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Flexible Low-cost Automated Scaled Highway (FLASH) Laboratory for Studies on Automated Highway Systems

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ABSTRACT

This paper addresses the development of a Flexible Low-cost Automated Scale Highway (FLASH) laboratory which is intended to serve as a catalyst for accelerating the development of many Intelligent Vehicle Highway System (IVHS) concepts. It also highlights the significance of the laboratory for the research, evaluation, and testing of Automated Highway System (AHS) configurations, architectures, designs and technologies. This laboratory, using small scale standardized vehicles will serve as a test bed for the economical development and evaluation of various hardware, software, and management systems before full scale testing and deployment.

The laboratory will provide the capability to test day and night, and will be immune to adverse weather conditions. It will be able to evaluate and test situations from various points of view including control, communication, routing, sensing, etc., which otherwise would be very expensive and dangerous —if human operators are involved— to test on test sites like Smart Road, a proposed testbed for ITS (IVHS) technology in Virginia. The development of this laboratory complements the development and utilization of the Smart Road, and is in harmony with the mission of the Center for Transportation Research.

1. INTRODUCTION

The present highway system in the United States is not adequate for the ever increasing demand made on it. Even with the present population, the transportation system has several problems which are evident by frequent traffic jams and the large number of highway accident fatalities. One of the various solutions to the transportation problem is to use Intelligent Transportation Systems (ITS), formerly known as Intelligent Vehicle Highway Systems (IVHS). The solution of just building more highways is not very attractive because of the high costs of land resource, labor, materials, etc. In fact, traditional solutions of expanding road capacity do not always relieve congestion, and in some cases can even make the condition worse [1]. U.S. DOT (Department of Transportation) has established an AHS program within the FHWA (Federal Highway Administration) under the DOT IVHS program office.

Systems Definition Phase of this program will define AHS performance and design objectives, identify and evaluate various AHS representative system configurations (RSC), demonstrate on a test track the technical feasibility of the AHS system in year 1997, choose a specific RSC, and construct a prototype of the chosen RSC so that it can be tested, evaluated and demonstrated [3].

The research community has done considerable work in the areas related to AHS, especially in the past few years [3,4,8]. Most previous research has used computer simulations for analysis and design of AHS. There are plans by some research groups to design complete software simulation packages for AHS. Computer simulations provide an economical way of analysis and design of these systems. However, there are limitations to software simulation. For instance the presence of crucial unmodelled dynamics of a system can not be predicted by analysis alone. Hence, there is a need for hardware testing for AHS. Some researchers have been using hardware for testing to a limited extent [5,17]. There is also some interest in making medium scale models of vehicles to experiment under such areas as longitudinal and lateral control. Testing of a complete AHS system however is very difficult, because it is a very big system, and also complex and inter-connected. Hence, testing of such a system will be very expensive.

The Flexible Low-cost Automated Scaled Highway (FLASH) laboratory, described in this paper, will provide a complete, standard way of analyzing, designing, and evaluating various system concepts and individual technologies by providing a crucial bridge between software simulation and full scale testing and deployment. The FLASH laboratory will be composed of tens of small vehicles which will be modular in design to provide flexibility in testing various configurations. These vehicles will run on a modular highway, which will also be flexible, so that various highway schemes can tested by making easy modifications. For instance, we can have different road geometry, use different surface conditions at different places, and change the weather

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conditions, etc. Finally, the laboratory will have a complete communication set up, to provide road-vehicle communication (RVC) as well as control center to control center communication for highway central supervision. It will also have the complete software to support the laboratory work with complete documentation. Connection to the Advanced Traffic Management Systems (ATMS) laboratory is also envisioned in the design. There will also be some other miscellaneous infrastructure for AHS related studies.

In the next section, we discuss the role of FLASH in ongoing AHS research. Section 3 defines the significance of the laboratory in AHS. The vision of the completed FLASH is given in Section 4, while the subsequent section discusses the plans for the completion of the laboratory. Current developments are mentioned in Section 6.

2. WHERE FLASH FITS INTO AHS PLANING AND IMPLEMENTATION SCHEME

The progression in AHS development from conceptualization to implementation has four steps according to our approach (Figure 1 and Table 1). The FLASH laboratory is envisioned as the second step in this four block configuration for a methodological evaluation and testing of AHS and technologies employed in the development and implementation of AHS. The first block is computer software simulation, which is preceded by mathematical modeling. The second block consists of conducting small scale experiments in the FLASH laboratory. Then, hardware tests comprising the third block, are performed on a test site with actual vehicles. The "Smart Highway" being built near Virginia Tech 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.

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-block process but, as having some feedback and feedforward loops depending on the results obtained at each block. For instance, FLASH lab could be used to improve the computer simulation.

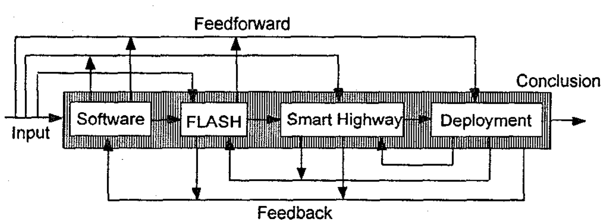

Figure 1. Four-Block Structure for AHS Evaluation Process

The FLASH laboratory can be seen as a precursor to a full-scale highway, and serve as a focal point for many separate but related aspects of the AHS program. The laboratory will provide a platform for experimental work as well as an arena for demonstration of AHS systems. The use of small low-cost vehicles with known mathematical models will be beneficial for researchers seeking to verify their computer simulations quickly and economically. These vehicles can be made available for researchers to use at their site prior to testing in the FLASH laboratory. The use of the standard vehicle eliminates some of the uncertainty due to particular vehicle models that make comparisons of different AHS approaches difficult. The laboratory can provide researchers with the vehicle as well as its verified mathematical model. Researchers can test various schemes, which have been proposed for automatic control of vehicles [5,13,12,6,9-11]. 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 future automated highway system. The FLASH laboratory will be extremely useful in the analysis phase the AHS development. Most of the activity areas of the Precursor Study Analysis (PSA) research sponsored by the Federal Highway Administration, such as urban and rural AHS comparison, automated check-in, automated check-out, lateral and longitudinal control, malfunction management and analysis, among others can be studied and analyzed in this proposed laboratory. We can create rural conditions on one scaled highway and urban conditions on another, and study the differences. We can also study different algorithms and strategies for longitudinal and lateral control. The laboratory and its vehicles can serve as a benchmark or standard through which various configurations, architectures, and technologies can be compared. The laboratory can be an integral part of the systems definition phase of the ongoing AHS program. Evaluation of alternative AHS system concepts, selection of a system approach based on analysis, test and evaluation, demonstration of prototype configuration of the selected program on a smaller (and cheaper) scale will be the focus of the laboratory. Furthermore, the laboratory can be used to obtain preliminary data for the third phase (Operation Evaluation) of the AHS program, and be a test bed for several issues which may not be tested on selected locations because of considerations of insurance and safety.

Stage	Software Simulations	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 1. Comparison of different stages.

Hardware tests are important since they provide the means to validate computer results or to modify them in case of discrepancies, due to unmodelled or inadequately modeled dynamics. Without hardware testing, it would be foolhardy to jump into actual implementation. Although testing with real sized vehicles will provide the most accurate results, it has some 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 the testing situation, which would involve humans, the costs can become prohibitive, and the situations dangerous, which could lead to insurance and safety problems. In order to test all infrastructure based systems, requiring complex communication scenarios, it might also become cost prohibitive. We can perform some tests like longitudinal and lateral control on individual vehicles, or a relatively small platoon of vehicles, by using real sized vehicles or medium scale vehicles, but in order to test real highway situations involving dense traffic situations with complex realistic scenarios of merging, splitting, exit, entrance, accidents, etc., we propose to use small scale vehicles (approximately 1:15 scale), designed in a modular fashion, so that they are flexible enough to incorporate different system configurations. The FLASH laboratory will be composed of tens of these small vehicles (of different sizes to show light and heavy), with a flexible highway system, and communication network. In addition to the gains described above, the FLASH laboratory concept can make the construction of specifically designed scaled highway configurations possible in a short period of time and at much less cost than would be required for the construction of a similar configuration for full scale testing.

It is also possible to use FLASH as a visual display of the computer simulations. Although this would not provide much contribution to research, it would be a good tool to showcase our software package being developed in the Center for Transportation Research (CTR) at Virginia Tech for specific AHS scenarios and configurations proposed by CTR and other research institutions (DYNAVIMTS) [14]. FLASH will also be used in conjunction with the ATMS laboratory being conceptualized at present for CTR [2]. We could simulate situations in order to study safety, fault tolerance, and also human factors. At the time when the actual AHS is implemented, the FLASH laboratory would still have enormous significance, since it could be used to ensure proper functioning of the system. In case of unforeseen problems, the laboratory could be used to test the ideas for enhancement.

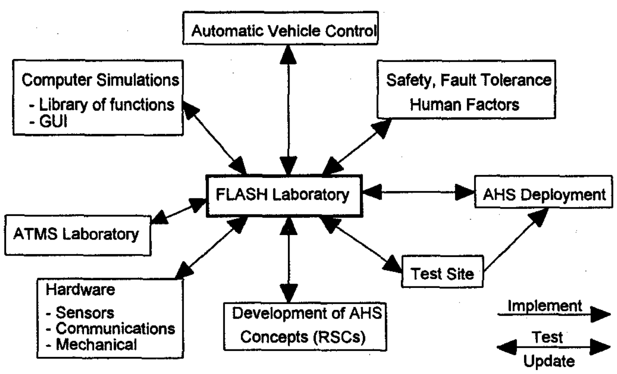

Figure 2. The Relationship of the FLASH laboratory to the AHS research.

Another advantage of the FLASH laboratory would be that, the development time and cost to create the scenarios for researchers for evaluating and testing their concepts would be short to moderate, as compared to development time needed at the test sites.

3. SIGNIFICANCE TO SMART ROAD AND INTERACTION WITH OTHER FACILITIES AND RESOURCES

Smart Road is a proposed 6 mile highway section connecting the town of Blacksburg, Virginia to I-81 south of Roanoke, Virginia, for evaluating and testing Intelligent Vehicle Highway Systems (IVHS) technologies. The studies, under the sponsorship of FHWA and Virginia Department of Transportation, are being conducted by the Center for Transportation Research at Virginia Tech. It is hoped that the Smart Road will be one of the test sites chosen by the AHS consortium for the demonstration of the IVHS technologies. The relationship of the Smart Road to FLASH will be the same as that of a test bed (see Figures 1 and 2). Any researcher, company, or research group (customer) who wants to use the Smart Road for testing and evaluation would have to test their product or concept at the laboratory first. Some customers might want to just use the laboratory and not use the Smart Road at all. Many concepts which will involve a large number of vehicles, will be unrealistic to test on the Smart Road, but would lend themselves to be very easily tested by FLASH.

FLASH Laboratory will be used in ongoing system analysis tasks of the Smart Road project. Some of the key issues identified for the Smart Road project are [15]: (1) development of feasible concepts, (2) conducting systems analysis studies, (3) assessment and evaluation of these concepts, (4) selecting and designing the promising concepts, (5) obtaining support from industry and federal government, (6) developing engineering requirements and specifications, (7) integrating into the road design, (8) developing specifications for road instrumentation, and (9) developing implementation strategies. FLASH will be an integral part in addressing and solving each of these issues. For instance, decision on distribution of functions between roadside and vehicle, and characteristics of hardware and communication may be based on the research done in FLASH, since it is much more expensive to implement everything on Smart Road.

FLASH laboratory will also provide essential feedback to AHS tasks defined in Smart Road for development and utilization of mathematical models relevant to vehicle dynamics. Testing of different models will be carried out easily and will require less time than it would take for implementation on test sites, thus greatly minimizing the development effort and time. The laboratory will also provide an easily accessible test bed during the early stages of simulation design process.

Furthermore, the amount of tasks that can be accomplished in developing AHS system in the Center is limited for the time. The realization of this laboratory will give the researchers an access to a relatively inexpensive facility for investigating many approaches already existing, and develop new ones, such as the Transponder Based AHS, and Intelligent Vehicle Control using Learning Automata [16], which are currently being considered in the Smart Road Project.

The research conducted in the FLASH laboratory will provide us with strong indications to the way the Smart Road development should take place. Experiments can be conducted specifically for that task to evaluate issues of which technologies should be installed at Smart Road, which kind of roadway should be built, what materials should be used, what communication infrastructure should we commit to, etc.

The FLASH laboratory will be a resource which facilitates the contributions of a diverse group of researchers toward the realization of Automated Highway Systems. This will be a primary platform for much of the work done by the Center for Transportation Research as well as other similar organization throughout the nation.

Other research groups on the Virginia Tech campus will also benefit from the capabilities provided by the laboratory. Since communication is a critical technology which must be developed for IVHS, the laboratory will provide a test bed for work done by the Fiber and Electro-Optics Research Center (FEORC), the Mobile and Portable Radio Research Group (MPRG), and the Satellite Communication Group. Various interfaces between vehicle operators and IVHS systems can be developed in FLASH by researchers in the Human Factors Laboratory.

4. VISION OF THE COMPLETED FLASH

Automated Highway System is a complex system, composed of sub-systems working together: Vehicles, Highways, Sensors, Communication System, Information System, and Control System. The environment, which is an external factor, is another sub-system, and has strong effect on all sub-systems. The laboratory can also be classified into software and hardware blocks. All the sub-systems, except for the external one, have software and hardware components.

4.1 Software

Software will be used for programming hardware devices like microprocessors, simulation of various dynamic systems, communication, and information processing.

The laboratory will have complete library of functions/behaviors for different vehicle and highway models, where we can interface them to a simulation environment easily. The library will have two components: one for high level languages (such as C, C++) where the subroutines will define control models and/or simple actions of individual vehicles to be interfaced into GUI, and one for low level languages (assembly) where the subroutine will be downloaded into actual on-board microprocessors.

Using a modular approach, any vehicle/highway system can be simulated on a computer where it is possible to easily switch between models and to change parameters in order to see their immediate effect on the global system. The low level subroutines corresponding to computer simulations (DYNAVIMTS [14]) will also be tested simultaneously on a scaled model and/or test bed, and reconfigured based on the feedback obtained from simulations and implementations. Some of the platforms we are currently using are mentioned in Section 6.

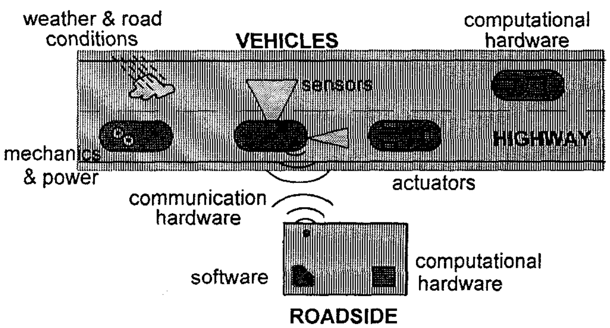

Figure 3. Sub-Systems of the FLASH Laboratory

We will have more than one computer for supervision of the highway. The computers will be networked together and will exchange information to operate different sections of the highway. Software will be used to accomplish the communication and information processing.

4.2 Hardware

The testing of the proposed AHS configurations in the Center for Transportation Research, Virginia Tech, and other institutions will be done using the hardware configured and realized in FLASH laboratory. The hardware considerations include sensing, communication, vehicle models/characteristics, structures (of highways), mechanical accessories for vehicles and miscellaneous issues such as materials to create artificial road conditions (greasy or icy surfaces, grade, fog, etc.).

4.3 Scaled Model Vehicle Design

We expect the vehicle models to have an approximate size of 20cm.×15cm.×10cm. These specifications will provide a simulation of a 2.5km. highway by a scale model of 100m (taking the average length of a car as 5m.). The vehicles will have an on-board microprocessor (68HC11) with several I/O ports for sensor data and communications, two-wheel drive, two-wheel steering, RF modem and battery pack as standard modules. The modular structure of the autonomous vehicles will enable researchers to incorporate different sensors, communication schemes and several vehicle characteristics concerning acceleration, steering capabilities, etc.

4.4 Sensors

We are initially planning to test ultrasonic and IR sensors for headway calculations and lane changing behavior of vehicles. Issues such as interference, effect of the weather conditions, investigation of new sensor types, optimal sensor positions and basic characteristics of sensors as well as homogeneity, can be addresses using (then) existing FLASH hardware. Use of "magnetic markers" [8] for lane keeping is one of the ongoing projects.

4.5 Communication

Several communication schemes such as RF broadcast, digital transmission, and transducers, have to be investigated as they prove to be promising approaches in AHS communications. The implementation of a (say) 10-vehicle platoon (or two 5-vehicle platoons using the same highway) with real communication devices will provide a more realistic evaluation of different schemes while avoiding the "traps" of a computer simulation and, the cost and risks of a full-scale implementation. The basic design of the scale models will take into account the possible hardware requirements of specific communication schemes.

5. PROPOSED PLAN

This section describes the steps needed for the development of the FLASH laboratory. The steps described below will generally be taken in parallel, although some research might be dependent on the completion of some other.

5.1 Study of Scaling Effects

In order to build this laboratory, we need to understand the scaling issues involved, so that the scale model will accurately represent the full scale environment. We will perform a literature survey, in order to benefit from any previous research done in this field. The study performed by SMARF [17] will show us how to build the vehicles preserving the vehicle motional dynamics. Scaling laws which preserve motional dynamics with respect to parameters like acceleration, jerk, braking and coasting distances, and maneuvering spatial requirements, will be used for the design of vehicles. The vehicle body shape will be designed to scale aerodynamic effects. Appropriate tires will be used for preserving road-tire interaction. Similar work will be performed on other subsystems of the laboratory, like the highway, communication system, etc. to ensure that all the scale subsystems truly represent the modeled system. After evaluating and verifying the scaling laws, all the subsystems of the laboratory will be built.

5.2 Design of Vehicles

The general strategy to build the scale vehicles will be the same as the one taken to build mobile robots in the Mobot Lab [7], with the exception that the scaling effects will be given important considerations. The study performed for scaling effects will probably decide various features of the vehicle such as the surface area, shape, and weight distribution. The scale model may look like the one shown in Figure 4, which is equipped with batteries, wheel encoders, headway sensors, etc. The construction can be divided into the following sections.

Computational Hardware: After evaluating the complexity of the performance needed, a processor will be chosen to perform computations for control and decision making. It is very likely that 68HC11 will be chosen as the processor.

Actuators: Actuators are needed for the vehicles to provide the motion in the longitudinal and lateral directions. In order to model existing vehicles, we will have one actuator for forward motion, and one for steering. We will evaluate different types of actuators like electric motors (direct current brushed, brushless alternating current type, etc.) and engines. Choosing electric actuators in the beginning will speed the development process considerably.

Sensors: There are various sensors needed for the vehicles. Initially, we need sensors for measuring headway between vehicles. These could be utilizing technologies like ultrasonic and infrared. We will also have sensors to measure vehicle speed, wheel angular velocity, and to determine obstacles on the sides of the vehicles.

Mechanics: This includes the chassis, wheels, axles, sensor mountings, weight, etc. Most of these will be decided by the scaling study results, as well as technology available. We will plan to keep the structure flexible, so that the same vehicles can have variable weight and length in order to model different classes of vehicles.

Power: The vehicle will need power for actuation as well as for running its processing hardware. The power for processing will be electric, and will be provided by a suitable battery, which will be re-chargeable. The power needed for actuation will depend upon the kind of actuation chosen.

Communication Hardware: Depending on the communication system used between the vehicles and the highway, the corresponding hardware will have to be installed on the vehicles. These could be just passive receivers, active transmitters, or both. These could also include an RS-232 connection.

Software Requirements: The software on the vehicle will be needed for programming the processor on board. This can be done in assembly or a higher level language using a compiler. The software will have modular characteristics in order to create multi-purpose scale model vehicles. Reprogramming will be achieved using E(E)PROMs or, better yet, serial communications via radio modems (as is the case in the prototype vehicles).

5.3 Design of Highway System

The highway system will have many components, and can be divided into the following sections.

Mechanical Parts: The mechanical parts for the highway include various lanes with either fixed or variable geometry. This will depend on the material chosen for the highway. If the material is flexible, we might be able to just physically bend the lanes into the required shape. On the other hand, if the material is rigid, we will identify the basic shapes needed to represent the whole range of highway geometry. The scale structure will represent the kinematics of the actual highway. For instance to study control laws for merging of automated vehicles [18], we will construct a highway with an entrance and a representative kinematic shape.

Sensors: We will also need sensors used by the highway system. For instance, we might use probes to find out the velocities of vehicles. Magnetic markers for lane following and speed detection are also part of the highway system.

Communication Hardware: We will need the communication hardware for the highway infrastructure. This would depend on which communication structure is being used. This would correspond to the communication used on the vehicle, as well as to the communication used between various computers used to control different parts of the highway.

Software: Software will be used for supporting communication, information processing and decision making. Software platforms will be decided based on the computer hardware chosen, which would be networked PCs and/or Workstations.

Miscellaneous: We will also need some chemicals for producing different weather conditions and road conditions. We will also develop facility for performing peripheral experiments, such as traction control on tires. The system will consist of a dedicated computer, data acquisition board and some related hardware.

6. CURRENT DEVELOPMENTS

We are currently developing the simulation software for vehicle following using traction control, combined longitudinal and lateral control of vehicles, and intelligent vehicle control using AI methods [16]. The preliminary results of these experiments will be published in subsequent papers. Furthermore, design of the graphical interface is underway. Several programming and operation system platforms are used (e.g., C/C++, OpenGL, Matlab, Simulink, and Nonsim). Structure of the data files is being standardized in order to obtain optimum compatibility.

Current communication hardware is based on spread spectrum radio modem technology. We are currently using ultrasonic sensors for headway detection; the use of proximity sensors for additional on-board sensors is considered. Magnetic sensors seem to be a feasible choice for lane keeping and vehicle speed calculations, and the design of magnetic sensors is underway. The system for studies on traction control is also one of the projects under consideration.

The design of the first scale-model vehicle is completed; the prototype consists of an ultrasonic sensor, a motor controller and a radio modem controller by a 68HC11 microprocessor board, and is designed for maintaining the desired headway distance. The model vehicle design is also being updated.

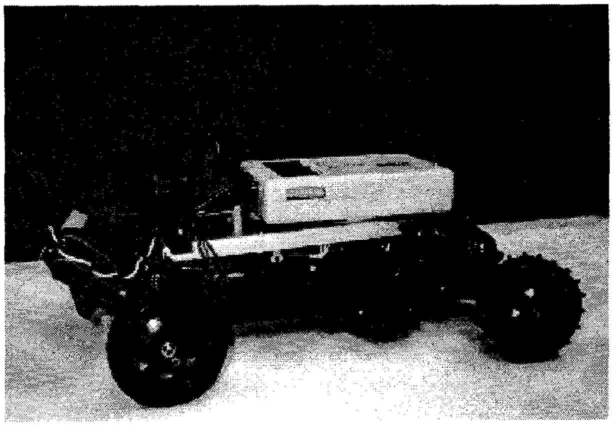

Figure 4. Prototype *FLASH vehicle*

Preliminary tests can soon be performed[1] for simple scenarios such as involving small platoons of 2-5 vehicles. Also, researchers at Virginia Tech Center for Transportation Research in conjunction with the Virginia Department of Transportation are working on the

[1] Projected date is September 1995.

design and planning of the Smart Highway which will be built near Virginia Tech. The Smart Highway will be the first automated highway built from the ground-up and designed to serve as a test bed and test track for AHS technology.

7. CONCLUSION

In conclusion, due to aforementioned advantages, we have planned a low-cost flexible, automated scaled highway laboratory, which can be easily developed at the Center for Transportation Research at Virginia Tech with the support of the University and Industry to enhance the study of Automated Highway Systems in general, and support the development of the Smart Road in particular.

8. ACKNOWLEDGMENTS

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