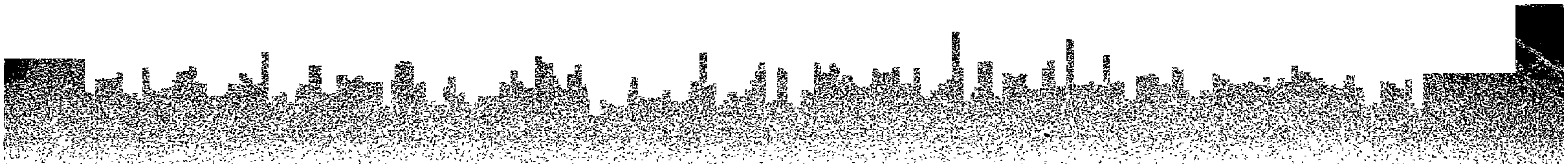

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Variable Dynamic Testbed Vehicle Study

Final Report

Volume II: Technical Results

August 30, 1994

Prepared for

U. S. Department of Transportation
National Highway Traffic Safety Administration
Through an agreement with

National Aeronautics and
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by

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California Institute of Technology

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Volume II: Technical Results

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VARIABLE DYNAMIC TESTBED VEHICLE STUDY

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VARIABLE DYNAMIC TESTBED VEHICLE STUDY

1. INTRODUCTION

1.1 GENERAL

The National Highway Traffic Safety Administration (NHTSA) commissioned the Jet Propulsion Laboratory (JPL) to conduct a study of an instrumented test vehicle that may satisfy a number of requirements for NHTSA as well as others doing work associated with the Intelligent Vehicle Highway System. The vehicle concept was named the Variable Dynamic Testbed Vehicle (VDTV), denoting an intended testing capability for a range of dynamic characteristics.

This report is published in three volumes: Volume I is an executive summary; Volume II contains the technical results; Volume III is a set of Appendices. In this volume, Section 2 describes a questionnaire sent to potential VDTV users early in the study, and provides the results. Section 3 concentrates on the identification and assessment of users and their perceived needs, and the benefits of VDTV in meeting these needs. Section 4 provides a conceptual design of a full-capability VDTV that would satisfy the requirements identified in the user assessment. Section 5 then looks at several implementation alternatives and provides an estimate of cost, benefits and risks of various acquisition approaches that include vehicles with less than full capability. Section 6 identifies certain unresolved issues that arose during the study, and Section 7 closes with the principal conclusions of the study. Section 8 is a list of references.

1.2 BACKGROUND

The IVHS program spans a large spectrum of vehicle and infrastructure improvements. As part of this program, NHTSA has begun a major research effort to facilitate the development and implementation of cost-effective technologies for improving capability of the driver-vehicle system. A significant aspect of this development activity is to provide the assurance that the introduction of new vehicle capabilities is done in a way that will not compromise safe driving. The NHTSA Office of Crash Avoidance Research (OCAR) has the responsibility to analyze vehicle-driver interactions relative to crash avoidance, identify vehicle-related characteristics associated with driver performance in crashes, and to develop and evaluate vehicle-based crash avoidance concepts and devices. In each of these endeavors, OCAR has the additional responsibility of assessing the safety implications of the introduction of these technologies into production vehicles.

The development of crash avoidance technology requires a comprehensive set of tools and facilities. One such facility is NHTSA's Vehicle Research and Test Center (VRTC) at which full-scale vehicle and component testing is conducted on a variety of systems and technologies. Another test facility currently under development is the National Advanced Driving Simulator (NADS). This full vehicle-size simulator will be used in studying driver behavior in situations where collisions might occur and investigating concepts for advanced crash avoidance technology. Other parallel programs such as the Automated Highway (AHS) and the California Partners for Advanced Transit and Highways (PATH) program are conducting research in crash avoidance technologies and have needs for test facilities and vehicles.

To support its own test requirements and to augment the above facilities and programs, OCAR has defined the concept of a VDTV. This vehicle would be capable of simulating a broad range of automobile dynamic characteristics and would be beneficial in crash avoidance concepts development, in human factors research, validation of NADS models and in support of other national or regional research programs. The VDTV would be the only tool available to NHTSA for conducting research in the limit-performance regime with high dynamic fidelity. While NHTSA's VDTV concept was for a single vehicle, the term "VDTV" as used herein allows for the possibility of more than one vehicle to fully meet the complete set of user requirements. This report will provide the results of JPL's assessment of the VDTV potential to satisfy these needs.

1.3 THE VDTV CONCEPT

The underlying concept of variable performance in a test bed has its roots in the aircraft industry where variable stability airplanes have been used extensively in research, and more recently in practice. The ability to quickly and easily change the dynamic response characteristics of a vehicle gives the investigator a powerful tool to conduct systematic testing of a broad range of research topics, including vehicle, driver-vehicle, and vehicle-environment areas of interest. This capability is extremely important at the vehicle performance limit.

The VDTV will consist of one or more passenger-automobile-class vehicles representative of a range of passenger cars from small to large. The steering, suspension, traction and braking subsystems will be designed such that their operating characteristics can be varied over a prescribed range. This variability will be achieved by replacing components, by adjusting their properties mechanically, or by varying properties electronically via a laptop computer. In addition, the characteristics of some of the subsystems will be adaptable; that is, controlled in real time by software executed using the on-board processor. The vehicle's mass and inertia properties will be varied mechanically and/or by software simulation. The vehicle will also be designed to accommodate a range of tire types and sizes.

The VDTV will be instrumented to record all data pertinent to the vehicle dynamic behavior as well as to human factors associated with driver performance in different test scenarios. The testbed will be equipped with an on-board measurement system to accommodate experiment-specific data acquisition requirements as well as permanently installed vehicle functions. To prevent vehicle collision, an operational safety system will have the capability to override any experiment-specific automated vehicle control commands. An on-board laptop computer will provide access to the vehicle controller as well as to the measurement system.

To support post-test analysis, an off-board workstation will also be provided. Field support will assure maximum test availability.

1.4 SCOPE AND METHODOLOGY

A VDTV study objective was to determine the perceived need for such a test capability within the IVHS community and then to ascertain the benefit of this type of vehicle for identified uses. To do this, the potential users were divided into the following general categories:

- NHTSA and other government agencies/programs
- Universities and other research institutions
- U.S. automobile industry
- Foreign automobile industry

Information regarding utilization of and need for a VDTV capability was sought from each user category.

Early in the study, the team met with NHTSA program managers within OCAR including those representing NADS, DASCAR, the VRTC, and human factors research to discuss their programs and potential needs for a VDTV. Representatives of the AHS program were also present. These meetings established an initial basis for both the need assessment and user requirements.

The next step was to generate and send a questionnaire to a representative sample of potential users in the above categories. Approximately 200 questionnaires were sent. The responses were analyzed and the results added to the user base. For those respondents expressing an interest in the VDTV concept, or indicating experience with similar vehicles, selected follow-up telephone interviews were conducted. In several instances, meetings were held with organizations that expressed a defined need for the vehicle.

Based on information derived from the above interactions, a user requirements report (Reference 8.1) was written and provided to NHTSA for review and feedback. This report served to confirm JPL's understanding of the users and their perceived needs at this point in time. A set of top-level functional requirements was developed from this user requirements base.

JPL then examined several design and implementation approaches. A system architecture was defined as were major subsystems and interfaces. Design characteristics of vehicles that would meet the requirements of the major use categories were defined. To assist in this design definition, a matrix of vehicle capabilities (subsystems) for specific NHTSA research tests was constructed. Using a weighted rating technique, candidate VDTV configurations were derived for various user categories. Costs were developed using two approaches. Lotus Engineering, under contract to JPL for this study, was asked to provide detailed cost information for several vehicle options. Lotus has built approximately 30 such vehicles (of varying capabilities). The second approach was to gather cost data from U.S. manufacturers and organizations having experience in building applicable components or similar complete vehicles. The costs of four different limited-capability VDTVs were determined from this data base.

The last step in the study was to make an assessment of the benefit of the VDTV concept relative to the perceived needs and to alternatives.

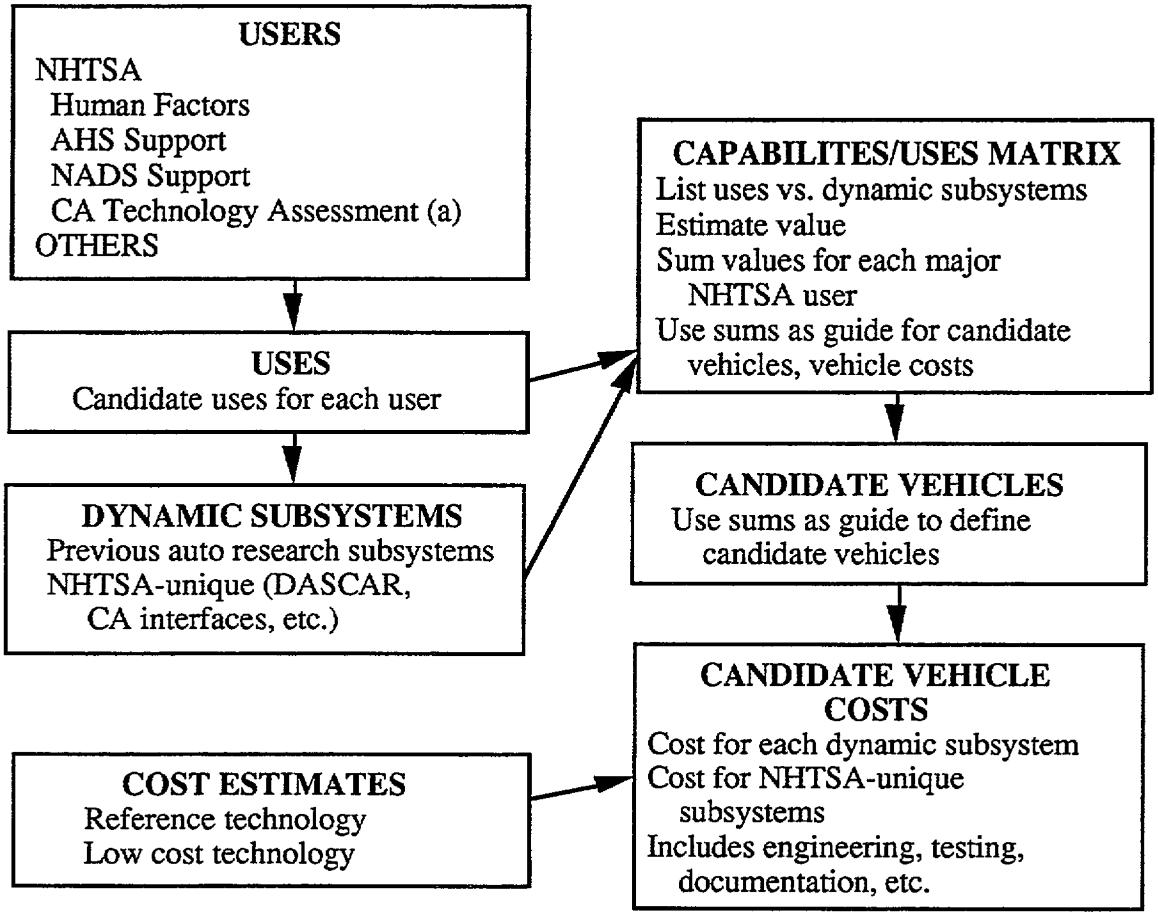
Figure l-l illustrates these activities.

1.5 NHTSA PRIORITIES FOR USE

A broad range of potential users and uses of the VDTV was identified during the course of the study. In order to focus the assessment of these uses, it was necessary to understand NHTSA's priority in this regard. Accordingly, the following guidelines were established relative to the use categories previously identified:

a. The study would assume primary use of VDTV to be by NHTSA in crash avoidance testing and human factors evaluation of driver-vehicle interaction during such testing. Included in this category is support of the IVHS, NADS and AHS programs. Universities, research institutions and industrial companies under contract to NHTSA could have access to the vehicle.

b. The study would identify interest and potential use of the VDTV outside of the above programs, with no implied commitment by NHTSA relative to the availability of the vehicle. Such use would be established by NHTSA in the future when test programs and specific utilization demand had been defined. The interest outside NHTSA would also guide NHTSA in additional uses of VDTV in their mission.



(a) CA = Crash Avoidance

Figure 1-1 Development of VDTV Users, Uses, and Costs

1.6 REQUIREMENTS

The determination of requirements during the study included meetings with people at NHTSA, NADS, and the AHS, included follow-up interviews with responders to the questionnaire described earlier in this report, and with other contacts involved in the transportation arena. JPL evaluated this information in order to: (1) understand the VDTV user requirements to a level sufficient for developing a VDTV operational concept and to develop top-level functional requirements; and, (2) determine the vehicle requirements at a level to support a conceptual design and implementation analysis.

The direction given by NHTSA and the information obtained during the study established that the primary objective for building the VDTV was to support the Office of Crash Avoidance

Research (OCAR) testing for vehicle dynamics, human factors, and safety parameters, primarily associated with the assessment of crash avoidance concepts in the IVHS program. The vehicle will be instrumental in the study of driver-in-the-loop responses to changes in dynamic behavior, and outside stimuli in the limit-performance regime. In addition, there are parallel requirements that the VDTV have the capabilities to support the validation of the National Advanced Driver Simulator (NADS) mathematical models, and the Automated Highway System (AI-IS) program.

Top-level functional requirements established for VDTV and documented in Appendix A assumed a full-capability implementation. As discussed later in this report, there are several ways in which NHTSA could acquire a VDTV capability, ranging from a minimum level of functions and dynamic capabilities to the full-capability vehicle. The requirements for any approach less than the full-capability vehicle would obviously be downgraded to match the needs of the program. No attempt to do this for the various implementation options discussed in this report has been made.

2. USER QUESTIONNAIRE

2.1 USER QUESTIONNAIRE BACKGROUND

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 selected from IVHS and AHS conference participants; selection criteria were based on a 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.

2.2 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 crash 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.

2.2.1 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 2-l and for purposes of comparison the percentage breakdown by organization type of the companies/organizations receiving a questionnaire is also shown.

A summary of the main results of the survey broken down by organization type are provided in Table 2- 1. Table 2- 1 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.

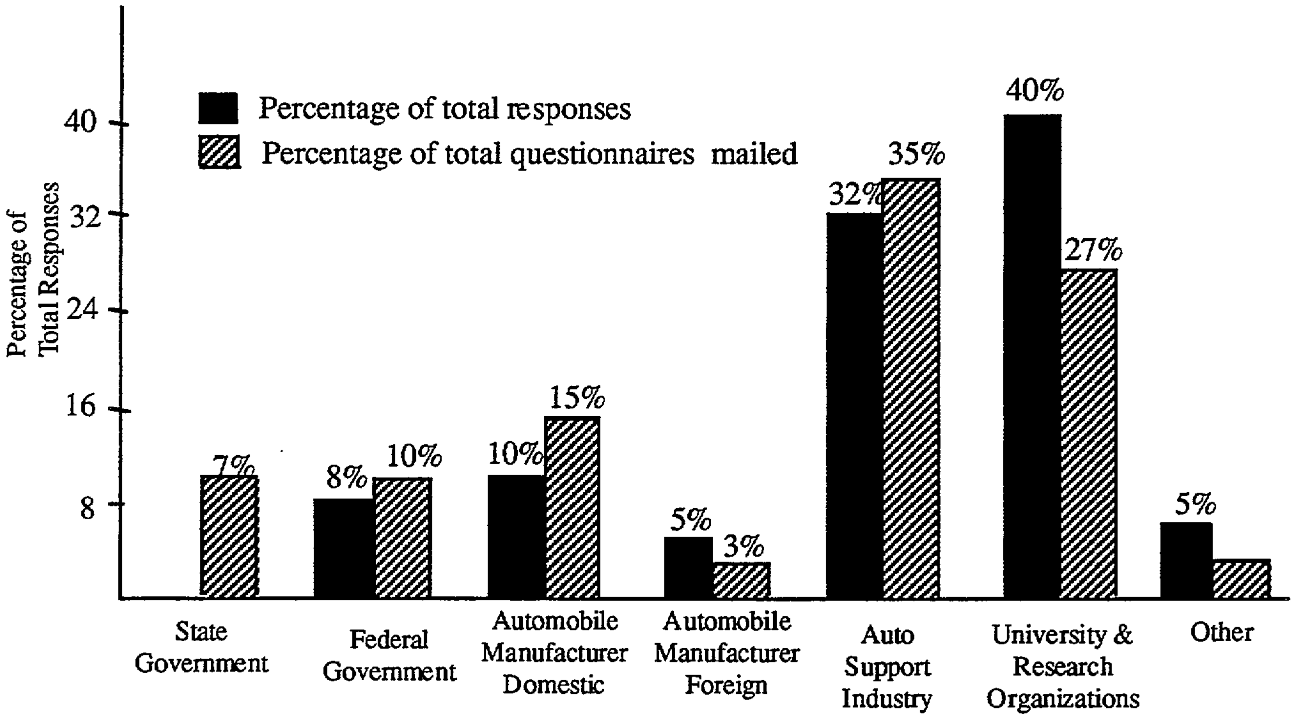


Figure 2-1 Percentage of Survey Respondents and Recipients by Type of Organization

Table 2-1 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

2.2.2 Additional Uses

The major uses by type of organizations and use identified by the questionnaire results are listed in Table 2-2. The uses as listed in Table 2-2 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 latter 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 uses receiving broad based support are (1) object detection and crash avoidance, (2) automated car following and braking (3) smart cruise control and **(4)** braking and steering performance.

Table 2-2 List of Highest Rated Uses 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
Automotive 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

2.3 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. In several cases, the interest in VDTV found in subsequent meetings was different from that expressed by the survey. To some extent, this result is explained by different people being involved in the questionnaire and follow-up interviews. A good example of this is the greater interest shown by some of the automobile manufacturers in more recent meetings as is discussed further in Section 3.3.5.

3. EVALUATION OF VDTV USERS AND USES

This section describes VDTV uses in three categories in Sections 3.1 through 3.3: (1) vehicles similar to the VDTV that have been developed by the world's major auto firms for the last ten years, (2) the four major NHTSA user categories (human factors research, automated highway system (AHS), National Advanced Driving Simulator (NADS), and NHTSA technology assessment, and (3) other users (other government programs, research organizations, and the auto industry). Alternatives to a VDTV are contained in Sections 3.4. Possible VDTV utilization, based on these users and uses, is discussed in Section 3.5, Section 3.6 provides a comparison of the operation cost of VDTV to the cost of alternatives, followed by a discussion of benefits and conclusions in Sections 3.7 and 3.8, respectively.

3.1 PREVIOUS VARIABLE DYNAMIC VEHICLES

Table 3-l shows a summary of variable dynamic vehicles developed by Lotus Engineering (LE). LE is widely acknowledged to be the world's leading firm in this technology. In this capacity, LE has developed variable dynamic vehicles intended for passenger car research for more than 30 projects, dealing with automobile manufacturers throughout the world. Although no single vehicle includes all the dynamic subsystems envisioned for the VDTV, the aggregate of the subsystems listed in Table 3-l clearly shows the considerable interest of the world's auto community in variable dynamic subsystems.

Since auto manufacturers are interested in product development as well as research, the relationship of the dynamic subsystems listed in Table 3-l to NHTSA's crash avoidance research must be considered. This relationship is established by the following analogies:

- Ride is related to vertical linear motion and pitch rotation.
- Performance is related to longitudinal acceleration.
- Handling is related to lateral acceleration, longitudinal deceleration, and yaw rotation. Since weight transfer affects front wheel braking, pitch rotation also has a secondary handling impact.

Crash avoidance thus has a strong correlation with vehicle handling and some correlation with longitudinal acceleration. From this correlation, those dynamic subsystems which affect vehicle handling and longitudinal acceleration are definite candidates for crash avoidance research. In addition, a dynamic subsystem which can vary pitch rotationmay have an impact on human factors research.

In 1988, Lotus Engineering developed a vehicle with six dynamic subsystems for human factors research. Also, Table 3-l shows that the world's auto manufacturers have spent significant research funds for dynamic subsystems which directly affect crash avoidance research. The expenditure of these funds by the world's automobile community shows that a variable dynamic testbed vehicle is considered a valuable tool for research activities.

Table 3-1 Dynamic Subsystems History

Vehicle Type & Client	No. off	Year	Subsystems	Usage
Turbo Espirit Team Lotus	1	1982	Active Suspension	The first experimental active suspension vehicle used to prove and develop the concept for use in Formula 1 racing
Lotus T92 F1	1	1982	Active Suspension	First use of active suspension in Formula 1 racing. Primarily used to produce a stable vehicle platform to improve aerodynamic performance.
Buick "C" Car Goodyear	1	1983	Active Suspension	Evaluation of active suspension for tire development.
2+2 Sports Car	2	1985	Active Suspension	Active suspension research vehicle
Chevrolet Corvette	2	1985	Active Suspension	Active suspension research vehicle
Volvo 760	2	1985	Active Suspension	Active suspension research vehicle
US Mid-Size Sedan	2	1986	Active Suspension	Active suspension research vehicle
UK Luxury Saloon	2	1986	Active Suspension	Active suspension research vehicle
Lotus Excel	1	1986	Active Suspension	Active suspension research vehicle and technology demonstrator
T99 Lotus F1 Team Lotus	5	1987	Active Suspension	Race system used to produce a stable vehicle platform to improve aerodynamic performance and tire contact loads.
GTP Corvette GM Special Projects	1	1987	Active Suspension	Race system used to produce a stable vehicle platform to improve aerodynamic performance and tire contact loads
CERV III Mule GM CPC	1	1987	Active Suspension Rear-Wheel Steer Brake-by-Wire Throttle Control 4-Wheel Drive	Mule vehicle for technology demonstrator. The aim was to provide a directional control and stability system to improve vehicle ride, handling and safety.
Volvo 740 Turbo Michelin	1	1987	Active Suspension	Evaluation of active suspension for tire development
Opel Senator	1	1988	Active Suspension Rear-Wheel Steer Steer-by-Wire Steer Feel Brake-by-Wire Brake Feel	Research vehicle for Human Factors studies. A key part of this vehicle was to maintain a standard interior and exterior appearance.
CERV III prototype GM CPC	1	1988	Active Suspension Rear-Wheel Steer	First prototype for technology demonstrator used to prove a limited number of technologies.
CERV III Vehicle GM CPC	1	1988	Active Suspension Rear-Wheel Steer Brake-by-Wire Throttle Control 4-Wheel Drive	Technology demonstrator to show a directional control and stability system that improves vehicle ride, handling and safety.
Volvo 760	1	1988	Rear-Wheel Steer	Technology research vehicle—vehicle dynamics
Mid-Size US Sedan	2	1988	Active Suspension	Active suspension research vehicle

Table 3-1 Dynamic Subsystems History (Continued)

Vehicle Type & Client	No. off	Year	Subsystems	Usage
Chevrolet Corvette	2	1989	Active Suspension	Production active suspension research vehicle
10-Ton Light Tank DRA (UK)	1	1989	Active Suspension	Active suspension research vehicle
Audi 90 Quattro Michelin	1	1989	Rear-Wheel Steer	Technology research vehicle for vehicle dynamics and tires
European Saloon	1	1989	Active Suspension	Active suspension research vehicle
European Saloon	1	1989	Active Suspension	Active suspension research vehicle
European Saloon	2	1990	Active Suspension	Production active suspension research vehicle
Opel Senator Goodyear	2	1990	Active Suspension	Production active suspension research vehicle
US Mid-Size Sedan	1	1990	Rear-Wheel Steer Steer-by-Wire Steer Feel	Steering system and vehicle dynamics research vehicle
Japanese Utility	2	1990	Active Suspension	Active suspension research vehicle
US Mid-Size	1	1990	Rear-Wheel Steer	Technology demonstrator
Volvo 780 TRW	1	1990	Active Suspension	Production active suspension research vehicle
European Saloon	1	1990	Active Suspension	Production active suspension research vehicle
SID Research Vehicle Lotus	1	1990	Active Suspension Rear-Wheel Steer	Research vehicle for improved understanding of vehicle dynamics
US Mid-Size	2	1991	Active Suspension	Production active suspension research vehicle
10-Ton Light Tank TACOM	1	1992	Track Tensioning	Research vehicle
European Saloon	1	1992	Active Suspension Rear-Wheel Steer	Technology demonstrator and research vehicle
HMMWV TACOM	1	1993	Active Suspension	Active suspension research vehicle

3.2 MAJOR NHTSA USERS

NHTSA is expected to be the major VDTV user. Within NHTSA, there are four major categories discussed in this section. The VDTV's capability, which is dependent on its dynamic subsystems, is a key factor in determining the VDTV's benefit to potential users. VDTV capabilities were thus analyzed for each major NHTSA user. A matrix, discussed in Appendix C.l and summarized in Table 3-2, was used for this analysis. Numerical values in the table were determined by assigning a weighted rating to each subsystem for a number of specific lower-level research tasks under each user area. Higher values represent greater need of a given subsystem for that application. The results at the major user level then guided the selection of subsystems for vehicle configurations that are discussed in detail in Section 5, which deals with VDTV implementation. The dynamic subsystems directly impact VDTV cost, thus providing the link between users, VDTV capability, and VDTV cost.

3.2.1 Human Factors Research

Discussions with NHTSA program managers and others contacted during the study found that many believed that the most beneficial use of the VDTV would be in the area of human factors research and assessment, especially in the high-limit-performance regime. This conclusion stems from the unique characteristics of the vehicle that permit the variation of performance parameters (both vehicle and subsystem) in the high-fidelity environment of road tests while providing a complete vehicle/driver measurement capability. Some candidate human factors research uses are:

a. Relationship of dynamic subsystem performance and driver capabilities. The VDTV will include all dynamic subsystems relevant to crash avoidance technology. The performance of each dynamic subsystem can be varied individually or in combination via an on-board laptop computer, providing an efficient means to conduct parametric programs. This will permit rapid investigation of performance attributes of dynamic subsystems (active suspension, 4-wheel steering, traction control, etc.) as they affect driver response to vehicle actions. The VDTV can be programmed to respond in a predetermined and measurable way, enhancing such studies.

> The VDTV's ability to change only one parameter at a time, while holding others constant, will significantly improve research quality. Separation of multiple interacting variables, which is inherent in tests conducted with multiple vehicles, is a difficult and inefficient process requiring attention of senior researchers. The VDTV can greatly reduce this problem, thus improving NHTSA's research quality.

b. Testing of driver cues. Vehicle attitude cues, such as roll angle during cornering and dive during braking, can be varied throughout and beyond the range of normal vehicles. This includes maneuvers near performance limits, such as ~0.95g lateral acceleration and braking. Virtually every crash avoidance concept has strong human factors implications. Thus, the assessment of these technologies cannot be divorced from human factors issues. The combination of this capability with that of variable performance subsystems (e.g., active suspension) make it an ideal test platform for human factors testing.

c. Driver behavior adaptation. The ability of classes of drivers to adapt to the capabilities of different dynamic subsystems can be studied with the VDTV. This can include: (1) dynamic subsystems with significantly greater capabilities than those of normal passenger cars, and (2) loss of capability due to malfunction, such as loss of ABS during a maneuver near tire/road adhesion limits,

Table 3-2 Summary of VDTV Capabilities/Uses Matrix

	DYNAMIC SUBSYSTEMS														
	SBW (b)	PSF	BBW	PBF	TBW	PTF	SA SUS	A SUS	4WS	TRAC	ABS	4WD	CA INT	A ROLL	V MASS
MAJOR NHTSA USER (a)															
Human Factors	15	13	15	12	13	10	7	18	15	14	4	9	16	**2**	**8**
AHS	15	7	15	2	15	3	7	6	6	6	3	0	22	**5**	**7**
NADS	9	4	5	2	2	0	5	11	9	5	4	6	6	**1**	**9**
Technology Assessment	6	3	7	3	6	3	3	10	8	7	3	5	9	**0**	**7**
Total	45	27	42	19	36	16	22	45	38	32	14	20	53	**8**	**31**

(a) User Ratings	Numbers represent a weighted assessment of the value of a given subsystem to the area of use. Higher numbers correspond to greater value.
(b) Dynamic Subsystem Key	
SBW	Steer by Wire. Electronically controlled front wheel steering
PSF	Programmable Steering Feel. Change feel via software
BBW	Brake by Wire. Electronic control of braking, independent at all four wheels
PBF	Programmable Brake Feel. Change brake pedal feel via software
TBW	Throttle by Wire. Electronic control of throttle
PTF	Programmable Throttle Feel. Change accelerator pedal feel via software
SA SUS	Semi Active Suspension. Performance of production passenger cars
A SUS	Active Suspension. Research quality dynamic performance at all four wheels
4ws	Four Wheel Steering. Front and rear steering, both electronically controlled
TRAC	Traction Control. Automatic control of wheel slip during acceleration
ABS	Automatic Braking System. Automatic control of wheel slip during deceleration
4WD	Four Wheel Drive. All four wheels can apply power
CA INT	Crash Avoidance Interface. Interface with research level crash avoidance devices or other sensors
A ROLL	Active Roll. Electronic control of vehicle roll
VMASS	Variable Mass. Vary mass to simulate performance of heavier vehicles

d. Human factors data. The VDTV will include the Data Acquisition System for Crash Avoidance Research (DASCAR), so complete human factors measurements will be provided. DASCAR is designed as a human factors research tool, so the combination of the VDTV's dynamic performance, its comprehensive measurement system, and DASCAR should make an ideal research vehicle.

e. Comprehensive. quality data. The VDTV will also include a large number of data channels which objectively define the VDTV's performance. All measurements will be standard and traceable to the National Institute of Science and Technology (NIST). When coupled with DASCAR's human factors measurements, the VDTV's data will be comprehensive with a quality accepted throughout the Nation and internationally.

f. Test fidelity. Full-scale road tests will provide optimum fidelity which will have the best possible credibility with legislative bodies and the automobile industry. When coupled with the data quality, results of NHTSA research will be able to withstand close scrutiny, better supporting NHTSA's rule making activities.

Table Cl-l, Appendix C. 1, as well as the summary in Table 3-2, shows the applicability of potential dynamic subsystems to specific human factors research topics. These dynamic subsystems can be expected to cover the full range of vehicle dynamic performance to efficiently support NHTSA's research program.

3.2.2 Automated Highway System (AHS)

JPL contacted several persons involved with the AHS project to gather information on potential VDTV support to the AHS program. At the time that this report was written, the AHS program was in the process of selecting a consortium to implement the program. There was a consensus that, even though the consortium will maintain their own test vehicles, the VDTV would be useful in supporting the testing of various AHS concepts.

The AHS must be compatible with the dynamic performance of conventional passenger cars to permit mass access to this system. The AHS vehicle fleet must have dynamic performance at least equal to, and preferably somewhat better, than normal passenger cars. The performance requirements for VDTV, which will have state-of-the-art performance in all its dynamic subsystems, will be considerably greater than those of AHS. Thus, the VDTV can play a vital role in AHS activities. There are two time domains discussed below.

a. Support of AHS Vehicle Fleet Acquisition

A near-term VDTV activity to support acquisition of AHS vehicle fleets would assure that AHS vehicles had the needed characteristics without overspecification.

i. The VDTV's dynamic capabilities can be used to objectively determine the minimum requirements for AHS vehicles. This information can then be included in specifications for AHS vehicle fleets, greatly reducing the risk of an incorrect specification.

ii. A subset of the VDTV's performance requirements, based on tests conducted in the AHS environment, can be used in the procurement of AHS vehicle fleets, greatly reducing the risk in under- or over-specification.

iii. Should the AHS consortium determine a need to build a similar test vehicle, it could base their requirements and design on those of the VDTV or simply replicate the vehicle. The latter would result in lower overall costs because the expensive engineering and testing activities would be greatly reduced.

b. Support of AHS Operations

The VDTV can support on-going AHS activities which require high performance beyond that economically feasible for the multiple AHS vehicles. Because of its excellent dynamic performance, interfaces with crash avoidance subsystems, and capability for automated control, the VDTV can be used to answer specific questions quickly during the AHS development activities.

i. The VDTV's superior dynamic performance can be used to answer questions near, and exceeding, the performance bounds of AHS vehicles during the life of the AHS program. Since the VDTV will have a fully developed, comprehensive measurement system, answers to questions can be provided in a minimum time.

ii. The VDTV will have research quality interfaces with crash avoidance systems provided by research firms, private industry, and other organizations. These interfaces will be linked to the VDTV's on-board control system, permitting automated VDTV operation for such maneuvers as lane changing and longitudinal distance control. The VDTV can thus provide timely integration with AHS devices throughout the AHS development cycle, greatly decreasing the time to investigate new technologies that may arise.

iii. The VDTV's unique operational capabilities of the VDTV could be utilized to determine the dynamic requirements that a production vehicle must meet before its design is certified for AHS operation. Operation in high-g areas can be investigated by the VDTV, assuring that the entire spectrum of dynamic requirements has been investigated.

iv. A potential use of VDTV is development of automatic vehicle check-in prior to entering controlled lanes. VDTV will have interfaces to external devices and a vehicle health reporting system which should assist early investigations in this area.

v. There may be a need for independent safety assessments by NHTSA of technologies being developed within the AHS program.

It was perceived by the FHWA AI-IS program manager that the VDTV could play a central role in the AHS program. From the point of view of timing, if VDTV were to support the AHS program, it would be desirable to have it in place by the beginning of calendar year 1996. However, the VDTV's role cannot be completely defined until the AHS consortium is in place, expected later this calendar year. In any near-term time frame, the VDTV's advanced capabilities make it a primary tool to support AHS.

3.2.3 National Advanced Driving Simulator (NADS)

The combination of NADS and VDTV will provide an excellent research capability with essentially no voids. Each has its own strengths and deficiencies; when closely coupled into a research system, they will provide NHTSA with an unequaled capability.

A cooperative role between the VDTV and NADS, coordinated by good system engineering practices, can be expected to provide significant advantages to NHTSA's research program. The VDTV's role should thus be one of supporting NADS in the normal driving range and augmenting NADS in the limit-performance range. This support will be in two different time frames: (1) during NADS development, and (2) throughout the life of NADS. Close coordination between early NADS and VDTV designs, then the operational activities, will provide an opportunity for a cost-effective, widely accepted validation of NADS products.

a. During NADS development, the VDTV's primary role will be validation of actual NADS performance. The VDTV can provide cost-effective validation support in different ways:

   i. Provide physical validation by adding masses at different locations to actually vary the VDTV's inertias, CG, and other parameters. This activity will be done as part of the VDTV's development process and will be proven in its final acceptance tests. This will result in a range of physical parameters on a single vehicle, fully documented by the VDTV's on-board measurement system. The VDTV's performance under a range of conditions of these physical parameters can then be used to validate the NADS mathematical models.

   ii. Provide validation throughout the range of NADS performance by using the VDTV's variable dynamic performance capability. This capability is dependent on on-board software, which will be fully verified by the development process using physical weights discussed in (i) above. The software-controlled dynamic performance is thus an essentially continuous interpolation between discrete points of the physical validation of (i). Since the dynamic parameters can be individually controlled with minimum interaction of other parameters, NADS validation throughout its operation range can be done efficiently. In addition, the VDTV's comprehensive on-board measurement system will provide data for most, if not all, of the parameters needed to develop and validate NADS models.

   iii. Conduct tests in dynamic regimes not possible with NADS or conventional vehicles, thus extending the data set available to NADS developers. Examples are operation at yaw rates and lateral acceleration not possible with conventional vehicles, but well within the range of the VDTV.

   iv. Validation of a vehicle dynamic model is a matter of degree. For NADS-related applications, the main concerns are with models that can accurately reproduce the "gross" motion of the vehicle (for example, its yaw rate). The VDTV measurement system will provide over 60 data channels, thus providing validation data for all gross vehicle motions. In addition, suspension and wheel motions will be included in the VDTV's data set to provide validation data of these important parameters. Reference 8.2 describes several validation tests that could be conducted for this purpose.

   v. Because NADS is a major acquisition it is not expected to be fully operational before 1999. VDTV could provide a significant pre-NADS test capability for NHTSA.

b. During NADS' operational lifetime, the VDTV can provide NADS support and augmentation in several areas:

i. VDTV can provide the full-scale fidelity needed for those research problems where the fidelity question is likely to arise, as in the limit-performance regime. In this mode, VDTV would support NADS by providing spot checks of NADS results in specific areas. Validation of NADS results in these areas through full scale tests can be expected to lend credibility to NADS results over the complete range of research problems.

ii. VDTV may be able to provide objective data outside the performance boundaries provided by NADS. An example is sustained lateral acceleration at high g levels. For several research problems defined in Appendix F of the NADS Requirements Study Final Technical Report (Reference 8.3), the VDTV will be capable of providing data near tire/road adhesion limits for sustained periods.

iii. The VDTV will be capable of providing timely answers to questions asked by industrial firms and legislative bodies who have had a tendency not to accept NADS data. Answers to such legislative questions could be provided in a time frame of a week or two, as discussed in the scenario shown in Appendix C.4.

iv. During the VDTV's operational lifetime, it could continuously support NADS by providing full-scale validation of specific NADS questions. The VDTV would be particularly valuable during NADS upgrades. The VDTV could provide preliminary data to support upgrade design efforts, then validate the upgraded performance.

v. The VDTV can support iterative refinements of model parameters, typically equation coefficients, to provide an increasingly close match between responses predicted by models and those recorded in road tests.

vi. Drivers behave differently in the environment of the NADS simulator than in road tests. The VDTV can be used to conduct spot checks, using the same drivers for NADS and VDTV, to compare driver behavior. This will further validate NADS results, especially with respect to human factors.

Discussions with the NHTSA NADS program manager determined a strong interest in the use of VDTV for NADS model validation. Initial validation is being conducted by VRTC using instrumented production vehicles. Both VRTC and the University of Iowa brought up the issue of the degree to which VDTV represented "real" automobiles. The fact that VDTV would have to be validated in this regard has been recognized and time has been allotted for this in the various implementation modes discussed later in this report.

With the ability to vary mass and subsystem performance, and thereby vehicle response characteristics, it is believed that the VDTV can be made to closely emulate a broad range of production vehicle types. Section 4.8 discusses this capability in detail. This capability will increase the VDTV's value to NADS.

3.2.4 NHTSA Technology Assessment

IVHS crash avoidance (CA) technologies provide significant potential for achieving improvements in highway safety and reductions in collision-caused congestion and vehicle delay. The U.S. DOT will ensure that no loss of safety occurs from the deployment of IVHS services including those not primarily designed to enhance safety. [Reference 8.4]

OCAR is charged with the responsibility of demonstrating that improved crash avoidance technology performance can be achieved safely through the application of IVHS technology, and with facilitating the successful development of promising crash avoidance concepts (Reference 8.5). In order to accomplish this safety role, performance specifications for crash avoidance technologies need to be developed for various crash categories. This development will include the identification of the specific causal factors and potential countermeasures for each category.

The VDTV will have four capabilities which will directly support NHTSA's assessment of new crash avoidance technology:

a. Interfaces which will mate with crash avoidance systems developed by research organizations, such as universities, and private industry. These interfaces will provide electrical power, accept both analog and digital signals, and have defined mechanical specifications. All electrical interfaces will conform to common national standards, assuring wide use with minimum burden on the suppliers.

b. These interfaces will transmit data to the VDTV's on-board control system, permitting the supplier's crash avoidance systems to be directly linked with the VDTV's dynamic subsystems, thus permitting full automatic control of high performance vehicle maneuvers.

c. The VDTV's measurement system will provide nationally-accepted data, eliminating opinions concerning the actual performance of the crash avoidance device.

d. The VDTV will be a fully developed system and will support assessment of crash avoidance technology with a minimum of special preparation, and will thus minimize cost.

3.2.4.1 VDTV Use in Technology Assessment Tests

With these capabilities, the VDTV can efficiently conduct tests in the following areas:

a. Test and evaluation of IVHS crash avoidance hardware and systems. VDTV will be designed to accommodate commercial products and prototype devices under development. The variable inertial and vehicle subsystem characteristics would allow the evaluation of these items over a wide range of controlled test conditions. The VDTV would be particularly useful in assessing the relationship of these new technologies to vehicle dynamics over a range of test scenarios in which the performance of the subsystems (e.g., 4-wheel steering) would be varied. Specific crash avoidance systems that could be tested with VDTV are:

   i. Longitudinal CA Systems (rear-end collision warning and control, autonomous intelligent cruise control, cooperative intelligent cruise control, head-on warning and control, passing warning, and backing collision warning);

   ii. Lateral CA Systems (lane change/blind spot situation displays, crash warning and control, and road departure crash warning and control);

   iii. Intersection Collision Avoidance.

b. The variable characteristics of the VDTV make it an ideal test platform in the development of performance specifications for the above countermeasure systems. These specifications of functional requirements would serve as design targets for industrial development of IVHS hardware. Again, the VDTV could play a primary or support role, depending on the type of system being evaluated and the complexity of the test objectives.

c. The VDTV can conduct independent performance and safety assessments of technologies being developed in parallel programs such as AHS. The VDTV's dynamic performance and comprehensive, nationally-accepted data will provide reference quality data for such assessments.

d. Before any IVHS CA device can be committed to production, it must be field-tested to ensure that it is effective, acceptable to drivers, and does not introduce new safety concerns. NHTSA may be required to certify that a CA device meets defined objectives before the device manufacturer will start production. In spacecraft terms, a formal qualification test may be the single method for NHTSA to provide such certification. NHTSA can use the VDTV to perform such qualification tests. The VDTV will be highly instrumented for both vehicle and driver data, will accommodate CA technologies, will emulate a range of automobile classes, and will have the dynamic performance essential to explore CA performance at the limits of tire/road adhesion.

The VDTV can play a primary role in NHTSA's evaluation of future crash avoidance technology. Although there are many organizations which have the specialized technology (physics, radar, microwave, electronics, etc.> needed for innovative crash avoidance systems, very few have the resources essential to developing and verifying a new system in the road test environment. This capability is probably limited to the major auto manufacturing firms and a limited number of multinational major suppliers to the auto industry. Further, the road test capability is highly specialized and expensive, limiting the tendency of research organizations and private industry to commit resources to CA technology. Universities are a primary example of potential VDTV users in this area. Others are medium to small private firms with a high technological capability but with a void in the auto test area. Availability of the VDTV could increase the tendency of capital investment by research institutions and private industry, thus bringing crash avoidance technology to a production status earlier.

Many organizations can be expected to be unwilling to commit to the major costs essential to fully test a new crash avoidance technology. The VDTV can play a role in this area by providing a fully developed capability with proven measurements available for an operational use cost. A nationally-known test capability is thus likely to foster development of crash avoidance technology otherwise inhibited by high test costs.

3.2.4.2 VDTV Support for Rule Making

The nature of NHTSA's support of rule making often requires rapid response to Congressional inquiries, petitions, and questions regarding the enforceability of Administration standards. The VRTC plays a key role in full-scale vehicle testing as well as component tests on a variety of systems and technologies. VRTC also provides support in the area of vehicle dynamics model assessment and validation. It is probable that the VDTV would be located at VRTC. With the VRTC/VDTV capability, the VDTV performance could be changed to emulate dynamic performance of any normal passenger vehicle within a short time, probably less than a day. Response time of such inquiries would be far less than any other approach and would have the validity of a proven vehicle and nationally accepted data. To be useful in this area, the VDTV will have to be validated using production vehicles representative of various automobile classes.

It is expected that the auto industry is unlikely to accept NADS data products at this time, so the VDTV may have a primary role to support rule making. Experience with other simulators shows that a period of five to ten years will be required for simulation to gain the credibility essential for rule making. During this period, the VDTV may be an important NHTSA tool to provide data to Congress and to the world-wide auto community in support of the rule making process. A major advantage of the VDTV for this purpose is the rapid response provided by its programmability feature.

3.3 OTHER VDTV USERS

3.3.1 Other Government Programs

There is a potential for the VDTV to support other government programs. One such program investigated was the California PATH program. The California Partners for Advanced Transit and Highway (PATH) program has emphasized work on Advanced Vehicle Control Systems (AVCS) technology to a greater extent than any other current IVHS programs. The AVCS work in the PATH program has recently passed important milestones which demonstrate the initial longitudinal (platooning) and lateral control (autonomous lane-following) systems' successful performance. Numerous discussions with researchers at PATH indicated a strong interest in VDTV. Specific uses identified were:

1. Vehicle Lateral Control System ("lane following" or "lane tracking").
    a. Evaluate the performance and control system stability robustness of the vehicle lateral control system at off-design vehicle conditions. For example, the sensitivities of lateral control system's tracking accuracy with respect to the following variations in vehicle's parameters:
        i. front and rear roll stiffnesses,
        ii. control sensitivity (lateral acceleration gain),
        iii. yaw mode frequency and damping factor, and others.
    b. Evaluate the performance of the vehicle lateral control system with a vision-based roadway measurement system, instead of the current magnetic roadway reference system.
2. Vehicle Longitudinal Control System ("platooning").

a. Evaluate the performance and control system stability robustness of the vehicle longitudinal control system at off-design vehicle conditions. For example, the sensitivities of the longitudinal control system's vehicle-to-vehicle separation accuracy with respect to the following variations in the vehicle's parameters:

   i. front and rear roll stiffnesses,

   ii. control sensitivity (lateral acceleration gain),

   iii. yaw mode frequency and damping factor, and others.

b. Evaluate the compatibility of using vehicles with different longitudinal and lateral dynamics in a multiple-car platoon.

c. Evaluate the performance enhancement potential of using both the throttle-by-wire and brake-by-wire systems in the vehicle longitudinal control system (currently, "platooning" in PATH is achieved with only a throttle-by-wire system).

3. Combined Longitudinal and Lateral Control System ("lane change").

The VDTV's steer-by-wire, brake-by-wire, and throttle-by-wire sub-systems can be used to investigate issues related to the design of an integrated controller needed to perform relatively complex maneuvers such as "change lane and merge into a platoon," and/or "change lane to depart a platoon."

3.3.2 Research Institutions

The variable dynamic vehicle can be used as a development and testing platform of control algorithms and vehicle-related or crash-avoidance technologies being studied at various research institutions/universities. The following are representative research areas in which the variable dynamic vehicle could play a significant role:

1. Development of vehicle control algorithms: control algorithms that are developed for the active/semiactive suspension system, four-wheel steering system, antilock braking system, and traction control systems.

2. Development of vehicle-related technologies: low-cost, light-weight, high-performance sensors, microprocessors, pattern recognition systems, fault-tolerant systems, developed for vehicle controlled system.

3. Development and testing of advanced vehicle control systems (AVCS)-related technologies: vehicle systems developed for the purpose of steering assistance, collision warning, headway control, platooning, automatic lane change, adaptive cruise control, vision enhancement, and numerous other operational modes.

Apart from noting the strong interest expressed by this user category in the VDTV concept, JPL did not pursue it further. Should NHTSA find that they can make the VDTV available as a test facility in the future, several universities would probably choose to use it if the cost to do so were not prohibitive.

3.3.3 Automobile Manufacturers

3.3.3.1 Domestic

The needs of the domestic automobile manufacturers were established from four sources: responses from the user survey, telephone interviews; a meeting with the crash avoidance committee of the American Automobile Manufacturers Association (AAMA); and meetings with Ford, GM and Chrysler vehicle dynamics managers (discussed in 3.3.5). The three major U.S. automobile manufacturers all utilize test vehicles similar to the VDTV and find these vehicles very useful. Detailed information on the characteristics and the utilization of such vehicles is not available because of the proprietary nature of such testing.

The information obtained from telephone interviews leads to the conclusion that for the most part, the test vehicles used by the automobile manufacturers do not have the comprehensive capabilities in variable dynamics but are designed to satisfy specific test objectives. The major U.S. automobile manufacturers already have capabilities similar to those proposed for VDTV but not in the same vehicle, and hence are not able to evaluate the dynamic interactions of the various vehicle subsystems. Their preference seems to be in using their own vehicles for research studies in crash avoidance. Several suggestions made by the automobile manufacturers are worth noting. A General Motors representative indicated that GM would be interested in utilizing the VDTV for generic studies in vehicle dynamics. Such studies could address crash avoidance or other issues and would have to be of a noncompetitive nature. GM would consider co-funding such studies with Ford and Chrysler. Another contact at General Motors suggested that GM would be interested in utilizing the VDTV for studies relating to IHVS, but that the vehicle would have to be made available for at least one year. A Ford Motor Company representative indicated that they would be interested in using the VDTV for validation of their “driver-in-loop” simulator. Other representatives of Ford, GM and Chrysler at the AAMA meeting provided little information, exhibiting concern of NHTSA’s rationale for considering the VDTV.

The response of the automobile manufacturers to the questionnaire indicated that the major interest for utilizing the VDTV is in crash avoidance research and human factors studies as shown in Table 2-l.

3.3.3.2 Foreign

Eight foreign auto manufacturers were contacted in an attempt to ascertain interest in the VDTV concept. One firm replied that they would have a VDTV use in their engineering activity, with an analogy to other high-cost facilities such as a wind tunnel. Others expressed no interest or did not respond. An exception is Lotus which stated an interest in the VDTV to develop commercial products.

3.3.4 Automotive Support Industry

The needs for a VDTV by the automotive support industry are focused on the testing of collision sensors and crash avoidance subsystems. Information on potential uses of the VDTV by the U.S. Automotive Support Industry has been gathered mainly from telephone interviews as a follow-up to questionnaire responses. Several examples of needs for a VDTV will be cited. The TRW Active Control Systems (ACS) Division, Florida, a developer of closed loop, microprocessor controlled steering systems indicated a strong interest in testing their system using the VDTV. Their objectives are to study the effect of variable vehicle characteristics on the performance and safety of their subsystems as well as the integration with a realistic system. Another division of TRW, ECL in Sunnyvale, CA is developing crash avoidance subsystems for AHS and would welcome the use of the VDTV for evaluation and verification of their subsystems before committing these to service on the AHS. A third division of TRW, the Automotive Technology Center (ATC) is developing proximity sensors for crash avoidance and would use the VDTV in the evaluation of human factors. The Northrop Advanced Technology and Design Center is currently under contract to the Los Angeles County Metropolitan Transportation Authority to develop an Advanced Technology Transit Bus. Northrop has indicated interest in using the VDTV to test some of the components of the crash avoidance system. Allied Signal, Inc. has expressed interest in testing some of their brake system components using the VDTV. Such testing would have to be limited to pre-competitive development since Allied has serious concern about the protection of proprietary information. Personal contacts with personnel of the Test Research Center (TRC) in East Liberty, Ohio were made. They expressed interest in using the VDTV for various research activities in crash avoidance and safety studies, a service they provide for their customers.

The major value perceived in the use of VDTV for this segment of industry is the opportunity to test concepts or components on a fully instrumented, capable test platform, thus permitting an integrated systems evaluation that would be difficult to obtain elsewhere.

3.3.5 Alternative Utilization of the VDTV

Milliken Research Associates (MRA), under subcontract to JPL in this study, suggested a different focus for the use of VDTV. This concept is modeled after the National Advisory Committee for Aeronautics (NACA) that was the predecessor to NASA. NACA played a role that provided fundamental research facilities to the aircraft industry, a cooperative program that put the US in a world-leadership position that it still enjoys. MRA proposed a similar cooperative venture between the automotive industry and the government to which the VDTV would contribute and would be placed at VRTC. A meeting was held with Ford, Chrysler and General Motors vehicle dynamics and test managers to solicit their interest in this concept.

The meetings indicated a range of views with regard to this idea. Each company expressed a concern about proprietary data, although the majority felt that an acceptable arrangement could be made that would separate fundamental research information that could be shared from application- or design-related data that would be considered proprietary. There was enough encouragement from these interactions to warrant further, more detailed discussions with the automobile companies and the appropriate government agency. A suggestion that the US CAR program might be able to incorporate this concept was made.

The complete description of this proposed alternative for VDTV use is provided in Appendix C-2.

3.4 ALTERNATIVES TO A VARIABLEDYNAMIC VEHICLE

The VDTV, if built, would be one of several test approaches available to NHTSA in meeting future research objectives. The conventional method of instrumenting production vehicles to meet particular research objectives is another approach. NADS, when operational, will offer a significant expansion of NHTSA's research capability, particularly for human factors research related to emerging crash avoidance technologies. Additionally, computer simulation techniques will continue to have a role in the overall spectrum of NHTSA's future research. The question, then, is what are the additional benefits accruing from a VDTV capability, considering the alternatives that exist or will exist. Following is a discussion of these alternatives and a subjective assessment of areas for which VDTV would add to or complement the capabilities of these alternatives.

3.4.1 Multiple Instrumented production Vehicles

Many of NHTSA's testing requirements could be satisfied using instrumented production vehicles, each selected for the specific objectives under consideration. The following factors are important in assessing this alternative relative to a VDTV capability:

- The acquisition cost, including installation of an instrumentation system, for a limited number of vehicles would be considerably less than for a VDTV. See following Section 3.6 for a discussion of cost.

- The VDTV's continuous dynamic variability will provide far greater test data content in a test day than an instrumented production car.

- A single VDTV can emulate the performance of many vehicles in a much shorter time period. For equal data, a large number of production vehicles will be required, each providing a data set at a particular point. In the cost analysis in Section 3.6, nine were assumed.

- Instrumented production vehicles are poorly suited to a test which varies one dynamic parameter over a range while holding others constant. An example is varying the yaw response during a test series to determine crash avoidance parameters in a hard turn and braking, a common crash avoidance scenario. For maximum research value, the test should be conducted under conditions of the same initial speed, same steering wheel rotation vs. time input (automatically done by VDTV), same deceleration (again automatically controlled by the VDTV), same roll and pitch, etc., to assure repeatable test conditions. The VDTV could vary only yaw velocity in this scenario, and vary it in a number of small increments to completely characterize the primary research variables. Duplication of the same research value would require many vehicles, each with its own characteristics, and extensive data reduction to minimize effects of unwanted variables.

- Use of production vehicles is likely to cause continued purchase and instrumentation modifications through the life of NHTSA's research program, resulting in unpredictable total program costs.

- NADS validation could only be done at discrete points. As discussed previously in Section 3.2.3, it is believed that there is an advantage in using a VDTV for this purpose.

These arguments suggest that the VDTV offers an important addition to the use of production vehicles to satisfy many of the user requirements previously identified.

3.4.2 NADS

NADS, when operational, will provide a significant test capability for NHTSA. It should be particularly valuable in evaluating the human factors aspects of crash countermeasures in potentially hazardous situations without putting subjects at risk (References 8.5 and 8.6). There are, however, limitations to simulation, several of which are documented in Reference 8.7.

An example is that sustained high-g maneuvers at vehicle performance limits are difficult to achieve because of physical linear motion restrictions. Reference 8.8 discusses some of the challenges in this regard. Another example is an inability to produce the high-fidelity dynamic performance that can be achieved with test vehicles on a test track. The VDTV could be a valuable complementary test tool to NADS in both of these areas. It would provide NHTSA with a capability to perform testing over a complete range of performance in crash avoidance scenarios, while generating dynamic data of excellent quality. These results could be correlated with those of NADS, thereby effectively extending the test envelope.

This study disclosed a reluctance of the auto industry to accept simulator data products. Validation of NADS data products will thus be an important factor for several years. This assessment is compatible with that of the Daimler-Benz (D-B) simulator, which has been operational for about ten years. A period of about five years was required to get acceptance of simulator data, even though the D-B simulator had access to their corporate testing data and used such data for extensive tuning. This experience indicates that the VDTV could play a valuable role in concert with NADS, providing a highly capable tool to continuously validate NADS data,

While NADS will be an important addition to NHTSA’s research capability, there are aspects of the test spectrum for which a VDTV would be an advantageous alternative. Further, there are specific research areas in which a combination of NADS and VDTV would provide a high degree of synergism to enhance NHTSA’s research capability.

3.4.3 Computer Simulation

Whereas NADS employs a combination of hardware and software simulation, it is possible that some NHTSA research requirements could be satisfied by software alone. However, computer simulation using unvalidated models is less likely to be accepted by the automobile industry or by the government in assessing technologies or human factors that may ultimately influence legislation than full scale testing would be. While there are research areas for which computer simulation could be the appropriate and most cost-effective approach, no further evaluation of this alternative was made in this study.

3.5 UTILIZATION ASSESSMENT

The preceding sections identified potential VDTV uses and users. Qualitative VDTV benefits as well as alternatives were discussed. However, NHTSA’s benefit will result only through extensive VDTV utilization to increase the pace of crash avoidance research. This section thus addresses VDTV utilization during its estimated five year life.

3.5.1 Rationale for the Utilization Estimate

Utilization estimates correspond to the same users as those of Sections 3.2 and 3.3. Since only limited documentation of research plans and information from prospective users outside NHTSA were available, assumptions were necessary. These assumptions are documented in Appendix C-3, with only summary information presented in this section.

The full capability VDTV, described in Section 5.2.5.2, is assumed for this utilization assessment. Although funding constraints may limit the VDTV's initial capability, it is reasonable to use the full capability version for a valid assessment of potential VDTV utilization.

3.5.2 Utilization Summary

Because the limited documentation did not permit an objective analysis, this study developed a set of analysis sheets which addressed the uses defined in Sections 3.2 (Major NHTSA Users) and 3.3 (Other Users). The form of the sheets and the users are correlated with information gathered in this study. However, it was necessary to estimate times that the VDTV would be used if it were available. Estimates were based on typical operations in the research environment, and are subjective but are believed to be reasonable. Given the iterative nature of such work, the estimates may be conservative.

A summary of the potential VDTV use, based on the work contained in Appendix C-3, is contained in Table 3-3.

Table 3-3 shows the time, in months, that a VDTV could be expected to be used over a period of five years. The estimates are believed to be conservative, taken between the minimum and maximum for each user category. The major NHTSA users alone are likely to oversubscribe a single VDTV.

Table 3-3 VDTV Utilization Analysis Summary

	---VDTV USE TIME RANGE---		ESTIMATE
Summary of All Users	Minimum Time	Maximum Time	Average Time
1. Human Factors Research	(a)	(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

(a) Not estimate.& see Appendix C-3 for discussion of average time.

(b) Total time is over a five-year period.

The Other Users category may be the most important to accomplish NHTSA's mandate: facilitate the successful development of promising crash avoidance concepts (Reference 8.5). By offering the VDTV as a proven test tool, NHTSA is likely to foster crash avoidance interest in the auto support and research communities. The user survey discussed in Section 2 showed a high interest from these communities, and a high interest in crash avoidance. Although the interest in the VDTV was only medium, it is likely that this interest would increase with a full disclosure of the VDTV capabilities which could decrease test costs necessary to develop crash avoidance technology. These two communities may be able to use at least one VDTV full time.

3.5.3 Supporting Scenarios

Operational scenarios supporting the users of Section 3.2 and 3.3 were developed and are contained in Appendix C-4.

3.6 COSTCOMPARISON

An estimate of the cost to perform tests using the VDTV, multiple instrumented production vehicles (MIPV) and NADS was made and the results are shown in Table 3-4. Several key assumptions were necessary to generate these data:

1) Two VDTV options are included: (a) a limited-capability vehicle and (b) a full-capability vehicle (see Section 5 for a discussion of these options, including acquisition costs).

2) Nine MIPVs are assumed during a one-year test period based on the following:

   - NADS validation was used as a reference.

   - Minimum-Three different vehicles (each in the center of large, medium, and small classes) with two vehicles for each class (good and poor dynamic performance). NADS would then have six validation points.

   - Desired-Four different vehicles (upper edge of the large class, both sides of the medium class, and lower edge of the small class) with three vehicles for each class (very good, average, and very poor dynamic performance). NADS would then have 12 validation points.

   JPL assumed an average of 9 vehicles between these two bounds.

3) Acquisition costs are amortized over the life of the facilities: 5 years was assumed for VDTV and MIPVs and 10 years for NADS.

4) NADS annual facility costs are taken from Reference 8.6.

5) The technical and test team support costs are based on Reference 8.6.

6) Both acquisition costs and operating costs are annualized using a present value analysis assuming a government discount rate of 10%.

As shown, the cost to operate a VDTV on an annualized bases would be of the order of $800/hr to $1000/hr depending on the implementation option selected. Comparable costs for the suite of instrumented production vehicles is about the same, while NADS would be considerably greater. Caution must be exercised in interpreting these costs on a relative basis because each test approach provides different capabilities with associated strengths and weaknesses, as indicated in the previous paragraphs. Additionally, if VDTV were acquired, it would tend to reduce the numbers of instrumented production vehicles required. It must also be emphasized that nine MIPVs would not begin to yield the number of test data points that could be acquired by a NADS or a VDTV.

Table 3-4 Hourly Operations Cost Comparison

COST AREA	COSTS ($M)			
	VDTV		MIPV	NADS
	Limited Capability	Full Capability		
Number of Units	1	1	9	1
ACQUISITION				
Design, Fabricate, Validate*	0.8	2.7	1.0	34
Assumed life (years)	5	5	5	10
One year annualized cost**	.13	.45	.16	3.4
OPERATIONS†				
Test Track/Facility/Maintenance††	.51	.51	.51	1.20
Test Support Labor	.94	.94	.94	1.26
Yearly operations cost**	1.07	1.07	1.07	1.82
Total Annual Cost	1.20	1.52	1.23	5.22
Hourly Cost ($)‡	800	1015	820	2610

VDTV = Variable Dynamic Testbed Vehicle
MIPV = Multiple Instrumented Production Vehicles
NADS = National Advanced Driving Simulator

* VDTV costs are contained in Section 5.

** Based on present value analysis using government discount rate of 10%

† Operations costs were taken from Table 13, page 64 (NADS) and Table 14, page 67 (VDTV) from Reference 8.3.

†† MIPV costs were assumed equal to VDTV costs. VDTVs are more complex, so will require more maintenance. The nine MIPVs are assumed to share four instrumentation sets which must be moved to support specific tests. Overall differences are expected to be small.

‡ Hourly costs assume 1500 hours operations per year for VDTV and MIPV and 2000 hours/year for NADS

An alternate approach to compare NADS and a VDTV is based on the NADS Technical Report, Appendix F (Reference 8.3). This approach updates the report to include a VDTV, which was not included. Based on the NADS analysis, a VDTV would have a lower cost than NADS for the 14 research problems defined in Appendix F of Reference 8.3. Results are shown in Appendix C-5.

3.7 BENEFITS

Within the scope of this study, JPL made only a subjective assessment of the benefits of VDTV. The principal results can be expressed by the following observations:

1) The major benefit of VDTV lies in its unique design features of programmable performance variability and its ability to emulate a range of automobile classes and vehicle characteristics. These and other key features are summarized in Table 3-5.

2) VDTV would be a significant addition to NHTSA' s existing or planned capabilities. It helps fill the spectrum of tools that will be necessary to meet the challenges of ever-advancing automobile sophistication and complexity, particularly considering the introduction of new crash avoidance technologies that are expected in coming years.

3) The conventional approach to testing and evaluating automobile designs, concepts and devices is to instrument a vehicle (or vehicles) having the desired features, or to install the component being evaluated on a vehicle and then perform a series of tests within a limited performance envelope. This process must be repeated with other point designs to achieve some degree of coverage of vehicle sizes and characteristics of interest. The VDTV would allow the tester to perform the same type of evaluation more effectively by offering the capability of readily and easily varying the vehicle dynamic subsystem characteristics in a controlled way over an extended test range. Parameters could be varied singly or in combination, depending on test objectives. It is this programmable variability that is the unique feature of the VDTV concept. A complete performance, dynamic and driver response measurement capability is an inherent aspect of the VDTV design. Thus, the VDTV provides a highly capable, integrated test platform making a systems approach to vehicle testing possible. Further, the programmable variability allows changes to be quickly made, resulting in an efficient test program.

4) VDTV can be used cooperatively with NADS to strengthen NHTSA' s overall test program. While NADS offers certain test capability advantages, especially in human factors crash avoidance testing in which a driver may be at risk, it is limited in sustaining high-g maneuvers and in providing high-fidelity dynamics data under certain test conditions. It is believed that VDTV, because of its specific design features, would complement simulator testing in these areas, thereby extending the test envelope and increasing NHTSA' s overall testing capability. Thus, the combination of NADS and VDTV should be highly synergistic, providing NHTSA with unequaled crash avoidance research capability.

5) VDTV offers an alternative and potentential enhancements to future NADS validation. Its benefit for this use lies in its ability to rapidly provide repeatable, high-fidelity dynamics data (at the subsystem or system level) for a range of automobile classes.

6) VDTV could be on-line in one to two years and would thus provide a more comprehensive test capability than currently exists. It would help meet test needs in advance of NADS, which is not at present scheduled to be generally available before 1999.

7) Until legislative bodies and the automobile industry accept simulator data, road test data will be required to support rule making activities. The VDTV is of significant benefit for this application because of its ability to provide information on a rapid turnaround basis.

Table 3-5 VDTV Benefit Assessment

VDTV UNIQUE FEATURES	BENEFIT
Variable programmable dynamic subsystems	• Provides effective tool for study of interaction of CA technology and S/Ss on vehicle and vehicle/driver system
Variable mass properties	• Improves range of performance/dynamics simulation capability • Enhances NADS validation capability
Specifically designed to accommodate CA technologies	• Rapid turn-around in testing • Common test base in well-characterized vehicle(s)
Combined human factors instrumentation, vehicle instrumentation and variable performance	• Allows systems approach to HF testing-variables can be independently changed, singly or in combination
Limit-Performance Capability	• Expand test range beyond NADS and single vehicle capabilities

CA: Crash Avoidance S/S: Subsystem HF: Human Factors

3.8 CONCLUSIONS REGARDING USE AND NEED

JPL believes that the VDTV would be of significant benefit to NHTSA and potentially to other public agencies, industry, and academia. The VDTV would provide a unique capability to dynamically test a large variety of technologies emerging from the IVHS programs from the standpoint of safety and human factors. Discussions with the most experienced automobile firms have indicated that no similar comprehensive capability currently exists in a single test vehicle. The advantage and uniqueness of VDTV lies in its variability and its ability to simulate and test a range of automobiles and dynamic characteristics by rapidly making configurational changes.

Specifically, the VDTV would provide beneficial support to the OCAR in testing crash avoidance technologies emerging from the IVHS program. It would provide a significantly capable dynamic platform for component and human factors testing. The VDTV could support the NADS program in both software and hardware validation and in performing testing beyond the NADS range. It could also provide a capability useful to the AHS program, possibly offsetting its need to acquire similar test vehicles. The VDTV could provide NHTSA with a capability for independently evaluating AHS technologies from the point of view of safety and other human factors.

The numerous uses identified for VDTV, the benefits accruing from its unique capabilities, and the realization that the sophistication and complexity of future automobiles will continue to increase, provide a strong argument for the acquisition of a VDTV capability by NHTSA. The acquisition of VDTV should be viewed as complementing and extending existing test capabilities such as single-vehicle testing and NADS, in that no one approach can satisfy all future test objectives.

4. VDTV DESIGN DESCRIPTION

The approach used in designing the VDTV was to provide for maximum variation of dynamic characteristics with a minimum number of vehicles and at a minimum cost. The goal was to design one or more vehicles to encompass the inertia and dynamic characteristics of passenger vehicles ranging from small compact economy cars to large luxury sedans. The total vehicle weights to be simulated range from approximately 900 kg to 2300 kg. An artist's conception of the vehicle is shown in Figure 4-l and a schematic of the vehicle architecture is shown in Figure 4-2.

4.1 PHYSICAL CHARACTERISTICS

In as much as feasible, the VDTV physically resembles a production type vehicle, designed to be driven on public roads and includes all passenger safety features such as safety glass, seat belts, and airbags. The front compartment of the vehicle accommodates the driver and one vehicle operator. The function of the vehicle operator is to assure the execution of the appropriate test procedures via a laptop computer terminal. The rear passenger compartment provides seating for a minimum of two observers.

4.2 MECHANICAL SUBSYSTEM

The major mechanical subsystems of the VDTV are the chassis, the power plant, the drive train, the suspension, the wheels/tires, steering and traction, and braking. Figure 4-2 shows the interfaces of the major mechanical subsystems.

The chassis, designed to minimize weight, accommodates safety features for the passengers, such as roll-over bars, and provides structural support to all the subsystems within their expected variation in weight and volume. The chassis also has provisions for carrying additional weights to simulate the moments of inertia of larger vehicles.

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 for adding weights at specific locations 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. Appendix D-1 provides a discussion of vehicle weight and inertia characteristics.

A baseline vehicle was defined that weighs about 1450 kg, has a 1 Hz natural yaw frequency, accelerates to 100 km/hr (-60 mph) in 9 seconds, stops from 100 km/hr in 45 m, and can reach 0.80 lateral g on a skidpad[1]. When the automated control systems are inactive, the modified vehicle would weigh about 1725 kg, with all dynamic performance parameters degraded by about 10% because of the additional weight and the location of the additional weight. Emulation of smaller vehicles may be difficult because of the increased weight. This question is addressed later in Section 4.8.

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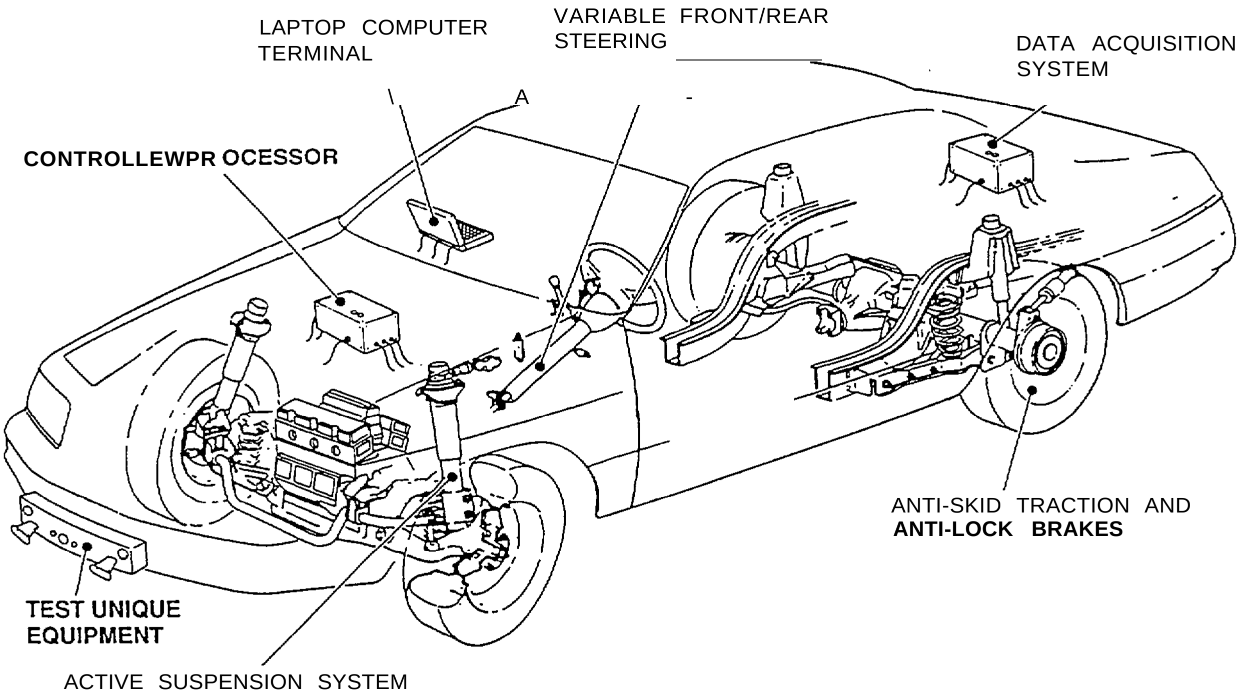
[1] Average performance of US 5 passenger sedans taken from track test summary data, Road and Track magazine, January 1994, pp. 134-135.



- DRIVE-BY-WIRE CAPABILITY
  - THROTTLE
  - STEERING
  - BRAKING

. COMPUTER CONTROLLED SUBSYSTEMS
  - POWER TRAIN
  - TRACTION AND BRAKING
  - STEERING
  - **SUSPENSION**

Figure 4-1 Artist's Conception of Vehicle

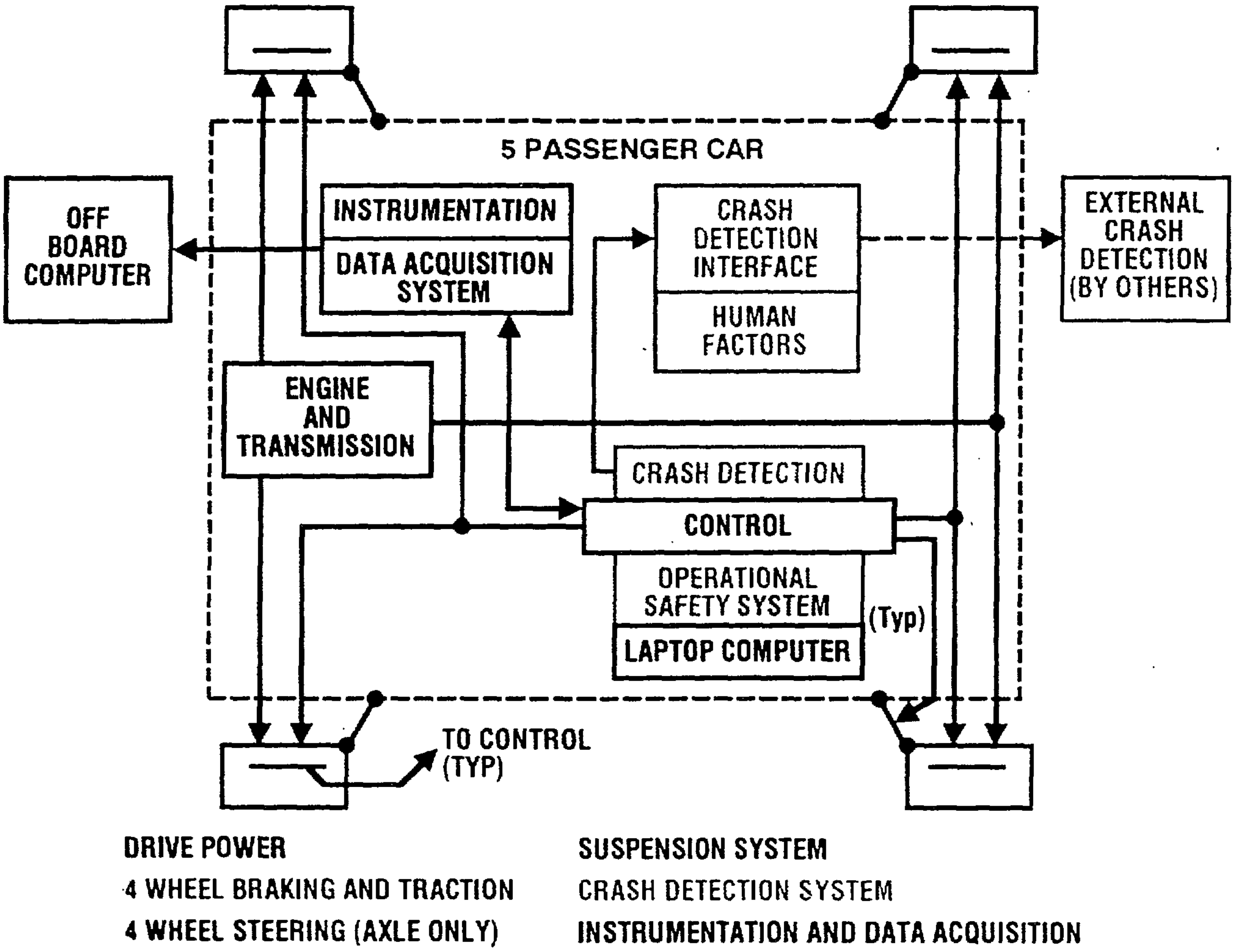


FIGURE 4.2
VDTV Conceptual Design Schematic

The power plant is sized to meet the vehicle performance requirements for the maximum range of vehicle weights and inertias and provides mechanical and electrical energy to operate all the subsystems. The drive train consists of a fully automatic transmission with electronic shift, and provisions for switching to front-, rear-, or four-wheel drive.

The suspension system has the capability to vary force, stiffness, and damping to accommodate changes in weight and inertia to simulate the dynamic behavior of vehicles from small economy cars to large sedans.

The traction and braking subsystem, including the wheel and tire, is equipped with the appropriate sensors and actuators for accommodating traction control and antilock braking.

The steering system has the provision for four-wheel steering with a variable ratio of rear-wheel-to-front-wheel steering coefficients.

4.3 CONTROL SUBSYSTEM

The vehicle lateral, longitudinal and heave dynamics will be varied using control algorithms. To alter the lateral dynamics of the vehicle, a four-wheel steering system will be used. Similarly, a full active suspension system and an antilock braking system will be used to change the heave and braking dynamics of the VDTV vehicle, respectively. A schematic of the control architecture is shown in Figure 4-3.

The VDTV will be equipped with sensors, such as vehicle accelerometers and yaw-rate gyroscopes, and actuators, such as an electro-hydraulic steering servo system. Sensor signals will be filtered and processed by properly designed control algorithms whose outputs consist of commands to various actuators. Changes in control algorithm software will be used to alter both the steady state and transient characteristics of the VDTV’s lateral/longitudinal/heave dynamics.

Drive-by-wire technology, including the steer-by-wire, brake-by-wire, and throttle-by-wire, will be implemented to support various human factors related research programs as well as the requirement to support the Automated Highway System. In these drive-by-wire systems, the mechanical connections between the driver and the actuators are removed and the driver commands are measured by sensors. Electric and/or hydraulic servo systems are then slaved to the driver commands. All these systems will contain fail-safe features that will re-establish the mechanical linkages between the driver and the actuators when failure is detected, or when commanded by the driver. Detailed descriptions of these control systems are given in Appendix D.2.

4.4 POWER SUBSYSTEM

The VDTV system provides power for all the vehicle subsystems and for the test-unique sensors and actuators. A schematic of the vehicle power system is shown in Figure 4-4.

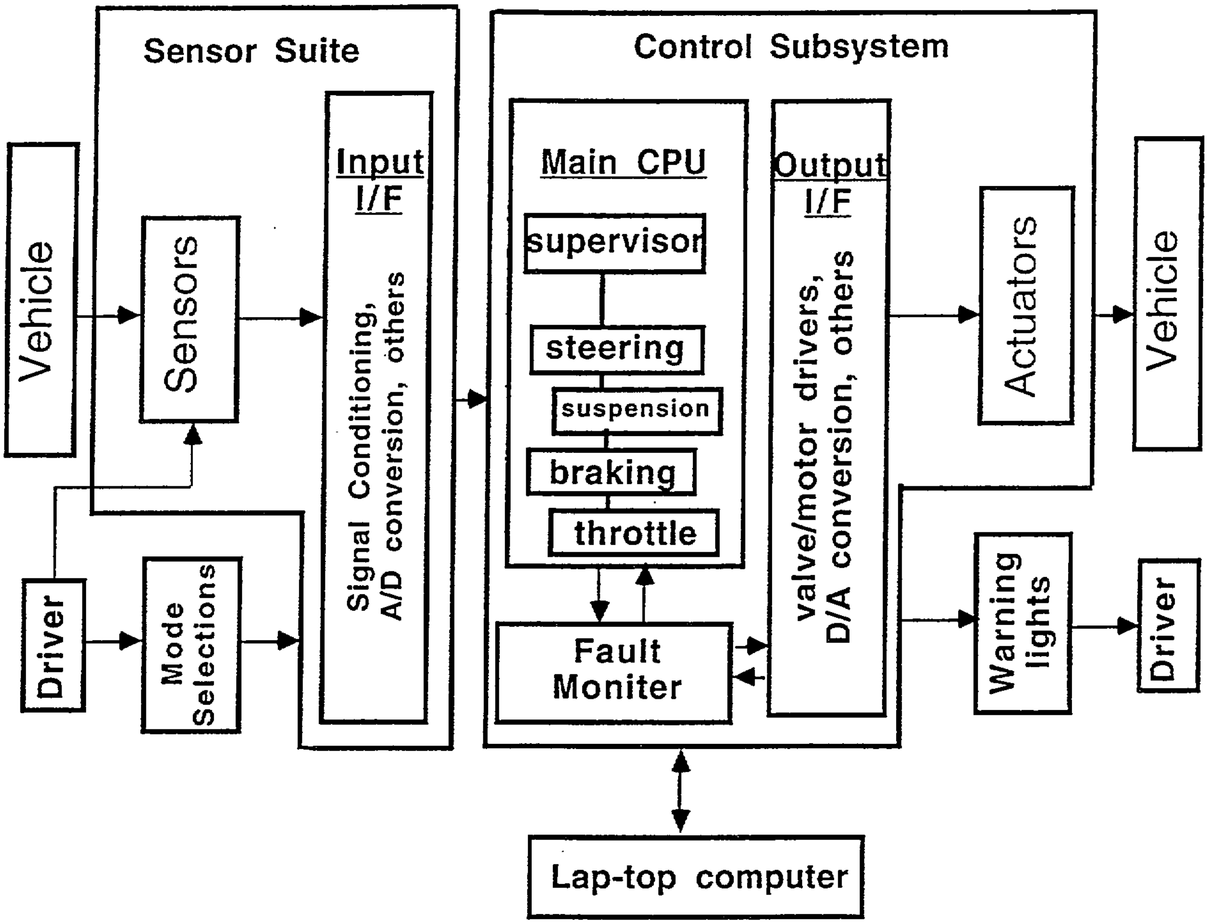


Figure 4-3 Control Architecture

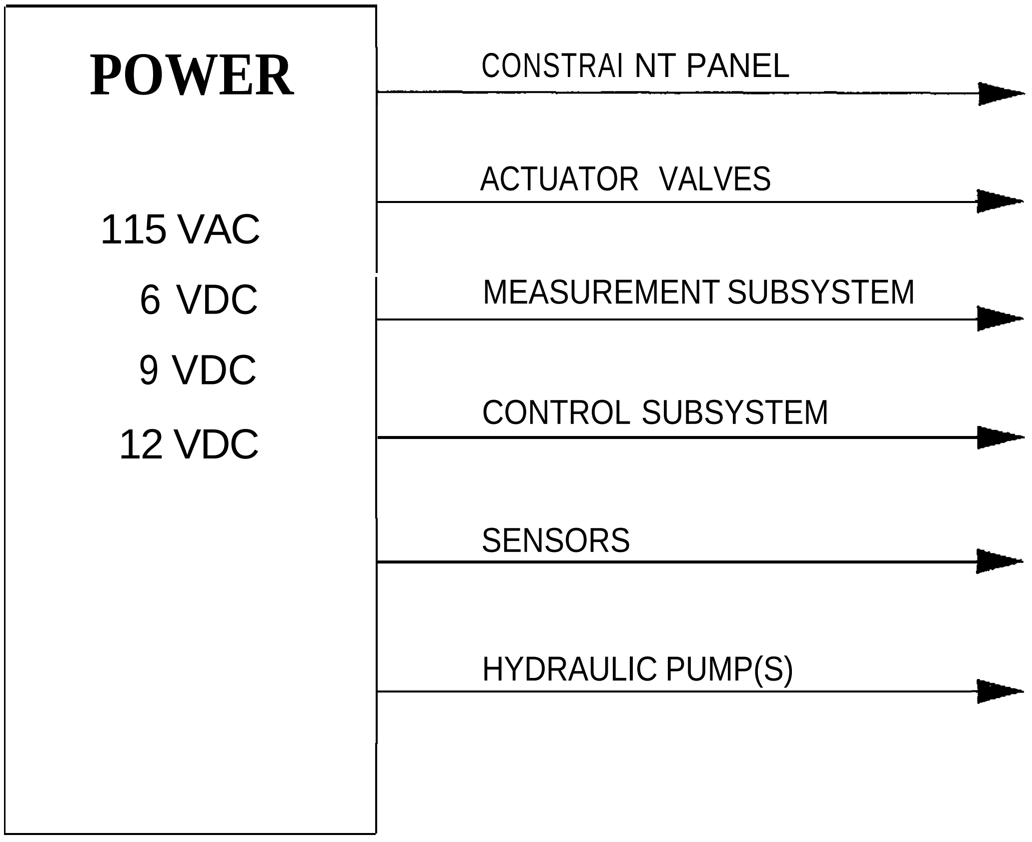


Figure 4-4 Power Architecture

4.5 ON-BOARD MEASUREMENT SUBSYSTEM

The VDTV Measurement Subsystem will consist of five major components: the power supply, sensors and actuators, the data acquisition platform, the controller, and the data storage/-transmission subsystem. A block diagram of the measurement subsystem is shown in Figure 4-5.

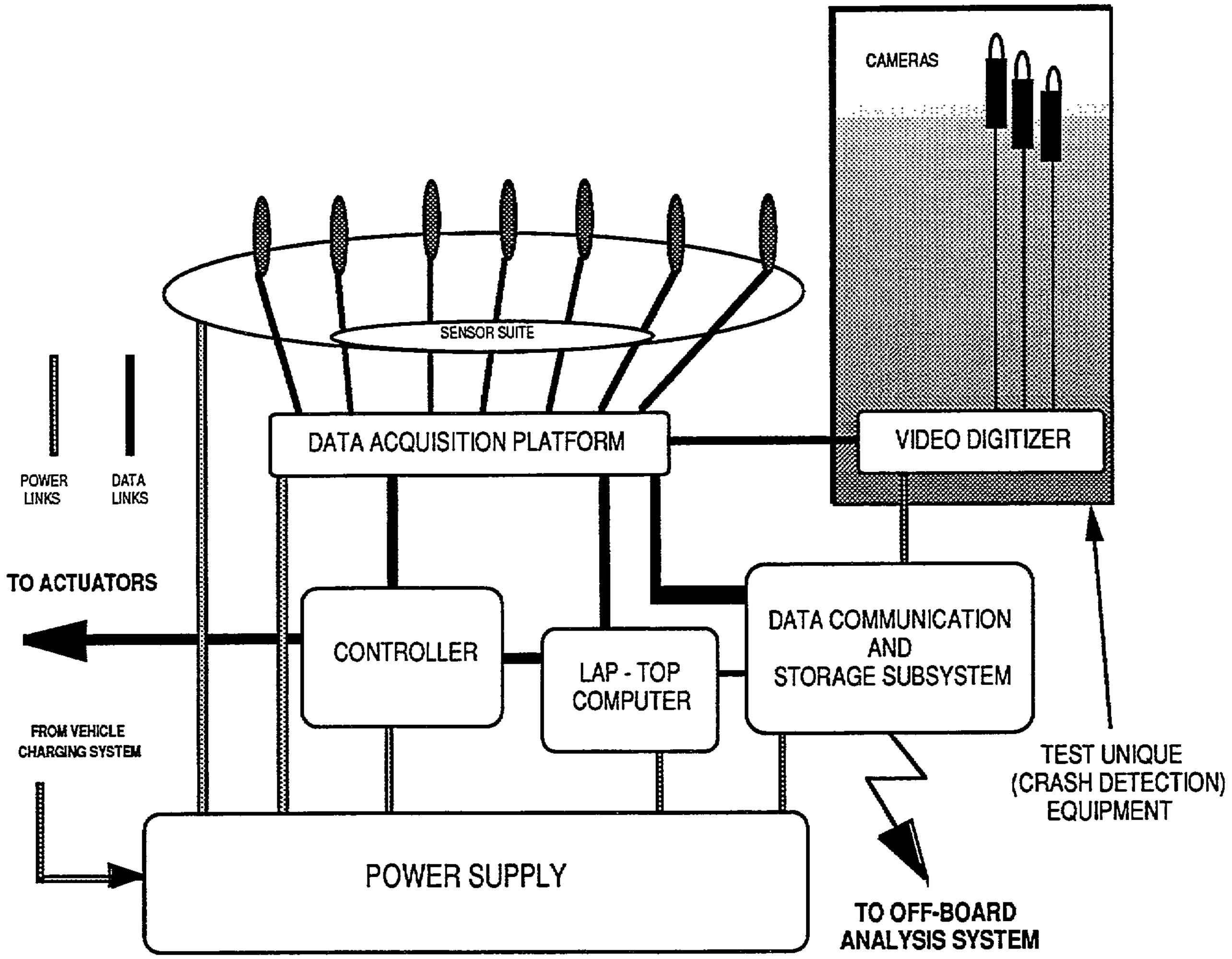


Figure 4-5 Block Diagram of Conceptual Design of the Proposed Measurement Subsystem for VDTV

The power supply will provide the required power to the measurement system. It will be isolated from the vehicle main power system and will consist of a minimum of one 12 volt battery and a switching system.

The VDTV will be equipped with extensive sensors. These sensors will be used to monitor vehicle dynamic parameters such as the linear and rotational velocities and accelerations, throttle position, brake pressure, steering, suspension system and drive train parameters as well as the general status of the vehicle such as seat belt indicators, turn signals position, and door and window monitors.

The data acquisition platform will contain the signal conditioning equipment as well as the analog-to-digital converters. This conversion will be done in a distributed fashion to enhance signal-to-noise ratio and processing efficiency. The system will be designed to accept a variety of different signals' and will provide a complete and flexible software system. It will accommodate the maximum needed number of sensors, provide ample capacity for onboard storage and backup and a sampling rate high enough for all measurements.

The controller, via the processor or a set of communicating processors, will have the capability for the installation of various control algorithms and will provide the required signals to each of the actuators. The controller will provide a compiler with a common programming language, such as C, and standard interfaces to other controllers.

The data storage and communications subsystem will provide the data handling facilities for the VDTV. It will also contain backup capabilities in the event of radio link failures. A more detailed discussion of the measurement subsystem is contained in Appendix 0.3.

4.6 OFF-BOARD DATA PROCESSING SUBSYSTEM

An off-board Data Processing Subsystem (DPS) provides the required capability to process, integrate, interpret, and analyze data recorded by the onboard Measurement Subsystem. These data are presented to the user in a specified format.

DPS hardware provides capability to communicate with the onboard Measurement Subsystem, has enough memory to store recorded data, and has a user-friendly operator interface. DPS software offers standard analysis routines along with a capability for custom programming.

4.7 OPERATIONAL SAFETY SUBSYSTEM

The operational safety subsystem provides control of the drive-by-wire subsystems. A key requirement for the operational subsystem is the transition of the VDTV from the automatic to the manual operations mode. This transition may occur during transient operation near limits of vehicle maneuvers. This transition will be made without introducing sudden transients that could cause an unsafe operating condition. The operational safety subsystem will be actuated either by a manual panic button or a signal from the controller. Appendix D.4 contains a more detailed discussion of this subsystem

4.8 VDTV EMULATION CAPABILITY

4.8.1 Emulation range

An important factor to both implementation approaches is the VDTV's emulation range. NHTSA stated that the emulation range should include small economy cars/sports cars through at least a US large luxury sedan, with a desired range extending to a minivan and four wheel drive vehicles. This range raised the question: can a single mid-size passenger car, with the added weight of the dynamic subsystems, emulate the performance of a small vehicle? This question is illustrated in Figure 4-6.

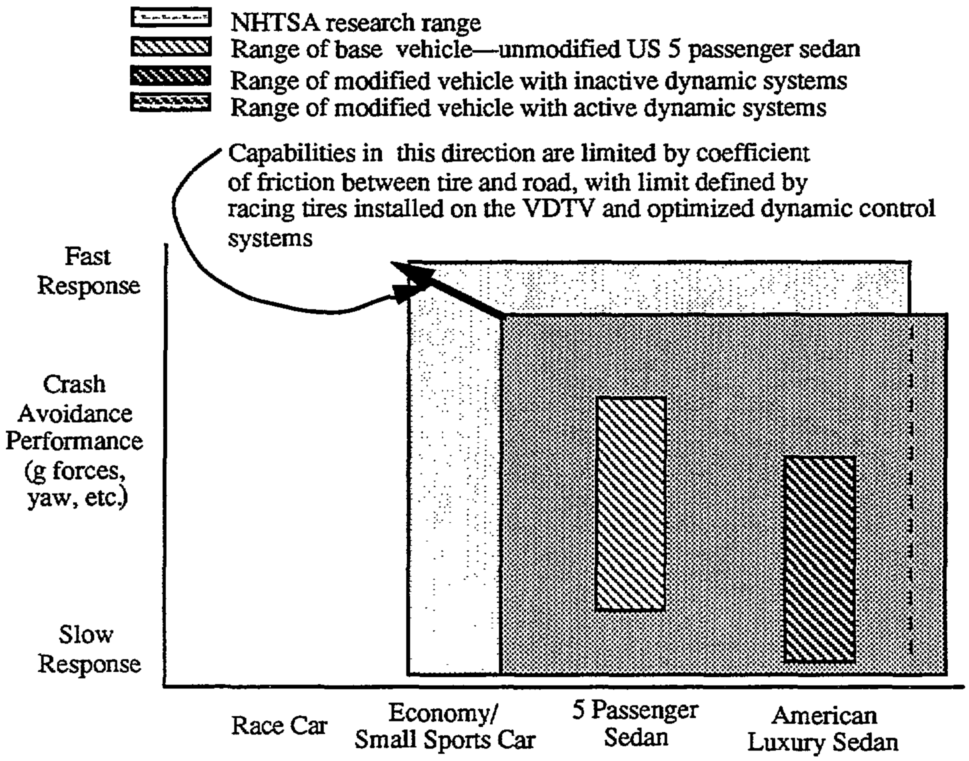


Figure 4-6 VDTV Emulation Range

Lotus Engineering has provided data which shows that one VDTV, based on a mid-size US passenger car, can achieve the desired emulation range. However, it is highly probable that excellent performance of several interacting dynamic subsystems will be required to achieve this emulation range with a mid-size vehicle as the base. The emulation range, both from NHTSA's requirements in this regard and the ability to achieve the range, is thus an important factor in any future implementation decision. Appendix D.5 contains a further discussion of this question.

4.8.2 Limited Lateral Dynamics Analysis

While further analysis needs to be performed using non-linear programs to fully characterize this capability, a limited-scope study was carried out to investigate the extent to which the lateral dynamics of a range of vehicles can be emulated by a single variable dynamic vehicle. Here, the variability in the vehicle lateral dynamics is to be achieved via the combined use of: (a) adding dummy weights to the vehicle's sprung mass[2], and (b) steering the rear wheels of the vehicle.

To analytically investigate how well this can be done, a vehicle handling model, VEHDYN, was employed that was developed in this study. In VEHDYN, the lateral dynamics of a vehicle are modeled using the approach proposed in Reference 8.9. The model includes both the vehicle's yaw and roll degrees of freedom. For simplicity, VEHDYN uses a linear tire model. Lateral forces and aligning torques generated by the

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[2] See advisory note regarding this assumed variable later in this section.

tires are computed as functions of the tires' slip and camber angles. Estimates of vehicle and tire parameters needed by the VEHDYN model, for a spectrum of passenger sedans (from small to full-size), are made based on data given in Refs. 8.10 and 8.11.

Using VEHDYN, and the estimates of vehicle and tire parameters, both the steady-state and transient characteristics of the selected sedan models can be computed. One of the most important steady-state characteristics of a vehicle is its control sensitivity. At a given forward speed, it is defined as the vehicle's steady-state lateral acceleration (at the vehicle's c.g.) per 50 degrees of steering wheel excursion. It is also sometimes called the vehicle's steering sensitivity or lateral acceleration gain.

Representative time-domain vehicle transient performance metrics are the 90% rise times and "percent overshoots" of a vehicle's acceleration responses to a "pseudo" step steering input. These commonly used vehicle performance metrics are defined in Reference 8.11. The lateral dynamics of a vehicle can also be measured using frequency-domain performance metrics. A representative frequency-domain performance metric is the vehicle's yaw rate-based bandwidth (BW). It is the frequency at which the magnitude of the transfer function from the steering wheel to the vehicle's yaw rate has dropped below 70.7% (-3 dB) of its steady-state value (see Reference 8.11).

As can be seen from Fig. 4-7, both the steady-state and transient vehicle performance metrics generally increase monotonically with the forward speed of the vehicle. At a constant forward speed of about 100 km/h there are also significant differences between the control sensitivities of small and full-size vehicles. Our objective is then to be able to manipulate the variable dynamics vehicle so that it can emulate the characteristics of a "small" sedan in one configuration and a "full-size" sedan in a next configuration.

One way to alter the steady-state and transient responses of a vehicle is to add dummy weights on the vehicle's sprung mass. This is because the additions of "dummy" weights on a vehicle can increase the mass and yaw moment of inertia of the vehicle's sprung mass, move the vehicle's c.g., and alter the tires' cornering and camber stiffnesses, resulting in significant changes in the vehicle lateral dynamics.

It should be noted that while the analysis was run assuming that a variable mass capability was to be available, no decision has been made nor is one implied regarding the use of this capability in an operational test vehicle. It has the advantage of offering another degree of freedom in changing the dynamic response of the vehicle and improving its emulation capability, but it adds complexity that, ultimately, may not be desirable or needed. Further studies will have to be conducted to resolve this issue.

The lateral dynamics of a vehicle can also be substantially altered by steering its rear wheels in conjunction with those at the front. For example, the control sensitivity of a four-wheel-steering vehicle at a given forward speed can be increased/decreased by steering the rear wheels out-of-phase/in-phase with the front wheels (see Reference 8.12). Additionally, the transient characteristics of the vehicle can also be "manipulated" via carefully designed control algorithms (see Reference 8.13). The combined use of adding dummy weights and steering the rear wheels thus allows us to conveniently emulate the directional characteristics of a wide range of passenger sedans.

With the above-mentioned approach, the computed levels of variability that one can achieve are as indicated by the shaded areas depicted in Fig. 4-7. However, it should be emphasized here that all our results were obtained with linear vehicle and tire models, and are accurate only up to about 0.3 g's of vehicle maneuvers. Beyond that, models which include both the tire saturation effects and suspension nonlinearities should be used. This is beyond the scope of our study. However, given the results of Lotus Engineering analyses with rear-steering and active suspension, and the results of this analysis, it is concluded that a VDTV with a combination of these features can emulate a reasonably broad range of automobile types.

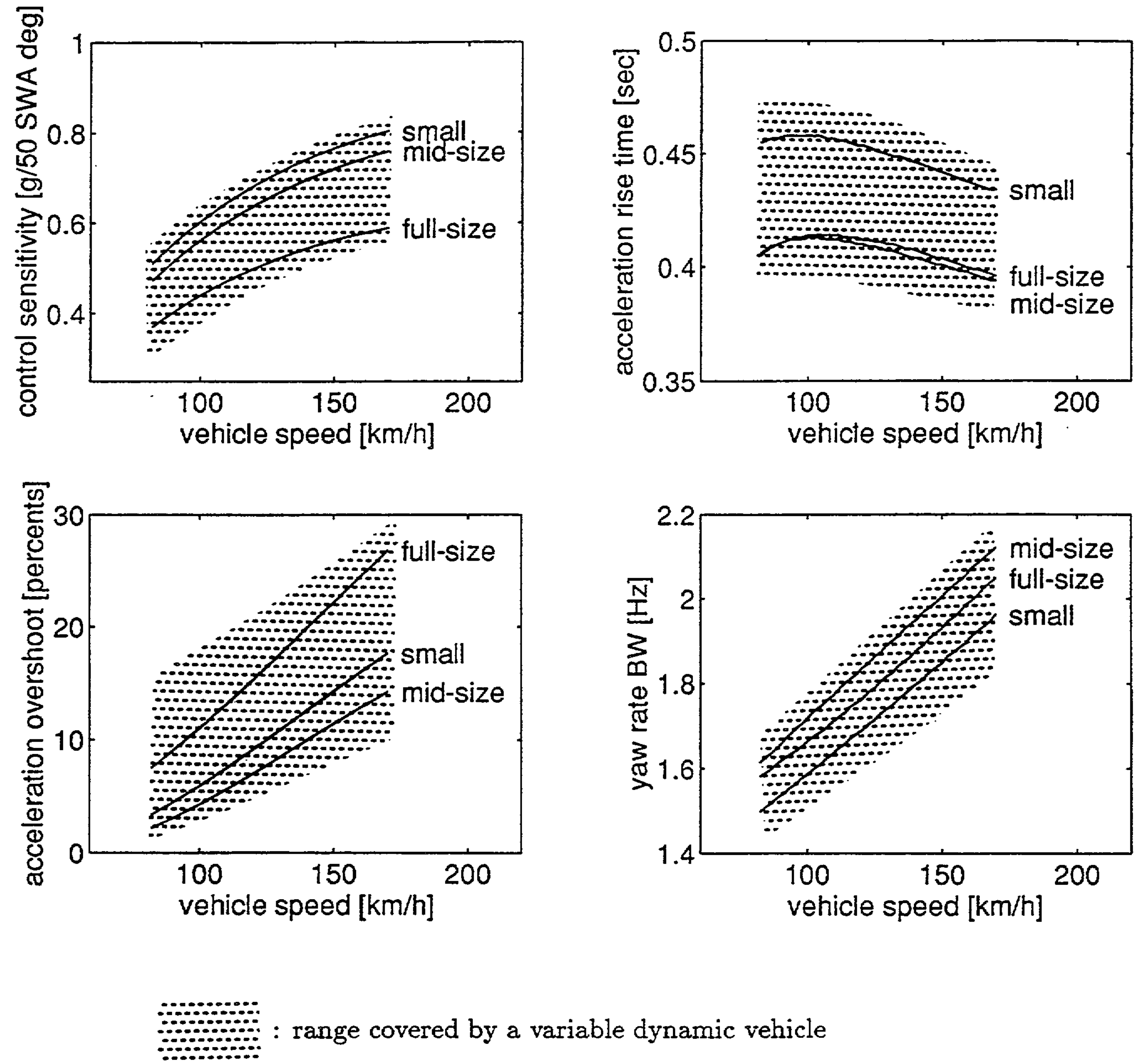

Figure 4-7
Variations of Lateral Vehicle Performance Metrics with Vehicle Forward Speed

5. IMPLEMENTATION APPROACHES

5.1 INTRODUCTION

During the course of the study, NHTSA directed JPL to investigate lower cost options than those presented at a mid-term review. Four different vehicle configurations, whose capabilities were expected to meet minimum requirements of the four major NHTSA users (human factors, AHS support, NADS support, and technology assessment), were discussed during that review. This section discusses lower cost implementations with emphasis on a division of costs by dynamic subsystem and major functions within each subsystem. This is intended to provide NHTSA with information to correlate capabilities of individual dynamic subsystems with costs.

This section also discusses two different implementation approaches:

1. VDTV implementation using technology developed by Lotus Engineering (LE). In this report, vehicles incorporating this technology are referred to as reference *vehicles* or reference configurations. These techniques have been frequently used by LE to implement variable research vehicles for the last ten years. In general, these approaches provide dynamic performance considerably greater than that of current passenger cars, full variability of each dynamic subsystem, and reasonably well known performance parameters.

2. Lower cost options based on modification of a production passenger car by different firms who have had experience with such modifications using technology mainly from US supliers. While such modifications have been made, their performance and cost are not as well defined.

This section contains three major topics. The implementation using reference technology is discussed in Section 5.2, and includes definition and cost of vehicles for the four major NHTSA applications. Lower cost options are contained in Section 5.3. Section 5.4 closes with conclusions and recommendations concerning any future VDTV implementation.

Three major implementation assumptions guided this work: (1) NHTSA's performance, cost, and schedule needs had to be met; (2) a competitive procurement must be used to acquire the vehicle(s); and (3) the vehicle must be built by a US company. These assumptions are discussed in Appendix E.l. Also, all costs are those for a contract to build the VDTV; management and contract monitoring costs are not included.

In this discussion, the term "VDTV" will be used for one or more vehicles. In the case of multiple vehicles, their combined performance will equal that of the single full capability VDTV described in Section 5.2.5.2.

5.2 REFERENCE TECHNOLOGY IMPLEMENTATION

The full capability VDTV, broadly defined by NHTSA at the start of the study, includes many dynamic subsystems to provide a highly capable research vehicle. To provide NHTSA with lower cost options, the number of dynamic subsystems has been reduced with corresponding loss of capability. The subsystem technology remains the same.

Performance and costs of this section are based on information from Lotus Engineering, commonly regarded as the world's leader in variable dynamic vehicle technology. A VDTV based on this technology would have the benefit of extensive experience for many years, as described in Table 3- 1, Section 3. Because of this experience, the dynamic performance is well known and can be quantified based on measured performance of delivered products.

5.2.1 Framework for the Reference VDTV Technology Implementation

This implementation approach is based on a core subsystem and dynamic subsystems which are added to the core subsystem. Basic features are listed to assist understanding of both definitions and costs:

- Core Subsystem. Includes the vehicle, electrical power, hydraulic power, control subsystem, and measurement subsystem. The core subsystem will support all the dynamic subsystems. The hydraulic power consists of the pump, reservoir, accumulator, control valves, and plumbing throughout the vehicle. Dynamic subsystems requiring hydraulic power are then attached at their location. The electrical power services the control and measurement subsystems and also the interfaces where future crash avoidance devices would be connected. The control and measurement subsystems include the computers, I/O equipment, resident software such as the operating system, and also serve the crash avoidance interfaces.

- Dynamic subsystems. Includes the hardware (actuators, control valves, sensors, etc.) directly used by the dynamic subsystem, and software for the subsystem. The software would be resident in the control or measurement computers, but are costed in each dynamic subsystem. Tests specific to each dynamic subsystem are also included in its cost. Any dynamic subsystem can be connected to the hydraulic, electrical power, control and measurement functions of the core subsystem.

- System engineering. Activities from start of work to delivery define interfaces, system dynamic performance, and related activities.

- Development and performance verification tests. Tests are conducted at the subsystem level, then VDTV system-level development and performance verification tests are done. Costs are included in the core and dynamic subsystems.

- Documentation and training. These are included and are contained within the core and dynamic subsystems.

This method provides a means of making a first-level definition of a VDTV targeted for a specific NHTSA use area. However, this is a complex problem which requires considerable engineering judgment to arrive at an actual implementation. Examples are the degree of front-end dynamic analysis, interactions between the various dynamic subsystems (which can have a significant impact on software and testing costs), and the degree of future expansion.

For a VDTV with a limited number of dynamic subsystems which have little interaction, the cost of the core and dynamic subsystems can be added to get a reasonable indication of the VDTV capability and cost. However, this information should not be used to develop detailed cost estimates for more complex vehicles as discussed in Section 5.2.6.3.

5.2.2 Dynamic Subsystem Description

The dynamic subsystems necessary to provide the VDTV performance are shown in Table 5-2, with a brief description of each subsystem. Note that drive-by-wire (steering, brake, throttle) subsystems for operator “feel” are separated from the subsystems which actually control the vehicle. This permits selection of dynamic subsystems for each major NHTSA user to optimize capabilities for different research problems while minimizing initial cost. When needed, dynamic subsystems include a safety function which transfers control from automatic to manual operation quickly. This capability is noted separately in Table 5-2 to emphasize its importance, but its cost is contained within each dynamic subsystem that requires this function.

5.2.3 VDTV Capabilities

This VDTV implementation would provide state-of-the-art research capabilities. The performance of each dynamic subsystem would be significantly better than that of corresponding functions of current passenger cars, permitting the VDTV to investigate research problems in regimes beyond those available with standard production vehicles. Capabilities would also include limited interaction between the dynamic subsystems for optimum overall VDTV capability.

5.2.4 Dynamic Subsystem Performance

Dynamic subsystem performance was also provided by LE. These performance figures are reliable, having been attained in several vehicles. A summary is shown in Table 5-1. Other implementations may not achieve this dynamic performance.

Table 5-l Dynamic Performance of Reference Vehicle Subsystems

SUBSYSTEM	RESPONSE (Hz)	COMMENTS
Front Steering	>10	Peak velocity ~40°/sec. Typical car response is -3 Hz.
Front Steering Feel	>10	Peak velocity – 1800°/sec
Rear Steering	>10	Peak velocity -70°/sec, +/- 15° steering angle
Active Suspension	**-25**	Typical wheel natural frequency is -1oto 12Hz

Table 5-2 VDTV Dynamic Subsystems

- Automated/Manual Control-Considered to be the most important subsystem. Safety subsystem that transfers vehicle control from electronic to a full manual mode equivalent to a standard passenger car. Transfer is made quickly and smoothly to assure safe operation. Included in each steer-by-wire subsystem (steer, brake, and throttle).
- Steer-by-Wire-Electronic control of front steering which includes fixed steering feel, similar to that of an average vehicle, implemented by a spring or friction device.
- Steering Feel-Electronic control of front wheel steering feel. Continuously variable feel from torque only (no steering wheel angular motion) to angular motion with little torque. Includes non-linear feel anywhere within this range.
- Brake-by-Wire-Electronic control of braking which includes fixed brake pedal feel, similar to that of an average vehicle. Separate control of all four wheels. Pedal motion and/or force could control deceleration.
- Brake Feel-Electronic control of brake feel. Continuously variable feel from force only (no brake pedal motion) to motion with little force. Includes non-linear feel anywhere within this range.
- Throttle-by-Wire-Electronic control of engine power. Continuously variable throttle movement.
- Throttle Feel-Electronic control of accelerator pedal feel, including motion to indicate potential problem conditions.
- Semi-active Suspension---Limited control of suspension such as available on some production cars.
- Active Suspension-Full variable electronic control of active suspension, individual at all four wheels.
- Four Wheel Steering-Capability for front axle steering only, or front and rear axle steering. Full variability of control algorithms via electronic control of front and rear actuators. Includes overall steering feel based on the front wheel device.
- Traction Control-Control of drive wheels to avoid slippage during acceleration.
- ABS--Antilock Braking System. Independent control of all four wheels to avoid slippage during deceleration.
- Four Wheel Drive-Capability for front wheel drive only, rear wheel drive only, and all wheel drive. Selection made by laptop computer. Power ratio between front and rear drive power **is** fixed.
- Crash Avoidance System Interfaces-Defined interfaces for addition of future crash avoidance systems. Includes volume, mechanical mounting, electrical power to the system, and data transfer between the VDTV and the system. At least two interfaces on the front and rear of the car. Can access vehicle control via the Dynamic Control subsystem.
- Active Roll Control-Vary front and rear roll stiffness via characteristics of front and rear anti-roll bars.
- Variable Mass--Ability to add physical mass to the front and rear of the vehicle to change is inertia and CG characteristics.
- Human Factors Data-DASCAR device to measure human factors data, such as head and eyeball motion and physiological factors.

5.2.5 Development of Candidate VDTVs

Information concerning NHTSA users, their VDTV uses for research problems, dynamic subsystem performance, and dynamic subsystem cost were used to develop candidate VDTVs for each major NHTSA user. In addition, a candidate VDTV which provided full research capability was defined. The process to develop these candidates is shown in Figure l-l. The dynamic subsystems for the four major NHTSA users were determined by the following process:

1. Identification of research problems for each major NHTSA user. An example of a source of such material is Appendix F of a NADS study[3].

2. Development of the Capability/User Matrix, summarized in Table 3-2 and explained in Appendix C. 1.

3. The dynamic subsystems most needed to support each major NHTSA user. These subsystems were developed from the Capabilities/User Matrix ratings, normalization of these ratings by dividing the ratings by the number of items to obtain an average rating. The results are shown in Table 5-3.

5.2.5.1 VDTV's for Major NHTSA Users

Four candidate VDTVs, based on the above process, are shown in Table 5-4. This table identifies the major features of each vehicle in terms of the vehicle, its dynamic subsystems, and its measurement capability. The necessary control and core subsystems are included, but not listed in this table. Costs for the subsystems were obtained from Lotus Engineering and are shown in Table 5-5 as a function of their development process. A summary of the four candidate VDTVs, including their estimated cost, is then shown in Table 5-6.

These costs assume little interaction between the dynamic subsystems. As discussed in Section 5.2.6.3, such interactions can significantly increase costs. Note that the costs have been rounded to the nearest $5K. Detailed definition of each VDTV will be necessary to get better cost estimates.

These candidate VDTVs provide a capability which will meet most of NHTSA's needs for each major user. For the reference technology approach, they provide the lowest cost commensurate with this capability.

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[3] National Advanced Driver Simulator (NADS) Requirements Study, Final Technical Report, DOT Report Number HS 807 827, November 199 1.

Table 5-3. Dynamic Subsystem Ratings

	HUMAN FACTORS				AHS SUPPORT				NADS SUPPORT				TECHNOLOGY ASSESSMENT			
SUBSYSTEM	Rating E (a)	# Items (b)	Average Rating (c)	Included (d)	Rating E (a)	#Items (b)	Average Rating	Included (d)	Rating E (a)	#Items (b)	Average Rating	Included (d)	Rating E (a)	# Items (b)	Average Rating	Included (d)
Steer-by-wire	15	13	1.15	Yes	15	11	1.36	Yes	9	6	1.50	Yes	6	5	1.20	Yes
Steering feel (e)	13	13	1.00	Yes	7	11	0.64		4	6	0.67		3	5	0.60	
Brake-by-wire	15	13	1.15	Yes	15	11	1.36	Yes	5	6	0.83		7	5	1.40	Yes
Brake feel (e)	12	13	0.92	Yes	2	11	0.18		2	6	0.33		3	5	0.60	
Throttle-by-wire	13	13	1.00	Yes	15	11	1.36	Yes	2	6	0.33		6	5	1.20	Yes
Throttle feel	10	13	0.77		3	11	0.27		0	6	0.00		3	5	0.60	
Semi active suspension	7	13	0.54		7	11	0.64		5	6	0.83		3	5	0.60	
Fully active suspension	18	13	1.38	Yes	6	11	0.55		11	6	1.83	Yes	10	5	2.00	Yes
Rear wheel steering	15	13	1.15	Yes	6	11	0.55		9	6	1.50	Yes	8	5	1.60	Yes
Traction control (f)	14	13	1.08	Yes	6	11	0.55		5	6	0.83		7	5	1.40	Yes
ABS (g)	4	13	0.31		3	11	0.27		4	6	0.67		3	5	0.60	
Four wheel drive	9	13	0.69		0	11	0.00		6	6	1.00	Yes	5	5	1.00	Yes
CA interface	16	13	1.23	Yes	22	11	2.00	Yes	6	6	1.00	Yes	9	5	1.80	Yes
Active roll control	2	13	0.15		5	11	0.45		1	6	0.17		0	5	0.00	
Variable mass	8	13	0.62	Yes	7	11	0.64		9	6	1.50	Yes	7	5	1.40	Yes

NOTES

(a) Numerical ratings taken from the VDTV Capabilities/Use Matrix, subtotal row for each major NHTSA user
(b) Number of items evaluated for each user.
(c) Numerical ratings divided by the number of items to obtain a normalized evaluation for all users
(d) Subsystems are included in the vehicles if the average rating is 0.90 or greater
(e) Feel systems include the by-wire systems in the costs
(f) Traction control hardware is included in the brake- and throttle-by-wire subsystems, but additional software is in the costs
(g) ABS is included in the brake-by-wire subsystem

Table 5-4 Candidate VDTVs for Major NHTSA Users

HUMAN FACTORS	AHS SUPPORT	NADS SUPPORT	TECHNOLOGY ASSESSMENT
VEHICLE			
Good appeaerance Slightly degraded interior noise	Adequate appearance Significantly increased interior noise is permissible	Adequate appearance Significantly increased interior noise is permissible	Adequate appearance Significantly increased interior noise may be permissible
DYNAMIC SUBSYSTEMS			
Steer-by-wire Steering feel Brake-by-wire Brake feel Throttle-by-wire Active suspension Rear wheel steering Traction control Crash avoidance interface	Steer-by-wire Brake-by-wire Throttle-by-wire Special engine control Crash avoidance interface	Steer-by-wire Active suspension Rear wheel steering Four wheel drive Crash avoidance interface	Steer-by-wire Brake-by-wire Throttle-by-wire Active suspension Rear wheel steering Traction control Four wheel drive Crash avoidance interface
MEASUREMENTS			
Gross body motions Sensors for dynamic subsystems	Gross body motions Sensors for dynamic subsystems	Detailed body motions (1) Wheel motions Sensors for dynamic subsystems	Detailed body motions (1) Wheel motions Multiple interfaces to vendor devices Sensors for dynamic subsystems

(1) More sensors than in Vehicle 1, such as lateral acceleration at both axles, ride height, etc.

Table 5-5 VDTV Dynamic Subsystem Costs

$K

Subsystem	Specification	Design	Procure (Incl. Mtrl.)	Vehicle Conversion	Development	Total
Steer Feel	15	120	87	57	35	314
Steer-by-Wire	14	113	80	53	18	276
Brake Feel	15	80	83	38	35	249
Brake-by-Wire	12	60	60	30	18	180
Throttle-by-Wire	12	30	30	15	18	105
Throttle Feel	15	38	30	18	27	128
Semi-Active Suspension	23	120	75	30	30	278
Active Suspension	23	120	113	60	51	366
Rear Steer	12	80	53	38	17	198
Core System	18	120	158	60	35	390

Table 5-6 VDTV Dynamic Subsystems and Costs for Major NHTSA Users

	REFERENCE TECHNOLOGY IMPLEMENTATION			
	HUMAN FACTORS Cost ($K) (a)	**AHS** SUPPORT Cost ($K)	**NADS** SUPPORT Cost ($K)	TECHNOLOGY ASSESSMENT Cost ($K)
SUBSYSTEM				
Steer-by-wire (b)		275	275	275
Steering feel (c)	315			
Brake-by-wire (b)		180		180
Brake feel (c)	250			
Throttle-by-wire (b)	105	105		105
Throttle feel				
Semi active suspension				
Fully active suspension	365		365	365
Rear wheel steering	200		200	200
Traction control	50			50
ABS				
Four wheel drive			100	loo
CA interface	50	50	50	50
Active roll control				
Variable mass	20		20	20
Total dynamic SS cost	1355	610	1010	1345
OTHER COSTS				
Core subsystem (d)	390	310	310	390
DASCAR driver info	40			40
VDTV operator software	50	20	50	50
On-board data storage	10	10	10	10
Off-board data processing	100		100	100
Total other cost	590	340	470	590
Total vehicle cost ($K)	1945	950	1480	1935

(a) Dynamic and core subsystem costs are taken from Table 5-5 and Appendix E2

(b) The "by-wire" subsystems actuate the wheels, brakes or throttle with futed feel provided by a non-progammable device such as a spring

(c) The "feel" subsystems include the "by-wire" subsystems in their cost, so only the feel subsystem cost is included

(d) The AHS and NADS core subsystem costs have been reduced to reflect the limited number of dynamic subsystems

5.2.5.2 VDTV with Maximum Crash Avoidance Research Capability

NHTSA broadly defined VDTV capabilities which would meet all research requirements at the start of this study. This vehicle, called the Full-Capability VDTV (FCVDTV), includes all dynamic subsystems. If implemented, the FCVDTV would clearly be the world's most capable automotive research vehicle. This is confirmed by discussions with experienced personnel from the US auto industry; none had a vehicle with the FCVDTV capabilities. The dynamic subsystems of Table 5-2, except for semi-active suspension and active roll control which are not needed with a fully active suspension subsystem, are included. Full engineering and test activities are also included, since these would be essential to build and validate such a vehicle. To minimize risks associated with a complex vehicle, costs for thorough subsystem tests prior to integration into the vehicle are included. After all subsystems are integrated into the vehicle and the first shakedown tests have been completed, a ten month period to develop the hardware and software, then validate the on-board software, is costed. Validation costs are thus a significant percentage of the FCVDTV's total cost.

A summary of the dynamic subsystems and additional tests for the FCVDTV is shown in Table 5-7. Cost is then shown in Table 5-8 which includes comments on the tasks needed to develop the FCVDTV. Testing costs, both at the subsystem and system level, are an appreciable factor but are essential because of the complex nature of the vehicle.

The FCVDTV represents the upper end of the capability and cost spectrum. Its implementation in a phased sequence could be a logical NHTSA goal.

5.2.6 Reference Vehicle Implementation Cost Estimates

5.2.6.1 Overview

To assure reasonable cost estimates for the four approaches, JPL established the following criteria:

1. Any source providing cost estimates must have directly applicable experience with the functions defined in their estimate.
2. Efforts to cross check cost estimates were included whenever possible.

As stated earlier, the most lmowledgeable firm was LE so their estimates, obtained under a support contract, were used for the reference technology approach.

Core and dynamic subsystem costs were divided into functions of specification, design, procurement, vehicle conversion, and development. These costs are shown in Table 5-5; an analysis showing percentage costs for each cost item is shown in Table 5-9. Note that the "feel" systems include the systems which control vehicle motions. As an example, the cost of steering feel includes the servo system which drives the front wheels and the servo system which provides feel to the steering wheel.

Table 5-7 Full-Capability VDTV Engineering, Subsystems and Tests

SUBSYSTEMS (a)	**COMMENTS**
CORE SUBSYSTEM	Provides hydraulic, electrical power, control and measurement subsystems to the entire vehicle
DYNAMIC SUBSYSTEMS	These subsystems were included in Lotus Engineering (LE) costs
Front Steer-by-Wire	High bandwidth control of front wheel steering
Steer-by- Wire Feel	
Brake-by-Wire	Deceleration control
Brake-by-Wire Feel	
Throttle-by-Wire	Engine power control
Throttle-by-Wire Feel	
Active Suspension	Research quality performance: >> production versions
Rear Steer-by-Wire	Fully variable control of rear wheel steering
ABS	Independent control of all four wheels
ADDITIONS	Additions to the Lotus Engineering cost estimates
DASCAR Human Factors Module	Drivers' head, eye movement, physiological parameters.
Traction Control	Hardware is included in LE costs. Add for software which will individually control of all four wheels
Four Wheel Drive	Assumes that base vehicle has 4WD which is modified
Crash Avoidance Interfaces	Electric power, multiple I/O signal interfaces, four ports, software interfaces to Control & Measurement software
VDTV Operator Software	Menu-driven software to facilitate rapid VDTV configuration changes
On-board Data Storage, Transfer	Store data in form for transfer to off-board data processing
Off-board Data Processing	Hardware and software costs for data processing at site
Front-end System Engineering	Essential to define subsystem performance and interactions of a complex vehicle
Dynamic subsystem tests	Performance, reliability tests prior to integration into the vehicle
Development and validation tests	Comprehensive tests covering a ten month period

NOTES

(a) Subsystems refer to Table 5- 1

Table 5-8 Full-Capability VDTV Engineering, Subsystems and Costs

Costs for the first vehicle, including full non-recurring costs

SUBSYSTEMS (a)	COMMENTS	ESTIMATED COST ($K) (b)
CORE VEHICLE	Includes same items as those for the four major NHTSA users: DASCAR interface, operator software, data storage, and off-board data processing	590
DYNAMIC SUBSYSTEMS &FEATURES		
Front Steer-by-Wire, Feel	Included in the Lotus Engineering cost estimates	315
Brake-by-Wire, Feel	Included in the Lotus Engineering cost estimates	250
Throttle-by-Wire, Feel	Included in the Lotus Engineering cost estimates	130
Active Suspension	Included in the Lotus Engineering cost estimates	365
Rear Steer-by- Wire, Feel	Included in the Lotus Engineering cost estimates	200
Traction Control	Software, interaction between subsystems, and test costs	50
ABS	Software labor, analog control, and test	20
Four Wheel Drive	Modification to base vehicle's capability only. If base vehicle does not have 4WD, cost is extremely high	100
Crash Avoidance Interface	Hardware at each interface, installation and checkout labor	50
Variable Mass	Capability to add mass to vary weight, inertia and center of gravity	20
Total subsystems		2090
ADDITIONS (c)	Changes to the Lotus Engineering cost estimates	
Front-end System Engineering	Detailed dynamic analysis of subsystem interactions which will define subsystem specifications and software	100
Dynamic subsystem tests	Assumes contractor has some test capability. Hardware and labor to test each subsystem, including temperature ranges	100
Development, validation tests	Proving ground rental and labor, including data reduction. Largely for subsystem interaction test, validation. Assumes that normal testing has been included in the subsystems	400
Total additions		600
Reference VDTV Estimated Cost		2690

NOTES

(a) Subsystems refer to Table 5- 1

(b) Costs of additional items are subjective, but are based on work throughout the study.

(c) Additions are discussed in Appendix E.2

Table 5-9. Percentage Analysis of Dynamic Subsytem Costs

Amounts are in $K

Two different configurations are shown: semi active and full active supension

SEMI ACTIVE SUSPENSION

DYNAMIC SUBSYSTEM	LABOR AND PROCUREMENTS										INDIVIDUAL SUBSYSTEMS	
	-Specification-		----Design---		---Procure---		---Vehicle--- ---Conversion---		--Development--		$	% of Total
	$	% (d)	$	%	$	%	$	%	$	%		
Steer-by-wire (a)	14	5%	113	41%	80	29%	53	19%	18	7%	276	13%
Steering feel (b)	15	5%	120	38%	87	28%	57	18%	35	11%	314	15%
Brake-by-wire (a)	12	7%	60	33%	60	33%	30	17%	18	10%	180	9%
Brake feel (b)	15	6%	80	32%	83	33%	38	15%	35	14%	249	12%
Throttle-by-wire (a)	12	11%	30	29%	30	29%	15	14%	18	17%	105	5%
Throttle feel (b)	15	12%	38	29%	30	24%	18	14%	27	21%	128	6%
Semi active suspension	23	8%	120	43%	75	27%	30	11%	30	11%	278	13%
Rear wheel steering (a)	12	6%	80	40%	53	27%	38	19%	17	8%	198	9%
Core system (c)	18	5%	120	31%	158	40%	60	15%	35	9%	390	18%
Total	135	6%	759	36%	654	31%	338	16%	231	11%	2117	

FULLY ACTIVE SUSPENSION

	LABOR AND PROCUREMENTS										INDIVIDUAL SUBSYSTEMS	
	-Specification-		----Design---		---Procure---		---Vehicle--- ---Conversion---		--Development--		$	% of Total
	$	% (c)	$	%	$	%	$	%	$	%		
Steer-by-wire (a)	14	5%	113	41%	80	29%	53	19%	18	7%	276	13%
Steering feel (b)	15	5%	120	38%	87	28%	57	18%	35	11%	314	14%
Brake-by-wire (a)	12	7%	60	33%	60	33%	30	17%	18	10%	180	8%
Brake feel (b)	15	6%	80	32%	83	33%	38	15%	35	14%	249	11%
Throttle-by-wire (a)	12	11%	30	29%	30	29%	15	14%	18	17%	105	5%
Throttle feel (b)	15	12%	38	29%	30	24%	18	14%	27	21%	128	6%
Fully active suspension	23	6%	120	33%	113	31%	60	16%	51	14%	366	17%
Rear wheel steering (a)	12	6%	80	40%	53	27%	38	19%	17	8%	198	9%
Core system (c)	18	5%	120	31%	158	40%	60	15%	35	9%	390	18%
Total	135	6%	759	34%	692	31%	368	17%	252	11%	2205	

NOTES

(a) Cost includes the safety system which changes from automatic to manual operation quickly
Cost of actuators, servovalves, special transducers, etc, are included in each subsystem

(b) The feel systems include the steering by wire, etc. subsystems so the two do not have to be added

(c) The core system includes electronics for the control and measurement systems, basic hydraulic system (pump, accumulator, filters, pressure control valves, reservoir, engine modifications, etc.

(d) Note that these percentages are % of the cost of each subsystem

These costs assume interaction between dynamic subsystems where LE has existing experience. An example is optimization of vehicle yaw response using front and rear steer-by-wire subsystems. This is a reasonable assumption, given the limited number of subsystems on the four vehicles. As more subsystems are included, dynamic interactions will become important. Additional costs for these interactions, including system engineering and thorough validation of on-board software, must be included.

The costs provided by LE did not exactly match NHTSA's VDTV requirements. An example is the DASCAR system that measures human head and eyeball movement, physiological parameters, etc. Modifications to the LE cost were made for such changes to provide a more realistic total VDTV cost as shown in Tables 5-7 and 5-8. The rationale for these additions is shown in Appendix E.2.

A phased implementation approach was considered in which more than a single vehicle or upgrade to the first delivery would be made. In this approach, a second vehicle will be considerably less expensive. An example is the acquisition of a second FCVDTV where consideration of updating the second vehicle and conducting the tests necessary to verify its performance are done. Costs are shown in Table 5-10, which is derived from Table 5-7, but with reduced engineering and test costs. The reduction in total cost is about l/3, with the second vehicle costing about $1.8 million compared to the $2.7 million for the first vehicle.

5.2.6.3 Future Use of Cost Information

The cost information is believed to be the best available with currently defined requirements. Definitive requirements and formal quotes in response to a procurement action will be necessary to provide better cost information. The following caveats are thus listed to guide readers in future use of this cost information:

1. Costs will be highly dependent on the contractor: experience, existing designs, and existing staff with directly applicable skills.

2. Different dynamic subsystems require different hydraulic, electrical, measurement and control support. Addition of subsystem costs should provide an approximation of total vehicle costs, but minor differences will occur and will be dependent on the subsystems selected.

3. Testing levels, both subsystem prior to integration into the vehicle and road tests to fully validate the on-board software, will affect the total vehicle cost.

4. Documentation, training, and service/maintenance costs after delivery will affect the total vehicle cost.

5. Some dynamic subsystems **will** have significant interactions requiring extensive engineering, software and testing so will greatly increase these costs. Dynamic interactions will thus have a major impact on total vehicle costs. Accordingly, simple addition of dynamic subsystem costs in Table 5-5 may not provide a reasonable estimate of the total vehicle cost for a complex vehicle.

Table 5-10 Reference VDTV, Second Vehicle

Engineering and test costs have been reduced from those of first vehicle

SUBSYSTEMS (a)	COMMENTS	ESTIMATED COST ($K) (b)
CORE SUBSYSTEM	Reduced by 0.9 from $590K of the first vehicle	530
DYNAMIC SUBSYSTEMS	Reduction factors and comments are noted below	
Front Steer-by-Wire, Fee.1	0.9	300
Brake-by-Wire, Feel	0.9	145
Throttle-by-Wire, Feel	0.9	210
Active Suspension	0.9	105
Rear Steer-by-Wire, Feel	0.9	160
Traction Control	0.6; software improvements can be expected	50
ABS	0.5; ABS should have minor improvements	10
Four Wheel Drive	$100K for first vehicle. Minor mods, mostly parts for the second vehicle	25
Crash Avoidance Interface	Minor mods, mostly parts for the second vehicle	20
Total subsystems		1555
ADDITIONS	Changes to the first FCVDTV	
VDTV Operator Software	Increase capability based on experience with first FCVDTV	30
Front-end System Engineering	Labor for optimization of dynamic analysis	40
Dynamic subsystem tests	Limited tests compared to the first FCVDTV	50
Development, validation tests	Limited tests compared to the first FCVDTV	100
Total additions		220
Full-Capability VDTV Estimated Cost (Second Vehicle)		1775

NOTES

(a) Subsystems refer to Table 5-l

(b) Costs are based on those from Table 5-7 for the first full capability VDTV

5.2.7 Schedules

Schedules were developed for several implementation approaches. For purposes of this Section, these approaches can be divided into two categories:

1. Develop a vehicle with FCVDTV capabilities in one contract.
2. Use a phased approach to develop two or more vehicles, leading to a vehicle(s) whose total capability is equivalent to that of the FCVDTV.

Schedules typical of these two categories are shown in Figures 5-1 (a single procurement for the FCVDTV) and 5-2 (phased approach for two vehicles). These are generic schedules, but are believed to be applicable to approaches considered in this study. Although some VDTV approaches may contain more dynamic subsystems, most of this work can be done in a parallel effort with small schedule impact. It is noted that costs will increase, and will generally be proportional to capability. The schedule activities that cannot be decreased without high risk are those associated with interactions between dynamic subsystems. VDTVs having complex subsystem interaction will require about 3 months of front-end engineering and an additional 4 to 6 months of testing. In general, it is concluded that a minimum-capability vehicle could be delivered as early as 18 months after contract start and a full-capability vehicle in about 24 months.

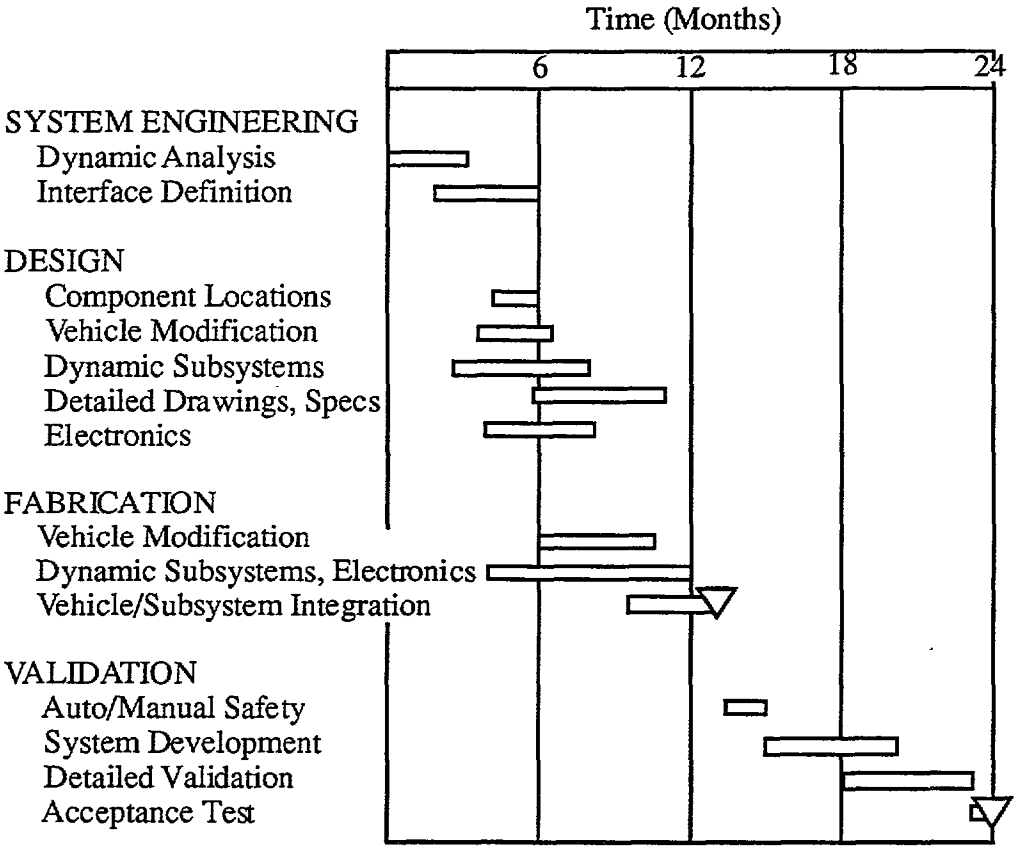

Figure 5-1 Generic Schedule for Procurement of One Full Capability VDTV

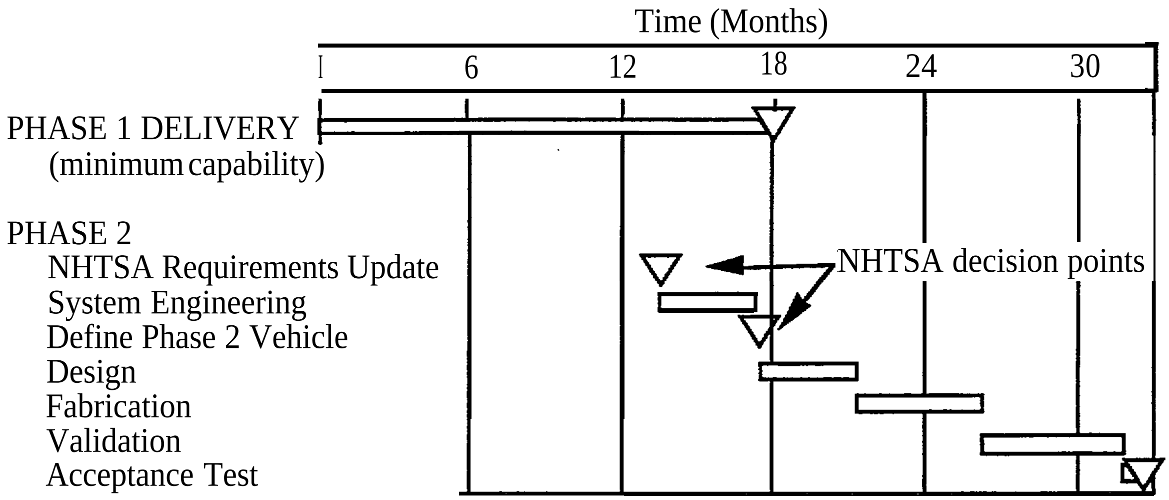

Figure 5-2 Generic Schedule for a Phased Approach for Two VDTVs

5.3 LOWER COST VDTV IMPLEMENTATION

5.3.1 Introduction

This study investigated the feasibility of, and costs associated with, the development of a low cost limited capability VDTV that could meet near-term needs. A limited capability VDTV is one that could meet or partially meet the research objectives defined in Table 3-2. The discussion of the low-cost option vehicle will include descriptions of four concept vehicles and their associated cost range. The functional capability of the vehicle subsystems are also discussed. The results of the low-cost feasibility study indicate that low-cost vehicles are feasible. The limited study could not determine the level of performance that could be achieved in sufficient detail to allow any comparison with the detailed information provided by Lotus Engineering, the result of a much more extensive analysis.

5.3.2 Low Cost Implementation Description

The base vehicle would be a current US production, mid-to-full size sedan, modified to provide dynamic subsystem features. The purpose of the vehicle would be to provide limited research capability, when compared to the capabilities discussed in Section 5.2, at a reduced cost while maintaining good reliability. The principle users are the same as those in Section 5.2: human factors, AHS support, NADS support, and crash avoidance technology assessment.

Vehicle modifications would generally utilize existing or developed hardware from production or previously developed components. This approach would reduce initial engineering costs. A second cost reduction measure is to control each dynamic subsystem independently, limiting subsystem interactions to safety shutoffs. The single system approach simplified both the control system software and validation testing. Further simplification is achieved in controls by providing control algorithms that are binary, step functions, linear, or exponential. If these are not adequate for NHTSA's research needs, more complex algorithms would have to developed. Such algorithms are not costed here, but would be provided as part of the experiment costs.

Cost estimates are based on a cooperative development atmosphere with the procuring agency working together with the builder from a functional description. Significantly higher costs can result from using a detailed performance specification and formal requirements verification through acceptance tests. Cost estimates include checkout and verification that each subsystem is functional over the required range, but would not include a complete mapping of all vehicle characteristics,

5.3.3 Vehicle Functional Capability

In general, the dynamic subsystems listed in Table 5-l were used as a guide for this low cost implementation study. Specific subsystems for the low-cost approach are defined in Table 5- 11.

Table 5-11 Low-Cost VDTV Dynamic Subsystems

1. Steer-by-Wire	Provides the ability to control the vehicle through the steering wheel or from an external control source. The system would provide a variable ratio but would have a fixed feel at the wheel, most likely from a spring or friction device. The approach would add actuators to the existing steering system.
2. Programmable Steering Feel	Provides variable steering ratio and steering feel, at least over the range of conditions for current production autos. Feel could be implemented by adding the actuators and sensors to the steering input shaft to provide the programmable feel while maintaining the production steering and steer-by-wire actuators. The approach may require a change out of the power steering pump.
3. Brake-by-Wire	Provides continuously variable control including ABS independently to each wheel. The system would probably replace a production ABS rather than adapt the production system since production systems are typically a one-vehicle empirical design.
4. Programmable Braking Feel	Provides a variable brake pedal feel or force to achieve stopping forces.
5. Throttle-by-Wire	Provides throttle position control to simulate reduced engine performance, response to braking commands and speed control.
6. Semi-Active Suspension	Provides step or continuously variable damping changes independently at each comer. Variable roll stiffness for front and rear.
7. Control Subsystem	Provide a microprocessor- or PC-based control subsystem with third-party boards to provide servo drivers. Programs would be developed in C or C++ language to implement the algorithms. There would be minimal algorithmic interaction between subsystems except for safety overrides.
8. Four-Wheel Steering	Provide the addition of rear-wheel steering to the steer-by-wire capability. Steering angle would be limited to approximately six degrees and used primarily to increase lateral acceleration.
9. Active Roll Control	Provides variable roll stiffness by using active anti-roll bars
9. Data Processing	Provided by DASCAR. DASCAR and associated sensors would be used for monitoring of vehicle operation and dynamic motion and driver response, but are not in the control loop.

5.3.4 Dynamic Subsystem Performance

This limited study did not provide known, objective performance data for the low-cost dynamic subsystems. However, subjective observations are:

1. The performance range could vary from less than that of a standard passenger car to somewhat better than that of the reference approach discussed in Section 5.2. An example is the TRW active suspension, which may have a higher bandwidth than that of the Lotus Engineering system
2. Semi-active suspension will have a bandwidth slightly higher than that of typical vertical ride frequency (about 1 Hz). Production semi-active suspensions are usually in the range of 3 Hz to 5 Hz.
3. Performance of steering and brake systems are not known.

5.3.5 Low-Cost Implementation Cost Estimates

Cost information was obtained from telephone contacts with the following firms and agencies:

- Milliken Research Associates
- TRW-ACS
- PATH
- Frontier Engineering

These firms were provided with brief verbal descriptions of the needed subsystem capabilities and general intended use. Discussions included previous experience, degree of success, and approach. There was not sufficient time, nor funds to solicit cost studies or to have personal meetings to exchange detailed information. Because of these limitations, the costs cannot be compared directly with those obtained from Lotus Engineering. Also, little objective information on dynamic performance parameters was available. The following summarizes the cost and estimates and subjective confidence level of information obtained from each contact.

5.3.5.1 Milliken Research Associates

Milliken Research Associates personnel have an extensive background in dynamic subsystems from the early 1950 period. They have designed and built a low band width active camber vehicle about five years ago. The cost, including development, was on the order of $250,000. Based on their experience, they could develop and deliver an active, two actuator roll control capability, including the hydraulic power system, for $50,000. Milliken Research Associates had no other applicable subsystem experience.

5.3.5.2 CALSPAN

CALSPAN has no recent experience in converting an automobile to a drive-by-wire configuration. They have extensive experience converting aircraft to variable stability, variable feel, fly-by-wire for research activities.

CALSPAN stated with confidence a cost of converting a Lear Jet at $2.1 million. This includes measurement of aircraft feel, software with extensive safety protection, and testing. CALSPAN makes their own low friction actuators needed to provide the correct variable feel. The main problem is present during the on-center driving of an automobile. CALSPAN estimated the cost of these actuators at $50,000 each and that a steer-by-wire system, with feel, including software and testing should be costed in the range of $150,000 to $200,000.

5.3.5.3 TRW-ACS

TRW-ACS was once part of Lotus Engineering, and is now owned by TRW. They have experience in modifying production vehicles for drive-by-wire and active suspension. They are currently beginning work on a vehicle for PATH.

The following estimates are for modifications to a new platform. They assume familiarity and experience with the dynamic subsystems and are not a new development. Each subsystem cost includes the control system cost (software, documentation, and testing). The estimates also assume a co-operative development atmosphere not involved with detailed specification and requirements verification.

The full vehicle costs reflect some synergism in hardware and controls:

• Active suspension	$600K
• Semi active suspension (damping control)	$75K - $100K
• Steer-by-wire, with feel, front wheels	$300K
• Rear wheel steer	$200K - $250K
• Brake-by-wire, throttle-by-wire	$150K
• Full capability with active suspension	$1000K - $1200K

In response to questions regarding ratios of development and engineering costs to modification costs, the following were estimated:

- About 50%/50% for previously developed subsystems.
- About 75% engineering cost for newly developed subsystems.

Estimates for control software were very reasonable for establishing variable control capability. Control would be implemented using a personal computer with third party I/O boards for the hardware interface. Programs would be implemented in C or C++ language. Estimated workforce time (in workmonths) was:

Active suspension	1 workmonth
Steering control	2 - 3 workmonths
Brake-by-wire	1 workmonth

These costs include debug and checkout but do not include setting up for specific performance parameters. The costs for setting parameters for a given performance would be charged to the experiment.

Previous discussion with TRW indicated that they are assuming a wide bandwidth active suspension system (dc to 30 Hz), which is equal to or better than the Lotus Engineering bandwidth.

5.3.5.4 Frontier Engineering

Frontier Engineering is building a drive-by-wire van with full instrumentation for rear-end crash avoidance and intelligent cruise-control studies. Frontier Engineering has spent $200,000 on equipment and a small amount on labor and software development. The vehicle is just now operable. The drive-by-wire capability uses a commercial system costing $25,000. This is estimated to be a low performance system, but specific data has not been assessed.

5.3.5.5 PATH

PATH provided the following estimates on their work and contacts:

Steer-by-wire for lane following experiments	$200K- $400K
Brake-by-wire	$50K - $100K
Throttle-by-wire	$3K- $5K

PATH uses a 486-based PC for the control computer.

5.3.6 Candidate Configurations

Four candidate VDTV configurations were established to help determine costs and relative research capabilities. Vehicle configurations were selected to support the four major NHTSA users (human factors, AHS support, NADS support, and technology assessment). These four configurations are equivalent to those of Section 5.2.5.1 and are listed in the same order and format. Major characteristics are shown in Table 5-12. The terminology in this table is consistent with that of the Lotus Engineering information of Section 5.2 so the term “core subsystem” is used. One low-cost dynamic subsystem that was considered is active roll control, which would control vehicle roll by changing characteristics of the front and rear control bars. Although this was given a low priority by the Capabilities/Use Matrix, active roll control was included as an example of specific capabilities possible with low-cost technology.

Cost uncertainties were discussed in Section 5.3.5. With the available information, performance uncertainties are greater. Consequently, this study cannot estimate the value of these low-cost approaches to NHTSA’s research program.

Table 5-12. Low Cost VDTV Dynamic Subsystems and Costs for Major NHTSA Users

LOW COST LIMITED CAPABILITY IMPLEMENTATION

SUBSYSTEM	HUMAN FACTORS Cost ($K)	AHS SUPPORT cost ($K)	NADS SUPPORT Cost ($K)	TECHNOLOGY ASSESSMENT Cost ($K)
Steer-by-wire (SBW)	300	100	100	100
Steering feel (a)				
Brake-by-wire (BBW)	150	50	50	50
Brake feel (b)				
Throttle-by-wire (c)				
Throttle feel				
Semi-active suspension	75		75	
Fully-active suspension				
Rear-wheel steering	200		200	200
Traction control				
ABS				
Four-wheel drive				
CA interface (c)				
Active roll control	50		50	
Variable mass				
Total dynamic SS cost	775	150	475	350
OTHER COSTS				
Core subsystem	180	145	180	180
DASCAR driver info (c)				
VDTV operator software				
On-board data storage				
Off-board data processing				
Total other cost	180	145	180	180
Total vehicle cost ($K) (b)	955	295	655	530

(a) Steering feel is included in SBW for Human Factors

(b) Brake feel is included in BBW for Human Factors

(c) Included in the core subsystem

5.3.7 summary

The results of the discussions with potential suppliers produced fragmentary results. Some contacts lacked experience with all subsystems, or lacked specific information or cost details, or could provide only educated guesses. The most comprehensive response was from TRW which provided estimated costs for each subsystem There is little performance information, but all firms have had experience. TRW and CALSPAN have produced very usable vehicles.

There is insufficient information to draw anything but basic conclusions:

1. Useful vehicles can be built in the range of $300K - $1000K
2. The intended use and performance requirements need to be clearly defined and understood before credible cost estimates can be made.

This information shows that a low-cost VDTV is feasible and can provide a useful value in a cost-constrained environment. Further, as more functional capability is added and total costs approach that of a full dynamic vehicle, little additional value per dollar is added. At this level, the full capability dynamic vehicle with better dynamic performance may be the better choice.

5.5. IMPLEMENTATIONCONCLUSIONS

The following conclusions relate to possible future VDTV implementation activities:

1. The full-capability VDTV would be the world's most capable research vehicle. The technology of its dynamic subsystems is known. However, integration of all the desired subsystems into one vehicle at this time represents a major advance with corresponding risk.
2. A wide range of implementation options are available. The major parameters are dynamic subsystem performance, initial cost, and the core vehicle. Each parameter has several options. The combination provides many approaches to a successful VDTV.
3. Based on known NHTSA research needs, there is no clear "best" approach path through the implementation options.
4. The cost and performance information contained in this section should permit NHTSA to select options which best meet OCAR programmatic objectives.
5. Limited capability vehicles will require from 12 to 18 months to build if formal contract management procedures are not invoked. A full capability Reference VDTV will require about 24 months to build. The major differences in these times are engineering and test activities.
6. Because of extensive experience, a fully active suspension is relatively low risk if implemented by an experienced firm.
7. Programmable feel systems have the greatest performance uncertainty. Lotus Engineering has delivered only three such systems. Comments from auto industry

personnel with extensive experience indicate little success in trying to duplicate the performance of a specific vehicle. However, the auto industry does use such systems to investigate varying feel for product development.

8. A phased VDTV procurement, not one where the first vehicle includes all the desired features and capabilities, is preferable. This is the near-unanimous opinion of all persons in firms experienced with similar research vehicles. (The single exception is Lotus Engineering, which believes that their extensive experience would permit them to build the full-capability VDTV.) This phased procurement should build on the first VDTV, then pursue more capable VDTVs as funding, benefit to NHTSA's research programs, and operational performance become known. Reference 8.14 provides further information on a phased implementation approach.

9. The selection of dynamic subsystems which will be of most value to NHTSA's programmatic goals needs to be validated. With this information, a VDTV development plan could be written.

10. While cost information is representative of the types of vehicles described (i.e., reference and limited capability), it is believed that firm costs will be obtained through a procurement process that is based on a specification for the specific system of interest.

6. ISSUES

During the course of this phase of the VDTV study, several issues were identified and are discussed here to bring them to NHTSA's attention.

6.1 OPERATION ON PUBLIC ROADS

This requirement should be examined in light of potential liability concerns. The PATH program has decided to exclude this requirement for their vehicles because of this concern.

6.2 FOUR-PASSENGER REQUIREMENT

A four-passenger sedan has two deficiencies for the VDTV's intended use:

1. It necessarily increases yaw inertia because much of the added weight must be placed in the trunk if the back seat functionality is to be maintained. There is little space in the engine compartment, particularly with front-wheel drive vehicles, to place additional components.

2. The physical space available for maintenance and repair will be limited because the back seat volume is not available.

The back seat is expected to be used only infrequently, probably for interested observers. A one-seat VDTV could carry one observer at a time for demonstrations where the driver also operated the laptop computer under a limited scenario, such as changes only while the vehicle was stopped.

6.3 OVERSUBSCRIPTION

Section 3 of this report identifies several potential users for a VDTV, should it be built. Dynamics and human factors testing can require significant test times. A single vehicle, or even two or three, may limit the desired uses or test programs envisioned.

6.4 TESTING CONSTRAINTS.

VDTV operation without testing constraints will increase safety requirements and also risk of VDTV damage or loss. This is particularly true of VDTV operation, whose function will frequently place the vehicle in the regime near the tire/road adhesion limit.

Normal proving ground practice often defines constraints to testing procedures with experimental vehicles. Examples are operation on skid pads with no obstructions that may damage the vehicle, stated in terms of speed and distance constraints, and straightaway operation only on roads with shoulder distance, slope, and other constraints. Such constraints will greatly decrease the probability of a serious impact. Without testing constraints, increased safety requirements will lead to cost increases. An example is addition of a roll bar or roll cage. Addition of a roll bar to a standard 5 passenger sedan, while attempting to retain the appearance of a normal car and functionality of the rear doors, is an appreciable task. A discussion is contained in Appendix D.

Serious damage or loss of the vehicle would delay NHTSA research schedules for at least a year. Unfavorable publicity and budget impacts are likely. These factors may be more important than the cost increase.

It is recommended that NHTSA consider VDTV operation only under a set of prudent constraints which should have little, if any, impact on crash avoidance research.

6.5 NADS VALIDATION

Closure was not reached on the issue of the use of VDTV for NADS validation. During the course of the study, discussions were held with University of Iowa personnel, representatives of VRTC, the NADS contract technical manager at NHTSA, and the U.S. auto manufacturing industry on the subject of NADS model validation. The opinion expressed by some of these organizations is that discrete-point testing using instrumented production vehicles is adequate and possibly preferable to using a test vehicle such as VDTV. This study expresses the view that benefits can be shown in a variable dynamic capability to support both NADS model validation and human factors testing in which both NADS and the VDTV could be involved.

6.6 USE OF VARIABLE MASS PROPERTIES IN OPERATIONAL VEHICLE

While analyses were performed during this study assuming that a variable mass capability was to be available, no decision has been made nor is one implied regarding the use of this capability in an operational test vehicle. It has the advantage of offering another degree of freedom in changing the dynamic response of the vehicle and improving its emulation capability, but it adds complexity that, ultimately, may not be desirable or needed. Further studies will have to be conducted to resolve this issue.

6.7 ADDITIONALDYNAMICSANALYSIS

The complexity of a vehicle with several interacting advanced subsystems (e.g., active suspension and four-wheel steering) requires that a comprehensive dynamic analysis be performed prior to a contractor being given the approval to proceed into fabrication. Such an analysis could be done by a contract manager or by the contractor.

6.8 VDTV CAN AUGMENT NADS PERFORMANCE

Simulators, including NADS, are unable to cover all of the possible longitudinal and lateral performance space with high fidelity. VDTV will provide NHTSA with a tool for performing crash avoidance research throughout this regime, and particularly in the crucial limit-performance range, that will be difficult for NADS to achieve with acceptible fidelity.

7. MAJOR FINDINGS AND CONCLUSIONS

1. JPL concluded from this study that a VDTV would be of significant benefit to NHTSA, and very likely to other potential users as well.

2. VDTV with four-wheel steering and variable mass properties can emulate the lateral dynamics of a range of passenger automobiles from small to full-size. Active suspension will improve the fidelity of this emulation.

3. The research area best suited to VDTV is that in which high-fidelity dynamics information is related to the interaction of advanced vehicle subsystems and crash avoidance systems. Fully integrated instrumentation also permits human factors testing to be accomplished in this regime.

4. The acquisition of VDTV should be viewed as complementing existing alternatives such as single-vehicle testing and NADS. No one approach can satisfy all future test objectives. The combination of VDTV and NADS has a high degree of synergism that could be expected to provide an unequaled research capability.

5. The VDTV acquisition cost is driven primarily by technical capability and performance. A reasonably reliable cost of $2.7M was estimated to acquire the capabilities needed to satisfy all identified research and test requirements. Several options are available to achieve partial or full capability. The schedule depends on the functionality of the vehicle and would range from 18 to 24 months.

6. A lower-cost option for a limited capability vehicle that would meet several near-term needs was developed. Such a vehicle could be acquired for $0.3M to $1M, the range depending on the procurement approach and quality of technical capabilities. At a minimum, this vehicle would be instrumented for vehicle and human factors testing and would have an on-board controller capable of interfacing with vehicle subsystems and sensors. The cost estimate for this approach is not as reliable as the previous estimate. A 15 month schedule is judged to be adequate for this procurement.

7. An implementation approach is possible that should satisfy many of the test requirements while meeting cost and schedule constraints. This approach, sometimes referred to as the Rapid Development Method, provides an early delivery of partial capability, followed by incremental upgrades until the full capability to meet all defined requirements is met. In essence, it is a build-to-cost approach allowing the customer early involvement with the product and giving him the opportunity to make decisions affecting the ultimate capability of the system.

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