SAE TECHNICAL PAPER SERIES

950032

The Variable Dynamic Testbed Vehicle

Alan T. Marriott
Jet Propulsion Lab. California Institute of Technology

SAE *The Engineering Socieiy For Advancing Mobility Land Sea Air and Space,*
I N T E R N A T I O N A L

International Congress and Exposition
Detroit, Michigan
February 27 - March 2,1995

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (412)776-4841 Fax:(412)776-5760

ISSN 0148-7191

Printed in USA 90-123D/PG

950032

The Variable Dynamic Testbed Vehicle

Alan T. Marriott
Jet Propulsion Lab. California institute of Technology

ABSTRACT

This paper describes the concept of a potential test vehicle for the National Highway Traffic Safety Administration (NHTSA) that is designed to evaluate the dynamics, human factors, and safety aspects of advanced technologies in passenger class automobiles expected to be introduced as a result of the Intelligent Vehicle/Highway System (IVHS) program. The Variable Dynamic Testbed Vehicle (VDTV) requirements were determined from the inputs of anticipated users and possible research needs of NHTSA. Design and implementation approaches are described, the benefits of the vehicle are discussed and costs for several options presented.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) was commissioned by the National Highway Traffic Safety Administration to investigate and assess the need for an instrumented test vehicle to be used by NHTSA in the evaluation of new crash avoidance technologies emerging from the Intelligent Vehicle/Highway System program.

It would also provide a test capability that could support related programs such as the Automated Highway System (AHS) and the National Advanced Driving Simulator (NADS) programs. The concept of a test platform having programmable variable performance was named the Variable Dynamic Testbed Vehicle. JPL considered three general aspects of the VDTV concept:

- potential uses and users
- need and benefits
- design, cost, and implementation approaches.

The following sections of the paper summarize the program results.

THE VDTV CONCEPT

The need for a VDTV is motivated by the rapid advancement in automotive technology and transportation infrastructure expected to result from the IVHS program. [Ref. 1] NHTSA has identified the VDTV as one of several test capabilities it may need to evaluate and guide the safe introduction of these technologies into the public sector. [Ref. 2] The part of the test spectrum that VDTV could uniquely fill is that for which an integrated, systematic approach to acquiring high-fidelity data concerning the interaction of advanced vehicle technologies, new collision avoidance systems, and the driver is of paramount importance.

The underlying concept of variable performance in a test bed vehicle 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. Additionally, and equally important the simulation attributes of a VDTV would assist NHTSA in conducting an integrated test program in which the needs and results of collision avoidance, vehicle technology, and simulator testing, as well as the support of other IVHS programs, can be coordinated and validated using a common test platform.

Features that make the VDTV a unique and versatile test tool are:

- On-board computer-controlled variable performance subsystems that allow rapid emulation of a range of automobile classes over a large envelope of test conditions.
- Complete instrumentation system package for both human factors and vehicle performance testing.
- Designed-in capability to accept a variety of collision avoidance technologies as they become available in future years for testing.

Figure 1 illustrates the main functions of the VDTV. In addition to those shown, the system includes an off-board data processing capability.

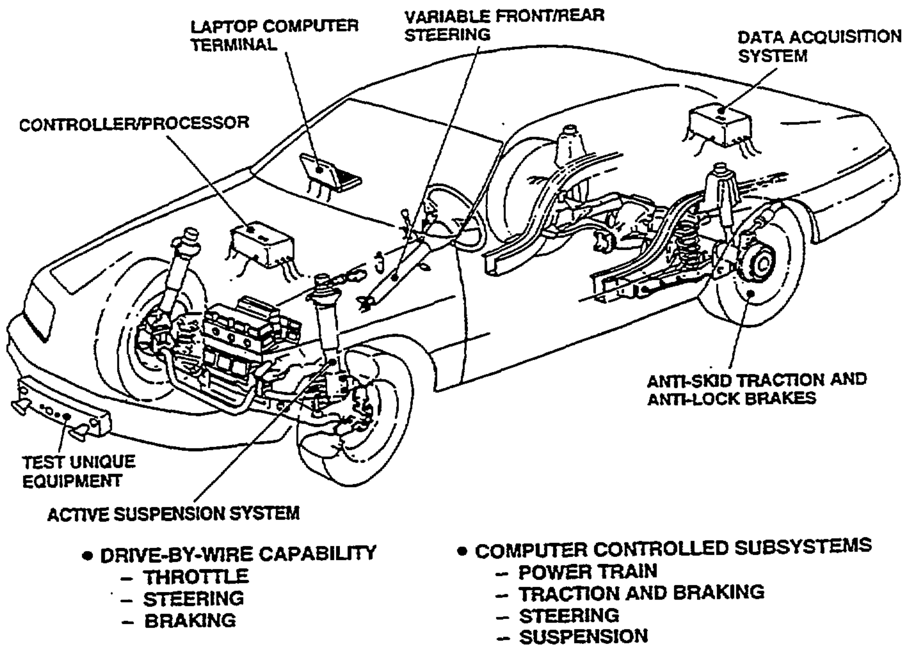

Figure 1. VDTV Concept

The VDTV emulation feature is illustrated in Figure 2 which is selected as an example of the expected VDTV dynamics capability. In this figure, the control sensitivity (lateral acceleration per unit steering wheel angle (SWA)) as a function of speed for a range of vehicles, from small- to full-size, is approximated by a mid-size vehicle with four-wheel steering and variable inertial properties. Active suspension, if included, would improve the lateral/directional response and, therefore, the emulation range. While variable mass was assumed in these analyses, no decision has been made regarding its ultimate value in an operational test vehicle. A combination of four-wheel steering and active suspension is expected to provide good lateral dynamic emulation capability.

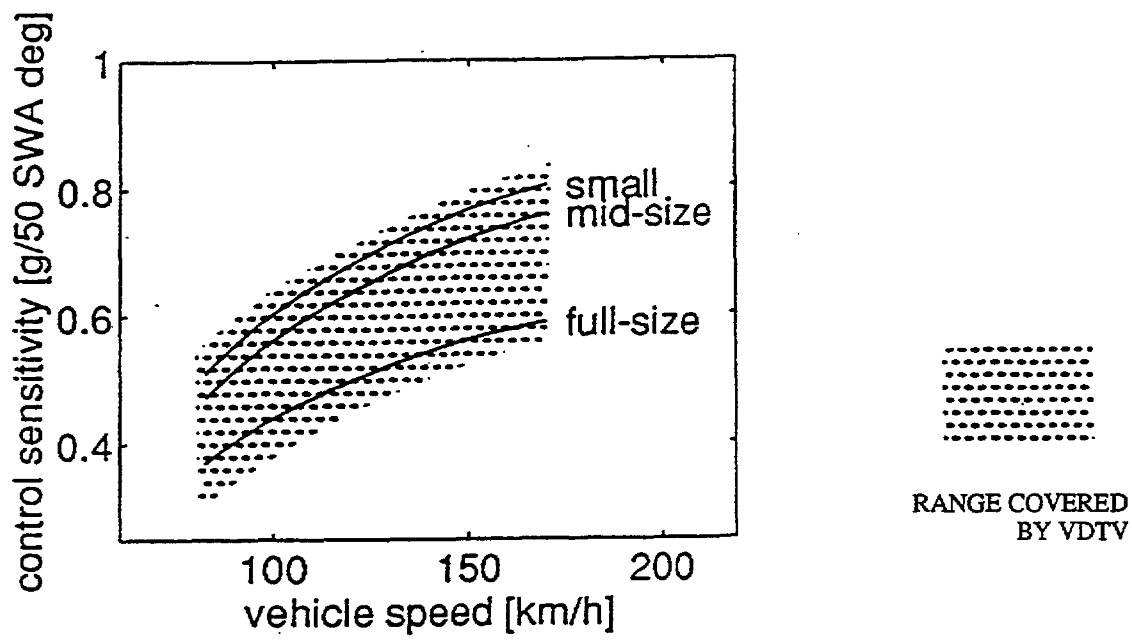

Figure 2. Example of VDTV Lateral Dynamics Emulation Capability

The VDTV concept is flexible in terms of implementation. JPL considered options ranging from a minimum capability vehicle as a possible first step, to a fully integrated design of all ultimately desired capabilities. In the latter option, there is the additional possibility of a phased approach to acquisition which would provide incremental delivery of capability with significantly reduced initial capital outlay, Each of these options is described in following sections.

VDTV USES

The combination of variable-performance advanced automotive technology, human factors instrumentation and the ability to accommodate sensors and other instrumentation for collision countermeasures makes VDTV a flexible and capable test tool for a large number of potential uses in a variety of research areas. To identify and validate the uses, JPL met with **NHTSA** managers and researchers and managers in related programs such as AI-IS and the California Partners for Advanced Transit and Highways (PATH). Additionally, a survey was conducted among government, research institutions, and industries involved in automotive development. Follow-up interviews were conducted to refine areas of applicability.

Four primary use categories were identified:

- Human factors testing in which driver-vehicle behavior in the presence of advanced subsystem (steering, braking, suspension) technologies with and without collision avoidance systems is of interest
- Support of parallel IVHS programs such as AHS.
- Validation of NADS models and cooperative (complementary} research in conjunction with NADS.
- Evaluation of advanced vehicle and M-IS technologies in the development of performance specifications, safety standards, and in vehicle design.

Table 1 describes specific examples of research topics that could be beneficially addressed by VDTV in each of these areas. [Ref. 33 These uses are at a summary level, all of which may be further disaggregated into detailed experiments or tests.

VDTV USERS

Potential users were also identified The principal user will be NHTSA particularly the Office of Crash Avoidance Research (OCAR) in its assessment of new technologies in terms of human factors and safety. The NADS program is a potential user in future vehicle model validation and in support of the simulator testing after it comes on line. Interest was expressed in the use of VDTV by the AHS program manager. Interaction with PATH program personnel led to the definition of specific tests for which VDTV would be well suited. Other potential users identified through the survey are research institutions,. the automotive supply industry, and the automobile manufacturers. With respect to the latter, interest was expressed by Ford and Chrysler in a possible joint industry-government arrangement whereby the VDTV (and perhaps other test articles) would be viewed as a research facility made available to the public and private sectors to advance the state-of-the-art in automobile technology. The aircraft industry benefited significantly from an analogous collaboration when the National Advisory Committee for Aeronautics was created in 1915.

BENEFITS

The benefits of a VDTV were assessed by considering the value of its unique features and by comparing it to alternatives. Findings in this regard are summarized as follows:

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 vat-lability 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.

- VDTV can be used cooperatively with NADS to strengthen NHTSA's overall test program. While NADS offers many 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 research data under certain crash avoidance 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.
- VDTV offers an alternative 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.
- 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.
- Until legislative bodies and the automobile industry accept simulator data, road test data is likely to be needed 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.

Thus, in consideration. of the identified uses, the perceived needs of the users, and recognizing the probable future rapid advancements in automotive technology, this study concluded that there is a sufficient benefit to warrant the development of a VDTV capability. The specific &sign and programmatic approach must match NHTSA's budget and schedule constraints.

Table 1 Examples of VDTV Uses

USE	RESEARCH AREA
	Effect of advanced technological systems(eg, IVHS devices) on driver workload
	Effect of driver perceptual factors on design of advanced vehicle systems
	Effect of driver risk taking proclivity on driver/vehicle performance & safety
	Effect of vehicle defects on lateral/directional control & accident causation
	Effect of lateral/directional dynamics on design of advanced vehicle systems
	Effect of radar collision warning/braking system on long. dynamics/performance
HUMAN	Effect of longitudinal dynamics on driver response/performance re: ride qualities
FACTORS	Effect of intersections on driver's use of advanced technology systems/displays/controls
	Effect of presence of pedestrians on driver behavior in various situations
	Effect of presence of highway maintenance equip. on driver's performance
	Effect of loss of driver's cues with advanced vehicle technologies
	Effect of advanced subsystems on classes of drivers
	Effect of loss of advanced subsystem capability on driver performance
	Evaluate robustness of vehicle lateral control system at off-design conditions
	Evaluate performance enhancement potential of command augmentation systems
	Evaluate lateral control system with vision-based roadway reference system
	Investigate human factors issues in lateral control system design
AHS	Evaluate longitudinal control system robustness at off-design conditions
	Evaluate performance enhancement using TBW and BBW in platooning
	Investigate human factors issues in longitudinal control system designs
	Investigate lane change maneuvers using TBW, BBW & SBW
	Evaluate compatibility of various vehicle types in platooning mode
	Evaluate safety aspects of AHS program technologies
	Study failure modes that would affect drive-by-wire safety
	Validate NADS algorithms for range of vehicle types and dynamics
	Conduct tests at limit maneuvers beyond the range of NADS
	Conduct high-fidelity tests beyond the range of NADS
NADS	Provide road test data to quickly answer simulation fidelity questions
	Conduct limited validation tests of NADS research programs
	Verify NADS test results on collision avoidance systems
	Assessment of collision avoidance technologies for safety
NHTSA	Develop performance specs/standards for emerging collision avoidance hardware
TECH	In-service testing of near-commercial collision avoidance systems
ASSESS.	Assessment of advanced subsystem technologies: vehicle dynamics & safety
	Rule making support
	TBW=throttle-by-wire
	BBW=brake-by-wire
	SBW=steer-by-wire

DESIGN, COST, AND IMPLEMENTATION APPROACHES

JPL 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. Table 2 relates the vehicle configurations in terms of subsystems needed to meet the requirements of the four major NHTSA use areas. 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. Because Lotus has built approximately 30 such vehicles (of varying capabilities), their cost estimates are considered credible. Vehicles in this category are identified as reference systems. The second approach was to gather cost data and experiences from U.S. manufacturers and organizations having experience in building applicable components or similar complete vehicles. These costs are much less reliable because time did not permit them to be validated. The costs of four configurations identified as limited-capability VDTVs were determined from this data base. A fifth configuration, the full-capability VDTV broadly defined by NHTSA at the start of this study, contains all subsystems and capabilities. Table 3 summarizes the costs for these configurations.

Table 2 Candidate VDTVs for Major NHTSA Users

HUMAN FACTORS	AHS SUPPORT	NADS SUPPORT	TECHNOLOGY ASSESSMENT
VEHICLE			
Good appearance 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 Semi-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 Vehic 1, such as lateral acceleratic at both axles, ride height, et

The following observations are made based on this analysis:

1. A full-capability VDTV will cost approximately $2.7M, excluding government procurement and management costs, for a vehicle with all dynamic subsystems. Other reduced options in this category tailored for specitic use areas will range from approximately $1.0M to $2.0M depending on specitic capabilities.
2. The full-capability VDTV could-be acquired in a 24 month program. The schedule for other reference vehicles is from **18 to 24** months.
3. A limited-capability VDTV could be acquired for $0.3M to $1.0M, depending on desired capability, excluding government procurement and management costs. The specitic functionality and performance of this vehicle would be defined in the procurement process on the basis of a delinitive specification and industry proposals. The engineering, testing, and performance of the dynamic subsystems are not known at this time and, consequently, neither is the achievable quality of the research capability. However, this vehicle would include a DASCAR* instrumentation system, an on-board controller capable of interfacing with subsystems and sensors, four-wheel steering, and steer-, throttle-, and brake-by-wire capabilities.
4. The limited-capability VDTV could be acquired in a 15 month program.
5. If a full-capability VDTV were desired, JPL would recommend a phased implementation program consisting of at least two deliveries with increasing capability in each delivery. A general consensus found during this study is the high technical risk in building a single vehicle with all of the advanced subsystems. This view was confirmed by discussions with senior, experienced auto industry personnel from Ford, GM, and Chrysler.

Table 4 provides a comparison of the cost to operate VDTV with the cost to operate multiple instrumented production vehicles (MIPV) and NADS. [Ref. 3] It shows that the test benefits discussed can be achieved at no greater cost than conventional techniques and with considerably less cost than NADS.

---

* DASCAR: Data Acquisition System for Crash Avoidance Research

Table 3 Summary of Configuration Options and Costs ($K)

SYSTEM CAPABILITY >	REFERENCE VEHICLES					LIMITED CAPABILITY VEHICLES			
PRIMARY USE AREA >	Human Factors	AHS	NADS	Tech Assessment	Full Capability VDTV	Human Factors	AHS	NADS	Tech Assess.
SUBSYSTEMS									
Steer-by-Wire	315	275	275	275	315	300	100	100	100
Steering Feel	(a)	—	—	—	(a)	(a)	—	—	—
Brake-by-Wire	250	180	—	180	250	150	50	50	50
Brake Feel	(a)	—	—	—	(a)	(a)	—	—	—
Throttle by Wire	105	105	—	105	130	(b)	(b)	(b)	(b)
Throttle Feel	—	—	—	—	(a)	—	—	—	—
Semi-Active Suspension	—	—	—	—	—	75	—	75	—
Fully Active Suspension	365	—	365	365	365	—	—	—	—
Rear Wheel Steering	200	—	200	200	200	200	--	200	200
Traction Control	50	—	—	50	50	—	—	—	—
Antilock Braking System	—	—	—	—	20	—	—	—	—
Four Wheel Drive	—	—	100	100	100	—	—	—	—
CA Interface[d]	50	50	50	50	50	(b)	(b)	(b)	(b)
Active Roll Control	—	—	—	—	—	50	—	50	—
Variable Mass	20	—	20	20	20	—	—	—	—
TOTAL SUBSYSTEM COST	1355	610	1010	1345	1500	775	150	475	350
CORE VEHICLE	590	340	470	590	1190[c]	180	145	180	180
TOTAL VEHICLE COST	1945	950	1480	1935	2690	955	295	655	530

(a) = Included in the number directly above
(b) = Included in Core Vehicle
(c) = Includes additional engineering and test costs for full subsystem vehicle
(d) = Crash Avoidance Interface

Table 4 Comparison of Annual Cost of Using VDTV and Alternatives.

	VDTV		NADS	MULTIPLE INSTRUMENTED PRODUCTiON VEHICLES
	LIMITED CAPABILITY	FULL CAPABILITY		
No. of Units	1	1	1	9
Acquisition Cost ($M/Yr)*	0.13	0.45	3.40	0.16
Operations ($M/Yr)*	1.07	1.07	1.82	1.07
Use Hours/Year	1500	1500	2000	1500
Cost per Hour($)	800	1015	2610	820

* Present Value Analysis

MAJOR FINDINGS AND CONCLUSIONS

1. ***JPL concluded from this study that a VDTV would be of significant benefit to NHTSA and 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 required to demonstrate the interaction of advanced vehicle subsystems and collision avoidance systems. it would be especially valuable when operating in the limit-performance regime. Fully integrated instrumentation***

also permits human factors testing to be conducted throughout the performance range.

4. *The VDTV has been shown to complement existing alternatives such as single-vehicle testing and NADS. No one approach can satisfy all required future test objectives. The combination of VDTV and NADS has a high degree of synergism that is 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 reduced options are available to achieve partial or full capability. The schedule, which depends on the functionality of the vehicle and whether a single or phased procurement, 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 &pending on the procurement approach and quality of technical capabilities. At a minimum, this vehicle would be instrumented for vehicle and human factors testing, would have an on-board controller capable of interfacing with vehicle subsystems and sensors and would include steer-, brake- and throttle-by-wire subsystems having capabilities consistent with their cost. 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 for all &fined 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 enhanced capabilities of the system.*

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Highway Traffic Safety Administration through an agreement with the National Aeronautics and Space Administration. The author wishes to thank the JPL VDTV team that included Frank Condos, John Garba, Dan Griffin, Allen Kanner, Mike Koffman and Allan Lee for their valuable contributions. Lotus Engineering and Milliken Research Associates also contributed significantly to this study. Cost information is for planning purposes only and does not imply a commitment on the part of the provider of the information, the Government, nor JPL.

REFERENCES

1. National Program Plan for Intelligent Vehicle-Highway Systems (IVHS) Draft October 15, 1993
2. SMART Program Plan, Office of Crash Avoidance, National Highway Traffic Safety Administration, U.S. Department of Transportation. Final Draft, September 30, 1992.
3. Weir, D.H., Halfley, R. K. "National Advanced Driving Simulator (NADS) Requirements Study: Vol. II, Final Technical Report," DOT HS 807 826, September 1991.