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Feasibility Study of Advanced Technology HOV Systems

Volume 4: Implementation of Lateral Control Systems in Transitways

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W.B. Zhang
J. Walker
F. Javandel
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FEASIBILITY STUDY OF ADVANCED-TECHNOLOGY HOV SYSTEMS

Volume 4:

Implementation of Lateral Control Systems in Transitways

by

T. Chira-Chavala
W.B. Zhang
J. Walker
F. Javandel
L. Demsetz

December 1992

PREFACE

Lateral guidance/control technologies are emerging advanced technologies that can be deployed independently to enhance traffic operation and safety. They can also be deployed in conjunction with longitudinal control systems to increase capacity of the transportation network. These capacity increases can occur because the use of lateral control may lead to reductions in the lane width requirement, which in turn allows additional lanes to be created within existing right-of-ways. Research to develop and test practical lateral control systems has been ongoing at the California PATH since 1988.

This study is conducted as part of the ***Feasibility Study of Advanced-Technology HOV Systems***. It investigates some issues concerning the implementation and impacts of lateral guidance/control systems. It proposes phased implementation of these systems, initially in exclusive-access HOV lanes. The rationale for focusing on these HOV lanes now is that implementation in such systems is likely to be less complex than that on multiple-lane freeways, and the implementation in HOV facilities appears to have its own merit from a policy standpoint.

This report is organized into two parts. Part one, which addresses the strategy and impacts of phased implementation of lateral guidance/control systems in HOV facilities, is written by Dr. T. Chira-Chavala and Mr. W.B. Zhang. Part two, in which issues involving human factors and possible approaches to addressing these issues are identified, is written by Ms. J. Walker, Mr. F. Javandel, Dr. L. Demsetz, and Dr. Chira-Chavala.

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EXECUTIVE SUMMARY

Introduction

Knowledge of the vehicle lateral position is important in operating vehicles on the roadway. Currently, the knowledge and the task of keeping vehicles in the travel lane are the responsibilities of drivers. Emerging lateral guidance/control systems can help to maintain the vehicle position along the lane center more precisely and reliably than drivers can do. Therefore, these systems provide a means for improving transportation systems. Control of vehicle lateral displacement may eventually lead to reductions in the lane width requirement. If so, added capacity through the additional lanes within existing right-of-ways would result.

Evidence in the literature suggests that discrete magnetic-based lateral control systems, due to the semipassive nature of magnetic markers, are less likely to be influenced by weather and debris. This is a chief advantage over other roadway sensing technologies including vision-based technologies. Research at the California PATH program has focused on the development and testing of discrete magnetic-based lateral control systems. This study examines strategies for early deployment of lateral control systems that use discrete magnetic markers as the roadway reference.

The ultimate goal is to eventually implement fully-automated systems on all roadways, to maximize safety and capacity benefits of the lateral control technology. Progress toward this goal calls

for an incremental implementation plan on existing highway facilities. Candidate facilities for early deployment of lateral control systems include high-occupancy-vehicle (HOV) facilities, particularly those separated from the freeway main lanes by permanent barriers and having controlled access and egress, which are generally known as transitways.

Study Objective

Objectives of this study are to:

- o Identify lateral guidance/control systems that use discrete magnetic markers as the roadway reference for incremental implementation in existing transitways, as a stepping stone toward the eventual deployment on all roadways.
- o Assess the safety and traffic impacts of these incremental systems.
- o Identify human-factors issues related to the implementation of these systems, as well as possible approaches for addressing these issues.

Summary of Principal Findings

1. In Phase 1, steering assistance information systems (SAIS's), essentially warning systems, can be implemented in transitways to enhance driver perception and provide warnings to drivers when vehicles are unintentionally encroaching on adjacent lanes or drifting outside their own lane. With SAIS's, drivers will still perform all steering-related tasks. The adoption of

SAIS's by transitway users can be voluntary, with SAIS's providing the following real-time information to drivers: vehicle lateral position, edge warnings, and information about upcoming road geometry.

2 . As a minimum, SAIS's can consist of the following components: discrete magnetic reference/sensing system, information processing unit, and human/machine interface unit.

The magnetic markers may be installed in single file along the lane center, with spacing of at least 100 cm. The magnetic fields can provide information about the vehicle lateral position, as well as information about upcoming roadway geometry. Magnetic signals generated from the magnetic markers are picked up by the on-vehicle magnetic sensors (or magnetometers). Tests conducted at the California PATH program indicate that signals from the magnetic reference/sensing system are not degraded by water and ice, and that magnetometers are capable of acquiring signals at both low and high speeds.

3. For the information processing unit of SAIS's, a workable algorithm to process signals from the magnetometer has been developed at the California PATH program. This algorithm has been tested with satisfactory results.

4. The human/machine interface unit of SAIS's can provide visual and/or audio output to drivers. For example, upcoming road curvature and the vehicle's lateral position relative to the lane center can be visually displayed. Audio warnings can be given to the driver when the vehicle moves outside their own lane. Warnings will not be given during deliberate lane-changing maneuvers. In

this regard, the SAIS's on/off switch and the turn-signal switch can be integrated to temporarily deactivate the SAIS during a lane-changing maneuver, and to resume the SAIS as soon as the lane change is complete.

5. 'Results from the accident analysis indicate that SAIS's could be useful as countermeasures for up to eight percent of transitway accidents. These are accidents that involve vehicles drifting outside their own lanes because of the driver inattentiveness, which led to striking barriers or channelization.

6. In Phase 2, partially automated lane-keeping systems (ALKS's) could be implemented in transitways. These systems can perform lane-keeping without driver input, with manual override allowable during lane changes. The adoption of ALKS's in Phase 2 by transitway users can be voluntary. ALKS's and SAIS's share a number of common components -- the roadway reference/sensing system and information processing unit are identical. In addition, ALKS's also require a battery of vehicle sensors, a vehicle control unit, and a steering actuator. They also require a human/machine interface unit that is different from that for SAIS's. Vehicle sensors required for ALKS's include: accelerometers, angular-rate sensors, steering-angle sensors, and speed sensors. The vehicle control unit for ALKS's generates steering commands in accordance with some ride-quality and steering-accuracy criteria. Both "feedback" and "preview" control algorithms have been developed at California PATH. The former generates steering commands from the "feedback" information (e.g., vehicle lateral position, lateral accelerations, and yaw), while the latter estimates anticipatory

steering angles from the information on upcoming road geometry. Experiments conducted at California PATH indicate that a maximum vehicle lateral displacement observed is within ± 20 cm, and that lateral accelerations could be controlled within an acceptable level required for good ride quality. More research is needed for the steering actuation unit, which is used to operate steerable wheels to achieve required steering angles. Finally, the human/machine interface unit for **ALKS's** can be designed to turn the automatic steering on and off. The **ALKS's** on/off switch and the turn-signal switch can be integrated to facilitate manual lane-changing. The interface unit can incorporate a feature that would permit the driver to select ride-comfort levels versus tracking errors. Research is needed on human factors and the safety design of the human/machine interface for **ALKS's**.

7. **ALKS's** could be potential accident countermeasures for 18 percent of transitway accidents. Of these, 8 percent are those for which **SAIS's** are found to be possible countermeasures; 7 percent are ran-off-road accidents on water-covered or icy pavements at highway speeds; and 3 percent are accidents involving tire blowouts causing the vehicles to strike the barriers (i.e., **ALKS's** can lower the probabilities of striking the barriers given the tire blowout, but they cannot prevent the tire blowout itself).

8. In Phase 3, fully automated lateral control systems (**ALCS's**) can be introduced in transitways to take over from the driver the tasks of lane-keeping, lane changing, merging, and diverging. With the mandatory adoption of **ALCS's** by transitway users, significant lane-width reductions may be possible. **ALCS's**

would have all the components of the ALKS's, plus some additional ones. As a minimum, the deployment of ALCS's in transitways would also require information links between individual transitway vehicles to facilitate automated lane-changing and merging maneuvers. These information links may be vehicle-to-vehicle and/or vehicle-and-roadside communication systems.

9. Results from the accident analysis indicate that ALCS's can be useful as possible countermeasures for up to 24 percent of transitway accidents. Of these, 18 percent are the accidents for which the ALKS's in Phase 2 are found to be possible countermeasures, and the remaining 6 percent are accidents that occur during lane-changing maneuvers in transitways.

10. It is conceivable that the adoption of ALCS's in Phase 3 can potentially lead to increases in transitway capacity, if the lane-width requirement can be reduced to yield additional travel lanes within existing right-of-ways. Preliminary estimation results suggest that practical capacity for one-lane transitways with no shoulder could increase by up to 14 percent. Practical capacity for existing two-lane transitways could increase much more substantially, up to 47 percent and 60 percent for existing two-lane transitways with and without shoulders, respectively.

11. If the lane-width requirement can be reduced through the deployment of ALCS's, future constructions of HOV facilities would require less right-of-way than at present. This may result in lower capital costs for future HOV facilities. In addition, reductions in the lane-width requirement may make it possible to construct HOV facilities in locations where existing right-of-ways

are currently deemed inadequate.

12. In addition to the implementation in existing HOV facilities, there are other relatively near-term utilities of lateral control systems. They include:

- * **SAIS's** and **ALKS's** can improve driving comfort and safety in regions of the country where adverse weather conditions persist for several months in a year.
- * **SAIS's** and **ALKS's** can have many useful applications for large vehicles (such as transit buses and trucks). First, many arterial and surface streets on which these vehicles operate have lane width substantially smaller than 12 feet, frequently resulting in lane encroachments. The use of **ALKS's** on narrow city streets may lead to enhanced traffic flow and safety. Second, **ALKS's** can be used to effectively guide transit buses in and out of bus bays. Third, **ALKS's** can help transit buses to achieve desired alignment along the curbs at bus stops, to facilitate boarding and alighting of handicapped passengers in wheelchairs or other special equipment.

13. R&D activities to facilitate the development and testing of lateral control systems toward full maturity are needed. Currently, many R&D activities remain to be completed or initiated before technology demonstration of even the nearest-term **SAIS's** could be planned. Principal R&D activities for **SAIS's** include: track tests of the **SAIS's** using full-scale vehicles in real-world conditions; assessment of the compatibility between the discrete magnetic roadway reference/sensing system and existing roadway

infrastructure (particularly the influence of steel reinforcements on the magnetic fields); assessments of the cost-effectiveness of magnetometers; and identification of methods for providing warnings effectively and safely to drivers.

14: This study identifies several human-factor issues and questions concerning deployment of lateral guidance/control systems. There are many different ways to evaluate these **human-**factor issues -- surveys, instrumented vehicles, video techniques, test tracks, and driving simulators. Among these, simulators and test-track appear to be promising. However, there may be some problems in using available driving simulators to test lateral control systems. They include: the lack of side viewing screens; spacing of lateral projection screens to simulate adjacent vehicles; and simulator sickness caused by discrepancies between visual and vestibular cues.

Part One:

Implementation of Lateral Control Systems in Transitways:
Incremental Systems and Their Impacts

by

T. Chira-Chavala

W.B. Zhang

INTRODUCTION

Knowledge of the vehicle lateral position is important in operating vehicles. Currently, this knowledge and the task of keeping vehicles in the travel lane are the responsibilities of drivers. Emerging lateral guidance/control systems can help to maintain the vehicle position along the lane center more precisely and reliably than drivers can do. Therefore, these systems provide a means for improving the transportation system. Control of vehicle lateral displacement may lead to reductions in the lane width requirement without compromising traffic safety. If so, additional travel lanes can be created, and added capacity can result within existing right-of-ways.

Lateral guidance/control technology is not new. In fact, it has been investigated by researchers since the 1950's (1-8). However, research to implement lateral guidance/control technology in the highway environment is still at an early stage. Parsons et al (9) investigated relative merit of various types of lateral control systems for applications on the highway -- electromagnetic, radar, acoustic, optical, vision-based, and magnetic. The authors concluded that the discrete magnetic based systems had advantages over other roadway reference/sensing technologies for applications on the highway. This is because the semipassive nature of magnetic markers makes the system less likely to be influenced by weather and debris.

This study examines a strategy for early deployment of lateral guidance/control systems that use discrete magnetic markers as the

roadway reference.. To fully realize potential safety and capacity benefits of lateral control technologies, fully automated systems have to be deployed on all roadways. Progress toward this goal calls for a plan to start implementing these technologies in existing, facilities -- warning systems, lane-keeping systems, and fully automated control systems.

Candidate facilities for the initial implementation include high-occupancy-vehicle (HOV) facilities, particularly those separated from the freeway main lanes by permanent barriers and having controlled access and egress. Initial implementation in these HOV facilities, generally known as transitways, is desirable because:

(a) This limited-scale deployment of the new technology is likely to be less complicated than the deployment on the mainline.

(b) The barriers separating transitways from the main lanes and the **transitways'** controlled access/egress can help to assure maximum safety of the new system without on-the-road experience.

(c) This limited-scale deployment will allow collection and evaluation of data concerning on-the-road system performance, as well as driver acceptance. This can help to stimulate technology improvement toward full maturity.

(d) Prior to the implementation of this new technology without on-the-road experience, extensive on-site tests may be needed. Transitways during off-peak hours are ideal for this purpose, because they can be closed to HOV traffic during this time without causing traffic disruption.

STUDY OBJECTIVE

Objectives of this study are to:

- o Identify lateral guidance/control systems that use discrete magnetic markers for phased implementation in existing transitways, as a stepping stone toward the eventual deployment on all roadways.
- o Assess the safety and traffic impacts of these incremental systems.
- o Identify human-factors issues related to the implementation of these systems, as well as possible approaches for addressing these issues

ORGANIZATION OF THE REPORT

This report is organized into two parts. Part one presents incremental systems for implementation in existing transitways and potential safety and capacity impacts of these systems. Part two presents human-factor issues relevant for the implementation of these systems.

Part one is divided into six sections, as follows. Section 1 presents an overview of the vehicle guidance/lateral control technology. Section 2 describes a strategy for implementing lateral guidance/control systems in existing transitways. Sections 3 through 5 describe capabilities, functional requirements, system structure and components, and potential impacts of three

incremental systems. Finally, policy implications concerning the use of lateral guidance/control systems are presented in Section 6.

Part two is divided into a number of sections. They are human-factor issues, driving simulator review, and detailed **human-factor** review.

PART ONE

Implementation of Lateral Control in Transitways: Incremental Systems and Their Impacts

TECHNOLOGY OVERVIEW

The literature on vehicle lateral guidance/control systems generally emphasizes systems that perform the lane-keeping function. Such systems require roadway reference/sensing, vehicle controller, and vehicle actuation technologies. An overview of these component technologies is presented below.

Roadway Reference/Sensing System

The roadway reference/sensing system requires both roadway reference and in-vehicle sensing devices. The roadway reference provides information about the lane lines or road edges. Possible roadway reference includes painted lines, raised pavement markers, as well as wires or magnetic markers embedded in the pavement to transmit electromagnetic or magnetic signals. The in-vehicle sensing device consists of sensors to receive signals from the roadway reference. These signals are then converted into information about the vehicle's lateral position. Depending on the kind of roadway reference/sensing technology employed, additional information such as upcoming roadway geometry (known as "preview" information) could also be obtained.

Roadway reference/sensing systems could be based on a number

of technologies, for example, electromagnetic, radar, acoustic, optical including vision-based, and magnetic. To date, these technologies have been investigated primarily in simulations and/or laboratory experiments. Two most promising technologies for **large-scale** applications in the highway environment appear to be **vision-based** systems and those using discrete magnetic markers (Parsons et al, 1988). Their advantages and disadvantages are presented below.

Vision Based Systems

Roadway reference/sensing systems based on "**vision**" sensing technologies (e.g., video-cameras) could directly acquire information on both the vehicle lateral position and the upcoming roadway geometry from existing lane lines or roadway delineation. Therefore, they are vehicle "**autonomous**" systems, which do not require special installation of roadway reference. Currently, there are uncertainties about applications of vision-based systems on the highway due to possible effects of debris, adverse weather, and light condition on performance; the requirement of large amounts of data in order to provide real-time guidance; and unknown reliability and costs of the in-vehicle data processing capability (9). R&D efforts to develop vision-based systems and their information processing capability have been reported in the literature (e.g., 10-12). However, whether these systems would be workable in diverse real-world weather and operating conditions remains largely unknown.

Discrete Magnetic Marker Systems

These roadway reference systems use small magnetic markers, buried vertically in the center of the lane, to provide the roadway reference. Magnetic fields from these markers are picked up by magnetic-type sensors installed on the vehicle. Relative to vision-based systems, the discrete magnetic reference system is not sensitive to debris or weather and light conditions (Parsons et al, 1988). It could also provide "preview" information about upcoming road geometry by means of some magnetic coding scheme. However, it would require special installation of magnetic markers in the pavement.

Other features of the **discrete** magnetic reference system include the following: the roadway in which the magnets are installed does not require electrification; any magnetic damage or fault would affect the system locally, but not the entire network; repairs or replacements of the damaged magnets could be done quickly; and the system could offer flexibility in installing temporary markers to lead vehicles around construction zones, even without having to remove the markers already in place (9).

Vehicle Controller

Vehicle controllers for lane-keeping systems usually consist of computers and control algorithms. The computers process sensory information, as well as executing control algorithms in real time. The control algorithms may include "feedback" and "feedforward" components. The "feedback" control algorithm receives information

about the vehicle. status with respect to the lane center and corrects local lateral deviations of the vehicle in an incremental manner. The "feedforward" control algorithm receives information on upcoming road geometry and issues commands to the steering actuation unit, in preparation for negotiating the change in roadway geometry ahead.

Vehicle Actuation Unit

The vehicle actuation unit receives steering commands from the vehicle controller, for use in turning the steerable wheels. Currently, there are no commercially produced actuators for lane-keeping systems, and research on such steering actuators is sparsely reported.

PHASED IMPLEMENTATION OF DISCRETE MAGNETIC BASED LATERAL GUIDANCE/CONTROL SYSTEMS IN TRANSITWAYS

One strategy for early deployment of lateral guidance/control systems that use the discrete magnetic reference technology in existing transitways follows a building-block approach. That is, the implementation can start with systems that are relatively limited in terms of the degree of driver-assisted tasks. These near-term systems can then be built upon in stages until fully automated systems are achieved. This study proposes three incremental implementation phases, as follows:

Phase 1: Implementation of steering assistance information systems

(SAIS's); essentially lateral warning systems, to enhance driver perception and provide warnings to drivers when vehicles are unintentionally encroaching on adjacent lanes or drifting outside their own lane; drivers will still perform all steering-related tasks.

Phase 2: Implementation of partially automated lane-keeping systems (ALKS's) to control the vehicle position along the lane center, with manual override for lane changes.

Phase 3: Implementation of fully automated lateral control systems (ALCS's) that automatically perform lane-keeping, lane changing, merging, and diverging; the system could take over lateral steering tasks from the driver.

PHASE 1: STEERING ASSISTANCE INFORMATION SYSTEMS (SAIS's)

Capabilities, functional requirements, system structure and components of SAIS's (that use the discrete magnetic reference/sensing system) to be implemented in transitways in Phase 1 are described below. In addition, potential traffic and safety impacts due to the implementation of SAIS's are also presented.

Capabilities of SAIS's

We believe that adoption of SAIS's by transitway users will be voluntary. SAIS's can provide the following real-time information to drivers:

o **Vehicle Lateral Position:** SAIS's can provide information to drivers about vehicle lateral position with respect to the lane center. This is true in normal conditions, with poor or invisible lane marking, in poor-visibility conditions (e.g., night-time), and in adverse weather condition.

o **Edge Warnings:** SAIS's can provide warnings to drivers when vehicles are inadvertently encroaching adjacent lanes or drifting outside their own lanes. These inadvertent vehicle maneuvers, which are frequently results of driver fatigue, inattentiveness, or sleepiness, may be corrected by drivers if they receive warnings soon enough.

o **Information About Upcoming Road Geometry:** SAIS's can provide information to drivers about changes in the upcoming road geometry (e.g., road curvature). Therefore, they can help to better prepare drivers to make required steering actions sooner.

Functional Requirements

Functional requirements are defined as desired capabilities and/or performance goals for which the systems should aim to achieve. Functional requirements for SAIS's, with respect to the deployment in transitways, include:

(i) When an SAIS mistakenly gives a warning that the vehicle is drifting outside the lane when it actually is not, this warning is said to be a "**false alarm.**" Although false alarms, per se, may not be hazardous, a high rate of false alarms could result in a loss of user confidence. Effects of the rate of false alarms, and

thus an acceptable false-alarm rate, for **SAIS's** have not been explored. This knowledge is needed before reasonable rates of false alarms can be specified for practical **SAIS's**. Nevertheless, a very low rate of false alarms may be essential for public acceptance of the device.

(ii) When an SAIS fails to detect the vehicle drifting out of its own lane, it is said to have a system **"miss."** System **"misses"** can be hazardous enough to result in traffic accidents. Therefore, system **"misses"** should be eliminated through the system design. Possible means for accomplishing this include: the incorporation of sufficient redundancies for **"weak"** links within the system; and the elimination of failures that can result in adverse consequences through systematic design.

(iii) Correct warnings on required steering correction actions (e.g., steer left or right) must be assured. The incorporation of redundancies for **"weak"** links may help to enhance this system accuracy.

(iv) Warning signals to drivers must be effective, both when drivers are alert and when they are fatigued or inattentive.

(v) The discrete magnetic reference/sensing system must be robust in all weather and operating conditions.

(vi) Installation and replacement of magnetic markers should be simple and capable of being carried out quickly, because pavements are periodically resurfaced as part of the regular maintenance. The magnetic markers should require minimal maintenance, and their life cycle should be compatible with that of

the pavement.

System Structure and Components

A conceptual structure of near-term SAIS's to be implemented in transitways are shown in Figure 1. Principal components of these SAIS's include magnetic markers and an in-vehicle magnetic-sensing device (collectively called the magnetic roadway reference/sensing system), information processing unit, and human/machine interface unit.

Discrete Magnetic Reference/Sensing System

The discrete magnetic reference/sensing system that is currently being researched at California PATH consists of a series of small permanent magnetic markers. Each marker is 2.5 cm in diameter and 10 cm long), and buried vertically in the pavement. These magnetic markers can be installed in single file along the lane center, with spacing of at least 100 cm. Dynamic tests on this system are being conducted at California PATH to determine the effects of the magnetic-marker spacing on system performance. The magnetic fields provide information about the vehicle lateral position with respect to the lane center. In addition, by alternating the polarities of the magnetic markers, a series of binary information (0,1) can be encoded to provide information about upcoming roadway geometry. Checking/correcting codes can be used to assure the reliability of the preview information.

Magnetic signals generated from the magnetic markers are

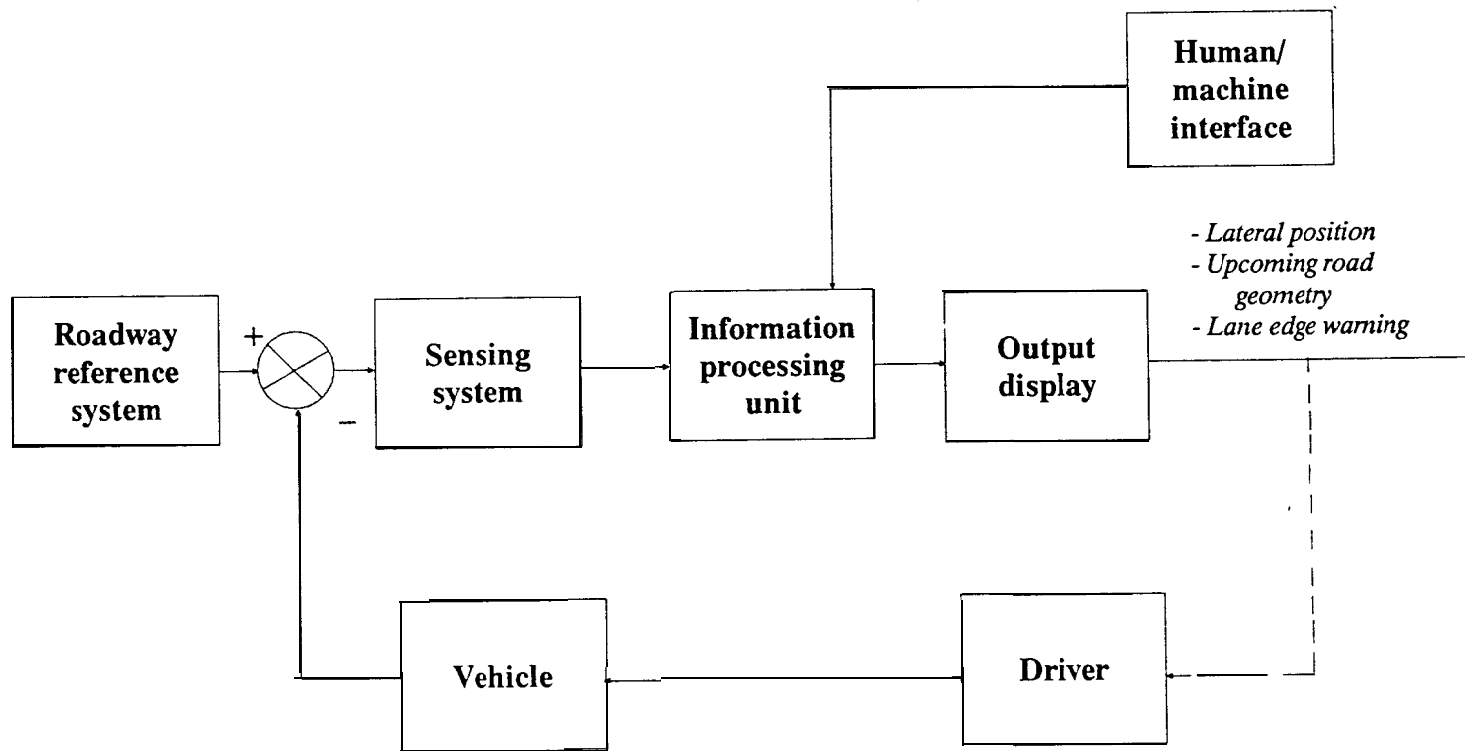


Figure 1. A Steering Assistance Information System

picked up by the **on-vehicle** sensing device. In this regard, magnetic sensors (or magnetometers) designed to be compatible with the magnetic markers, can be installed under the front bumper of the vehicle. The signals acquired by the magnetometers are then converted into vehicle lateral deviation by the information processing unit. Tests of magnetometers conducted at California PATH indicate that they are capable of acquiring signals at very low speeds (zero or close to zero) as well as at highway speeds (5). The magnetometers used in these tests are **"off-the-shelf"** devices. Magnetometers to be used by vehicles in transitways may have to be specially designed to assure a high degree of reliability and low costs.

Tests were also conducted at California PATH to measure signals from the magnetic reference/sensing system when pavements were covered with water and ice. Test results indicate that the signals are not degraded by these adverse conditions (5). Findings from experiments and tests conducted at California PATH to date indicate that the discrete magnetic/sensing system appears to be a possible system for applications in transitways. Future tests of the discrete magnetic reference/sensing system will continue at California PATH for roadways that have steel reinforcements.

Magnetic markers are relatively inexpensive. Those used in experiments at California PATH are produced in small quantities and cost about three dollars per magnet. Production volumes of these magnets are likely to lower their cost. Magnetic markers are also relatively easy to install. Existing construction technologies

(including the advanced robotics technology) can be adapted for the magnet-marker installation.

Information Processing Unit

The information processing unit consists of an **onboard** computer to process signals from the magnetometer and to produce output information for the driver. An algorithm to process signals from the magnetometer has been developed at California PATH (5). In addition, methods to overcome interference problems in the lateral position measurement -- the overlapping with the earth's magnetic field, high-frequency magnetic noise generated by the vehicle engine system, and spontaneous vertical movements of the vehicle -- were also developed and tested (5). This algorithm has since been tested at California PATH, in bench tests, as well as in track tests using a scaled vehicle (1 meter long and 0.5 meter wide) and a full-size experimental vehicle. The test results indicate that this algorithm works satisfactorily.

Human/Machine Interface Unit

Information and warnings to drivers can be provided as visual and/or audio output. For example, upcoming road curvature and the vehicle lateral position relative to the lane center can be visually displayed. Audio warnings can be given to the driver when the vehicle moves outside its own lane. Warnings will not be given during deliberate lane-changing maneuvers. In this regard, the **SAIS's** on/off switch and the turn-signal switch can be integrated

to temporarily deactivate the SAIS during a lane-changing maneuver, and to resume the SAIS as soon as the lane change is complete. Research is needed to determine effective output display modes for practical SAIS's.

Impacts of SAIS's

The implementation of SAIS's in transitways is likely to have little direct impacts on the transitway flow or capacity. However, it can bring about reductions in the number of transitway accidents. Estimated benefits of Phase 1 are presented below.

Estimation of Potential Safety Benefit of SAIS's

The use of SAIS's can help to reduce frequencies of run-off-road and sideswipe accidents in transitways. Estimation of this potential safety benefit is performed by means of in-depth examinations of hard-copy accident reports (as opposed to analyses of computerized accident data). This is because accidents on transitways can be difficult to identify from computerized data for the following reasons: First, there are relatively fewer lane-miles of transitways than freeways in the U.S., and transitways are likely to be associated with much lower accident rates than in the mainline. These make the number of transitway accidents negligibly small relative to the frequency of mainline accidents. Second, existing data programs in many states do not code transitways, making it difficult to differentiate transitway accidents from mainline accidents. Furthermore, computerized accident data are

not likely to **have sufficient** details for determining whether the accident outcome might be influenced by the use of new devices such as lateral control systems.

Because transitway mileage in any one state is usually small, and accidents in transitways are even rarer events than accidents on the mainline, we had to obtain data on transitway accidents from a number of states to have a reasonable sample size. Hard-copy reports of transitway accidents from California, Houston (Texas), and Virginia (the I-66 transitway) are available for analysis. The reports from California represent all reported transitway accidents for four months in 1990; the reports from Texas represent all reported transitway accidents in Houston for 12 months in 1990; and the reports from Virginia represent reported transitway accidents in the I-66 facility for six months in 1990. In all, 72 hard-copy reports of transitway accidents were analyzed. For each accident, the in-depth analysis of the hard-copy accident report follows these steps:

1. All information in the accident report, including the accident diagram(s), is critically examined to identify a sequence of events/actions that culminate in the accident. This sequence of events is useful for determining possible points of intervention by the new device.

2. Probable contributing factors of that accident are identified from all the evidence available in the accident report.

3. An evaluation is performed to see whether at least one of the identified contributing factors may respond to the new device.

We consider that if one contributing factor could be eliminated by the new device, the new device would be considered useful as a possible accident countermeasure.

The results of this safety analysis indicate that **SAIS's** could be useful as possible countermeasures for up to 8 percent of transitway accidents. These are accidents in which vehicles drift outside their own lanes and strike the barriers or channelization at highway speed, as a result of the driver inattentiveness.

This estimated safety benefit should be considered as an upper-bound benefit for the following reasons (15):

(a) We believe that the adoption of **SAIS's** will be voluntary for transitway users. However, the safety analysis assumes that all transitway users are equipped with **SAIS's**. If **SAIS's** are adopted by only a fraction of transitway users, the estimated benefit will have to be proportionally discounted by the number of users.

(b) In the accident analysis, we assume that **SAIS's** will perform as they are expected.

(c) We assume that there would be no changes in driver behavior due to adopting **SAIS's**.

(d) The accident analysis cannot take into account the extent to which the use of **SAIS's** may introduce new kinds of accidents, for example, those related to system malfunctions or failures. This determination requires on-the-road data that are not currently available.

Potential Capacity Impact of SAIS's

As previously mentioned, the implementation of SAIS's in existing transitways is not expected to result in ~~direct~~ capacity increases. Nevertheless, reductions in transitway accidents as a result of adopting SAIS's can help to minimize non-recurring traffic congestion that is caused by accidents and accident clearing activities.

PHASE 2: AUTOMATED LANE-KEEPING SYSTEMS (ALKS's)

In Phase 2, automated lane-keeping systems (ALKS's) can be introduced in transitways. Capabilities, functional requirements, system structure and components, and potential impacts of these ALKS's are described below.

Capabilities

ALKS's are capable of performing partially automated vehicle lateral control. That is, when the system is activated, it would automatically control the vehicle lateral position. However, this lane-keeping function can be temporarily deactivated when the driver engages the turn signal to perform manual lane-changing in two-or-more-lane transitways. As soon as the manual lane change is complete, the automatic lane-keeping will be resumed.

The adoption of ALKS's in Phase 2 by transitway users can be voluntary, which will not result in reductions in the lane-width requirement. Phase 2 is considered a desirable step before the implementation of fully automated lateral control systems because

it would allow drivers to become familiar with using automated devices and learn to share tasks with them; and it would allow on-the-road data concerning system performance to be collected for use in developing long-term fully automated lateral control systems.

Functional Requirements

In addition to the functional requirements previously described for SAIS's, further functional requirements for the partially automated ALKS's include the following:

(i) ALKS's should be "fail-safe" systems. That is, system failures that can result in catastrophic consequences should be eliminated through the system design. Should system failures occur, they must not lead to a loss of vehicle controllability.

(ii) In this phase, drivers of equipped vehicles should have the option of turning the device on or off as they wish.

(iii) ALKS's must perform the lane-keeping task with good accuracy. In this regard, the allowable vehicle deviation (for ride-quality, safety, and efficiency reasons) is being researched at California PATH. Nevertheless, as an absolute minimum, ALKS's must be able to steer vehicles wholly within the lane boundaries.

(iv) ALKS's should have reasonably good ride quality in order to encourage system adoption. There are trade-offs between lane-keeping accuracy and ride quality that need to be addressed by further research.

System Structure and Components

ALKS's and **SAIS's** share a number of common components. Figure 2 shows a conceptual structure and major components of the **ALKS's** for Phase 2. The roadway reference/sensing system and information processing unit are identical to those for **SAIS's**. In addition, **ALKS's** also require a battery of vehicle sensors, a vehicle control unit, and a steering actuator. It also requires a human/machine interface unit that is different from that for **SAIS's**. These additional components for **ALKS's** are described below.

o **Vehicle Sensors:** These include accelerometers, angular-rate sensors, steering-angle sensors, and speed sensors for measuring vehicle lateral accelerations, yaw rates, actual ground wheel steering angles, and vehicle speeds, respectively. These technologies are largely available. However, more research is needed to assess whether their resolution and accuracy will be sufficient for applications in transitways.

o **Vehicle Control Unit:** This unit generates steering commands in accordance with some ride-quality and steering-accuracy requirements. This unit can share the same computer with the information processing unit. Vehicle control algorithms can incorporate the "**intelligence**" that is capable of determining the vehicle status and environmental conditions for use in issuing steering commands appropriate for prevailing conditions. The vehicle control unit can also incorporate safety logics to

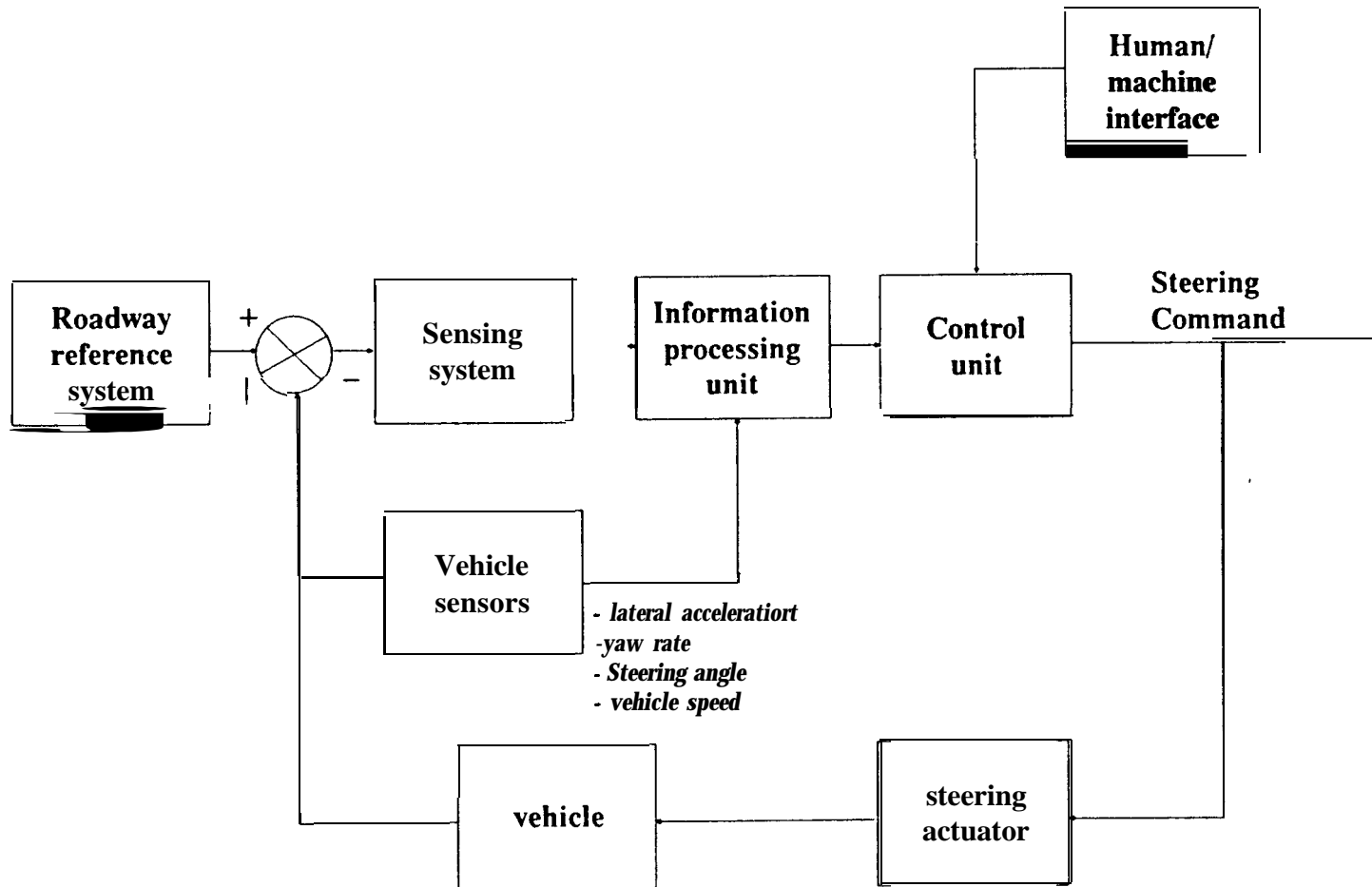


Figure 2. An Automated Lane Keeping System

coordinate the transfer between automatic control and manual steering.

Both **"feedback"** and **"preview"** control algorithms have been developed at California PATH (7,8). The **"feedback"** control algorithm generates steering commands from the **"feedback"** information (which includes the vehicle lateral position, lateral accelerations, and **yaw**). The **"preview"** control algorithm incorporates both the **"feedback"** and **"feedforward"** control components. The latter component estimates anticipatory steering angles from the information on upcoming road geometry.

Experiments on **ALKS's** were conducted at California PATH (13). These experiment used a scaled vehicle (1 meter long and 0.5 meter wide), **"feedback"** and **"feedforward"** control algorithms, and the magnetic reference/sensing system. The test vehicle was equipped with electrical driving, a steering motor, a computer, and the above-mentioned vehicle sensors. Information concerning upcoming roadway geometry was coded in the magnetic markers. The vehicle's maximum speed during the tests was 3 meters per second. In these tests, a maximum vehicle lateral displacement of ± 20 cm was observed. Further, the test results also indicate that lateral accelerations could be controlled within an acceptable level required for good ride quality. Therefore, it appears that **ALKS's** using the discrete magnetic reference/sensing system are plausible systems for applications in transitways. PATH is planning to conduct further tests with a full-scale experimental vehicle. In this regard, a 700-meter test track has been constructed at the

California **PATH's** Richmond Field Station. These tests are expected to be completed soon.

o *Vehicle Actuation Unit:* The steering actuator unit is used to operate steerable wheels to achieve required steering angles. These actuators, which may be hydraulic or electric servos, receive commands from the vehicle control unit. Research is needed to determine the maximum allowable steering angle for lane-keeping. One possible solution is to limit the maximum allowable steering angle of **ALKS's** to the minimum radius of curvature commonly recommended for the highway design.

o *Human/Machine Interface Unit:* This unit is different than the one used in **SAIS's**. For **ALKS's**, this unit is used to turn the automatic steering on and off. This interface unit can be designed to perform a number of functions. For example, the **ALKS's** on/off switch and the turn-signal switch could be integrated to facilitate manual lane-changing, as follows: This integrated switch could temporarily turn off the automatic lane-keeping when a lane-changing maneuver is taking place, and resume the automatic lane-keeping once the maneuver has been completed. The interface unit could also incorporate a feature that would permit the driver to select ride-comfort levels versus tracking errors.

Research on human factors and the safety design of the human/machine interface for **ALKS's** is needed.

Impacts of ALKS's .

The Phase-2 implementation of **ALKS's** could result in reductions in transitway accidents. Estimation of this safety benefit is presented below.

Estimation of Safety Benefit of ALKS's

With the aid of **ALKS's**, the lateral position of equipped vehicles can be automatically controlled. In this way, driver errors or misjudgment in vehicle steering (due to driver fatigue or inattentiveness; poor-visibility conditions; pavements covered with debris, water, mud, or snow; poor roadway delineation; or strong crosswinds) may be eliminated. The previously mentioned in-depth analysis of hard-copy transitway accident reports indicate that **ALKS's** in Phase 2 could be useful as countermeasures for about 18 percent of transitway accidents, as follows:

(a) The 8 percent of transitway accidents for which the **SAIS's** in Phase 1 are found to be possible countermeasures;

(b) An additional seven percent of transitway accidents that are ran-off-road accidents on water-covered or icy pavements at highway speed, in which vehicles finally strike the barriers; for these accidents, the drivers did not state that they had actually applied brakes prior to running off the lane. It is not possible for the authors to determine, from the information available in the accident reports, how many of these accidents actually involved braking. **ALKS's** can be beneficial for those that do not involve braking, and they can also lower the probabilities of some

accidents that involve braking.

(c) Another 3 percent of transitway accidents, which involve tire blowout causing the vehicles to strike the barriers; that is, the probabilities of striking the barriers as a result of the tire blowout may be lower with **ALKS's** than without **ALKS's**.

The above estimated accident benefit of **ALKS's** is likely to be an upper-bound benefit for the same reasons previously mentioned for the estimated safety benefit of **SAIS's**.

Potential Capacity Impact of ALKS's

The implementation of **ALKS's** in Phase 2, which is not accompanied by reductions in the lane width, is not expected to have significant direct impacts on the transitway flow rate or capacity. A possible exception might be the application in exclusive bus lanes (i.e., lanes specially reserved for buses) that have no shoulder and/or lane width smaller than 12 feet. If all the buses in these facilities are equipped with **ALKS's**, it is conceivable that **ALKS's** can help to counter the adverse effect, due to the lack of lateral clearance and/or narrow lanes, on the flow rate. **ALKS's** may eliminate the need for large lateral clearance between the vehicle and the roadside objects, which is deemed important for maximizing the flow rate under manual driving. The Highway Capacity Manual (HCM; 14) describes a procedure for quantifying adverse effects due to the lack of lateral clearance on the flow rate. Based on this **HCM's** procedure, and if the **ALKS's** are assumed to be able to eliminate the need for full lateral

clearance, the practical flow rate in single-lane bus lanes with no shoulder could increase by up to 13 percent. However, in the absence of actual on-the-road data concerning the use of **ALKS's**, human-factors research is required to verify this assumed benefit of **ALKS's**.

Reductions in the frequency of transitway accidents as a result of implementing **ALKS's** in transitways could also lead to reductions in non-recurring congestion. This congestion is caused by the accidents themselves and by the clearing of accidents.

PHASE 3: FULLY AUTOMATED LATERAL CONTROL SYSTEMS (ALCS'S)

In Phase 3, implementation of fully automated lateral control systems (**ALCS's**) can take place. Capabilities, functional requirements, system structure and components, and impacts of these long-term **ALCS's** are described below.

Capabilities

ALCS's can take over the lateral steering of the vehicle. As with the Phase-2 **ALKS's**, **ALCS's** are capable of automated lane-keeping. In addition, **ALCS's** can also accomplish other **steering-related** maneuvers, such as lane changes and merging. These additional automated capabilities call for the integration of additional devices. Further, all transitway vehicles would have to be equipped and the operating status of their **ALCS's** checked before entering the transitway to prevent failures due to equipment malfunctions. With the mandatory system adoption by transitway

users, reductions in the lane-width requirement may be possible without degrading traffic safety within the transitway.

Functional Requirements

Functional requirements for **ALCS's** are similar to those for the Phase-2 **ALKS's**, with the notable exceptions being the elimination of the manual override for lane changes and the driver option to turn the system on and off. From the safety perspective, such manual override and the on/off switch option appear to be undesirable for **ALCS's**. Research is needed to determine if these features could be allowed in **ALCS's**.

System Structure and Components

Long-term **ALCS's** are the extension of **ALKS's**. Therefore, **ALCS's** would have all the components of the **ALKS's**, plus some additional components. As a minimum, the deployment of **ALCS's** in transitways would also require information links between individual transitway vehicles to facilitate automated lane-changing and merging maneuvers. These information links may be **vehicle-to-vehicle** and/or **vehicle-and-roadside** communication systems. Figure 3 shows a conceptual structure and components of the **ALCS's**.

Impacts Of **ALCS's**

Potential benefits of implementing **ALCS's** in transitways include reductions in the frequency of transitway accidents and increases in the transitway capacity. Estimations of these

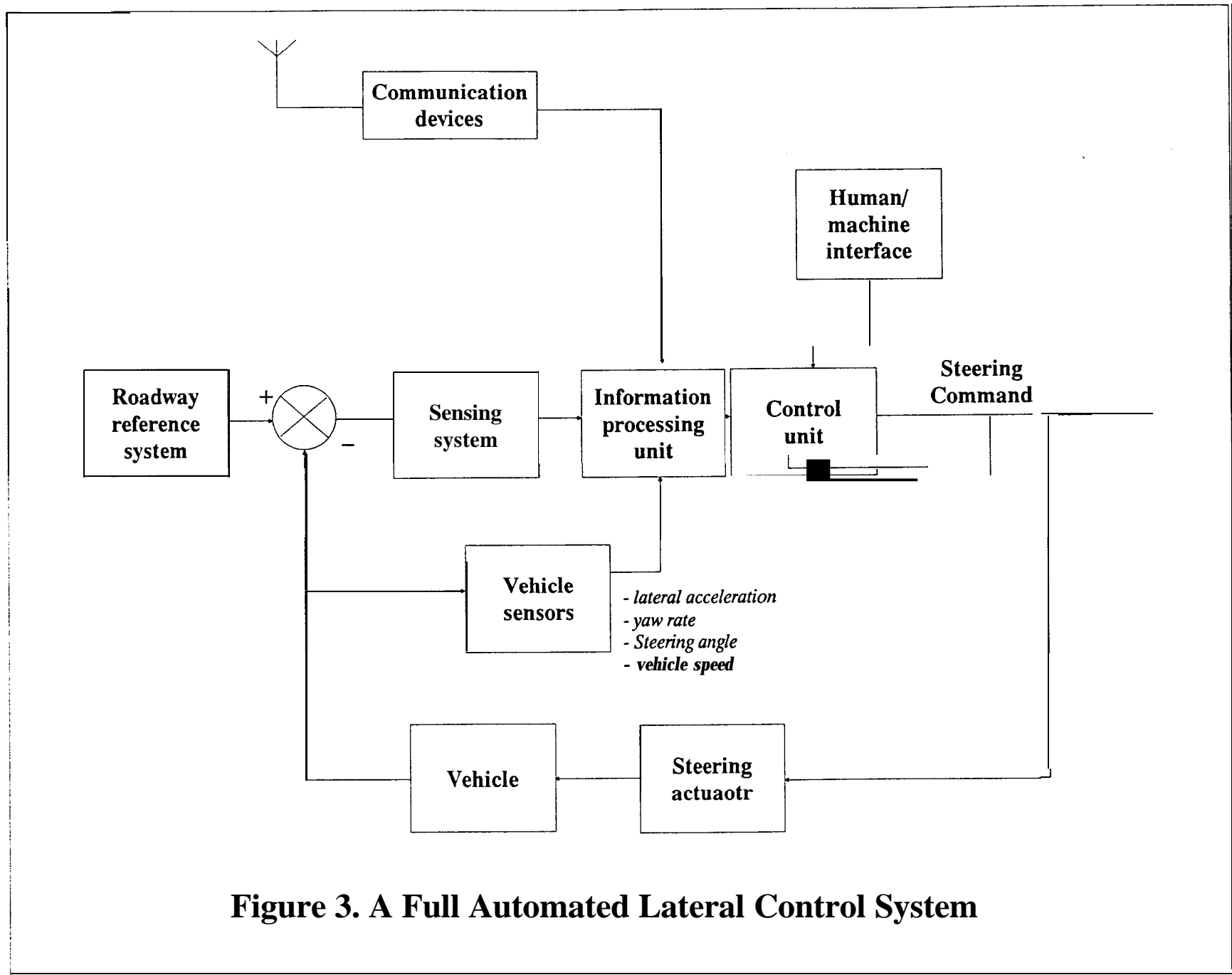


Figure 3. A Full Automated Lateral Control System

potential benefits **are** presented below.

Estimation of Safety Benefit of ALCS's

Similar to the **ALKS's** in Phase 2, **ALCS's** can eliminate driver errors in lane-keeping, thus reducing accidents caused by such errors. In addition, the automated lane-changing and merging capabilities of **ALCS's** may also reduce the number of accidents related to lane-changing maneuvers in transitways. Results from the previously described in-depth analysis of transitway hard-copy accident reports indicate that **ALCS's** can be useful as possible countermeasures for up to 24 percent of transitway accidents. Of these, 18 percent are the accidents for which the **ALKS's** in Phase 2 are possible countermeasures. The remaining 6 percent are accidents due to lane-changing maneuvers in transitways.

Estimation of Direct Capacity Benefit of ALCS's

The adoption of **ALCS's** could result in increases in transitway capacity, if the lane width can be reduced and additional travel lanes created within the existing right-of-way. Capacity increases through lane-width reductions could be expected for existing transitways that currently have at least two travel lanes. For most existing single-lane transitways, the lane-width reduction due to the use of **ALCS's** is not likely to be sufficient to create an additional travel lane, although some increases in the flow rate are possible if the single-lanetransitways currently lack shoulder and/or have travel lanes less than 12 feet.

TABLE 1

Expected Capacity and Flow Rates at LOS C Before and After Adopting ALC S's

HOV-Lane Configuration	Practical Capacity ^(e) (vph)	Flow Rate at LOS C ^(e) (vph)
BEFORE: Existing 1-lane HOV facilities with no shoulder ^(a) AFTER: Same	1,400 1,600	1,100 1,300
BEFORE: Existing 1-lane HOV facilities with shoulder ^(b) AFTER: Same	1,600 1,600	1,300 1,300
BEFORE: Existing 2-lane HOV facilities with no shoulder ^(c) AFTER: 3-lane HOV facilities with no shoulder ^(f)	3,500 5,600	2,600 4,500
BEFORE: Existing 2-lane HOV facilities with shoulder ^(d) AFTER: 3-lane HOV facilities with shoulder ^(f)	3,800 5,600	3,200 4,500

(a) 12-foot l a n e

(b) 12-foot lane, 5-8 foot lane

(c) 24-26 foot pavement

(d) 24-26 foot pavement, 5-8 shoulder

(e) Assuming 10 percent buses

(f) New facilities with ALC S have 3 lanes, two S-foot lanes for automobiles and one 10-foot lane for buses plus automobiles

Based on the procedure published in the Highway Capacity Manual (14), possible increases in transitway capacity as a result of adopting ALCS's for various transitway configurations are estimated, as shown in Table 1. Table 1 also shows estimated changes in the transitway flow rate for the level-of-service (LOS) C, as a result of adopting ALCS's. Estimates in Table 1 are based on the following assumptions:

(a) The transitway traffic is comprised of 10 percent buses and 90 percent passenger vehicles.

(b) The adoption of ALCS's may eliminate the need for 12-foot lanes and full lateral clearance of 6-8 feet as recommended in the HCM for under manual driving. That is, it is conceivable that multiple-lane facilities may have one 10-foot lane for buses and other lanes of no more than 8 feet. Currently, many transportation researchers believe that the use of ALCS's could result in lane-width reductions. However, the magnitude of such reductions, which depends on the system accuracy, ride comfort, and driver capability, is under investigation at California PATH.

Table 1 indicates that, as a result of Phase-3 implementation,

- Practical capacity for single-lane transitways with no shoulder could increase by up to 14 percent.
- Practical capacity for existing two-lane transitways could increase much more substantially, when the use of ALCS's leads to reductions in the lane width and the creation of an additional lane (or lanes) within existing right-of-ways. Capacity increases of up to 47 percent

and 60 percent could result for existing two-lane transitways with and without shoulders, respectively.

POLICY IMPLICATIONS

This study proposes that, in the relative near term, lateral control technologies can be introduced in existing transitways in an incremental manner. The proposed phased implementation provides a plan for early deployment of lateral guidance/control technologies, and may help to accelerate progress of these technologies toward full maturity. Information/warning systems can be first introduced, which can later be built upon to achieve automatic lane-keeping systems (driver-assisted systems). Finally, fully-automated systems, capable of operating within reduced lane width as well as taking over from the driver the tasks of lane-keeping, lane-changing, merging, and diverging, can be deployed. There are many reasons for suggesting existing transitways as **testbeds** for these incremental systems, as a stepping stone toward the eventual implementation on all roadways. First, the reliability and safety of all incremental systems under real-world conditions must be accepted by potential users, and transitways provide a safe environment to demonstrate such driver acceptance. Second, limited-scaled implementation of these incremental systems in these exclusive-access facilities is likely to be the least complex. Therefore, it could take place relatively more quickly than implementation on the mainline.

Potential safety and capacity benefits of lateral control

technologies will **be** fully realized after the fully automated systems are deployed on all roadways. Even though transitways can serve as **testbeds** to facilitate initial implementation of lateral control technologies on the highway, the implementation in HOV facilities does command its own merit. If lane-width reductions can be achieved through the deployment of fully automated lateral control systems without compromising driving comfort and safety, available right-of-ways can be more efficiently utilized. This may result in constructions of future HOV facilities requiring less right-of-way than at the present time, thus lowering capital costs for future HOV facilities. In addition, reductions in the **lane-width** requirement may make it possible to construct HOV facilities in locations where existing right-of-ways are deemed inadequate at the present time.

In addition to the implementation in existing HOV facilities, there are other near-term utilities of lateral control systems. Examples of these include:

- * **SAIS's** and **ALKS's** can improve driving comfort and safety on rural roadways, particularly in regions of the country where adverse weather could persist over several months in a year. In this regard, their applications are analogous to installing "**intelligent**" roadway delineation that is capable of communicating with the vehicle.
- * Large vehicles (such as transit buses and trucks) which operate on arterial and city streets in particular can benefit from adopting **ALKS's**. Many arterial and surface

streets have lane width substantially smaller than 12 feet, which frequently results in buses or trucks encroaching upon adjacent lanes. Deployment of **ALKS's** may improve traffic flow and safety on narrow city streets.

* **ALKS's** can be used to help guide transit buses in and out of bus bays. **ALKS's** can also help transit buses to achieve desired alignment along the curbs at bus stops. This will facilitate handicapped passengers with wheel chairs or other special equipment in boarding or alighting the vehicle.

* **ALKS's** can be implemented on special facilities (such as bridges and tunnels), which usually have limited **right-of-way**, lanes narrower than 12 feet, or little to no lateral clearance. Such applications can improve the flow rate, enhance driving comfort, and lower probabilities of sideswipe accidents, on these facilities.

Currently, a significant amount of R&D remains to be completed or initiated before technology demonstration of the nearest-term **SAIS's** could be planned. Principal R&D activities for **SAIS's** include:

- o Track tests of the **SAIS's** using full-scale vehicles in real-world conditions.
- o Tests to assess the compatibility between the discrete

magnetic roadway reference/sensing system and existing roadway infrastructure, particularly the influence of steel reinforcements on the magnetic fields.

- Assessments of the cost-effectiveness of magnetometers
- Methods for providing warnings effectively and safely to drivers.

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Part Two:

**Lateral Control Systems:
Human Factors and Simulation Issues**

by

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PART TWO

HUMAN FACTORS AND SIMULATION ISSUES

Introduction

Lateral control systems to assist in, or completely assume, the steering task for vehicles are being investigated as a means of improving highway safety and increasing the capacity of existing roadways. In the long run, lateral sensing and control could become part of an intelligent transportation system. There are a variety of issues -- policy, technical and human factors -- that must be addressed during the development and implementation of lateral sensing and control systems. Of these, the human factors aspect of lateral control has received relatively little attention. The objective of this report is to identify some human factors issues and their importance in lateral control of vehicles. A common method of studying human factors for transportation is the use of driving simulators. There are a wide variety of simulators now available with various costs and capabilities; therefore, a portion of this report is devoted to describing and evaluating these simulators. Due to high costs and/or imperfections of driving simulators, other methods of research are also addressed.

Lateral control

Two major tasks involved in driving are the control of velocity and the control of lateral position. Much research and public policy work has emphasized velocity control, including speed limits, cruise control, anti-lock brakes, and even 'smart brakes' which use radar to detect obstacles and then stop the vehicle automatically. Lateral control systems are not a new technology, and recently, there have been more serious attempts to develop and test lateral control systems for transportation applications. Part of the motivation for this is an effort to improve comfort, safety and transportation system capacity [U.S. Congress 1989, Peng 1990]. One of the weak links in the safety of the current vehicular system is the driver's slow reaction time and imperfect judgement. Part of a lateral control system would be an advisory system that could augment the driver's ability to judge the exact lateral position of the vehicle. Giving the system the additional ability to control steering would avoid errors by eliminating human delay. With increased steering precision comes the possibility of reducing lane widths from the current standard of twelve feet (an

average car is about six feet wide). Reducing lane width on existing multi-lane highways could in some cases provide space for an additional lane within existing right-of-ways.

The specific technology of the lateral control system to be implemented has not yet been decided. A variety of sensing technologies and control strategies are under investigation, but very few have been implemented or even tested in the highway environment [Chira-Chavala 1991]. The requirements for an appropriate system are that it be accurate, safe, not significantly influenced by local faults or breakdowns, and easy to install and repair. In addition, it should have all-weather capability and the potential to provide additional information such as downstream geometry. Some of the leading systems now under consideration would utilize electromagnetic, magnetic, optical, radar, acoustic, and video technology. More details on these systems, their benefits and drawbacks are available in a very good report by Parsons [Parsons 1988].

Implementation is perhaps a more difficult problem than developing the technology for lateral control. It is always difficult to make major changes in such a large and important part of our daily lives as the transportation system. There are a number of potential barriers to the implementation of lateral control. Among these may be public resistance due to apprehensions of new technology and mistrust of the system's dependability. Questions also exist regarding the the potential of the system to improve safety, as well as its cost-effectiveness. The best implementation program may be one that brings about a large change by taking one small step at a time. This allows for early detection of any problems as well as allowing the public to adjust to the system gradually.

Many transportation professionals believe that implementation of lateral control could occur in phases. In the first, roadways and vehicles would be equipped with lateral sensing systems to provide the driver with feedback on vehicle position within the lane, and produce warnings when the driver is in danger of a collision. In the second phase, automatic vehicle control capability would gradually be implemented. Initially, the system would control vehicle position within a lane. Subsequently, the system would also assist in lane changing, merging, and other steering tasks. The third phase of implementation would involve reductions in the lane width to increase the capacity of existing roadways [Chira-Chavala 1991].

Many human factors issues must be answered prior to the final design and implementation of a lateral control system. The remainder of this paper deals with identifying human factors questions, their importance in systems implementation, and methods that may be used to address them.

Human factors Issues

As described above, implementation of lateral control could be done in three stages: sensing only, sensing and control with standard lane width, and sensing and control with reduced lane width. In this report, human performance has been divided into three categories: during normal driving, transition driving, and

emergency driving. **Normal driving** refers to day-to-day driving while lateral control systems are fully activated and properly functioning. This includes warnings by the sensing device to indicate improper lane position or proximity to other objects. False alarms and valid warnings will be part of normal driving. **Transition driving** assumes that the system is not always operational or cannot work on all roadways. Thus, at some point while driving, the vehicle operator (or an external signal) will need to activate the system. What happens immediately before, during and after the transition will be called 'transition driving. **Emergency driving** refers to unexpected failures in the system or potentially dangerous situations. Failures in the system include malfunctions of both the roadway and the vehicle. A potentially dangerous situation is any situation which is life threatening, such as pedestrians on the roadway, an out of control vehicle, or other obstacles such as large objects dropped from other vehicles. This of course does not include routine warnings regarding poor lane position.

The three stages of implementation and the three different driving states create the following matrix of situations.

	sensing only	sensing and control; standard lane width	sensing and control; reduced lane width
normal driving			
transition driving			
emergency driving			

For each of the nine situations described by the matrix, human factors issues have been identified (Appendix A). The matrix assures that human factors for all possible situations are considered, but due to the length of this list and the fact that there are many issues that fall into multiple categories, a different organization is used in the remainder of this report.

The following table contains a more succinct listing of human factors research issues/questions in lateral control, divided into four main groups: **acceptability and public confidence, displays and warnings, driver skill, and attentiveness.** **Acceptability and public confidence** address the feelings of the public towards the lateral control system. **Displays and warnings** address communications between the system and the driver, both inside the vehicle and in the external environment. **Driver skill** addresses the abilities of the driver relative to the steering task. **Attentiveness** addresses the extent of driver awareness of the driving task and the external environment. The issues are ranked by their importance: (I) for those which are the most urgent to (IV) for those which are the least important, as follows.

Acceptability and Public Confidence in the System

- I. Very Important
 - Will the public accept the system?

- What are drivers' inherent reactions to the system (i.e. do people want the system)?
 - How will drivers react to false warnings; what are acceptable rates of false alarms?
 - How will drivers deal with system failure?
- II. Fairly Important
- Does the public have confidence in the system?
 - Will drivers feel safe with automatic lane changes and merges?
 - Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia?
 - How simple must the system be for drivers to understand and be able to share driving tasks?
 - Would the driver want or need manual override / disengage switch?
 - Will the system reduce the driver's workload or will it create additional work due to increased anxiety or the need to monitor new controls?
 - How smooth does the ride have to be for acceptance?
- III. Helpful to Smooth Operations
- How well will drivers adapt to the new system?
 - What degree of redundancy will people want the system to have in terms of backup systems?
- IV. Low Importance
- Larger vehicles may be assigned a separate lane. Will drivers of automobiles feel safer?

Displays and Warnings

- I. Very Important
- How much information should be given to drivers in both normal and emergency situations? How much information can the driver assimilate?
 - What is the most effective display and/or warning: audio or visual, standard or HUD (heads up display), discrete or continuous, length of warning, location, volume/intensity, color, tone, digital or analog, etc.?
 - Will the alarm prompt panic or corrective action?
 - How will the driver know whether the system is activated or not?
- II. Fairly Important
- How easy is it to interpret displays, and should all displays be standardized?
 - What happens to the display during a malfunction?
 - Should the driver have a manual on/off switch, and if so what type?
- III. Helpful to Smooth Operations
- How will the driver know what roads the system works on?
- IV. Low Importance
- What will happen to the display during transition?

Driver Skill

- I. Very Important
- For what situations should the warning come on, and how much time will the driver be given to react?
 - What is the combined reaction time of driver and system to an emergency?

- If the roadway system fails, can large quantities of vehicles operate in narrower lanes without automatic guidance?
 - If the control system fails, is the driver capable of taking over lateral control?
 - How extreme is the change in the driver's performance level when the system is activated?
- II. Fairly Important
- How easy is it for the driver to adapt to the loss of automatic control? How long does it take to be able to resume the tracking task manually?
 - Does driving with the lateral control improve drivers' tracking skills on roadways without the system or, instead, will it impair their driving skills on these roads?
 - How fast should the transition into and out of automatic control work? Should it gradually give control back to the driver?
- III. Helpful to smooth operations
- Is there a long range loss/gain of tracking skill?
 - How gradual does the lane width change have to be for drivers to cope?
- IV. Low Importance
- What does the narrow lane width do to driver's perception in wider lanes without the automatic system?
 - How will people react to variable lane widths within the system?

Attentiveness

- I. Very Important
- What is the effect on driver vigilance?
 - Does the driver need to be awake? How should the system react to a sleeping driver?
 - What is the necessary attentiveness to be able to react to a warning?
- II. Fairly Important
- If system fails to give a warning, will the driver be able to respond independently?
 - How much interaction is necessary to keep the driver attentive to the driving task?
 - Will drivers become less attentive because they know they will be warned of any critical situation?
- III. Helpful to Smooth Operations
- How should the drivers or systems of other cars be alerted if the system fails?
- IV. Low Importance
- No applicable questions.

Driving simulator review

The previous section provides a long and exhaustive list of human factors issues to be resolved prior to the implementation of lateral control systems. The next step is to determine how these issues might be addressed from research methods documented in the literature. Answers to some issues may be found in the literature, and solutions to some others may be found by taking public surveys. For questions that are deemed to have fairly low importance, answers may be acquired simply by obtaining expert opinions. For many issues, answers may not be readily available without further research. A variety of research tools have been used to assess human performance in driving tasks. It is possible to collect data by means of instrumented vehicles on public roads, but this frequently is difficult due to safety considerations and the need to recreate exact situations. Another approach is track tests, which could be expensive and may require a working prototype of the system to be tested.

Another attractive, and frequently used, approach to obtain the desired data is through driving simulators. Among the major advantages are the ease of data collection, the lack of any physical danger, the ability to recreate precisely the same situation over and over again, and the ability to model almost any system or situation. Interest in using simulators to address human factors issues for IVHS' that have no on-the-road experience have been heightened in recent years. Therefore, much of the effort in this report is devoted to an evaluation of currently available simulators. There are a great many types of simulators available for use; these range from part task systems to large and complex motion based simulators capable of modeling the actual driving experience in a very realistic manner. In addition, Congress has approved \$32 million for a National Advanced Driving Simulator (NADS) but has yet to allocate the funds to a particular research institution.

Existing driving simulators fall into two classes: fixed base and motion base. A fixed base simulator is exactly what the title implies; the graphics change in response to the steering wheel and the accelerator and brake pedals, but the seat and entire simulator in which the subject is sitting do not move at all. Benefits of a fixed base system are that such simulators are usually less expensive, smaller, and more accessible than motion based systems. In a motion based simulator, both the graphics and the cab react to the drivers' control inputs. The theory behind the moving base is that it artificially induces all of the forces on the driver which would occur in a real driving environment. Rapid motions will be felt by the driver after which the simulator will return to a neutral position so slowly as to be imperceptible to the driver. It is necessary to return to a neutral position because of the limited range of motion available. Advantages of a motion based simulator include increased realism, the presence of more realistic cabs, and the possibility of testing smoothness of the ride and the ability to evaluate vehicle design.

Motion based systems are much more expensive than the fixed based simulators, or the following reasons. First, there are costs of designing the mechanical system and installing the motion base. Second, good fidelity simulation

requires a system with rapid response time, which can be expensive. Discrepancies between visual and vestibular (motion detected by the inner ear) cues can cause simulator sickness which leads to questions regarding the validity of the simulator results. This was documented in Casali (1985,1986) and Frank (1988). One way to avoid this problem is to have a very quick system (driver dynamic response $<.04$ seconds). This is very costly to do in a motion base simulator, because both the graphics and the mechanical movements must fit into this reaction time. It is known that the motion base is a valuable tool for vehicle design, but its value to human factors research is unclear. In an effort to evaluate the effectiveness of a fixed based simulator, a research study on the Atari Race Drivin' simulator (a fixed base simulator with good graphics, a fairly slow response time, a single television screen and an unrealistic cab) found that 30% of the subjects came away from the simulator feeling that it moved [Wachtel 1991]. Thus, it seems that many of the human factors questions listed above may be answered adequately with the use of a fixed base system.

Driving simulators are fairly expensive and there is limited access to large simulators. Therefore, it is important to select appropriate simulators for specific purposes. For example, dynamic simulators are usually needed to test vehicle design. For some human factors questions, such as those more related to instrument displays, may just as easily be addressed using small desk-top simulators at a fraction of the cost [Wachtel 1991]. To be able to select appropriate simulators for testing human factors issues associated with lateral control, it is important to know the capabilities and limitations of the various systems that are available. To this end, a list of simulators and their characteristics is compiled. Each one is presented in a standardized form, so as to facilitate comparisons between them. The listed contact is the person who verified or provided the information about the simulator. Also, a great deal of the information was synthesized from the references which are listed at the end of each simulator description. For facilities that can provide dynamic motion, information on costs and available motion are also mentioned.

Table 1 contains definitions of terms used in describing simulators. Available driving simulators are described in more detail in Appendix B.

TABLE 1
Definition of Terms Used in Describing Simulators

Simulator: The name of the simulator.

Contact: The person (and address, if known) who, by phone or fax, confirmed the information obtained from the literature and provided any missing information.

Phone/Fax: Phone and/or fax number of the contact.

Location/Address: The location/address of- the simulator.

Year made: The year the simulator was completed.

Cost of simulator: Includes indication of whether the value listed is the purchase price for those simulators which may be purchased or the design and development costs for one-of-a-kind or prototype models.

Rental cost: The cost of renting the simulator for research purposes.

Size: The size of the simulator. It is specified what is included in the dimension (e.g. the entire room housing the simulator or only the simulator's cab).

Dynamics: The following indented list is included if the system has a motion base, otherwise a fixed base is indicated. If known, this space describes the type of motion base and the characteristics of the dynamic system. The magnitude given is the maximum angle, distance or acceleration which can be generated.

Degrees of freedom: The number of motions available. The maximum degrees of freedom possible are 3 for translation and 3 for rotation.

Acceleration: Acceleration in terms of gravity and its direction.

Vertical/vibration: Vertical control is primarily used to simulate vibrations from the engine and road. Vibration is very important for realism [Nordmark 1990].

Translation: Horizontal movement of the cab, involves two degrees of freedom.

Pitch: Tilts the cab forwards and backwards around the lateral axis. Used for longitudinal acceleration as well as uneven terrain.

Yaw: Left/right rotation about the vertical axis. Used for turning.

Roll: Sideways tilt around the longitudinal axis. Used to produce lateral acceleration as well as driving on a banked road.

Graphics: If known, this space will contain the type of graphics and the following indented list describes the characteristics of the graphic system.

Visual field: Describes the viewing screen size. This is typically measured in degrees of sight from the subject's perspective since the size is relative to distance. This is important to convince the driver that they are actually on a real road as opposed to sitting in a simulator. It is especially important in lateral control to be able to see to the side.

Frames per second: How rapidly the picture is updated. If the graphics are too slow, the picture will appear jerky and unrealistic.

Cost of graphics: The cost of graphics when compared to the cost of the entire simulator may give an indication the quality of the graphics.

Special graphics: This can include such things as weather and road conditions,

Distance from driver to screen: Values given for both forward and side views. The distance of the side screen is important in lateral control for the simulation of adjacent vehicles.

Driver dynamic time delay: The reaction time of the system (both mechanical and graphic) to the driver input. It is important that this be low (many experts believe the delay must be less than 0.04 seconds) to avoid simulator sickness.

Force feedback on driver controls: Resistance to motion of the controls is important to the realism of the controls. An example of feedback is the tendency of the steering wheel to resist turning from the center position. There are two types of feedback: one is to spring mount the controls so that the force varies linearly with displacement, and the other is to control the resistance by a computer, allowing a more complicated force/displacement relationship.

Sound: Includes such sounds as engine, screeching tires, other vehicles and wind.

Type of vehicle simulated: The importance of this is the flexibility of the simulator in simulating different types of vehicles. For instance, some simulators can simulate automatic or manual transmission vehicles, as well as trucks.

Realism of cab: Some simulators use a buck (industry term for a car without an engine) and others have just a seat and steering wheel. This is important for realism.

Special features, Advantages and Disadvantages: What sets this simulator apart from others.

Other: any interesting or useful information which does not fit in any of the other categories is included here

Typical use: Included to help determine which human factors questions the simulator is best suited to answer.

References: literature on the simulator

Detailed human factors review

Having discussed the various simulators available and briefly mentioning other testing techniques, we now return to the human factors issues itemized by their importance with a better idea of how the questions might be addressed. For each question, the italicized number in brackets indicates the current status of research on that particular human factor question. The numbers correspond to the following categories:

- [1] Has been satisfactorily answered.***
- [2] Has probably been answered.***
- [3] Has not been answered, but we have a good idea how to answer.***
- [4] Has not been answered, and we are uncertain about the best way to answer.***
- [5] If the system was better defined, we would have a good idea how to answer.***
- [6] The system must be better defined, but it is still difficult to answer.***
- [7] Cannot be judged until the system is implemented.***

Following each question, reference will be made concerning methods for conducting research on these questions: surveys, simulation, simulation*, test track, instrumented vehicles or video observation techniques. The following are explanations of these terms.

Survey involves asking questions of people from a wide variety of backgrounds after having defined applicable terms such as lateral control systems.

Simulation (without an asterisk), corresponds to research which can be done on the wide variety of driving simulators already available. These simulators range from part-task or low cost simulators to high fidelity, motion base systems. One problem with existing simulators is that the lateral screen, if present, is too far away to accurately simulate a car in the adjacent lane, which is particularly important for assessing behavior of driving in much narrower lanes in the presence of lateral control.

Simulation* corresponds to an ideal driving simulator which has one or more essential features not currently available in existing simulators. For example, in cases where the reaction of other drivers is needed, it may be necessary to use several simulators which are linked such that many of the vehicles on the screen are controlled by real people as opposed to a computer. This is important because it is not known how drivers will react to situations in the new system, and thus a computer cannot model an unknown reaction of other vehicles in the simulation. Another example is a high fidelity simulator which has side screens or a hologram close enough to accurately simulate adjacent vehicles.

Test track refers to a safe, controlled environment road upon which instrumented test vehicles may be driven. For research of human factors in lateral control, guide tracks down the middle of the lane may be used to safely simulate a lateral control system. This eliminates the problem associated with driving simulators by having other cars present in their actual size and proper distance, particularly to the side.

Instrumented Vehicles are normal vehicles with special equipment to record data regarding driver behavior such as reaction times, heart beat, pedal actions, accelerations, road positions, etc.. The benefit of this method is that the tests occur in a real environment, but situations deemed dangerous to the driver may not be tested [Van Der Horst 1989].

Video observation techniques is a way to obtain data on drivers' behavior in actual traffic situations without the subject knowing that he or she is being tested. The data is normally collected with a fixed camera, but it is possible to fix a camera to a moving vehicle (for example this would be a good method to collect tracking data). As of yet, the processing of the data is tedious, time consuming work and thus the technique would benefit greatly from increased automation [Van Der Horst 1989].

Human Factor Research Questions With Comments

Acceptability and Public Confidence in the System

I. Very Important

- Will the public accept the system? [5] **Difficult to find out before implementation, but using a test track or simulator on a large number of people (greater than 100) from a wide variety of backgrounds would give a fairly good picture. Use of a current simulator would give an approximate answer, but it would not include the effect of cars directly adjacent to the subjects vehicle. The answer depends on the degree of implementation (sensing only or automatic control with both normal and narrow lanes).**
- What are drivers' inherent reactions to the system (i.e. do people want the system)? [3] **A fairly simple method would be to conduct a survey, an alternative method, though more difficult and expensive, is to use simulation to let driver know the feel of the system before judging it. The answer will depend on the degree of implementation (sensing only or automatic control with both normal and narrow lanes).**
- How will drivers react to false warnings; what are acceptable rates of false alarms? [3] **The best way to test this is on a simulator. The situation is analogous to fire drills, which have a very high false alarm rate. Thus, there may be useful research on such related subjects.**
- How will drivers deal with system failure? [6] **A good simulation* (which could overcome the problem of distant side screens) can be used to address this question. Linked simulators would also be helpful.**

II. Fairly Important

- Does the public have confidence in the system? [7] **This goes along with acceptance. It is easy to have confidence in any situation which is simulated, but driving in a non-laboratory environment introduces the possibility of injury or death. People will probably be hesitant when the system is first installed regardless of how good the system is, but if it works (i.e. safe and dependable) then their confidence will grow. A further question is, how long would the system have to be failure-free for the public to feel comfortable with the system. The answer will depend on the degree of implementation (sensing only or automatic control with both normal and narrow lanes). Sensing only will probably have a much higher confidence level. A gradual implementation of the system, from sensing only to control with normal lane widths to control with narrower lanes, will yield greater confidence.**
- Will drivers feel safe with automatic lane changes and merges, in addition to lateral control? [5] **This is a modification that will have to be introduced after**

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer,

[7] Cannot be judged until the system is implemented.

automated lane-keeping systems have been in use for some time. Simulation or simulation* is the best way to answer this question.

- Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia? [4] **A simulator is unlikely to cause a feeling of claustrophobia due to the distance of the screens. Therefore, a simulator* (for example a simulator with a hologram projection system for adjacent vehicles) or test track is needed.**
- How simple must the system be for drivers to understand and be able to share driving tasks? [2] **There has been extensive research on how much information can be processed. For example, Ogden 1989 contains a helpful graph which plots sensory input versus performance level.**

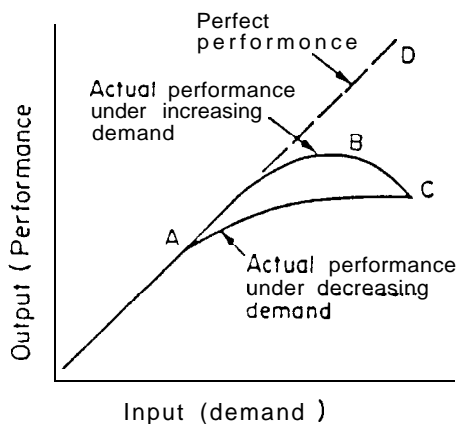


Figure 1: Information Processing Model [Ogden, 1989]

Also see other literature on displays and performance versus information (for example [SAE 1984, Human Factors 1963]). The solution specific to lateral control has not been investigated. Perhaps before more new information is acquired for lateral control, a synthesis of the literature should be performed.

- Would the driver want or need manual override / disengage switch? [4] **Simulation may help answer this, or it could be compared to similar features such as cruise control. Applies only to automatic control.**
- Will the system reduce the driver's workload or will it create additional work in terms of anxiety or monitoring new controls? [5] **Monitoring new controls may be tested in a simulator and there is also a lot of information on displays and the accompanying work load [Ogden 1989, SAE 1984, Olson 1983]. It is more difficult to test in a simulated environment whether the system will cause anxiety, but the question can probably be answered with a test track or by simulation. Also, anxiety will become less of an issue as people feel more comfortable with the system.**

Status of Human Factor Research on These Questions

- [1] **Has been satisfactorily answered.**
- [2] **Has probably been answered.**
- [3] **Has not been answered, but we have a good idea how to answer.**
- [4] **Has not been answered, and we have uncertainties on the best way to answer.**
- [5] **If the system was better defined, we would have a good idea how to answer.**
- [6] **The system must be better defined, but it is still difficult to answer.**
- [7] **Cannot be judged until the system is implemented.**

- How smooth does the ride have to be for acceptance? [3] **A test track or comparing the comfort of the system to that of a rough road may be the best way to test this.**
- III. Helpful to Smooth Operations
 - How well will drivers adapt to the new system? [5] **A simulator, simulator*, or test track are good ways to answer this question. The answer will depend on the degree of implementation (sensing only or automatic control with both normal and narrow lanes).**
 - What degree of redundancy will people want the system to have in terms of backup systems? [3] **A survey combined with a simulation or test track study could be used. This situation may also be compared to other systems of similar importance such as the brakes (in terms of a one car failure) or nuclear reactors (in terms of an entire system failure).**
- IV. Low Importance
 - Larger vehicles may be assigned a separate lane. Will drivers of automobiles feel safer? [3] **Due to the low importance level, a survey should adequately answer this question.**

Displays and Warnings

- I. Very Important
 - How much information should be given to drivers in both normal and emergency situations? How much information can the driver assimilate? [2] **There has been extensive research on how much information can be processed (see literature on displays and performance versus information for example [Ogden 1989, SAE 1984, Olson 1983], but the solution specific to lateral control has not been given. A synthesis of prior studies is needed.**
 - What is the most effective display and/or warning (audio or visual, standard or HUD, discrete or continuous, length of warning, location, volume/intensity, color, tone, digital or analog, etc.)? [3] **There are extensive guidelines in the literature for selection of displays. See [Ogden 1989, SAE 1984, Olson 1983, Weihrauch 1989, Wierwille 1989]. Once the questions concerning how much and which information to provide is answered, then the solution becomes rather simple.**
 - Will the alarm prompt panic or corrective action? [2] **This has probably been answered for the situations concerning pilots or nuclear reactor operators, but unless these situations are determined to have a strong correlation with driving the information may not be applicable. No specific references to driving have been found, but it is clear that an alarm system must be selected that will give the driver the appropriate reaction.**
 - How will the driver know whether the system is activated or not? [I] **Through displays the driver should easily be able to identify the status of the system. There are extensive guidelines in the literature for selection of displays.**

Status of Human Factor Research on These Questions

- [1] **Has been satisfactorily answered.**
- [2] **Has probably been answered.**
- [3] **Has not been answered, but we have a good idea how to answer.**
- [4] **Has not been answered, and we have uncertainties on the best way to answer.**
- [5] **If the system was better defined, we would have a good idea how to answer.**
- [6] **The system must be better defined, but it is still difficult to answer.**
- [7] **Cannot be judged until the system is implemented.**

II. Fairly Important

- How easy is it to interpret displays, and should all displays be standardized? [1] **The displays should have certain key similarities (as with those currently employed in automobiles) to avoid confusion. Certainly the display should be as simple as possible while still getting the necessary information across. The only remaining question is which of the available displays types the designer prefers.**
- What happens to the display during a malfunction? [2] **This can be compared to similar functions and system responses to a malfunction of other systems that have been in use. The answer is likely to depend on the malfunction and any accompanying warning.**
- Should the driver have a manual on/off switch, and if so what type? [2] **Although this is more a technical implementation question, it is influenced by user confidence, comfort with the system, desire for control, etc.. Probably the lateral control designers have already answered this question.**

III. Helpful to Smooth Operations

- How will the driver know what roads the system works on? [3] **The choices are signing or marking on the road (how often?), a signal on the display panel or a combination of both. A survey could help decide what people want, and then a simulator can test the decision.**

IV. Low Importance

- What will happen to the display during transition? [5] **It depends whether the transition itself will gradually take control or give back control. This situation may be compared to other systems which are turned on and off such as headlights or cruise control.**

Note: Although there is extensive information regarding design of the display, the final display should be tested on a simulator.

Driver Skill

I. Very Important

- For what situations should the warning come on, and how much time will the driver be given to react? [4] **The driver should be given as much time as possible to react without causing too many false alarms. To answer this, a simulator or simulator* may be used. This only applies to the sensing only version of the system.**
- What is the combined reaction time of driver and system to an emergency? [3] **Drivers' reaction times have been studied quite well. However reaction times from a state of inattentiveness have not been studied. The reaction time of the system may be as low as .1-.3 seconds. It is important to test drivers' reaction time in a real or simulated driving environment and not in a lab with no references to driving. This is because Olson and Sivak found in 1986 that the results of the classical lab reaction type studies are very different than those**

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

results from tests in a driving environment [Olson 1986]. A simulator would be the perfect environment for inattentiveness studies because of the reality of the environment and the safety factor.

- If the roadway system fails, can large quantities of vehicles operate in narrower lanes without automatic guidance? **[4] Should be studied on interactive simulators* (i.e. several linked simulators so that many vehicles in the system are controlled by real people as opposed to a computer model of people).**
 - If the control system fails, is the driver capable of taking over lateral control? **[3] This may be done on a simulator. The answer depends on attentiveness and lane width. Several simulators have been used to measure drivers performance based on tracking skills.**
 - How extreme is the change in the driver's performance level when the system is activated? **[3] Test on a simulator or test track.**
- II. Fairly Important
- How easy is it for the driver to adapt to the loss of automatic control? How long does it take to be able to resume the tracking task manually? **[3] Test on a simulator when the driver is both warned and surprised by the shutdown of the system.**
 - Does driving with the lateral control improve drivers' tracking skills on roadways without the system or, instead, will it impair their driving skills on these roads? **[5] Test on a simulator. After implementation, this question will be more completely answered, perhaps by instrumented vehicles. The question applies to sensing only.**
 - How fast should the transition into and out of automatic control work? Should it gradually give control back to the driver? **[3] Test on simulator with instant cutoff and a gradual transition and see what yields better driving performance and what people are more comfortable with.**
- III. Helpful to smooth operations
- Is there a long range loss/gain of tracking skill? **[7] This might have to be assessed after initial implementation of the system, perhaps by instrumented vehicle tests. The answer will depend on the degree of implementation (sensing only or automatic control with both normal and narrow lanes).**
 - How gradual does the lane width change have to be for drivers to cope? **[2] This is probably specified in the highway design manual.**
- IV. Low Importance
- What does the narrow lane width do to driver's perception in wider lanes without the automatic system? **[3] A combination of a simulation followed by a survey of the drivers might be performed.**
 - How will people react to variable lane widths within the system? **[3] Study the performance of drivers in areas which now have variable lane widths (for example areas undergoing road construction where traffic is diverted to temporary lanes) by either instrumented vehicle or video techniques. Also this could be studied on a simulator* with side screens or a hologram which could accurately simulate adjacent vehicles.**

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

Attentiveness

I. Very Important

- What is the effect on driver vigilance? [3] **Testing in a simulator would be ideal. The results will be conservative because of the non-life-threatening test, environment.**
- Does the driver need to be awake? How should the system react to a sleeping driver? [6] **The question of how to regain the attention of a fatigued driver has not been addressed. A simulation (not necessarily a high fidelity one) of tired drivers might be performed in which the driver must still perform some other driving task.**
- What is the necessary attentiveness to be able to react to a warning? [3] **The simulation for the previous question could also answer this.**

II. Fairly Important

- If system fails to give a warning, will the driver be able to respond independently? [3] **A simulator or simulator* (if one is concerned with adjacent vehicles) might be used.**
- How much interaction is necessary to keep the driver attentive to the driving task? [2] **There is probably research regarding this question in airline pilot studies since flying is "hours of monotony interspersed with moments of panic."**
- Will drivers become less attentive because they know they will be warned of any critical situation? [4] **It is difficult to test in a simulator, because the subject is aware that there is no real danger. A test track may be a better option.**

III. Helpful to Smooth Operations

- How should the drivers or systems of other cars be alerted if the system fails? [3] **The system is analogous to an air traffic controller with an out of control airplane. This knowledge would help answer the question.**

IV. Low Importance

- No applicable questions.

Implementation Questions

I. Very Important

- What is the adaptability and/or flexibility of the system. Does it know the present lane width if they are not standard?

II. Fairly Important

- How will the cars with and without the system activated interact?
- On what types of roads is the system used?

III. Helpful for Smooth Operations

- Where does transition occur . . . at the same place for every car?

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

Recommendations

Human Factors Research Questions

It is essential to attempt to find the solutions to those questions in importance categories I and II when designing and planning lateral control systems. Many questions in importance categories III and IV, could well be answered in conjunction with the research done for the more important questions. Questions in categories III and IV that require a major effort to answer may not be a matter of immediate concern. In many cases a cost-effective way to answer less important questions is to seek expert opinions as a first course of action.

Recommendation # 1

A survey might be conducted in parallel with R&D efforts on lateral control to find out what the public feels about the system. A survey also allows many other questions to be answered at the same time.

Recommendation #2

In addition to such a survey, research is needed answer questions in importance categories I and II which (1) have not already been answered, (2) we have a good idea of how to answer, and (3) do not need the system to be better defined. The asterisk(s) following each question correspond to the earliest implementation stage at which it is an issue. They include the following questions:

- How will drivers react to false warnings; what are acceptable rates of false alarms? *
- How smooth does the ride have to be for acceptance? **
- If the control system fails, is the driver capable of taking over lateral control? **
- How extreme is the change in the driver's performance level when the system is activated? *
- How easy is it for the driver to adapt to the loss of automatic control? How long does it take to be able to resume the tracking task manually? **
- What is the effect on driver vigilance? *
- What is the necessary attentiveness to be able to react to a warning? *
- If system fails to give a warning, will the driver be able to respond independently? *
- The display should be chosen with attention to the available information. The final display should be tested on a simulator and then adjusted if necessary. *
- How fast should the transition into and out of automatic control work? Should it gradually give control back to the driver? **

Recommendation #3

Status of Human Factor Research on These Questions

- [1] Has been satisfactorily answered.***
- [2] Has probably been answered.***
- [3] Has not been answered, but we have a good idea how to answer.***
- [4] Has not been answered, and we have uncertainties on the best way to answer.***
- [5] If the system was better defined, we would have a good idea how to answer.***
- [6] The system must be better defined, but it is still difficult to answer.***
- [7] Cannot be judged until the system is implemented.***

Next, researchers should work on those questions from importance categories I and II which are more difficult to answer but are possible without further definition of the system such as the following:

- Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia?***
- Would the driver want or need a manual override / disengage switch?***
- For what situations should the warning come on, and how much time will the driver be given to react?*
- If the roadway system fails, can large quantities of vehicles operate in narrower lanes without automatic guidance?***
- Will drivers become less attentive because they know they will be warned of any critical situation?*

Recommendation #4

Once the system is better defined, it is necessary to answer those questions from importance categories I and II which we have a good idea how to answer but which require a more complete definition of the system:

- Will the public accept the system?*
- Will drivers feel safe with automatic lane changes and merges?***
- Will the system reduce the driver's workload or will it create additional work in terms of anxiety or monitoring new controls?*
- What is the combined reaction time of driver and system to an emergency?*
- How easy is it for the driver to adapt to the loss of automatic control? How long does it take to be able to resume the tracking task manually?***

Recommendation #5

The questions for which the system needs to be defined but are more difficult to answer should be addressed next:

- How will drivers deal with system failure?*
- Does the driver need to be awake? How should the system react to a sleeping driver?***

In answering any of these questions, it is important to consider which other, lower priority questions may be easily answered along with the currently planned research.

There are a variety of different ways to evaluate human factors issues including surveys, instrumented vehicles, video techniques, test tracks, simulators and simulators*. It is debatable which method will produce the best results and be most cost effective. It is possible that a number of these methods could be used to answer any single question. In choosing a test method, researchers should be aware

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

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[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

of the other questions which could be concurrently answered. Currently, simulators appear to be a promising method of evaluating human factors issues. Of the other methods a test-track has the potential to be just as useful for human factors research in lateral control.

Simulators,

One major problem with using the available driving simulators for tests involving lateral control is the lack of side viewing screens. Even when these screens are present, the distance appears to be too great to accurately simulate an adjacent vehicle. To carry out experiments on human factors (such as the effect of closer vehicles due to narrow lanes), this shortcoming must be overcome. There are several possible alternatives: (a) an improved simulator that includes closer lateral projection screens or even holographic projections of adjacent vehicles, (b) the use of controlled environment test tracks.

Another problem with using simulators is simulator sickness typically caused by discrepancies between visual and vestibular cues. To avoid simulator sickness, the dynamic reaction time must be very fast to avoid simulator reaction time lags. While opinions vary upon how fast the reaction must be, the most commonly mentioned number is a driver dynamic time delay of less than 40 milliseconds [Wachtel 1991]. Simulator sickness usually occurs only in conjunction with a motion base. A motion base is necessary for vehicle design, and possibly for studying some human factor issues.

A survey of drivers on the fixed-base Atari Race Drivin' video arcade driving simulator found that 30% of the subjects felt that the simulator moved [Wachtel 1991]. The Atari simulator used in that study consisted of one 25 inch television screen and a small, unrealistic cab and fairly good graphics. A larger screen and more realistic cab would probably yield even better results.

The importance of a motion base for human factors studies is not well documented. Research is needed to compare results using fixed and motion based simulators and some form of testing in a more realistic environment (for example unobtrusive observation of vehicles on the roadway, instrumented vehicles, or a test track). Such research will also help to assess the realism of results when subjects know that they are being tested.

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

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[7] Cannot be induced until the system is implemented

APPENDIX A

	sensing only	sensing and control; standard lane width	sensing and control; reduced lane width
normal driving			
transition driving			
emergency driving			

Sensing Only

Normal Driving

1. Acceptability/ public confidence in the system

- Will the public accept the system?
- Does the public have confidence in the system?
- What are drivers' inherent reactions to the system (i.e. do people want the system)?
- How will drivers adapt to the new system?
- How simple must the system be for drivers to understand and be able to share driving tasks?
- Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia?
- How will drivers react to false warnings; what are acceptable rates of false alarms?
- Will the system reduce the driver's workload or will it create additional work due to increased anxiety or the need to monitor new controls?

2. Displays / Warnings

- How will the driver know whether the system is activated or not?
- How will the driver know what roads the system works on?
- How easy is it to interpret displays, and should all displays be standardized?
- How much information should be given to drivers in both normal and emergency situations? How much information can the driver assimilate?
- What is the most effective display and/or warning: audio or visual, standard or HUD (heads up display), discrete or continuous, length of warning, location, volume/intensity, color, tone, digital or analog, etc.?
- Will the alarm prompt panic or corrective action?
- For what situations should the warning come on, and how much time will the driver be given to react?

3. Driver skill

- Is there a long range loss/gain of tracking skill?

Status of Human Factor Research on These Questions

- [1] Has been satisfactorily answered.***
- [2] Has probably been answered.***
- [3] Has not been answered, but we have a good idea how to answer.***
- [4] Has not been answered, and we have uncertainties on the best way to answer.***
- [5] If the system was better defined, we would have a good idea how to answer.***
- [6] The system must be better defined, but it is still difficult to answer.***
- [7] Cannot be judged until the system is implemented.***

- Does driving with the lateral control improve drivers' tracking skills on roadways without the system or, instead, will it impair their driving skills when unassisted on these roads?
- How extreme is the change in the driver's performance level when the system is activated?
- What is the combined reaction time of driver and system to an emergency?

4 . Attentiveness

- Will drivers become less attentive because they know they will be warned of any critical situation?
- What is the effect on driver vigilance?
- What is the necessary attentiveness to be able to react to a warning?
- If system fails to give a warning, will the driver be able to respond independently?

Transition Driving

1. Acceptability/ public confidence in the system

- How simple must the system be for drivers to understand and be able to share driving tasks?
- Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia during transition?

2 . Displays / Warnings

- How will the driver know whether the system is activated or not?
- How will the driver know what roads the system works on?
- Should the driver have a manual on/off switch, and if so what type?
- What will happen to the display during transition?
- How easy is it to interpret displays during transition?
- How much information should be shown during transition? How much information can the driver assimilate?
- What is the most effective display for the transition?

3. Driver skill

- How easy is it for the driver to adapt to the loss of information/warnings? How long does it take to be able to resume the tracking task?
- How fast should the transition into and out of automatic control work? Should it gradually give control back to the driver?

4. Attentiveness

Emergency Driving

1. Acceptability/ public confidence in the system

- How will drivers deal with system failure?

2. Displays / Warnings

- How will the driver know whether the system is activated or not in the case of failure?
- Should the driver have a manual on/off switch, and if so what type?

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer,

[7] Cannot be judged until the system is implemented.

- How much information should be shown in emergency situations? How much information can the driver assimilate?
- What is the most effective emergency display and/or warning?
- Will the alarm prompt panic or corrective action?
- What happens to the display during a malfunction?

3. Driver skill

- What is the combined reaction time of driver and system to an emergency?
- If the system fails, is the driver capable of taking over lateral control?

4. Attentiveness

- What is the necessary attentiveness to be able to react to an emergency?
- If system fails to give a warning, will the driver be able to respond independently?

Sensing and Control: Standard Lane Width

Normal Driving

1. Acceptability/ public confidence in the system

- Will the public accept the system?
- Does the public have confidence in the system?
- What are drivers' inherent reactions to the system (i.e. do people want the system)?
- How will drivers adapt to the new system?
- How simple must the system be for drivers to understand and be able to share driving tasks?
- Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia?
- Will drivers trust the system in low visibility situations such as dense fog, or downpours?
- How smooth does the ride have to be for acceptance?
- How will drivers react to false warnings; what are acceptable rates of false alarms?
- Would the driver want or need manual override / disengage switch?
- Will the system reduce the driver's workload or will it create additional work due to increased anxiety or the need to monitor new controls?
- Will drivers feel safe with automatic lane changes and merges?

2. Displays / Warnings

- How will the driver know whether the system is activated or not?
- How will the driver know what roads the system works on?
- Should the driver have a manual on/off switch, and if so what type?
- How easy is it to interpret displays and should all displays be standardized?
- How much information should be given to drivers in both normal and emergency situations? How much information can the driver assimilate?
- What is the most effective display and/or warning?

Status Of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

- Will the alarm prompt panic or corrective action?

3. Driver skill

- Is there a long range loss/gain of tracking skill?
- Does driving with the lateral control improve drivers' tracking skills on roadways without the system or, instead, will it impair their driving skills on these roads?
- What is the combined reaction time of driver and system to a warning?

4. Attentiveness

- Will drivers become less attentive because they know they will be warned of any critical situation?
- What is the effect on driver vigilance?
- Does the driver need to be awake? How should the system react to a sleeping driver?
- What is the necessary attentiveness to be able to react to a warning?
- How much interaction is necessary to keep the driver's attentive to the driving task?

Transition Driving

1. Acceptability/ public confidence in the system

- How simple does the transition need to be for drivers to easily understand and work with the system?
- Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia during transition?
- How smooth does the transition have to be for acceptance?

2. Displays / Warnings

- How will the driver know whether the system is activated or not?
- How will the driver know what roads the system works on?
- Should the driver have a manual on/off switch, and if so what type?
- What will happen to the display during transition?
- How much information should be shown while the system is in transition?
- What is the most effective transition display?

3. Driver skill

- How easy is it for the driver to adapt to the loss of automatic control? How long does it take to be able to resume the tracking task manually?
- How fast should the transition into and out of automatic control work? Should it gradually give control back to the driver?

4. Attentiveness

- Does the driver need to be awake? How should the system react to a sleeping driver if the control system turns off automatically?

Emergency Driving

1. Acceptability/ public confidence in the system

- How will drivers deal with system failure?

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered. and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

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[7] Cannot be judged until the system is implemented.

- Would the driver want or need manual override / disengage switch?
- What degree of redundancy will people want the system to have in terms of backup systems?

2. Displays / Warnings

- How much information should be shown in emergency situations?
- What is the most effective display and/or warning?
- Will the alarm prompt panic or corrective action?
- What happens to the display during a malfunction?

3. Driver skill

- What is the combined reaction time of driver and system to an emergency?
- If the control system fails, is the driver capable of taking over lateral control?

4. Attentiveness

- Will drivers become less attentive because they know they will be warned of any critical situation?
- What is the effect on driver vigilance?
- Does the driver need to be awake? How should the system react to a sleeping driver?
- What is the necessary attentiveness to be able to react to an emergency?
- If the control system fails is the driver capable of taking over the lateral control?

Sensing and Control: Reduced Lane Width

Normal Driving

1. Acceptability/public confidence in the system

- Will the public accept the system?
- Does the public have confidence in the system?
- What are drivers' inherent reactions to the system (i.e. do people want the system)?
- How will drivers adapt to the new system?
- How simple must the system be for drivers to understand and be able to share driving tasks?
- Larger vehicles may be assigned a separate lane. Will drivers of automobiles feel safer?
- Will capacity increases on the freeway cause feelings of decreased safety or claustrophobia?
- How smooth does the ride have to be for acceptance?
- Would the driver want or need manual override / disengage switch?
- Will the system reduce the driver's workload or will it create additional work due to increased anxiety or the need to monitor new controls?
- Will drivers feel safe with automatic lane changes and merges?

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

2. Displays / Warnings

- How will the driver know whether the system is activated or not?
- How will the driver know what roads the system works on?
- Should the driver have a manual on/off switch, and if so what type?
- How easy is it to interpret displays . . . should all displays be standardized?
- How much information should be shown while the system is activated or not in normal situations? How much information can the driver assimilate?
- What is the most effective display and/or warning: audio or visual, standard or HUD (heads up display), discrete or continuous, length of warning, location, volume/intensity, color, tone, digital or analog, etc.?

3. Driver skill

- Is there a long range loss/gain of tracking skill?
- Does driving with the lateral control improve drivers' tracking skills on roadways without the system or, instead, will it impair their driving skills on these roads?
- When the system is turned off, do the lanes have to be wider?
- What does the narrow lane width do to driver's perception in wider lanes without the automatic system?
- How extreme is the change in the driver's performance level when the system is activated?

4. Attentiveness

- Will drivers become less attentive because they know they will be warned of any critical situation?
- What is the effect on driver vigilance?
- Does the driver need to be awake? How should the system react to a sleeping driver?
- How much interaction is necessary to keep the driver attentive to the driving task?

Transition Driving

1. Acceptability/public confidence in the system

- Will the public accept the system?
- Does the public have confidence in the system?
- Do drivers want the system . . . what is their inherent reaction to the system?
- How will drivers adapt to the new system?
- How fast should the transition into and out of automatic control work? Should it gradually give control back to the driver?
- How smooth does the ride have to be for acceptance?
- How will people react to variable lane widths within the system?

2. Displays / Warnings

- How will the driver know whether the system is activated or not?
- How will the driver know what roads the system works on?
- Would the driver want or need manual override / disengage switch?
- What will happen to the display during transition?

Status Of Human Factor Research on These Questions

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[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

- How easy is it to interpret displays, and' should all displays be standardized?
- How much information should be given to drivers in both normal and emergency situations? How much information can the driver assimilate?
- What is the most effective display and/or warning: audio or visual, standard or HUD (heads up display), discrete or continuous, length of warning, location, volume/intensity, color, tone, digital or analog, etc.?

3. Driver skill

- Does driving with the lateral control improve drivers' tracking skills on roadways without the system or, instead, will it impair their driving skills on these roads?
- How easy is it for the driver to adapt to the loss of automatic control? How long does it take to be able to resume the tracking task manually?
- How fast should the transition out of automatic control work? Should it gradually give control back to the driver?
- What does the narrow lane width do to drivers perception in wider lanes without the automatic system?
- How gradual does the lane width change have to be for drivers to cope?

4. Attentiveness

- Does the driver need to be awake? How should the system react to a sleeping driver when exiting automatic control?

Emergency Driving

1. Acceptability/ public confidence in the system

- How will driver deal with system failure?
- Would the driver want or need manual override / disengage switch?
- What degree of redundancy will people want the system to have in terms of backup systems?

2. Displays / Warnings

- How will the driver know whether the system is activated or not?
- How much information should be given to drivers in both normal and emergency situations? How much information can the driver assimilate?
- Will the alarm prompt panic or corrective action?
- What happens to the display during a malfunction?

3. Driver skill

- What is the combined reaction time of driver and system to an emergency?
- What is the necessary attentiveness to be able to react to a warning?
- If the control system fails, is the driver capable of taking over lateral control?
- If the roadway system fails, can large quantities of vehicles operate in narrower lanes without automatic guidance?

4. Attentiveness

- Will drivers become less attentive because they know they will be warned of any critical situation?

Status Of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

[4] Has not been answered, and we have uncertainties on the best way to answer.

[5] If the system was better defined, we would have a good idea how to answer.

[6] The system must be better defined, but it is still difficult to answer.

[7] Cannot be judged until the system is implemented.

- What is the effect on driver vigilance?
- Does the driver need to be awake? How should the system react to a sleeping driver?
- What is the necessary attentiveness to be able to react to a warning?
- Will the alarm prompt panic or corrective action?
- How much interaction is necessary to keep the driver's attentive to the driving task?

Status of Human Factor Research on These Questions

[1] Has been satisfactorily answered.

[2] Has probably been answered.

[3] Has not been answered, but we have a good idea how to answer.

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[5] If the system was better defined, we would have a good idea how to answer.

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[7] Cannot be judged until the system is implemented.

Appendix B Driving Simulator Descriptions

Simulator: Atari Race Drivin' (Figure 2)

Contact: James (Jim) Flack, Director of Simulation Products
Atari Games Corporation, 675 Sycamore Dr.
P.O. Box 361110, Milpitas, CA 95035

Phone: (408) 434-3737, fax (408) 434-3776

Location: Video Arcades

Year made: 1991

Cost of simulator: \$25,000 purchase price, \$3.5-4.5 million development cost

Rental cost: N/A

Size: 5 ft. x 6 ft. base, 5 ft. high

Dynamics: fixed based

Graphics:

Visual field: Three 25 inch diagonal color CRT displays (160° ahead) and rear view mirror which shows vehicles but no scenery (note: a simulator with 1 screen is available for \$15,000)

Frames per second: 20-30

Cost of graphics:

Special graphics:

Distance from driver to screen:

Driver dynamic time delay: c 0.08 seconds

Force feedback on driver controls: computer controlled resistance on steering wheel, gas and break pedal

Sound: engine, screeching tires, horns of other vehicles, crashes

Vehicle simulation type: the dynamics of four different cars have been programmed into the computer

Realism of cab: minimal - bucket seat (adjustable), steering wheel, gas, break, clutch, shift, ignition and dash with gas, speed and rpm, but the parts are not realistic and are not in the proper positions.

Special features: It now has the capability to link two machines but in the future eight to ten may be linked so that several cars on the screen may be controlled by other drivers and not by the computer.

Advantages: inexpensive, small, easily purchased

Disadvantages: made for video arcades under a very cost conscious company, the speeds are too high and the cab is not realistic. Modifications are costly, and Atari avoids doing modifications on single units.

Other: In June of '92, a modified, more realistic simulator (both in the graphics, speeds and cab) will be available. The target market is for police training. In addition, Atari will have a software package available in about a year allowing people not familiar with the system programming architecture to be able to make alterations in such things as roadway geometry, and possibly vehicle speeds.

Typical use: video game

References: [Goodenough 1989]

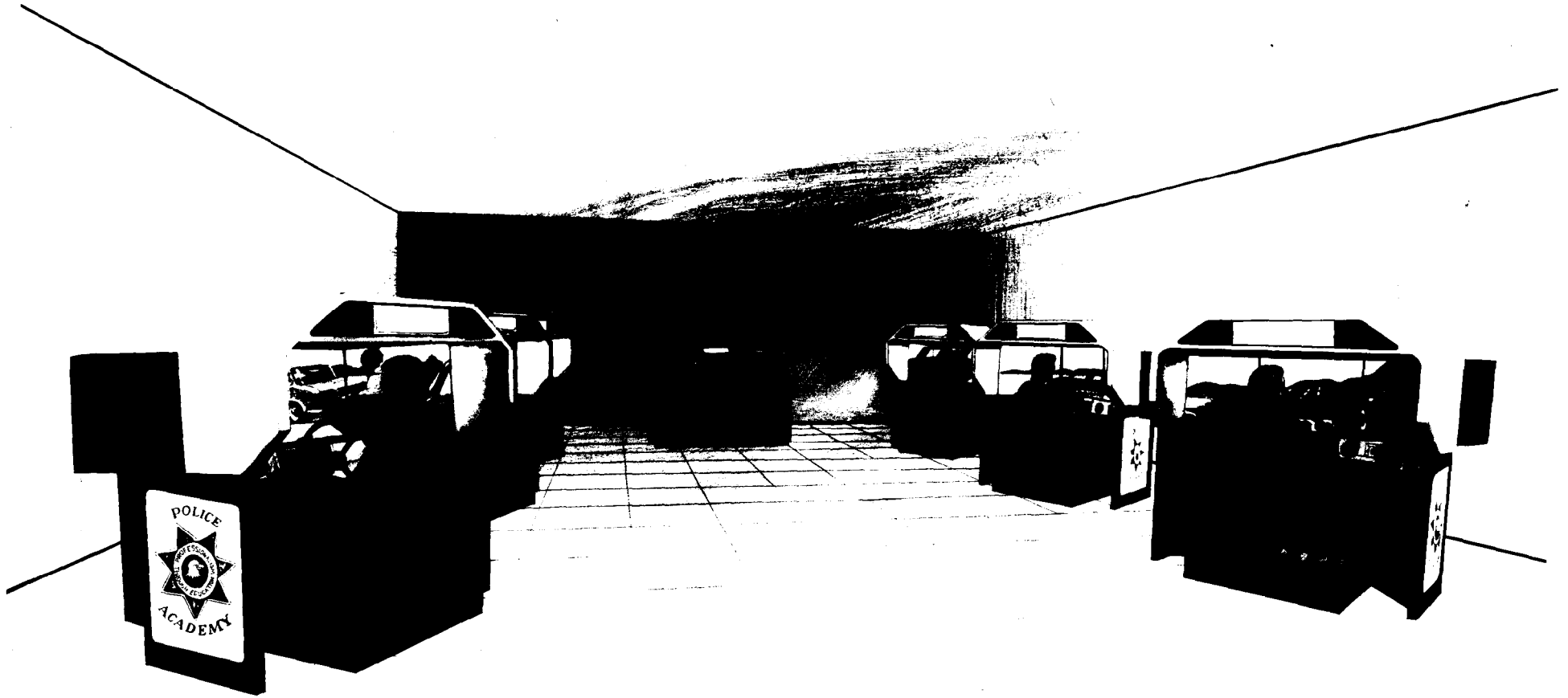


Figure 2. Atari Driving Simulator concept drawing
Source: [J. Flack, 1991]

Simulator: Daimler-Benz (Figures 3 and 4)
Contact: None
Phone: None
Location: Berlin Daimler-Benz Marienfelde Plant, Berlin, Germany
Year made: 1985
Cost of simulator: \$8.5 million
Rental cost: \$2800/hour
Size: 7.4 m diameter capsule, 4.7 tons
Dynamics: Digital
 Degrees of freedom: 6
 Acceleration: 1.5 g longitudinal, .7 g lateral
 Vertical/vibration: yes
 Translation: ± 1.5 m
 Rotation: ± 33 to 45°
 Pitch: yes
 Yaw: yes
 Roll: yes
Graphics: Computer generated raster scan with 6 projectors, 256 colors, 3000 shapes
 Visual field: 33" vertical 180" horizontal
 Frames per second: 50
 Cost of graphics:
 Special graphics: Fog, rain, ice and other road and traffic conditions
Distance from driver to screen:
Driver dynamic time delay: .08 s
Force feedback on driver controls: computer controlled resistance on steering wheel, gas and break pedal
Sound: 22 speakers. wind, engines, tires
Vehicle simulation type: car or truck
Realism of cab: actual body of vehicle, sans engine
Special features: Capable of full 360" skid on ice
Advantages: high quality
Disadvantages: not very accessible, more expensive than the other motion base systems
Other: higher speed yields better realism
Typical use: Driver behavior, vehicle handling and vehicle design
References: [Bak 1987, *Simulation* 1987, Scott 1985, Schill1990]

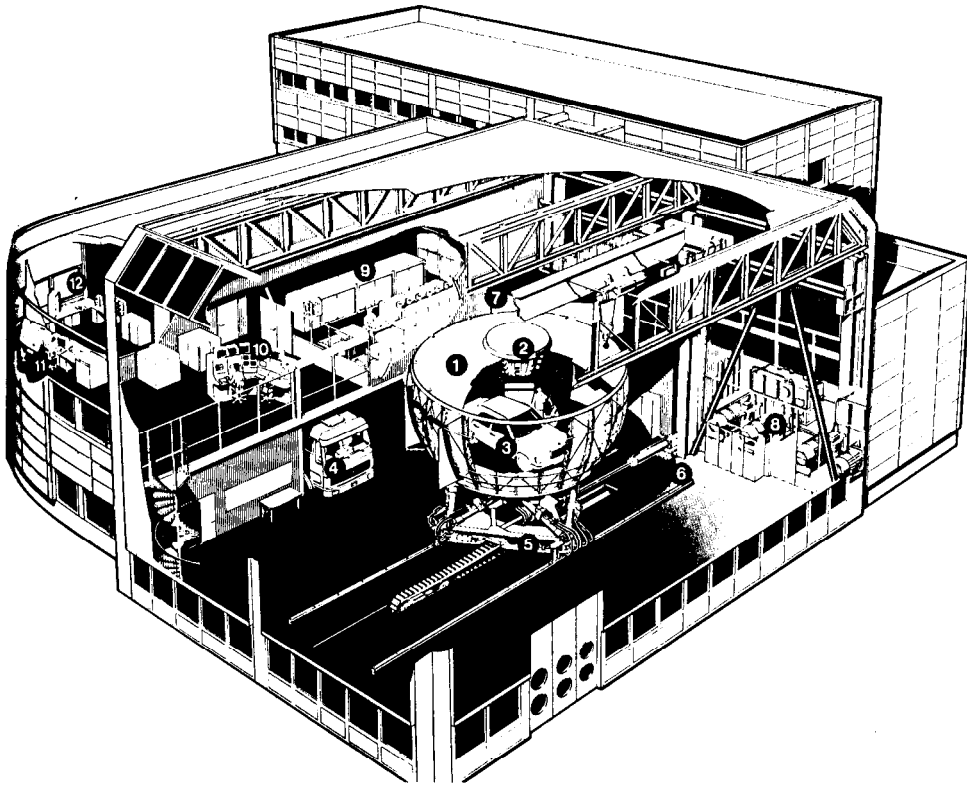


Figure 3. Daimler-Benz Driving Simulator
Source: [D. Scott, 1985]

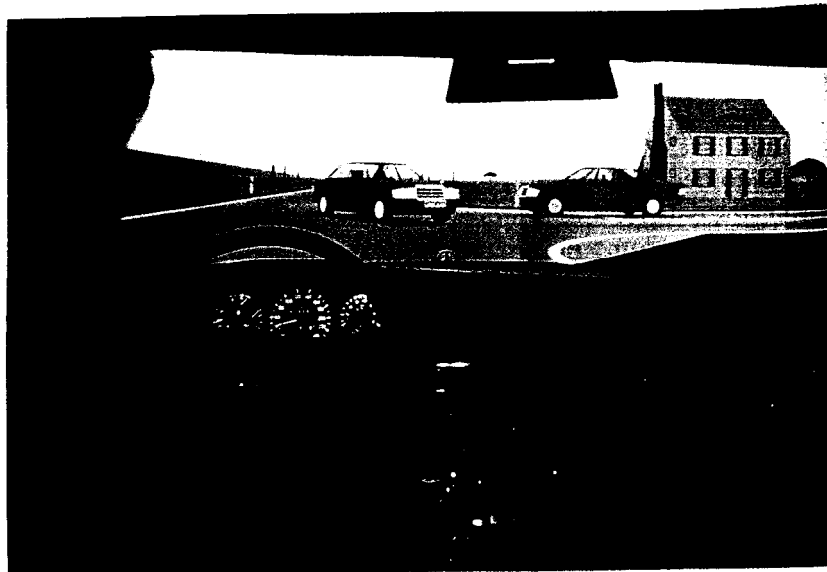


Figure 4. Daimler-Benz view from inside cab
Source: [D. Bak, 1987]

Simulator: Hughes Driving Simulator (Figure 5)
Contact: Cheryl Hine
Phone: (213) 3052666
Location: Los Angeles
Year made: 1987
Cost of simulator: \$2 million
Rental cost: Not available
Size: 25' x 30' room, 12' high
Dynamics: fixed base
Graphics: 3 projectors, 20' diameter toroidal screen
Visual field: 170"
Frames per second: now 30, will be 60 in a few months
Cost of graphics: biggest cost was the image generator
Special graphics: fog, mist, next year they will have textured graphics
Distance from driver to screen:
Driver dynamic time delay: now between 100 and 200 ms, it will be 33 ms when the quicker graphics are added
Force feedback on driver controls: a torque motor attached to the steering wheel and also an accelerator spring and brake hydraulics
Sound: yes
Vehicle simulation type: modified Oldsmobile Cutlass Supreme (Bucks)
Realism of cab: very good - an actual car is used
Special features: eye and head movement tracking to 6 degrees of freedom, can measure reaction time to .1 or .01 seconds,
Advantages: this is the only large screen, non motion base simulator
Disadvantages: with the current slow graphics, simulator sickness is a major problem, but the quicker graphics should remedy this
Other:
Typical use: Head up display (HUD) simulation, can track eye and head movement in 6 degrees of freedom, navigation, lane keeping, reaction time, intelligent cruise control. Hughes has done work for the National Transportation Safety Board (NTSB), National Highway Transportation Safety Association (NHTSA) and Caltrans, concerning displays and drivers controls.
References: [Synergy 1989]

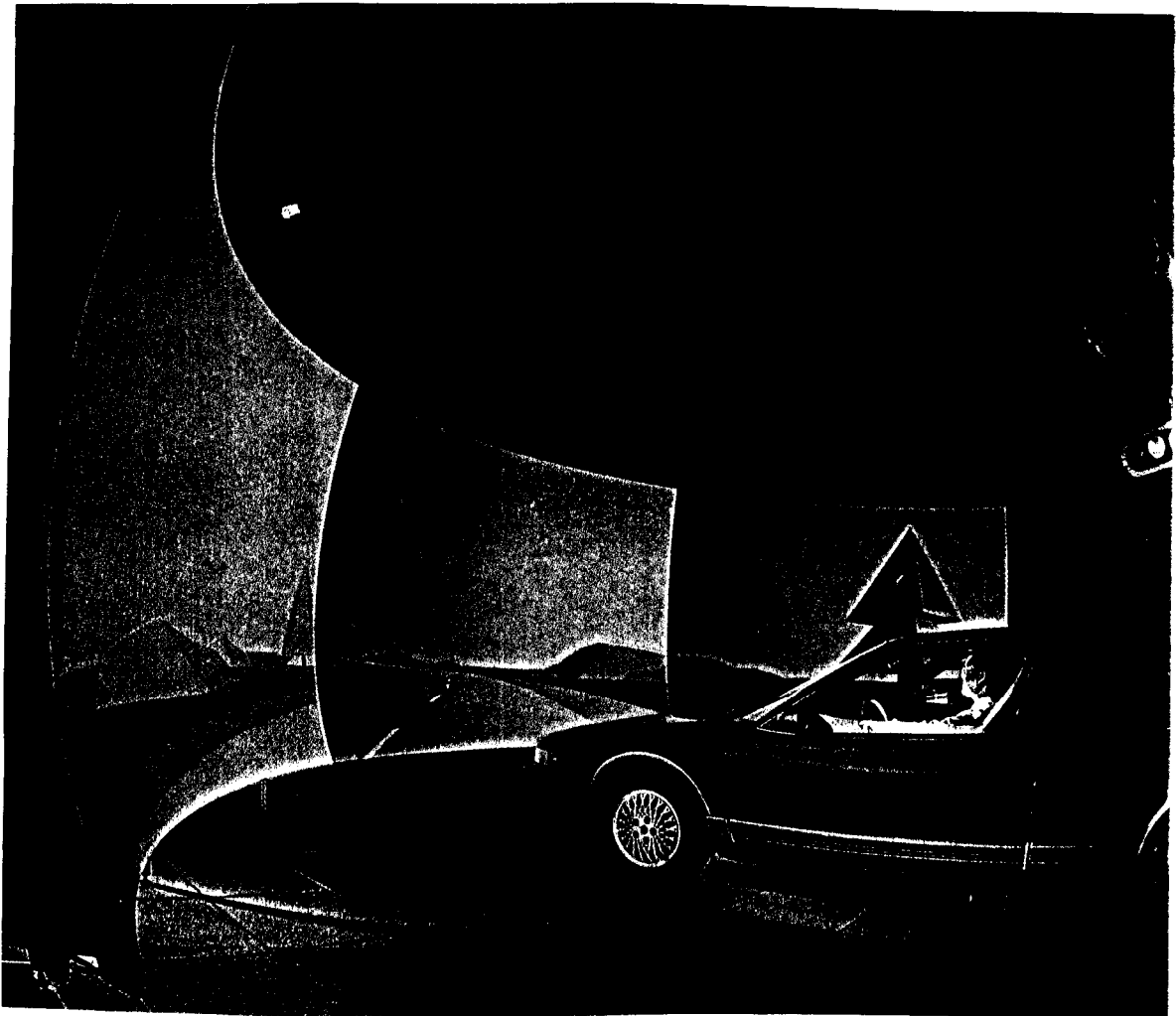
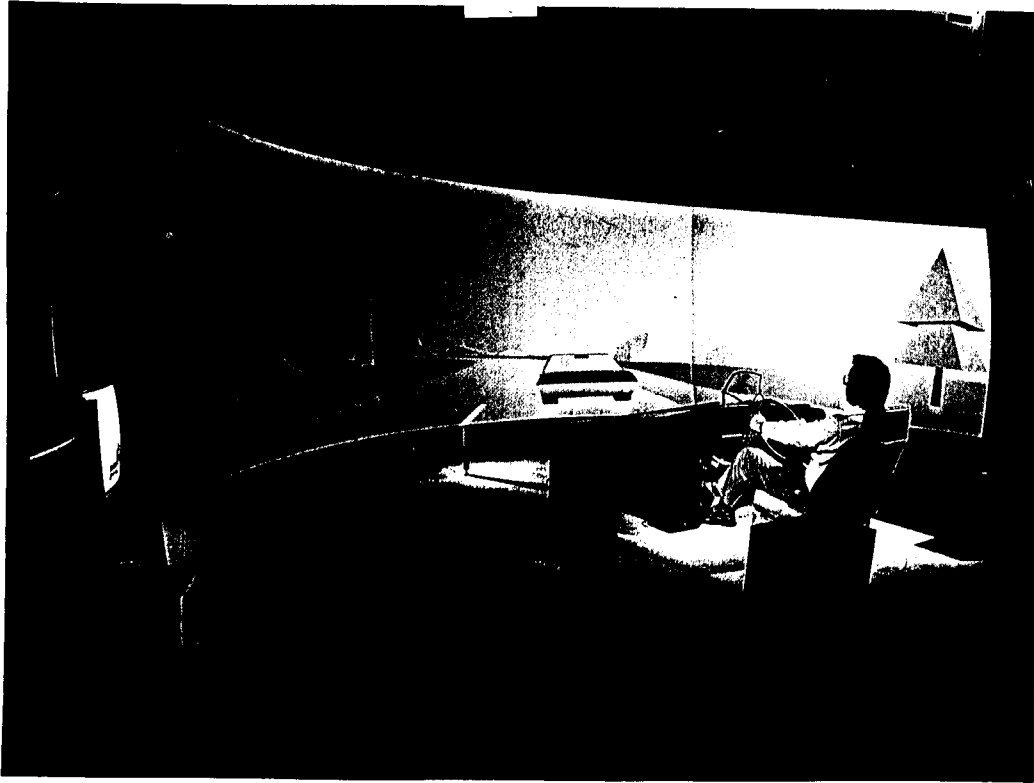


Figure 5. Two views of Hughes Simulator
Source: [Synergy, 1989]

Simulator: Iowa Driving Simulator (Figure 6)
Contact: Richard Romano, Jim Stoner, Edd Haug
Phone: (319)335-5679, Fax (319)335-6061 (General (319) 335-5722)
Location: University of Iowa, Iowa City
Year made: The motion base additions will be completed May of '92
Cost of simulator: \$12 million (including motion base)
Rental cost: \$750/hr (preliminary projection)
Size: simulator is housed in a 1600 feet squared, two-story facility
Dynamics:
Degrees of freedom: 6
Acceleration: .7 g
Vertical/vibration: 42 inch vertical excursion, $\pm .75$ g acceleration
Translation: \pm 28 inch lateral, + 32 inch longitudinal at .6 g each
Pitch: \pm 30" and - 25"
Yaw: \pm 22°
Roll: \pm 22"
Graphics: CT-6 image generator from Evans and Sutherland
Visual field: 150° forward view, 50" rear view, 30" high, 7.3 m diameter dome
Frames per second: 60
Cost of graphics: \$6 million
Special graphics: variable road conditions, wind, night, dusk, low visibility, fog, mist, traffic light
Distance from driver to screen: 7.3 m diameter dome
Driver dynamic time delay: many numbers given: 105 ms total step response, 89 ms visual dynamic response, and 30 ms motion base response.
Force feedback on driver controls: computer controlled resistance on steering wheel, gas and break pedal
Sound: high quality digital recordings of engine, road, suspension, tire, and other vehicles are directional projected
Vehicle simulation type: Currently, a Ford Taurus but will soon have others such as a truck and a BMW
Realism of cab: very good, an actual car is used
Special features: Graphics, Evans and Sutherland CT6 150"
Advantages: the most accessible among the large, motion base simulators, excellent graphics, rear view screen,
Disadvantages: motion base is not yet completed, the long driver dynamic time delay may lead to simulator sickness difficulties
Other: Iowa will find out in October of '91 about funding for a National Simulator, but this is independent of the work on the current simulator.
Typical use: Human factors research such as older driver studies and IVHS
References: [Mills 1991, Stoner 1990]

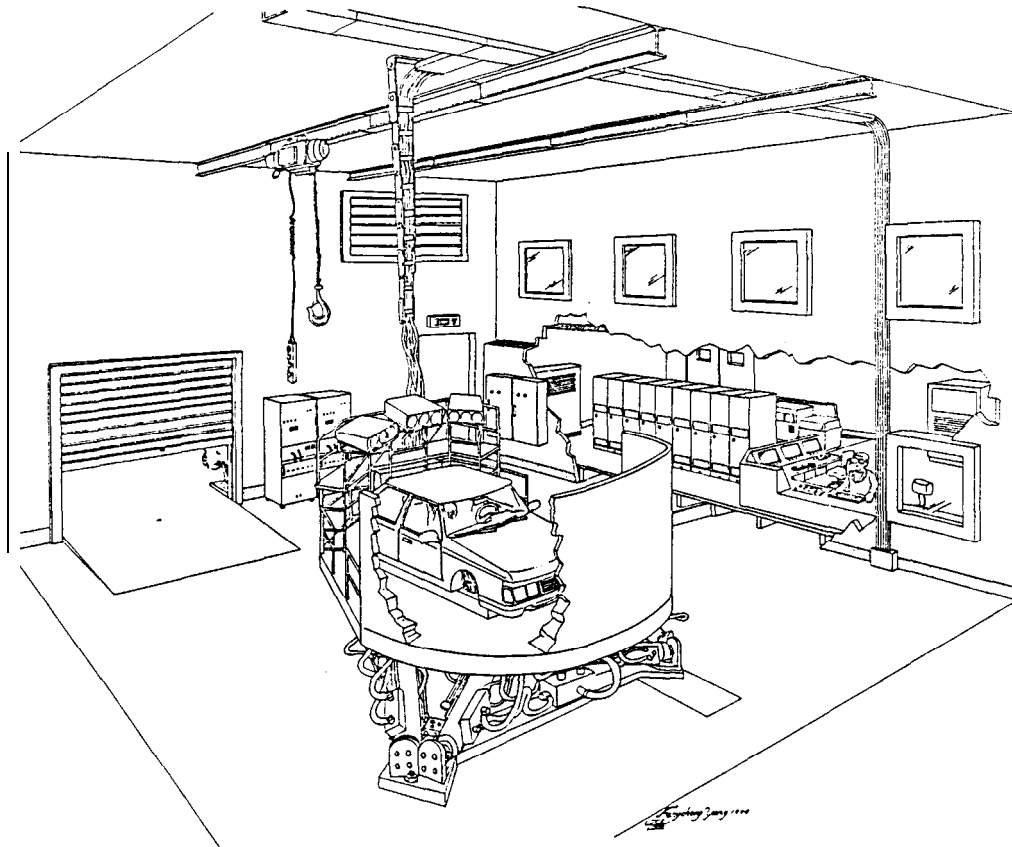


Figure 6. Iowa Driving Simulator
Source: [J. Stoner, 1990]

Simulator: Mazda Dynamic Driving Simulator (Figure 7 and 8)
Contact: Katsumi Inoda at Mazda in Japan
Phone/Fax: phone 045-461-1211, fax 045-461-1221
Location/Address: Yokahoma Technical Research Center near Tokyo
Year made: 1990
Cost of simulator: \$3 million
Rental cost:
Size: 5.5 meters squared, 14 tons
Dynamics: car-like cockpit moves along a 14 m rail
 Degrees of freedom: 4
 Acceleration: .8 g lateral
 Vertical/vibration:
 Translation:
 Lateral: ± 8.6 m maximum displacement, 8 m/s maximum velocity
 Pitch: $\pm 40^\circ$ maximum displacement, 20°/s maximum velocity
 Yaw : $\pm 160^\circ$ maximum displacement, 50°/s maximum velocity
 Roll: $\pm 40^\circ$ maximum displacement, 20°/s maximum velocity
Graphics: run on Alliant supercomputers
 Visual field: 72° lateral, 35° vertical
 Frames per second: 20
 Cost of graphics:
 Special graphics:
Distance from driver to screen:
Driver dynamic time delay:
Force feedback on driver controls: computer controlled resistance on steering wheel, gas and break pedal
Sound: tire noises, engine pitches
Type of Vehicle simulated:
Realism of cab:
Special features: 360° skid on ice
Advantages: inexpensive for a motion base system, large lateral displacement and acceleration capabilities
Disadvantages: not readily accessible (Japan)
Other: it was not built for automobile design development
Typical use: human factors
References: [Machine Design 1990, Yamaguchi 1989, Neray 1990]

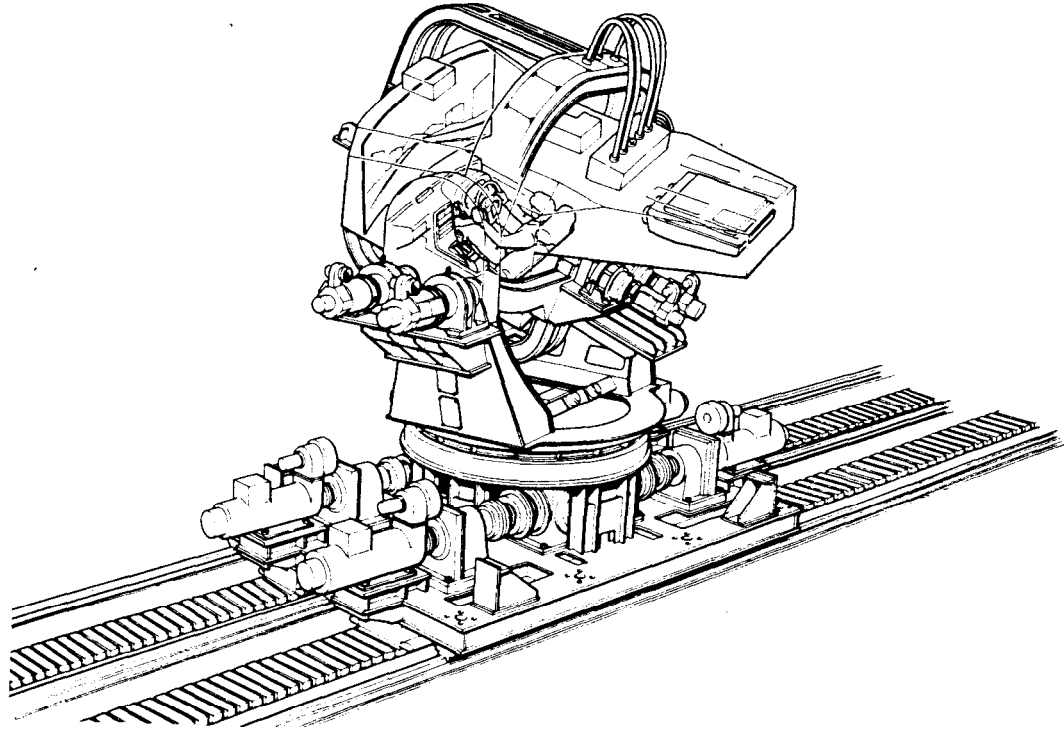


Figure 7. Mazda Driving Simulator
Source: [J. Yamaguchi, 1989]

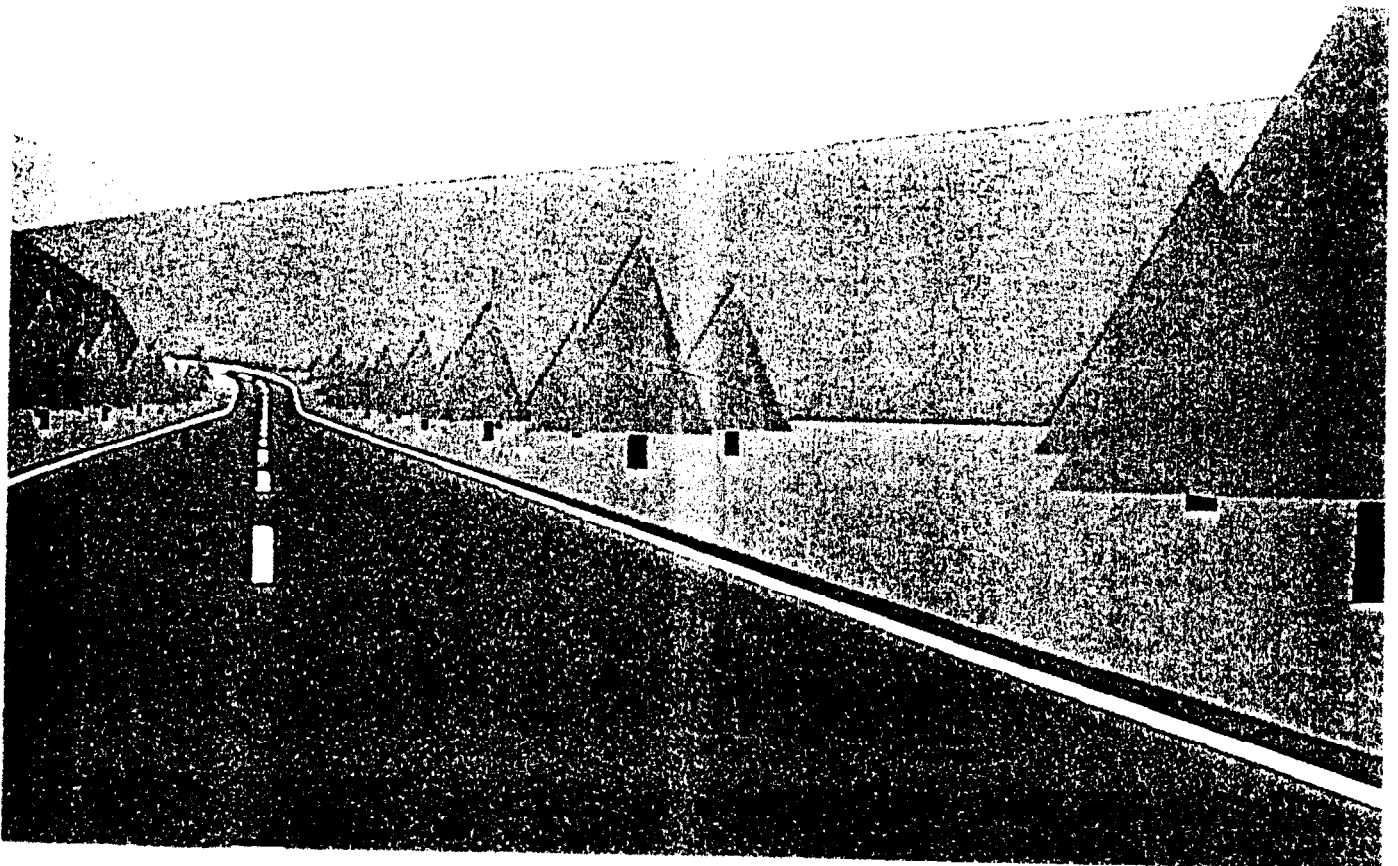


Figure 8. Mazda Simulator graphics
Source: [Neary, rP, 1990]

Simulator: Systems Technology Inc. (STI) (Figure 9 and 10)

Contact: Anthony Stein or Wade Allen

Phone: (213) 679-2281

Location: 13766 Hawthorne Blvd. Hawthorne CA 90250

Year made:

Cost of simulator: \$25,000 to purchase made to order simulator

Rental cost: N/A

Size: variable ("desk-top" computer system plus the size of any additions such as seat, steering wheel, pedals, etc.)

Dynamics: fixed base

Graphics: Diamond Scan Monitor

Visual field: (on personal computer screen)

Frames per second:

Cost of graphics:

Special graphics:

Distance from driver to screen:

Driver dynamic time delay:

Force feedback on driver controls: the system comes with potentiometers to the controls which the purchaser may use to get force feedback

Sound: the system comes with an amplifier and speakers

Vehicle simulation type:

Realism of cab: no cab included

Special features:

Advantages: can be specially tailored, fairly flexible, company has a lot of experience, and a research facility may own instead of renting

Disadvantages: the mechanical system does not come ready to use, and buyer must provide a car mockup or other such controls

Other: they have done dual screen before

Typical use: human factors, for example effects of age, alcohol, and fatigue on driver performance

References: [Allen 1981,1987,1989,1990]

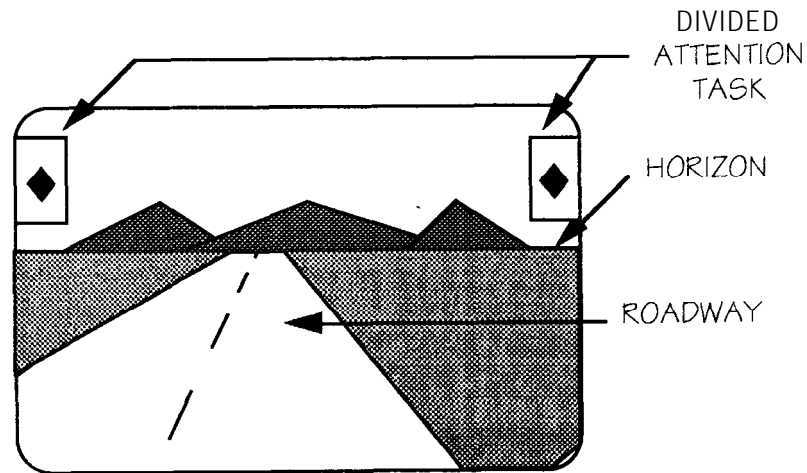


Figure 9. Sample graphics from a Systems Technology Institute Driving Simulator
 Source: [A. Stein, 1991]

Model 100A: This system uses one monitor to display all information (both the operators information and the roadway display). The driver controls the simulator using a commercially available flight simulator game control yoke (for steering and divided attention response) and rudder pedals (for accelerator and brake application). This system does not require a car buck, and can be mounted on a desk top if desired.

Cost: US\$ 20,000.00 FOB Hawthorne, CA

Model 100B: This system uses one monitor to display all information (both the operators information and the roadway display). The operator controls are via high quality linear potentiometers which must be mounted in a vehicle buck.

Cost: US\$ 23,500.00 FOB Hawthorne, CA

Model 100C: This system uses separate monitors for the operators information and the roadway display. The operator controls are via high quality linear potentiometers which must be mounted in a vehicle buck.

Cost: US\$ 25,000.00 FOB Hawthorne, CA

Figure 10. Price list for STI Simulators
 Source: [A. Stein, 1991]

Simulator: University of Michigan Transportation Research Institute, UMTRI (Fig. 11 and 12)

Contact: Paul Green

Phone/Fax: (313) 763-3795, fax (313) 936-1081

Location/Address: University of Michigan Transportation Research Institute, Human Factors, 2901 Baxter Road, Ann Arbor, MI 48109-2150

Year made: 1984-1985

Cost of simulator: \$15,000 - \$20,000 (\$500 -hardware)

Rental cost: \$0 (available for any research work)

Size: 1985 Chrysler Laser

Dynamics: fixed base

Graphics: Kloss Nova Beam Model 1 Color Video Projector Connected to Commodore

Visual field: it projects about a lane which is the equivalent to about 6 feet in width, the screen is 70 inches x 49.5 inches

Frames per second: 30

Cost of graphics:

Special graphics: night time

Distance from driver to screen: 15 - 20 feet

Driver dynamic time delay:

Force feedback on driver controls: no computer controlled feedback, but the steering wheel is spring mounted

Sound: no

Type of vehicle simulated:

Realism of cab: good, a mockup of an '85 Chrysler Laser is used

Special features: cheap, easy to learn, 30 minutes to run, 1 crew, programmable road geometry, flexible display

Advantages: inexpensive, in fact free for anyone who wants to use it, and it takes about an hour to train users.

Disadvantages: poor graphics, the entire driving scene is a night time scenario featuring only a horizon line and roadside markers

Other:

Typical use: instrument, signs, brake lamps, tracking performance monitoring

References: [Green 1989]

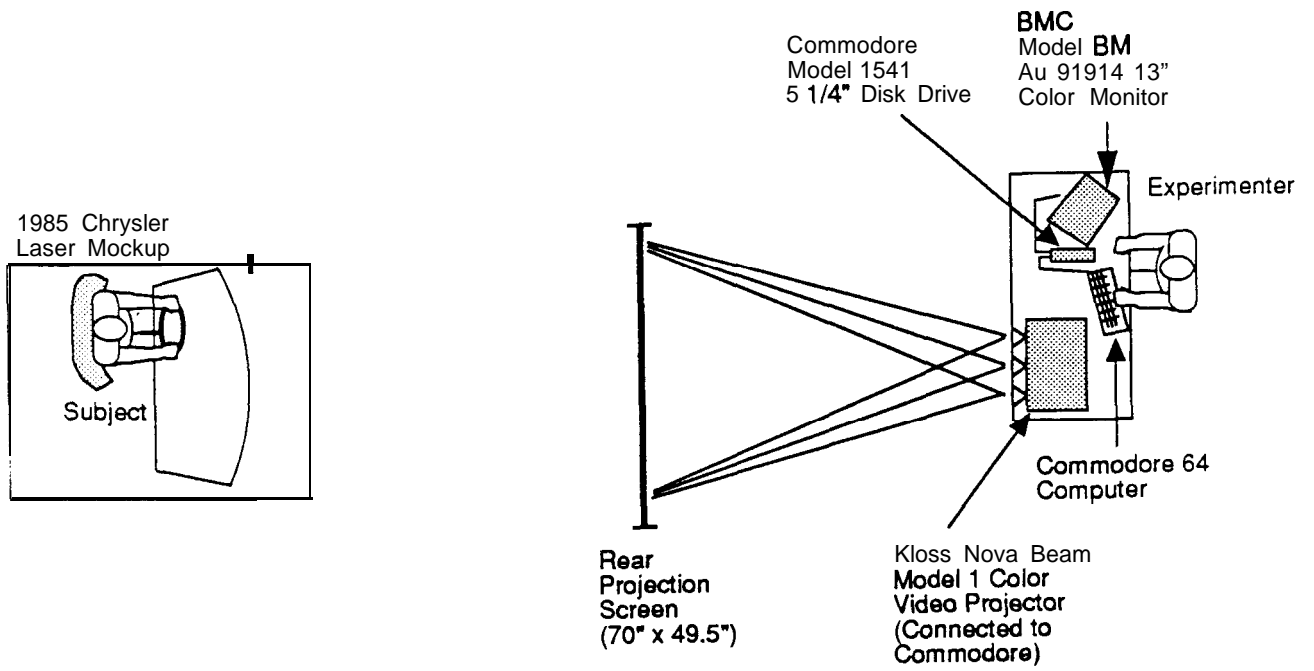


Figure 11. UMTRI Driving Simulator layout
 Source: [P. Green, 1989]

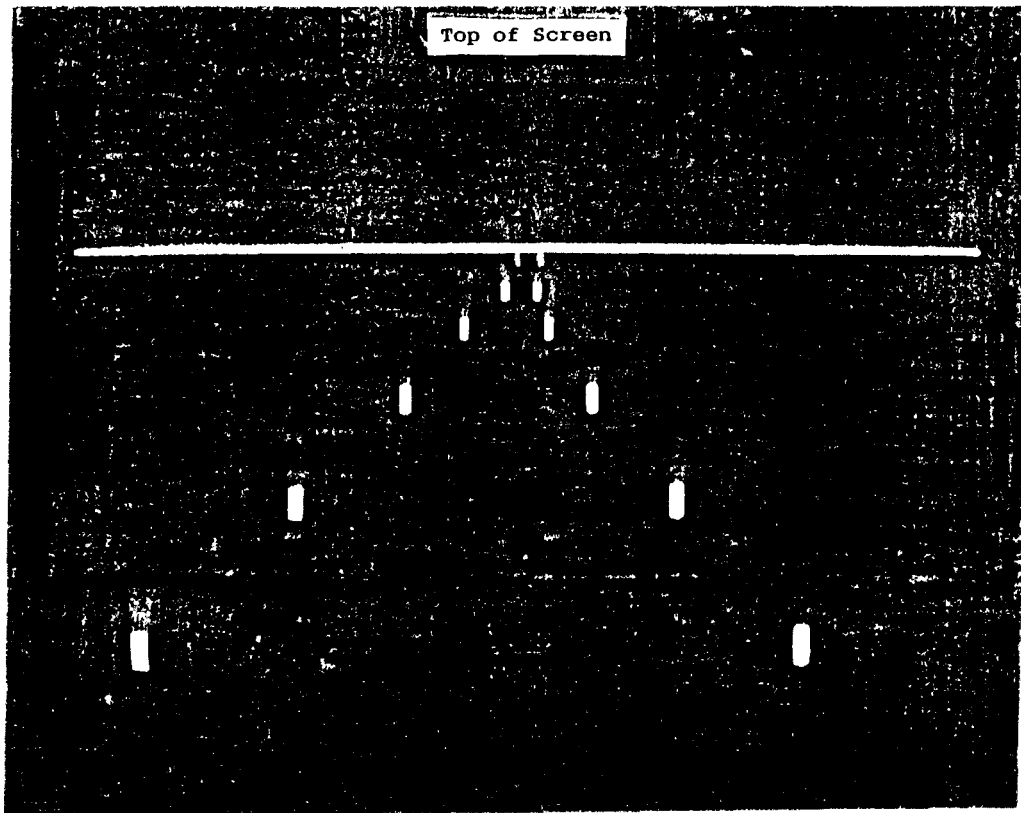


Figure 12. UMTRI Driving Simulator sample graphics
 Source: [P. Green, 1989]

Simulator: Vag-och Trafik-Institutet (VTI) Simulator (Figure 13)

Contact: Kare Rumar, Swedish Road and Safety Institute

Phone: 01 1-46-1320-4229 , fax: 011-46-1314-1436

Location: Stockholm, Sweden

Year made: 1983

Cost of simulator: 25.000.000 SEK (approximately \$4 million) development; apparently a number of years ago, VTI was selling simulators for about \$1 million.

Rental cost:

Size:

Dynamics: motions are operated by hydraulic engines via chains

Degrees of freedom: 3

Acceleration: .4 g lateral

Vertical/vibration:

Translation:

Rotation:

Pitch: simulates longitudinal acceleration

Yaw: replaced by pure lateral motion along rails

Roll: max 24°

Graphics: 3 color TV projectors mounted above driver's head

Visual field: 40° per projector (120° total)

Frames per second:

Cost of graphics:

Special graphics: fog and pot holes

Distance from driver to screen:

Driver dynamic time delay: possible for a 40 ms delay, but the graphics are better if a 60 ms delay is used

Force feedback on driver controls:

Sound:

Vehicle simulation type: heavy truck, passenger car

Realism of cab: good - uses Volvo 760 automatic and Saab 9000 manual

Special features:

Advantages: if in fact VTI is selling simulators, this would be the only motion base driving simulator which is commercially available.

Disadvantages: the use of chains to drive the dynamics leads to the possibility of backlash in the motion system.

Other: There will be a new simulator completed in 1991 for Trygg Hansa a Swedish insurance company.

Typical use: driver training and research (for example fatigue and eye movements)

References: [Nordmark 1984/1990]

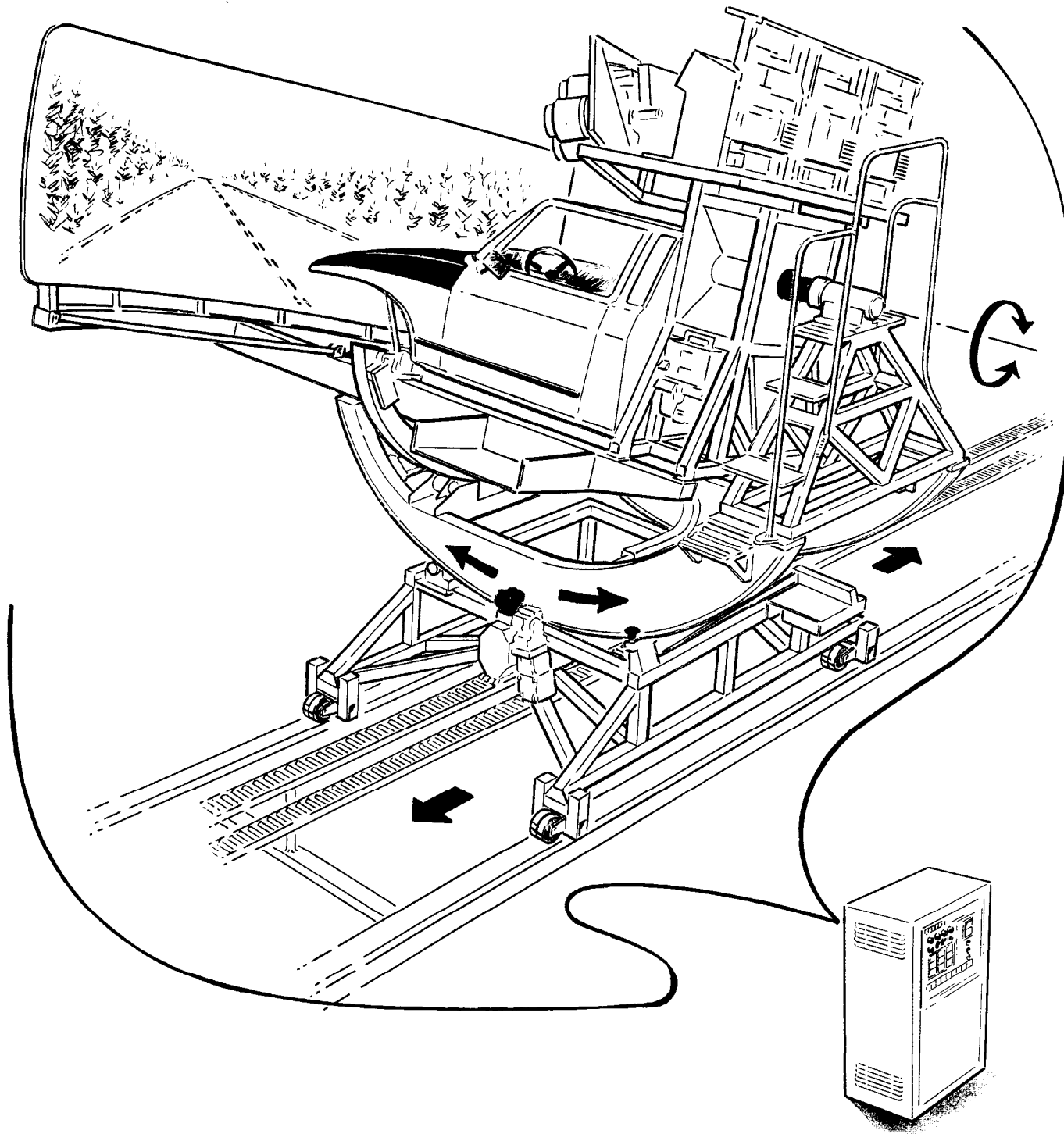


Figure 13. VTI Simulator
Source: [S. Nordmark, 1991]

Simulator: Virginia Polytechnic Institute (VPI)
Contact: Walter Wierwille
Phone/Fax: (703) 231-7952
Location/Address:
Year made:
Cost of simulator:
Rental cost:
Size:
Dynamics: analog hybrid
 Degrees of freedom: 4
 Acceleration:
 Vertical/vibration:
 Translation: 2
 Pitch:
 Yaw: yes
 Roll: yes
Graphics
 Visual field:
 Frames per second:
 Cost of graphics:
 Special graphics:
Distance from driver to screen:
Driver dynamic time delay:
Force feedback on driver controls:
Sound:
Type of vehicle simulated:
Realism of cab:
Special features:
Advantages:
Disadvantages:
Other:
Typical use: highway
References:

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