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SCALE MODEL AHS RESEARCH FACILITY (SMARF)

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This investigation was completed as part of the ITS-IDEA Program, which is one of three IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in surface transportation. It focuses on products and results for the development and deployment of intelligent transportation systems (ITS), in support of the U.S. Department of Transportation's national ITS program plan. The other two IDEA programs areas are TRANSIT-IDEA, which focuses on products and results for transit practice in support of the Transit Cooperative Research Program (TCRP), and NCHRP-IDEA, which focuses on products and results for highway construction, operation, and maintenance in support of the National Cooperative Highway Research Program (NCHRP). The three IDEA program areas are integrated to achieve the development and testing of nontraditional and innovative concepts, methods, and technologies, including conversion technologies from the defense, aerospace, computer, and communication sectors that are new to highway, transit, intelligent, and intermodal surface transportation systems.

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EXECUTIVE SUMMARY

SRI International was awarded a contract by the Transportation Research Board's (TRB) Intelligent Vehicle-Highway Systems (IVHS) IDEA Program to explore the potential application of physical scale modeling techniques to the development of Automated Highway Systems (AHS). AHS is a significant and challenging program element in the IVHS arena which has, as its goal, full vehicle and roadway automation. Scale modeling of the AHS problem is a unique concept developed by SRI International in an attempt to provide a safe and cost-effective route to development of AHS and related subsystems.

The Scale Model AHS Research Facility (SMARF) was proposed to the TRB as the seminal step in the build out of an innovative testbed capability for AHS development. SRI International proposed to develop an innovative scale-model of AHS vehicles. Once developed, the system would embody the dynamics realism necessary to portray an automated driving process on specialized roadways while saving development cost and time, reducing safety risks, and offering repeatability and accuracy of test scenarios. The concept initially proposed to the TRB was a scale model consisting of two vehicles, both under automatic lateral and longitudinal control. The lateral and longitudinal sensors proposed were small radar systems which would be built into the model cars during the course of the SMARF project. The cars selected, l/4 scale, were designed for the scale model racing hobby industry.

SRI's proposal to the TRB was viewed, correctly so, as a high risk venture due to the innovative nature of the concept in conjunction with the anticipated difficulty of resolving the sensor and dynamic scaling issues. Accordingly the TRB suggested that the proposed scope be reduced to establish the feasibility of the idea. A two step approach was used. First, a paper concept study was performed wherein the feasibility of scaling was explored. Second, having established scaling feasibility, a longitudinal control scheme was to be implemented and demonstrated using lead and follower scale model vehicles.

Several key project milestones were met. SRI analytically established the feasibility of the scaling concept. Once feasibility was established via paper and computer analysis, the go-ahead was given to initiate implementation of the longitudinal control scheme. As anticipated, most of the vehicle chassis functions were readily available off-the-shelf with some modification required. Problems were first encountered, and continued, in the area of the sensor and control subsystems. The key problem was the radar sensor employed. This sensor was obtained off-the-shelf and modified to operate in the SMARF environment. However, it was not possible within project resource constraints to overcome the problem of ground clutter interfering with the lead vehicle radar return. This made the task of acquiring and maintaining distance between the lead and follower vehicles impossible.

An integral part of the investigation was the development of scaling laws which are designed to allow AHS developers to translate small-scale vehicle results to the full-scale vehicle. Careful design of the scaling laws makes it possible to determine, prior to full-scale system or subsystem component development, what the various operating requirements for the full-scale system should be. This would apply particularly to actuator components, control loop cycle times, actuator position and velocity sensors, and to larger subsystems such as automated vehicle collision avoidance systems and associated sensors. Further, a comprehensive set of SMARF small-scale tools would encompass the interaction of the vehicle with the roadway infrastructure. Various competing schemes are being proposed by the AHS community to trade-off sensing, communications, and processing loads required by any AHS between on-board vehicle components and infrastructure-based components. SMARF could be employed to aid in the down selection process between competing schemes by actually implementing each one and running a statistically significant number of tests.

The most significant finding of SRI's investigation was that radar sensors employed in a scale environment require additional engineering for adaptation to longitudinal control applications. Indeed, research indicates that some manufacturers of collision avoidance radar systems for full scale vehicles are experiencing clutter related problems as well. The scope of this problem cannot be underestimated. Application of radar to precise station keeping or control functions for vehicle collision avoidance must be extremely reliable and requires dedication of research resources that were underestimated in the current investigation.

Notwithstanding the control and sensor problems several features of the investigation beyond our analytical analysis did yield positive results. For example, a brief study was undertaken, as part of the larger investigation, to explore the market potential of the SMARF concept for the transportation industry. Three major areas were identified as potential markets for the SMARF concept:

- Automated Highway Systems
- Safety Research
- Product Evaluation

It is anticipated that additional research and development could overcome the problems with the radar and control subsystems which were experienced with the current investigation. SMARF research is also being broadened by SRI, using internal research and development funds, to employ longitudinal and lateral GPS control using carrier phase techniques to provide the centimeter-level accuracies demanded from control systems in these scale ranges.

I IDEA PRODUCT

SMARF is intended as an innovative scale-model of an AHS vehicle system, the first step in the build out of an innovative testbed for AHS development. Once fully developed, the system would embody the dynamics realism necessary to portray an automated driving process on specialized roadways while saving development cost and time, reducing safety risks, and offering repeatability and accuracy of test scenarios. An integral part of the current investigation has been the development of scaling laws which are designed to allow AHS developers to translate small-scale vehicle results to full-scale vehicles. Careful design of the scaling laws permits researchers to determine, prior to full-scale system or subsystem component development, what the various operating requirements for the full-scale system should be. This applies particularly to actuator components, control loop cycle times, actuator position and velocity sensors, and to larger subsystems such as automated vehicle control systems (AVCS) and associated sensors. Further, a comprehensive set of SMARF small-scale tools would encompass the interaction of the vehicle with the roadway infrastructure.

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II CONCEPT AND INNOVATION

Various competing schemes are being proposed by the AHS development community to bade-off sensing, communications, and processing loads required by any AHS between on-board vehicle components and infrastructure-based components. SMARF could be employed to aid in evaluating competing schemes by actually implementing each one and running a statistically significant number of tests to make meaningful performance trade-offs.

It is reasonable to expect that a scale-model approach to development of AHS sensor and control systems could result in significant cost savings during the AHS life cycle. Like computer simulations of AHS, the scale-model approach cannot by itself be used for development. However, it serves as an excellent bridging technology between computer simulation and full-scale development and test. Through the development and implementation of dynamic scaling laws SMARF could provide data on inter-vehicle station-keeping dynamics, cornering, acceleration, maneuver rates, and jerk that can be readily converted to full-scale data. This is important, because due to the dynamic requirements imposed on AHS vehicles little test data exists which can be used to validate computer simulations. Thus SMARF, coupled with computer simulation and a judicious selection of full-scale tests, has the potential to safely and cost-effectively provide a significant research and development test bed and database on vehicle dynamics and sensor and control system operations.

III INVESTIGATION

The project proceeded in two distinct but coupled stages. Stage I was dedicated to establishing the applicability and feasibility of scale modeling as it pertains to AHS development. Stage II entailed the fabrication of a two scale-model vehicle longitudinal control scheme.

A. STAGE I INVESTIGATION

During Stage I a methodology for determining the applicability of scale modeling to AHS and subsystems was developed. Fundamental to the methodology was selection of candidate AHS systems and subsystems which are amenable to scaling. Four technical issues needed to be resolved:

(1) Restrictions placed on sensor and associated subsystems at scale sizes,

(2) Feasibility of accommodating sensor and control processing hardware in a scale vehicle,

(3) Scaling requirements of sensor operating frequencies (as may be the case with some radar and radar mode ranging systems), and

(4) Scaling laws necessarily treat high-order vehicle static and dynamic parameters disproportionately with first-order terms, such as velocity or turning rate, resulting in severe departure from full-scale dynamics as the scale factor is increased.

The first two issues are related in that the problem of accommodating sensor and processor hardware due to their physical size is exacerbated as the scale factor is decreased. Thus, one can see that it would be difficult to fit a radar sensor, associated signal conditioning and processing hardware, and controller hardware in a l/10-1/20 scale vehicle. The real problem here is two-fold. First, for a l/10-scale model, length has shrunk by a factor of 10 but volume has shrunk by a factor of 1000 ($v=kL^3$)! This would mean that a full-scale vehicle weighing 2500 lb would be represented by a scale vehicle weighing 2.5 lb. The scale model hobby industry produces l/l0 scale cars and trucks with a high degree of scale fidelity. However, in these cases there are only three major components that need be present: power plant (gas or electric), remote receiver, and actuator servo-mechanisms (servos). Scale cars used for hobby and sport are typically remotely operated and the on-board receivers, due to Very Large Scale Integration (VLSI) and surface mount technologies, can be as small as 1 cubic inch in volume and can weigh less than 2 ounces.

For SMARF, various additional components are required. In addition to the power plant and servos SMARF scale vehicles could ultimately require solid state rate gyroscopes, accelerometers, inclinometers, on-board controller, sensors and associated signal conditioning hardware, and sufficient electric power to supply the electronics, antenna, and telemetry transmitters. The SMARF research team estimates that these equipments can reach a total weight of about 15 to 20 lb. Thus payload requirements tend to drive the scale factor nearer to full-scale proportions.

The second problem is related to the sheer size of proposed controllers and sensor systems. In the extreme example where a large amount of control processing is required, with attendant large computer capacity, the controller will simply not be accommodated in the vehicle itself. SRI researchers have dealt with this problem on other programs where it is critical that the model have a high degree of fidelity, be of relatively small scale, and thus its associated controller cannot fit inside of the model. In these instances SRI has successfully mounted the controller hardware off-board and placed only the sensors and actuators on the model. The controller receives inputs from the sensors via high speed telemetry. Actuators on the vehicle respond to controller commands via telemetry links as well. Our research to date indicates that processing demands which would require the controller to be placed off-board (due to hardware size) may occur invision-based and image processing controllers. Most other sensor technologies that are potential AHS or AVCS candidates are available in packages small enough to easily tit on a vehicle in the l/4 scale range of SMARF.

The third issue, sensor frequency scaling requirements, is crucial since it may limit the fidelity with which SMARF vehicles can reproduce scale longitudinal and lateral tolerances between vehicles at AHS speeds. IVHS-AHS literature reviewed during our investigation reveals that inter-vehicle spacing (headway) requirements range from four meters to as little as one meter +/- one centimeter. Headway requirements apply throughout the AHS highway speed range which could be one hundred miles per hour (MPH)! The issue here is that for SMARF vehicles, using a linear scaling factor "p" (where $p<l$), the headway requirements are commensurably reduced by p for the scaled vehicles. For example, if $p=l/l0$ then the SMARF headway requirement would be 1 decimeter ±2.5 millimeters.

It would seem that the 1 meter headway requirement is infeasible, even at full scale, since automobile suspension systems, including tires, can allow several centimeters of longitudinal body motion, resulting in intolerable longitudinal headway control system instability. This, in turn, would lead to unacceptably high forces and jerk functions transmitted to the vehicle under these tight tolerances. However, a headway requirement of 12 feet ±3 feet seems reasonable. Depending on the sensor technology and ranging technique employed in SMARF, the operating frequency of the sensor will have to be increased to obtain meaningful results in SMARF. Preliminary investigation of available radar sensors indicated that SMARF vehicles would be able to use carrier phase radar ranging and maintain the required headway at specified tolerances.

Finally, it is necessary that the scale factor used in actual testing of the model vehicle's station-keeping within a platoon, or with respect to the infrastructure, not be so large that the model's motion parameters (such as accelerations caused by pitching over a bump or cornering) become disproportionately out-of-scale with respect to the full-scale vehicle. Satisfying the scale model's capabilities to maintain headway, for example, throughout platoon perturbations must be traceable to the full-scale vehicle's behavior in the same scenario, or the value of scaling will have been lost. Here again we have found that scale factors exceeding 5 or 6 (scale models l/5 or l/6 as long as the full-scale vehicle) result in just such difficulties, based on scale-model hobby literature reviews.

1. Scale Factors Analysis

Dynamic scaling laws were explored which will be required to replicate, with high fidelity, full scale vehicle dynamics. By employing the scaling laws it was possible to identify potential scaling infidelities which arise due to non-scaling parameters. In each case non-scaling parameters were analyzed and incorporated into a computer model of vehicle dynamics. The complete set of dynamic equations that fully describe the motion of a full-scale automobile in three dimensions are both non-linear and very complex. Fortunately, to illustrate the physical scaling issues that arise when a p ($p<l$) scale model is used to represent the full-scale automobile only a much simpler set is needed. Consider the motion of a vehicle traveling in the positive x-direction on a relatively flat surface. The differential equations that describe this motion are given by:

$$x'' = [T_X(t) - ax'^2 - bxmg] / m$$

and

$$z'' = [Tz(t) - mg - kz - dx'] / m$$

where x, x', and x'', are the distance, velocity and acceleration in the x-direction, z, z', and z'', are the distance, velocity and acceleration in the z-direction, m is the mass of the automobile, Tx and Tz are the applied forces in the x- and z-directions, a is the coefficient of drag, b the coefficient of friction, g the gravitational acceleration, k the spring constant, and d the damping constant associated with the automobile shock absorbers. To differentiate between the parameters associated with the full-scale automobile and small-scale model the subscripts f and s are used.

By choice the length of the scale model is p times the length of the full-scale automobile, hence, the volume of the scale model is p^3 times the volume of the full-scale automobile. Assuming the density of the materials in both the scale-model and full-scale automobile are the same, the mass of the scale-model (m_s) is p^3 times the mass of the full-scale automobile (m_f) Similarly, distance, velocity, and acceleration for the scale model (x_s, x_s', x_s'' is p times the values for the full-scale automibile (x_f, xf, x_f'') Multiplying p times the full-scale equations of motion gives

$$x_s'' = px_f'' = [pT_{xf}(t)]/m_f - [pa_fx_f'^2]/m_f - [pb_fm_fg_f]/m_f$$

and

$$z_s'' = pz_f'' = [pT_{zf}(t)]/m_f - [pm_fg_f]/m_f - [pk_fz_f]/m_f \; [pk_fz_f]/m_f$$

Equating term by term with the small-scale equations of motion and inserting $m_s=p^3m_f$ gives for the x-component,

$$[pT_{xf}(t)]/m_f = T_{xs}(t)/(p^3m_f)$$

$[pa_f x_f'^2]/m_f = [a_s x_s'^2]/(p^3 m_f)$

$[pb_f m_f g_f]/m_f = [b_s m_s g_s]/(m_s)$

and for the z-component,

$[pT_{zf}(t)]/m_f = [T_{zs}(t)]/(p^3 m_f)$

$[pm_f g_f]/m_f = [m_s g_s]/(m_s)$

$[pk_f z_f]/m_f = [k_s z_s]/(p^3 m_f)$

$[pk_f z_f]/m_f \; [k_s z_s]/(p^3 m_f)$.

Finally, substituting $x_s = px_f$, $z_s = pz_f$ and their derivatives gives,

$p^4 T_{xf}(t) = T_{xs}(t)$

$p^2 a_f = a,$

$pbf = b_s$ (using the fact $g_f = g_s$)

$p^4 T_{zf}(t) = T_{zs}(t)$

$pg_f = g_s$

$p3k_f = k_s$

$p^3 d_f = d_s$.

The above equations determine the values of scale-model parameters that ate required for the model to accurately represent the full-scale automobile motion. For example, if the scaling p is chosen to be l/4, then the applied x and z thrusts are l/256 of the till-scale thrusts, the drag coefficient is l/16 of the full-scale drag coefficient, the spring and damping coefficients are l/64 of the full-scale spring and damping coeffkients, and the scaled gravitational acceleration is 1/4 of the full-scale gravitational acceleration. By appropriate design of the scale model all of the variables can be set to their appropriate values except, of course, for gravitation. Scale-model gravitational acceleration is four times the value necessary for precise representation of the full-scale automobile. previous work at SRI in scaling vehicles for analysis of vehicle crashes has shown that in most cases the unscaled gravity does not significantly affect the results of the study. In some other cases were the gravity effect was important additional components were added to the scale-model to better represent the full-scale system. The non-scalability of gravity indicates that the scale-model will not precisely represent the full-scale system, but knowing which accelerations and forces do not scale prior to designing scale-model study will significantly minimize the impact of this loss of precision on the study's results.

2. SMARF Radar Sensor

Radar was selected as the headway maintenance sensor for our investigation. Radar is a mature full-scale technology which in recent years has been rejuvenated by the advent of VLSI, micro-miniature components, and surface mount technologies. The potential problem for SMARF, as mentioned earlier, is the ambiguous requirement to scale sensor frequencies. SRI's research experience coupled with a review of technical literature on the subject reveals that several methods exist to circumvent the perceived need to scale up radar frequencies. Pulsed radars would probably be prohibited for the scale vehicles due to extremely precise timing required to clock the time of arrival of the return pulse to derive range to the lead vehicle. To meet a lcm range resolution requirement with a pulsed radar the clock would have to be able to resolve timing down to 0.04 nanoseconds (ns). These timing requirements imply a radar sensor system having a 20 GHz bandwidth, and may make it impractical for SMARF. Frequency Modulation (FM) altimeter radars suffer from a similar timing problem in that the frequency ramping required of the carrier must be tightly controlled by a clock for later comparison with the return pulse. However, by combining waveform ranging modulation with echo carrier phase measurement, these timing and bandwidth requirements can be alleviated.

Carrier phase radar ranging employs a simple transmitter and a homodyne receiver. Small amounts of transmitted carrier energy are allowed to spill into the receiver front-end. Thus the radar return is compared directly with the transmitted carrier thereby eliminating the need for precise waveform modulation, clocking, and demodulation. The phase comparison yields a phase difference (angle) between the transmitted and received energy, which is directly proportional, in this application, to the distance to the lead car. At 1 gigahertz (GHz) 1 cm will exhibit an easily measured 12 degree phase difference. By also applying waveform modulation, or, conversely, multiple radar carrier frequencies, ambiguities in range inherent in phase-measurement ranging systems are eliminated.

B. STAGE II INVESTIGATION

Based on analyses and encouraging results obtained in our Stage I investigation, a scaling factor of l/4 was selected for implementation. Three factors contributed to the selection of l/4 scale:

- Scale parameters (acceleration, velocity, weight, and energy) in a l/4 scale model are well within measurable tolerances;

- Vehicle volume constraints are such that application of miniaturized sensors, actuators, and telemetry is possible; and

- High availability of low cost, off-the-shelf l/4 scale vehicle components including chassis, articulated suspension systems, power plants, and actuators.

The vehicles are approximately 40 inches long by 13 inches high. The suspension system was selected to provide the dynamic fidelity required to emulate a typical full scale vehicle suspension system. To this end, a front end was selected having independent left and right wheel suspensions with upper and lower control arms and a McPherson strut-type of shock absorber arrangement. The rear axle has a five point suspension system with a rigid axle. This axle has been modified to allow full differential power drive. It is expected that this arrangement can adequately reproduce the dynamics required for full-scale emulation.

The scale chassis was acquired from a vendor which services the model racing market. A high torque brushless direct current (dc) motor was selected as the vehicle powerplant. Selection of the dc motor was based on its capability to produce high torque throughout the entire scale speed range which would allow for more flexibility in reproducing full-scale vehicle dynamics attributable to internal combustion engines. These include acceleration, deceleration, coasting, etc.

Each vehicle is equipped with a rudimentary disk brake system located on the rear axle. This brake system will be used to maintain emergency control over a remote link and preclude crashes during testing. Normal deceleration will be by power plant loading upon power reduction.

An off-the-shelf single board computer was originally selected to perform the station keeping and sensor acquisition functions on the follower vehicle. The controller is made up of an erasable EPROM and a basic interpreter plus some analog interface components. Since the unit is a self contained computer which fits in a 2.5 inch by 2 inch package and requires a 9 volt supply current it makes it very convenient for SMARF vehicles. Due to its inherently small size and power consumption requirements several of the controller units could be employed on the follower vehicle if required. Programming the unit is done through a parallel printer connection to a personal computer.

Some experimentation and further research into the vehicle control function indicated that digital control would be inadequate to satisfy the timing requirements of the control loop. To overcome the timing requirements a combination radar processor-control unit was obtained and modified to generate the proper signals (sent to the motor controller) based on headway distance.

The controller was interfaced to the dc propulsion motor controller (supplied with each motor) as well as to the sensor and actuator circuits. All other actuators, such as steering and brakes, on both the lead and follower vehicles are standard model industry l/4 scale servo-mechanisms (servos). Servos are controlled by the user from a standard model radio control unit for each vehicle for automatic longitudinal control system override. The lead vehicle is controlled via a standard model radio control set.

An X-band emitter/receiver arrangement was intended for longitudinal relative station-keeping. A homodyne circuit was selected for the receiver to eliminate the need for frequency synthesis in the scale model. (A full-scale car on a highway where other vehicles could cause emission interference would require far better frequency control.) Coded passive reflectors on the lead vehicle provide the echo coding needed for automatic detection and ranging on that vehicle.

As anticipated, most of the vehicle chassis functions were readily available off-the-shelf with some modification required. Problems were first encountered, and continued, in the area of the sensor (via radar clutter) and control subsystems (via lack of a lateral control system):

1) The ground immediately in the forefront of the rear vehicle (which carries the radar) is so much closer to the radar antenna than the lead vehicle, and has such a large radar cross section, that it contributes a high level of clutter to the radar receiver. These observations were derived from radar bench test results. For this reason the lead vehicle radar cross section had to be increased through the use of resonant antenna elements (dipoles and a reflector).

2) The reflector then had excessive azimuthal gain, and was visible by the rear vehicle's radar only when the tear vehicle was "aimed" directly at the lead vehicle, and the lead vehicle was oriented directly away from the rear vehicle.

3) The timing involved in controlling the vehicles was such that a digital processor approach was seen to be cost prohibitive. An analog processor tightly integrated with the radar sensor was the chosen method for longitudinal control.

4) The speeds involved and timing required made manual lateral control impossible. This in turn required the follower vehicle to implement some method of automatic lateral control.

Solutions to these problems proved to be beyond the available project resources; however, SRI believes these problems could be surmounted to provide a valuable SMARF research and development tool.

IV PLANS FOR IMPLEMENTATION

A new direction of research needs to be identified for SMARF in order to establish its own unique place in the AHS and AVCS research fields. The following are proposed research areas as potential markets for SMARF. They are divided into:

A. Automated Highway System Area

B. Safety Research Area

For each topic, the importance and urgency for conducting the research is ranked as high, medium, or low. The time framework within which the research project will be delivered to the market is stated as short term (within 6 years), medium term (within 10 years), and long term (beyond 10 years). Whether this research topic is complementary or duplicative of the current SMARF research efforts or is a totally new effort is also indicated. The size of the research effort that needs conducted compared to the current effort is also indicated by a qualitative measure (small, medium, or high). The constraints that could act as bottlenecks for conducting the research are also briefly mentioned. The potential sponsors of the research topics are also stated mentioned.

Discussions of the topics and research areas follows. An alternative sensor approach for SMARF based on the Global Positioning System (GPS) is described briefly at the end of this section. A detailed description, being implemented by SRI using IR&D funds, is provided in the Appendix to this report.

A. AUTOMATED HIGHWAY SYSTEM (AHS) AREA

The National AHS Consortium (NAHSC) has defined the following functions for AHS:

- I) Destination selection
- II) Entry
- III) Vehicle and driver validation
- IV) Transition to automatic control
- V) Merging
- VI) Completed Automated Travel
- VII) Exit
- VIII) Vehicle and driver check-up.

The NAHSC has also identified the following constraints:

- a) Affordable
- b) Marketable
- c) Support dual mode vehicles
- d) Safe and reliable
- e) Accommodate trucks and busses
- f) Support inter-modal travel.

The above functions and constraints have been taken into account in the development of the potential research topic areas:

1. AHS-1 - Mixed Vehicle Longitudinal Control

To limit the AHS operation to cars only is unrealistic. To provide separate additional AHS lanes for trucks and buses is economically infeasible. Therefore it is imperative to include mixed vehicles in the AHS traffic stream.

Urgency/Importance	High
Timing	Short-Term
Complementary/Duplicative/New	Complementary
Size of Effort	Small to Medium
Constraints	Size of truck and bus
Potential Clients	FHWA, AHS Consortium, Truck and Bus Operators, and Manufacturers
Potential Gains	Medium to High

2. AHS-2 -Merging Into and Leaving an AHS Traffic Lane

The operations of merging into and leaving from an AHS traffic lane are quite complex. They involve several traffic variables as well as various highway geometry constraints. These types of complex operations could come from an entrance ramp to the AHS lane or leaving the AHS lane to an exit ramp, or could come from a non-AHS traffic lane which runs parallel to the AHS equipped vehicles would like to merge into the AHS lane.

The National AHS Consortium in all likelihood would not be able to physically demonstrate these operations in a live environment because of safety considerations and because it involves closing entrance and exit facilities to a freeway. Merging become extremely difficult to demonstrate if it is taking place from a non-AHS traffic lane, even in a controlled test-track environment. SMARF has an assistance role to play in this AHS function. SMARF research emphasis should be directed towards the merging functions and requirements from non-AHS lane to an AHS lane.

Urgency/Importance	High
Timing	Short-Term
Complementary/Duplicative/New	Complementary and New
Size of Effort	High
Constraints	(1) Increase in the number of SMARF equipped vehicles (2) using two lanes instead of one for demonstration (3) introducing steering control to SMARF vehicles
Potential Clients	FHWA, NHTSA, AHS Consortium, and in the long run Highway Departments because the research has implications on future highway design
Potential Gains	Medium to High

3. AHS-3 – Entry To and Exit From an AHS Facility

An AHS equipped vehicle needs to be checked and validated before it enters into an AHS facility. Entry check-up requirements involve sensors, image processing, diagnostics equipment, vehicle to infrastructure communication, computer models, and approval and rejection procedures. These functions could be carried with or without an operator in the loop, and with without the driver assistance. Although these systems could be developed and tested in laboratories and test-track facilities, SMARF could assist in narrowing down the options and evaluate various vehicle to infrastructure sensing and communication equipments and protocols.

Urgency/Importance	High
Timing	Medium Term
Complementary/Duplicative/New	Primarily New
Size of Effort	High
Constraints	Additional laboratory space, human interface analysis, implementation of on board vehicle diagnostics, involvement of many disciplines
Potential Clients	AHS Consortium, FHWA, sensor/control/communication companies, toll operators
Potential Gains	Small to Medium

B. SAFETY RESEARCH AREA

Independent of the National AHS Consortium, NHTSA and several companies are pursuing the development of collision avoidance as a separate market product. The concept parallels the longitudinal control in an AHS facility. However, the difference lies in that the collision avoidance should work in a normal traffic stream made up of equipped and non-equipped vehicles. A subset problem to collision avoidance is the reaction of non-equipped vehicles to braking of equipped vehicles under regular traffic conditions. SMARF could mix equipped and non-equipped vehicles in a traffic stream, and exercise several scenarios to driver’s braking reaction under various traffic and environmental conditions.

Urgency/Importance	High
Timing	Short Term
Complementary/ Duplicative/ New	Complementary
Size of Effort	Small to Medium
Constraints	Simulating driver reaction (although it is well documented in the literature), introducing slippery factors for various environmental conditions
Potential Clients	NHTSA, vehicle manufacturers
Potential Gains	Medium

C. ALTERNATIVE SENSOR APPROACH

In addition to these potential research areas, SMARF research is being continued by SRI in the area of GPS vehicle control. This development will focus on a GPS carrier phase control approach instead of radar oriented approach. The intention is to demonstrate the capability of laterally and longitudinally controlling scale model cars using carrier phase GPS. Control would include the ability to accurately and repeatedly navigate a test track, maintain separation between two cars, follow the leader, and ultimately control a platoon of cars in a simulated Automated Highway System (AHS) environment. The SMARF equipments employed during the current investigation will be re-used for the GPS efforts. This work is more fully described in the Appendix.

V CONCLUSIONS

SRI's investigation established the feasibility of the SMARF scaling concepts, and the utility of SMARF as a research tool in the development of a full-scale AHS and other related technologies such as collision avoidance systems. A set of scaling laws were developed that will aid AHS technology developers in evaluating components, subsystems and control schemes prior to full-scale implementation and in translating small-scale vehicle results to full-scale vehicles.

Several problems were encountered in the implementation phase of our investigation that require additional research and alternative approaches to achieve a working SMARF. Most significantly, development of a radar sensor for SMARF requires additional effort to overcome the significant radar clutter problems experienced in this investigation. This difficulty parallels problems being encountered by developers of full-scale vehicle radar systems for applications such as intelligent cruise control. In addition, our investigation has shown that if realistic scale speeds are to be employed within SMARF then automatic lateral and longitudinal control are required. The timing involved in the maneuvering and cornering at scale AHS speeds is too demanding for manual operator control. This was not anticipated during the concept formulation phase of SMARF and resulted in additional difficulties during execution. In retrospect, the minimum demonstrable configuration for SMARF is to implement both automatic longitudinal and lateral control. .

SRI is continuing to develop the SMARF concept with IR&D funds in an effort to overcome the problems described above. We are investigating a GPS-based sensor approach that can provide data for both lateral and longitudinal control (via an intervehicle datalink and trajectory/map database stored onboard the scale model car) in a leader-follower configuration. This follow-on research is described in the Appendix.

INVESTIGATOR PROFILE

In addition to Raul Vera, the Principal Investigator, Edwin Lyon III, a senior scientific advisor at SRI International, was instrumental in the controller and sensor research for this project. Dr. Antoine Hobeika, a recognized authority in traffic engineering and AHS development fields, was responsible for the market analysis and application potential development for SMARF.

APPENDIX: SRI GPS/SMARF MODEL CAR EXPERIMENTS

SRI is pursuing, using Internal Research and Development (IR&D) funds, a program to implement a GPS controlled model car. Less risk is involved in developing a control system for SMARF that uses GPS data because GPS can provide both relative (between the scale model vehicles) and absolute positioning data, allowing all SMARF vehicles to remain on track and maintain separation between vehicles. The model car will be controlled by a differential carrier phase GPS system where a GPS reference receiver is in a fixed location and corrections are sent using a datalink radio. This effort will demonstrate that GPS has the accuracy and availability needed to control vehicles. It will also provide a testbed capability for integrating other sensors (optics, IR, radar) on-board the scale model cars before eventually instrumenting full size vehicles. Two preliminary experiments have already performed and computer simulations have also been constructed to aid in expertimental designs.

The first experiment was conducted on a modified soap box racer. The soap box racer has front and rear steering so that a GPS antenna mounted on the rear of the racer will precisely track (within about 1 cm) a GPS antenna mounted on the front of the racer. This allows us to check the operation of the GPS carrier phase tracking algorithms. The idea behind this experiment was to test a “follow the leader” concept in which the lead vehicle carrying a GPS reference receiver would be manually steered, and the tailing vehicle would be automatically steered (by an onboard computer and control system) to follow the lead vehicle at a fixed distance. The experiment showed consistent relative GPS measurements to within 2 **cm.** However, simulations showed that it was difficult to control the tailing vehicle without having either accurate heading information for both vehicles or absolute position. At this point a decision was made to first proceed with a single vehicle experiment in which the vehicle will be automatically controlled using information from a fixed position GPS reference station. In this case an initial heading will have to be given to the car and an approximate heading can then be computed from the velocity vector. If this proves inadequate either a GPS-based attitude measurement system or a gyro will need to be used to obtain an accurate vehicle heading.

A stop and go test was made to test the accuracy of a differential carrier phase GPS system. The soapbox racer was manually maneuvered and stopped at each of four very accurately surveyed points, or "truth positions,” for 1 minute intervals at each point around a square course with approximately 100’ sides. (The soapbox racer has a long handle so that the person pulling it does appreciably obscure the sky.) Stopping accuracy was approximately 1 to 2 cm. The GPS receiver mounted on the soapbox was set to give 0.2 second updates.

The results relative to the “troth position” are show in Figure 1. The times when position error is plotted as zero correspond to when the soapbox was moving between surveyed points. A scanning of the data during moves shows smooth transitions when accelerating away from a spot and when walking between spots, and a bit of jiggle when positioning over the next spot, as expected. Biases of up **to** 10 cm appear, but the standard deviation of the short term random error is less than 2 cm.

Development Plan: SRI will use SRI-developed GPS carrier phase processing software, which provides a robust solution that is adequate in accuracy and update rate. The processing performed includes using GPS carrier data to smooth the GPS code measurement. This will alleviate the immediate need to perform carrier **cycle** ambiguity resolution. For advanced vehicle control work, ambiguity resolution algorithms customized for vehicle control will need to be developed. SRI is currently experimenting with dual frequency GPS receivers, which provide a more robust solution.

Future experiments will use the SMARF model cars. Steering and throttle control algorithms will be implemented onboard, with each vehicle performing its own processing to determine vehicle position. A computer onboard the car will calculate its own GPS position, its desired trajectory, and the position of other vehicles/obstructions.

In addition to the SRI funded IR&D effort, a joint project with the Center for Environmental Research and Technology (CERT) at the University of California at Riverside will develop a combined GPS and inertial navigation system (GPS/INS) for AHS research and development. The first product of this development effort will be an integrated (hardware and software) system that provides 10-50 centimeter location accuracies and l-3 cm/s velocity data at an update rate of 20-100 Hertz. Later phases of the project will provide three-dimensional attitude data in addition to increased location and velocity accuracies. This GPS/INS will be integrated on the SMARF vehicles for initial concept evaluaiton.

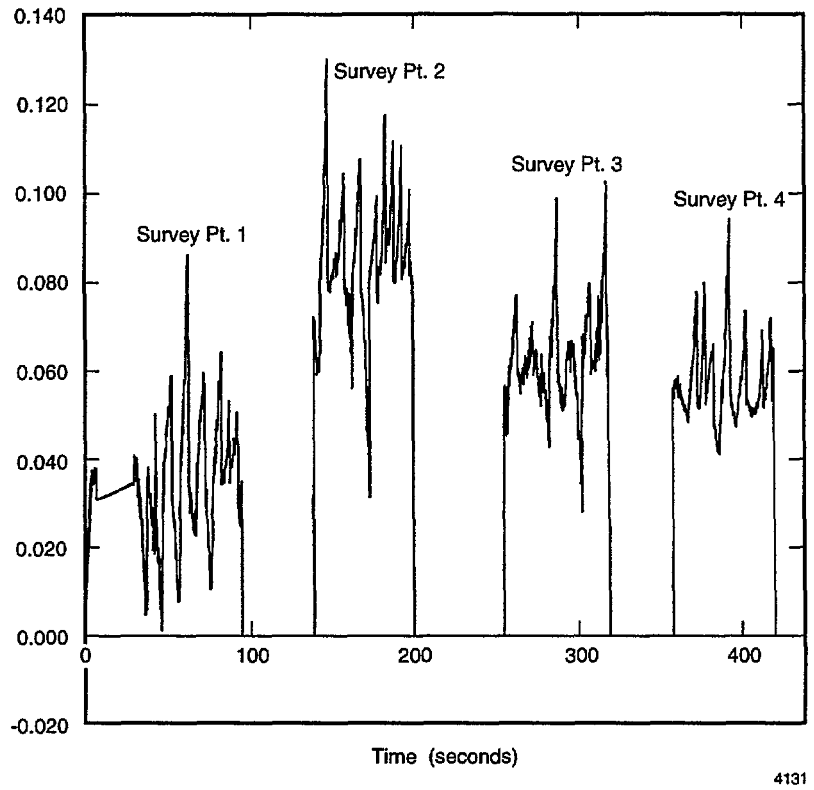

FIGURE 1 Stop at surveyed point experiment.