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Variable Dynamic Testbed Vehicle Study

Final Report

Volume III: Appendixes

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INTRODUCTION

This volume of the VDTV Study Final Report contains detailed information gathered or generated during the course of the study. It is intended as backup material to results documented in Volume II, Technical Results, in which case it is referenced in the report, or as unreferenced data that may be of value to readers of the report.

APPENDIX A

REQUIREMENTS

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APPENDIX A REQUIREMENTS

A.1 TOP LEVEL USER/FUNCTIONAL REQUIREMENTS

The following set of requirements expresses the needs of the various potential users of the VDTV.

A. 1.1 Programmatic Requirements

- The VDTV shall support the Office of Crash Avoidance Research testing for vehicle dynamics and safety parameters.
- The VDTV shall provide the variability necessary for NHTSA's future crash avoidance research activities while minimizing the need to acquire new vehicles.
- The VDTV shall be capable of providing data necessary to validate and extend the NADS.
- The VDTV shall be capable of providing vehicle dynamic and performance parameters to support the AHS program.
- The VDTV shall have the capability to provide human factor data, integrated with other test data.
- The VDTV shall be designed to minimize life cycle costs.

A. 1.2 Collision Avoidance Requirements

The VDTV shall:

- Emulate the dynamics of collision avoidance maneuvers for classes of vehicles in the range of a small economy car up to a large sedan.
- Have the capability to accommodate crash avoidance systems which may be provided by various users.
- Have the capability to accept different subsystems which affect crash avoidance tests within the limitation of no wheel base or track width changes.

A. 1.3 Vehicle Design Requirements

The VDTV shall:

- Have the appearance of a conventional automobile.
- Be capable of the functional performance of a conventional automobile.
- Possess physical parameters which affect dynamic maneuvers necessary for crash avoidance research, for a particular class of vehicle, that are better than those of current production cars by at least 10%.

A. 1.4 Operational Requirements

The VDTV shall:

- Be capable of operating and performing all functions in support of collision avoidance research under various road conditions.

- Be capable of operation on the public roads.

- Have an on-board measurement subsystem capable of the monitoring and recording of the vehicle's dynamics, the vehicle operating parameters, human factors of the driver, and test-unique equipment.

- Have an off-board data processing capability which receives data from the on-board measurement subsystem with minimum human interaction.

- Have an on-board lap top computer that is to be used for changing the parameters of the control laws, and for downloading and displaying data from the on-board measurement subsystem.

- Include complete documentation which will petit the vehicle to be operated at test sites throughout the Nation.

- Provide the capability for being maintained in the field (its support equipment shall provide this same capability).

- Be designed to provide a high level of test time.

A. 1.5 Safety Requirements

The VDTV shall provide for occupant safety under all conditions of its intended use. The Control Subsystem will not allow a maneuver outside the envelope of VDTV's safety constraints. The safety override module, which interfaces with the On-Board Measurement Subsystem, will switch the vehicle from a Drive-by-Wire configuration to manual mode if a dangerous situation is encountered. The driver may activate the safety override capability. The occupants are provided with physical constraints, roll-over cage, and a fire suppression system.

A.2 DERIVED REQUIREMENTS FOR A FULL-CAPABlLlTY VDTV

A.2.1 General Requirements

A.2.1.1 The VDTV shall have drive-by-wire capability that allows the vehicle's steering, braking, and throttle to be controlled through the use of electro-mechanical mechanisms.

A.2.1.2 The VDTV shall have the capability for dynamic control of all vehicle subsystems via software resident in the vehicle Controller Subsystem.

A.2.1.3 The VDTV dynamics control capability shall include:

A.2.1.3.1 Steering Subsystem

A.2.1.3.2 Braking/Traction Subsystem

A.2.1.3.3 Suspension Subsystem

A.2.1.3.4 Power Train Subsystem.

A.2.1.4 The VDTV shall have the capability to be driven in a conventional driver-controlled manual mode equivalent to the driving capability provided by production cars.

A.2.1.5 The VDTV shall be equipped with a manual safety default system.

A.2.1.6 The VDTV shall have the capability to report the health of all systems and instrumentation to the on-board test operator, and to the On-Board Measurement Subsystem.

A.2.1.7 The VDTV shall include the capability for the installation and operation of collision avoidance devices.

A.2.1.8 The VDTV shall be capable of testing the following approaches and concepts to support the Automated Highway System program:

A.2.1.8.1 Safety and dynamics of automated vehicle platooning at various speeds and headway spacings.

A.2.1.8.2 Safety and dynamics of automated acceleration and deceleration.

A .2.1.8.3 Safety and dynamics of automated emergency braking under various operating conditions.

A.2.1.8.4 Safety and dynamics of lane merging/leaving under various vehicle platooning scenarios.

A-2.1.9 The VDTV shall have the appearance of a conventional automobile.

A.2.1.10 The VDTV shall accommodate at least 4 people, including the driver and the test operator.

A.2.2 Chassis and Power Train (Power Plant and Drive Train)

A.2.2.1 Chassis

A.2.2.1.1 The total mass of the VDTV shall be variable up to a total vehicle mass of 2300 Kg.

A.2.2.1.2 The chassis shall provide mounting interfaces for the following subsystems and equipment:

a. Power Plant
b. Drive Train
c. Suspension Subsystem
d. Steering Subsystem
e. Braking/Traction Subsystem

f. Control Subsystem
g. On-board Measurement Subsystem
h. Cabling
i. Passenger Compartment
j. Vehicle Body
k. Inertia Ballast
l. Electrical Power Generation
m. Hydraulic Pump
n. Communications module with antenna(s)
o. Test-unique Equipment

A.2.2.1.3 The Chassis design shall consider for the worst case weight for all of the equipment mentioned in section A.2.2.1.1 and section A.2.2.1.2.

A.2.2.1.4 The Chassis shall be designed to support all the VDTV Subsystems during worst case vehicle loads without exceeding the material strength design limits.

A.2.2.1.5 The Chassis shall be designed to support all the VDTV subsystems during worst case vehicle loads without deleterious deflections.

A.2.2.1.6 The Chassis shall be designed to meet all public highway safety requirements.

A.2.2.1.7 The Chassis shall be designed to minimize vehicle weight and inertia.

A.2.2.2 Power Plant

A.2.2.2.1 The Power Plant shall consist of a high performance gasoline engine.

A.2.2.2.2 The Power Plant shall provide adequate power to meet the VDTV vehicle performance requirements for the worst case weight and ancillary power load configuration.

A.2.2.2.3 The Power Plant shall be compatible with the requirements for a four-wheel, front-wheel, or rear-wheel drive.

A.2.2.2.4 The Power Plant shall have the capability for Throttle-by-Wire acceleration that allows the driver or the Control Subsystem to accelerate the vehicle.

A-2.2.2.5 The Power Plant shall provide the capability for the driver to accelerate the vehicle in a normal manual mode equivalent to the type of acceleration control provided in production cars.

A-2.2.2.6 The Control Subsystem shall have the capability to switch the Power Plant between Throttle-by-Wire and manual mode.

A.2.2.3 Drive Train

A.2.2.3. I The Drive Train shall provide drive torque to the wheels in the following three modes:

a. Four-wheel drive
b . Front-wheel drive
c. Rear-wheel drive

A.2.2.3.2 The Drive Train shall be designed to meet the VDTV performance requirements for the maximum expected vehicle weight and inertia.

A.2.2.3.3 The Drive Train shall be equipped with an electronic shiftable automatic transmission.

A.2.2.3.4 The VDTV shall be equipped with four-wheel traction control.

A.2.2.3.5 The Drive Train shall be compatible with the Power Plant, Steering Subsystem, Suspension Subsystem, and the Braking/Traction Subsystem.

A.2.3 Suspension Subsystem

A.2.3.1 The VDTV shall be equipped with an independent four-wheel active Suspension Subsystem.

A.2.3.2 The active Suspension Subsystem shall be capable of its full range of operating parameters when suppdrting a vehicle with a weight range of 1150 Kg to 2300 Kg.

A.2.3.3 The active Suspension Subsystem shall be capable of responding to operational commands sent from the Control Subsystem.

A.2.3.4 The active Suspension Subsystem shall have the capabilities to achieve the following objectives:

a. to improve the ride quality of the vehicle,
b. to improve the road holding of the tires, and
c. to control the attitude of the vehicle during cornering (anti-roll), acceleration (anti-squat), and deceleration (anti-dive).

A.2.3.5 The active Suspension Subsystem shall have the capabilities to perform the following:

a. vary the jounce and rebound damping characteristics at each wheel.
b. vary the jounce and rebound spring rates at each wheel.
c. control the vehicle's pitch and roll attitudes under various driving conditions.

A.2.3.6 The active Suspension Subsystem shall have a fail-safe feature capable of performing a smooth transition from the active to passive suspension control configuration.

A.2.3.7 The driver and the Controller Subsystem shall both have the ability to activate the fail-safe feature.

A.2.4 Steering Subsystem

A.2.4.1 The VDTV shall be equipped with four-wheel steering.

A.2.4.2 The VDTV shall have the capability to switch between four-wheel steering and two-wheel steering.

A.2.4.3 The driver and the Controller Subsystem shall both have the ability to switch from four wheel steering to two wheel steering and vice-versa.

A.2.4.4 The VDTV capability shall include Steer-by-Wire which allows the driver or the Controller Subsystem to control the steering.

A.2.4.5 The VDTV shall provide the capability for the driver to steer the vehicle in a normal manual mode which is equivalent to the type of steering control provided in production cars.

A.2.4.6 The Steering Subsystem shall be actively controlled by the Controller Subsystem to achieve the following objectives:

a. to improve the lateral stability of the vehicle at highway speeds.
b. to improve the responsiveness of the vehicle in lateral, high-speed collision avoidance maneuvers, and
c. to enhance the road-feel of drivers under various driving conditions.

A.2.4.7 The VDTV shall have the capabilities to perform the following:

a. to vary the Steering Subsystem's lateral control sensitivity at different vehicle speeds.
b. to vary the Steering Subsystem's transient characteristics of lateral dynamics, and
c. to vary the Steering Subsystem's steering feel (steering torque) as a function of the vehicle's speed and steering angle.

A.2.5 Braking/Traction Subsystem

A.2.5.1 The VDTV shall have the capability of a four-wheel Anti-Lock Braking System.

A.2.5.2 The VDTV shall have the capability to provide variable levels of braking torques independently at all wheels as a function of vehicle and road conditions.

A.2.5.3 The VDTV shall have the capability to provide the driver with a programmable Brake Feel.

A.2.5.4 The VDTV shall have the capability for Brake-by-Wire braking that allows the driver or the Control Subsystem to brake the vehicle.

A-2.5.5 The VDTV shall have the capability for the driver to brake the vehicle in a normal manual mode equivalent to the type of braking control provided in production cars.

A.2.6 Control Subsystem

A.2.6.1 The Control Subsystem shall include the following functional capabilities:

a. Processing of VDTV variable control law algorithms.
b. Analog-to-digital signal conversion.
c. Digital signal processing.

A.2.6.2 The Control Subsystem shall have:

a. an interface to the on-board lap-top computer.
b. an interface to the on-board data acquisition system.
c. an interface to the Constraint Module.

A.2.6.3 The man-machine interface to the Control Subsystem shall be accomplished through the on-board lap-top computer.

A.2.6.4 The Contro1 Subsystem shall have the capability to regulate the VDTV's dynamic behavior by transmitting commands to the various subsystem actuators and receiving feed-back information from the subsystem sensors.

A.2.6.5 The Control Subsystem shall have an electrical interface(s) with the sensors and actuators associated with the following Subsystems and devices:

a. Test-unique devices.
b. Steering Subsystem.
c. Braking Subsystem.
d. Power Train Subsystem.
e. Suspension Subsystem.

A.2.6.6 The Control Subsystem shall receive information from the sensors associated with the:

a. Vehicle's accelerations in all longitudinal, lateral, and vertical directions.
b. Vehicle's velocities in all longitudinal, lateral, and vertical directions.
c. Vehicle's angular rates.
d. Steering Subsystem.
e. Braking/Traction Subsystem.
f. Power Train Subsystem.

A.2.7 On-Board Measurement Subsystem

A.2.7.1 The On-Board Measurement Subsystem shall have the following functional capabilities:

a. to perform analog-to-digital signal conversion.
b. to perform digital signal processing.
c. to accommodate a distributed signal processing system.
d. to accommodate the needed number of sensors.

A.2.7.2 The On-Board Measurement Subsystem shall have the capability to share information with the Control Subsystem.

A.2.7.3 The On-Board Measurement Subsystem shall have the capability to interface with test-unique sensors.

A.2.7.4 The On-Board Measurement Subsystem shall have the capability and performance characteristics to record all the information transmitted by the VDTV sensors.

A.2.7.5 The On-Board Measurement Subsystem shall have the capability and performance characteristics to record all the commands issued by the Controller Subsystem and lap-top-computer.

A.2.7.6 The On-Board Measurement Subsystem shall have the memory capacity to store the data referred to above.

A.2.7.7 The On-Board Measurement Subsystem shall have the capability to up-load data to the lap-top computer.

A.2.7.8 The lap-top computer configuration shall be at least equal to a 486/33 processor with 200 MB Hard Disk Drive, 3 1/2 inch floppy drive, 16 MB RAM, 8K cache, 2 - Type II PCMCIA slots, 1 - RS232 Port, and color active matrix screen, and shall include the following add-on equipment:.

a. 1 - PCMCIA Modem Card.
b. 1 - PCMCIA Ethernet Adapter Card.

A.2.7.9 The On-Board Measurement Subsystem shall include a Safety Override Module with a display mounted in a location convenient to the driver.

a. The Safety Override Module shall validate all Controller Subsystem commands against pre-programmed parameters to ensure that the VDTV's response to the command is within the vehicle's operational envelope.

b. The Safety Override Module, upon determining that a command is outside of operational parameters shall:

   1. Cancel the command.
   2. Display an error message.

A.2.7.9.1 The VDTV Safety Override Module shall have a capability to periodically sample a list of sensors and compare them with a set of operational parameters to determine the “health” of the vehicle (Wellness Token).

a. The Safety Override Module shall have the capability to display the Wellness Token status on the lap-top computer.

b. The Wellness Token shall be recorded by the On-Board Measurement Subsystem.

A-2.7.9.2 The VDTV Safety Override Module shall have a capability to periodically sample a subset of the sensors and compare it with a set of safety parameters to determine if a dangerous situation exists.

A.2.7.9.3 The VDTV Safety Override Module shall, upon sensing a dangerous situation:

a. Return all Subsystems to manual operation mode.
b. Display a message to the driver.
c. Record the information pertaining to the dangerous situation in the On-Board Measurement Subsystem.

A.2.8 Ancillary Equipment

A.2.8.1 Cables/Wiring

A.2.8.1.1 The VDTV cabling shall meet the applicable SAE requirements.

A.2.8.1.2 The VDTV cable connectors shall meet the applicable SAE requirements.

A.2.8.1.3 The VDTV cables shall be designed using a modular approach so as to allow for test unique cable reconfiguration.

A.2.8.2 Safety Devices

A-2.8.2.1 The VDTV shall be equipped with a Roll-Over Bar(s).

A.2.8.2.2 The VDTV shall have a Default Operational Mode switch located in a location convenient to the driver that switches all Drive-By-Wire operating modes to the manual operating modes.

A.2.8.2.3 The VDTV shall be equipped with passenger safety constraints.

A.2.8.2.4 The VDTV shall be equipped with driver and front passenger air bags.

A.2.8.2.5 The VDTV shall include a hands-free two way radio.

A.2.8.2.6 The VDTV shall be equipped with a driver activated on-board Halon fire extinguishing system vented to the engine bay, electrical equipment area, and passenger cabin.

A.2.9 Availability, Maintainability, Evolvability

A-2.9.1 Availability

A.2.9.1.1 The VDTV shah be available for use in testing 4 out of 5 days.

A.2.9.2 Maintainability

A.2.9.2.1 The VDTV and all its Subsystems shall be designed for maximum accessibility and maintainability.

A.2.9.3 Evolvability

A.2.9.3.1 The VDTV shah be designed to easily accommodate planned updates to the hardware and software.

A.2.10 Maintenance And Transportation

A.2.10.1 Transportation Of The VDTV

A.2.10.1.1 The VDTV shall meet the requirements for movement under the following modes of transportation:

a. Commercial type truck traveling on public highways.
b. Standard commercial type flatbeds/freight cars used on the railway systems of the United States.
c. Commercial type aircraft.

A.2.10.2 Maintenance

A.2.10.2.1 A Support Trailer(s) shall be provided for the field maintenance of the VDTV.

A.2.10.2.2 The Support Trailer(s) shall be equipped with:

a. Spare parts.
b. Special tools.
c. Calibration equipment.
d. Maintenance manuals.

A.2.10.2.3 The personnel responsible for the VDTV maintenance shall be trained in the operation, calibration, and maintenance of the vehicle.

A.2.11 Documentation

A.2.11.1 The delivery of the VDTV shall include drawings and documentation with the following engineering data:

a. location of the vehicle center of gravity relative to front and rear axles.
b. vehicle mass and vehicle moment of inertia.
c. location of roll center.
d. Power train technical specifications.
e. Tire performance specifications.

A.2.11.2 The delivery of the VDTV shall include the following base vehicle manuals:

a. Operation Manual.
b. Maintenance Manual.
c. Actuator Manuals.
d. Sensor Manuals.
e. Instrumentation Manuals.
f. Subsystems Hardware and Software User’s Manuals.

APPENDIX B

THE USER QUESTIONNAIRE

B.l QUESTIONNAIRE

Variable Dynamic Testbed Vehicle Questionnaire

Jet Propulsion Laboratory/California Institute of Technology

4800 Oak Grove Drive

Pasadena, CA 91109

INTRODUCTION

The following questions have been compiled to help JPL determine which capabilities of a Variable Dynamic Testbed Vehicle (VDTV) would be most important to its potential users. The information gathered, by personal contacts, and in interviews, will be instrumental in two important areas; (1) in determining the extent of the perceived need for a VDTV, and, (2) if support for the VDTV is favorable, in helping to develop the VDTV functional requirements.

JPL is a Federally Funded Research and Development Center (FFRDC) and, as such, may not compete with industry. Therefore, JPL should not be perceived as a commercial competitor by respondents.

OVERVIEW

If the decision is made to build the VDTV, it would be operated as a test vehicle in the sense that it would be highly instrumented and could accommodate a variety of design and operating characteristics. It would be used to test new and existing collision avoidance devices, human behavior under real driving scenarios, further the development of the automated car, and help validate the National Advanced Driver Simulator (NADS) model.

The VDTV would be constructed by modifying a “stock” vehicle with fixed and variable controls and suspension systems. In actuality, the VDTV may consist of more than one passenger automobile-class vehicle. The capability will exist to change its operating characteristics through a “man-machine” interface to an on-board computer, and/or by physical change-out of the mechanical subsystems. The VDTV will also have some degree of variable mass and inertial capabilities.

The output of the on-board computer will be linked to the VDTV’s “control system”, which in turn, will have the ability to modify select operating characteristics (i.e., steering, braking, suspension) in near real-time. In addition, the on-board computer will also be used to gather and store test result information provided by the VDTV’s microprocessors. The VDTV will be operated at a DOT test facility but could be made available to research institutions and industry for testing purposes.

If you have any questions please contact Al Kanner at 818-354-7583.

1. Is your company/organization currently engaged in collision avoidance or other advanced control vehicle technology research, development or testing?

[] Yes [] No

If you answered yes to question 1 then continue with 1.1 else skip to question 2.

1.1. How is your company/organization currently testing or planning to test collision avoidance technology? (check all that apply)

[ ] Using the National Advanced Driver Simulator (NADS)

[] Privately owned simulation. Please describe: ______________________________

[ ] Test vehicle operated on a NHTSA test track

[ ] Test vehicle operated on a privately owned test track

[] Other. Please describe: ______________________________

[] Don't Know

1.2. **If** your company/organization is currently operating an instrumented test vehicle, what type of vehicle is it? (check all that apply)

[] Compact or smaller vehicle

[] Mid-size vehicle

[] Full-size vehicle

[] van

[] Other. Please describe: ______________________________

[] Other. Please describe: ______________________________

1.3. If your company/organization is currently operating an instrumented test vehicle, does it have an on-board data acquisition system?

[] Yes [] No

2. During the next 6 years is your company/organization planning to continue or to become engaged in collision avoidance technology research, development or testing at some time in the future?

[] **Yes** **[] No** [] Under consideration [] Don't know

If you answered **No** or Don't know to Question numbers 1 and 2 then you are done and please return the questionnaire in the enclosed self addressed stamped envelope.

3. To the best of your knowledge during what calendar year is your company/organization planning to start collision avoidance technology testing?

[] During 1995 [] From 1996 through 1997

[] From 1998 through 1999 [] After 1999 [] Don't know

4 . Given that NHTSA has to cover the maintenance and operations costs of the VDTV and that these costs are a function of the capability and complexity of the VDTV then, to the best of your knowledge, what would your company/organization consider access to a VDTV, to perform collision avoidance research, technology development or testing, to be worth :(pick one)

[] From $3,001 to $4,000 per day

[] From $2,001 to $ 3,000 per day.

[] From $ 1,000 to $2,000 per day

[] Less then $ 1,000 per day

[] Only if it were free

[] Not interested because already have sufficient testing capability

[] Not interested because already have access to a VDTV or similar vehicle

[] Other. Please describe: ________________________________

5. To the best of your knowledge your company/organization would be interested in the use of a VDTV to perform collision avoidance technology research or testing if it had the following vehicle capabilities: (Please check all)

Strongly Interested	Interested	Not Interested	Strongly Not Interested	Don't Know	
[]	[]	[]	[]	[]	Directional Control
[]	[]	[]	[]	[]	Adaptive (active) suspension
[]	[]	[]	[]	[]	Variable steering assistance
[]	[]	[]	[]	[]	Variable drive tram
[]	[]	[]	[]	[]	Four wheel drive
[]	[]	[]	[]	[]	Traction control
[]	[]	[]	[]	[]	Smart cruise control
[]	[]	[]	[]	[]	Drive by wire
[]	[]	[]	[]	[]	Braking control
[]	[]	[]	[]	[]	Automated car following and braking
[]	[]	[]	[]	[]	Heads-up display .
[]	[]	[]	[]	[]	Four wheel steering
[]	[]	[]	[]	[]	Vehicle condition and performance
[]	[]	[]	[]	[]	Vehicle wellness reporting
[]	[]	[]	[]	[]	Platooning
[]	[]	[]	[]	[]	Waming indicator systems
[]	[]	[]	[]	[]	Loss of traction warning
[]	[]	[]	[]	[]	Other. Please describe: ________________
[]	[]	[]	[]	[]	Other. Please describe: ________________

6. To the best of your knowledge your company/organization would be interested in the use of a VDTV to perform collision avoidance technology research or testing if it had the following collision detection capabilities: (Please check all)

Strongly Interested	Interested	Not Interested	Strongly Not Interested	Don't Know	
[]	[]	[]	[]	[]	Augmented vision systems
[]	[]	[]	[]	[]	Object detection and collision avoidance
[]	[]	[]	[]	[]	Blind spot coverage
[]	[]	[]	[]	[]	Forward direction surveillance
[]	[]	[]	[]	[]	Road surface conditions reporting
[]	[]	[]	[]	[]	Automated car following and braking system
[]	[]	[]	[]	[]	Lane departure warning
[]	[]	[]	[]	[]	Intersection safety management
[]	[]	[]	[]	[]	Other. Please describe: ______________

7. To the best of your knowledge your company/organization would be interested **in the use of a** VDTV to perform collision avoidance technology research or testing if it could be used to study driver response with respect to: (Please check all)

Strongly Interested	Interested	Not Interested	Strongly Not Interested	Don't Know	
[]	[]	[]	[]	[]	Braking and steering performance
[]	[]	[]	[]	[]	Hazard perception and notification
[]	[]	[]	[]	[]	Interaction of multiple drivers
[]	[]	[]	[]	[]	Performance with active/adaptive controls
[]	[]	[]	[]	[]	Motion perception
[]	[]	[]	[]	[]	Driver condition and performance
[]	[]	[]	[]	[]	Road surface
[]	[]	[]	[]	[]	Weather/Visibility
[]	[]	[]	[]	[]	Signs and road markers
[]	[]	[]	[]	[]	Other. Please describe: ______________
[]	[]	[]	[]	[]	Other. Please describe: ______________

8. **Which of the following best describes the type of organization you currently work for?**

[] Federal Government [] State Government

[] Automobile Manufacturer [] Automobile Supplier

[] Research Institution [] Engineering Company

[] Other. Please describe: ______________

9. How many employees are there in your Company/Organization?

   [] Under 10 [] 11-25 [] 26-50 [] 51-100

   [] 101-250 [] 251-500 [] 501-1000 [] 100-3500

   [] 3501- 5000 [] over 5000

10. Which of the following best describes your current position?

    [] Vice President or higher, [] Research Department Head [] Senior staff,

    [] Senior research engineer [] Other. Please describe: ________________

11. Would you be willing to participate in a follow up phone interview in order to provide more detailed information on your required capabilities for a VDTV?

    [] Yes [] No

12. Briefly describe the types of experiments you are currently conducting or plan to conduct that can be supported by a VDTV. Use the back of the questionnaire form if necessary.

13. Additional comments, remarks, or suggestions are welcome. We are especially interested in any additional capabilities of a VDTV which you need to support current and planned collision avoidance technology research, development or testing. Use the back of the questionnaire form if necessary.

B.2 ANALYSIS OF RESULTS

In order to gain a more comprehensive understanding of the potential VDTV user community, a questionnaire was formulated and sent to a representative segment of industrial firms, universities and government agencies. Potential respondents were identified by IVHS and AHS, conference participants and general knowledge of the organizations interested and involved in related research, testing or manufacturing activities. The objective of the survey was to a) determine the degree of interest in access to a general purpose VDTV; b) identify additional high level requirements beyond those already identified by NHTSA; and c) identify individual and organizational contacts with related experience and interest in VDTV who were willing to provide additional information for identifying lower level user requirements and/or experiential data. The respondents were guaranteed anonymity. A copy of the questionnaire sent to firms and government agencies is provided in Appendix B.l. Appendix B.2 contains the complete analysis of the returns. Key information is summarized in the following paragraphs.

B .2.1 Results of Questionnaire

A total of 209 questionnaires were sent out and 51 were returned. Of these, 37 respondents from 33 different organizations reported that they were currently or planned to become active in collision avoidance or other advanced vehicle control technology research, development or testing. A list of the parent organizations of the respondents is provided in Appendix B.3 as a partial check on the validity of the sample. Each questionnaire contained 13 main questions requesting information on interest in collision avoidance or other advanced control vehicle technology research, development or testing; basic demographic information; current and planned testing activities; willingness to pay for access to a third party VDTV, and the degree of interest in a variety of VDTV capabilities. These capabilities were grouped by whether they were most closely related to advanced vehicle capabilities, collision detection capabilities or driver response. In a few cases the capability was duplicated in the different categories.

B.2.1.1 Interest in the VDTV Concept

In order to understand the composition of the sample, each respondent was asked to select the best description of their company or organization from a specified list. This list also included an Other option. The responses were then grouped into 7 categories, State Government, Federal Government, Domestic or Foreign Automobile Manufacturer, Automotive Support Industry, University and Research Organizations and Other. The Automotive Support Industry consisted of automotive parts manufacturers as well as companies/organizations providing engineering services and products.

The results are displayed in Figure B-l and for purposes of comparison the percentage breakdown by organization type of the companies/organizations receiving a questionnaire is also shown. Since the actual distribution of the population of organizations interested in VDTV is not known this is the only formal test of the representativeness of the response sample that is possible. The organization type of the companies which received questionnaires was determined primarily by the name of the company/organization. In many cases there was an obvious choice. However, in some cases it was difficult to distinguish between engineering and research organizations. The result was that 10 of the 209 mailed questionnaires could not be labeled.

While there are observable differences, these distributions are statistically the same. This conclusion is based upon a chi-square test at the 1% level. From the company/organization breakdown it can be seen that, with respect to the number of organizations, the main group of potential users of a VDTV, outside of the Federal Government, are from the Automotive Support Industry and University and Research Organizations. In addition, these company/organizations are the least likely to have sufficient funds to support an extensive research or testing program based upon a VDTV. The other category consists primarily of companies that are part of the trucking industry. There were no responses from representatives of state government agencies.

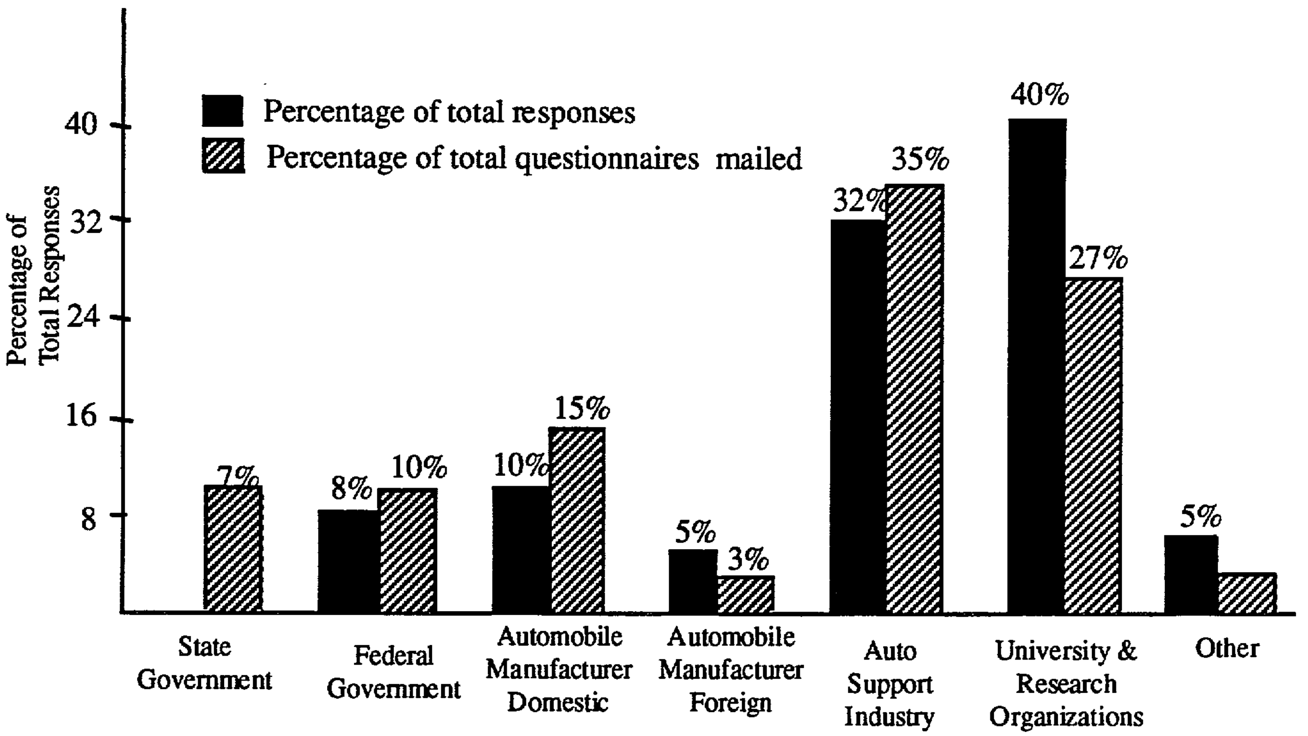

Figure B-1 Percentage of Survey Respondents and Recipients by Type of Organization

A summary of the main results of the survey broken down by organization type are provided in Table B-l. Table B-l provides the number of observations, the degree of interest in access to a third party VDTV and independent of the degree of interest in a third party vehicle, the **degree of** interest in using a VDTV type vehicle for research and/or testing purposes.

Table B-l High Level Summary of the VDTV Survey Results

Sector of Industry	No. of Resp.	General Area of Interest			Degree of Interest in VDTV
		Collision Avoidance	Advanced Vehicle Capabilities	Driver Response	
Federal Government	3	High +	High	Medium	High
Domestic Auto Manufacturer	4	Medium	Low	Medium -	Low
Foreign Auto Manufacturer	2	High -	Low	High +	Low
Auto-Support Industry	12	High	High	Medium-	Medium
University or Research Inst.	15	High	Medium	High -	Medium
Other	2	Low	Low	Low	High

The degree of interest was determined by **(1)** whether an organization reported that it was willing to pay for access, (2) would only use a VDTV if it was provided for free, (3) conditional interest or (4) was not interested. Non-interest was most frequently due to already having sufficient testing capability. Degree of interest was rated as high if all respondents reported they were interested in access to a VDTV even if only for free. Degree of interest was rated as low if 50% or more of the responses were not interested. The degree of interest was rated medium if the responses were mixed with some respondents willing to pay, some wanting access for free and some simply not interested.

Overall 48% expressed significant interest and 78% of the respondents reported having at least conditional interest in access to a third party VDTV. However, these results are very likely to be optimistic when taking into consideration currently only two non-government organizations either currently uses or plan to use a government provided simulator or test track.

The results with respect to different sectors of the automotive industry are the following. The Federal Government revealed a high degree of interest in having access to a VDTV which is primarily due to its support of IVHS. The automotive manufacturers have a low degree of interest because they have the capability to develop their own testing facilities and they need to protect proprietary information. The automotive support industry and the research institutes reported mixed interest. This is most likely because they form such a large sub-group with diverse interests. Of the companies that were categorized as part of the automotive support industry, the engineering companies did report a higher degree of interest than the manufacturing companies. Unfortunately, due to the small sample size no statistically significant results were found which could identify other factors that might be correlated with the degree of interest. For example, differences in size of organization were not correlated with degree of interest. Also, whether an organization was currently active in testing or only had future plans was not correlated with the degree of interest either.

To summarize the strength of interest in the different VDTV capabilities a ranking of the degree of interest was derived based upon a variation of a voting algorithm. The original questions had each respondent rate whether they were strongly interested, interested, not interested, strongly not interested or Don't Know. There were numerous cases were there was no response. The voting algorithm was to give 2 votes for each strongly interested, 1 vote for each interested response and 0 votes for all other responses. From this a weighted expected value was computed. The number of votes was averaged over the number of respondents to get the individual score for each capability. There are a total of 34 individual capabilities listed in the questionnaire with the option to provide additional capabilities. These were then averaged over the individual capabilities to get the average for each area of interest, Collision Avoidance, Advanced Vehicle Capabilities and Driver Response. The behavior of the index produced by the algorithm described above is (1) if every person rated every individual capability as strongly interested then it produced a value of 2.0, (2) if every person rated every individual capability as interested then it produced a value of 1, (3) if every person rated every individual capability as not interested then it produced a value of 0. The way the index was interpreted was that a score of 1.5-2.0 was labeled as high+, LO-l.5 as high, .75-l as medium, .7-.75 as medium- and less than .7 as low. The results of these computations are displayed in Table B-2.

Given the focus of the questionnaire, it is not surprising to find that virtually every sector of the automotive industry expresses a high degree of interest in collision avoidance capabilities. The Federal Government and the automotive support industry also expressed a high degree of interest in testing advanced vehicle capabilities, and the research organizations and foreign automotive manufacturers expressed a high degree of interest in studying driver response.

Because of the large number of Don't Know responses the index which was used can produce distorted results as demonstrated by respondents in the Other category who expressed a high degree of interest in a VDTV vehicle but expressed a low degree of interest in any of its capabilities. This result occurs when there exists a small number of different capabilities which respondents are interested in and many which are unknown. Therefore these results need to be verified. A similar but slightly different view is provided by Table B-2 which lists the top 10 requirements by type of organizations and requirements area. The specific contents of Table B-2 will be discussed in the next section. At this time simply count the number of requirements in each box. This reveals the significantly heavier emphasis placed on studying driver response compared to the other sectors in the industry and a much greater emphasis on advanced vehicle capabilities by the auto-support industry than exhibited above.

B.2.1.2 Additional Requirements

The top 10 requirements by type of organizations and requirements are listed in Table B-2. These were derived by using only the voting portion of the algorithm described in section B. 1.1. Ties were broken by counting only the number of strongly interested responses. The top 10 requirements as listed in Table B-2 reveal broad based support for only a few requirements and a fundamental difference in focus between the government and research institutions as compared to companies directly involved in the production of automobiles. The later is concerned with VDTV capabilities which can be of use with the current highway system (smart cruise control) and the former are looking at much more advanced capabilities such as those needed to support automated highways (platooning). Those requirements receiving broad based support are (1) object detection and collision avoidance, (2) automated car following and braking (3) smart cruise control and (4) braking and steering performance.

There are a number of different interpretations of these results. One interpretation is that the focus should be on collision avoidance and minimize getting distracted by other issues. This is a large industry with very diverse interests. If it is decided to extend the focus of the VDTV then it must be decided which part of the industry one wants to support. If the decision is primarily to support the automotive supply industry, then the focus would be more on supporting advanced vehicle capabilities. Alternatively, if the decision is to provide support to the auto manufacturers then the focus should be on supporting the testing of driver response. In either case the emphasis should be on subsidizing those aspects which are high risk with respect to generating a return or aspects which are socially desirable but less likely to provide sufficient pecuniary return to generate private R&D spending.

Table B-2 List of Highest Rated Requirements by Type of Organization

Sector of Industry	Collision Avoidance	Advanced Vehicle Capabilities	Driver Response
Federal Government	**Object detection and collision avoidance** Blind spot coverage Automated car **following** and braking system Forward direction **surveillance**	**Platooning** Smart cruise control Automated car following and braking **Variable steering assistance** **Heads-up display**	**Driver condition and performance**
\utomotive Manufacturers	Object detection and collision avoidance Lane departure warning Augmented vision systems		**Driver condition and performance** Hazard perception and notification Signs and road markers **Weather/visibility** Performance with active controls Braking and steering performance **Road surface**
Auto-Support Industry	**Object detection and** collision avoidance **Road surface** conditions reporting	**Braking control** **Drive by wire** Automated car following **and braking** Smart cruise control Directional Control **Vehicle condition and performance**	Performance with active/ adaptive controls Braking and steering performance
University or Research Inst.	**Forward direction surveillance** **Automated car following and braking system** **Object detection and collision avoidance** Augmented vision systems Road surface conditions **reporting** **Blind spot coverage**	**Braking control** **Automated car following and braking** **Smart cruise control**	**Braking and steering performance**

B.2.2 Follow-up Interviews

Responses to the questionnaire identified several companies and organizations that had specific interest in the VDTV concept. Respondents were contacted and in many cases, the exchange of information was valuable in determining the degree of interest by potential users, identifying or substantiating requirements, or in understanding other experiences in the use of similar vehicles. A list of contacts made is included as Appendix B.4.

B.3 ORGANIZATIONS RESPONDING TO QUESTIONNAIRE

Advanced Systems Group International

Allied Signal

Battelle

Battelle Human Factors Transportation Center

Carnegie Mellon University

Detroit Diesel Corporation

Eaton Corporation

Federal Highway Administration

Florida Atlantic University

Ford Motor Company

General Motors Research Laboratories

Georgia Institute of Technology

ITT Automotive

Johns Hopkins University-APL

Litton Amecom

Michelin Americas R&D

National Institute of Standards and Technology

National Public Services Research Institute

Navistar International Transportation Corporation

NHTSA

Nissan R&D, Inc.

Northrop Corporation

Penn State University-PTI

SAIC-Science App Int’l Corp.

SEI Technology Group

Toyota Motor Corporation

University of California-ITS(2)

University of Michigan-TRI (3)

USC Center for Advanced Transportation Technologies

Vehicle Research & Test Center

Zexel USA Corporation

3M-IVHS Development Group

B.4 ORGANIZATIONS CONTACTED

Organization	Purpose
Ford Motor Co.	Information exchange on Instrumented Test Vehicles (ITVs)
Chrysler Corp.	Information exchange on ITVs
International Automotive Design	Discussion of Company's capability to build VDTV
Metal Crafters	Discussion of Company's capability to build VDTV
Mike McCloskey	Discussion of Company's capability to build VDTV
Powers Design International	Discussion of Company's capability to build VDTV
Industrial Design Research	Discussion of Company's capability to build VDTV
All American Racers, Inc.	Discussion of Company's capability to build VDTV
University of Iowa	Discussion concerning NADS and the use of VDTV for NADS validation
University of California, Berkeley	Discussion of PATH program and possible use of VDTV in PATH, AHS
Battelle	Discussion of their experience with ITVs
Carnegie-Mellon University	Discussion of their experience with ITVs
General Motors Corporation	Follow-up to questionnaire response-ITV information
US Army Tank-Automotive Research, Development and Engineering Center	Follow-up to questionnaire response-ITV information
Bendix Automotive Systems, Allied Signal, etc.	Follow-up to questionnaire response-ITV information
TRW	Discussion of company's capability to provide VDTV subsystems and AHS
American Automobile Manufacturers Association	Information exchange on ITVs
Frontier Engineering	Discussion of their experience in converting van for rear-end collision research
Kelsey-Hayes	Request for information on brake-by-wire system

APPENDIX C

VDTV USES/USERS

APPENDIX C VDTV USERS/USES

c.1 USER AND DYNAMIC SUBSYSTEM MATRIX

Early in this study, the differing needs of the major NHTSA users was apparent. This led to development of a VDTV based on a core subsystem which included the vehicle itself plus the common elements needed by most, or all, dynamic subsystems. Different dynamic subsystems could then be integrated with the core subsystem, providing a flexible method to develop both VDTV capabilities and costs.

An assessment of potential VDTV support to each major user (human factors, AHS, NADS, and technology assessment) was based on documentation, information from NHTSA personnel, and telecons during the User Requirements activity discussed in Section 2. This resulted in a series of lower level tasks for each major user. These tasks were listed, then combined with the potential dynamic subsystems to form a matrix. The result is a VDTV Capabilities/User Matrix which relates user needs to 15 different dynamic subsystems. For each task/dynamic subsystem intersection, a subjective rating of 0 (not required), 1 (desirable) or 2 (must have) was assigned. Four persons provided their individual ratings; the final consensus values were reached after several reviews.

Totals for each major user then gave an indication of the value of each potential dynamic subsystem. The total for all major users gave an indication of the value for a general-purpose VDTV, referred to as the Full-Capability VDTV in Volume II, Section 5. The higher-ranked dynamic subsystems were candidates for initial cost-constrained VDTVs for the four major users.

With the overall concept of a core vehicle and dynamic subsystems, a building block approach was established for both users and costs. There are several interactions between the vehicle, the core subsystem, and the individual dynamic subsystems so it is not possible to simply add capabilities or costs to arrive at an estimate of the complete VDTV. Some judgment and policy decisions are needed, notably the expandability of the initial VDTV. As an example, two scenarios are:

1. The dominant factor is lowest initial cost. The core subsystem is to be tailored to support only those dynamic subsystems that will be included in the initial VDTV. All front-end system engineering activities will be minimal, with risks of problems accepted. There will be no costs for future expansion, such as a larger hydraulic pump or electrical power supply. All installation is to the minimum essential for the initial VDTV.

2. The initial VDTV will be designed for long-term use and retrofitting with additional subsystems as needs and funding are known. The front-end system engineering will be thorough and will include designs and documentation necessary for future retrofitting of additional dynamic subsystems. The hydraulic system will be sized and tested for the future full capability; this will apply to all other core subsystem elements. Installation of the core subsystem will include provision for installation of other future dynamic subsystems.

There are considerable differences, particularly initial cost, in these two approaches. Analysis of these differences must be included in the combination of dynamic subsystems to arrive at any particular initial configuration.

Table C-1 VDTV CAPABILITIES/USER MATRIX

USE	RESEARCH AREA	SBW	PSF	BBW	PBF	TBW	PTF	SA SUS	A SUS	4WS	TRAC C.	ABS	4WD	CA INTER	ARC	V. MASS	TOTAL	AVERAGE	COMMENT
	Driver's workload with technological systems	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2		Assumed IVHS technology, only
	Driver perceptual factors on design of advanced vehicle systems	2	2	2	2	2	2	1	2	2	2	N/A	1	0	N/A	1	21		Advanced vehicle systems, only
	Effect of driver risk taking on driver/vehicle performance & safety	2	2	1	1	0	0	1	2	2	1	2	1	2	N/A	0	17		
	Effect of vehicle defects on lat/dir control & accident causation	2	1	0	0	0	0	1	2	2	1	1	0	0	N/A	1	11		Interaction of vehicle dynamics and driver
	Effect of lat/dir dynamics on design of advanced vehicle systems	2	1	0	0	1	0	1	2	2	1	1	0	2	N/A	2	15		Including IVHS devices
	Effect of radar collision warning/braking on long. dynamics/performance	0	0	2	1	1	1	1	1	0	1	N/A	1	2	1	0	12		
HUMAN	Effect of long. dyn. on driver response/performance re: ride qualities	0	0	2	1	1	0	1	2	0	2	N/A	0	0	N/A	1	10		
	Effect of intersections on driver's use of adv. tech. systems/displays/controls	1	1	2	1	2	1	1	1	1	1	N/A	0	2	1	0	15		
FACTORS	Effect of presence of pedestrians on driver behavior in various situations	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1		Base vehicle could be used. Minimal VDTV applicability
	Effect of presence of highway maintenance equip. on driver's performance	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1		Base vehicle could be used. Minimal VDTV applicability
	Effect of loss of driver's cues with advanced vehicle technologies	2	2	2	2	2	2	0	2	2	1	N/A	2	0	N/A	1	20		
	Effect of advanced subsystems on classes of drivers	2	2	2	2	2	2	0	2	2	2	N/A	2	2	N/A	1	23		Including IVHS technologies
	Effect of loss of advanced s/s capability on driver performance	2	2	2	2	2	2	0	2	2	2	N/A	2	2	N/A	1	23		Including IVHS technologies
	SUBTOTAL	15	13	15	12	13	10	7	18	15	14	4	9	16	2	8	171	13.2	
	Evaluate robustness of veh. lat. control sys. at off-design cond. *	2	0	1	0	0	0	1	1	1	0	0	0	2	1	1	10		Assume need for sensor (CA and others) interface for all
	Evaluate perf. enhancement potential of command aug. sys. *	2	1	0	0	1	0	1	0	1	1	1	0	2	1	0	11		AHS applications
	Evaluate lat. control sys. with vision-based meas. sys. *	2	1	0	0	0	0	1	1	1	1	1	0	2	1	0	11		
AHS	Investigate human factors issues in lat. control sys design *	2	2	0	0	0	0	1	1	2	1	1	0	2	1	1	14		
	Evaluate long. control sys. robustness at off-design cond. *	0	0	2	0	2	0	1	1	0	0	N/A	0	2	0	1	9		
	Evaluate perf enhancement using TBW and BBW in platooning *	0	0	2	0	2	0	0	0	0	1	N/A	0	2	0	0	7		
	Investigate HF issues in long. control sys. designs *	0	0	2	0	2	0	1	0	0	1	N/A	0	2	0	0	8		
	Investigate lane change maneuvers using TBW, BBW & SBW *	2	1	2	1	2	1	0	1	1	1	N/A	0	2	0	1	15		
	Evaluate compatibility of various vehicle types in platooning mode*	1	0	2	0	2	0	0	1	0	0	N/A	0	2	1	1	10		
	Evaluate safety aspects of AHS program technologies	2	1	2	1	2	1	0	0	0	0	N/A	0	2	0	1	12		
	Study failure modes that would affect drive-by-wire safety	2	1	2	0	2	1	1	0	0	0	N/A	0	2	0	1	12		
	* See Allan Lee's Memo 343-94-159 for details																		
	SUBTOTAL	15	7	15	2	15	3	7	6	6	6	3	0	22	5	7	119	10.8	
	Validate NADS algorithms for range of vehicle types and dynamics	2	1	2	1	0	0	0	2	2	0	N/A	1	0	N/A	2	13		
	Conduct tests at limit maneuvers beyond the range of NADS	2	1	0	0	0	0	2	2	1	1	1	1	0	N/A	2	13		
NADS	Conduct high-fidelity tests beyond the range of NADS	2	1	0	0	0	0	2	2	1	1	1	1	0	N/A	2	13		
	Provide road test data to quickly answer simulation fidelity questions	0	0	0	0	0	0	0	2	2	1	1	1	2	N/A	1	10		
	Conduct limited validation tests of NADS research programs	2	1	2	1	1	0	0	2	2	1	N/A	1	2	N/A	1	16		
	Verify NADS test results on collision avoidance systems	1	0	1	0	1	0	1	1	1	1	1	1	2	1	1	13		
	SUBTOTAL	9	4	5	2	2	0	5	11	9	5	4	6	6	1	9	78	13	
	Assessment of CA technologies for safety	0	0	0	0	0	0	1	2	2	1	2	1	2	N/A	1	12		
NHTSA	Develop performance specs/standards for emerging CA hardware	1	0	2	0	1	0	0	2	1	1	N/A	1	2	N/A	1	12		
TECH.	In-service testing of near-commercial CA systems	1	0	1	0	1	0	0	2	1	1	1	1	2	N/A	1	12		
ASSESS.	Assessment of advanced subsystem technologies: veh. dyn & safety	2	2	2	2	2	2	1	2	2	2	N/A	1	1	N/A	2	23		Advanced vehicle subsystems
	Rule making support	2	1	2	1	2	1	1	2	2	2	N/A	1	2	N/A	2	21		Maximum capability desired for rapid response
	SUBTOTAL	6	3	7	3	6	3	3	10	8	7	3	5	9	0	7	80	16	
	TOTAL	45	27	42	19	36	16	22	45	38	32	14	20	53	8	31			

ABBREVIATIONS		WEIGHTING CRITERIA
SBW=Steer-by-wire	V. MASS= Variable mass	2= Must have
PSF=Programmable steering feel	SA SUS=Semi-active suspension	1= Desirable
PBF=Programmable braking feel	A SUS= Active suspension	0= Not required
PTF=Programmable throttle feel	CA INTER=Collision avoidance interface	
	ARC=Active roll control	

C.2 ALTERNATIVE UTILIZATION OF VDTV[1]

An alternative emphasis on the requirements of the VDTV is suggested. Rather than emphasizing its use for support of government sponsored programs such as NADS, AHS and PATH, we recommend that VDTV be used as a research tool to investigate fundamental issues of the driver-vehicle system in support of the U.S. Automotive industry.

Unlike most modem industrial countries, notably Japan and Germany, the United States has no government entity whose primary function is to perform basic research in automotive vehicle dynamics (apart from direct safety implications) although such is urgently needed by our car companies in global competition. An analogy is drawn to the National Advisory Committee for Aeronautics (NACA, predecessor of NASA), which provided basic research and design information for the aircraft industry. It is noted that NHTSA's VRTC (in East Liberty, Ohio) could expand its research activity to the benefit of industry and build a cooperative research program with industry around a VDTV.

Several specific automotive research topics are described and minimum requirements of the VDTV and minimum cost programs are suggested.

It is recommended that automotive industry representatives be contacted to solicit interest in this more circumscribed use of VDTV. The industry personnel have always performed car development on proving grounds, so they can readily appreciate the potential of VDTV for fundamental investigations.

C.2.1 Introduction

The utilization assessment for VDTV, as reported in Reference C.2.7.1, indicated low levels of interest by the domestic auto manufacturers. Two reasons given are (a) they have the capability to develop their own such test equipment and (b) they require that results obtained from tests remain proprietary. Furthermore, the level of interest was measured, in part, by the willingness of the user, in this case the auto manufacturer, to rent time on the testbed. Without having a clear idea of how they would use VDTV, the manufacturers would naturally be reluctant to commit to paying for such use.

It is noteworthy, however, that a contact at General Motors expressed interest in generic investigations. It is just such generic or more fundamental issues that are recommended for emphasis in designing and using VDTV. In this sense, VDTV need not initially include such advanced technologies as object detection, road surface condition reporting, automated car following and braking, smart cruise control, heads-up display, lane departure warning, augmented vision systems, blind spot coverage, etc. Instead, emphasis would be on capabilities to vary the handling and ride characteristics of the vehicle to simulate ranges of performance and to investigate the interaction of the man-machine, i.e., driver-vehicle, systems. Included in this category of investigations would be:

- Desirable or preferred ride and handling qualities that result in reduced driver fatigue and more precise control.

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1 This section of the report has been contributed by H. Radt and W.F. Milliken, Jr., of Milliken Research Associates, 245 Brompton Road, Williamsville, NY 14221

- Minimally acceptable handling and ride behavior from the standpoint of user preference and controllability.
- Handling characteristics optimized for object collision avoidance and post-avoidance recovery.
- Development of correlations between subjective ratings and objective measures of vehicle response.
- Factors affecting driver assessment of on-center handling and feel.
- Alternatives to steering wheel control wherein steer angle and steering torque are directly related (e.g., side-stick control, variable ratio steering)
- Relative importance of body roll, vehicle sideslip and other driver cues on driver-vehicle system performance and driver subjective evaluations.
- Automatic skid warning, prevention and recovery systems.

Such a change in emphasis on the uses of VDTV would yield government-industry cooperation that might well result in improvements in U.S. automotive products and their competitiveness worldwide.

C.2.2 Government-Industry Cooperation

C.2.2.1 Historical Perspective-NACA

The National Advisory Committee for Aeronautics (NACA) was established in 1915 by Act of Congress. Its purpose was to "Supervise and direct the scientific study of the problems of flight, with a view to their practical solution." It was also to "Direct and conduct research and experiments in aeronautics."

To discharge the above responsibilities, the NACA was to establish technical subcommittees in various branches of aeronautics with members of the committee from governmental agencies, the aircraft industry and from "private life." These subcommittees were to prepare and recommend research programs. The work of NACA was to be directed to both civil and military aircraft.

The membership of the committee over the years was very impressive. At one time Vannevar Bush was chairman and the membership consisted of people like General Arnold, Jerome Hunsaker, Orville Wright, Edward P. Warner, and Charles Abbot (Secretary of the Smithsonian).

It was the practice of the NACA to publish technical reports, technical notes and technical memoranda. The first reported the results of major investigations, the second reported results of minor investigations and the memoranda were devoted to translations of foreign technical papers. The technical reports were sold through the government printing office at a very nominal price and were published in a bound volume once a year. The bound volume contained 20 to 30 technical reports. The reports were a model of technical writing. They followed a standard format and were put through a committee prior to publication.

From the beginning, it was policy of the NACA to work very closely with industry. It not only listened intently to industry needs but made its specialized facilities available to industry for specific test and development work. Over the years, the NACA developed some very specialized and elaborate research facilities which were not available at the aircraft companies, nor could they have financed them.

Some of the facilities available at the Langley facility for basic research and also for cooperative development work with industry were the variable density wind tunnel, full-scale wind tunnel, early high speed wind tunnels, spin tunnel, stability tunnel and free-flight tunnel.

Although the NACA did a great deal of very basic research, it also provided much design information of direct use to aircraft development. Additionally, the NACA personnel frequently came up with innovative ideas which were adopted by industry. Included, among many others, were design and evaluation of several complete series of airfoils, techniques for calculating the load distribution on wings of all planform shapes, flutter theory and recommended calculation procedures, flight instrumentation development, early handling qualities specifications and a variety of flight test procedures.

In summary, the NACA working in conjunction with industry and on a most cooperative basis was very much responsible for making the U.S. aircraft industry a world leader. Furthermore, the industry was in a very solid technical position when we become involved in World War II, at which time it had to expand to very large aircraft production. The X-aircraft developments which were participated in by the NACA, the military and the aircraft industry gave us leadership in high speed flight. Preeminence in jet transports followed directly from that activity.

In a sense the U.S. automotive industry is facing an international competitive "war" in which technological innovation and its practical application are the weapons. We need government participation for our automotive research in this country, comparable to the way the NACA operated, to enable our industry to remain preeminent.

C.2.2.2 Basic Investigations vs. Industry "Mules"

One argument against VDTV is as follows: "If industry needed such an experimental vehicle, it would build or buy one." In order to answer this argument, one must first understand the situation in the automotive industry. First, basic research on vehicle dynamics and control is considered a luxury, done when profits are high and steady, curtailed during retrenchments. Sometimes the research is too basic to lead directly to vehicle improvements. The result in the past 10 to 15 years was a transfer of engineers and technicians from research areas to work on specialty vehicles and advanced development, then to work with operating divisions responsible for vehicle design and development. An occasional experimental vehicle is still fabricated, but it is usually for demonstration of a particular subsystem or approach.

More common is development of vehicles referred to as mules, which are primarily redesign of a previous model, but with changes and improvements. Rarely are major innovations incorporated in the mules, primarily because there does not exist a sufficient base of research or advanced development to justify the expenditure and risk. Goals for vehicle ride and handling are often set in relation to existing vehicles, rather that being based on research on driver acceptance or driver-vehicle performance criteria.

Vehicles with active suspensions have been purchased from Lotus Engineering by Goodyear, Chrysler and General Motors. Manual front steer and active rear steer is incorporated in at least one of the Goodyear cars. A similar, but more comprehensive test vehicle was purchased by General Motors on project TRILBY (later the Systems Division). In addition to active suspension, it has both electronically controlled front and rear steer and an artificial feel system to produce steering torques. This feel system was found to be inadequate as judged by test drivers and engineers at GM. Initial investigations with this vehicle concentrated on the ride behavior rather than handling. The authors are not aware of any dissemination of results of such studies, nor of research of handling using this test vehicle.

In summary, the auto manufacturers, because of cost cutting measures, are even less likely in the future to devote research and advanced development dollars to ride and handling. Instead, internal company efforts will probably continue on incremental development using mules and/or increasing technical understanding of existing vehicles via field and laboratory experiments and analyses.

C.2.3 Research Areas of Potential Interest

C.2.3.1 Vehicle Ride

Experiments on whole human body vibration have been conducted to determine levels of human comfort. Analyses have also been performed to relate seat vibration to roadway height variation via simplified vehicle models. Idealized characteristics of active and semi-active suspensions have been derived using optimal control theory. Rules of thumb exist for passive suspension design to minimize pitching during traversal of single bumps. However, tests have not been conducted on real vehicles wherein suspension, roadway and seat parameters were systematically varied. Questions remain as to the relative importance of vertical, sideways and fore-and-aft linear vibrations on the driver and acceptance of higher vibration tolerance in smaller or sportier cars. Driver sensitivity to pitching and rolling oscillations have not been studied independent of linear vibrations. Such investigations can be done in a vehicle with active suspension by using selectively controlled inputs to the four wheels, including random inputs representative of road roughness. Also, desired bounds on brake dive and acceleration squat can be determined, via driver opinion, when varied using active suspension.

C.2.3.2 Vehicle Handling

If vehicle handling (in the low lateral acceleration regime) is improved in the sense of driver acceptance, relative safety is likely to increase because of reduced driver fatigue. Because of driver adaptability, we don’t have criteria for degraded handling qualities on the boundary of uncontrollable or unacceptable behavior. Furthermore, handling characteristics play a role in selection by the buyer of a vehicle. On-center handling, a little understood regime, appears important in driver preference as well as driver fatigue. At higher lateral accelerations, more typical of collision avoidance and recovery, systematic research has not been done to determine how much of the vehicle's ultimate performance, e.g., maximum lateral acceleration, is utilized by the "average" driver and whether the "average" driver prefers terminal understeer and if so, how much.

In the conventional vehicle, the dynamic response to steer input (e.g., response or rise time) is closely related to the steady-state response; mass and inertia being essentially fixed by vehicle size. With the advent of rear steer, however, vehicle sideslip can nearly be eliminated, thereby shortening the lateral acceleration response time to nearly the same as the yaw rate response time. By appropriate yaw rate feedback, these response times can be somewhat reduced, the extent depending on effects of tire dynamics and control system bandwidth. Such capability to vary response time and magnitude and direction of vehicle sideslip (analogous to location of the turning center referred to by Lotus Engineering) begs the questions:

- What steady-state response is desired by the driver and how does it vary with speed?
- Is vehicle sideslip a significant cue to the driver?
- How short a response time is desired by the driver and what level of damping is necessary? (E.g., how much overshoot is acceptable?)
- How long a response time is acceptable?
- How do the above changes affect performance of the driver-vehicle system, e.g., path following, lane change, passing and obstacle avoidance?
- How should rear steer be combined with use of the active suspension (in modifying the lateral load transfer distribution between front and rear) to provide a smooth transition from low to high lateral acceleration response?
- Can the driver rapidly accommodate to degradation in performance of the rear steer control system in the event of failure and what form of "fail-safe" algorithms should be implemented?

In the more general sense, there are areas of research that have not been sufficiently addressed. A partial list would include:

- The importance of vehicle roll as a driver cue.
- Handling criteria in terms of steady state and dynamic responses that represent optimum, acceptable and unacceptable or uncontrollable boundaries.
- Similar criteria when traversing a rough road.

- Skid control by reducing vehicle . with rear steer or inhibiting vehicle spin (terminal oversteer) on either dry or slippery surfaces.

- Behavior and optimization of ABS and traction control in a turn.

- Use of automatic control to compensate for degraded components such as poor tires or to eliminate the need for design compensations such as front aligning torque steer compliance or roll steer.

- Development of correlations between subjective ratings and objective handling response measures.

- Minimization of response to road and wind disturbances via automatic control and/or aerodynamic devices.

- Steering system optimization, *i.e.*, determination of acceptable levels of friction, lash, erc.; optimum steering ratios and steering torques as functions of speed.

- Evaluation of alternatives to the steering wheel, e.g., side-stick control.

C.2.4 Minimum VDTV Requirements

A four wheel active suspension system is required to perform research on ride phenomena, to provide control of the distribution of lateral load transfer between front and rear and to vary the roll response. A rear steer servomechanism is essential with inputs available from front steer angle, yaw rate, lateral acceleration, vehicle slip angle and possibly their time derivatives. However, there may be disagreement as to the need for automatic control of front steer on the first VDTV. Rear steer , alone, can produce variable steady-state sideslip, zero transient sideslip and variable yaw rate response time. As an alternative to controllable steady-state sideslip, the steady-state yaw rate or lateral acceleration sensitivity can be varied as a function of speed. However, steady-state sideslip and yaw rate cannot be varied arbitrarily with only rear steer, and the range of available response times will be limited by both tire dynamics and control system bandwidth (Reference C.2.7.2). Furthermore, no research can be done on steering torques, force control dynamics or on-center handling.

The advantages of active steer on both front and rear include (Reference C.2.7.3):

- Independent control over vehicle sideslip and yaw rate.

- Elimination of coupling of the roll motion into the yaw/sideslip response despite effects of camber change and roll steer.

- Larger variations in yaw rate and lateral acceleration response times, despite tire lags and control system dynamics.

- Changes in simulated vehicle size by employing artificial mass and artificial inertia effects, *i.e.*, feedback of lateral acceleration and yaw acceleration, respectively.

There is no practical way to incorporate active front steer without isolating the steering wheel from the front wheels. That is, drive-by-wire becomes essential. To simplify the vehicle system, it might be feasible to provide steering torque by a spring, perhaps one that is nonlinear, but such an artificial feel system would be unlikely to represent any real car nor would it be acceptable to a company test driver. Accordingly, inclusion of active front steer virtually requires a control system to provide steering torque, referred to as an artificial feel system. Such a system then provides additional advantages for investigating the following:

- On-center handling
- Free control or force control response behavior
- Determination of optimum, acceptable and unacceptable steering torques as a function of speed, parking, etc.
- Use of steering torque feedback for loss of control warning or skid warning.

C.2.5 Reduced Cost Approach

A phased program would be one means for reducing the initial system costs, but provision would have to be made for later incorporation of active front steer and controlled steering torque, An alternative would be to have a system contractor who most likely would subcontract to Lotus Engineering for the active suspension because of their extensive experience. However, the system contractor could design and fabricate the front and rear steer control systems or could subcontract to one of several companies with extensive experience on such subsystems (e.g., TRW, Delco Electronics, Hughes, Calspan, Moog Inc., Moog Controls, etc.). This approach of using subcontractors could reduce cost n the long run because of competitive bidding. Other advantages of having a system contractor are the need for:

- An overall system simulation to assess subsystem requirements, the range of static and dynamic capabilities of the system and approaches for simultaneous changing of input and feedback gains to obtain specific response behavior.
- An initial shakedown phase
- Conduct of an early set of tasks to prove the utility of VDTV in performing necessary research.

C.2.6 Recommendations

C.2.6.1 Location of VDTV

Although there is no designated governmental center for fundamental automotive research n Vehicle Dynamics, it is noted that NHTSA's Vehicle Research Test Center (VRTC, in East Liberty, Ohio) has engaged in programs which have proven useful to industry. Examples are inertia and suspension measurements and certain analytical studies. Representatives of VRTC's staff are members of the SAE Vehicle Dynamics Forum committee, have organized and chaired technical sessions at the SAE Annual Congress and have presented technical papers. Thus a well-established rapport exists between VRTC's staff members and engineers in the automobile industry.

It seems logical that VRTC's activities might be extended to provide the fundamental research support so needed by the automotive industry. A program of cooperative government-industry research could be developed to utilize the unique capabilities of VDTV. This program could be developed through a committee composed of both government and industry representatives and, as such, could lead to joint government and industry financial support. Because VDTV is readily transportable, it could also be rented by industry for proprietary research. This corresponds closely to the use of NACA wind tunnel facilities for proprietary development work on aircraft company prototypes.

NHTSA was originally established to develop and promulgate automobile safety standards. Unfortunately the atmosphere as regards automobile safety which existed when NHTSA was started promoted opposition rather than cooperation between government and industry. This has softened over the years and the present Administration recognizes that our industry needs support from government in order to remain competitive in the world market. It is clear that our industry needs fundamental vehicle dynamics research at a level unlikely to be undertaken by industry or universities, which thus can only be provided by government. NACA provided this capability for the aircraft industry, with phenomenal results. A comparable opportunity exists for NHTSA, at VRTC for example, which would enable it to extend its influence far into the future.

C.2.6.2 Industry Contacts

It is recommended that representatives of the automotive manufacturers be contacted again, but with the proposed revised emphasis on the requirements and uses of VDTV. The objective would be to solicit interest in government/industry cooperation in performing more fundamental research on vehicle ride and handling, especially using VDTV and the basic experimental tool.

It is important to contact those in the industry that are most familiar with the research needs of engineers charged with determining the requirements, characteristics and potential innovations of future vehicles.

C.2.7 References

C.2.7.1 Garba, J.A., Griffin, D.C., *et al.*, "Variable Dynamic Testbed Vehicle Study-Mid-Term Report," Jet Propulsion Laboratory, California Institute of Technology, Report JPL D-l 1265, March 8, 1994.

C.2.7.2 Radt, H.S., Jr., "Analysis of Rear Steer Algorithms," Milliken Research Associates, January 20, 1988.

C-2.7.3 Radt, H.S., Jr., "Analysis of Four Wheel Active Steer," Milliken Research Associates, January, 1990.

C.3 UTILIZATION ASSESSMENT

The utilization assessment was based on information from the four major NHTSA users. Both the users and their uses were derived from the Capability/User Matrix discussed in Section 3-2 of Volume II and in Appendix C. 1. The Other Users follow the discussion of Section 3.3.

All utilization is expressed in months during the VDTV's estimated life of five years. This period is consistent with the VDTV's expected life and the time when various users will be in the development mode, and thus have a need for a highly capable test vehicle.

C. 3.1 Estimated Utilization for VDTV Users

1. Human Factors Research-The base data, NADS Time and Full Scale Time, was taken from Appendix F of the NADS Technical Requirements Report (Reference 8.3). Since this report was based on modification of individual vehicles for each research problem instead of the VDTV, the full scale times were modified to equal those of NADS. The rationale was that the VDTV's programmable capabilities would be essentially equal to those of NADS. The percentage of time that the VDTV could be used to support each of the research problems, and perform some of the work, was based on the problem statements contained in Appendix C-4. Some times were limited (5%), where the VDTV would only validate selected points to gain better acceptance of NADS data. Others had a higher percentage consistent with a need for high-fidelity test data which could be obtained by the VDTV. The VDTV use time is the percentage of VDTV use multiplied by the modified full scale time. Results are shown in the Human Factors Research table.

HUMAN FACTORS RESEARCH

ALL TIMES ARE IN MONTHS

RESEARCH PROBLEMS FROM APPENDIX F, NADS TECH RQMNTS REPORT	GADS REPORT ESTIMATE: NADS TIME	GADS REPORT ESTIMATE: FULL SCALE TIME	WITH VDTV: FULL SCALE TIME	VDTV UTILIZATION: %TO VDTV USE	VDTV UTILIZATION: VDTV USE TIME
1. Driver's workload with technological systems	6	8	6	20%	1.2
2. Driver's knowledge of traffic rules and signs	9	10	9	10%	0.9
3. Effects of driver aging on driver ergonomics	8	12	8	5%	0.4
4. Driver perceptual factors of advanced vehicle systems	9	12	9	20%	1.8
5. Effect of driver risk taking on driver/vehicle performance	8	11	8	5%	0.4
6. Variations of lateral-direction control on accident causation	8	12	8	40%	3.2
7. Effect of lateraldiiection dynamics ***on*** advanced vehicle system	8	10	8	40%	3.2
8. Effect of radar collision warning/braking on longitudinal dynamics	9	15	9	20%	1.8
9. Ride characteristic effects of longitudinal dynamics on driver performance	9	8	9	10%	0.9
10. Effect of roadway geometry on development of navigation/route system	8	10	8	5%	0.4
11. Effect of intersections on driver's use of advanced technology systems	8	12	8	20%	1.6
12. Effect of roadway illumination on driver behavior in degraded environment	8	12	8	5%	0.4
13. Effect of pedestrians on driver behavior	6	8	6	10%	0.6
14. Effect of highway maintenance equipment on driver performance	6	8	6	10%	0.6
Total Time (Months	104	140	104		16.2

Column Descriptions

Human Factors Research: research problems taken directly from Appendix F. NADS Technical Requirements Report

NADS Report Estimates: times in months for NADS and full scale test times for the research problems

With VDTV Full Scale Time: times in months if the VDTV were available and used for the research problem

VDTV Utilization. % to VDTV: subjective estimate of % of the task that could be done efficiently with the VDTV

VDTV Utilization, VDTV Use Time: multiply the VDTV Full Scale Time by the % to VDTV to get VDTV Use Time in months

2. AHS Support--The minimum and maximum VDTV use times were estimated for each activity. These estimated times were based on typical field test times, and thus considered driving the vehicles to and from the test site, field maintenance and operations, *etc. The* longest time, 12 months, assumed that private industry would need a vehicle of the VDTV's capability to perform final checks on their products (three weeks) prior to submission for tests in the actual AHS environment, followed by tests in the AHS environment (one week). The latter tests could be treated as qualification tests prior to incorporation in the AHS vehicle fleet. Average times between the minimum and maximum were assumed.

AHS SUPPORT	ALL TIMES ARE IN MONTHS		
	VDTV USE TIME RANGE		ESTIMATE
	MINIMUM TIME	MAXIMUM TIME	AVERAGE TIME
SUPPORT OF AHS FLEET ACQUISITION			
1. Objectively determine AHS vehicle fleet requirements via tests	1	4	2
2. Define subset of VDTV performance essential for AHS fleet	0	1	0
3. VDTV class vehicle dedicated to AI-IS activities	0	1	0
SUPPORT OF AHS OPERATIONS			
1. Determine AHS operation in regime of performance bounds	2	6	4
2. Use VDTV to test performance of candidate AHS systems	2	12	6
3. Determine dynamic requirements of production vehicles	0	6	4
4. Evaluate performance of technology for vehicles entering an AHS lane	2	6	3
Total Time (Months	6	32	17

Column Descriptions

VDTV Use Time Estimates: subjective estimates of the minimum and maximum times of VDTV use

Average Time: Estimate of the average between the minimum and maximum

3. NADS Support-The same process as for AHS support was followed. Two time periods were used: the initial NADS validation, and NADS operation. The former assumed that the VDTV would conduct a series of tests, using its comprehensive on-board measurement system, to obtain data over the entire research envelope from small economy cars to large luxury sedans and up to the limits of tire/road adhesion. During NADS operational life, five uses whose objective was to obtain early acceptance of NADS data products were defined. In general, the VDTV could perform the necessary high-fidelity road tests quickly, providing spot checks to answer questions concerning NADS data quality for any particular issue.

NADS SUPPORT	ALL TIMES ARE IN MONTHS		
	VDTV USE TIME RANGE		ESTIMATES
	MINIMUM TIME	MAXIMUM TIME	AVERAGE TIME
NADS VALIDATION			
1. Obtain validation data with physical masses	2	3	2
2. Obtain validation data with VDTV variable dynamic capabilities	2	4	3
3. Obtain validation data with tests in tire/road adhesion limits	1	2	1
SUPPORT OF NADS OPERATIONS (Months during five years)			
1. Full scale tests for spot checks of NADS data products	2	12	4
2. Conduct tests outside dynamic capability of NADS	2	12	6
3. Conduct full scale tests to answer questions from legislative bodies	0	5	2
4. Conduct full scale tests for NADS update designs, validate updates	5	15	10
5. Conduct full scale tests with same drivers to validate NADS data products	0	5	3
Total Time (Months:	12	55	29

Column Descriptions

VDTV Use Time Estimates: subjective estimates of the minimum and maximum times of VDTV use

Average Time: Estimate of the average between the minimum and maximum

4. Technoloev Assessment-These utilization times assumed that the VDTV would have a primary role in assessing crash avoidance systems develop outside the Government. Tests would vary from relatively simple data gathering to automatic control of vehicle motions (such as deceleration) using existing VDTV capabilities. The latter tests would be complex, requiring parameter adjustments to attain optimum performance, so would require at least a month each. The VDTV could also conduct a series of in-house tests which would develop specifications for crash avoidance systems, thus leading the development of such systems. High-fidelity tests to qualify candidate crash avoidance systems and to support rule making are also included. These latter uses were estimated to take two months for each test to acquire the comprehensive data necessary for these significant actions.

TECHNOLOGY ASSESSMENT	ALL TIMES ARE IN MONTHS		
	VDTV USE TIME RANGE		ESTIMATE
	MINIMUM TIME	MAXIMUM TIME	
Note: times are in months over a five year period			
1. Test and evaluation of crash avoidance systems	10	60	30
2. Develop specifications for crash avoidance systems	6	20	10
3. Conduct independent performance and safety assessments	5	20	10
4. Conduct formal crash avoidance system qualification tests	5	10	6
5. Conduct tests to support rule making	5	15	10
Total Time (Months:	21	65	36

Column Descriptions

VDTV Use Time Estimates: subjective estimates of the minimum and maximum times of VDTV use

Average Time: Estimate of the average between the minimum and maximum

5. Other Use s--Since only information gathered from the User Questionnaire (Section 2) and conversations with automobile manufacturers and the auto support industry was available, the spread between the minimum and maximum is large. These conversations indicated considerable interest commensurate with the maximum times. One auto firm stated that they could use a VDTV full time for a year, others also indicated specific uses over long periods.

OTHER USERS	VDTV USE TIME RANGE (ALL TIMES ARE IN MONTHS)		ESTIMATE
	MINIMUM TIME	MAXIMUM TIME	AVERAGE TIME
Note: times are in months over a five year period			
1. Other government organizations (PATH, IVHS, etc.)	5	15	5
2. Research organizations (5 firms, 1 device/year, 5 years, 2 months each)	10	50	20
3. Automobile manufacturers	0	60	0
4. Automotive support industry; use VDTV to verify product performaince	0	60	10
5. Alternative VDTV test activities	10	60	15
Total Time (Months)	20	230	45

Column Descriptions

VDTV Use Time Estimates: subjective estimates of the minimum and maximum times of VDTV use

Average Time: Estimate of the average between the minimum and maximum

C.3.2 Summary

Data from the above tables is shown in the following summary.

Summary of all Users	VDTV USE TIME RANGE		ESTIMATED TIME
	MINIMUM TIME	MAXIMUM TIME	
1. Human Factors Research	N/A	N/A	16
2. AHS Support	6	32	17
3. NADS Support	12	55	29
4. CA Technology Assessment	21	65	36
5. Other Users	20	230	45
Total Time (Months	59	382	127

Notes and Column Descriptions

"CA" is crash avoidance

Use times are in months during a 5 year period

VDTV Use Time Estimates: subjective estimates of the minimum and maximum times of VDTV use

Estimated Time: Conservative estimate between the minimum and maximum

Minimum Time: equivalent to one VDTV for a period of five years: the estimated time is equivalent to two vehicles. There is a potential broad use justifying additional VDTVs.

C.4 VDTV TEST AND OPERATIONAL SCENARIOS

This section contains a number of hypothetical scenarios that were written to illustrate potential uses of VDTV. It also contains three sections describing scenarios for VDTV uses. The sequence follows that of Sections 3.2 (Appendix C.4.1) and 3.3 (Appendix C.4.2) for most uses, then closes with two general operational scenarios in Appendix C.4.3.

C.4.1 Major NHTSA Uses

C.4.1.1 Human Factors: Effect of body roll on crash avoidance maneuvers

Research Objective-Define the effect of body roll on a driver's ability to maneuver a vehicle during a crash avoidance maneuver.

VDTV Configuration -- The normal VDTV configuration is used No added subsystems or other equipment is needed.

Drivers-Drivers are selected by NHTSA researchers based on their specific research objectives. Drivers need no special skills and can be taken from the general US population. About 30 drivers might participate in this test.

Observer-The normal trained VDTV observer is on board to control the vehicle dynamics and follow written test procedures.

Test Location-Tests are conducted on a large, flat paved surface devoid of physical obstructions which could damage the VDTV. The surface will permit the VDTV to reach maximum speed, encounter the test area, provide time to engage the VDTV's safety subsystem which transfers full manual control to the driver, decelerate, then stop with adequate safety margin before encountering any physical objects which could damage the VDTV.

Simulated Test Obstacles-A set of test obstacles fabricated from light materials, such as Styrofoam, is set up on the test surface. For purposes of this test, these obstacles portray a crossroads on a two lane highway in a suburban area. Signs, curbs, shrubs, traffic lights, *etc. are* included. The cross road is simulated by equivalent items. Two vehicles, one from each direction, are stopped at the intersection. These are also Styrofoam replicas with reasonable appearance and mounted so they can be pushed onto the intersection without any real physical obstructions which could damage the VDTV.

Pre-Test Driver Training-The VDTV is driven under full manual control along a prescribed path to familiarize the driver with the vehicle. The operator then switches the VDTV to the drive-by-wire configuration which emulates the normal manual control. When the driver is familiar with the vehicle, the test sequence starts.

Pre-Test VDTV Performance Verification-Since every data set must have a consistent baseline, the operator directs the driver to position the VDTV at a specific location. The operator then enables an automated driving sequence, consisting of accelerations, turns, and decelerations, over a short distance. This maneuver is controlled by the VDTV's Control Subsystem without driver (hands and feet off controls) or operator intervention to assure a repeatable maneuver. The VDTV Measurement Subsystem records all data, compares this data to limits established by previous automated maneuvers, and sends a signal to the laptop computer that the entire VDTV is operating within its normal envelope. This assures that test data will be valid with little labor spent to investigate anomalies encountered during data reduction processes.

Normal Configuration Tests-The operator instructs the driver to drive down a road leading to the flat test surface. The speed reaches 60 kilometer& as the driver approaches the intersection with a green traffic light. At a predetermined distance from the intersection, one of the two cars suddenly moves forward and stops in the intersection. The time that the vehicle moves is included in the VDTV's data set. The driver then attempts to miss the car. In this test, the VDTV emulates the roll performance (angle, transients,) of a normal passenger vehicle.

Roll Variations-The operator then defines different vehicle roll characteristics via the laptop computer. The sequence is defined by NHTSA researches and incorporated into the test procedure. Roll is changed from essentially zero roll angle to angles considerably beyond those encountered in normal passenger vehicles so objective data on the entire envelope can be obtained. The VDTV's active suspension and steering systems perform the functions, but the operator needs only to input roll parameters. During the roll variations, all other parameters which may affect driver performance are maintained constant. Subjective parameters such as vehicle appearance, ride, and noise are constant because there is one vehicle. Dynamic parameters such as pitch, deceleration, brake force, steering wheel torque and angle are maintained constant by the Control Subsystem.

Dynamic Parameter Changes--After each test, the driver returns to the starting location and stops. The operator then inputs another roll characteristic.

Test Sequence--The test sequence can then be repeated, providing a complete data set within a period of about 10 minutes. Either of the two vehicles parked at the intersection can intrude into the intersection at varying distances if needed to meet research objectives. For some tests, neither vehicle will move.

Post-Test VDTV Performance Verification-The pre-test performance verification procedure is repeated, thus bounding the research tests with a data set taken under known conditions. Data within the pre-test and post-test bounds thus has a high probability of providing quality data with minimum time spent to analyze and reconstruct faulty data.

Data Analysis–The on-board Measurement Subsystem data is transferred to the data reduction computer, part of the VDTV system, for further processing.

C.4.1.2 AHS

1. Define Dynamic Performance of AHS Vehicle Fleets

Objective: Provide Nation-wide AHS activities with objective data that defines the dynamic performance essential for test vehicle fleets.

VDTV Configuration-The VDTV has its basic configuration plus equipment provided by AHS:

- Fore and aft distance sensors with a range suitable for manual vehicle operation of the order of tens of meters.
- Lane sensors, including buried wires, strips on the surface, *etc.*
- Engine control algorithms.

Test Conditions-Conducted on a two (or more) lane road segment which has been constructed specifically for AHS development. This road segment has several critical characteristics which will allow off-road excursions (may occur in R&D activities) with little damage to the vehicle and a lower risk to occupants than normal driving on public roads. These characteristics, which have been documented for many years, define slopes, distances, obstruction constraints, *etc.* necessary for a safe roadway. The roadway includes entrance and exit lanes with the same safety precautions.

VDTV Test Plan-The VDTV is assigned to support AHS for a period of several months. Because of many uses for VDTV, the test plan has been defined, reviewed, and agreed to by AHS and NHTSA to assure that the AHS support tests can be completed within the schedule, and yet obtain the data quality needed for future procurements of a vehicle fleet.

VDTV Role-The VDTV has considerably greater dynamic capability than required for a fleet of AHS vehicles. The test plan uses this range of continuously variable dynamic performance to gather data not only over expected ranges of interest, but to extend these ranges so the maximum dynamic performance needed for AHS development is known.

VDTV Tests-Each tests starts and ends with the automated validation test to assure quality test data. Early tests investigate normal operating ranges, which are gradually extended to define the AHS possible operating envelope. Retests cover specific areas with a great deal of detail by using the continuously variable VDTV capabilities. The test series is structured to define performance that is not needed, thus saving costs of extraneous performance in future multiple vehicle procurements.

Particular emphasis is given to extremely fine longitudinal speed changes which are essential for short vehicle-to-vehicle distances in platooning scenarios. The VDTV's capability to apply brakes under precise control of electrohydraulic servovalves, rather than the on/off operation of current ABS devices, is used to define limits of expected future performance. Precise engine power output, for both acceleration and deceleration modes, is done by varying spark timing as well as throttle position control.

C.4.1.3 NADS

1. Driver's Workload with Technological Systems

   The VDTV is assigned to support this research problem in a support role to NADS. The NADS role is concerned with multiple long-term tests which include driver degradation caused by fatigue, each of which requires an hour of simulator time. The VDTV role is concerned with detailed testing to fully verify the NADS results via checks of specific operations. The simulator performance requirement is defined as medium to high, so a major VDTV role is operation in regimes where high fidelity is essential to valid research results.

   The VDTV requirement includes provision for interfacing with devices which support IVHS technology. This includes mechanical and electrical interfaces at the front, rear, and sides of the exterior and mounting provision for driver displays on the interior. Accordingly, no modifications to the VDTV are needed.

   The IVHS devices are delivered to the VDTV test site. The VDTV original procurement includes a mechanical fixture which defines the mounting interface and an electronic interface simulator, so integration tests have been completed prior to delivery. Integration thus is accomplished on schedule. Initial performance tests are then done according to both normal VDTV and vendor procedures. After a review of the data, the VDTV is ready to perform the tests.

   The VDTV has been assigned tests concerned with highly complex roadway scenarios. To assure safety, a section of proving ground roadway has been allocated for these tests, so only vehicles authorized to participate in the test are present. The roadway is two lanes which includes large runoff areas where the VDTV can travel with no structural damage and only a small probability of cosmetic damage in the case of driver error. A variety of simulated objects are available for the test; all are fabricated of lightweight material which can be struck with only minor cosmetic damage to the VDTV. These objects include pedestrians, other vehicles parked adjacent to the roadway, construction zones, and two intersections. The test segment of the roadway is accessed via other proving ground roads which permit the driver to travel in a continuous manner at essentially the same speed.

   The tests starts with the driver running two laps of the test section with no objects to establish a baseline performance. On following tests, different objects are added to the roadway in increasing numbers. IVHS trigger devices located adjacent to the roadway transmit signals to the devices located on the VDTV so the driver must simultaneously pay attention to his primary driving task and also the IVHS equipment. A key part is interjection of a pedestrian into the roadway immediately after the IVHS requires attention, causing the driver to conduct a maneuver at the limit of tire/road adhesion to avoid the pedestrian. Such a series of maneuvers is used to validate the NADS results, providing good correlation between NADS and track tests.

An auxiliary investigation concerns vehicle dynamics. A limited set of the same maneuvers is conducted with higher body roll, while all other VDTV dynamic characteristics remain unchanged. This provides NHTSA researchers with preliminary information on the effect of body roll on driver/vehicle performance. Since the body roll can be adjusted during the time the VDTV is not in the test scenario, while continuing the same speed as normally done, this test data is available with little additional cost.

2. NADS Model Verification

NADS model information was available early in the VDTV activity. Detailed technical discussions with cognizant NADS personnel led to a list of parameters: (1) required to verify the model, and (2) desired for the existing model or believed to be of interest in the future. This parameter list was an important driver for the entire vehicle, especially the Control and Measurement Subsystems, and was worked to the level of detail of consistent nomenclature, units, and limiting high/low performance parameters early in the task. Further, the acceptance test procedure included specific tests which would verify performance of each parameter. Since this acceptance test procedure was developed early in the activity, the entire design effort was aware of objective parameters that had to be satisfied. Documentation of the VDTV acceptance test performance was part of the package made available to users.

NADS was the first user with the purpose of verifying their crash avoidance model. Since the VDTV-to-NADS data transfer technology had started shortly after subsystem tests of the Measurement Subsystem were conducted, and continued until the data transfer was routine, the test sequence was conducted according to schedule. This first test required two weeks, which provided data for two month's analysis at NADS. During this time, the NADS model was modified and the next test parameters identified.

The VDTV was assigned other uses during the time the NADS model was being adjusted, so there was no VDTV idle time.

Verification of the NADS model had been assigned high priority for VDTV use, so the sequence of tests followed by NADS analysis and model changes continued at intervals of one to two months. During this time, the VDTV's NADS test configuration was under formal configuration control to assure consistent VDTV performance. A part of this assurance was pre-test and post test maneuvers which provided objective VDTV performance data. This test data was verified within an hour by an automated VDTV performance assurance program. This permitted tests to continue with a high degree of assurance of quality data.

The NADS model was verified in a year. At this time, NADS started work on an updated model which required additional control system and measurement capability. Since the Control and Measurement Subsystems were initially specified to have a capability to expand to a specified limit (thus avoiding an open-ended and expensive system), the additional measurements were included in time for the next NADS test. Modifications were made under a development contract and included in the VDTV configuration control.

After two years, NADS embarks on a virtual reality program intended to use the latest technology to acquire a far larger data base than possible with the VDTV. The NADS ultimate objective is to disseminate this technology in an affordable form throughout the Nation for both data and driver education. The VDTV is updated to acquire additional information for this NADS activity.

3. Support NADS Operations

Research Objective-Validate NADS data during its lifetime operation.

Test Conditions-Conducted on the large test area where simulated obstacles pose essentially no threat of structural damage to the VDTV. The simulated obstacles are tailored to be similar to those used in the NADS visual environment. Drivers, operator, pre-test scenario, *etc.* follow the same sequence as that for the roll scenario.

A possibility is to use the VDTV to obtain visual images which would be transferred to NADS.

NADS/VDTV Roles-NADS research is the dominant activity; the VDTV acts in a support role. This VDTV role would be particularly important during early NADS operation, where many organizations familiar only with road tests may not readily accept NADS results.

NADS/VDTV Coordination-During formulation of the NADS research plan, a limited set of VDTV tests is included. These tests are designed to be highly similar to specific NADS scenarios to provide direct correlation between NADS and VDTV data.

VDTV Tests-Drivers from NADS tests are used for VDTV tests to assure maximum correlation. The VDTV conducts a limited number of tests to provide data under conditions highly similar to those of NADS tests. Results are intercompared, and tests rerun if necessary. The result is a limited set of road test data which validates the more extensive NADS data.

Time Period-The VDTV acts in this support role during its life. The validation tests become less frequent in the future as the NADS facility becomes mature and its research products are better accepted.

C.4.1.4 Technology Assessment

1. Evaluation of Intersection Crash Avoidance Device

Technology Objective: Objectively evaluate the performance of an intersection crash avoidance sensor, developed by private industry, under known conditions.

VDTV Configuration--Normal configuration plus installation of a crash avoidance sensor.

Crash Avoidance Sensor-The crash avoidance sensor has been developed by a private firm to the point where system-level performance data is essential to evaluate its capabilities in a realistic scenario. The firm has provided the sensor according to defined interface specifications (size, weight, mounting, electronic signal interfaces, electrical power, *etc.)* published by NHTSA and available throughout the Nation.

Test Conditions-Same as for the roll scenario, but the setup simulates an urban intersection. No simulated obstacles pose a threat of structural damage to the VDTV. Drivers, operator, pre-test scenario follow the same sequence as that for the roll scenario.

Detection Sensitivity Evaluation-After the VDTV's pre-test performance has been verified, the first tests investigate the sensor's sensitivity. Parameters are VDTV speed, distance from the intersection, and movement of the simulated vehicles which enter the intersection. The test sensor data is included in the data stream. All data is recorded in a format which permits millisecond resolution. These tests provide no information to the driver or automatic vehicle control.

Driver Warning-The second series of tests uses the test sensor's outputs to give visual or audible cues to the driver. The VDTV's human factors data (eye movements, head motions, foot and hand response, *etc.)* are included in the data stream to permit post-test evaluation of the time differences between the test sensor and normal driver reactions.

Automated Crash Avoidance-The test sensor output signals are sent to the VDTV's Control Subsystem and interfaced to test-unique software which permits fully automatic crash avoidance maneuvers. Initial tests are conducted on a bare area devoid of any obstacles. After debugging, a formal acceptance test is conducted to assure minimum damage to the Styrofoam simulated obstacles. A series of fully automated crash avoidance tests is then conducted. The test sensor, VDTV Control Subsystem, and VDTV dynamic subsystems steer and brake the VDTV.

Another research objective, affect of yaw inertia and ABS under fully automatic control, is investigated near the end of the test sensor evaluation. This is a preliminary investigation which provides early objective data needed to define a more comprehensive test series.

C.4.2 Other Users

C.4.2.1 Legislative Evaluation

Congress issued an urgent request to NHTSA to evaluate a possible deficiency in the crash avoidance program. Since this question was raised in a political sense, a rapid reply was desirable. NHTSA informed the current VDTV user, a university, that the VDTV was to be used for several days to support a NHTSA program. Such use was included in the contract. NHTSA flew two persons to the university while other personnel were developing the laptop computer programs and menus. These were electronically transmitted to the university the next morning, then used in the late morning and afternoon to conduct initial tests. Slight changes were made in the evening. Final tests were conducted the next day, with data electronically transmitted to NHTSA overnight. NHTSA personnel completed the data reduction and preliminary report the next day, ready for transmission to Congress within a week.

NHTSA placed a high priority to support legislative actions. The VDTV was offered to firms throughout the Nation to provide objective data, comparable to a large body of other data, to support crash avoidance claims. NHTSA established a liaison activity which monitored unsubstantiated PR claims, analyzed the VDTV's ability to verify the claim, and offered the VDTV for use if appropriate. This resulted in a decrease of claims which had little technology basis, but provided the Government with an excellent data base which correlated applicable developments throughout the Nation.

Results were distributed to Congress, permitting Congress to make intelligent decisions concerning future legislation.

C.4.2.2 Research Institutions

The VDTV's role was sent to research organizations, particularly universities, to inform them of this test tool. Since acquisition of quality objective data was a major cost to any research activity, particularly since a one-of-a-kind vehicle would be required, the VDTV availability increased research expenditures.

For such activities, there is a high risk of unforeseen problems. NHTSA thus offered the VDTV on the basis of a limited objective which had to be passed before the next VDTV use was available. This process made the VDTV available for a short period of time to assess the current development status. The research organization then developed the next phase of their technology while the VDTV was used elsewhere. This process avoided committing the VDTV to an activity where it would be idle during frequent development work.

C.4.2.3 Automobile Manufacturers

The three US auto manufacturers monitored the VDTV development closely. After the VDTV passed its acceptance tests, its operation was kept within NHTSA for six months for personnel training, additional debugging of minor items, and detailed development of on-board to off-board data transfer and the first level of data processing. The latter included data transmission from the test site to selected NHTSA researchers throughout the Nation. After operations and performance were well proven, auto industry personnel were invited for a demonstration and review.

The ability of a single vehicle to quickly emulate performance of a wide range of vehicles was new to the attendees, since they had typically built Mules for a specific purpose. A key point was the auto industry's need to have a test facility whose data would be accepted by the Government, thus maintaining their R&D expenditures on a path devoid of future disagreement concerning the data acquisition process.

Discussions with NHTSA led to requests for either the documentation to build their own VDTVs, or to acquire use of a NHTSA VDTV at a use fee. Different firms opted for different approaches, but the VDTV was used by all firms and quickly became the standard for crash avoidance research.

C.4.2.4 Automotive Support Industry

This scenario concerns a crash avoidance device partially developed by a private firm to the state where road tests are necessary to determine its potential under actual conditions. This is a proprietary product, so some data must be confidential.

1. Overview

   A NHTSA/user contract which protects proprietary information is developed. Also, NHTSA documentation is adequate to permit users to perform essentially all integration activities devoid of outside assistance. The VDTV thus permits users develop their crash avoidance subsystems according to their own practices, subject to NHTSA approval concerning driver/operator qualification and VDTV safety requirements.

2. Pre- test Preparation

   NHTSA delivers the test fixtures and any other detailed documentation needed by the user according the contractual schedule. The user performs final fabrication with these test fixtures, assuring a high probability of mechanical mating when the new technology is fitted to the VDTV. To protect proprietary interests, the user is responsible for all initial integration activities.

3. VDTV/Crash Avoidance Integration

   The NHTSA/user contract includes cost and schedule for NHTSA support (at the user's cost) during the final integration phases. This support included training, driver certification, and related activities necessary to assure proper, safe VDTV use. During the first six months, this support was found to primarily consist of Control and Measurement subsystem integration at a level not clearly defined by the documentation. Documentation and integration time schedules were updated, resulting in good adherence to published schedules after a year's operation.

   In addition to mechanical integration, activities included the user's processing of sample test data (provided by NHTSA early in the program) on the user's computers. This test data specifically included the automated verification tests which the user was required to conduct, then provide certified results to NHTSA before the user could start any test activities. This assured NHTSA that end-to-end, timely data processing could be attained so NHTSA could track VDTV use on a daily basis.

   NHTSA and the user conducted a review of the test plan, and an on-site survey of the test area, to assure that the VDTV would not be damaged. NHTSA formally signed an acceptance of this test plan.

4. User's VDTV Operation Constraints

The test plan allowed some deviations to accommodate experience as the tests progressed, but strict adherence to all safety requirements were met. Since the user was aware that the VDTV Measurement subsystem included accelerometers which would clearly define impacts, thus making the user contractually liable for damage to the VDTV, users had an excellent safety record.

NHTSA required the user's test plan to include the automated pre- and post-test VDTV performance verification tests. Users were required to transmit this pre- and post-test data to NHTSA, via electronic means, every day. Vehicle performance and health were thus checked daily, assuring NHTSA of quality data which was directly comparable to all other VDTV data sets. The VDTV test numbers were compared to the schedule, permitting NHTSA to look forward to future VDTV schedules. The user's proprietary data content was not required to be submitted.

5. Driver Envelope Tests

The user's crash avoidance technology concerned avoidance of intersection crashes, and used an active sensor system. Performance was dependent on driver reactions. To quantify driver characteristics and evaluate the system performance, the user selected a variety of drivers. Each driver was trained to go through a prescribed maneuver which depended on visual inputs for the initial reaction.

The operator entered the driver's ID number into the laptop computer, which linked the test data to the complete driver profile which was stored in the off-board computer. The human factors tests started with the VDTV's parameters set to those of an average 5 passenger vehicle; vehicle weight, inertias, damping factors, steering ratio, brake pedal force, *etc.* were defined by menu selection and simple keyboard entries into the laptop computer. The control system then controlled the VDTV's dynamic response to that of the selected vehicle. A set of three baseline tests was conducted in this configuration.

Before each test, the VDTV was returned to the same point on the skidpad and stopped. The operator then manually actuated a data acquisition set which defined the at-rest condition, permitting Measurement subsystem drifts to be recorded. The driver then proceeded to the crash avoidance maneuver, starting evasive action after a visual cue. The entire dynamic behavior from the actual visual cue, to the driver's perception of this cue, to the driver's first reaction, to front wheel movement, and finally to vehicle movement was recorded. The driver hit balloons which simulated another vehicle on several occasions, but there was no damage to the VDTV. The driver then returned to the starting point, at-rest data was taken, then the next run begun.

Driver-related parameters, such as steering ratio, were then varied by operator inputs to the keyboard. Since all inputs were menu-driven with entries entered in simple units, and the program performed real-time validity checks prior to transmitting the data to the control subsystem, the error rate was extremely low.

Since a change in the VDTV's configuration required about 15 seconds during the at-rest condition prior to every run, the VDTV could conduct a test and change vehicle configuration within a period of 5 minutes. This short time provided better data because environmental changes normally experienced in outdoor tests were minimized.

The data set for the 5-passenger vehicle configuration was completed within a day. Shortly before the end of the day, the vehicle configuration was changed to both larger and smaller vehicles, again with laptop keyboard inputs. The set of vehicle parameters had been defined prior to the tests and made available to the operator on a menu, so the operator needed to make only a simple menu selection to change the vehicle configuration. Each change thus required about 15 seconds, permitting 20 tests with different vehicle configurations to be made under the same conditions as that of the 5-passenger vehicle before the end of the day. This data set also provided comparison for later tests, with different configurations, which could be expected to be conducted under slightly different environmental conditions.

During following test days, the range of fully manual to fully automated vehicle responses were investigated to determine the envelope of feasible crash avoidance parameters. The VDTV's ability to change its configuration quickly permitted the test matrix to define performance of the crash avoidance system as functions of different drivers and different vehicle characteristics. Also, repeat tests of any configuration could be run quickly with the keyboard entry of different vehicle configurations.

6 Vehicle Envelope Tests

Tests to investigate performance of the crash avoidance system were conducted in the same manner, but with a single skilled driver tdremove this variable from the data. Different vehicle characteristics (weight, inertias, damping factors, etc.) were defined in a menu. Test configuration was selected by a single menu selection. Since this menu selection was not proprietary, it was reported to NHTSA daily (with the calibration data) to provide timely information of schedule progress.

The performance envelope of the crash avoidance system was thus defined in a range of small to large vehicles, including investigation of vehicle parameters outside the range of normal production to better define the envelope of satisfactory performance.

7. NHTSA Data

At the end of the tests, the user provided a summary data set to NHTSA according to terms of the contract. Proprietary data was not included. An end-of-test calibration set, intended to verify the post-use VDTV condition, was included.

C.4.3 Operational Considerations

C.4.3.1 Background

These scenarios are intended to surface some operational considerations which may increase the VDTV's value by providing quality data throughout its life.

These scenarios assume that work has progressed to the point where a VDTV vehicle has been built, its performance verified in thorough road tests, acceptance tests have been passed, user-oriented documentation has been developed and verified during these acceptance tests, and NHTSA has started research operations. Further, the VDTV has been used by several NHTSA researchers in trial periods and all significant problems have been resolved. The VDTV is thus a somewhat mature system ready for a variety of crash avoidance research uses.

This scenario explores operations believed to be well outside those possible with a single vehicle and possibly outside those planned by NHTSA at this time. The purpose is to expand the possible VDTV use envelope so future plans can investigate any low-cost options which could significantly expand the VDTV's use. The term "VDTV" is thus taken to mean two or more vehicles, with similar capabilities, which might operate at several places simultaneously to speed the Nation's crash avoidance technology development.

C.4.3.2 Selection of VDTV Operational Assignments

NHTSA researchers initially request all available time for the VDTV. However, NHTSA advertises VDTV limited availability in the Commerce Business Daily to provide National awareness for all interested parties. NHTSA provides generic documentation defining the VDTV role, capabilities, priorities, and operational constraints to prospective users upon request. Use costs are also defined. Users then negotiate for VDTV use. Successful candidates are determined according to published criteria which prioritizes NHTSA's research interest. Contracts which define test objectives, schedules, user responsibilities, funding, etc. are signed. Milestones are included in each contract to assist schedule monitoring.

Replies show there are multiple potential users throughout the Nation, each willing to invest their funds in crash avoidance technology and scheduling their internal resources to conduct performance tests with the VDTV. Accordingly, the VDTV schedule must be strictly controlled. Part of the VDTV system is an automated scheduler, deliverable to NHTSA along with the VDTV, to permit NHTSA to monitor progress of each test with minimum workforce. Milestones are electronically reported to NHTSA, analyzed by the scheduler, with deviations and summary reports reported as outputs.

C-4.3.3 Operational Constraints

1. VDTV Safety

The VDTV is an expensive vehicle, so NHTSA cannot afford damage which would cause appreciable downtime. Reviews define that cosmetic damage, which might occur if the VDTV impacted a Styrofoam simulation of a guardrail, was acceptable. However, structural damage which would impair dynamic operation or shift the performance baseline was not acceptable. Further, damage would require complete rectification of baseline performance, an expensive process. NHTSA thus published a set of operational requirements which defined safety constraints. These requirements dictated deceleration areas as functions of vehicle speed, dynamic maneuvers, etc. The deceleration areas were required to be void of any obstacles which could damage the VDTV's performance.

2. Driver Safety

Safe operation from the viewpoint of VDTV damage may not eliminate the possibility of driver injury, so seat belts and air bags (both driver and operator) are required for VDTV operation. Operation in an environment of potentially high risk to a driver were assigned to NADS.

C.4.3.4 Proprietary Information

Since some users involved proprietary information, NHTSA management decides that NHTSA would not have access to such information to avoid potentially damaging publicity. Separation of proprietary data and generic data is readily accomplished by capabilities built into the Measurement Subsystem.

C.4.3.5 VDTV Drivers

A variety of drivers will be essential to meaningful data concerning effectiveness of crash avoidance technology.

1. Spectrum

A full range of drivers is necessary to evaluate affects of different crash avoidance technology. This includes age, driving experience, etc. from persons throughout the Nation. The VDTV thus had to appear like a normal passenger vehicle to make this range of drivers comfortable during tests.

2. Driver qualifications

There are three driver qualifications: (1) a valid driver's license, (2) no physical handicaps which would require special modifications to the VDTV, and (3) passing a driver's test under NHTSA supervision. The latter is a simple test whose purpose is to avoid damage to the driver and VDTV.

3. occupants

The VDTV is operated by a driver and operator. The driver is responsible for human inputs to the steering wheel, brakes, and other manually-operated systems. The operator is responsible for inputs to the Control and Measurement subsystems via the laptop computer, and also controlling the test series. This includes analysis of quick-look data which summarizes each test, following the test schedule, verifying satisfactory VDTV system operation, etc.

C.4.3.6 VDTV Validation

After the VDTV fabrication was complete and had passed its functional tests, a comprehensive test sequence developed the control system algorithms. The primary purpose of these algorithms was to slow VDTV response from its inherent high-response capability to that of heavier, slower vehicles. Algorithms were designed to include a full performance range, including non-linear tire characteristics in the lateral acceleration range experienced in crash avoidance maneuvers. Control law coefficient changes, which could be entered from a laptop computer, were the primary means of adjusting VDTV dynamic performance. Validation tests used addition of physical devices (weights, moment arms) to define performance of heavier vehicles. Control system parameters were then changed in a series of iterative tests until an acceptable simulation of a variety of vehicles was obtained.

To assure quality data consistent with future use, these validation tests were conducted after the Measurement subsystem performance had passed its acceptance tests. All validation test data is was thus available to start building the VDTV's performance history.

C. 4.3.7 VDTV Performance Verification During Operations

Measurement assurance is a primary VDTV function. Since the VDTV is available to the auto industry, inventors, and the Nation's research community, VDTV measurements must withstand close scrutiny of possible competitors whose financial future may be dependent on the measurements.

An automated verification capability is an inherent part of the VDTV design. To use this capability, users are required only to place the VDTV on a flat surface with defined length, width, and slope variations. A built-in dynamic procedure which uses automated steering wheel, accelerator, and braking actions then runs the VDTV through a known sequence. A basic data set is acquired, automatically compared to a baseline data set, and deviations are made available to the user via a laptop computer display. This process assures:

1. Valid measurements with minimum risk from user questions since the calibration process is done before and after tests at each user.

2. Cost effective verification because skilled NHTSA or system development personnel are not required.

3. Timely verification made on the user's schedule.

4. A data base which documents many of the VDTV parameters.

The VDTV is submitted to a detailed, formal calibration procedure at intervals initially defined by Measurement subsystem analysis. Initial intervals are six months, increasing to a year as soon as measurement assurance is established. The calibration interval is updated based on analysis of the database from the automated calibrations.

This calibration includes dimensional verification of all mechanical interface points. The interface fixtures are modified if necessary.

C.4.3.8 Maintenance

Although a VDTV implementation requirement was to use currently available technology with no research or development work, it was still a relatively complex vehicle. Planned maintenance was thus included in the schedule. Plans called for frequent maintenance, particularly inspections and analysis of automated performance verification data, during the first year. Components with frequent failures were gradually replaced and additional maintenance and diagnostic software was added to assist VDTV maintenance.

Experience during the first year showed that a major failure mode was frayed cable, faulty connectors, erc. This was traced to early design activities, which did not require use of connectors fully qualified for automotive use. Rather, connectors which would simplify fabrication had been used. This resulted in a month's downtime to replace most of the cable/connector subsystem.

C.4.3.9 Configuration Control

Early work identified configuration control as a critical function because the VDTV would be used to:

1. Make comparative evaluations of crash avoidance subsystems from different firms, many with a profit motive.

2. Provide data to National and State legislative bodies.

To protect NHTSA, a high degree of assurance of valid VDTV data was thus judged to be essential. A configuration management system was therefore an inherent part of the VDTV development activity.

A configuration control capability was turned over to NHTSA for operation, and was designed for minimum human intervention. Part of the deliverables, under the VDTV development contract, was a personal computer which largely automated the configuration control activities.

Configuration control is verified prior to the time the VDTV is sent to a different user.

As part of the VDTV contract, the user provides written documentation that the VDTV configuration has not changed. To protect proprietary information, and avoid having NHTSA in possession of proprietary information, the user does not provide documentation, photographs, or other information describing the subsystem. However, the user conducts tests of the VDTV in its known, baseline configuration immediately before and after the user test series. These tests are automated via on-board control systems, and the resulting measurement set is obtained and delivered to NHTSA as part of the contract.

The VDTV core structure (such as the control system, drive train, and measurement system) were under formal configuration control prior to the final acceptance tests. Changes to the core structure require a test series to define a new baseline.

NHTSA funds a development contract which updates the control and measurement systems as experience shows the need for improvements. Hardware/software which replicates that of the VDTV baseline configuration is supplied to the developer. After acceptance tests at the developer's lab, the modified equipment is installed in the VDTV. New baseline tests are then conducted.

C.5 NADS/VDTV ANALYSIS

C.5.1 Overview

This analysis, which compares VDTV and NADS characteristics, shows 'the potential synergism of these two crash avoidance research capabilities. The analysis is based on three sources:

1. Appendix F of the NADS Requirements Study Final Technical Report[2]. This report concerned a major future NHTSA facility and addressed its requirements. Further, Appendix F defined 14 specific research studies. This source was thus taken as the best available source of future NHTSA research activities, and is referred to as the Report in the following discussion.

2. VDTV capabilities as outlined by NHTSA and shown to be feasible by work of this study.

3. Discussions with auto industry personnel who have experience with both simulators and variable dynamic vehicles. It is noted that both NADS and the VDTV represent significant technological advances over any single existing capability.

Since the fourteen research problems are all defined as high priority in Appendix F of the Report, it is believed that these problems provide a good base for analysis of VDTV cost and performance for NHTSA's research program.

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2 National Advanced Driving Simulator (NADS) Requirements Study, Volume II, Final Technical Report: DOT HS 807 826, September 1991

C.5.2 Analysis Process

This analysis was primarily concerned with the research objectives and discussion of the full scale tests. Costs of both simulation and full scale tests were considered. This information led to: (1) a cost analysis of both simulation and full scale testing, and (2) development of proposed scenarios for a VDTV role to support the fourteen research objectives. In addition, the assumptions for simulation and full scale testing were reviewed.

Information was prepared in the form of spreadsheets (to define costs), scenarios (to provide information of candidate VDTV roles in future NHTSA research, and discussion of the work. The former two are contained in Appendices, while the latter information is presented in the following sections.

The process assumed the same guidelines as that used for the Report to provide a viable comparison of the VDTV and simulation approaches. The most important was that both the simulation (NADS) and full scale (VDTV) were treated equally. The initial cost for both NADS and VDTV were thus assumed to provide whatever capability was required for operations necessary to investigate the fourteen research problems.

C.5.3 summary

The most significant results were:

1. The Report was completed at a time prior to consideration of the VDTV. Because of this timing, the content of Appendix F properly assumed that special preparations for full scale testing were necessary. Costs and schedule for these special preparations were thus properly included in the Report

   A VDTV will result in significant changes in full scale testing costs, schedule, and performance from that defined in the Report. These changes are expected to have little impact on NADS use, but point to a linked, cooperative VDTV/NADS solution to the research problems.

2. The assumptions for simulation and full scale testing were well stated and generally fair, giving essentially equal balance to both approaches. There is the possibility that assumptions for both approaches were optimistic, yet balanced. Within the available information at this time, there is little reason to change these assumptions.

3. Concerns for safety of full scale testing expressed in the Report should be able to be reduced to acceptable levels for most of the research problems. This can be accomplished by early system engineering and normal proving ground practices. However, driving on public roads is deemed to be a very high risk from the viewpoint of damage to the VDTV and liability. Accordingly, the VDTV should not be assigned roles on public roads unless thoroughly reviewed by senior NHTSA management.

4. The Report addressed tradeoffs at the end of each research problem. However, a key parameter of fidelity was not addressed. This may be the most significant parameter, since all research products must bear scrutiny by the affected communities. Such fidelity assessments are clearly beyond the scope of this report, and should be made by NHTSA researchers and others in this particular research community.

C.5.4 Full Scale Test Safety

Comments for each research problem for full scale test start with "potential danger for full scale test". Because of personnel safety, this topic is essential. However, normal proving ground facilities and practices should be able to decrease the danger to acceptable levels. The following characteristics of VDTV operation are assumed, divided into four areas:

1. VDTV Design and Implementation

   1. The VDTV design emphasizes personnel safety. In particular, a capability to return to a fully manual mode for steering, braking, and throttle operation from automated operation is the single most important performance requirement. This change must be made in a short time and fully demonstrated in acceptance tests.

   2. Analysis of safe VDTV operation as part of the early system engineering activity, then review of this analysis by NHTSA management and also personnel with proving ground driving experience.

   3. Formal definition of VDTV safety operation as a result of the above work.

2. Proving Ground

   1. All possible tests are conducted on a large, flat paved area which will permit vehicle maneuvers at limit performance with no danger of impacting adjacent features which could damage the vehicle. Also, the test vehicle can enter this area at speeds up to 160 km/hr via access roads so test maneuvers can be initiated at high speeds with the vehicle path totally on the test area. Vehicle skids, braking, etc. can be conducted with large safety margins to engage the manual control and bring the vehicle to a safe stop well within the boundary of this paved area.

   2. The proving ground follows normal practices to assure safe operation if a vehicle inadvertently goes off the roadway. These practices include absence of rigid concrete sign emplacements adjacent to the road, properly sloped shoulders and adjacent drainage ditches to permit vehicle runoff with cosmetic or minor structural damage, consideration of shoulder distances for higher speed operation, etc.

3. Obstacles

   1. The procurement package defines the obstacles, pedestrians, construction equipment, signs, curbs, guardrails, vehicles, and other objects needed to conduct NHTSA's research scenarios.

   2. These objects are included in the safety analysis. The design and physical parameters of these objects are defined as a result of the safety analysis, along with safe operating areas (distance, speed, impact angles, etc.)

   3. The objects are procured as part of the system to assure safe operation.

4. Operation

1. Formal safety review of all new operations, including all the above parameters, prior to start of such operations.

2. Training for all test personnel to emphasize the critical importance of safe VDTV operation.

3. Monitoring by senior management personnel of the VDTV safety program.'

With these assumptions implemented into the VDTV operation, the VDTV safety risk for most research problems should be reduced to that equivalent to, or below, normal civilian driving.

c.5.5 costs

The basic assumption for the costs considers that the VDTV was not envisioned at the time of the Report. To assure comparable costing between simulator and full scale testing, the costing process followed in the report was used:

The simulator and VDTV costs both assume that the original procurement provides the full capability necessary to conduct tests.

Cost basis of the simulator and full scale thus remain the same with the exception that the VDTV is available.

Costs for both simulation and full scale approaches to the fourteen research problems were based on material in Appendix F. The analysis was based on:

1. Full scale labor costs estimated in the Report remain unchanged.

2. To be consistent with the NADS cost basis, the VDTV and obstacle costs were assumed to be included in the original procurement.

3. The months of operational time were assumed to be the same as NADS because the VDTV variability and its inherent capabilities will permit changes in about the same time as those for the simulator.

4. Full scale proving ground occupancy costs were reduced by a factor of (Report time)/(Revised time).

5. Material and site preparation costs were reduced by a factor of 4 to reflect the capabilities provided in the original procurement.

A cost summary is shown in Table C-2. Detailed costs for the fourteen research problems are shown in subsequent tables.

With the VDTV, the cost analysis indicates a small advantage for the full scale tests. However, this advantage is deemed to be well within the uncertainty of existing cost estimates. Much more definitive information will be essential to provide information adequate to make a decision based on cost parameters.

C.5.6 VDTV/NADS Synergism

Both the VDTV and NADS have advantages for specific data products. A major VDTV near-term advantage can be expected to be test fidelity. The VDTV can actively support NADS during the first few years of NADS operation by validating NADS data products via road tests. For many research problems, selected scenarios can be run by both VDTV and NADS to further validate NADS data products. NADS can conduct tests independent of weather and in test domains where human safety risks are unacceptable. The VDTV/NADS combination can be expected to provide NHTSA with a powerful crash avoidance research tool, using both capabilities in their optimum operational regimes.

TABLE C-2 SUMMARY OF RESEARCH PROBLEM COSTS WITH VDTV

RESEARCH PROBLEM	NADS REPORT ESTIMATE		REVISED
	NADS $	FULL SCALE $	FULL SCALE $
1. Driver's workload with technological systems	99,400	90,800	75,200
2. Driver's knowledge of traffic rules and signs	175,800	174,800	154,100
3. Effects of driver aging on driver ergonomics	167,400	162,300	123,900
4. Driver perceptual factors of advanced vehicle systems	181,000	20,600	131,100
5. Effect of driver risk taking on driver/vehicle performance	169,000	201,400	161,600
6. Variations of lateral-direction control on accident causation	171,200	168,400	139,800
7. Effect of lateral-direction dynamics on advanced vehicle system	172,200	149,200	125,400
8. Effect of radar collision warning/braking on longitudinal dynamics	203,800	230,600	179,400
9. Ride characteristic effects of longitudinal dynamics on driver performance	181,800	150,400	136,000
10. Effect of roadway geometry on development of navigation/route system	140,600	162,400	137,100
11. Effect of intersections on driver's use of advanced technologysystems	166,600	220,400	179,400
12. Effect of roadway illumination on driver behavior in degraded environment	183,200	204,800	175,200
13. Effect of pedestrians on driver behavior	153,600	200,400	156,200
14. Effect of highway maintenance equipment on driver performance	155,600	202,400	158,200
Total Cost	2,221,800	2,248,100	1,957,400
Rounded cost difference (NADS as reference)		26,300	-264,400

TABLE C-3 NADS COSTS WITH VDTV, RESEARCH PROBLEM 1.

DRIVER'S MENTAL WORKLOAD WITH ADVANCED TECHNOLOGICAL SYSTEM

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	6	8	6	Same as simulator because of VDTV variability
Engr/psych		40,000	40,000	Same as NADS report
Tech/data aide		12,000	12,000	Same as NADS report
Tech/mechanic		9,600	9,600	Same as NADS report
Secretarial		2,000	2,000	Same as NADS report
Course preparation		3,200	1,600	50%; simulated objects provided in initial procurement
Course occupancy		8,000	6,000	Reduced to reflect the shorter test duration
Simulation vehicles		8,000	0	Provided by initial procurement
Vehicle lease		4,000	0	VDTV is available
Travel and miscellaneous		4,000	4,000	Same as NADS report
Total Cost	99,400	90,800	75,200	

TABLE C-4 NADS COSTS WITH VDTV, RESEARCH PROBLEM 2.

DRIVER'S KNOWLEDGE OF TRAFFIC RULES AND RESPONSE TO SIGNING

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	9	10	9	Same as simulator because of VDTV variability
Engr/psych		75,000	75,000	Same as NADS report
Tech/data aide		18,000	18,000	Same as NADS report
Tech/mechanic		9,600	9,600	Same as NADS report
Traffic engineer		16,000	16,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		19,200	9,600	50%; all simulated materials provided in initial procurement
Course occupancy		16,000	14,400	Reduced to reflect the shorter test duration
Vehicle rental		2,000	0	VDTV is available
Materials		10,000	2,500	Most materials are available in original procurement
Travel and miscellaneous		6,000	6,000	Same as NADS report
Total Cost	175,800	174,800	154.100	

TABLE C-5 NADS COSTS WITH VDTV, RESEARCH PROBLEM 3.

EFFECTS OF DRIVER AGING ON DRIVER ERGONOMICS

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	8	12	8	Same as simulator because of VDTV variability
Engr/psych		90,000	75,000	Same as NADS report
Tech/data aide		18,000	18,000	Same as NADS report
Tech/mechanic		9,600	9,600	Same as NADS report
Secretarial		3,500	3,000	Same as NADS report
Course preparation		3,200	1,600	50%; all simulated materials provided in initial procurement
Course occupancy		16,000	10,700	Reduced to reflect the shorter test duration
Vehicle rental		16,000	0	VDTV is available
Travel and miscellaneous		6,000	6,000	Same as NADS report
Total Cos	167,400	162,300	123,900	

TABLE C-6 NADS COSTS WITH VDTV, RESEARCH PROBLEM 4. DRIVER PERCEPTUAL FACTORS OF ADVANCED VEHICLE SYSTEMS

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	9	12	9	4 months to modify vehicle are excluded
Engr/psych		85,000	85,000	Same as NADS report
Tech/data aide		18,000	18,000	Same as NADS report
Tech/mechanic		4,800	4,800	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		3,200	1,600	50%; all simulated materials provided in initial procurement
Course occupancy		10,000	6,700	Reduced to reflect the shorter test duration
Vehicle purchase		16,000	0	VDTV is available, so no vehicle purchase is necessary
Vehicle modifications		60,000	6,000	VDTV has full capability with minimum mods
Travel and miscellaneous		6,000	6,000	Same as NADS report
Total Cost	181,000	206,000	**131,100**	

TABLE C-7 NADS COSTS WITH VDTV, RESEARCH PROBLEM 5.

EFFECT OF DRIVER RISK TAKING ON DRIVER/VEHICLE PERFORMANCE AND SAFETY

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	8	11	8	Same as simulator because of VDTV variability
Engr/psych		80,000	80,000	Same as NADS report
Tech/data aide		24,000	24,000	Same as NADS report
Tech/mechanic		14,400	14,400	Same as NADS report
Traffic engineer		6,000	6,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		24,000	12,000	50%; all simulated materials provided in initial procurement
Course occupancy		16,000	11,700	Reduced to reflect the shorter test duration
Vehicle rental		4,000	0	VDTV is available
Obstacles		12,000	0	Obstacles provided in original procurement
Materials		10,000	2,500	Most materials are available in original procurement
Travel and miscellaneous		8,000	8,000	Same as NADS report
Total Cost	169,000	201,400	161,600	

TABLE C-8 NADS COSTS WITH VDTV, RESEARCH PROBLEM 6.
VARIATIONS OF LATERAL-DIRECTION CONTROL ON ACCIDENT CAUSATION

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	8	12	a	Same as simulator because of VDTV variability
Engr/psych		80,000	80,000	Same as NADS report
Tech/data aide		15,000	15,000	Same as NADS report
Tech/mechanic		19,200	19,200	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		3,200	1,600	50%; all simulated materials provided in initial procurement
Course occupancy		24,000	16,000	Reduced to reflect the shorter test duration
Vehicle purchase		16,000	0	VDTV is available
Modification materials		4,000	1,000	Most materials are available in original procurement
Travel and miscellaneous		4,000	4,000	Same as NADS report
Total Cost	171,200	168,400	139,800	

TABLE C-9 NADS COSTS WITH VDTV, RESEARCH PROBLEM 7.
EFFECT OF LATERAL-DIRECTION DYNAMICS OF ADVANCED VEHICLE SYSTEM

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	8	10	8	Same as simulator because of VDTV variability
Engr/psych		70,000	70,000	Same as NADS report
Tech/data aide		18,000	18,000	Same as NADS report
Vehicle dynamicist		4,400	4,400	Same as NADS report
Tech/mechanic		9,600	9,600	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		3,200	1,600	50%; all simulated materials provided in initial procurement
Course occupancy		16,000	12,800	Reduced to reflect the shorter test duration
Vehicle purchase		16,000	0	VDTV is available
Materials		4,000	1,000	Most materials are available in original procurement
Travel and miscellaneous		5,000	5,000	8
Total Cos	172,200	149,200	**125,400**	

TABLE C-10 NADS COSTS WITH VDTV, RESEARCH PROBLEM 8.

EFFECT OF RADAR COLLISION WARNING/ BRAKING SYSTEM ON LONGITUDINAL DYNAMICS

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	9	15	9	Same as simulator because of VDTV variability
Engr/psych		110,000	110,000	Same as NADS report
Tech/data aide		24,000	24,000	Same as NADS report
Tech/mechanic		24,000	24,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		1,600	800	50%; all simulated materials provided in initial procurement
Course occupancy		16,000	9,600	Reduced to reflect the shorter test duration
Vehicle purchase		32,000	0	VDTV is available
Obstacles		12,000	3,000	Most obstacles provided by initial procurement
Materials		4,000	1,000	Most materials provided by original procurement
Travel and miscellaneous		4,000	4,000	Same as NADS report
Total Cost	203,800	230,600	179,400	

TABLE C-11 NADS COSTS WITH VDTV, RESEARCH PROBLEM 9.

RIDE CHARACTERISTIC EFFECTS OF LONGITUDINAL DYNAMICS ON DRIVER PERFORMANCE

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	9	8	9	Same as simulator because of VDTV variability
Engr/psych		60,000	60,000	Same as NADS report
Vehicle dynamicist		6,600	6,600	Same as NADS report
Tech/data aide		12,000	12,000	Same as NADS report
Tech/mechanic		12,000	12,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		4,800	2,400	50%; all simulated materials provided in initial procurement
Course occupancy		32,000	32,000	Same as NADS report
Vehicle support		12,000	0	VDTV is available
Travel and miscellaneous		8,000	8,000	Same as NADS report
Total Cos	181,800	150,400	136,000	

TABLE C-l 2 NADS COSTS WITH VDTV, RESEARCH PROBLEM 10.

EFFECT OF ROADWAY GEOMETERY ON NAVIGATION/ROUTE SYSTEM

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	8	10	8	Same as simulator because of VDTV variability
Engr/psych		70,000	70,000	Same as NADS report
Tech/data aide		24,000	24,000	Same as NADS report
Tech/mechanic		9,600	9,600	Same as NADS report
Traffic engineer		8,000	8,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		4,800	2,400	50%; all simulated objects provided in initial procurement
Course occupancy		16,000	12,800	Reduced to reflect the shorter test duration
Materials		5,000	1,300	Most materials are available in original procurement
Vehicle rental		16,000	0	VDTV is available
Travel and miscellaneous		6,000	6,000	Same as NADS report
Total Cost	140,600	162,400	137,100	

TABLE C-13 NADS COSTS WITH VDTV, RESEARCH PROBLEM 11.

EFFECT OF INTERSECTIONS ON DRIVER'S USE OF ADVANCED TECHNOLOGY SYSTEMS

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	8	12	8	Same as simulator because of VDTV variability
Engr/psych		80,000	80,000	Same as NADS report
Tech/data aide		30,000	30,000	Same as NADS report
Tech/mechanic		18,000	18,000	Same as NADS report
Traffic engineer		16,000	16,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		14,400	7,200	50%; all simulated objects provided in initial procurement
Course occupancy		20,000	13,400	Reduced to reflect the shorter test duration
Materials		15,000	3,800	Most materials are available in original procurement
Vehicle purchase		16,000	0	VDTV is available
Travel and miscellaneous		8,000	8,000	Same as NADS report
Total Cost	166,600	220,400	179.400	

TABLE C-14 NADS COSTS WITH VDTV, RESEARCH PROBLEM 12.

EFFECT OF ROADWAY ILLUMINATION ON DRIVER BEHAVIOR IN DEGRADED ENVIRONMENT

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	8	12	8	Same as simulator because of VDTV variability
Engr/psych		90,000	90,000	Same as NADS report
Tech/data aide		24,000	24,000	Same as NADS report
Tech/mechanic		7,200	7,200	Same as NADS report
Traffic engineer		8,000	8,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		9,600	4,800	50%; all simulated materials provided in initial procurement
Course occupancy		40,000	26,700	Reduced to reflect the shorter test duration
Vehicle rental		4,000	0	VDTV is available
Lighting, materials		10,000	2,500	Most materials are available in original procurement
Travel and miscellaneous		9,000	9,000	Same as NADS report
Total Cost	183,200	204,800	175,200	

TABLE C-15 NADS COSTS WITH VDTV, RESEARCH PROBLEM 13.

EFFECT OF PEDESTRIANS ON DRIVER BEHAVIOR

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REVISED FULL SCALE $	RATIONALE
Full scale duration (months)	6	8	6	Same as simulator because of VDTV variability
Engr/psych		70,000	70,000	Same as NADS report
Tech/data aide		24,000	24,000	Same as NADS report
Tech/mechanic		18,000	18,000	Same as NADS report
Traffic engineer		8,000	8,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		14,400	7,200	50%; all simulated materials provided in initial procurement
Course occupancy		24,000	18,000	Reduced to reflect the shorter test duration
Vehicle rental		6,000	0	VDTV is available
Simulated pedestrians		25,000	0	Provided in initialprocurement
Travel and miscellaneous		8,000	8,000	Same as NADS report
Total Cost	153,600	200,400	156,200	

TABLE C-l 6 NADS COSTS WITH VDTV, RESEARCH PROBLEM 14.

EFFECT OF HIGHWAY MAINTENANCE EQUIPMENT ON DRIVER PERFORMANCE

FULL SCALE TEST ACTIVITIES	REPORT ESTIMATE		REVISED FULL SCALE ESTIMATE WITH VDTV	
	NADS	FULL SCALE $	REWED FULL SCALE $	RATIONALE
Full scale duration (months)	6	8	6	Same as simulator because of VDTV variability
Engr/psych		70,000	70,000	Same as NADS report
Tech/data aide		24,000	24,000	Same as NADS report
Tech/mechanic		18,000	18,000	Same as NADS report
Maintenance engineer		6,000	6,000	Same as NADS report
Traffic engineer		4,000	4,000	Same as NADS report
Secretarial		3,000	3,000	Same as NADS report
Course preparation		14,400	7,200	50%; all simulated materials provided in initial procurement
Course occupancy		24,000	18,000	Reduced to reflect the shorter test duration
Vehicle rental		6,000	0	VDTV is available
Simulated pedestrians		25,000	0	Simulated objects provided by original procurement
Travel and miscellaneous		8,000	8,000	Same as NADS report
Total Cos :	155,600	202,400	158,200	

APPENDIX D

VEHICLE DESIGN DESCRIPTION

APPENDIX D VEHICLE DESIGN DESCRIPTION

D.l VEHICLE WEIGHTS AND INERTIAS

D.l.l Introduction

The vehicle weight and moments of inertia are important parameters in determining the system dynamic characteristics. The desire, if not the requirement, is for the VDTV system to emulate the dynamic behavior of passenger cars ranging from economy cars to luxury sedans. As a general rule, it is much easier to emulate the dynamic behavior of a larger vehicle using a small, lightweight vehicle as a baseline rather than the other way around. Provisions must be made in the design, of course, for adding weights at specific locations such as to simulate the desired inertia properties in addition to the required software modifications. Given the above, it is clear that the design of the basic vehicle should strive for light weight and low moments of inertia.

This section of Appendix D examines the weight and inertia boundaries of several VDTV options.

D.1.2 Vehicle Weight Estimates

The approach was to first establish the lower bound of the vehicle weight by estimating the weight of a small, lightweight vehicle the design and the component weight of which are well known. Weight estimates of subsystems were then added to estimate the systems weights and inertias of the various options for the VDTV.

The weight of a Mazda race car, a breakdown of which is shown in the first columns of Table D-l, was taken as a baseline. Weights for the additional components of a mule vehicle were then estimated. These are listed in the second column of the same table. See Section 5 for the definition of this vehicle. The weights for a custom built VDTV were estimated by adding the additional subsystems weights such as the active suspension system, drive by wire capability, structural changes and body mounted sensors, as estimated by Lotus Engineering, to the weight of the custom built VDTV. These weights are shown in Table D-2. Weights for two additional options have been estimated, a modified Oldsmobile Ciera and a modified Ford Taurus. These weights are shown in Table D-3.

Table D-2 lists an estimated 280 kg for the additional subsystems. By comparison, an additional 355 kg were estimated for the subsystems of the modified production cars of Table D-3. The difference of 75 kg is attributed to the required structural modification for the production models.

The weights for the basic production cars were obtained from Reference D.6.1. This reference contains measured weights, inertia properties and basic dimensions for cars ranging from the Yugo to an Oldsmobile 98. Table D-4 has been reproduced from this reference.

D.1.3 Estimates of Vehicle Inertia

Estimates of total vehicle inertia values, rather than sprung mass inertias, have been used to evaluate the dynamic parameters of the different vehicle options. Vehicle sprung mass moments of inertia are better indicators of the system dynamics, but for the study of relative merits of the various options the total vehicle inertias, which are easier to estimate, are deemed sufficient.

The approach was first to calculate the moments of inertia of the Mazda race car, a vehicle with known weight distribution. These values were then compared with several inertia estimators published in the literature, References D.6.1, D.6.2. and D.6.3. The calculated vehicle inertia values are estimated to have an accuracy of from -0% to +20%. This estimate is based on the method of calculating local moments of inertia. Local moments of inertia have been calculated for all the major subsystems, such as the engine, transmission, etc., but have been neglected for the smaller subsystems. Thus the calculation will produce a lower bound of the inertias. Based on a comparison of the calculated vehicle inertias for the Mazda race car with those obtained from published estimators of References D.6.1 through D.6.3, Reference D.6.1 was the selected as the best estimator.

This reference suggests the following formulas for estimating total vehicle moments of inertia:

$$I_{yaw} = I_{pitch} = W\,a\,b$$

$$I_{roll} = 0.18\ W\ TH_r$$

where:
- W is the vehicle weight,
- a is the distance from the front axle to the vehicle cg
- b is the distance from the rear axle to the vehicle cg
- T is the average track width
- H_r is the roof height

Vehicle inertias obtained from Reference D.6.1 showed the best comparison with calculated values. Data from this reference, the most recent found in the open literature, were substantiated by actual vehicle measurement, Table D-4. A comparison of the calculated inertia values with those obtained from Reference D.6.1 are shown in Table D-5.

The above formulas were then used to estimate the total vehicle moments of inertia for the mule, the custom built VDTV, and the modified Oldsmobile Ciera and the modified Ford Taurus. For the custom built VDTV the dimensions of a Ford Tempo were chosen to give an optimistic lower boundary of inertia. As a first approximation it was assumed that the vehicle center of gravity will not be affected by the additional subsystem weights.

The results of these calculations have been superimposed on plots of measured vehicle data obtained from Reference D.6.1 and are shown in Figures D-l through D-3. The Yugo data and the Oldsmobile 98 data indicate the extreme values for these plots and have been so labeled. Table D-5 lists the types of cars from which these data have been derived.

D. 1.4 Weight and Inertia Boundaries

Ranges of emulation of vehicle dynamics have been estimated for the various VDTV options. These are shown in Figures D-l through D-3.

For the Mazda race car which, as was shown above, was used as the baseline for estimating the weights for the various VDTV options it was assumed that the weights were known to ± 5% and the inertias are shown as the minimum and maximum values from Table D-5.

For the **mule** and the custom VDTV it was assumed that the base vehicle could be made to act dynamically similar to a lighter, smaller vehicle by using special racing tires and software to reduce the effective weight and inertia by 10%. This establishes the lower boundaries of dynamic simulation shown in Figures D-l through D-3. These same assumptions have also been made to establish the lower boundaries for the modified cars. For the upper bounds it was assumed that 905 kg can be added to the total weight of the vehicle. This is not unreasonable if the frame is properly designed. Assuming that the weight is placed at the front and rear of the vehicle, boundaries for the yaw and pitch moments of inertia can be estimated. For the roll moment of inertia it was assumed that the weights will be mounted a maximum of 0.3 m above the existing center of gravity. For the modified cars the additional weight has been limited to a total of 455 kg due to the expected structural strength limitations of the frame.

Table D-l Mass Breakdown For Mazda Race Car and the Mule Option of the VDTV

	Mass, kg	
	MAZDA RACE CAR	MULE
Frame	225	225
RF Suspension	30	30
LF Suspension	30	30
RR Suspension	30	30
LR Suspension	30	30
Driveshaft	10	10
Differential	40	45
R Stub Axle, U-Joint	10	10
L Stub Axle, U-Joint	10	10
Engine	135	205
Transmission	45	90
Cooling	20	20
Wiring	10	20
seat	5	95
Dash, Instruments	20	45
Fuel Cell	20	20
Windows	25	50
Body	30	45
Battery	20	20
Misc. Cooling	25	25
Misc. Materials	-	45
Doors	-	25
TOTAL	770	1125

Table D-2 Masses for the Custom VDTV

	Mass, kg
Mule Weight	1130
Active Suspension System	30
Front Steer By Wire	30
Rear Steer	20
Brake by Wire	25
Structural Changes, Sensors, Miscellaneous	175
TOTAL	1410

Table D-3 Masses for a Modified Olds Cierra and a Modified Ford Taurus

	Mass, kg	
	Olds Ciera	Ford Taurus
Basic Car	1295	1420
Additions & Modifications	355	355
TOTAL	1650	1775

Table D-4 Typical Weights and Inertias of Production Passenger Cars (from Reference D.6.1)

	Vehicle Weight and Dimensional Data						Calculated Center of Gravity Positions and Inertia Values				
	Wheelbase	Track Width (in)		Roof Height	Weight	% Weight	CG Location (in)		Inertia (ft*lb*sec^2)		
Vehicle	(in)	Front	Rear	(in)	(lb)	Front Axle	Front Axle	Height	Pitch	Roll	Yaw
1987 Yugo GV	84.0	52.0	50.0	53.8	1810.0	65.5	29.0	20.86	680.7	186.0	696.1
1986 Mazda 323	94.5	55.0	56.0	55.5	2030.0	61.6	36.3	20.76	1029.7	239.1	1037.4
1986 Hyundai Excel	93.8	55.0	52.8	53.5	2040.0	61.4	36.2	21.25	1020.6	231.4	1062.3
1987 Pontiac LeMans	99.2	55.0	55.4	54.7	2040.0	60.4	39.3	20.50	1037.4	247.8	1046.1
1987 Nissan Sentra	95.7	56.3	56.3	54.3	2110.0	62.1	36.3	20.92	1081.7	254.3	1082.2
1987 Nissan Sentra	95.7	56.3	56.3	54.3	2140.0	61.3	37.0	20.59	1082.5	258.5	1082.2
1987 Toyota Corolla FX	95.7	56.1	55.3	53.0	2196.0	61.3	37.0	21.38	1099.8	240.3	1181.1
1985 Ford Escort	94.2	54.7	56.0	53.3	2220.0	65.3	32.7	20.10	1137.3	243.1	1144.2
1987 Subaru XT Coupe	96.5	55.5	56.5	50.5	2283.0	61.7	37.0	21.30	1230.0	250.3	1242.1
1986 Ford Escort (XR31)	94.5	56.0	56.7	53.1	2290.0	59.8	38.0	19.81	1104.0	249.7	1125.2
1986 Toyota MR2	91.3	56.7	56.7	48.5	2362.0	43.0	52.0	20.01	902.4	231.2	1057.4
1983 Toyota Camry	102.4	57.7	55.9	54.9	2462.0	60.0	41.0	21.63	1419.2	318.1	1508.4
1985 Pontiac Grand Am	103.7	56.0	55.3	53.2	2570.0	66.5	34.7	20.99	1382.0	297.5	1480.8
1987 Plymouth Sundance	97.0	57.6	57.2	52.7	2580.0	61.9	37.0	21.04	1362.5	348.4	1381.9
1987 Fort Tempo	99.7	55.4	57.3	54.8	2650.0	62.6	37.2	21.49	1539.4	351.2	1548.1
1987 Chrysler LeBaron	100.4	57.6	57.6	52.1	2690.0	62.2	38.0	21.67	1533.9	347.5	1563.1
1987 Chrysler Reliant	100.5	57.5	57.0	53.2	2690.0	62.2	38.0	21.37	1680.2	378.5	1600.7
1985 Chrysler LeBaron	103.3	57.0	56.5	54.9	2730.0	62.2	39.0	21.18	1654.3	367.9	1808.2
1986 BMW 3251	101.2	55.2	54.9	54.0	2760.0	53.3	47.3	20.99	1490.0	282.4	1501.1
1985 Pontiac Fiero	93.5	58.0	59.0	46.5	2770.0	41.5	54.7	19.96	1131.8	277.7	1198.9
1988 Ford Mustang GL	100.5	57.3	56.9	54.0	2770.0	56.3	43.9	20.82	1592.3	302.4	1648.1
1986 Buick Skylark	103.0	55.6	55.2	52.5	2783.0	64.0	37.1	21.37	1505.5	319.2	1542.2
1985 Oldsmobile Ciera	104.9	58.7	57.0	54.1	2820.0	63.8	38.0	21.07	1749.1	355.8	1783.1
1985 Oldsmobile Ciera	104.9	56.6	55.8	54.9	2860.0	54.5	47.7	21.83	1554.8	332.7	1565.1
1987 Mercedes 190	104.9	55.9	55.1	54.8	2870.0	54.5	47.7	21.95	1572.6	328.5	1583.0
1987 Mercedes 190	104.9	56.6	55.8	54.6	2870.0	54.3	47.9	22.02	1543.0	328.7	1552.0
1987 Mercedes 190	104.9	56.3	55.1	54.8	2880.0	54.2	48.0	21.65	1545.8	322.7	1586.8
1982 Toyota Cressida	104.1	54.7	54.5	54.3	2890.0	54.9	47.0	21.30	1742.2	269.9	1748.8
1987 Toyota Camry	102.3	58.3	57.0	53.0	2909.0	60.9	40.0	21.60	1847.1	342.4	1780.8
1986 Nissan Maxima	100.4	57.5	57.5	54.7	3110.0	65.3	34.8	21.29	1826.2	280.4	1810.8
1988 Ford Taurus	105.9	61.5	60.3	56.5	3130.0	64.6	37.5	22.17	1890.9	424.6	1990.0
1988 Nissan Maxima	100.4	57.5	57.5	54.7	3170.0	64.3	35.8	21.53	1869.1	387.0	1823.6
1988 Ford Mustang GT	100.8	57.8	57.5	53.9	3240.0	57.4	42.9	20.96	1902.0	335.5	1940.9
1986 Buick Electra	110.8	60.3	59.8	54.3	3322.0	63.0	41.0	21.48	2206.0	431.4	2276.3
1983 Chevrolet Caprice	115.5	61.5	60.8	57.5	3414.0	55.8	51.0	23.60	2501.3	556.0	1812.1
1984 Mercury Marquis	113.9	62.6	62.1	56.9	3660.0	57.9	48.0	21.61	2898.0	542.0	1893.7
1987 Ford Thunderbird	103.7	59.0	58.5	54.0	.9	56.3	45.3	22.05	2327.1	470.6	1470.5
1980 Oldsmobile 98	119.0	59.8	61.5	57.5	4164.0	56.3	52.0	23.09	3580.5	734.3	3692.2

Table D-5 Comparison of Calculated Vehicle Inertias for the Mazda Race Car with Those Obtained from the Estimator of Reference D.6.1

kg-m^2

	Calculated		Estimated per Reference D.6.1.
	Min	Max	
Yaw Inertia	914	1097	1089
Pitch Inertia	811	973	1089
Roll Inertia	235	282	247

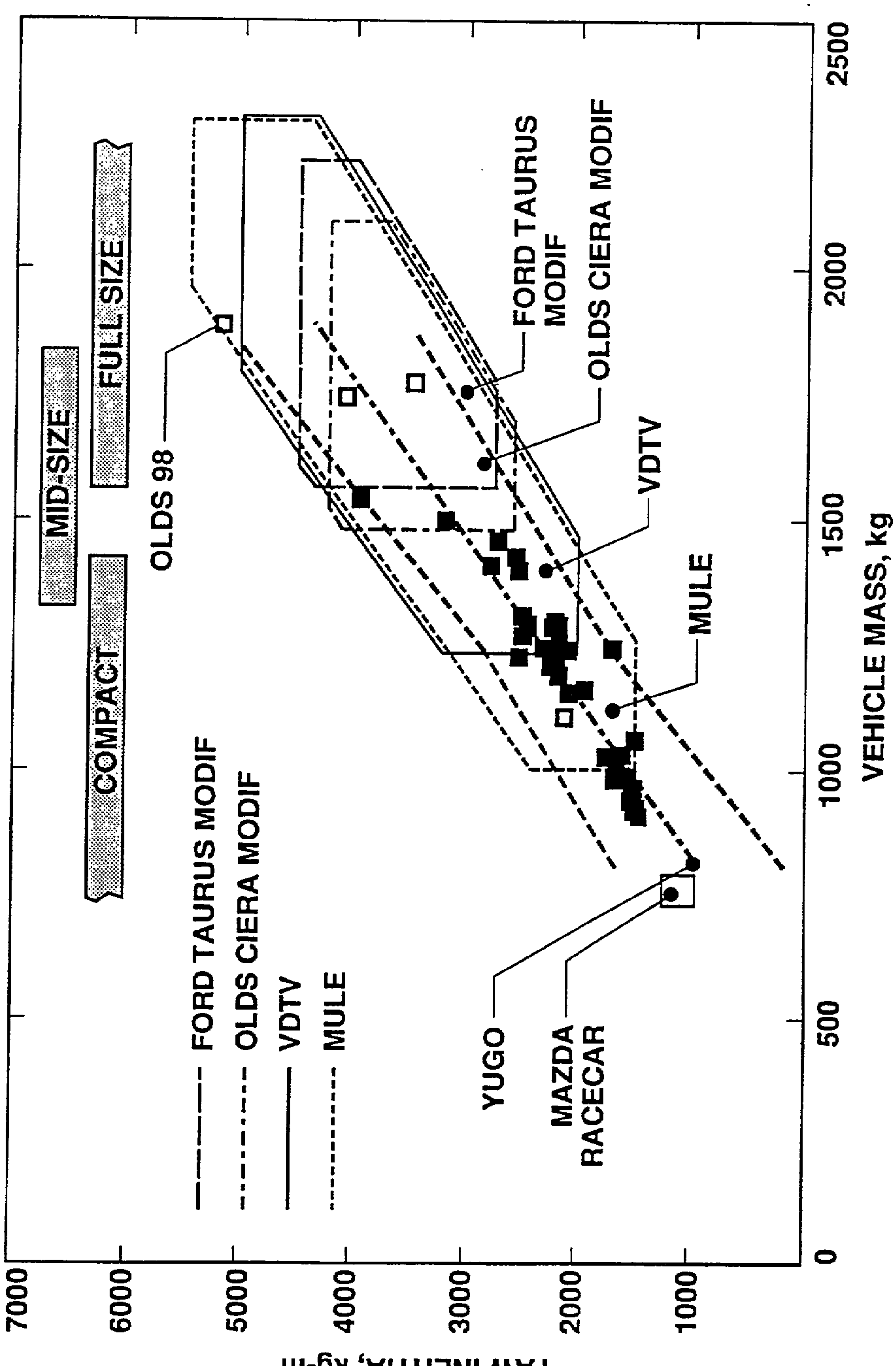


Figure D-1 Yaw Inertia vs. Weight

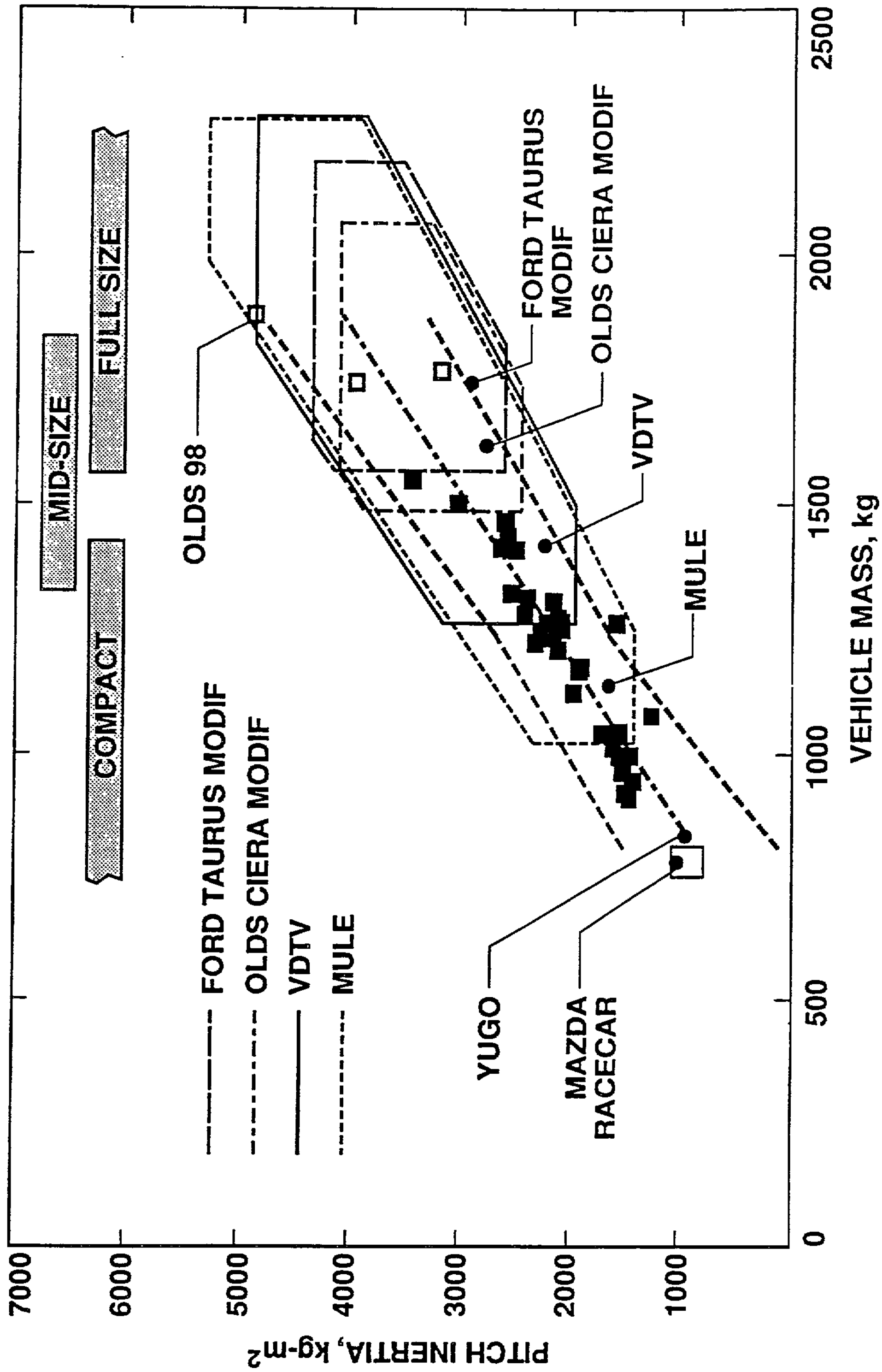


Figure D-2 Pitch Inertia vs. Weight

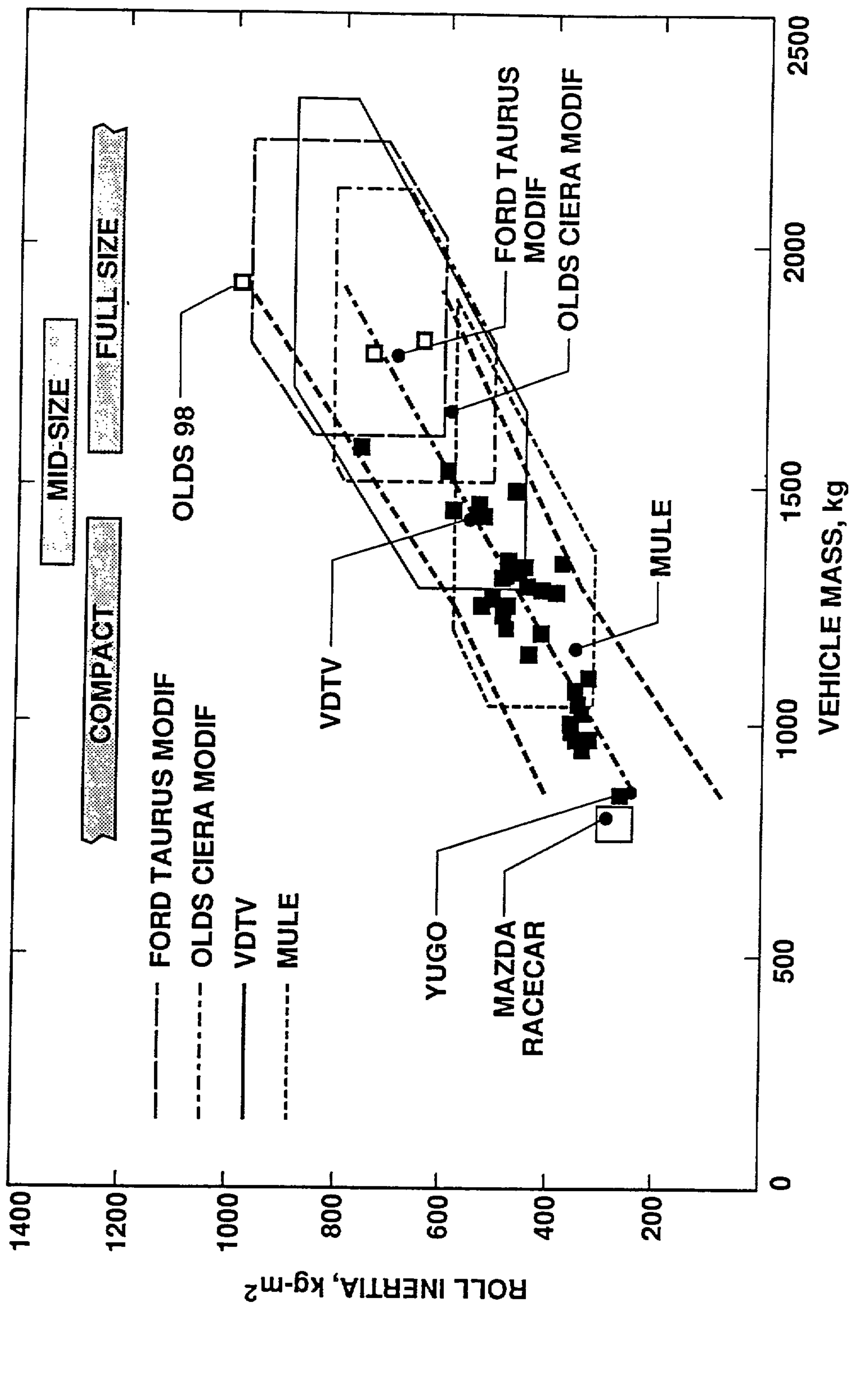


Figure D-3 Roll Inertia vs. Weight

D.2 CONTROL SUBSYSTEM

D.2.1 Suspension Subsystem

Both semi-active and fully active suspension systems are described in order to **support** different implementation options described in Volume II, Section 5.

D-2.1.1 Semi-active suspension system

A semi-active suspension (SAS) system is basically a computer-controlled variable damping shock absorber. With these systems, the driver can select between either “firm” or “automatic” ride control. In the “firm” mode, the SAS’s controller adjusts the shock absorber damping to provide a sporty suspension tuning. In the “automatic” mode, the controller adjusts the absorber damping to provide a soft ride during normal driving conditions. During hard cornering, braking, or acceleration, the damping is changed to firm to provide improved handling. To be effective, at least two but preferably three damping levels should be made available by the SAS system.

To distinguish between those conditions that require improved handling performance and those for which improved ride is desirable, various vehicle states must be measured. To estimate the levels of the vehicle lateral acceleration, and longitudinal deceleration and acceleration, a lateral accelerometer, brake hydraulic pressure sensor, and engine throttle position sensor are used, respectively. In one design approach, when the measured values of any of these variables exceed certain pre-selected thresholds, a control signal will switch the damping level of an electronically controlled shock absorber from “soft” to "firm,” and vice versa.

Other semi-active suspension design implementations are possible; the definite selection will depend on more detailed VDTV testing objectives which have yet to be developed.

D.2.1.2 Active anti-roll bar system

This is a system that will retain the conventional suspension spring and damper elements (the dampers might be replaced by the semi-active suspension system described in D.2.1. l), but will replace the anti-roll bars with active devices. One design of such an active anti-roll bas system is described in Reference D.4. With this active system, the front and rear roll stiffnesses of the vehicle can be actively controlled to generate different levels of vehicle’s roll attitude during different vehicle maneuvers. In this way, the vehicle’s handling characteristics can be altered, as well as driver’s motion cues.

D-2.1.3 Fully-active suspension system

A fully active suspension system can be used to actively control the vehicle attitudes (roll and pitch) during vehicle cornering and braking/acceleration. To actively control the vehicle attitude, the longitudinal and lateral accelerations of the vehicle are measured using accelerometers. The measured signals are then used to independently control four actuators at the four comers of the vehicle. For example, by increasing the pressures of the actuators at the outer wheels and decreasing the pressures of the actuators at the inner wheels, the steady-state roll attitude of the vehicle during cornering can be reduced. The transient dynamic of the vehicle roll/pitch motion can also be changed (improved) via control. This is achieved using the measured vehicle's roll and pitch rates in the control algorithm. In effect, the control algorithm can be designed to "emulate" vehicles with different front/rear roll stiffnesses and roll damping characteristics.

The architecture of a typical active suspension controller, showing the relation between the ride controller and the attitude controller is depicted in Fig. D-4. Additional sensors such as axle-mounted vertical accelerometers can also be used in the control algorithm. In effect, a suitably designed control algorithm such as that described in Reference 8.7 can emulate vehicles with different spring rates and damping characteristics.

The active suspension system must have a "fail-safe" feature: a "smooth" transition from the active to passive suspension control configuration, and vice versa. These transitions can be activated either by the driver or be done automatically. In the "automatic" mode, measured conditions of the vehicle and the actuation system are used to make a judgment on the system's health, and the active suspension system is shut down accordingly.

D.2.2 Steering Subsystem

D.2.2.1 Four-Wheel-Steering (4WS) System

With a 4WS system, the vehicle rear wheels can be steered in-phase with the front wheels to enhance the high-speed lateral stability of a vehicle. Rear wheels can also be steered out-of-phase to improve the maneuverability of the vehicle at low speed (e.g., at a parking lot), but this capability is of not interest here. Like a conventional two-wheel-steering vehicle, the steering wheel is controlled by the driver. The front steering angle, together with the forward speed of the vehicle are then measured, and fed to a control module. A rear steering angle command is then generated, and fed to a servo system, which steers the rear wheels accordingly.

4WS control algorithms that have been implemented are either open-loop or closed-loop (cf. Fig. D-5). A typical open-loop algorithm has a speed-dependent ratio between the rear and front steering angles: rear steering angle/front steering angle = K(U). Here, K is the steering ratio which is a function of the vehicle forward speed, U. Typically, that ratio is negative at parking lot speeds, zero at an intermediate speed, and positive at highway speeds. Closed-loop algorithms, such as that described in Reference 8.8 use the measured conditions of the vehicle (e.g., yaw rate) to effectively control the rear wheels under a variety of vehicle loading conditions.

The rear wheel servo actuation system can be either hydraulic or electric. Its bandwidth must be higher than driver steering input frequencies in accident avoidance maneuvers. The actuation system must also have a "fail-safe" feature: a "smooth" transition from the 4WS to 2WS control configuration, and vice versa. These transitions can be activated either by the driver or be done automatically. In the "automatic" mode, measured conditions of the vehicle and the actuation system are used to make a judgment on the system's health, and the 4WS system is shut down accordingly.

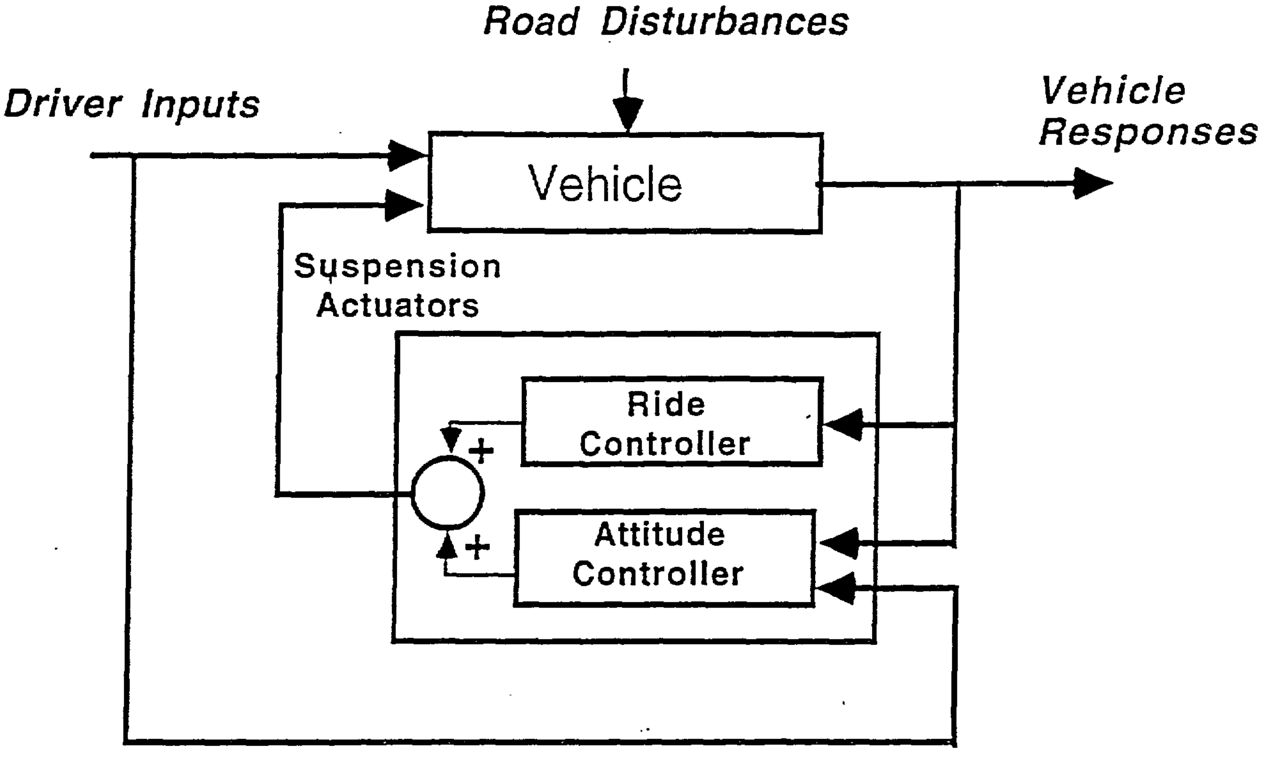
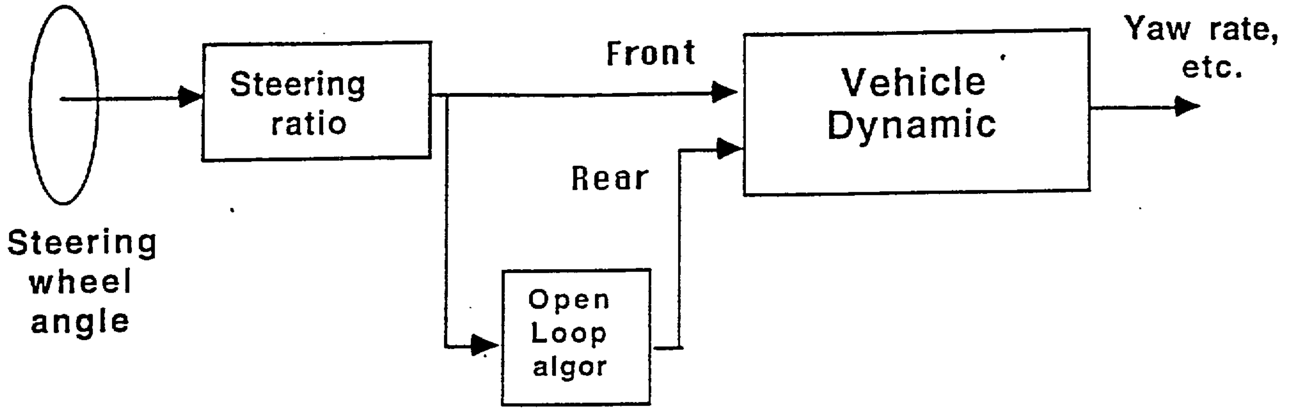
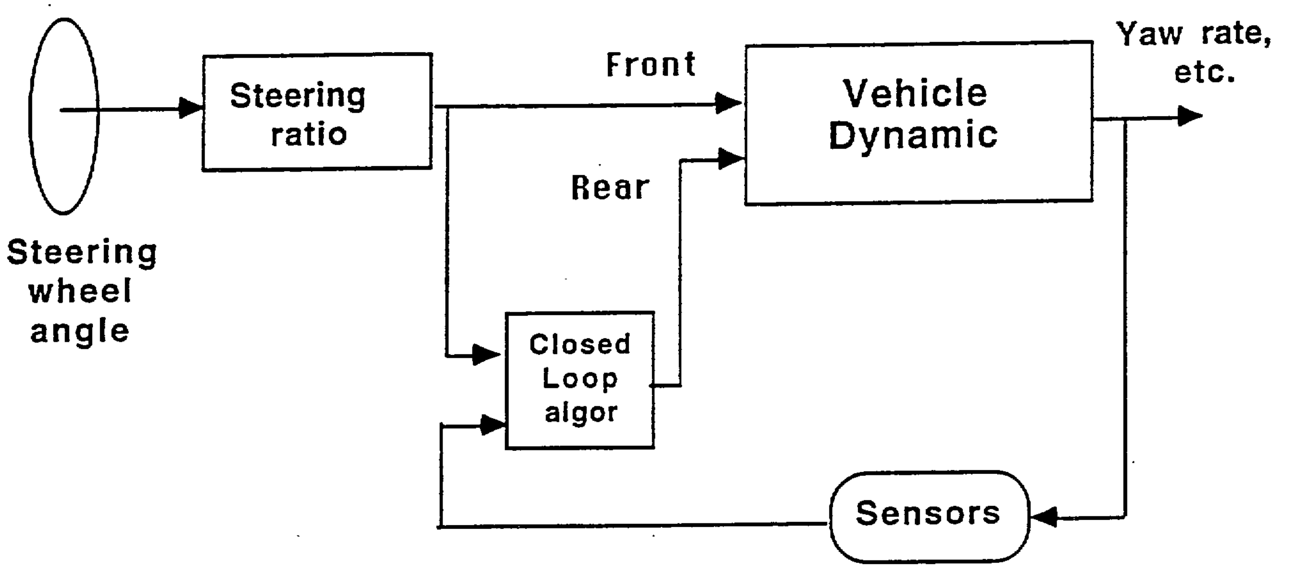


Figure D-4 Structure of Active Suspension Controller



Open-loop Algorithms



Closed-loop Algorithms

Figure D-5 Four-Wheel-Steering (4WS) Control Algorithms

D.2.2.2 Steer-By-Wire (SBW) System

The SBW capability can be implemented using a conceptual design illustrated in Figure D-6. In the SBW mode, a magnetic clutch is used to disengage the steering wheel from the vehicle's power steering system. The steering commands from the driver (steering angle and steering angle rate) are then measured. These measured driver steering commands are then used to control a front steering servo system. Simultaneously, the rear steering system is controlled by either the open-loop or closed-loop algorithm described above. That is, the SBW and 4WS systems can be operated simultaneously. Like the 4WS system, the SBW design must be "fail-safe." When commanded by the driver, the fast-acting magnetic clutch must re-engage the power steering system, and "return" the control of steering the front tires back to the driver.

A SBW capability allows the VDTV to do the following:

(1) Command augmentation system: augmentation of the driver commands with signals that reflect the actual vehicle conditions. See, e.g., Reference 8.8;
(2) Automated highway systems: replace the driver steering commands with commands received from, e.g., the leader of a 4-car platoon; and
(3) Automated lane control system: replace the driver steering commands with those derived from an on-board camera-based vision system. See, e.g., Reference 8.9.

D.2.2.3 Programmable Steering Feel (PSF) system

A PSF system is usually provided in conjunction with the SBW capability. The PSF system allows us to "inject into" a steering system a desirable steering torque profile (as functions of vehicle speed, steering angle, steering angle rate, etc.) against which a driver steers. Another servo torque system (cf. Figure D-6) must be used to implement this idea.

The measured steering commands and forward speed of the vehicle are first used to generate a desirable steering torque command. This command is then compared with the steering torque level actually experienced by the driver, as measured using a torque sensor. The difference between the desired and actual torques is the input to a fast-acting servo motor which then generates a torque proportional to that difference. This PSF system is "engaged/disengaged" together with the SBW system.

D.2.3 Traction and Braking Subsystems

D.2.3.1 Anti-lock Braking System (ABS)

An ABS is designed to prevent wheel lock on all wheels of a vehicle under a wide varieties of vehicle driving and road surface conditions. To this end, the forward speed of the vehicle, and the angular speeds (rpm) of all four wheels are measured. These data are then used by a controller module to generate commands to fast-acting electro-hydraulic actuators which modulate the braking torques on all wheels independently.

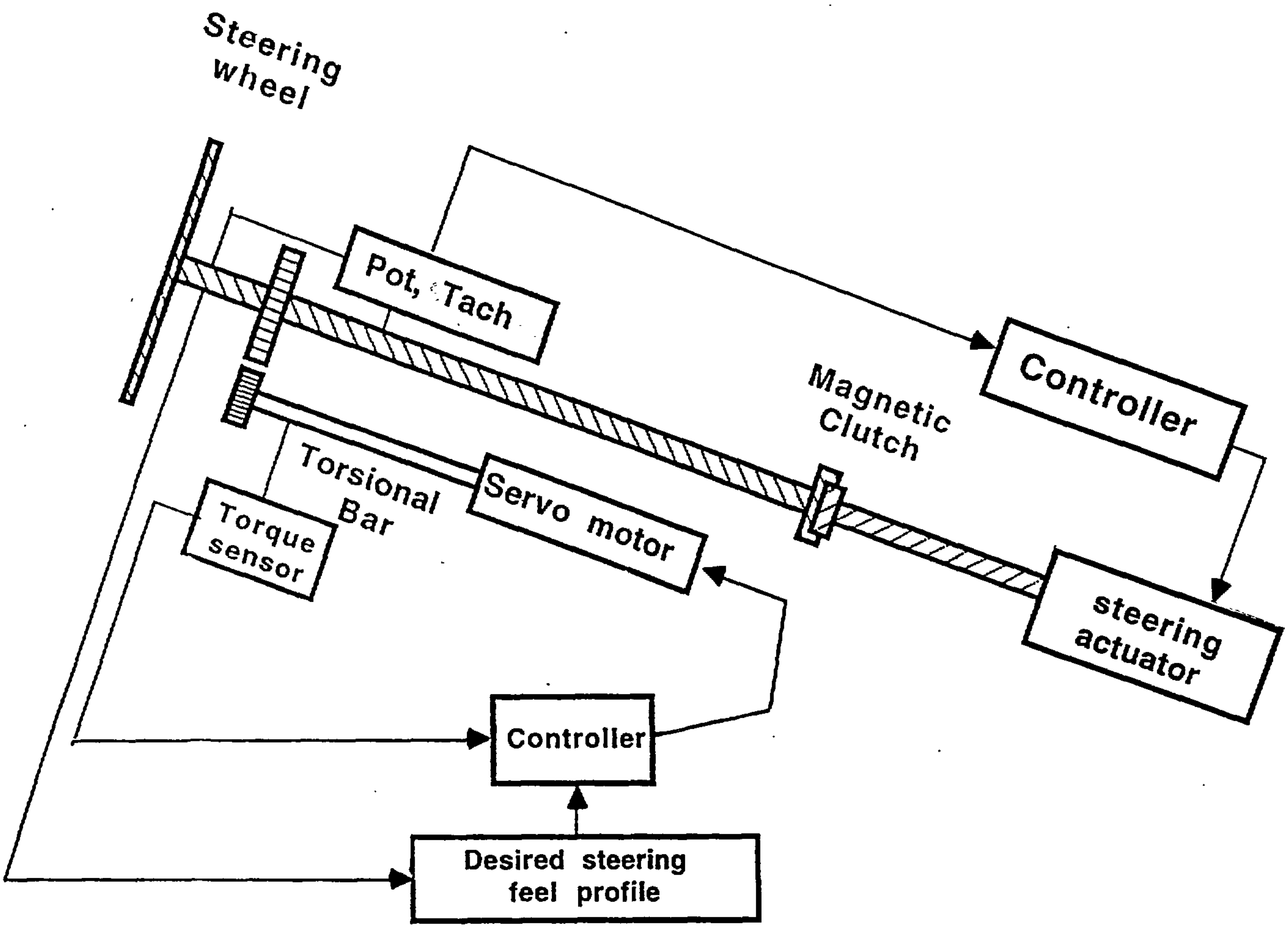


Figure D-6 A Design Concept for SBW and PSF

The braked wheels are subjected to a variety of external disturbances (including, e.g., road friction coefficient variation, dynamic wheel load variation, etc.). Regulating against these unpredictable disturbances is not a simple task, and typically a complex nonlinear control algorithm must be used (see, e.g., Reference D.6.8.) To achieve the shortest possible stopping distance, the control algorithm will regulate the longitudinal slip ratios at all wheels near their maxima. For braking-in-a-turn maneuvers, vehicle's controllability and stability are also of concern. By regulating the longitudinal slip ratios of all four wheels near different regions of the braking force-slip ratio curves, a compromise between stopping distance and vehicle lateral stability can be achieved.

The ABS's actuation system is usually a high bandwidth electro-hydraulic system. A typical system consists of a master cylinder, a pressure modulator, an accumulator, rear brake proportional valve(s), a hydraulic pump with piston accumulator and low/high pressure supply hose. The actuation system must also have a "fail-safe" feature: a partial or total "turn-off' of the ABS system, and the braking is "returned" to the conventional braking system. Simultaneously, the control module must blink a light (at the instrument panel) to notify the driver about the "failed" condition.

D.2.3.2 Brake-By-Wire (BBW) System

The BBW capability can be implemented using a conceptual design illustrated in Figure D-7. In this concept, the mechanical connection between the brake pedal (as controlled by the driver) and the brake cylinders can be disengaged via a solenoid valve. In the BBW mode, the driver braking command, as measured by a brake pedal force sensor, is used to control a DC motor actuator via a controller. The motor drives a ballscrew which in terms drives a piston into a brake cylinder. In this way, the brake cylinder pressure can be modulated. Additional sensors that measure the brake line pressure, and the wheel speed (rpm) are needed to complete this braking servo system. At the wheels, the brakes are identical to those used in conventional braking systems. If desired, all four wheels can be controlled independently.

A BBW capability allows us to do the following:

(1) Automated highway systems: replace the driver braking command with commands received from, e.g., the leader of a 4-car platoon, and
(2) Adaptive cruise control system: replace the driver braking commands with that derived from an on-board collision detection system.

The BBW design must be "fail-safe." When commanded by the driver, or when brake system anomalies are detected, "grounded" signal is sent to the DC motor, and the "normal" control mode is activated. The brake cylinders are then controlled directly via the master cylinders and the power boost system, as indicated in Fig.D-7.

The general idea behinds the implementation of a programmable brake feel (PBF) system is identical to that described for the PSF system (cf. Fig. D-6). It will not be repeated here.

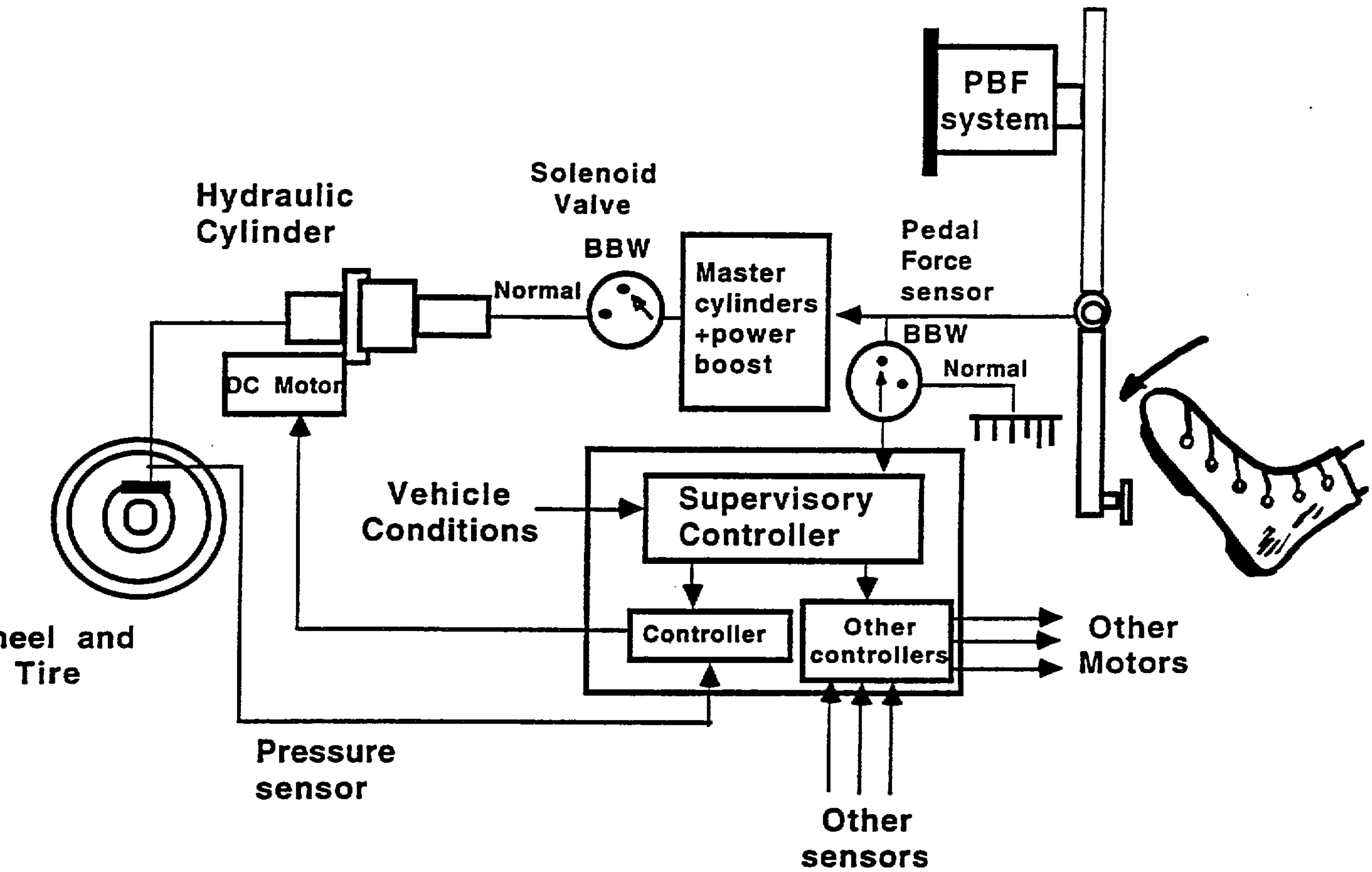


Figure D-7 A Design Concept for BBW and PBF

D.2.4 THROTTLE CONTROL SUBSYSTEM

The output torque of an engine is related to the throttle angle, spark advance, air-fuel (A/F) ratio, and exhaust gas recirculation (EGR). Throttle angle is considered the most influential control variable for powertrain control, and the other variables stated above are controlled separately for best fuel economy and exhaust emission control (engine control).

Typically, the throttle valve responds to the driver's accelerator command via a mechanical linkage. Drawbacks of such an arrangement include:

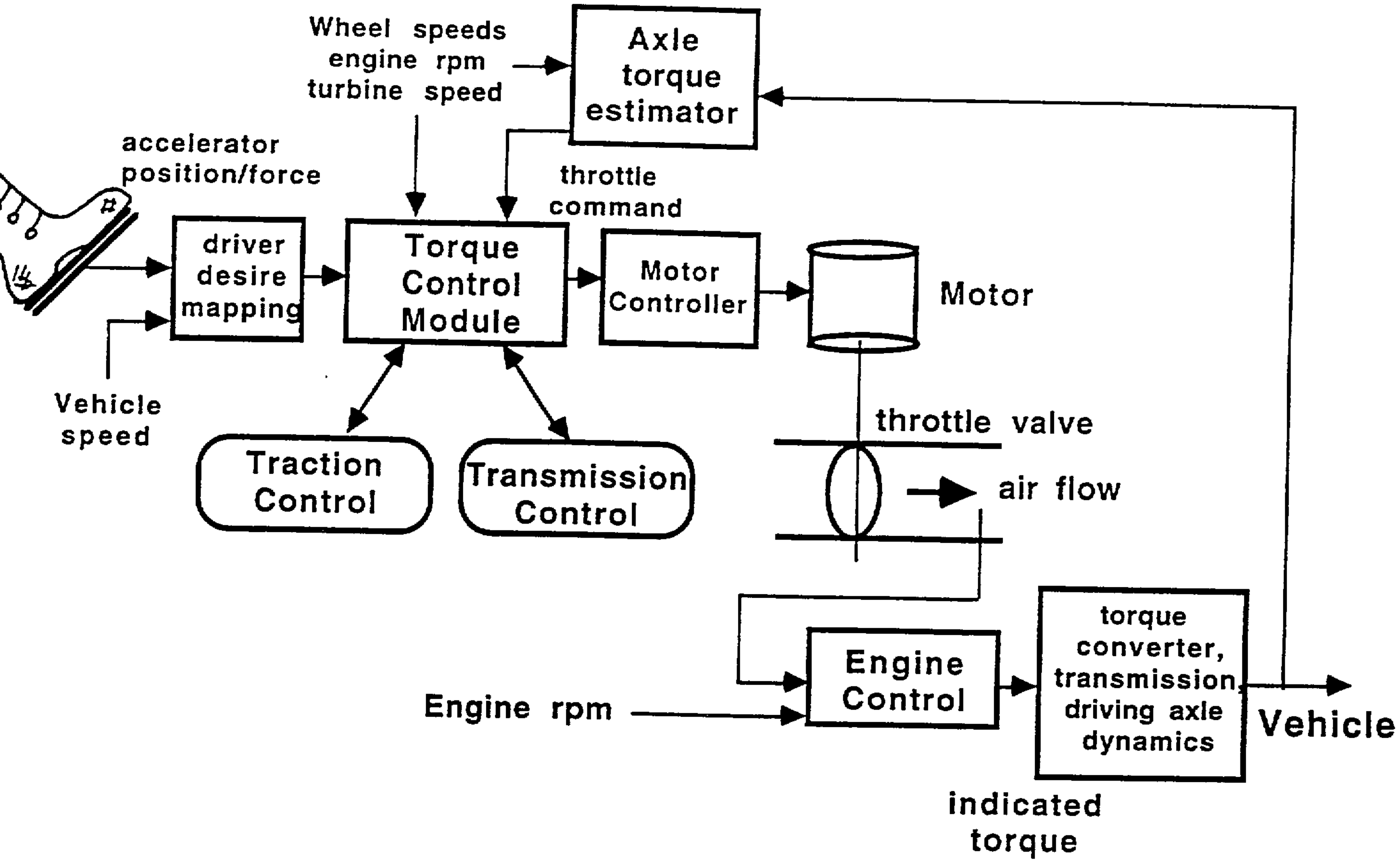
- the nonlinear relations between the engine indicated torque and the accelerator position, between the engine torque and the torque converter turbine torque, and between the turbine torque and the driving-axle torque, lead to undesirable "driveability."

- the throttle cannot response to commands other than that of the driver. Hence, it cannot support the AHS's platooning concept which might require the throttle to response to commands from the platoon leader.

A throttle-by-wire (TBW) system can overcome these drawbacks, and effects a better control of the vehicle's powertrain subsystem. A design concept of such a TBW system is depicted in Figure D-S.

In this TBW design concept, the driver command (either the accelerator position or pedal force) is electrically measured. That command is "interpreted" using the current vehicle's conditions (speed, acceleration, etc.), and translated into a driving-axle torque command. The torque control module then computes a throttle valve position command using that driving-axle torque command together with the measured engine rpm and turbine speed. That throttle valve command is implemented using a electric servo control system. Changes in the valve position alter the engine indicated torque, leading to changes in the torque converter turbine torque, transmission torque, and finally the driving-axle torque. The driving-axle torque can either be sensed using a torque sensor or estimated using the measured engine rpm, turbine speed, and the driven wheel speeds. The estimated driving-axle torque is then compared with the commanded torque level, and the control "loop" is closed. The same driving-axle torque controlled system cam also be used for traction control, adaptive cruise control, and other. See Fig. D-8.

Similar to the SBW and BBW systems described in prior subsections, the TBW system must include a fail-safe feature that can "re-establish" the mechanical linkage between the accelerator and the throttle. If a fault is detected, or when commanded by the driver, the electrical actuation of the throttle is shut down, and the throttle is controlled via a bowden cable. The necessary de-coupling of the motor and cable coupling can be achieved by a combination of overrun and de-coupling springs. The details of these fail-safe features are not given here.



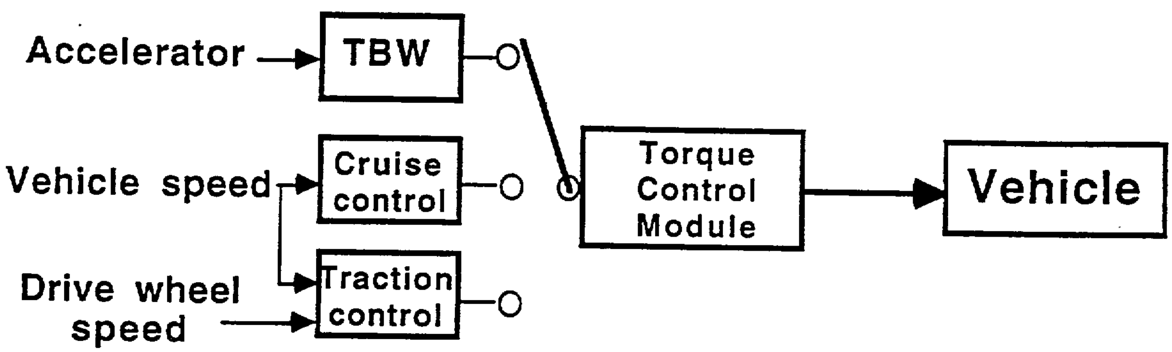


Figure D-8 A Design Concept for TBW System

D.3 MEASUREMENT SYSTEM

D.3.1 Subsystem Overview.

The VDTV Measurement Subsystem will consist of five major components: 1) power supply; 2) sensor and actuator subsystem; 3) data acquisition platform; 4) controller; 5) data storage/transmission subsystem. The block diagram of the subsystem is shown in Fig. D-9.

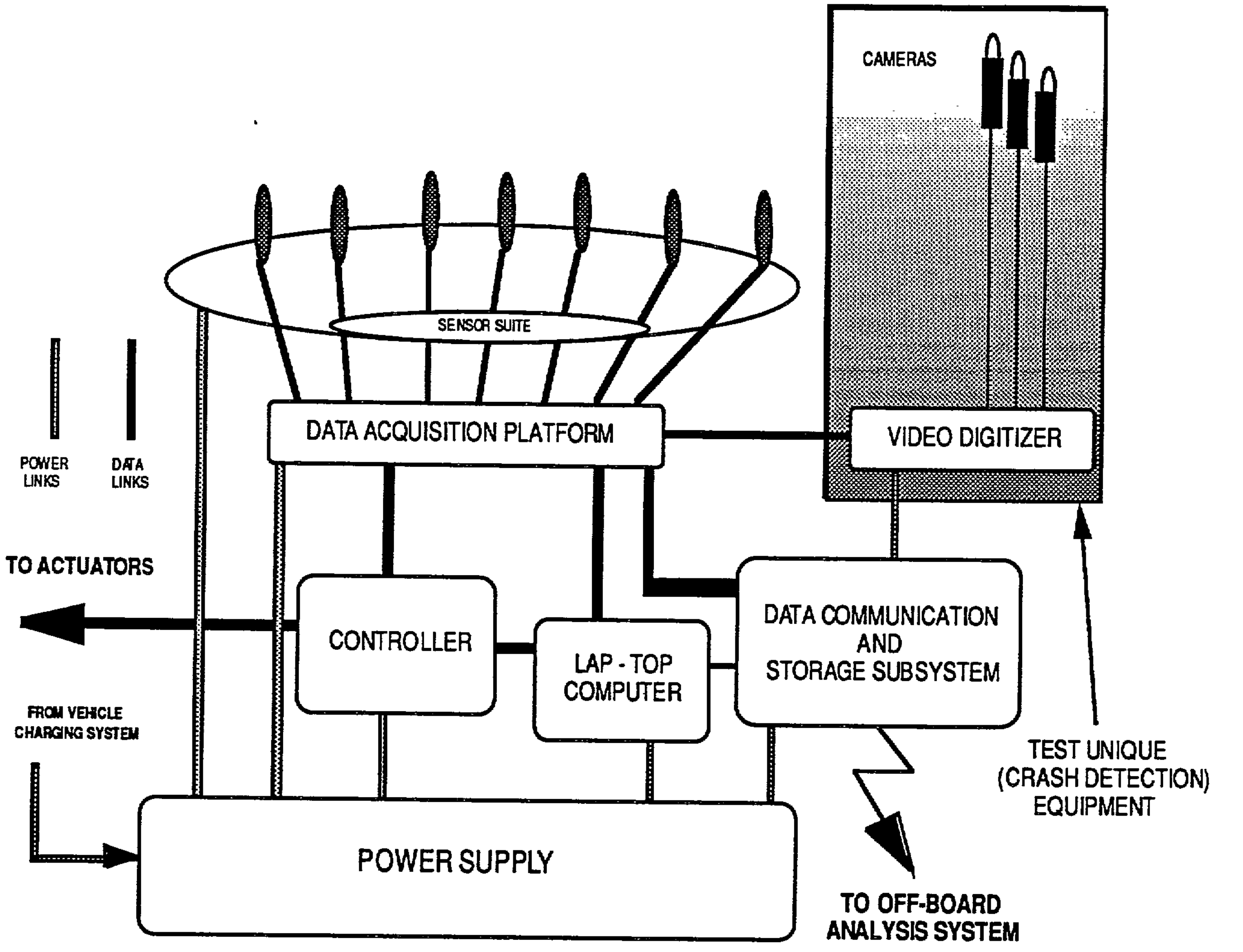


Figure D-9 Block Diagram of Conceptual Design of the Proposed Measurement Subsystem for VDTV

D.3.2 Power Supply

Power requirements. The power supply must provide sufficient and clean power (± 5v dc and ± 12v dc) for the VDTV Measurement Subsystem. It must provide power for volatile memory independently of the vehicle's electrical system, and be chargeable from the vehicle's alternator/battery system.

Design. There will be three main components to the power supply for the VDTV Measurement Subsystem: electronic isolation from the vehicle electrical system, battery, and switching precision power supply.

Isolation. An electronic isolation system provides total separation from the vehicle power system when the vehicle is powered down. This prevents the VDTV Measurement Subsystem from draining the vehicle's battery during power-down, which would preclude the user from starting the vehicle. This electronic isolation component also prevents fluctuations in the vehicle charging/electrical system from entering the VDTV Measurement Subsystem power system, when coupled with the 12-volt battery.

Battery. A 12-volt battery serves two purposes in the VDTV Measurement Subsystem power system. First, it serves a power-smoothing function, absorbing any ripples and spikes which occur as a result of irregularities in the vehicle charging system, and it compensates for lowered voltages which occur, for example, when the vehicle sits in traffic with the air conditioner going in summer heat. The battery also provides power required for volatile memory preservation during power-down of the system.

Switching power supply. The precision 12-volt dc switching power supply will provide the needed voltage for the various components in the VDTV Measurement Subsystem. The required switching power supply should provide the necessary flexibility for power needed by the VDTV Measurement Subsystem. It also should be expendable. If necessary, several power supply units should be used in parallel or cascaded.

D.3.3 Sensor suite

Three general areas were assessed: the driver, the vehicle, and the external environment. Generally, sensor technology for vehicle assessment is quite adequate, whereas that for physiological measures of the driver is clearly not. The modular design of the VDTV Measurement Subsystem should permit upgrading of various components as technology improves the capabilities of those components.

Vehicle parameters. Discussions with the automobile manufacturers have revealed that each manufacturer has its own proprietary data structure and data transmission system. Efforts are under way to develop an industry standard data structure and bus system, but any success is several years away. Vehicle parameters sensors include ones necessary to establish the overall orientation, positioning, and performance of the vehicle. Vehicle orientation refers to positioning and accelerations in roll, pitch, and yaw of the vehicle, as well as linear acceleration (forward and lateral) and braking. Recent technology has created a new family of solid-state gyroscopes and accelerometers which have no moving parts.

Headway/Tailway monitoring. At present, there appear to be two ways of gathering information on headway and tailway: video information from forward- and rearward-looking cameras, and range sensors such as ultrasonic, laser, or microwave (radar).

Lane tracking. A capability of lane tracking and detecting lane change presents one of the major advantages of using VDTV for AHS. Existing lane tracking systems use video cameras or radar to record the progress of the vehicle. The typical lane tracking video system uses a specialized digital camera (1X256 pixels CCD), whose output can be directly processed by computer at frame rate (30 Hz, the rate for "real-time" image processing).

Distance and Time. Distance and time are necessary for a variety of functions in the VDTV Measurement Subsystem. They provide the mechanisms for such functions as time-stamping the data acquired, and for locating critical incidents during the recording period, as well as for other derived data that might be required. Distance refers to the linear distance the vehicle travels. These data should be acquired directly from the odometer using a takeoff gear, or from the onboard computer's data stream. The time data should be obtained from the system clock in the computer onboard the vehicle or from a separate time code generator (IRIG B or GPS)

Engine and Drive Train. Information on engine/drive train is primarily centered on engine revolutions per minute and transmission gear selected. Computer-based engine control units, presently installed on vehicles for efficiency, provide a variety of measures. These data can be directly sent into a digital port on the data acquisition platform.

Suspension. Sensors used for suspension control and monitoring should be hardened, since the suspension parts are exposed to all types of weather and road contamination. Also they should be capable of both sensitive measurements for small and rapid changes and of sensing the full suspension travel. Thus, the ruggedness and sensitivity range become important for these sensors. Three types of sensors have been identified as potentially useful for these measurements: Linear position cable extension transducers (string pots), gyro chips, and silicon accelerometers.

Wheel rotation. Wheel rotation data are available from either of two sources, the standard ABS system, or a system based on Hall effect sensors.

Driver parameters. They provide measures of driver alertness, responsivity, and tension.

Steering. Sensing of steering activity can be accomplished by two different methods. Absolute or relative encoders can be placed at the steering wheel or a rotary encoder is placed somewhere in the steering system. For example, two string pots were used at the NHTSA test track in Ohio-one was wrapped around the steering column, and the other was attached between the pitman arm and the frame.

Accelerator/throttle. A string pot should be attached to the accelerator.

Brake pedal. Two sensor types are appropriate for measuring a brake pressure. One is a strain gage applied directly to the brake pedal. A second method is to insert a pressure gage in the brake hydraulic line.

Equipment status parameters. A variety of possible equipment status parameters are important for a human factor research. Among these are seat belts, turn signals, windows, radio/tape system, etc. Sensors to monitor these parameters are from the same set described above; e.g., contact switches, strain gages, etc.

D. 3.4 Data Acquisition Platform

The data acquisition platform will consist of boards, cables, and signal processing equipment necessary to acquire signals from the various sensors installed around the vehicle. An average automobile is electronically very noisy, with numerous sources of both radio frequency and electromagnetic (RFI and EMI) interference. These kinds of interference must be accounted for in the design of the instrumentation system. All signals should be converted from analog (as they typically come out from the sensor) to digital (as processed and stored) format. A digital signal is much more resistant to RFI and EMI than an analog signal. Thus, performing the A/D conversion at the sensor is the best solution from the interference point of view. Using existing lines (such as power bus) to link together the different elements of the VDTV Measurement Subsystem is convenient and inexpensive, and provides flexibility. Sensors, actuators, controls, displays, and associated equipment generally require electrical power for normal operation. When a sensor or effector is installed and connected to the power bus, it is also connected to the communication medium and, in turn, the data acquisition and control network system. When a device is added to the network, its power connection becomes the pathway by which it communicates with the rest of the networked system. This eliminates the need for dedicated wiring and greatly reduces the cost and complexity of the system installation.

One approach uses spread spectrum signaling which enhances the desired signal while suppressing the effects of power line noise. The spread spectrum transmission distributes the signal over a wide bandwidth for optimum performance against electrical noise. Packets of data are broadcast containing sending/receiving addresses, the data and/or control, and error correction information. Thus, the A/D conversion and signal conditioning should be done at the sensor ("smart" sensor) or in several distributed processing "centers" within the vehicle. This last option requires the placement of A/D conversion and signal conditioning hardware at several locations in the vehicle, such as under the hood, within the passenger compartment, and in the trunk.

Analysis of top-level requirements for the VDTV Measurement Subsystem shows that the Data Acquisition Platform should be

- flexible in terms of accepting a variety of different kinds of signals
- able to do signal processing and A/D conversion
- able to accommodate distributed signal processing system
- provided with a complete and flexible software
- easy to interface and connected to radio link/satellite communication system
- able to provide enough capacity of onboard data storage to backup
- able to be extended to accommodate needed number of sensors
- fast enough to provide needed sampling rate for all measurements

D.3.5 Controller

In the case where the VDTV is equipped with fully active suspension, closed loop, four-wheel steering, and fully automated ABS, some of the required measurements could be shared by the Measurement Subsystem. The following is a list of measurements needed to support various control algorithms:

Parameter	Quantity/Vehicle
Longitudinal Acceleration	1
Lateral Acceleration	1
Vertical Acceleration	1
Yaw Rate	1
Roll Rate	1
Pitch Rate	1
Vehicle Speed	1
Steering Wheel Angle	2
Steering Wheel Rate	1
Engine RPM	1
Front/Rear Tire Positions	2
Wheel Rotation (RPM)	4
Rattle Space Sensor	4
Suspension Load	4
Hub Acceleration	4
Brake Pedal Force Sensor	1
Accelerator Pedal Force Sensor	1
Brake Hydraulic Pressure Sensors	4
Turbine Speed Sensor	1
ABS Health Monitoring:	
Pump Pressure	1
Accumulator Pressure	1
Reservoir Fluid **Level**	1
Boost Pressure (Differential)	1
Pressure (Differential)	1
4WD Steering Subsystem Monitoring:	
Pump Pressure	1
Accumulator Pressure	1
Reservoir Fluid Level	1

The cycle-time of these subsystems is about 1- 4 msec. During this time, the system samples 19 - 40 sensor inputs, computes new control data, and delivers a drive signal to each output actuator. The processor (or set of communicating processors) should have enough computing power, memory, and speed to perform complex control law algorithms. It should be provided with a compiler for common programming language (like C) and use only a standard power supply.

It also should have a standard interface (e.g., RS-232C or SCSI) for control parameters modification (via a laptop PC for example) and to interface with other controllers.

Recommendations. Specific recommendations are difficult to make, especially in the area of sensors to be applied to the vehicle and driver. However, based on a comparison of VDTV requirements and Data Acquisition System for Crash Avoidance Research (DASCAR) capabilities, it was concluded that this system would be a good candidate for the VDTV Measurement Subsystem. Other available systems would also be assessed during an implementation of VDTV.

A good candidate for controller might be Texas Instrument DSP family TMS320C, which consists of five fully compatible (in hardware and software) microprocessors.

D.3.6 Data storage and communication system

The data storage and communications capabilities should include multiple ways of handling the data generated by the VDTV Measurement Subsystem. To provide a backup capacity in case of radio link failure, or in case of signal corruption during transmission it should have an onboard data storage. Determination of specific transmission frequencies will be made late and any requirements to use government-only communications bands should be met.

D.4 OPERATIONAL SAFETY SYSTEM

D.4.1 Operational Safety System Description

The operational safety system provides control of the three drive-by-wire subsystems from either the VDTV control computer or normal mechanical modes. The former provides vehicle operation via electronically driven actuators. The latter provides vehicle operation with the same reliability as conventional production vehicles.

A key requirement for the operational safety subsystem is the transition from automatic to manual operation. This transition may occur during a transient maneuver near limits of vehicle operation. The transition thus must be made without sudden transients which could cause vehicle motions which would exacerbate a dangerous condition.

D.4.2 Operational Safety System Actuation

The safety system should be actuated by two different means:

1. A manually-actuated panic button located for easy access to the driver and observer. When depressed, this large red button would return the three drive-by-wire subsystems to the manual mode.

2. A signal from the control computer, generated internally by programs which detected operation outside the normal performance envelope, which would return control to the manual mode prior to a failure in the control algorithm.

D.4.3 Operational Safety System Design

This system should go through a formal failure modes and criticality analysis in the design. A formal review with experienced personnel should review this analysis before any detailed design of the drive-by-wire subsystems is permitted to start.

D.5 POTENTIAL DYNAMIC RANGE SIMULATION PROBLEM

The VDTV's desired simulation range varies from a small economy car to a large sedan as shown in Figure 4-6, repeated here.

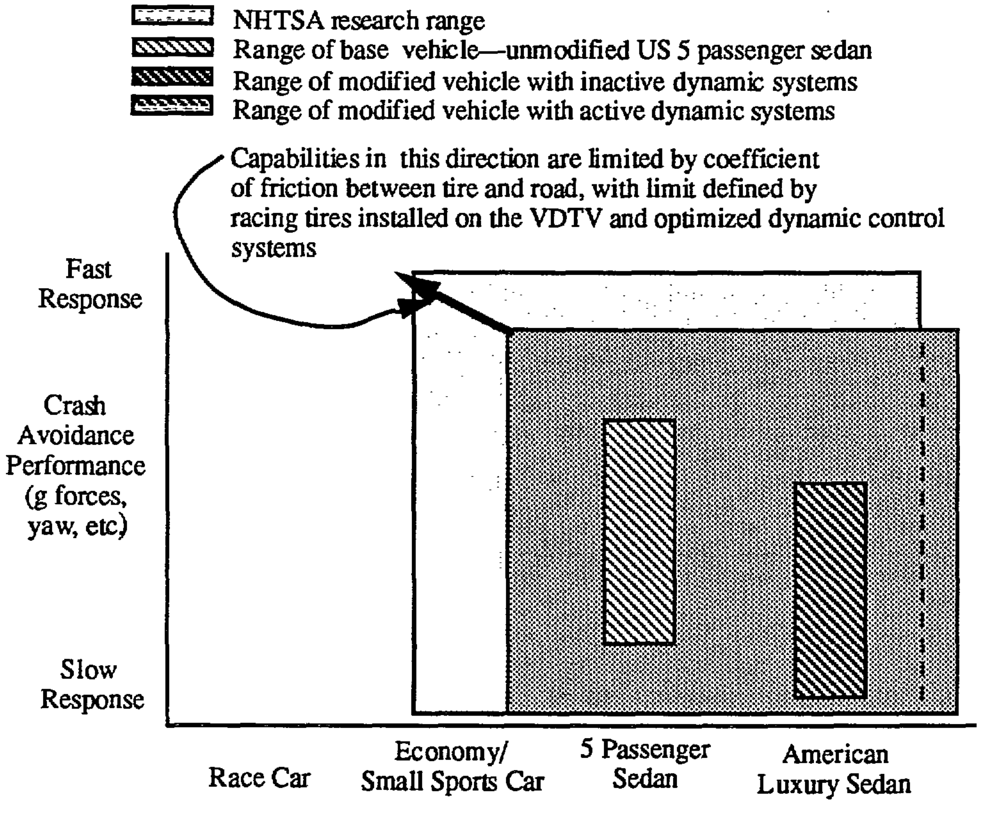


Figure 4-6 VDTV Emulation Range

The question of how far dynamic subsystems can move the VDTV's emulation range toward the upper left corner of NHTSA's desired research range is addressed here. Three factors are dominant in attaining this research range in a single vehicle:

1. The weight and inertia of the vehicle with all dynamic subsystems inoperative.
2. Tire and suspension characteristics.
3. Performance of the dynamic subsystems.

These factors are described below.

D.5.1 Weight and inertia

The unmodified vehicle will weigh about 1500 kg as shown in Appendix D1. This weight is typical of US four door, five passenger sedans. Competitive factors (fuel economy, acceleration performance) drive manufacturers toward minimum weight, so the 1500 kg weight represents an economically attainable value which is unlikely to be significantly lowered in the near future. The dynamic subsystems will add about 350 kg. An added weight of 350 kg to 400 kg was estimated by JPL; Lotus Engineering stated that 350 kg was a realistic value for the added weight. This added weight is largely attributable to hydraulic components (pumps, actuators, valves, tubing, etc.)

needed to provide the variable dynamic performance. The base vehicle will thus weigh about 1850 kg, the same as a large US sedan. With all dynamic subsystems inactive, its dynamic performance will thus be that of this class of vehicle.

D.5.2 Tire and Suspension Characteristics

Tire and suspension characteristics specifically intended for dynamic performance can increase this performance of a standard vehicle. However, a passenger car is finely tuned for optimum ride and interior noise, so this increase will be done at the expense of ride and noise.

For the purpose of crash avoidance research, the three primary dynamic performance parameters were estimated to be longitudinal deceleration, lateral acceleration, and yaw velocity. In addition, longitudinal acceleration must be maintained to at least the level of the base vehicle.

These parameters are limited by tire/road adhesion, which ultimately governs dynamic vehicle performance. Road test data published by a nation-wide auto magazine, with lateral acceleration on a skid pad as an indication of the ultimate tire/road adhesion, gives an objective measure of potential improvement for two different classes of vehicles:

Table D-6 Lateral Acceleration of Vehicle Classes

VEHICLE CLASS	LATERAL G
Standard 5 passenger sedan	.78 - .82
Exotic sports car	.92 - .98
Potential improvement	~0.15

This potential improvement is the result of the best available street tires, excellent suspension designed for handling with sacrifices to ride characteristics, low CG, and good front/rear weight distribution.

Improvements for a standard passenger sedan-Better tires can easily be added. However, tire size places practical limits on available tires; large tires will not be able to fully turn within the confines of the body structure. Racing slicks, whose adhesion will be in the range of 1.0 g, are thus not candidates for a modified passenger sedan. Suspension design can be somewhat improved if the cost of a new design (including development, safety analysis, testing, etc.) is incurred.

Decreases-Compliance of vibration isolation bushings may limit dynamic performance, particularly yaw rates. Practically, the CG, weight distribution, and inertia of a 5-passenger sedan cannot be improved and probably will be degraded by the added weight of the automated subsystems, which cannot be located specifically to improve these characteristics. Some of the subsystems would have to be located in the trunk to preserve the appearance of a 5-passenger vehicle, thus increasing the yaw inertia. The vertical location may be relatively high, thus increasing CG height and roll inertia.

D.5.2 Performance of Dynamic Subsystems

The addition of dynamic subsystems will provide much faster dynamic performance for crash avoidance research.

D.5.2.1 Yaw Response

For yaw response, this can be accomplished by:

1. Front Steering- At low g levels, dynamic front steering servos can provide a higher bandwidth than human response, providing some yaw response improvement. This servo must have the bandwidth and force to drive the tires to the desired excursion within short times.

2. Rear Steering-At low g levels, rear wheel steering can significantly improve yaw response. This servo must also have high bandwidth and force capabilities.

3. Active Suspension-Fully active suspension can control the vertical force on any tire, thus increasing the cornering force of this tire. In high g ranges, tires operate in non-linear regions so the total cornering force can be increased by optimizing vertical load distribution. However, this requires an active suspension with high bandwidth and force capability. Since wheel natural frequencies are typically about 10 to 12 Hz, the active suspension should have a higher natural frequency, at least 20 Hz, to maintain optimum vertical load. Active suspension systems typically available on production vehicles are about 3 Hz to 5 Hz for ride performance, so do not have the bandwidth necessary for this application.

Steering and active suspension subsystems thus have greater affects in different lateral g ranges as shown in Figure D- 10:

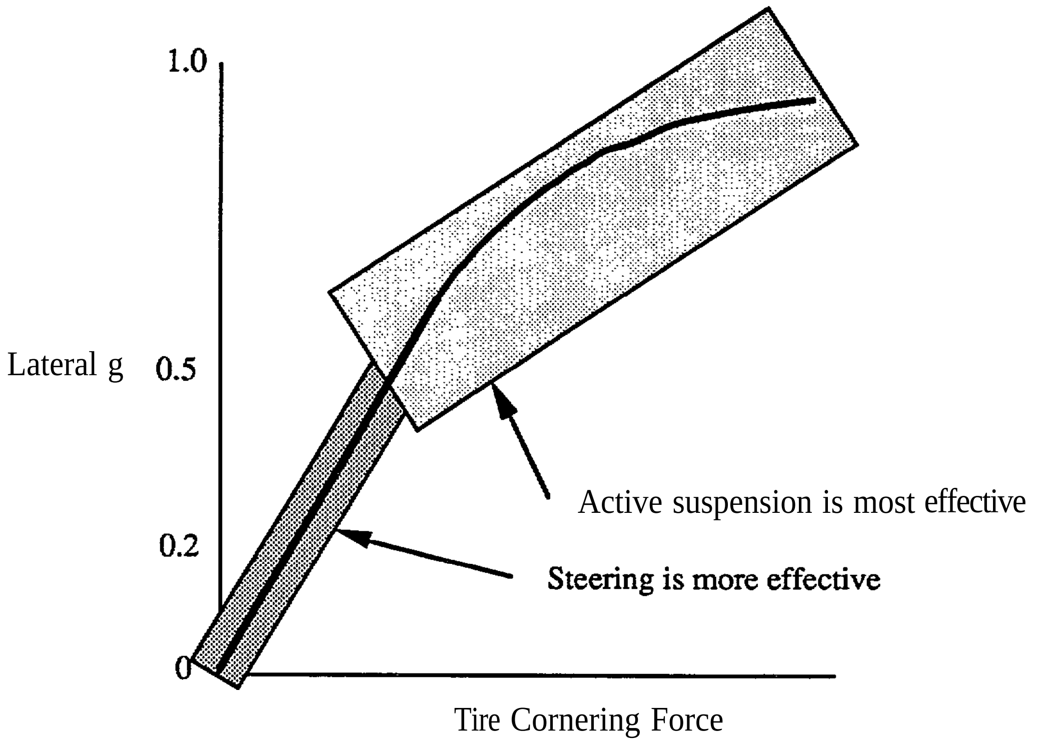


Figure D-10 Dynamic Subsystem Effective Range

D.5.2.2 Longitudinal and Lateral Acceleration

An ABS implementation which fully controls each wheel in a continuously variable mode, coupled with good tire and suspension, should provide deceleration to the 0.95 g range. The combination of a high bandwidth active suspension system, and good tires and suspension, should provide lateral accelerations in the 0.95 g range.

To attain the desired emulation range in a single modified production vehicle, high-performance dynamic systems will be necessary. There are complex interactions between these systems which must be analyzed to assure that a single VDTV, based on a modified production mid-sized four door sedan, can cover NHTSA's desired emulation range.

D.6 References

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D.6.2 Riede Jr., P.M., Leffert, R. L., and Cobb, W. A. "Typical Vehicle Parameters for Dynamic Studies Revised for the 1980's"' SAE paper No. 840561, 1984.

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D.6.8 Miller' R., "Bendix 4-Wheel Anti-lock Brake System for 4-Wheel Drive Vehicles," SAE 902224, 1990.

APPENDIX E

IMPLEMENTATION BACKUP

APPENDIX E IMPLEMENTATION BACKUP

E.l MAJOR IMPLEMENTATION ASSUMPTIONS

Four different approaches were developed to investigate performance, cost, and schedule tradeoffs. Appendix E contains additional information on these approaches. The implementation approaches considered three major assumptions:

1. NHTSA’s performance. cost, and schedule needs had to be met. This dominant assumption led to estimates of NHTSA’s research uses and schedule; NADS validation and AHS support were of particular schedule importance. A result was development of high-level functional requirements (FRs) shown in Table E-l. These FRs were used to assess each implementation, with results being shown in Appendix F for the four different implementation approaches.

2. A competitive procurement. Because some of the most capable firms in the VDTV technology area are likely to be outside the US, it was assumed that NHTSA would conduct a competitive world-wide procurement. Since potential bidders have significant differences in their dynamic subsystem technology, all approaches were structured to be compatible with such a competitive world-wide procurement.

3: A constraint of a US vehicle appearance for all implementations. This constraint was deemed necessary for NHTSA to show the vehicle throughout the Nation without negative publicity from the US auto industry or Congress. However, JPL assumed that components from foreign sources could be used if these components were not visible from the exterior or interior of the car. Examples are drive train and suspension components.

E.2 ADDITIONS TO LOTUS ENGINEERING COSTS

Costs of dynamic subsystems were provided by Lotus Engineering (LE) according to a statement of work. This was done after the mid-term review, so concentrated on the lowest cost commensurate with LE’s technology base. The LE costs included functions shown in Table E-l.

To provide the performance necessary to meet the functional requirements and needs of the major NHTSA users, additions to the LE costs shown in Table E-l are necessary, depending on the requirements for any particular VDTV. These costs with comments outlining their scope are shown in Table E-2. All costs include the installation labor, hardware and software interfaces, and checkout necessary to provide a completely operational system. These costs are for the first vehicle, with several items including mostly engineering labor which would not be required for subsequent vehicles. These costs are based on information received since the start of the study, and are believed to be adequate for budgetary estimates.

In addition, some judgment and policy decisions are needed when estimating VDTV costs from information in this report. As an example, two scenarios for the expandability of an initial VDTV are:

1. The dominant factor is lowest initial cost. The core subsystem is to be tailored to support only those dynamic subsystems that will be included in the initial VDTV. All front end system engineering activities will be minimal, with risks of problems accepted. There will be no costs for future expansion, such as a larger hydraulic pump or electrical power supply. All installation is to the minimum essential for the initial VDTV.

2. The initial VDTV will be designed for long-term use and retrofitting with additional subsystems as needs and funding are known. The front-end system engineering will be thorough and will include designs and documentation necessary for future retrofitting of additional dynamic subsystems. The hydraulic system will be sized and tested for the future full capability; this will apply to all other core subsystem elements. Installation of the core subsystem will include provision for installation of other future dynamic subsystems.

There are considerable differences, particularly initial cost, in these two approaches. Analysis of these differences must be included in the combination of dynamic subsystems to arrive at any particular initial configuration.

Table E-l Costs Included in Lotus Engineering Cost Estimates

FUNCTION	SCOPE AND COMMENTS
Specification	Activities to go from LE's existing experience to include these dynamic subsystems for application to one of the four candidate VDTVs for the four major NHTSA users. Take requirements, expected to be a the detailed functional level, and develop them into detailed requirements for each dynamic subsystem.
Design	Tailor the dynamic subsystems for the application.
Procurement	Purchase the parts.
Vehicle Conversion	. Convert a standard passenger car to the VDTV configuration. Make the necessary structural modifications. Add the core subsystem components, measurement' and control subsystems already developed by LE. Integrate the dynamic subsystems.
Development	Debug the system and verify its performance, including the interactions of the dynamic subsystems that are already known to LE, but not including mapping of all possible interactions.

Table E-2 Additional Costs to the Lotus Engineering Cost Estimate

ITEM	RATIONALEANDCOMMENTS	COST ($K)
DASCAR Human Factors Module	Measure driver characteristics (eyeball and head movements, etc.). Not included in LE. $8K procurement, 2 workmonths (WM) for interfacing to the LE system (hardware and software), and 1 WM checkout labor.	40
Traction Control	Hardware is included in the LE brake by wire and throttle control subsystems, but software is not. Objective is proportional control, not an on/off system which would degrade performance. 3 WM software, 2 WM development and final performance verification tests.	50
ABS	Also fully proportional control of each wheel, not an on/off system. Software for one subsystems so cost is lower than that of traction control. 2 WM.	20
Four Wheel Drive	Assumes that base vehicle has 4WD. Modify rear drive train to include rear wheel steer, including suspension design, fabricate new parts, install, then check under high-g conditions with varying steering angles. 10K parts, 5 WM design, fab, and installation, and 2 WM for thorough test	100
Crash Avoidance (CA) Interfaces	Purchase DASCAR modules for front and rear of the vehicle with capability to accept a wide variety of signals from unknown future CA devices. Modify vehicle to install these and provide mechanical interfaces to the future devices. Install and checkout the system with dummy inputs, including transmission of signals to the Control Subsystem. 16K parts, 1 WM vehicle mods, 1 WM installation, 2 WM checkout and performance test.	50
VDTV Operator software	Provide capability for operator to input simple commands to control the vehicle operation. Examples are set roll angle to 20 during a transient maneuver or emulate performance of a particular vehicle class. Involves complex interactions of several subsystems. 2 WM software, 2 WM test.	50
On-Board Data Storage	Software to provide on-board data storage file structures specifically intended to meet user needs. 1 WM	10
VDTV Operator software	Provide capability for operator to input simple commands to control the vehicle operation. Examples arc set roll angle to 20 during a transient maneuver or emulate performance of a particular vehicle class. Involves complex interactions of several subsystems. 2 WM software, 2 WM test.	50
On-Board Data Storage	Software to provide on-board data storage file structures specifically intended to meet user needs. 1 WM	10
Off-Board Data Processing	Hardware and software to meet NHTSA requirement for an off-board data processing capability at each test site. Would also provide electronic communication to NHTSA researches anywhere in the US. 50K hardware, 4 WM	100
Front-End System Engineering	Necessary to develop detailed requirements for the Reference VDTV. However, not needed for VDTVs with one or two subsystems which do not interact. One senior vehicle dynamicist, other dynamicists for each subsystem, plus a computer support/-documentation person for a period of three months. Deliverables are detailed specification for each dynamic subsystem, specifications for software which defines interactions between each subsystem, and documentation of the effort. Period of about 3 months.	100
Dynamic Subsystem Tests	Additional tests prior to integration into the VDTV to assure performance and reliability. Includes buildup of bucks to hold equipment for each dynamic subsystem, then operation over temperature ranges (with margins beyond those of expected temperatures within the vehicle) and operation for extended periods of time to assess and correct reliability problems. Selected for each dynamic subsystem as needed to assure long-term performance. Cost is a guess.	100
Development, Validation Tests	Needed to fully develop interacting dynamic subsystems, then completely validate performance under conditions of interacting variables. Additional cost over those of the LE estimates for a complex vehicle, but not needed for the vehicles costed by LE. Included proving ground rental and labor for a 6 month period	400