is to maneuver a vehicle so as to facilitate its entry and departure from a platoon of vehicles traveling in as automated lane of the highway. Hedrick et al. (1994) identified three basic maneuvers to accomplish such control task:

- Lane Change: The objective during a lane change operation is to maneuver a vehicle from its position at the initiation of the maneuver to a longitudinal position behind the last vehicle of a platoon or other free agent. Subsequently,

---

[14] See Carbaugh et al. (1999) for a comprehensive analysis on capacity and safety with respect to several different platoon configurations.

at the completion of the maneuver, the vehicle must position itself properly to maintain the specified separation distance from the trailing vehicle.

- Merge Procedure: This procedure or activity involves the maneuvering of a vehicle to a position behind or ahead of the platoon such that it is traveling at the platoon speed and maintaining the required intra-platoon distance.
- Split procedure: Finally, the split procedure involves maneuver of a vehicle to a position behind or ahead of the platoon it was member of. At the end of the maneuver, the distance between the maneuvered vehicle and the platoon must be at least the minimum specified inter-platoon spacing.

The vehicles enter the highway as *free agents*, also known as one-car platoons, and when they receive the command (activity) to form a platoon of size ‘n’, the vehicles perform a *join* maneuver. Furthermore, when a vehicle has to change lane, the platoon must perform a *split* maneuver to become a *free agent* and then change lanes. The current design only allows *free agents* to change lanes, so if a vehicle belongs to a platoon, a *split* maneuver is necessary to decouple the vehicles and perform the desired lane change activity. However, this may change in future designs and implementations. In recent years, Godbole and Lygeros (1997) suggested that relaxing this constraint may bring further increases in both safety and throughput. This design is not analyzed here, hence, the claims cannot be validated.

Furthermore, it has been suggested that vehicles traveling in platoons increases safety by reducing the relative velocity between neighboring vehicles (Varaiya, 1993). In the event of a collision, the relative velocity and, hence, the impact energy, is considered a ‘safe’ impact. Its relative velocity is governed by (not considering the aerodynamic drag effect):

$$\delta v = \sqrt{2 \cdot \delta a \cdot \delta x} \quad \text{and} \quad \delta a = a_1 - a_2 > 0$$

where a_1 represents the vehicle deceleration, a_2 the following vehicle deceleration in m/s^2 and δx = d is the intra-platoon distance.

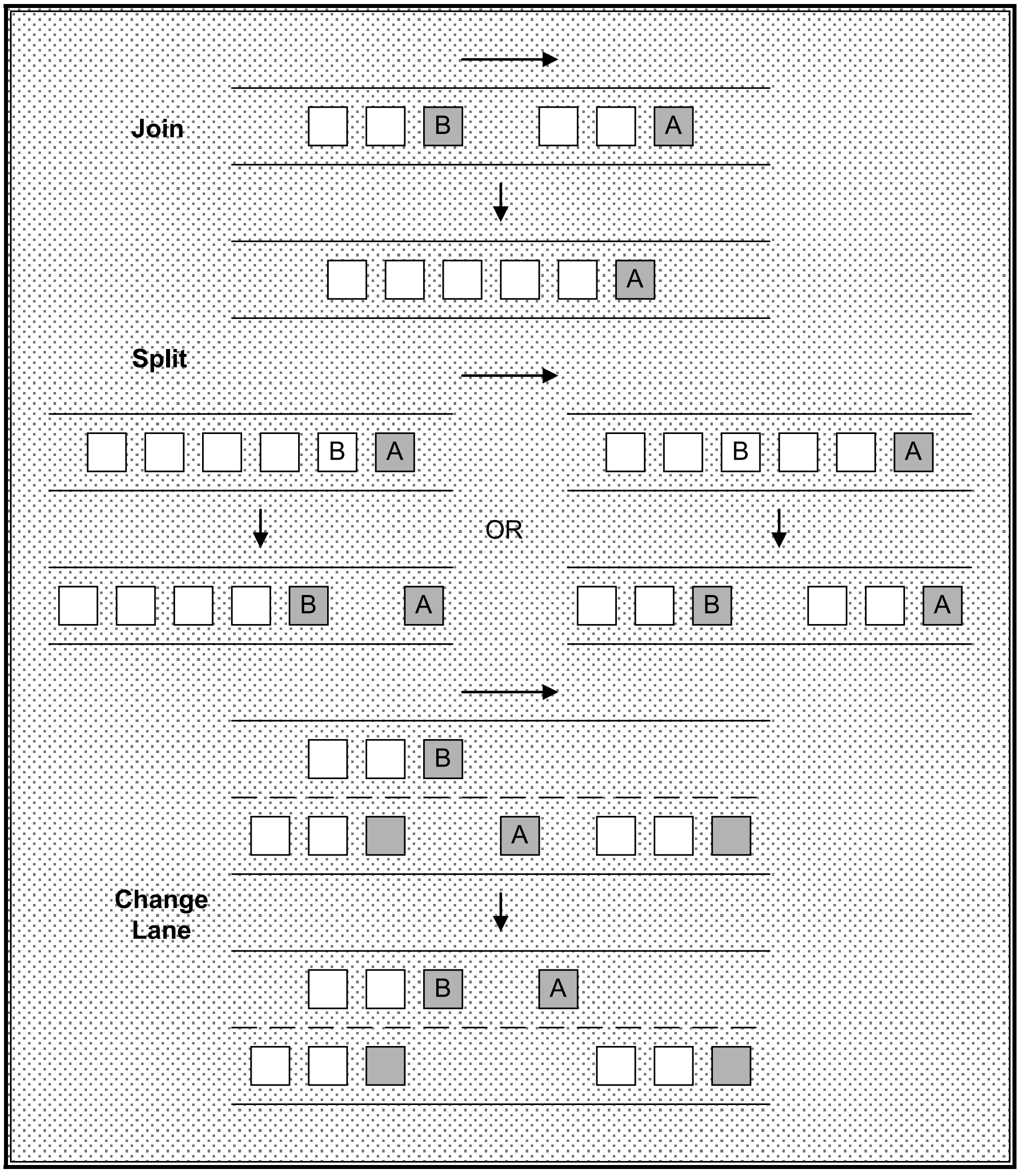

Figure 2.3: Basic Platoon Maneuvers

If, for example, we take $a_1 = 1$g deceleration, $a_2 = 7$ m/s^2 and $\delta x = 5$ m, then, $\delta v = 7$ km/hour which is considered a safe impact velocity.[15] In addition, as a result of such small headways and compact cluster of vehicles the aerodynamic drag is reduced, therefore, fuel consumption and carbon monoxide emissions are lower (Barth and Norbeck, 1996; Zabat et al. 1995). This research has identified the potential for dramatic drag reductions as the vehicle spacing becomes shorter. The vehicle dynamics under reduced drag on different points of the platoons needs further study. Nevertheless, some preliminary studies show drag reduction up to 50% for fuel economy and pollutants which demonstrate some of the significant benefits of this technology.

2.5 Link Layer Controller

As previously explained, the link layer controller as a roadside control layer is responsible for the smooth flow of traffic. A suitable design of the link layer allows the network layer to estimate the capacity of a highway, knowing that up to that capacity level, traffic will flow smoothly along that highway (Rao and Varaiya, 1994). To operate, the controller requires information about the current state of the traffic on each section of the highway. The data at this level of the hierarchy architecture does not distinguishes among individual vehicles on a particular section but operates with aggregates that characterizes the state of that section of the highway. Information such as flow (# vehicles/ hour/ lane) and density (# vehicles/ mile/ lane) is gathered by the layer in order to formulate an appropriate activity plan for the different types of vehicles at each section. A feasible plan is one that conform to a series of constraints regarding the

---

[15] The estimate assumes vehicles under automatic control. Human reaction time (delay) is usually on the order of 250-1200ms and cannot decelerate immediately, therefore, adequate safety is not guaranteed.

physical nature of the highway and desired destination of the vehicles traveling in the highway. To satisfy such constraints, a fundamental part of the layer design is the lane change control. Karaaslan et al. (1991) identified that congestion occurs mainly because of the inhomogeneities in the traffic stream. Therefore, traffic control laws should move load from congested to uncongested sections by means of lane change maneuvers. Rao and Varaiya (1994) identified four important constraints that if met, will produce a feasible activity plan to assign the origin-destination path to vehicles. The constraints are as follows:

1. Vehicles should not miss their chosen exits.
2. Usage of available capacity on the highway should be maximized
3. Lane changing should not result in speed degradation in either lane involved in the maneuver.
4. All other things being equal, paths with shorter travel times are preferred.

However, it is important to note that there is no explicit imposition on the number of lane changes a vehicle can make during its journey. Assuming that flow in all lanes is maintained smoothly, a vehicle will not suffer any additional delays due to lane changes. Nevertheless, unnecessary lanes changes are to be avoided or kept to a minimum for reasons of ride comfort.

2.6 Simulation

To evaluate the benefits of the proposed AHS architecture several tools have specifically been developed to address the difficulties imposed by the resulting hybrid[16]

---

[16] A hybrid systems involves the interaction of discrete and continuous dynamics. A typical system of this class is arranged in hierarchy of two or more layers. In addition, each layer is modeled at a different level of abstraction; at higher layers the description is more abstract.

system. Researchers have dedicated considerable time and resources in fundamental topics such as modeling (Brockett, 1993; Nicollin et al., 1993 and Branicky, 1994) and simulation (Tavernini, 1987 and Deshpande et al., 1997) of hybrid systems. In recent years, one application that attracted considerable attention is AHS. The nature of AHS poses considerable complex control problems. On one hand, higher throughput implies vehicles traveling at higher speeds and closer headway while increased safety requires slower traffic and large spacing. It is this conflicting nature of multiple control requirements coupled with large number of agents[17] trying to make efficient use of a common, scare resource (highway) that makes automated highway systems a formidable challenge for researchers.

The design of controllers of multilayered environments and performance analysis of closed loop systems is a complex and intricate task. Several powerful techniques have been developed for the design of controllers at each individual layer. However, there are no robust analytical tools for predicting and analyzing the performance of the architecture when the individual layers are brought together (Lygeros et al., 1994). It is this gap between techniques and the complex nature of hybrid systems that makes simulation a very important tools, if not indispensable, for the design and evaluation of complex, hybrid systems. Even though simulation can not replace formal proof techniques, either analytical or computational, it can provide valuable insight about the system performance. For examples, a successful experiment under extensive simulation indicates that the design is likely to behave as demonstrated, even though there may be countless other configuration or situations where the system behaves poorly. On the other hand,

---

[17] Refers to individual vehicles equipped with sensing equipment, communication and control capabilities required to operate in an AHS architecture.

unsatisfactory performance on the simulation testbed indicates a design flaw or that is unsuitable for the tested conditions and may suggest alternatives to eliminate the shortcomings. Moreover, simulation results can not be taken as proof that the design performs well in general, but only under specific conditions. More importantly, it can reveal its weaknesses and limitations under other tested conditions.

For the design and evaluation of AHS models, several simulation tools have been developed under different levels of abstraction. There are three major categories in terms of simulation granularity to evaluate the individual and/or the interaction between the different AHS hierarchy layers, namely: macro, meso and more recently, micro-scale simulation modeling tools. Macro-simulators rely on fluid flow models to generate throughput and density information for the highway (Daganzo, 1994). Meso-scale simulators use the same principles and computational efficiency found on fluid flow models to simulate the behavior of individual vehicles (Broucke and Varaiya, 1996). Finally, micro-scale simulators are gaining popularity in recent years with the advances in computing power and the virtual elimination of the human driver proposed by the PATH initiative (see Eskafi and Varaiya, 1992; Deshpande et al., 1997 and Kourjanski et al., 1997b). In the past, the modeling challenges imposed by human driver models made it difficult to obtain accurate micro-simulation results for highway traffic. However, with the elimination or reduction of the role of human drivers in automated vehicles, the problem is reduced and much more manageable. The nature of automatic vehicles is deterministic and behaves as designed. Therefore, more accurate information can be gathered from a simulation at the individual or even at the component level of the vehicle. The reader is referred to modeling tools such as Smart-Path (Eskafi et al., 1992) and SmartAHS (Kourjanski et al., 1997b) for more information in the micro-scale simulation framework.

For the remaining of this research paper, a meso-scale simulator will be used to evaluate the performance of the flow control methodologies presented in chapters 3 and 4. SmartCap (Broucke et al., 1996) is a meso-scale simulator that uses a vehicular flow model discretized in both space and time (Haddon, 1996). The simulator divides the highway into sections and considers the average space that different activities take up in each time-step. The simulator starts with the last section and calculates the space made available by vehicles from the previous section as it works upstream. In addition, it calculates how many vehicles have the necessary space available to move into the current section and finally the velocity in the previous section.[18] The model permits differentiation of discrete activities such as entry, exit, merge, join, lane change, and cruise performed by vehicles. The performance is measured by how the user specified activity profile affects highway productivity. An activity flow model is presented in chapter 3 and the SmartCAP simulation implementation in chapter 4.

---

[18] For more information on the SmartCAP model, see Broucke et at. (1996), Broucke and Varaiya (1996) and Broucke and Varaiya (1997a).

CHAPTER 3
TRAFFIC FLOW CONTROL

Traffic flow modeling at the macroscopic level involves the manipulation of crude traffic information gathered by vehicles as they enter and leave highway sections. The roadside controller process the information and broadcasts control commands to vehicles across all sections. The objective of the link layer controller commands is to ensure smooth traffic flow while maintaining good usage of highway capacity (Rao and Varaiya, 1994). The link layer consists of several control laws and constraints that when satisfied, achieve a feasible action plan for vehicles to follow.

3.1 Activity Based Flow Modeling

According to Broucke and Varaiya (1996), there are two important notions about the theory of traffic flow. One of the notions was introduced by Hall (1995a) where he establishes the concept of *highway service*. The idea is based on the simultaneous use of time and space dimensions on the highway model. The other notion is that of separation of *activities*. Activities are user defined to fit certain profile or investigate traffic behavior. An activity is closely related to a vehicle maneuver, it could represent a single or a set of maneuvers developed to achieve a specific vehicle behavior in a highway. An important corollary of the activity concept is that the overall behavior of vehicles on a highway can be defined by a finite set of activities. An important relationship exists between *highway service* and *activities*; in order to execute an activity, both space and time are needed. This symbiotic relationship imposes the single most important constraint on the theory traffic flow. The combination of activities and highway service dictates that the sum of the total length required by all activities in the highway has to be smaller than the total length of the highway (Alvarez, 1997). Analytically, if we specify that every vehicle must be performing any of the finite activities specified under the user activity profile, the following constraint holds,

$$\sum_{\alpha} \pi(\alpha, i, l, t, \theta) \equiv 1 \qquad (3.1)$$

Each activity proportion is represented by $\pi(\alpha, i, l, t, \theta)$, meaning that some proportion of vehicles type θ are performing an activity α, on section i, at lane l, at time t. Spacing requirements for activities is represented by $\lambda(\alpha, l, l_d \pm 1, \theta)$, the space allocated for activity α performed in lane l into lane $l_d \pm 1$. The number of vehicles in each section of the highway is denoted by $n(i, t, l, \theta)$. The highway section $i \in \{1,...,i_{\max}\}$, the highway lanes $l \in \{1,...,l_{\max}\}$, the activity $\alpha \in \{1,...,n_\alpha\}$ and finally, the vehicle type $\theta \in \{1,...,n_\theta\}$. Consequently, if we separate the activities vehicles perform on each section, the total space required by all activities must be smaller than the length of the section,

$$\sum_{l} \sum_{\alpha} \sum_{\theta} \lambda(\alpha, l, l_d \pm 1, \theta) \pi(\alpha, i, l, t, \theta) n(i, t, l, \theta) \le L(i) \qquad (3.2)$$

In this study the spacing requirement of activities is not dependent on the vehicle type, hence, $\lambda(\alpha, l, l_d \pm 1, \theta) = \lambda(\alpha, l, l_d \pm 1)$.[1] In addition, the section length, $L(i)$ is independent of the highway lane on every section and as a result, $L(i) = L(i, l) : \forall l \in \{1,...,l_{\max}\}$.

---

[1] Since no vehicle mix is used in this study, the vehicle type θ is utilized to represent the vehicle destination along the highway configuration.

To simplify the complex nature of vehicle conservation principles and reduce the number of possible path combinations, two important design considerations compliant with the SmartCAP simulator requirements are established:

- Every activity must be initiated and completed within one simulation time step.
- Secondly, an activity must be performed at each simulation time-step (see Chapter 4, section 4.5 for modeling limitations and possible implications when activities skip an entire simulation time-step).

In order to reduce the transient behavior of complex interactions in the traffic flow, the velocity of vehicles traveling on the same lane should be maintained relatively constant, except of course, when specific time-varying activities are performed (i.e. join), regardless of section or flow type. To achieve a steady-state behavior, it is necessary[2] to guarantee that $v(i,t,l,\theta) = v(i,t,l)$. However, to assure proper execution of activities within a sampling period (also referred as simulation time-step), the following velocity constraint must be satisfied,

$$\frac{\min\limits_{\forall i}\{L(i)\}}{T} \geq v_{\max} \tag{3.3}$$

It is important to note that the constraint restricts the general worst case scenario where $L(i)$ is minimum. On the other hand, in cases where $L(i)$ is not a global minimum, other problems arise when macro or meso-scale performance evaluation tools are used[3]. In the

---

[2] It is a necessary condition buy not necessarily a sufficient condition for steady state behavior.

[3] Refers to the uniformization of vehicles limitation, see Chapter 4, section 4.5.2.

hypothetical highway configuration developed for this work, however, the section length remains constant by design, therefore, further simplifications to the section length notation can be made, $L = L(i) : \forall i \in \{1, \ldots, i_{\max}\}$.

3.2 Vehicles Conservation Principle

Using the aforementioned design considerations, the dynamics of vehicle evolution can be described by the following vehicles conservation law resultant from approximations to partial derivations with respect to time,

$$\begin{aligned} n(i,t+\Delta t,l,\theta) = n(i,t,l,\theta) - n(i,t,l,\theta)(1-\tau(i,t,l,\theta)v(i,t,l)T/L(i) \\ + n(i-1,t,l,\theta)(1-\tau(i-1,t,l,\theta)v(i-1,t,l)T/L(i-1) \\ -\tau(i,t,l,\theta)n(i,t,l,\theta) + \tau(i,t,l-1,\theta)n(i,t,l-1,\theta) \\ +\tau(i,t,l+1,\theta)n(i,t,l+1,\theta) + f(i,t,l,\theta) - g(i,t,l,\theta) \end{aligned} \tag{3.4}$$

The term $\tau(i,t,l,\theta)$ represents the proportion of vehicles leaving lane *l* due to a lane change activity. Similarly, the terms $\tau(i,t,l \pm 1,\theta)$ depict the proportions of vehicles changing lanes from *l*+1 and *l*-1 to lane *l*. Finally, $f(i,t,l,\theta)$ and $g(i,t,l,\theta)$ represent the inflows and outflows from highway ramps, respectively, between the time period *t* and $t + \Delta t$. The vehicle conservation equation as stated in (3.4) once constrained by (3.1) and (3.2) is used to model the vehicle evolution through the automated highway, in essence, the traffic flow is governed by vehicle conservation principles.

On a platooning architecture the same principles apply. However, there is additional information that needs to be tracked to provide sufficient time-steps to split platoons into free agents in order to make a lane change and subsequently take the designated off-ramp to exit the highway.[4] In addition to tracking the number of vehicles in each section every simulation time-step, the number of platoon *leaders* and *followers* are recorded. At the beginning of a time-step vehicles that can become leaders on the next period are performing one of the following activities α : *leader, split, lane-change, ahsentry* or *ahsexit*. Similarly, followers are vehicles performing one out of two possible activities, either *follow* or *join*. Additional information on classification and description of activities is provided in chapter 4. Moreover, by implementing the vehicle conservation laws to track leaders and followers, the resulting conservation equation can be written as:

$$\sum_{\alpha = S_1} n_\alpha (i,t) = \sum_{\alpha = S_2} \eta_\alpha (i,t') \qquad (3.5)$$

for leaders, where the summation of $n_\alpha (i,t)$ represents the number of vehicles performing a maneuver or activity $\alpha = S_1 \in \{$*leader, join, lcleft, lcright, ahsentry, ahsexit*$\}$ which starts as a *leader* while the right hand side of the equation adds the number of vehicles which end up as leaders after the previous time-step, $\eta_\alpha (i,t')$. The activities related to the latter are included in the discrete set $S_2 \in \{$*leader, split, lcleft, lcright, ahsentry, ahsexit*$\}$.

For *followers*, the alternatives are more limited, the vehicle can either continue to *follow* or initiate a *split*. Given the nature of the activity and position within a platoon, the PATH design does not permit any other type of maneuver. The conservation equation is as follows:

$$n_{follower}(i,t) + n_{split}(i,t) = \eta_{follower}(i,t') + \eta_{join}(i,t') \qquad (3.6)$$

---

[4] Reminder: Vehicles can perform only one activity per time-step. Furthermore, only free agents can change lanes.

By definition, a *follower* cannot *join* since it has already performed that maneuver to *join* with the vehicle in front, hence, becoming a *follower*. As a result, two leaders are involve in a *join* maneuver, one will become a *follower* and the other will lead a larger platoon. In case of a split activity, the platoon leader must perform only the leader maneuver while the *split* maneuver takes place. If the *split* occurs behind the leading vehicle, the leader will become a free agent and be allowed to change lane or exit the highway when it reaches its destination.

To ensure every vehicle reaches its proper destination, it is important that vehicles become free agents on time to perform an exit maneuver when needed. Therefore, every follower with a vehicle of the exiting type immediately in front of it must perform a split maneuver. The number of splits required, in cases where more than one vehicle in the platoon needs to exit, is simply given by the number of exiting vehicles. Since each activity requires a time-step to complete and in turn, a highway section, plus any lane changes required, appropriate planning is required to broadcast a successful sequence of activities. Since the model does not keep track of individual position of vehicles on a platoon or on the highway[5], the position of exiting vehicles on a platoon is statistically determined. For example, the probability that a vehicle in front of a given vehicle has a destination θ is just $n(\theta)/n$, where n is the total number of vehicles irrespective of its destination. Additionally, to calculate the number of *follower* vehicles that must perform a *split* maneuver because of an exiting vehicle in front is given by,

$$\frac{n(\theta)}{n}[n_{followers} - n_{followers}(\theta)] \qquad (3.7)$$

---

[5] Property (or limitation) of macro and meso-scale traffic flow models. For more modeling limitations at this abstraction level see Chapter 4, section 4.5.

3.3 Lane-routing Strategies

There are essentially two schemes proposed for lane-routing on an AHS architecture: centralized (Medanic et al., 1995) and decentralized (Rao and Varaiya, 1994; Jong-kwon Lee and Ju-Jang Lee, 1997). A centralized strategy refers to a global lane assignment where a vehicle is assigned a lane to occupy for most of the trip. On the other hand, a decentralized lane-routing scheme is associated with local path planning where vehicles can adjust according to the dynamic and often unpredictable highway conditions (i.e. accidents). Jong-kwon Lee and Ju-Jang Lee (1997) demonstrated through simulation outputs that in order to achieve the level of 'intelligence' required to realize the potential capacity benefits an AHS architecture, a global lane assignment strategy was insufficient and therefore, a decentralized scheme is necessary. A centralized strategy alone proved to be unsatisfactory, except in cases or low traffic volume (clearly not in conformity with AHS design objectives).

Consequently, this work uses a decentralized routing scheme compatible with the SmartCAP (Broucke et al., 1996) model. The algorithm operates on each section locally, it serves only to recommend an activity (i.e. lane change) on a particular section i of the highway instead of formulating the complete path for a vehicle to follow from on-ramp to off-ramp. This helps alleviate the computational complexity of calculating the cost associate with the different path combinations. In fact, there are $i_{\max} \cdot l_{\max} \cdot n_{\alpha} \cdot n_{\theta}$ different equations of the form of (3.4) if all possible combinations of sections, lanes, activities and flow types (used as destinations) are considered.

Lane changes are instructed as vehicles approach their destination and to balance the use of highway capacity. However, lane changes are kept to a minimum to reduce inhomogeneities in the traffic stream which, in turn, disrupt the stabilization of vehicle velocities in downstream sections. In a highway entrance section, the velocity of *i*, *l* and *i*+1, *l*+1, has to be calculated simultaneously since both sections "compete" for space-time on the section *i*+1, *l* (see Figure 3.1). The free space in that section is given by $S(i+1,t,l)$ and comes from the upstream space, $S_U(i,t,l)$ from vehicles moving from section *i*, *l* to *i*+1, *l* and a second move up space from section *i*+1, *l*+1 to *i*+1, *l*. Given the velocity $v(i,t,l)$ the up space is described by,

$$S_U(i,t,l) = S'(i,t,l,l_d)v(i,t,l)\frac{T}{L(i)} \tag{3.8}$$

where,

$$S'(i,t,l\pm 1,l_d\pm 1) = \sum_{\alpha}\sum_{\theta}\lambda(\alpha,l\pm 1,l_d\pm 1)\pi(\alpha,i,t,l,\theta)n(i,t,l,\theta)$$

As a result,

$$S(i+1,t,l) = S_U(i,t,l) + S'(i+1,t,l+1,l_d)v(i,t,l)\frac{T}{L(i)} \tag{3.9}$$

For an exit section, the space calculation is computed in a similar fashion. It is assumed that the velocities in the exiting section, *i*, *l*+1 and the next regular section *i*+1, *l* are known. Consequently, the free space in section *i*+1, *l* is simply calculated by the normal section transition equation given by,

$$S(i+1,t,l) = L(i+1) - S'(i+1,t,l,l_d)[1 - v(i+1,t,l)\frac{T}{L(i+1)}] \tag{3.10}$$

In case of the exiting section, the free space is given by $S(i,t,l+1)$, while the lateral space from section i, l to the exit, i, $l+1$ is calculated from,

$$S(i,t,l,l+1) = S'(i,t,l,l+1)v(i,t,l)\frac{T}{L(i)} \tag{3.11}$$

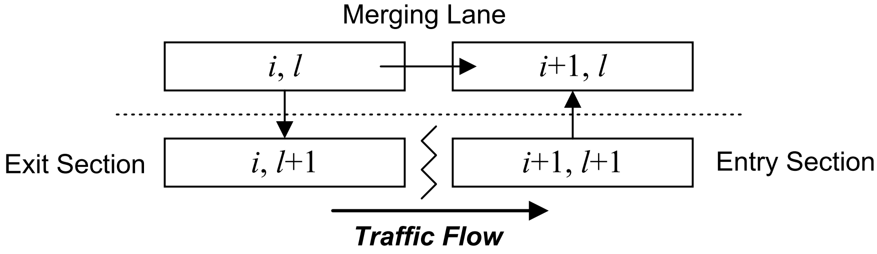

Figure 3.1: Entry-Exit Section Representation

In addition, as part of the controller functional requirements, communication needs are imposed by the controller which can be locally identified by the current section being described. From its own sensors, communication of average speed in each section per lane, average density per section per lane and activity proportions are seen by the controller. From the upstream section, the average density per section on each lane and activity proportions of vehicles that stay in the current lane per section per lane is communicated. Furthermore, from the downstream section the average speed in each lane is broadcasted.

Summarizing, the amount of information transmitted increases as the section look-ahead[6] is amplified. It is evident that information that needs to be transmitted between sections is at most $l_{\max}$ numbers for the average speed per lane. Moreover, since

---

[6] Look-ahead refers to the number of upstream sections in which information is requested in order to evaluate the activity proportions profile on the current section.

the section information is transmitted independently and locally, the information can be broadcasted asynchronously. However, this distributed and asynchronous nature in the controller produces traffic behavior which is almost unpredictable and difficult to describe analytically. As a result, to verify the operations and behavior of an activity based flow model a meso-scale simulator, SmartCAP (Broucke et al., 1996) is used. Chapter 4 further discusses the main issues regarding the model implementation, activity profile, boundary constraints and important model limitations.

CHAPTER 4
SMARTCAP SIMULATOR

The SmartCAP meso-scale simulator is introduced. This chapter presents the main aspects of the flow control methodology with respect to the design of a SmartCAP model. The simulator operates by breaking down vehicle actions into maneuvers (activities) and calculates the performance based on the action instructed by the activity profile in conjunction with the Traffic Management Control (TMC) which dictates the behavior of each vehicle type in each section and finally the velocity-entry plan, responsible for regulating entry rates of vehicles to the on-ramp and velocity control on each section. In addition, main characteristics, limitations and modeling assumptions are introduced.

4.1 The SmartCAP Model

The SmartCAP model is composed of three main areas, the input data file, the activities specification and the TMC controller specification. In addition to controlling the different activities the vehicle types perform along each section, the TMC regulates two important aspects of the highway behavior, the velocity plan and the entry plan. In conjunction they constitute the SmartCAP model. The following sections describe the main areas of the simulator with space-time derivations, boundary conditions and platooning characteristics.

4.1.1 Activities

The actions and distinct maneuvers are represented by activities in the simulator. It is required that vehicles perform a finite number of activities and no vehicle performs more than one activity at a time. Each activity requires certain amount of highway space and time. Space-time is the basic unit used by SmartCAP and it is defined as the integral of space with respect to time.

$$\lambda(\alpha) = \int_{0}^{T} x(t)dt$$

The simulator uses space-time curves for all its calculations. Furthermore, each activity can have its own unique spacing requirements according to vehicle characteristics (vehicle type) and velocity.

On a free agents architecture, the activities are simple and easily defined. The activities can be defined as follows:

- Cruise: This is a lane keeping activity. Vehicles perform this activity for most of the trip while staying in its assigned lane.
- Lcright: This is a lane change activity. The vehicle engages on a right lane change maneuver.
- Lcleft: The vehicles engages on left lane change maneuver.
- Ahsentry: Vehicles enter the AHS.
- Ahsexit: Vehicles leave the AHS.

During the *cruise* activity a safe distance needs to be maintained. To maximize highway capacity, the vehicles should use the minimum safe distance between adjacent vehicles. To define the minimum safe spacing, the game-theoretic approach by Lygeros, Godbole and Sastry (1996) is used. Monte-Carlo simulation runs on a micro-scale simulator, Smart-Path (Eskafi and Varaiya, 1992) is used to determine the spacing requirements for maneuvers. The minimum safe distance is defined as the distance which results on a zero relative velocity collision. As a result, the average spacing required is simply the summation of spacing between vehicles and the vehicle length through a period of one simulation time-step.[1]

In case of lane changes, the situation is more complex. The *cruise* activity occupies space only on the traversing lane. During a lane change, an entry, or an exit maneuver, the vehicles take space in the current and target lane. For safety reasons, no other vehicle can be within the spacing requirements range of the vehicle initiating a lane change maneuver before the activity begins (see Figure 4.2). The space-time is dependent upon the amount of information the vehicles can share. As information bandwidth increases, vehicles have more updated information about the surrounding vehicles and as a result, can initiate the maneuver closer to adjacent vehicles and use the scarce highway space more efficiently. The amount of time for the vehicle to move between lanes, however, will remain the same (see Table 4.1 for minimum spacing requirements for activities of free agents with different communication capabilities traveling at a top speed of 30 m/s). If adjacent lanes have different average speeds, then extra time is needed for the vehicle to adjust to the desired speed (either slow down or speed up[2]). As noted by Broucke and Varaiya (1997a), if we take the speed of the current lane to be v_c and the destination lane $v_d \leq v_c$ and the deceleration of vehicles $-a$, then the additional space

---

[1] SmartCAP restricts to one activity per vehicle per time-step. Therefore, it is assumed the vehicle performs the cruise activity during the entire duration of the simulation time-step.

[2] It is assumed that the coordination policy of automated travel is that faster lanes slow down to accommodate slower incoming vehicles and faster vehicles slow down in their starting lane to enter a slower lane (Broucke and Varaiya, 1997a)

required to decelerate on the current lane is $\frac{(v_c - v_d)^2}{2a}$ [meters] for a period of $\frac{(v_c - v_d)}{a}$ [seconds]. Assuming that a lane change maneuver takes λ_c [m-sec] in the current lane and λ_d [m-sec] in the destination lane when the speed are the same, then the space–time including lane speed differential for a right lane change is

$$\lambda(lc) = \lambda_c + \frac{(v_c - v_d)^3}{2a^2}, \; \lambda_r(lc) = \lambda_d$$

We denote λ_l (λ_r) to represent the space used in the adjacent left (right) lane for vehicles that engage on a left (right) lane change maneuver. Every time a vehicle engaged on an activity (α) leaves a section, its corresponding $\lambda(\alpha)$ space is made available to another vehicle from the upstream section. It is in this manner that the SmartCAP model captures the effect of queueing throughout the simulation run.

Table 4.1: Minimum Safe Spacing Requirements for Free Agents

Free Agent Concepts	Lane	Cruise	Lane Change Right	Lane Change Left
Limited range detection information	Self	47	47	47
	Left	0	0	47
	Right	0	47	0
Range detection and warning information	Self	40	16	16
	Left	0	0	40
	Right	0	40	0

For a platooning architecture, more activities are needed to distinguish vehicles depending on their role on the platoon and perform activities that are unique to platooning. The following activities are identified by PATH for platooning organization analysis:

- Leader: The first vehicle in a platoon. It is important to make a distinction in order to determine the vehicles that can initiate a join maneuver. Only leaders and free agents (considered a 1 car platoon leader) can perform a join maneuver.
- Follower: A vehicle that occupies any other position in a platoon. A unique characteristic of followers is that they can perform a split maneuver in order to become free agents or leader of the resulting platoon.
- Join: A leader vehicle accelerates to become a follower of the platoon in front.
- Split: A follower vehicle decelerates to become a leader of its own platoon. Subsequently, the vehicle can become a free agent and perform a lane change activity.

The following activities share the same characteristics as the free agents architecture:

- Lcright: The vehicle changes lanes to the right.
- Lcleft: The vehicle changes lanes to the left.
- Ahsentry: The vehicle joins the automated highway system.
- Ahsexit: The vehicle leaves the automated highway system and switched to manual driving.

The spacing requirements for *leaders* are calculated in the same manner as free agents performing a cruise activity. However, considering that the severity of failures resulting in an accident are far greater for a platoon organization (platoon collisions will involve multiple vehicles), a conservative approach is taken[3] (see Table 4.2 for minimum safe spacing requirements consistent with the parameter used for this study).

The *follower* activity is unique to platoons and it is a relatively simple activity to describe. It has been suggested that an intra-platoon spacing between 1-2 meters is a feasible and safe proposition given the current technological abilities and communication specifications by the PATH program (Ioannou, 1997). For this study, a constant distance of 2 meters is to be maintained behind the vehicle in front on a platoon. As a result, there is a 2 meters average space requirement in addition to the vehicle length.

The *join* and *split* maneuvers are also unique to platoon organizations. These maneuvers have opposite objectives, however, their analytical derivations are equivalent.[4] These activities are more complex that any other aforementioned maneuver, its spacing requirements are time-varying The *join* maneuver, for example, starts with the same space requirements as a leader activity and ends up with the same space as a follower. For this study, the laws governing these maneuvers were proposed by Frankel et al. (1996). The methodology uses a conservative approach and takes safety as the primary design goal.

Finally, the remaining maneuvers are not exclusive to platooning and share the same properties with their free agents counterpart. Since the PATH architecture requires that only free agents are allowed to change lanes, the lane change activities are comparable to those individual vehicles perform. To determine the proper space-time

---

[3] The vehicle dynamics on a platoon organization are complex. The intra-platoon collision effects are still being investigated, therefore, a conservative approach is used for the minimum safe inter-platoon distance. A combination of intricate technical and policy issues must be addressed.

[4] Haddon (1996) offers a complete space-time derivation for these maneuvers.

requirements for the lane change maneuver under automatic control, the lane changing logic deduced by Kourjanski et al. (1997b) is used.

Table 4.2: Minimum Safe Spacing Requirements for Platoon Activities

Platoon Organization						
Lane\Activity	Lead	Follower	Join	Split	Entry	Exit
Self	61	2	37	37	30	60
Left	0	0	0	0	61	0
Right	0	0	0	0	0	61

The lane change maneuvers dictated by the link layer controller are executed provided there is enough space-time available on the adjacent target lane. The total space-time needed for the lane changing maneuver involves the headway of car-following behavior on the current lane and the aforementioned velocity differential function in the adjacent lane (see Figure 4.1). As indicated in Haddon (1996), it is assumed that the entire maneuver takes 7.08 seconds.

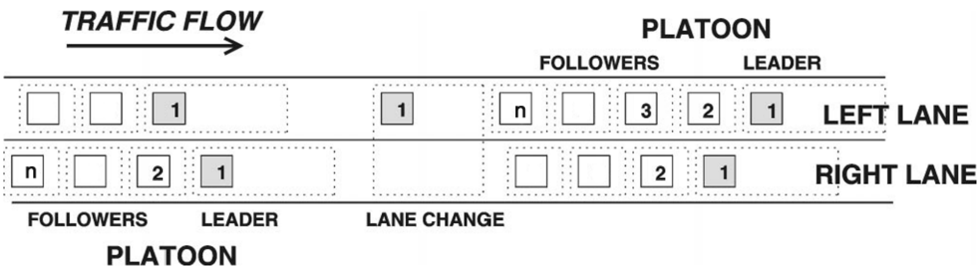

Figure 4.1: Sketch of Activity Spacing Requirements[5]

---

[5] The spacing depicted by the lane change maneuver assumes equal speeds on the current and target lanes ($v_c = v_d$) Therefore, the space requirement in this case have zero speed differential and can be defined as a function of constant gap headway and vehicle length, $D_d = h_g + s$.

4.1.2 Traffic Management Control

The TMC plan is the algorithm which specifies the behavior of each vehicle type at every section. Its purpose and objectives are analogous to the link layer controller. The policies described in chapter 3 are designed to reduce inhomogeneities in the traffic stream, thus, improving flow and minimizing traffic congestions. The TMC plan is divided in three main areas that in combination controls traffic behavior. The first, velocity plan, controls the desired velocity at each section of the highway; the entry plan regulates the rate at which vehicles enter the highway at each available on-ramp and finally, the activity plan,[6] controls and evaluates the different activities vehicles perform every simulation time-step.

The velocity plan and entry plan share a common operation policy. The SmartCAP simulator uses a greedy policy to calculate the optimal velocity at each section. As a result, every section will achieve the highest possible velocity without exceeding the maximum velocity bounds and overflowing the downstream section. The velocity calculation starts downstream and moves upstream until it covers all sections. The calculation is as follows,

> If we define $\rho(i,t) = 1 - v(i,t)T/L(i)$ to represent the proportion of vehicles in section *i*, at time *t* that remain in that section for time $t + 1$. Then, $[1 - \rho(i,t)]$ is the proportion of vehicles in section *i* at time *t* that leave the section at the end of the that period. Subsequently, the free space in the downstream section is given by the space available made by cars that have move out of that section.

---

[6] The activity plan is explored in detail in chapter 3. The interested reader is referred to Broucke and Varaiya (1996, 1997a) for more information on activity plans, entry and velocity plans.

$$
\begin{aligned}
S_{free}(i,t) = L(i)T \\
&- \sum_{\alpha}\sum_{\theta} n(i,l,\theta)\pi(\alpha,i,l,t,\theta)\lambda(\alpha)[1-\rho(i,t)] \\
&- \sum_{\alpha_r}\sum_{\theta} n(i,l+1,t,\theta)\pi(\alpha,i,l+1,t,\theta)\lambda_r(\alpha)[1-\rho(i,t)] \\
&- \sum_{\alpha_l}\sum_{\theta} n(i,l-1,t,\theta)\pi(\alpha,i,l-1,t,\theta)\lambda_l(\alpha)[1-\rho(i,t)]
\end{aligned}
$$

Next, the space used by vehicles upstream and incoming via entrances into section *i* is needed. The speed of vehicles arriving from the upstream section is $v(i-1,t)$ and at time *t*, section *i*-1 the vehicles continue with the prescribed activity plan. Assuming the vehicles are traveling at the maximum allowable velocity $V = v_{\max}$, the space taken by upstream is given by,

$$
\begin{aligned}
S_{up}(i,t) = \\
&\sum_{\alpha}\sum_{\theta} n(i-1,l,t,\theta)\pi(\alpha,i-1,l,t,\theta)\lambda(\alpha)\frac{TV}{L(i-1)} \\
&+ \sum_{\alpha_r}\sum_{\theta} n(i-1,l-1,t,\theta)\pi(\alpha,i-1,l-1,t,\theta)\lambda_r(\alpha)\frac{TV}{L(i-1)} \\
&+ \sum_{\alpha_l}\sum_{\theta} n(i-1,l+1,t,\theta)\pi(\alpha,i-1,l+1,t,\theta)\lambda_l(\alpha)\frac{TV}{L(i-1)}
\end{aligned}
$$

The method for finding the space-filling velocity uses backward recursion through all section. Finally, to compute $v(i,t)$, once the downstream is filled, the function $\gamma(i-1,t) = \min\{1, S_{free}(i,t)\cdot P_1(i)/S_{up}(i,t)\}$ is defined[7] in order to obtain $v(i-1,t) = \gamma(i-1,t)V$.

Similarly, the entry flows defined by $S_{in}(i,t)$ employs an analogous greedy policy comparable to the expression for incoming space taken by vehicles moving from the

---

[7] $P_1(i)$ is defined as the percentage of available space that can be used by upstream vehicles and $P_2(i)$ the percentage used by the entry flow, where $P_1(i) + P_2(i) = 1$ and $S_{in}(i,t) = P_2(i)\,S_{free}(i,t)$.

upstream section. In the simulation, the entry rate for each flow type are defined as a function of time. At the initialization phase, the number of vehicles, velocity and activity to perform are specified. In addition, the metering policies of the entry plan begin regulating incoming flow to the highway. For the interested reader, more information on entry and exit plans can be found on Broucke and Varaiya (1996).

4.2 Boundary Conditions

The boundary conditions of the simulation are defined by the SmartCAP input data file (see Appendix B). Boundary conditions refer to constraints due to the highway structure, periphery of simulation portion, traffic system interface and simulation parameter conditions. The physical constraints are given by the highway layout or topology described below.

4.2.1 Highway Topology

The simulator uses a highway representation based on connecting sections Each sections can take any length and some predefined shape (line, arc or u-shape), in this case 500 meters straight each, and can take irregular section values if the design requires it. The section length is denoted by $L(i)$, where i represents the downstream section of i-1. The boundary conditions at periphery of simulation portion are required at all entrances and exits of all lanes modeled (Rao and Varaiya, 1994). These include entrances and exits to lanes and also on-ramps and off-ramps that interface the highway to the rest of the traffic system. An hypothetical highway configuration is used in this study that represents a regular 2-lane 15 km, 500 meters per section, freeway corridor with 2 on-ramps and 3 off-ramps spaced at 5 km intervals (Figure 4.2). It is assumed that the highway is equipped with all the necessary technologies for full AHS operation (refer to Chapter 2 for more information).

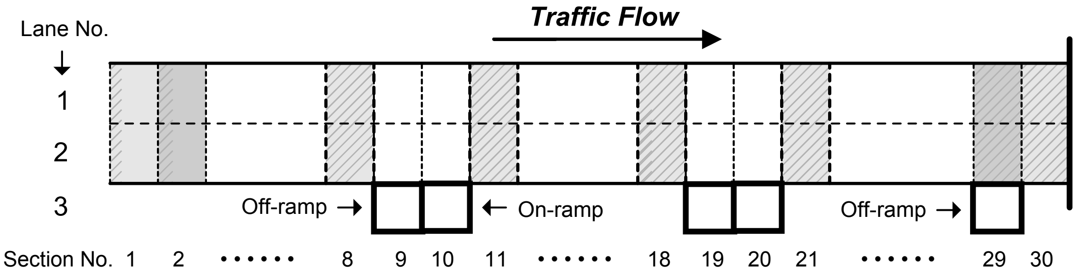

Figure 4.2: Highway Topology

The alternating configuration on-ramps and off-ramps is based on the design by Rao and Varaiya (1994). In general, this may not be the case of a real highway configuration, where several exits could be in succession before an entrance is found and vice-versa. Nevertheless, the control laws and spacing requirements are equally valid and could be easily modified to model more general scenarios.

4.2.2 Traffic System Interface

For this study, the boundary conditions are similar to the ones stated in Karaaslan, Varaiya and Walrand (1991). A flow, $\phi_{l,1}(t)$ is introduced on each lane of the first highway section and a stationary boundary condition at the final simulated highway section of each lane is assumed. Hence, the following condition apply:

First highway section: $\phi_{l,i-1}(t) = \phi_{l,1}(t)$

Last highway section: $k_{l,i+1}(t) = k_{l,i}(t)$
$v_{l,i+1}(t) = v_{l,i}(t)$

Similarly, the same assumptions apply to the ramps, a prescribed flow, $\phi_{on,r}(t)$ is applied to the on-ramp *r*, and a stationary boundary condition to each off-ramp. Consequently, there is no constraint to the exit of vehicles from the highway and as a result, no queue build-up occurs. Conversely, at the on-ramps, a queue will form in cases where demand exceeds highway capacity. A *greedy* policy of on-ramp metering is used to issue commands to the corresponding coordination layer and allow access to the highway when the spacing requirements are met.

On-ramps: $$\phi_{l_{\max},l_{\max}-1,i}(t)=\phi_{on,r}(t)$$

Off-ramps: $$k_{l_{\max},l_{\max}+1,i}(t)=k_{l_{\max},i}(t)$$
$$v_{l_{\max},l_{\max}+1,i}(t)=v_{l_{\max},i}(t)$$

4.2.3 Simulation Parameters

For every simulation run, the following fix parameters were set:

Table 4.3: Simulation Parameters

Parameter	Value
$i_{\max}$	30 sections
$l_{\max}$	2 lanes
L_i	500 m
$v_{\min}$	10 km/hr (2.77 m/s)
$v_{\max}$	108 km/hr (30 m/s)
$\phi_{l,1}(t)$	3000 vehicles/hr
$\phi_{on,r}(t)$	1000 vehicles/hr
T	16.5 s
D	61 m
d	2 m
s	5 m

4.3 Modeling Assumptions

Modeling a complex system usually involves conflicting objectives, to establish a reasonable balance between model complexity, simulation runtime and accuracy, some level of simplification of reality is needed. The goal is to design a model of an experimental system, a link layer controller, that neither oversimplifies the system to the point where the model becomes trivial or even misleading nor where the model complexity outweigh the benefits and contribute little or nothing to the solution or understanding of the problem. The following modeling assumptions were established to provide a standard testbed to carry out performance analyses on the link layer and simplify some of the complexities inherited by the diversity and intricate vehicle dynamics during highway travel.[8]

- Vehicle uniformity assumption: To establish the performance and throughput solely based on the control flow methodology and reduce the effect of other sources, vehicle traffic is modeled using a single vehicle configuration. For a mixed vehicle analysis (cars and buses) on vehicle throughput, see Alvarez (1997). The following vehicle characteristics are used:

  Vehicle Length: 5 meters (16.4 ft)

  Vehicle Width: 3 meters (9.8 ft)

  Maximum Acceleration: 5 m/s^2 (16.4 ft/s^2)

  Maximum Deceleration: -5 m/s^2 (-16.4 ft/s^2)

  Maximum Velocity: 30 m/s (~67 mi/hr)

---

[8] Similar test environments were presented by Rao and Varaiya (1994) and Alvarez and Horowitz (1997).

- The highway start empty at the beginning of the simulation. This assumption reduces the interaction effect of foreign agents during the simulation study. At the beginning of the simulation traffic is introduced at a rate of 3000 vehicles/hour on each lane and 1000 vehicles/hour at the on-ramps using a designated velocity, v_{opt}.[9]
- No collisions or any traffic incidents occur at any point in time. This study intents to show throughput and traffic flow under regular AHS operation and demonstrate its potential to increase highway capacity. For collision effects on highway capacity and flow see Rao and Varaiya (1994) and Jong-Kwon Lee and Lu-Jang Lee (1997).
- The vehicles may change lanes only as free agents (individual vehicles). In addition, when a vehicle is entering or departing a platoon, no other vehicle may do so. This restriction is consistent with PATH norms for platoon operations (see Hsu et al., 1991).
- A *greedy* policy is used to determine the vehicle's velocities at each section. Whenever possible, the highest velocity at each section will be used. The velocity is regulated by a simple constraint that neither exceeds the maximum velocity allowed per section nor overflows the downstream section. The desired velocity will remain under the following bounds:

$$v_{\min} \leq v_{l,i} \leq v_{\max}$$

---

[9] These parameters are introduced for consistency with studies from Karaaslan, Varaiya and Walrand (1991)

- During a lane change activity, it is assumed that vehicles begin the maneuver at the beginning of the simulation time-step. Since SmartCAP imposes the constraint that vehicles can perform only one activity per section, vehicles will occupy space in both current and destination lane[10] for a period of Δt. Subsequently, the remaining time $T - \Delta t$, vehicles will occupy space only on the destination lane. The spacing requirement on the destination lane is assumed to be equivalent to the cruise activity. Consequently, since space on the destination lane is required throughput the entire maneuver, the average spacing requirement on the destination lane is just the space required for the cruise activity, d_{cruise}. Conversely, at the current lane only a fraction $\Delta t / T$ is used, averaging a space requirement of $(\Delta t / T) d_{cruise}$.
- Communication delays that may be present in intra-platoon communications for maneuver coordination and between the roadside controller are assumed to be negligible. The meso-scale characteristics of SmartCAP prevents such low-level behavior.[11] As a result, activities are executed without any normal communication delays and/or message bottlenecks. Nevertheless, it was identified that in order to promote good dynamic platoon response, a 20ms cycle time in information exchange is needed (Ioannou, 1997). Experimentation by PATH showed that this information exchange rate easily

---

[10] See section 4.1.1 for more information on lane change activity requirements.

[11] Micro-scale simulators like SHIFT and SmartAHS (Deshpande et al., 1997) are able to reflect the low-level behavior to reproduce, among other things, communication delays, transmission errors and rate of information exchange.

reproduced using commercial of-the-shelf communication systems equipment (Sachs and Varaiya, 1993).

4.4 Scenarios

To test the performance of the activities and link layer controller in chapter 3, two main scenarios are devised for the study. The first scenario consists of free agents with different capabilities in terms of communication with neighboring vehicles and sensor technologies. The free agents concept is tested with limited range detection (LRD) information and with range detection and warning information (RDW). It is claimed that more bandwidth on communication parameters increases highway capacity. Haddon (1996) and Alvarez (1997) provide scientific research on the subject to support the claim. The former, LRD, refers to vehicles without the ability to communicate with other vehicles but with on-board sensors capable of measuring distance and relative velocity to the vehicle in front. At the next level of communication, RDW, the vehicles are capable of delivering low bandwidth messages in case of emergency maneuvers such as harsh braking or other situation that may benefit from warnings in advance. This capability allows to coordinate certain maneuvers and therefore, smaller distances can be safely maintained between adjacent vehicles.

The second scenario involves platooning and requires a higher communications bandwidth than the free agent alternatives. The vehicles must be able to continuously send acceleration information to the vehicle following it. Thus, each vehicle not only is aware of the distance and relative velocity but it also knows the acceleration of the neighbor vehicle, allowing it to adjust and maintain a close and constant headway to safely operate in compact platoon formations. In addition, the platoon size effect is investigated to provide insight on the highway spacing requirements as the maximum allowable platoon size increases.

4.5 Limitations

As a fluid flow meso-scale simulator, SmartCAP possesses advantages in run-time and is able to isolate and test the performance of specific roadside controller behaviors efficiently. However, given the nature of the simulator, it has some difficulties representing low-level, micro-scale behavior. These limitations are inherited in the model itself and are not specific to any particular implementation that uses the meso or macro-scale simulation granularity. Haddon (1996) identified several noteworthy limitations that should be acknowledged to set valid modeling assumptions and give correct interpretation to simulation outputs. Some important limitations are summarized below.

4.5.1 Uniformization of Free Space

The spacing distribution in SmartCAP presents some limitations. However, these do not present a significant source for unrealistic behavior once it is thoroughly analyzed. The simulator only looks at the available space for a maneuver in the current section and determines if it could be accomplish or not. For example, lets consider a maneuver that takes a constant spacing of 45 meters on a 500 meters section. If 10 cars want to perform that maneuver (activity), 450 meters are required to allow all vehicles to perform the desired activity. SmartCAP makes a uniform distribution of vehicles spacing in each section, therefore, the remaining 50 meters are ‘usable’ for another maneuver. Realistically this may not be the case since the remaining space could be distributed among the traveling vehicles in 5 meters intervals of unusable space. However, small perturbations is speed as the lane changes take place reduce the spacing between vehicles and may allow and eleventh vehicle in the section, even though this behavior is not reflected during the simulation run.

4.5.2 Uniformization of Vehicles

At the beginning of each time step of the simulation, SmartCAP assumes that all vehicles are uniformly distributed. The is a potentially serious problem if section length and time step are not properly set. Consider an example introduced in Haddon (1996), where traffic is moving at 25 m/s on a 1000 m sections and a simulation time-step of 20s is chosen. Traveling at this speed, it would take a vehicle exactly 2 time-steps to complete the section. If for example, an eight cars platoon is traversing a section with no other traffic on the highway, four will move to the next section at the first time-step. All cars will then uniformly distribute within its corresponding section. At the next time-step, two of the cars that just advanced to the next section will move on to the third section, while two cars will still remain on the first section. This process is repeated continuously as they advance to the next sections. Summarizing, the problem is apparent since the vehicles that are suppose to be traveling at the same velocity, take different amount of time-steps to traverse the same number of sections. In the above example, after three time-steps, one vehicle already reached the third section (>3000m) while another vehicle still remains in the initial section.

This problem was first identified by Dr. Kaurjanski and since, several approaches have been proposed to address the issue (as cited in Haddon, 1996, p.25). Unfortunately, none provides a satisfactory solution with no ill side-effects.[12] The most promising approach without moving towards a micro-simulation granularity, and the alternative chosen for this study, involves adjusting the section velocity (*V*), the simulation time-step (*T*) and the section length (*L*) so that all vehicles in one section advance to the next section on a single time-step. This can be accomplished by setting the parameter $VT/L = 1$. The effect reflected by the example[13] above is alleviated or null as the parameter reaches 1. Unfortunately, keeping that relationship constant is not trivial. The parameter *T* is, of course, constant and the maximum speed remains the same along the highway. Consequently, this leaves the section length, *L* which imposes a significant constraint on the construction of the highway. At the hypothetical scenario described for this study, one of the design objectives was to keep the section variability as small as possible. Nevertheless, even with the parameters set accordingly there is no guarantee that the parameter VT/L will remain constant. As more vehicles are admitted into the highway, the probability of congestion increases and inhomogeneities in the traffic behavior will eventually disrupt the section average speed causing the ratio to drop and accentuating the original problem.

On the other hand, if the parameter is incorrectly set so that $VT/L > 1$ at any point in time, it can cause a vehicle to 'skip' a section entirely. This is a potentially more serious problem since the simulator constraints to one activity per section and could cause disruptions on the upstream traffic behavior when vehicles are forced to postpone

---

[12] The interested reader is referred to Haddon (1996) for additional information on the issue and different solution approaches.

[13] Note: In the example given, $VT/L = 0.5$ and therefore, gives raise to the unacceptable and unrealistic behavior described.

the lane-change activities to reach their destination or split platoons to become free agents. Furthermore, it is important to constraint $VT/L \leq 1$, at every section to prevent unexpected behavior that could be mistakenly confused with lack of physical space to perform activities.

4.5.3 Non-linear Approximations

The way the fluid flow model works in SmartCAP is by approximating several non-linear and differential equations that are rather computational expensive to solve without approximations. The simulator starts working downstream and computes the space-time available after the vehicles move to the subsequent section of the highway. The space required for a given activity is usually a function of the velocity at any given section which lead to non-linear behavior. Alternatively, the simulator uses the space calculated from a previous section and estimates the space requirements based on the updated value of the velocity. There is an important inherit assumption about this behavior. The approximations are accurate as long as the velocity do not change radically between sections. Moreover, as the highway traffic flow reaches steady state, the approximations are solutions to the full nonlinear equations.

4.5.4 Arbitrary Parameter Dependence

The behavior of the model is strongly tied to the simulation time-step chosen for a particular run. In turn, accuracy depends on the time-step selected. However, the simulation time-step cannot be reduced below a certain value. SmartCAP imposes a restriction that every activity per section must be performed within one time-step. Therefore, the section length will affect the activities that could be performed within a single time-step. If for example, a vehicle needs to performs two or more activities (or maneuvers) before it can exit, the vehicles will have to traverse at least two sections. Assuming each section is 500 meters in length, the vehicle will have perform the necessary maneuvers on 1 km range before it can exit. If however, the section length is 1 km, the same maneuvers can be spread over a 2 km range. Hence, the behavior of the model depends on the arbitrary selection of a simulation parameter.

CHAPTER 5
RESULTS

Results from the simulation model are presented using Matlab (MathWorks, 1994). The plots present information on the number of vehicles and velocity as a function of time for a given section and lane of the highway. Table 5.1 presents the different flow types used for the scenarios studied. There are seven different flow patterns varying in parameters such as origin, destination, lanes used, vehicle inter-arrival times [seconds], duration of vehicle inflows [seconds] and hourly flow rates [vehicles/hr].

Table 5.1: Flow Type Characteristics

Flow Identifier	Origin		Destination		Ending Time	Arrival Interval [s]	Number of Vehicles	Hourly Flow
	Section	Lane	Section	Lane				
F1	1	1	9	3	1800	3.6	500	1000
F2	1	2	19	3	1800	3.6	500	1000
F3	10	3	29	3	1800	3.6	500	1000
F4	1	1	30	1	3600	1.8	2000	2000
F5	20	3	30	1	1800	7.2	250	500
F6	1	2	30	2	3600	1.8	2000	2000
F7	20	3	30	2	1800	7.2	250	500

The flow identifier varies from F1 to F7 representing each unique flow configuration. The traffic moves downstream on sections $i \in \{1, \ldots, i_{\max} = 30\}$, 1 being the most upstream section and 30 the most downstream. All inflows to the highway start at time 0 until they reach the predefined "Ending Time" expressed in seconds. Similarly, the constant vehicle interarrival times are also express in seconds. The highway flow balance is provided in table 5.2. A total of 8,000 hourly vehicles enter the highway via on-ramps and incoming through traffic from lanes 2 lanes (an average of 4,000 vehicles/hr/lane), a volume higher than double the normal highway throughput. In a manual highway, however, the proposed highway penetration would produce significant delays and poor service level. On the other hand, by calculated on-ramp metering the AHS keeps incoming vehicles flowing at their desired high-speed. The design for the simulated highway is sufficiently long (15 km; refer to Figure 4.2) to accurately represent queue build-up, vehicle dissipation and quantify the effects of the routing policies.

Table 5.2: Entry-Exit Highway Flow Balance

Flows	**Inflows**			**Outflows**			**Flows**
	Section	Lane	Hourly Flow	Hourly Flow	Lane	Section	
F1 + F4	1	1	3000	1000	3	9	F1
F5 + F7	20	3	1000	2500	1	30	F4 + F5
				2500	2	30	F6 + F7
F2 + F6	1	2	3000	1000	3	19	F2
F3	10	3	1000	1000	3	29	F3
	Total Inflows		**8000**		Total Outflows		

5.1 Performance Measures

To compare and evaluate the performance of the concepts described, the average velocity the unmet demand percentage are calculated. The average velocity is weighted by the number of vehicles traveling at the measured velocity,

$$\overline{v}(t) = \frac{\sum_i v(i,t,l)n(i,t,l)}{\sum_i n(i,t,l)}$$

The average velocity on all lanes is calculated and reported. In addition, as introduced by Haddon (1996), the unmet demand percentage measures the proportion of vehicles that could not gain access to the highway during the simulation time. Vehicles are held at the buffer queue at highway on-ramps regulated by metering policies designed to prevent overflows on upstream highway sections. The unmet demand percentage is given by,

$$\psi(t) = \frac{\sum_i q(i,t)}{\sum_i f(i,t)}$$

where $q(i,t)$ represents the number of vehicles on the queue at the on-ramp on section *i*.

5.2 Free Agents

The individual vehicles concept is evaluated under to two distinct communication sharing proposals. Table 5.3 presents the average speeds for the limited range detection and the range detection & warning concept (Chapter 4, section 4.1 provides a detailed description and characteristics about the two concepts). It is clear that automated driving produces high service level, close to a desired uninterrupted flow. As the information exchange increases, vehicles can coordinate maneuvers and communicate driving parameter to increase safety while making more efficient use of highway space, thus increasing throughput and average velocity.

Table 5.3: Free Agents Average Velocity

Concept	Target Speed	Average Speed
Limited Range Detection	25 m/s	24.32
	30 m/s	29.02
Range Detection & Warning	25 m/s	24.79
	30 m/s	29.32

The unmet demand percentage increases as the desired velocity increases. Higher speeds require higher inter-vehicle spacing for safe operation. Therefore, the available highway space becomes limited and scarce, producing longer delays at the on-ramps and as a result, increasing the size of the entrance buffer.

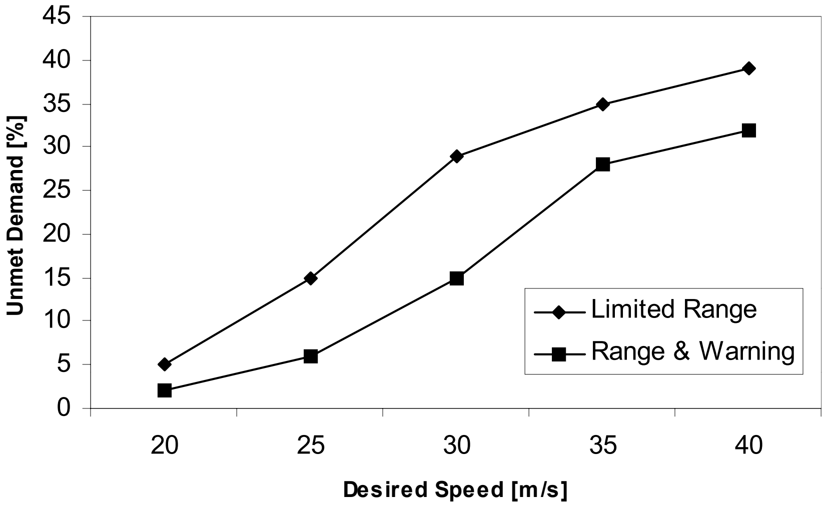

Figure 5.1: Free Agents Unmet Demand

5.3 Platooning

Platooning is a more advanced concept with higher communication and technological requirements. Although free agents are able to achieve average speeds comparable to a platooning architecture (Table 5.4), platoons are able to further increase highway capacity as depicted in figure 5.2. Unmet demand is dramatically reduced, allowing for higher throughput and more satisfactory service level. The platooning concept provides a more elastic response to higher traffic volumes (as highway demand increases the unmet demand increases more slowly than the free agents concept).

Table 5.4: Platoons Average Velocity

Concept	Target Speed	Average Speed
Platoons	25 m/s	24.81
	30 m/s	29.78

Finally, the platoon size effect is comparable with findings by Rao and Varaiya (1994). When lane density is high, “splitting” platoons to free vehicles to perform a lane change produces a cascading effect, decelerating the traffic stream. However, the effect is not noticeable for less than 10 vehicle platoons. In addition, as the maximum platoon size increases the available space to perform maneuvers that occupy highway space in adjacent lanes (i.e. lane change) is significantly reduced. Nevertheless, platoons of 5 to 8 vehicles do not exhibit any noticeable performance degradation.

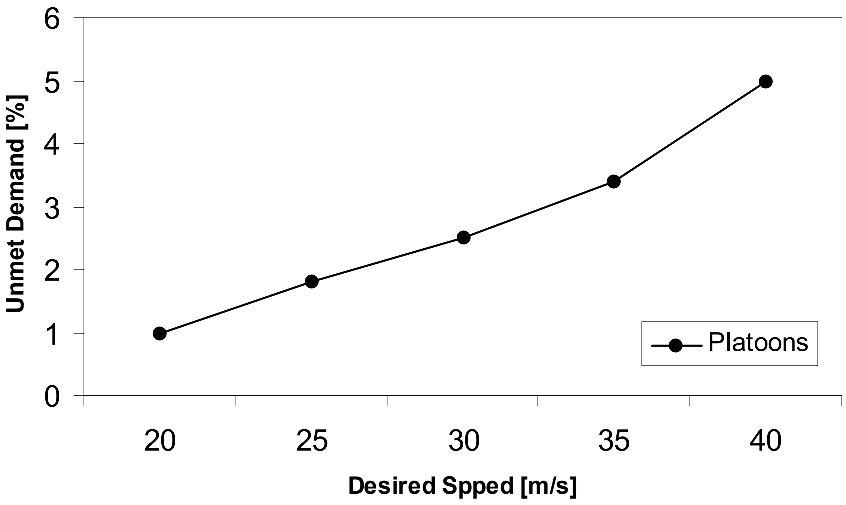

Figure 5.2: Platoons Unmet Demand

CHAPTER 6
CONCLUSION

6.1 Summary

A flow control methodology for multi-lane automated highways was described. The concepts are conforming with the PATH architecture for the design of a roadside link layer controller. The methodology makes extensive use of vehicle conservation laws and activity based flow models to represent the traffic behavior under automatic control on a multi-lane architecture compatible with proposals by the ITS and PATH programs under current development.

The simulation results from SmartCAP are consistent with those of Haddon (1996)[1] and shows the potential of an AHS architecture to increase highway capacity while maintaining a smooth traffic stream virtually free of the inhomogeneities introduced by manual driving that ultimately disrupt the traffic flow creating slowdowns and unnecessary delays. The average velocity measures show that even at high traffic volumes the desired velocity is maintained. The platooning concept in particular shows a high service level, maintaining the desired average speed throughout the entire trip and reducing the queue buffer levels at the highway entrances. Comparing the individual vehicles concepts with platooning it is clear that as the information exchange increases,

---

[1] The analysis presented in Haddon (1996) studies a single-lane highway. Nevertheless, the performance even when lane change maneuvers are permitted on a two-lane topology is maintained by virtue of the activities broadcasted by the link layer controller.

warnings and coordinated maneuvers allows for safe operation of closer inter-vehicle spacing. Consequently, the throughput increases allowing more vehicles/hr/lane to transit the highway while maintaining the safety level constant.

6.2 Future Work

Future works in activity based flow models will involve the extension of the methodology for more complex scenarios of highway designs with three or more lanes, were vehicle path selection becomes increasingly more complex. Additional testing is required on scenarios with mixed traffic involving buses and vehicles with different braking capabilities to develop more robust safety measures and adaptive time headways to accommodate differences in vehicle response when operating under platoon formations or as free agents. In addition, extensions of this work should include analysis on accidents and propose routing schemes to balance the use of available capacity when a lane blocking incident (i.e. an accident) occurs.

APPENDIX A
GLOSSARY OF TERMS

Symbol	Definition
T	Simulation time-step [s]
l	Lane number, 1 being the innermost and $l+1$ moving out
l_d	Destination lane, follows same convention as l
$l_{\max}$	Total number of lanes in highway
i	Highway section, 1 being the most upstream section
$i_{\max}$	Total number of highway sections
t	Time instant t within each time step [s]
α	Activity or maneuver the vehicle is allowed to perform
θ	Flow type, used to denote vehicle destination
D	Inter-platoon spacing [m]
d	Intra-platoon spacing [m]
s	Vehicle Length [m]
$n(i,t,l,\theta)$	Number of vehicles
$\tau(i,t,l\pm 1,\theta)$	Proportion of vehicles performing a lane change
$f(i,t,l,\theta)$	Inflows to the highway
$g(i,t,l,\theta)$	Outflows to the highway
$\lambda(\alpha,l,l_d\pm 1,\theta)$	Space required by activity α in lane l
$\pi(\alpha,i,l,t,\theta)$	Proportion of vehicles performing activity α
$v(i,t,l)$	Speed of traffic in section i and lane l
$L(i)$	Length of the highway section i
$S(i,t,l)$	Free space in highway s section i and lane l
$S_U(i,t,l)$	Upstream free space
$\phi_{l,i}(t)$	Flow of vehicles at lane l section i [veh/hr/lane]
$k_{l,i}(t)$	Density of vehicles in lane l section i [veh/km/lane]

APPENDIX B
SMARTCAP INPUT DATA FILE

Highway-Vehicle configuration and simulation parameters

```
SECTION SMARTCAP

LEFT 4
TIME      3600 // Simulation time [s]
STEPTIME  16.5 // in [s]
INTRAPLAT 2    // Intra-platoon spacing [m]
DETECTRANGE 61      // Detection Range for vehicles [m]
TRELAX      0
RAMPOUT     1       // Creates Ramp output
DENSEOUT    1       // Creates density output
SPACEVELOUT 1       // Creates space-velocity output
ACTOUT      1       // Creates activity output
DEBUG       1
TMCFILE     tmcDOT
ACTFILE     actDOT
VMAX        30      // Max velocity
//

SECTION CARTYPE

CARTYPE passenger
LENGTH  5      // Car length in [m]
WIDTH   3      // Car width in [m]
AMAX    5      // Max acceleration in [m/s*s]
AMIN   -5      // Max deceleration in [m/s*s]
VMAX    30     // Max Velocity [m/s]
//

SECTION HIGHWAY

HIGHWAY hw_1
LANE 1 AUTOMATED NONE_BARRIER SOURCE
LANE 2 AUTOMATED NONE_BARRIER SOURCE
GEOMETRY LINE 500
//
HIGHWAY hw_2
```

```
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_3
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_4
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_5
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_6
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_7
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_8
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_9
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
LANE 3 AUTOMATED NONE_BARRIER SINK
GEOMETRY LINE 500
//
HIGHWAY hw_10
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
LANE 3 AUTOMATED NONE_BARRIER SOURCE
GEOMETRY LINE 500
//
HIGHWAY hw_11
```

```
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_12
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_13
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_14
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_15
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_16
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_17
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_18
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_19
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
LANE 3 AUTOMATED NONE_BARRIER SINK
GEOMETRY LINE 500
//
HIGHWAY hw_20
LANE 1 AUTOMATED NONE_BARRIER
```

```
LANE 2 AUTOMATED NONE_BARRIER
LANE 3 AUTOMATED NONE_BARRIER SOURCE
GEOMETRY LINE 500
//
HIGHWAY hw_21
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_22
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_23
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_24
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_25
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_26
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_27
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_28
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
GEOMETRY LINE 500
//
HIGHWAY hw_29
LANE 1 AUTOMATED NONE_BARRIER
LANE 2 AUTOMATED NONE_BARRIER
```

```
LANE 3 AUTOMATED NONE_BARRIER SINK
GEOMETRY LINE 500
//
HIGHWAY hw_30
LANE 1 AUTOMATED NONE_BARRIER SINK
LANE 2 AUTOMATED NONE_BARRIER SINK
GEOMETRY LINE 500
//
PIN hw_1  0 0 0 0    // Highway Base reference Point
//
CONNECT hw_1 (1 2) hw_2 (1 2)
//
CONNECT hw_2 (1 2) hw_3 (1 2)
//
CONNECT hw_3 (1 2) hw_4 (1 2)
//
CONNECT hw_4 (1 2) hw_5 (1 2)
//
CONNECT hw_5 (1 2) hw_6 (1 2)
//
CONNECT hw_6 (1 2) hw_7 (1 2)
//
CONNECT hw_7 (1 2) hw_8 (1 2)
//
CONNECT hw_8 (1 2) hw_9 (1 2)
//
CONNECT hw_9 (1 3) hw_10 (1 2)
//
CONNECT hw_10 (1 3) hw_11 (1 2)
//
CONNECT hw_11 (1 2) hw_12 (1 2)
//
CONNECT hw_12 (1 2) hw_13 (1 2)
//
CONNECT hw_13 (1 2) hw_14 (1 2)
//
CONNECT hw_14 (1 2) hw_15 (1 2)
//
CONNECT hw_15 (1 2) hw_16 (1 2)
//
CONNECT hw_16 (1 2) hw_17 (1 2)
//
CONNECT hw_17 (1 2) hw_18 (1 2)
//
CONNECT hw_18 (1 2) hw_19 (1 2)
//
CONNECT hw_19 (1 3) hw_20 (1 2)
```

```
//
CONNECT hw_20 (1 3) hw_21 (1 2)
//
CONNECT hw_21 (1 2) hw_22 (1 2)
//
CONNECT hw_22 (1 2) hw_23 (1 2)
//
CONNECT hw_23 (1 2) hw_24 (1 2)
//
CONNECT hw_24 (1 2) hw_25 (1 2)
//
CONNECT hw_25 (1 2) hw_26 (1 2)
//
CONNECT hw_26 (1 2) hw_27 (1 2)
//
CONNECT hw_27 (1 2) hw_28 (1 2)
//
CONNECT hw_28 (1 2) hw_29 (1 2)
//
CONNECT hw_29 (1 3) hw_30 (1 2)
//
SECTION FLOW
//FlowTypeName      CarType   DestHwName     DestLane
FLOW f1        passenger      hw_9           3
FLOW f2        passenger      hw_19          3
FLOW f3        passenger      hw_29          3
FLOW f4        passenger      hw_30          1
FLOW f5        passenger      hw_30          1
FLOW f6        passenger      hw_30          2
FLOW f7        passenger      hw_30          2
//
SECTION INFLOW
//EntryHwName  EntryLane
// flowType    startTime endTime  interval weight activity
INFLOW    hw_1      1
FLOW f1        0         1800      3.60      1.0  automated
FLOW f4        0         3600      1.80      1.0  automated
INFLOW    hw_1      2
FLOW f2        0         1800      3.60      1.0  automated
FLOW f6        0         3600      1.80      1.0  automated
INFLOW    hw_10     3
FLOW f3        0         1800      3.60      1.0  automated
INFLOW    hw_20     3
FLOW f5        0         1800      7.20      1.0  automated
FLOW f7        0         1800      7.20      1.0  automated
//
```

```
SECTION OUTFLOW
//        hwName laneNumber MaxFlow (veh/hr) Activity
OUTFLOW   hw_9       3      100000     automated
OUTFLOW   hw_19      3      100000     automated
OUTFLOW   hw_29      3      100000     automated
OUTFLOW   hw_30      1      100000     automated
OUTFLOW   hw_30      2      100000     automated
//
```

LIST OF REFERENCES

Al-Ayat, R. A. and Hall, R. W. "A conceptual approach for developing and analyzing alternate evolutionary deployment strategies for intelligent vehicle/highway systems." Technical Report UCB-ITS-PWP-94-05, *Institute of Transportation Studies*, University of California, Berkeley, 1994.

Al-Deek, H. and Kanafani, A. "Some theoretical aspects of the benefits of en-route vehicle guidance." Technical Report UCB-ITS-PRR-89-2, *Institute of Transportation Studies*, University of California, Berkeley, 1989.

Alvarez, L. "Activity based highway capacity analysis: A case study." *IEEE Conference on Intelligent Transportation Systems*, pp. 153-158, 1997.

Alvarez, L. and Horowitz, R. "An activity based traffic flow controller for AHS." *Proceedings of the 36th Conference on Decision & Control*, San Diego, California, pp. 1062-1067, December 1997.

Alvarez, L. and Horowitz, R. "Safe platooning in automated highway systems. Part I: safety regions design." *Vehicle Systems Dynamics Special Issue: IVHS*, Vol. 32, No. 1, pp. 23-56, July 1999a.

Alvarez, L. and Horowitz, R. "Safe platooning in automated highway systems. Part II: velocity tracking controller." *Vehicle Systems Dynamics Special Issue: IVHS*, Vol. 32, No. 1, pp. 57-84, July 1999b.

Barth, M. and Norbeck, J. M. "Transportation modeling for the environment: Final report." Technical Report, PATH Research Report UCB-ITS-PRR-96-6, *Institute of Transportation Studies*, University of California, Berkeley, 1996.

Branicky, M. S. "Control of hybrid systems." PhD thesis, Massachusetts Institute of Technology, 1994.

Brocket, R. W. "Hybrid models for motion control systems." *Perspectives in Control*, pp. 29-54, Boston: Birkhäuser, 1993.

Broucke, M. and Varaiya, P. "A theory of traffic flow in automated highway systems." *Transportation Research, Part C: Emerging Technologies*, Vol. 4, No. 4, pp. 181-210, 1996.

Broucke, M. and Varaiya, P. "A dynamic model for traffic flow on automated highway systems." *Proceedings of the 8th IFAC Symposium on Transportation Systems*, Chania, Greece, June 1997a.

Broucke, M. and Varaiya, P. "Automated highway system: A transportation technology for the 21st century." *Control Engineering Practice*, Vol. 5, No. 11, pp. 1583-1590, November 1997b.

Broucke, M., Varaiya, P., Kourjanski, M. and Khorramabadi, D. "SmartCap user's guide." PATH Technical Memorandum No. D96-53, February 1996.

Carbaugh, J., Godbole, D. N. and Sengupta, R. "Safety and capacity analysis for automated and manual highway systems." PATH Technical Report UCB-ITS-PRR-99-36, *Institute of Transportation Studies*, 32 pages, 1999.

Collier, W. C. and Weiland, R. J. "Smart cars, smart highways." *IEEE Spectrum*, Vol. 31, No. 4, pp. 27-33, 1994.

Daganzo, C. F. "The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory." *Transportation Research*, Vol. 28B-4, pp. 69-287, August 1994.

Delco Electronics. "AHS User Interface." 1997. Retrieved August 24, 2001, from http://www.monolith-mis.com/ahs/delcoUser.htm.

Deshpande, A., Godbole, D., Göllü, A. and Varaiya, P. "Design and evaluation tools for automated highway systems." *DIMACS*, Rutgers University, Piscataway, NJ, October 1995.

Deshpande, A., Göllü, A. and Semenzato, L. "The SHIFT programming language and run-time system for dynamic network of hybrid automata." Technical Report UCB-ITS-PRR-97-7, *Institute of Transportation Studies*, University of California, Berkeley, 1997.

Eskafi, F. "Modeling and simulation of the automated highway systems." PhD thesis, Department of Electrical Engineering and Computer Science, University of California at Berkeley, 1996.

Eskafi, F and Varaiya, P. "Smart Path: An automated highway system simulator." University of California, Berkeley, Research Report UCB-EECS-PATH/ITS, June 1992.

Fenton, R. E. "IVHS/AHS: Driving into the future." *IEEE Control Systems*, Vol. 14, No. 6, pp. 13-20, December 1994.

Fenton, R. E. and Mayhan, R. J. "Automated highway studies at the Ohio State University: An overview." *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 1, pp. 100-113, February 1991.

Frankel, J., Alvarez, L., Horowitz, R. and Li, P. "Safety oriented maneuvers for IVHS." *Journal of Vehicle Systems Dynamics*, Vol. 26, No. 4, pp. 271-299, 1996.

Gardels, K. "Automatic car controls for electronic highways." General Motors Research Labs, Warren, Michigan, GMR 276, June 1960.

General Motors "System studies of automated highway systems." Transportation Systems Center, Warren, Michigan, PB-83-146266, Report No. FHWA/RD-82/003, July 1982.

Godbole, D. N., Eskafi F., Singh, E. and Varaiya, P. "Design of entry and exit maneuvers for AHS." *Proceedings of the American Control Conference*, pp. 3576-3580, 1995.

Godbole, D. N. and Lygeros, J. "Tools for safety and throughput analysis of automated highway systems." *Proceedings of the American Control Conference*, Albuqueque, New Mexico, pp. 2031-2035, June 1997.

Haddon, J. A. "Evaluation of AHS throughput using SmartCAP." Master Thesis, California PATH program, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, 1996.

Hall, R. W. "Time benefits of new transportation technologies: The case of highway automation." *Transportation Planning Technologies*, Vol. 19, pp. 1-17, 1991.

Hall, R. W. "Longitudinal and lateral throughput on an idealized highway." *Transportation Science*, Vol. 29, pp. 3499-3505, May 1995a.

Hall, R. W. "The architecture of transportation systems." *Transportation Systems: Part C*, Vol. 3, pp. 129-142, 1995b.

Hedrick, J. K., Tomizuka, M. and Varaiya, P. "Control issues in automated highway systems." *IEEE Control Systems Magazine*. Vol. 14, No. 6, pp. 21-32, 1994.

Heinrich, B. F. "IVHS, an automotive perspective." *Proceedings of the Vehicle Navigation & Information Systems Conference*, Dearborn, MI., pp. 377-384, 1991.

Hessburg, T. and Tomizuka, M. "Fuzzy logic control for lateral vehicle guidance." *IEEE Control Systems Magazine*, Vol. 14, No. 4, pp. 55-63, 1994.

Hsu, A., Eskafi, F., Sachs, S. and Varaiya, P. “Protocol design for an automated highway system.” *Discrete Event Dynamic Systems*. Vol. 2, pp. 183-206, 1993.

Hsu, A., Sachs, S., Eskafi, F. and Varaiya, P. “The design of platoon maneuvers for IVHS.” *Proceedings of American Control Conference*, pp. 2545-2550, 1991.

Ioannou, P. A. *Automated Highway Systems*. New York: Plenum Press, 1997.

IVHS America. “Strategic plan for intelligent vehicle-highway systems in the United States.” Report No. IVHS-AMER-92-03, May 1992.

Jurgen, R. K. “Smart cars and highways go global.” *IEEE Spectrum*, Vol. 28, No. 5, pp. 26-36, 1991.

Karaaslan, U., Varaiya, P. and Walrand, J. “Two proposals to improve traffic flow.” *American Control Conference*, Boston, MA., pp. 2539-2544, 1991.

Kourjanski, M., Broucke, M., Skabardonis, A. and Varaiya, P. “Car-driver models for manual and automated travel.” *Proceedings of the 8th IFAC Symposium on Transportation Systems*, Chania, Greece, June 1997a.

Kourjanski, M., Göllü, A., and Hertschuh, F. “Implementation of the SmartAHS using SHIFT simulation environment.” *SPIE Conference on Intelligent Systems and Advanced Manufacturing*, Pittsburgh, PA, October 1997b.

Lee, Jong-Kwon and Lee, Ju-Jang. “Discrete event modeling and simulation for flow control in an automated highway system.” *Transportation Research, Part C: Emerging Technologies*, Vol. 5, No. 3/4, pp. 179-195, 1997.

Li, P., Alvarez, L. and Horowitz, R. “AVHS safe control laws for platoon leaders.” *IEEE Transactions on Control Systems Technology*, Vol. 5, No. 6, pp. 614-628, 1997.

Lygeros, J., Godbole, D. N. and Sastry, S. “Simulation as a tool for hybrid system design.” *Proceedings of the 5th IEEE conference an AI, Simulation and Planning in High-Autonomy Systems*, pp. 6-12, 1994.

Lygeros, J., Godbole, D. N. and Sastry, S. “A verified hybrid controller for automated vehicles.” *Proceedings of the IEEE Conference on Decision and Control*, Kobe, Japan, pp. 2289-2294, 1996.

MathWorks. *MATLAB User Guide*, Natick, Massachusetts, 1994.

Medanic, J. V., Ramaswamy, D., Perkins, W. R. and Benekohal, R. “Partitioned lane assignment strategies for balancing excess capacity on AHS.” *Proceedings of the American Control Conference*, Seattle, Washington, pp.3581-3585, 1995.

NHTSA. “Traffic safety facts 1998.” U.S Department of Transportation, National Highway Traffic Safety Administration, National Center for Statistics & Analysis, DOT HS 808 956, 1998.

Nicollin, X., Olivero, A., Sikafis, J. and Yovine, S. “An approach to the description and analysis of hybrid systems.” *Hybrid Systems*, No. 736 in LNCS, pp. 149-179, New York: Springer Verlag, 1993.

O’Brien, R. T., Urban, T. J., and Iglesias, P.A. “Lane change maneuver via modern steering control methods.” *Proceedings of the IVHS America Conference*, 1995.

Peng, H. “Distributed link-layer control for automated highway systems.” *Transactions of the ASME*, Vol. 119, pp. 192-197, June 1997.

Pham, H. A., Hedrick, J. K. and Tomizuka, M. “Combined lateral and longitudinal of vehicles for AHS.” *Proceedings of American Control Conference*, Baltimore, Maryland, pp. 1205-1206, June 1994.

Rao, B. S. and Varaiya, P. “Roadside intelligence for flow control in an intelligent vehicle and highway system.” *Transportation Research, Part C: Emerging Technologies*, Vol. 2, No. 1, pp. 49-72, 1994.

Rockwell, “Electronics cost analysis.” Prepared for the Federal Highway Administration, Contract DTFH61-93-C-001-99, 1994.

Sachs, S. R. and Varaiya, P. “A communication system for the control automated vehicles.” *Institute of Transportation Studies*, University of California, Berkeley, PATH Technical Memorandum 93-5, 1993.

Sheikholeslam, S. and Desoer, C. A. “Longitudinal control of a platoon of vehicles.” *Proceedings of American Control Conference*, San Diego, California, pp. 221-296, 1990.

Shladover, S. “Potential freeway capacity effects of advanced vehicle control systems.” *Proceedings of the 2nd International Conference on Applications of Advanced Technologies in Transportation Engineering*, Minneapolis, Minnesota, pp. 213-217, August 1991.

Shladover, S., Desoer, C., Hedrick, J., Tomizuka, M., Walrand, J., Zhang, W., McMahon, D., Peng, H., Sheikholeslam, S. and McKeown, N., “Automatic Vehicle Control Developments in the PATH Program.” *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 1, pp. 114-130, 1991.

Swaroop, D. “String stability of interconnected system: An application to platooning in automated highway systems.” PhD thesis, Department of Mechanical Engineering. University of California, Berkeley, 1994.

Swaroop, D., Chien, C. C., Hedrick, J. K. and Ioannou, P. “A comparison of spacing and headway control laws for automatically controlled vehicles.” *Vehicle Systems Dynamics*, Vol. 23, 1994.

Tavernini, L. “Differential automata and their simulators.” *Nonlinear Analysis, Theory, Methods and Applications*, Vol. 11, No. 6, pp. 665-683, 1987.

Thorpe, C., Jochem, T. and Pomerleau, D. “The 1997 automated highway free agent demonstration.” *IEEE Conference on Intelligent Transportation Systems*, pp. 496-501, November 1997.

Varaiya, P. “Smart cars on smart roads: Problems of control.” *IEEE Transactions on Automatic Control*, Vol. 38, No. 2, pp. 195-207, February 1993.

Varaiya, P. and Shladover, S. E. “Sketch of an IVHS systems architecture.” Technical Report UCB-ITS-PRR-91-3, *Institute of Transportation Studies*, University of California, Berkeley, 1991.

Zabat, M. A., Stabile, N. S. and Browand, F. K. “Estimates of fuel savings from platooning.” *Proceedings of ITS America Annual Meeting*, pp. 1203-1208, 1995.

BIOGRAPHICAL SKETCH

Diego Orlando Terzano was born in Buenos Aires, Argentina, to Orlando and Graciela on December 10, 1976. He attended San Gabriel school until the third grade and then he transferred to Bede’s Grammar School to complete his elementary and high school education.

In April 1995 he started at the Universidad Católica Argentina and completed his freshman year in industrial and systems engineering. At the end of that year he and his family moved to the United States to Weston, Florida, where he attended Florida International University. He graduated *cum laude* with a Bachelor of Science degree in the same field on April 1999. That same year he was awarded the Student of the Year Award from Alpha Pi Mu, the industrial and systems engineering honor society. In addition, he was a recipient of the All-American Scholar Award.

In January of 2000, after an internship as a simulations engineer at the Jackson Memorial Hospital, he decided to move to Gainesville, Florida, to pursue a Master of Science in industrial and systems engineering (operation research option) at the University of Florida. His interests include discrete event simulation, manufacturing processes, supply chain management and transportation systems. He expects to graduate on December 2001 with a Master of Science. In the future, he hopes someday to pursue a Ph.D. in the same field.