Chapter 2

Automated Highway Systems

A major long-term element of Intelligent Transportation Systems research and development is Automated highway Systems (AHS). The AHS program is a broad international effort “to provide the basis for, and transition to, the next major performance upgrade of the vehicle/highway system through the use of automated vehicle control technology” [NAHSC96]. The detailed definition of the Automated Highway System is as follows [Plan93]:

> The term “fully automated intelligent vehicle-highway system” is interpreted to mean a system that:
> - Evolves from today’s roads (beginning in selected corridors);
> - Provides fully automated “hands-off” operation at better levels of performance than today’s roadways in terms of safety, efficiency, and operator comfort; and,
> - Allows equipped vehicles to operate in both urban and rural areas on highways that are both instrumented, and not instrumented.

The consensus in the AHS community is that AHS will evolve over a series of smaller steps in technology. The final step of full automation will not be a leap, but a logical consequence of previous development and deployment efforts. Each step in the technology will have its own benefits and be self-sustaining. Vehicle and infrastructure evolutions will be “synchronous” [James94]. We will briefly mention the steps of this evolution here before introducing the AHS program and discussing automatic vehicle control technologies in detail.

When the cruise control was first developed, there was much concern over the safety and user acceptance of the new system; however, it has become widely accepted and used. In the near future, obstacle and headway warning and Automatic Vehicle Identification (AVI) will be added to modern cruise control and existing communications infrastructure. The success of AHS depends on linking the power of cellular communications and the emerging range of high-performance computers to the ongoing vehicle based developments. Ideally, the highway system can be divided into a number of “cells” which contain local radio receivers or beacons that will be linked together through a fiber-optic network. Vehicles will also be equipped with a transceiver unit carrying several user services. The first applications of this technology are the Automatic Vehicle Identification (AVI) and Electronic Toll Collection (ETC). Obstacle and headway warning is the next step in AHS development in vehicles. Vehicle on-board radar (VORAD) systems in many commercial vehicles are already in use for the last two years. An important issue in warning systems is the capabilities of the sensor modules. Differentiating between a large vehicle and a small animal may not be possible using a simple system. A consequent application of the headway warning system is the automatic headway control. Adaptive cruise control systems are currently designed by many automobile manufacturers.

The market introduction of the first vehicle with adaptive cruise control is expected in 1997. This will enable the drivers to hold their desired speed as well as the desired headway distance. Although the drivers defined as “creepers” will be cut-of by more aggressive drivers (“hunters”), the ability to set the desired headway may be desirable to many users. Also, the issues such as sensor types, curve handling, merging vehicles, changing lanes, integration of steering and braking all have to be addressed to obtain a complete system design.

Applications in advanced traffic management, traveler information and public transportation systems (ATMS, ATIS, APTS) will require more sophisticated vehicle location capabilities. In addition, the number of uses for vehicle-to-roadside communications will eventually increase. MAYDAY services, fleet tracking and automatic vehicle location (AVL) applications will use radio-location beacons as well as more sophisticated transceivers. As a result of AVL and AVI, processing real-time information on vehicle locations will be possible. Although the number of vehicles equipped with AVI/AVL technologies will initially be small, traffic management centers can effectively use a small percentage of vehicles as “probes.”

Roadside-to-vehicle and vehicle-to-vehicle communications are also important for the future of AHS. Automatic braking systems may be activated by decelerating vehicles in front, or by the infrastructure sending a deceleration request to the headway control system. The vehicle must be *very* sure about the imminent danger, and knowledge of following vehicles and their speeds is an important factor to be considered. Inter-vehicle communications and rear sensing both would help in automatic braking.

Evolution of the AHS system will continue with lane departure warning. It will be the first system to control lateral movement of vehicles. The lane holding feature will consequently be added to the adaptive cruise control, shortly after the lane departure warning feature. Automatic lane holding will provide a "hands off/feet off" driving situation where the driver is still responsible for all command decisions in the vehicle and must be aware at all times of his surroundings. If the infrastructure knows the location of each vehicle, possesses the information about its current path, and is communicating with the vehicle, then the lateral control can be coordinated from the infrastructure.

Further advances in technology will force the driver to “lose” his control of the vehicle. In order to gain any additional benefit of safety and efficiency[1], the driver must be removed as the primary source of command and control. Of course, this change requires that the automated system perform better than a good driver, *i.e.*, no more than 1 critical error in 10^8 seconds be made. This step will be the natural consequence of the previous progress. Obviously, not all vehicles will be equipped with this technology right away. Automated and manually driven vehicles have to coexist for some time.

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[1] With the driver in control, the highway capacity can only be increased to 15% above the maximum value of 40 vehicle/lane/min. Furthermore, 90% of highway accidents are results of incorrect driver decisions.

A vehicle that can “predict” the actions of neighboring vehicles is an important step for safer highway transportation. Locating the position of all the vehicles in close proximity to the automated vehicle with high accuracy is essential. This can be accomplished through multi-sensor systems for adjacent vehicles and possibly inter-vehicle communications to give an idea of what to expect beyond adjacent vehicles. Alternatively, the “roadside control” may have knowledge of the positions of the vehicles relative to fixed reference points. This knowledge is obtained by either vehicle based or roadside based detection, and/or by communicating with the vehicle.

This technology requires extreme accuracy in vehicle location at all times. If the system is infrastructure-based, the infrastructure needs to know the locations of the non-automated vehicles, for safe and efficient implementation. The minimum update rate of information must be larger than 100 times per second with an accuracy less than 10 cm for the desired level of safety [James 94]. Automated vehicle control (AVC) systems are expected to boost the capacity by 50% even for mixed vehicle traffic. Once the system has knowledge of the surrounding environment to all extents, it can make decisions on merging and passing in addition to the headway control and lane keeping performed under driver control. Full system optimization and higher efficiencies can then be obtained as the percentage of automated vehicles on the road increases.

Highways contain many characteristics that simplify the problem of automation, such as uninterrupted traffic flow, controlled access. Therefore automation on arterials will lag significantly behind automated highways. However, many safety measures can be taken on arterials using the equipment already designed for the highway. For example, the problem of intersection collision can be reduced by activating the onboard warning systems and automatic braking systems with electronic signal lights in addition to the normal traffic signal. If the intersection detects a potential for a collision it can notify equipped vehicles. Problems to be encountered during AHS deployment on arterials include integration of cyclists and motorcyclists to the AVC system, and the effects of pedestrian and animal traffic.

The final step in the AHS’ future is fully automatic control, wherein the driver will have no control over the vehicle. All trip decisions will be automatically made using AVL and ATIS information. The driver may be able to include additional criteria for route selection. Once the trip decision is made, the infrastructure, utilizing AVC, will guide the vehicle while constantly updating the routing strategy based on the current information obtained through Advanced Traffic Management System (ATMS).

2.1 AHS Program Phases and the National Automated Highway Systems Consortium

The AHS program in United States is planned around three broad phases: Analysis (1993-96), System Definition (1994-2001), and Operational Tests and Evaluation (starting in 2001). The National Automated Highway System consortium (NAHSC) is responsible for conducting the second phase.

The Analysis Phase established an analytic program foundation. It consisted of Precursor Systems Analyses (PSA) [PSA94] by 15 contractor teams that addressed automated vehicle control requirements and issues in 16 topic areas, a human factors study effort to develop an AHS human factors design handbook, and National Highway Traffic Safety Administration (NHTSA) analyses to investigate other ITS automated vehicle control-based services that avoid collisions through warning and control. The PSA identified issues and risks associated with various AHS concepts and design areas. All contract teams submitted final reports in November 1994. The NAHSC is actively using these findings in their research.

The Systems Definition Phase is currently underway. The NAHSC is working in partnership with the federal government. The consortium includes representatives from the vehicle industry, highway industry, State and local governments, regional and metropolitan transportation agencies, and electronics/communications industries associated with the vehicle and communications market.

The milestones of the consortium program are as follows: (a) establishment of performance and design objectives, (b) a 1997 proof-of-technical-feasibility demonstration, (c) identification and description of multiple feasible AHS system concepts, (d) selection of the preferred AHS system configuration, (e) completion of prototype testing, and (f) completion of system and supporting documentation.

The Operational Test and Evaluation Phase is currently not funded. It would logically follow a successful completion of the Systems Definition Phase.

The National Automated Highway System Consortium (NAHSC) was formed to “specify, develop, and demonstrate a prototype Automated Highway System (AHS)” [NAHSC96]. The specification provides for an evolutionary deployment that can be tailored to meet today’s transportation needs. The Consortium will seek opportunities for early introduction of vehicles and highway automation technologies to achieve benefits for all surface transportation users, while incorporating public and private stakeholder views to ensure that an AHS is economically, technically, and socially viable.

The consortium’s proof-of-technical-feasibility demonstration is one of the major milestones of the AHS program, and is scheduled for October 1997. This demonstration will be a full-scale exhibition with multiple vehicles on a segment of the I-15 interstate highway near San Diego, integrating the technological achievements of the participants of the consortium and the transportation industry. The demonstration will focus on existing technologies and concepts that can be integrated quickly to provide a solid proof of feasibility.

The selection of the final AHS system configuration will be made during 1999, and the final decision on the preferred AHS configurations will be made in February 2000. Immediately after that date, the design, development and testing of the prototype system will begin. The design process will be finished before the end of year 2000; the development will conclude in 2001, and the prototype system’s testing will be completed in August 2002.

The detailed description of the national automated highway program, information on NAHSC and its participants, and the detailed schedule of AHS tasks and subtasks can be found at [NASHC96]. The information about the past and future of the AHS program can also be found at [AHS96].

Outside of the US, similar AHS programs are being conducted in Japan [ITSJ96], and in Europe [Braess95]. Almost all automotive companies in Japan have automated vehicles in the design and/or testing phase [Construction96]. Similar activities are reported in the PROMETEUS program in Europe [Rault95].

2.2 Vehicle Control

Vehicle control is probably the most important part of the advanced AHS applications. Implementation of AHS necessitates automatically controlled vehicles as mentioned previously. Achieving the optimal solution to congestion and safety problems requires extensive research in system modeling, lateral (steering) controls and longitudinal (speed and headway) controls. In a fully automated highway system, these control systems will rely on vehicle-to-vehicle communication, as information on velocity and acceleration of other vehicles will be utilized in individual vehicle controllers [Varaiya93]. The same information and much more (*e.g.*, desired speed and lane) may also be received via vehicle-to-roadside communications. Here, we will briefly discuss the previous research on lateral, longitudinal and combined lateral and longitudinal control of vehicles.

2.2.1 Lateral Control

Hessburg and Tomizuka [Hessburg91] designed a fuzzy rule-based controller for lateral guidance of a vehicle. This system is based on human-type reasoning. Advantages of such a controller include flexibility in the choices of input/outputs, and on-line/off-line training capability. Their focus was achieving good tracking for a variety of roadway curves over a range of longitudinal vehicle speeds. Simulations to demonstrate its performance under parameter variations and external disturbances gave satisfactory results.

An alternative approach is presented in [Lubin92]. It concentrates the intelligence in the vehicle, using the visual sensing approach described in [Kornhauser91]. In this model, no infrastructure modification is needed, but considerable cost and complexity is added to each individual vehicle. With the current rate of technology improvement, this system may become feasible for production purposes. During the last five years, the research on lateral vehicle control and lane changing maneuvers was extensive. For a (non comprehensive) list of publications on the subject, see [PathDb96].

Besides the theoretical modeling and simulations for lateral control of vehicles, there are a few important experimental accomplishments: the use of magnetic markers, and the use of visual information for lateral position handling. The first method was designed by the PATH Program [PATH96] and employs magnetic markers imbedded into the road to detect the lateral displacement from the center of the lane [Tan96]. Current tests with a vehicle equipped with magnetic sensors on its front bumper are reported to be successful [Lee95]. The second application for lateral control uses visual data and on-board computing resources to obtain the steering command, and is designed by another NASHC participant. In order to locate the road ahead, the "rapidly adapting lateral position handler" (RALPH) uses a template-based matching technique to find parallel image features such as lane markings or tire and oil markings. During the experiment called "No Hands Across America," the test bed vehicle equipped with the RALPH system drove 98% of the 2850 mile journey autonomously. An average speed of 63mph in conditions that included bright sunlight, dusk, rain and nighttime, and a maximum stretch of 69-miles autonomous driving are reported [Pomerlau96]. A third application for lateral control consists of a vision-based system with a neural network learning from a driver. Performance levels comparable to the human driver are reported in [Moon96]. Özgüner *et al.* reported successful results for lane following using a vision sensor [Özgüner96].

2.2.2 Longitudinal Control

Longitudinal control is an important aspect of the future AHS. One of the major concepts in this area is *platooning,* which is a formation of traveling vehicles that maintain close spacing at highway speeds. The concept requires inter-vehicle communication links to provide velocity and possibly acceleration information from the lead vehicle to each of the following vehicles, as well as the velocity and acceleration of the preceding vehicle in the platoon. Sheikholeslam and Desoer [Sheikholeslam89] showed that inter-vehicle communications increases the stability of the platoon formation in the case of identical vehicle platoons.

In the case of a platoon of non-identical vehicles, the situation is more complex. Frank, Liu, and Liang [Frank89] explicitly considered the case of non-identical vehicles. The control scheme presented combines three nested control loops for speed regulation, spacing control, and speed synchronization. They also concluded that (a) the platoon size must be limited to approximately 15 vehicles, (b) nonlinearities significantly affect the response characteristic of the platoon, and (c) emergency situations need further investigation before proper sensor specifications can be set.

It has also been shown that communicating the lead vehicle's information to other vehicles is not a requirement if we can tolerate degradation in the performance. This degradation is said to be not catastrophic [Sheikholeslam91].

Recent research on longitudinal control includes vehicle follower control design for heavy-duty vehicles [Yanakiev96], adaptive control of a nonlinear platoon model [Spooner96], automatic braking systems and their effects on capacity [Hedrick96], advanced control techniques [Kachroo95b], and adaptive traction control [Lee96]. Again, A relatively comprehensive list of publications on longitudinal vehicle control can be found at [PathDb96].

Experimental results of longitudinal vehicle control include a platoon of four vehicles traveling at 55mph with a headway distances under 50 cm [Hedrick96]. Again, lead vehicle's information is transmitted to following vehicles in order to achieve string stability.

2.2.3 Combined Lateral and Longitudinal Control

Although much of the research to date has focused primarily on either lateral or longitudinal control, an overall automated driving system combining both lateral and longitudinal control is vital for future automated highway systems.

System models which incorporate longitudinal and lateral dynamics are very rare. Kachroo and Tomizuka [Kachroo95c] studied combined longitudinal and lateral control to investigate the resulting behavior of the coupled system. It is shown that longitudinal controllers that directly control the wheel slip are inherently more stable, especially during lateral maneuvers on very slippery road conditions. Spooner and Passino [Spooner95] also developed sliding mode controllers for longitudinal and lateral control. Their fault tolerant algorithms were found to be stable for a variety of faults such as braking, powertrain, and steering systems. Yu and Sideris [Yu95] considered combined control using partial state-measurements of longitudinal and lateral deviations, longitudinal velocity and yaw rate. The research on combined control of vehicles is moving toward more realistic systems. New control approaches for more platoon operations in more complex situations such as entry and exit maneuvers are being studied [Yang96].

The PATH program investigates the use of machine vision for guiding lane change maneuvers [Malik95]. The vision system is modularly interfaced with the existing magnetic sensor system for lateral position measurements, and with active range sensors. Özgüner [Özgüner95] also described a vehicle-roadway system in which the control of vehicle movement is based on instrumentation located both in the vehicle and the roadway. A radar based system is used for both cruise control, and for providing position information in lateral maneuvers.

Combined lateral and longitudinal control experiments are yet to be designed and implemented; the 1997 AHS Demonstration will be a good occasion for combined control tests.

2.3 Hierarchical Control Structure

Varaiya introduced a structure for designing ITS functions and their relation to driver decisions [Varaiya93]. The focus of AHS applications is mainly on the in-trip phase of the ITS activities. An automated vehicle has to (a) choose its route to reduce travel time, (b) plan its path to ensure a smooth traffic flow, (c) maneuver in coordination with other vehicles, and (d) regulate the proper spacing and steering to increase traffic flow in a safe manner.

An automated highway that leaves the driver in the control of the vehicle can only achieve a capacity of 15% above the maximum value of 40 vehicle/lane/min[2]. Driver behavior is the capacity ‘bottleneck’ in such a system. Furthermore, 90% of highway accidents are results of incorrect driver decisions [Varaiya93]. Therefore, an automated system might increase both the capacity and the safety.

In order to increase the capacity of the existing highways, the California PATH program suggests organizing the traffic in platoons. A platoon size of 15 with intra-platoon spacing of 2m, inter-platoon spacing of 60m, and a steady-state speed of 72km/h will increase the capacity to 105 vehicle/lane/min, which is much larger than maximum empirically observed values. Decreasing

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[2] This value is suggested by empirical studies.

the distance between vehicles to 0.20m will change this number to 130 vehicles/lane/min, although it may not be feasible for a heterogeneous platoon of vehicles. For intra-platoon distances discussed here, it is impossible for a driver, who has a reaction delay of 0.25-1.20 sec, to guarantee adequate safety.

According to Varaiya, the tasks for an automated vehicle-highway system to accomplish can be achieved by a four-layer hierarchical control architecture [Varaiya93]. The layers of the architecture, from the top, are *network*, *link*, *planning*, and *regulation*. The network layer assigns a route to each vehicle as it enters the system. The link layer assigns each vehicle a path which balances traffic for all lanes, and assigns a target speed for each section of highway. This layer may also assign platoon size. The planning layer creates a plan which approximates the desired path. The regulation layer controls the vehicle trajectory so that it conforms to this plan. Below the regulation layer, a physical layer that provides sensor data and responds to actuator signals, is assumed.

Different choices of partition of control authority between the infrastructure and the vehicle are compatible with this architecture. The regulation and planning layer controllers are on-board vehicles, the link and network layers are on the roadside. It is important to find a design that combines the advantages of a fully centralized control system and an architecture based on autonomous vehicles and local sensor information.

In this thesis, we introduce an intelligent controller which can be seen as the planning layer of an autonomous vehicle. The planning layer, as defined in [Varaiya93], has three tasks:

- Decision on maneuvers to attempt in order to realize the assigned path,
- Coordination of maneuvers with the planning layers of neighboring vehicles,
- Supervising the regulation layer in the execution of a trajectory corresponding to the chosen maneuver.

In our application, where the scenario includes non-automated vehicles and minimal communications, the coordination of maneuvers between planning layers does not exist. The communication between planning and regulation layers is fairly simple: the planning layer sends a command, and the regulation layer returns a reply once it successfully completes the command. A richer interface may be required: the planning layer could pass multiple parameters to the regulation layer, which could then return parameters indicating the ‘success’ or ‘errors’ and ‘exceptions.’ The theory of control of such a system is not yet developed. There is a need for research as to how the regulation layer should switch from one control law to another. Lasky and Revani state that this represents an open research issue whose solution maybe vital to the implementation of a full AHS [Lasky93].

The approach above is one of the many different approaches to AHS[3]. Some of these concepts are based on cooperative architectures [McKendree96], maximum adaptability

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[3] We emphasized this architecture since it is used in DYNAVIMTS, the Virginia Tech Center for Transportation Center’s simulation program (See Section 2.6).

[Schuster96], autonomous vehicle architectures [Bayouth96], and infrastructure assistance [Godbole96b].

2.4 Other AHS Issues

Besides the automatic vehicle control, there are several important issues that need to be carefully considered for a successful implementation of an automated highway system. During the first few years of the AHS research efforts, the problems related to the issues given here were not investigated as much as vehicle control problems. However, as the AHS related research progressed, it expanded to the areas of sensing and communications, fault tolerance, and human factors. In this section, we will emphasize related research efforts on these areas.

2.4.1 Sensors and Communication

The realization of full AHS needs hardware both in infrastructure and the vehicle. Roadside monitors will measure traffic flow and speed, and vehicle paths will be calculated based on this information. Such measurements are currently made with loop detectors, ultrasonic sensors, AVI tags or vision systems. Information may be communicated by infrared beacons, broadcast and cellular radio, or using emerging ultra wideband technologies [James96]. The vehicles need a longitudinal sensor to measure distance and relative speed of the preceding vehicle. Such sensors may be based on radar, ultrasound, or vision [Özgüner95, Hedrick96, Pomerlau96]. Microwave radar sensors perform very well in fog and heavy rain, but they are very expensive. Laser radar systems are low-cost, but cannot handle low visibility conditions [Yanagisawa92].

To facilitate lane changes at a range of relative speeds, the vehicle must be equipped with sensors that locate vehicles on the side with a longitudinal range of about 30m. Infrared and laser range finding techniques may prove to be useful in this area.

Besides headway and side sensor information, longitudinal and lateral velocity and acceleration, yaw rate, front steering angle, and lateral deviation data is needed to obtain a robust combined lateral and longitudinal control. All of these except the last one can be obtained using on-board accelerometers and encoders. For vehicle position sensing, there are two alternatives: magnetic markers [Lee95], and vision systems [Pomerlau96]. Recent research done on vision systems showed significant promise, however these systems are more expensive than magnetic markers which, in turn, require infrastructure deployment as well as on-board sensors.

A sequence of single magnetic markers can also form a “word” that transfers information such as curvature, and number of lanes. However, this magnetic marker data contains only the static information (roadway characteristics), not dynamic information (such as information on other vehicles incidents), unlike the vision system.

Roadside-vehicle communications is also a critical aspect of AHS. Vehicles need to be identified, speed must be communicated to vehicles, and actions need to be coordinated for a fully automated system. In addition, there is a need for vehicle-to-vehicle communications because of the designed longitudinal control methods and coordination issues. Precise control can be obtained using full duplex communication. Networking represents a higher level of communications, in which traffic and hazard information detected by one group of vehicles can be communicated to other vehicles. There are a variety of methods for roadside-vehicle communications; most of them are discussed in [Field92]. Recent research on communications includes interference studies for vehicle transceivers [Gavan96], design of communication protocols [Godbole96], WaveLAN radio [Chen96], and network architectures and protocols for vehicle-to-vehicle communications [Bolla96, Fuji96].

2.4.2 Safety and Fault Tolerance

Although the solutions to most of the technical problems in vehicle control, traffic management, information systems, and communications have been found, the envisioned AHS will never be deployed unless the safety of the overall system can be verified. One issue which is often overlooked by researchers is the possibility of undesirable interaction of the systems. An example in [Safety92] mentions two devices which try to maintain vehicles at constant lateral spacing using side range sensing. If the devices (and the vehicles) have different dynamics, it is possible that one or both vehicles may become unstable, possibly resulting in a collision.

Furakawa [Furakawa92] approaches the automobile safety question from an interesting perspective: the instinctive ability of humans (and animals) to sense and avoid dangers, an ability which is impaired when driving a car. Furakawa notes that building this instinctive function into automobiles as a form of intelligent control technology is a good approach to improve safety.

Current research on safety and fault tolerance includes lane crossing studies [Lin96], sensor validation [Agogino96,Singer95], fault tolerant design for AHS [Lygeros96], emergency maneuvers for automated vehicles [Shiller95], and design constraints on intelligent vehicle controllers [Puri95].

2.4.3 Human Factors

In an advanced system such as AHS, the driver will be confronted with significantly more information, and possibly more controls, than are currently used in vehicles. In a system that uses complete automation during some segments of a trip, the safe transition from automated driving to manual driving is a difficult issue. Also, there exist several advanced vehicle control systems (AVCS) related problems such as the acceptance of a system which takes the control away from drivers, privacy issues related to AVI and AVL systems, and “platooning claustrophobia.” For users to accept the AHS, a successful AVC system must address important issues such as dealing with false alarms and system failures to gain acceptance and public confidence, displays and warnings with the right amount and content of information, and driver skills and attentiveness for smooth automated-manual switching [Chira92].

Human factors assessment of the drivers interfaces of existing collision avoidance systems is currently under investigation [Mazzae96]. On the other hand, although AHS deployment has not started yet, simulator tests are conducted to see how drivers behave when they are in the lead vehicle in a string of vehicles and another vehicle enters the automated lane ahead of them [Bloomfield96]. Also, the effect of different AHS automation degrees (manual, semi-automated, fully automated) on driver behaviors while entering the automated lane are tested using a driving simulator [Bloomfield96b]. Levitan presented a comprehensive report on human factors considerations related to the design of AHS. The report is intended as a guideline for effective, efficient, safe and user-acceptable AHS design [Levitan96].

2.5. An Experimentation and Evaluation Framework for AHS

According to Center for Transportation Research's approach, the progression in AHS development from conceptualization to implementation has four steps, [Kachroo95]. The intelligent controller described in this work is part of the four-block structure visualized at the center. As seen in Figure 2.1, the first block is computer software simulation (see Section 2.6 for a detailed description) that is preceded by mathematical modeling. The second block consists of conducting small scale experiments in the Flexible Low-cost Automated Scaled Highway (FLASH) Laboratory. Then, hardware tests comprising the third block are performed on a test site with actual vehicles. The "Smart Road" being built near Blacksburg, Virginia will be a suitable test bed for conducting such experiments using actual vehicles and controlled traffic conditions. The fourth block is the deployment of AHS on conventional highways.

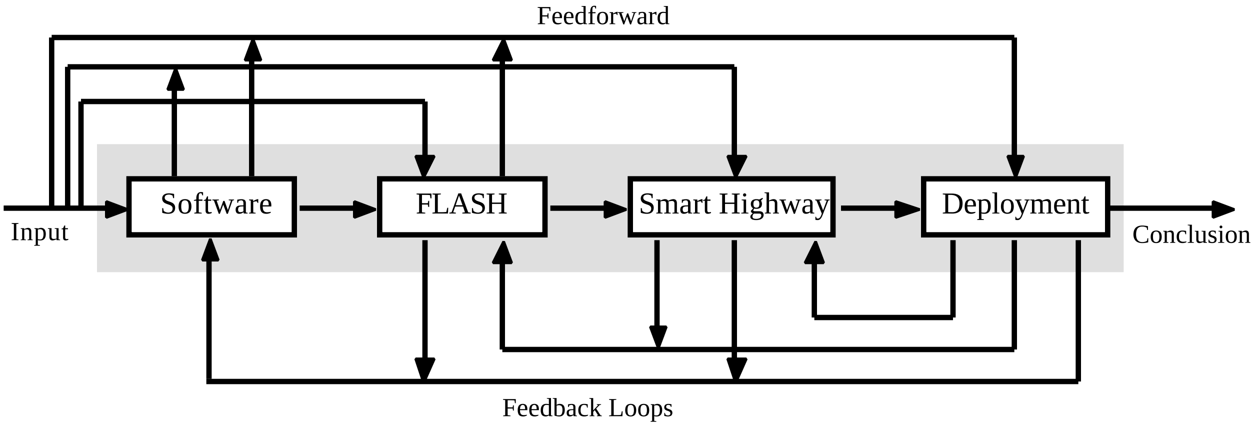

Figure 2.1. Four-block evaluation and experimentation framework for AHS.

These four blocks can be considered as the building blocks of a comprehensive testing and evaluation methodology for AHS. The input can be a hypothesis, a model, or technologies. The evaluation and testing procedure defined by this methodology is not seen as a single feedthrough four-step process, but as having some feedback and feedforward loops depending on the results obtained at each block. These loops represent the changes made to the hypothesis, model or the technological concept. Hardware tests are important since they provide the means to validate computer results or to modify them in the case of discrepancies, due to unmodeled or inadequately modeled dynamics. Without hardware testing, it would be foolhardy to jump into actual implementation. For instance, the FLASH Laboratory could be used to improve the computer simulation via scale model tests before starting the tests with full scale vehicles.

Although testing with real-sized vehicles will provide the most accurate results, it has significant cost, safety and liability considerations. In order to test highway traffic and similar situations, there is a need for a large number of automated and non-automated vehicles. This is very expensive, and due to a testing situation involving humans, the costs can become prohibitive and the situations dangerous, which could lead to insurance and safety problems. Also, full-size testing of infrastructure based systems which require complex communication scenarios may be expensive due to (roadside and in-vehicle) installation costs. The four-block structure is designed to overcome these problems. A comparison of the design/development stages for different characteristics is given in Table 2.1.

Stage	**Simulation**	**FLASH Lab.**	**Test Site**	**Deployment**
Agents	Vehicle models	Scaled vehicles	Real vehicles	Real vehicles
Tasks	Experimentation & Demonstration	Experimentation & Demonstration	Experimentation & Demonstration	Implementation
Cost	Low	Moderate	High	Very High
Development Time	Short	Short to Moderate	Long	Very Long

Table 2.1. Comparison of different stages.

2.5.1. FLASH Laboratory

The Flexible Low-cost Automated Scaled Highway (FLASH) Laboratory is visualized a precursor to a full-scale highway [Kachroo95]. It will provide a platform for experimental work as well as an arena for demonstration of AHS systems. In order to test highway situations with complex realistic scenarios of merging, splitting, exit, and entrance, small scale vehicles (1:10 to 1:15 scale) are designed in a modular fashion. Modularity will guarantee inexpensive and fast incorporation of different system configurations. The FLASH laboratory will be composed of tens of small vehicles (of different sizes) with a flexible highway system and communication network. The FLASH laboratory concept makes the construction of specifically designed scaled highway configurations possible in a short period of time, and at much less cost than it would be required for the construction of a similar full scale test bed.

The use of small low-cost vehicles with known mathematical models would be beneficial for researchers seeking to verify their computer simulations quickly and economically. The use of standard vehicles eliminates some of the uncertainty due to particular vehicle models that make comparisons of different AHS approaches difficult. The laboratory will provide researchers with the vehicle as well as its verified mathematical model. This capability will enhance the results from computer simulations.

The FLASH laboratory has significance not only to all the phases of AHS development programs, but also to the improvement and maintenance of the actual automated highways. The laboratory will be extremely useful in the analysis phase of the AHS development. The laboratory and its vehicles may serve as a benchmark through which various configurations, architectures, and technologies can be compared. Evaluation of alternative AHS system concepts, selection of a system approach based on analysis, test and evaluation, and demonstration of prototype configurations on a smaller and cheaper scale are the foci of the laboratory. Furthermore, the laboratory can be used to obtain preliminary data for the operation evaluation (third) phase of the AHS program, and be a test bed for several issues which cannot be tested on selected locations because of considerations of insurance and safety.

Currently, the laboratory is equipped with multiple small scale vehicles with different types of tires and shock mechanisms. The vehicles have infrared and magnetic sensors, and wireless video camera for lateral displacement measurements, ultrasonic sensors for headway sensing, encoders for speed measurements. Sensing and control is provided by GCB-11 microcontroller. Wireless radio modems provide full duplex serial communications (Figure 2.2.) Remote control station includes IBM PC computers equipped with frame grabber DSP board, a micro-kernel operating system, and a data acquisition board for lateral feedback control via image processing, as well as a steering wheel, control pedal and monitor for manual control (Figure 2.3). Single- and double-lane small scale modular tracks with inclines and multiple radius left and right turns are designed using EPDM rubber membrane (Figure 2.4). The laboratory also has an experimental testing platform designed for traction control and vehicle plant modeling tests [Kachroo96, Schlegel96].

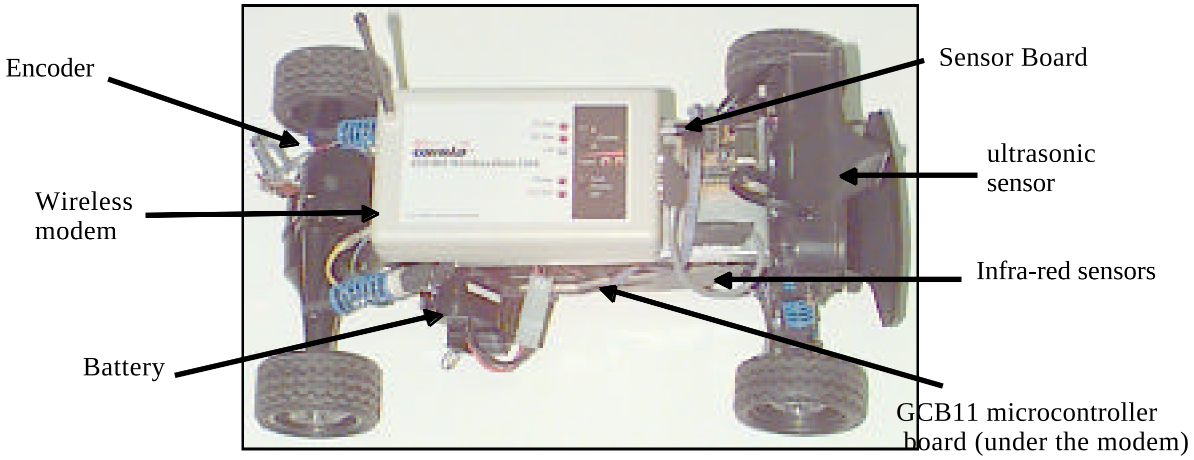

Figure 2.2. Automated FLASH Car: Test Model.

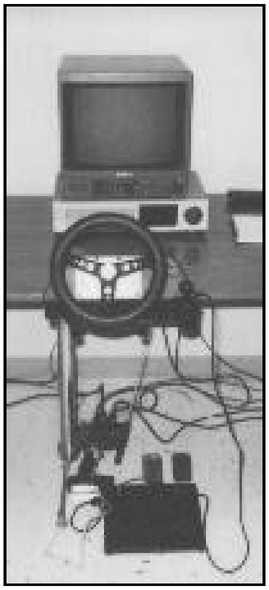

Figure 2.3. Driving station.

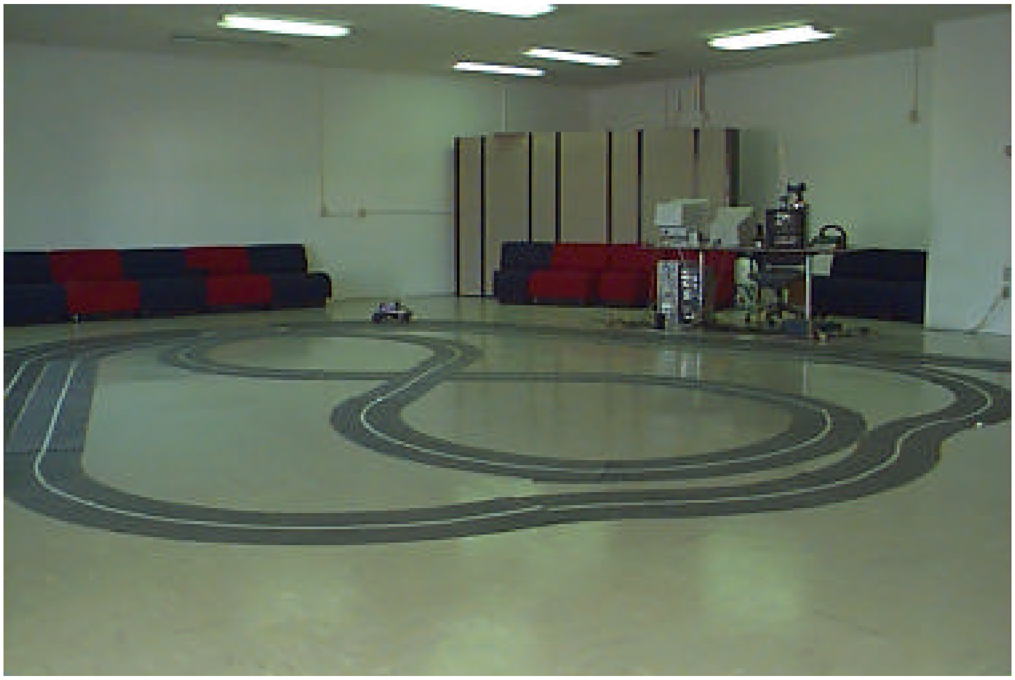

Figure 2.4. Test tracks and the control station in the FLASH Laboratory.

2.5.2. Smart Road

When completed, the ‘Smart Road’ [Smart94] will be a 6-mile roadway between Blacksburg and I-81 interstate highway in southwest Virginia, linking the Roanoke and New River Valleys. The first 2 miles is designated as a controlled test facility (Figure 2.5). It will be the first of its kind to be built from the ground up with an ITS infrastructure incorporated into the roadway. This full-scale test bed will provide controlled testing of a variety of ITS technologies and concepts with varied terrain and environmental conditions. Research involving crash avoidance, driver behavior, vehicle dynamics, sensors, and automated vehicle control will take place under a broad range of carefully controlled testing conditions.

For the roadway, an advanced communication system consisting of a local area, wireless network interfaced with a complete fiber optic backbone is planned. Thus, the road is designed to have the capability to service a multitude of sensors and messaging equipment concurrently. The test bed design also incorporates the ability to simulate a diverse range of weather conditions, from mild to severe (fog, rain, and snow). In addition, the all-weather testing area will overlap the variable lighting area to provide simulation capabilities for night driving conditions. To facilitate continuous testing, the road will be equipped with turnarounds at both ends. Overhead structures are designed to accommodate variable signing as well as overhead sensors. Two safety zones with 50-foot clearance areas and additional crash protection features for prototype testing of advanced in-vehicle systems are also planned.

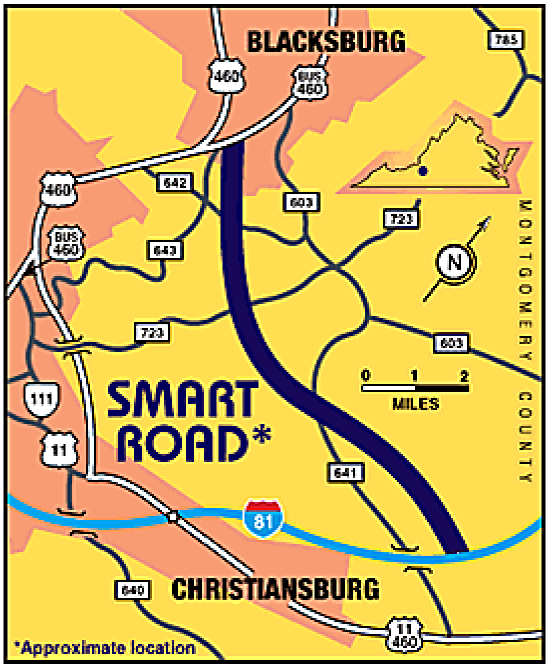

Figure 2.5. Location of the Smart Road.

2.6. A Simulation Tool for AHS Systems: *DYNAVIMTS*

During the last few years, many computer programs for microscopic and macroscopic level simulations of vehicles in an automated system have surfaced. *Paramics* (Parallel Microscopic Simulation) is currently used to find the reasons for large-scale congestions in the Controlled Motorway pilot project on the M25 highway in England, by dividing the the network into a number of regions [Duncan96, Cameron96]. *DYNAVIS* is another dynamic visualization package specifically designed for evaluating automatic control of vehicles [Xu96]. This package is part of a bigger effort by the California PATH program, *SmartPath* [Eskafi95]. SmartPath is a simulation package for an automated highway system, designed to provide a framework for simulation and evaluation of AHS alternatives. It is again a micro-simulator, *i.e.*, the functional elements and the behavior of each vehicle are individually modeled. SmartPath has two separate simulation and animation modules.

An example of a macroscopic simulation is KRONOS developed at the University of Minnesota [Kwon95]. It is a PC based simulation using a simple continuum modeling approach to evaluate the flow behaviors such as merging and diverging. Argonne National Laboratory’s prototype simulation includes the modeling of automated vehicles with in-vehicle navigation units and a Traffic Management Center (TMC) using distributed computer systems or massively parallel computer systems [Ewing95].

The Center for Transportation Research of Virginia Tech is developing a simulation package that models micro and macroscopic behavior of vehicles over a network. The software is envisioned to integrate the different research efforts at CTR into one comprehensive ITS software package. In the development of this tool, particular emphasis is given to modeling the AHS system based on the control architecture developed under the PATH program [Varaiya93]. The package is called DYNAVIMTS, Dynamic Visual Micro/Macroscopic Traffic Simulation Tool.

2.6.1. Software System Architecture

DYNAVIMTS is a multi-purpose AHS simulation software currently developed using different software tools and platforms [Kachroo96b]. It has a distributed system architecture enabling the user to distribute several time consuming functions of DYNAVIMTS to separate computers. The main simulation currently runs on a Sun^{â} Sparc 2000 Workstation. The output of the simulation is transferred to a Pentium PC which has animation software developed using OpenGL^{â}. DYNAVIMTS consists of three main modules: the Communicator, the Simulator, and the Animator (Figure 2.6).

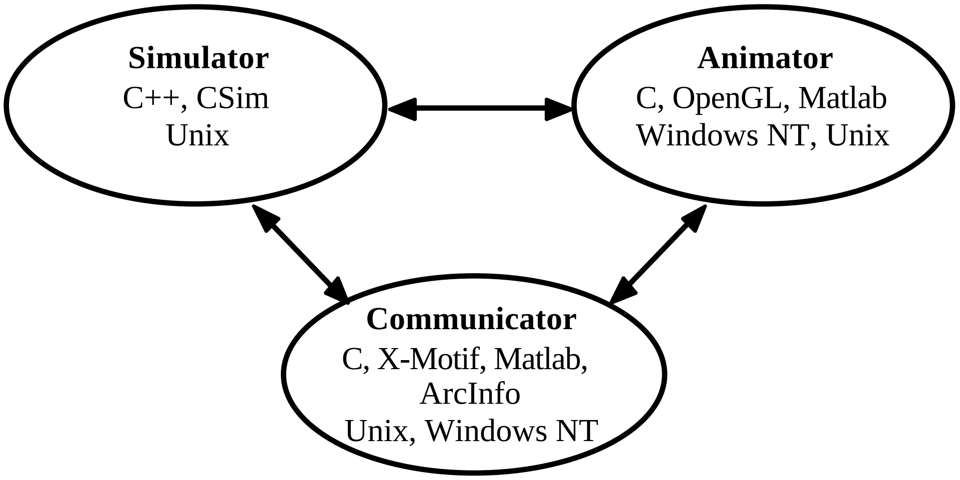

Figure 2.6. Software System Architecture

Depending upon the spatial dimensions of the problem at hand, macroscopic and microscopic simulation models will be used. For example, DYNAVIMTS is currently capable of studying the effects of vehicle dynamics on the stability of platoons. Incorporation of different brake technologies are also underway. DYNAVIMTS has a range of vehicle dynamics and control models that can be used for microscopic simulation studies. On the other hand, DYNAVIMTS is also designed to study the effects of highway automation on the overall traffic flow in the traffic network.

The simulation software is developed using C++ with CSIM libraries [CSIM96], and Matlab [Matlab96]. As we move toward the macroscopic models, the design of the package will be completely object-oriented, and multi-processor machines or parallel processing with multiple machines will become necessary. A detailed description of the DYNAVIMTS package can be found in [Nagarajan96].

2.6.2. Components of DYNAVIMTS

As mentioned above, there are three main modules in the DYNAVIMTS software package (Figure 2.7). The front-end graphical user interface (Communicator, Figure 2.8) is developed in C using OSF/Motif and Xt Intrinsics libraries on a Sun^{â} Sparc. The structure of the interface and the underlying modules again have been modeled based on the four-layer structure of the California PATH Program. The submodule for the network layer design calls ARC/INFO's ArcEdit [Arc96] utilities to construct the network. The GUI also consists of routines to invoke incident management software, traffic assessment algorithms, and other related programs to form the central part of an integrated ITS simulation package. The microscopic level simulator is a C++ program using CSIM libraries. There are three basic classes - vehicle, link and sensor. These objects interact among themselves and with the CSIM objects, through their member functions. The animation module is started after a run is executed by the simulator. The Animator consists of two components: graphical plots and animation. The graphical plots generated by Matlab give the detailed information about the control parameters and sensor data. The animation submodule is developed in C using OpenGL libraries on a NT^{â} workstation. The simulation data is currently transferred via a pre-formatted ASCII data file. This module also contains the graphical data for the planned Smart Road project. A detailed description of the package, its file structure and graphic user interface is given in [Nagarajan96].

The control structure we introduce in Chapter 4 is incorporated in the DYNAVIMTS simulation package as part of the planning layer simulator. Since the link layer development in DYNAVIMTS is not complete, the planning layer simulator on Matlab assumes that the link layer data is available (if at all necessary), and the resulting data is transferred to the animator submodule in the form of an ASCII file. At the end of each simulation run, the user is also able to use the GUI to plot different parameters and values using Matlab. The connection between the planning and regulation layers does not yet exist as is the case in similar simulation packages. A snapshot of the planning layer GUI is given in Appendix C.

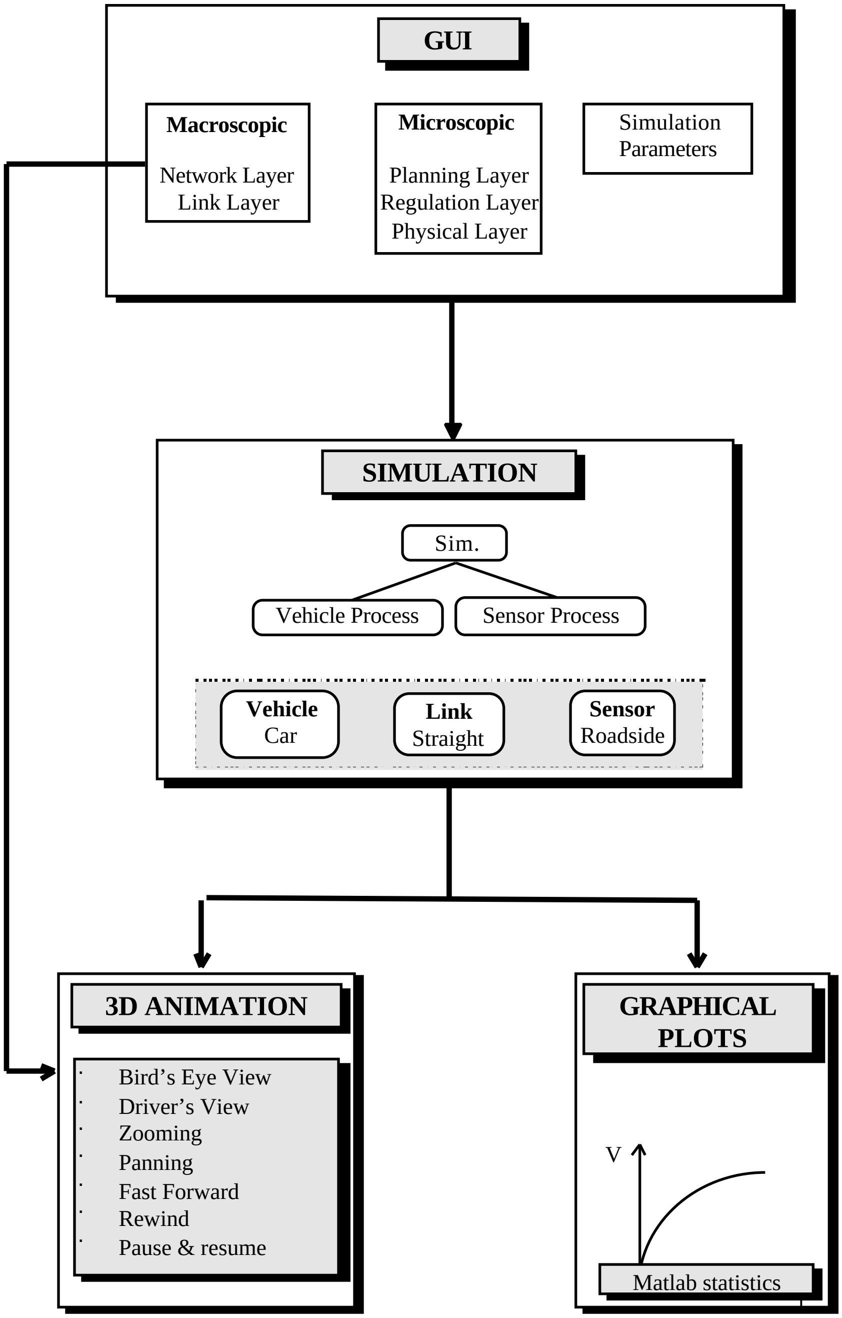

Figure 2.7. Components of DYNAVIMTS simulation package.

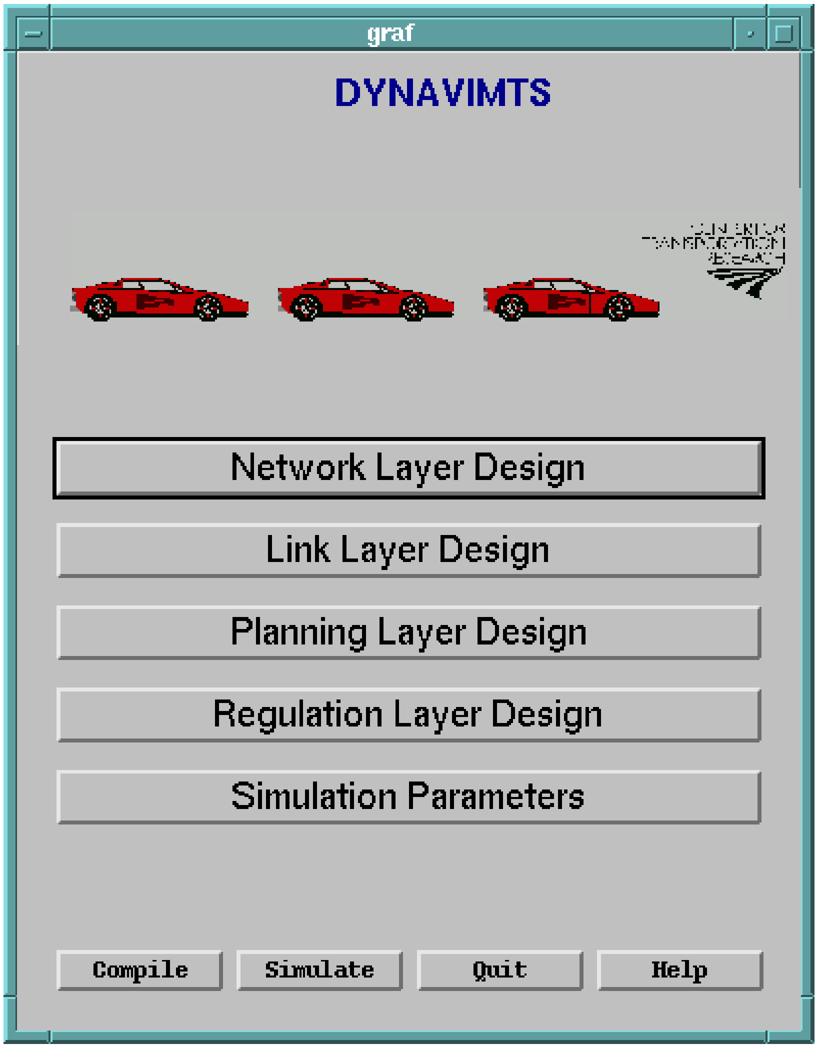

Figure 2.8. Opening screen of DYNAVIMTS [Nagarajan96].