

## DESIGN AND CONSTRUCTION OF A VARIABLE DYNAMIC VEHICLE

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### ABSTRACT

This paper is a Progress Report describing the design and construction of a "Variable Dynamic Testbed Vehicle", VDTV, suitable for use as a test tool by researchers in the field of automotive safety. The VDTV project was sponsored and funded by the United States Department of Transportation, Intelligent Transportation System/Joint Program Office. The VDTV performance will be programable by way of an Onboard laptop computer readily accessible to the test driver or a test conductor. The vehicle systems available for programming are the vehicle "by wire" systems which are the front and rear steer; steering feel; brakes with ABS, traction control, and yaw control; throttle; front and rear anti-roll bars; and the variable rate suspension. The base vehicle is a Roush Technologies modified 1995 Ford Taurus SHO used in the Bob Bondurant high performance driving school in Phoenix, Arizona. This base vehicle has an experience history of proven performance, low maintenance and high reliability. This base vehicle already contained a roll cage, high performance springs, heavy duty subframe mounts, and a fire control system. Tier one automotive component suppliers provided their latest "ready for production, by wire" components, at essentially their incremental cost for modifying these systems to VDTV requirements for the vehicle systems outlined above. These components were installed on the base vehicle by Roush Technologies. ERIM Automotive was the primary contractor and the Jet Propulsion Laboratory acted as the contract technical manager for the Department of Transportation. The VDTV is designed to be capable of simulating the braking and dynamic performance of a large variety of generic vehicle types ranging from small to large vehicle sizes. A comprehensive onboard data acquisition system is available to record all data from all vehicle sensors. An offboard data processing system will process data into user format. User-supplied equipment can be added to the VDTV by using VDTV supplied power and electronic interface to the

control and measurement subsystem. Vehicle and test condition safety has been provided through the VDTV design and construction process. The VDTV will provide researchers a safe, versatile research tool that can quickly and economically simulate a variety of vehicle test conditions for studying vehicle dynamic performance, human factors, driver physiological performance, and intelligent vehicle crash avoidance systems both singularly or in combination.

### INTRODUCTION

The U. S. Department of Transportation (U. S. DOT), has been conducting crash avoidance research into such vehicle systems as brake performance, vehicle yaw stability, vehicle rollover stability, tire performance, and driver performance for a number of years. Recently, the U. S. DOT has been examining the potential of new high technology crash avoidance system concepts for preventing and/or reducing the severity of crashes in such crash scenarios as rear-end and road departure. Research in these areas often require the testing of many different levels of independent variables. For example, the need to test an array of human factors as a function of different vehicle performance parameters in the past has always required that either the vehicle systems, such as suspension systems, be laboriously changed by hand or that the test equipment be laboriously changed from one test vehicle to another. It was recognized that testing cost could be greatly reduced and testing efficiency could be greatly increased if one could more easily change the test vehicle performance parameters. A feasibility study was conducted to determine if a variable testbed vehicle was technically feasible and what the approximate specifications of such a vehicle might be (1). The study concluded that the design and construction of such a vehicle was technically feasible and that such a testbed vehicle would be extremely valuable for conducting conventional as well as high technology safety research. Based on the favorable results of the above study, a contract entitled, "Variable Dynamic Testbed Vehicle Implementation" was issued by the National

Highway Traffic Safety Administration, United States Department of Transportation, as part of the Intelligent Transportation Initiative, Joint Program Office in September 1996, to design, construct, and test a variable dynamic testbed vehicle.

## **METHODOLOGY**

The vehicle design part of this study determined that the required vehicle must meet the following two constraints: (1) the vehicle dynamic performance range must be adjustable to cover the production vehicle range from low performance to high performance for crash avoidance research and, (2) the vehicle must look and feel like a production vehicle environment for human factors research. A VDTV requirements document (2) was created which spelled out in detail what the safety, functional, and quality assurance requirements the delivered VDTV must meet. The VDTV will be required to pass a "performance verification test", (PVT) at the beginning and end of a test sequence to demonstrate that the vehicle meets all of the design requirements with respect to safety and function.

## **SAFETY**

The VDTV system, which includes drivers, roads, maneuvers, and operational experience as well as the vehicle itself, shall provide the level of safety expected to be equivalent to that experienced in normal passenger car operation throughout the US. The VDTV will be used on approved test track roads and surfaces, not on public roads. Approved roads will have safe run-off areas or barriers which significantly reduce the probability of a severe impact in case of a failure. Occupant safety was given primary consideration. The vehicle has a four-point harness available for the driver and system manager, a full roll cage, and a halon fire control system in the occupant compartment, trunk, and engine compartment.

Analysis performed early in the vehicle design program demonstrated that the VDTV is secure from rollover on a flat surface under the following most severe conditions:

- (1) Vehicle configuration with the highest performance tires used during any part of the "Acceptance Test" on a dry high friction surface.
- (2) Operation on a large, flat, paved surface including:
  - (a) Any combined turn and brake maneuver, both at limit performance.
  - (b) The J turn and the obstacle avoidance maneuver of the PVT.

## **PROJECT CONSORTIUM**

The base vehicle displaying the most requirements calculated to be necessary for a viable VDTV was found to be a Roush Technologies prepared 1995 Ford Taurus SHO used in the Bob Bondurant school of high performance driving. This base vehicle has an experience history of proven high performance, low maintainability, and high safety and reliability. This vehicle already contained a roll cage, high performance springs, heavy duty subframe mounts, and a fire control system. This vehicle satisfied several of the high priority requirements which are: high availability for testing, low maintenance downtime for maximum availability and low maintenance cost, proven durability during high stress high acceleration testing, built in safety items such as a proven roll bar cage, four point safety harness and a halon fire control system in the vehicle engine compartment, passenger compartment, and vehicle trunk.

Tier one automotive component suppliers supplied near production or "ready for production, by wire" components for installation on the base vehicle. The VDTV program participants are the following:

- (1) U. S. DOT/ National Highway Traffic Safety Administration/Federal Highway Administration Joint Program Office
- (2) Jet Propulsion Laboratory - Technical Manager and Measurement Subsystem
- (3) ERIM Automotive - VDTV System Contractor, Hardware Integrator and Software Developer

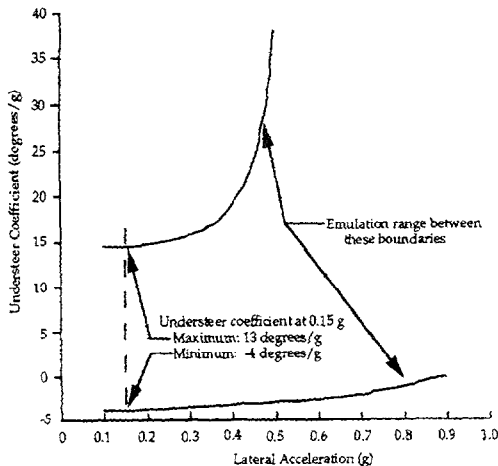
- (4) Roush Technologies - Vehicle Design, Integration, Construction, and Test Support
- (5) GM - Delphi - Brake-by-wire (ABS, Traction Control & Yaw control), Variable Shock Absorber, and Variable Anti-Roll Bar
- (6) TRW - Steer-by-Wire (Front and Rear) and Steering Feel
- (7) Bosch - Throttle-by-Wire
- (8) Goodyear - High Performance Tires
- (9) Milliken Research Associates - Dynamic Modeling Analysis & Control Algorithms

## VEHICLE PERFORMANCE REQUIREMENTS

The VDTV dynamic performance was designed to be controllable throughout its entire range via commands from a laptop computer using a single vehicle mechanical configuration. The following examples demonstrate various important vehicle performance measures and levels the VDTV has been designed to achieve:

### Understeer Coefficient

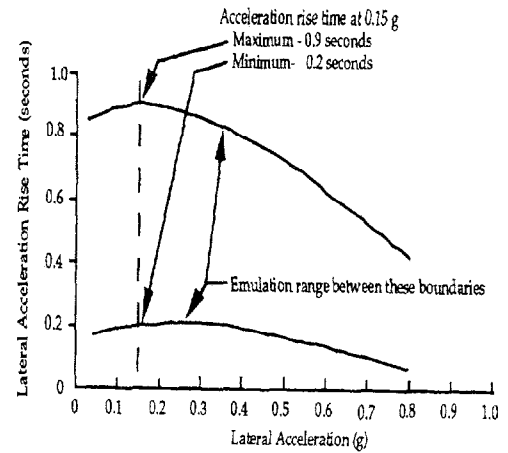
The understeer coefficient simulation range is shown in Figure 1. The understeer coefficient range is plotted as a function of lateral acceleration. The possible VDTV understeer simulation range at 0.15G lateral acceleration is shown to be from plus 13 degrees/G down to minus 4 degrees/G.



**Figure 1.** Understeer Coefficient Emulation.

### 90% Lateral Acceleration Rise Time

The 90% rise time range for the VDTV lateral acceleration resulting from a “step steer” input J turn type maneuver is plotted in Figure 2. At a specified level of lateral acceleration, the VDTV shall be programmable to achieve a 90% acceleration rise time that falls between the upper and lower bounds depicted in Figure 2. The 90% acceleration rise time as a function of lateral acceleration.



**Figure 2.** Lateral Acceleration rise time versus Lateral Acceleration.

### Steady State Lateral Acceleration

The VDTV is designed to attain a steady state lateral acceleration of at least 0.95G under the following conditions:

- i. A 30 meter diameter circle.
- ii Production type tires and normal road surfaces. (P279/40 ZR-17 GSC)

The VDTV can attain higher lateral accelerations when equipped with the same size S-compound racing tires.

### Longitudinal Acceleration

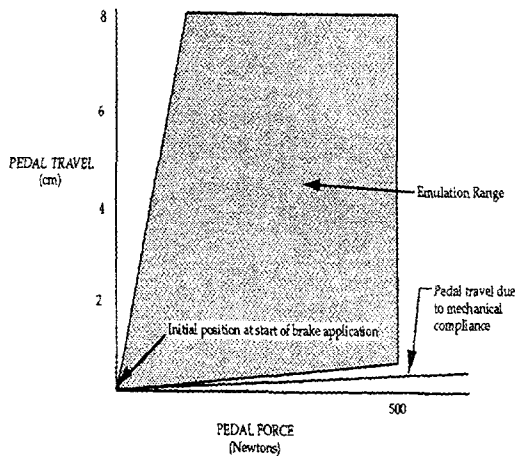
The VDTV is designed to accelerate from 0 to 100 km/h in less than 9 seconds, with a starting condition of the engine idling. The VDTV is designed to accelerate from 70 to 105 km/h in less than 5.5 seconds.

### Longitudinal Deceleration

The VDTV is designed to decelerate from 100 km/h to 0 in less than 40 meters and from 130 km/h to 0 in less than 70 meters. The VDTV is also designed to do 10 successive 0.5G stops from 100 km/h with an increase in pedal force from the first stop to the tenth stop not greater than 50% of the first stop under conditions of full acceleration between stops. The brake-by-wire system is designed to be capable of locking all four wheels at a speed of 160 km/h. The VDTV brake feel system will provide mechanically variable pedal travel/force characteristics within the simulation range shown in Figure 3.

The VDTV will be equipped with the latest ABS, traction control, and yaw control systems with on/off capability and multiple control algorithms available which are programmable from a laptop computer.

The VDTV is designed to have very fine longitudinal speed control to investigate possible platooning boundaries, as well as to study intelligent cruise control and crash avoidance systems.

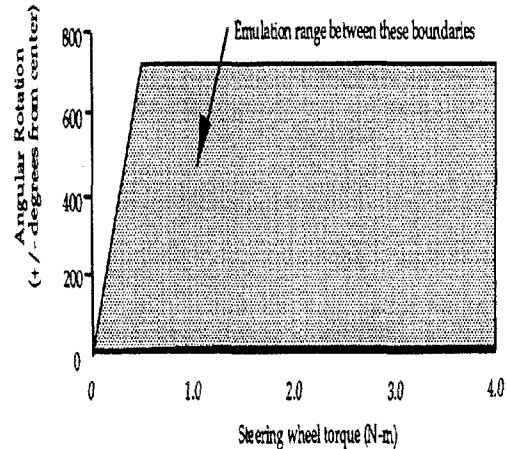


**Figure 3.** Brake Feel Emulation Range

### Steering Wheel Feel

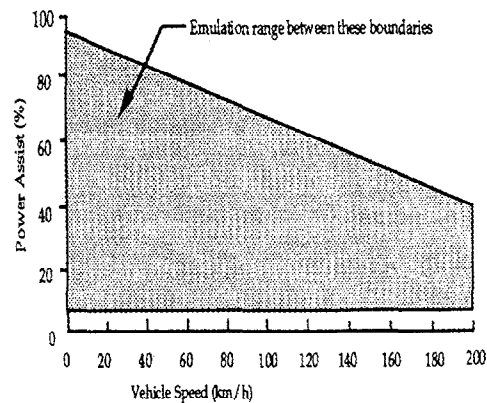
Steering wheel feel is an important parameter for human factors research. Since the by-wire implementation of the front wheel steering disconnects all energy normally transmitted via mechanical connections from the road/tire interface to the steering wheel, the steering feel subsystem

must simulate the basic force characteristics of a representative vehicle such as self-aligning torque from mechanical and pneumatic trail. The steering system torque/rotation simulation is designed to include the range shown in Figure 4.



**Figure 4.** Steering Wheel Torque/Angular Rotation Emulation.

The steering ratio variability in terms of steering wheel angle/front wheel angle is variable via laptop computer commands in a range from the full torque/no angular rotation mode to 20:1. The steering power assist shall be variable within the simulation range shown in Figure 5.



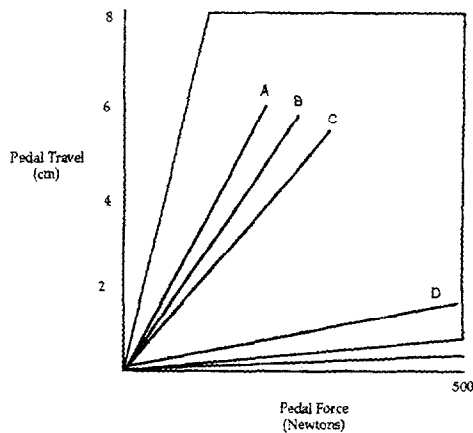
**Figure 5.** Power Assist Emulation Range.

The laptop computer commands provide a selection of different power assist algorithms.

The steering system also has the capability to program in, via laptop computer, vibration, friction, and haptic inputs.

### Throttle-by-wire

The VDTV throttle control system has two different operational modes: (1) typical operation during research activities, and (2) fine power control for longitudinal distance keeping. Throttle feel characteristics are changed by changeable springs with a range as shown in Figure 6.



**Figure 6.** Throttle Pedal Feel..

### Rear Wheel Steer-by-wire

Rear wheel steer is used to enhance the fidelity of small car emulation. The rear wheel steer system is designed to have a rotation capability of +/- 2 degrees with a -3 dB bandwidth of 15 Hz. The rear wheel steer system includes the capability to deactivate for front wheel steer only or control the rear steering angle according to algorithms selected via laptop computer commands.

### Semi-Active Suspension

The VDTV has semi-active suspension dampers controllable from the laptop computer. The damping rates for all four wheels have the capability of being

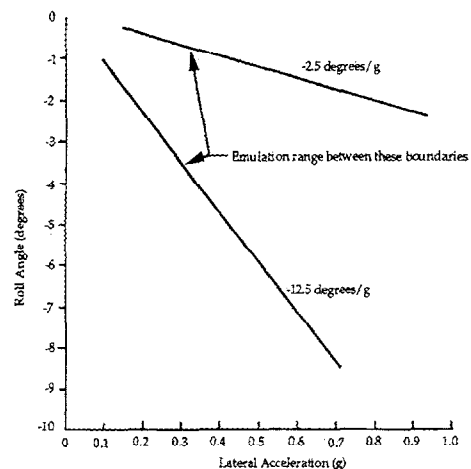
automatically changed on an individual basis under the control of algorithms and/or preset. At least three levels of damping forces were to be provided by the semi-active suspension:

At a piston speed of 75 cm/sec, the “hardest” damping forces were to be at least 3400 and 900 Newtons in extension and compression, respectively.

- (1) At a piston speed of 75 cm/sec, the “softest” damping forces were to be at least 1200 and 670 Newtons in extension and compression, respectively.
- (2) At a piston speed of 75 cm/sec, the third damping force was to be approximately midway between the hardest and softest forces.

### Front and Rear Active Anti-Roll Bar System

The VDTV is fitted with front and rear active anti-roll bar systems that are programmable from a laptop computer. Variable rate front and rear anti-roll bars are important in changing the total roll stiffness and/or the front to rear load transfer distribution and limit understeer of the VDTV. Consequently, these actively controlled systems will greatly facilitate human factor investigations and dynamic maneuver investigations. The required simulation range of the VDTV active anti-roll bar controlled system is shown in Figure 7.



**Figure 7.** Emulation Range of an Active Anti-Roll Controlled System.

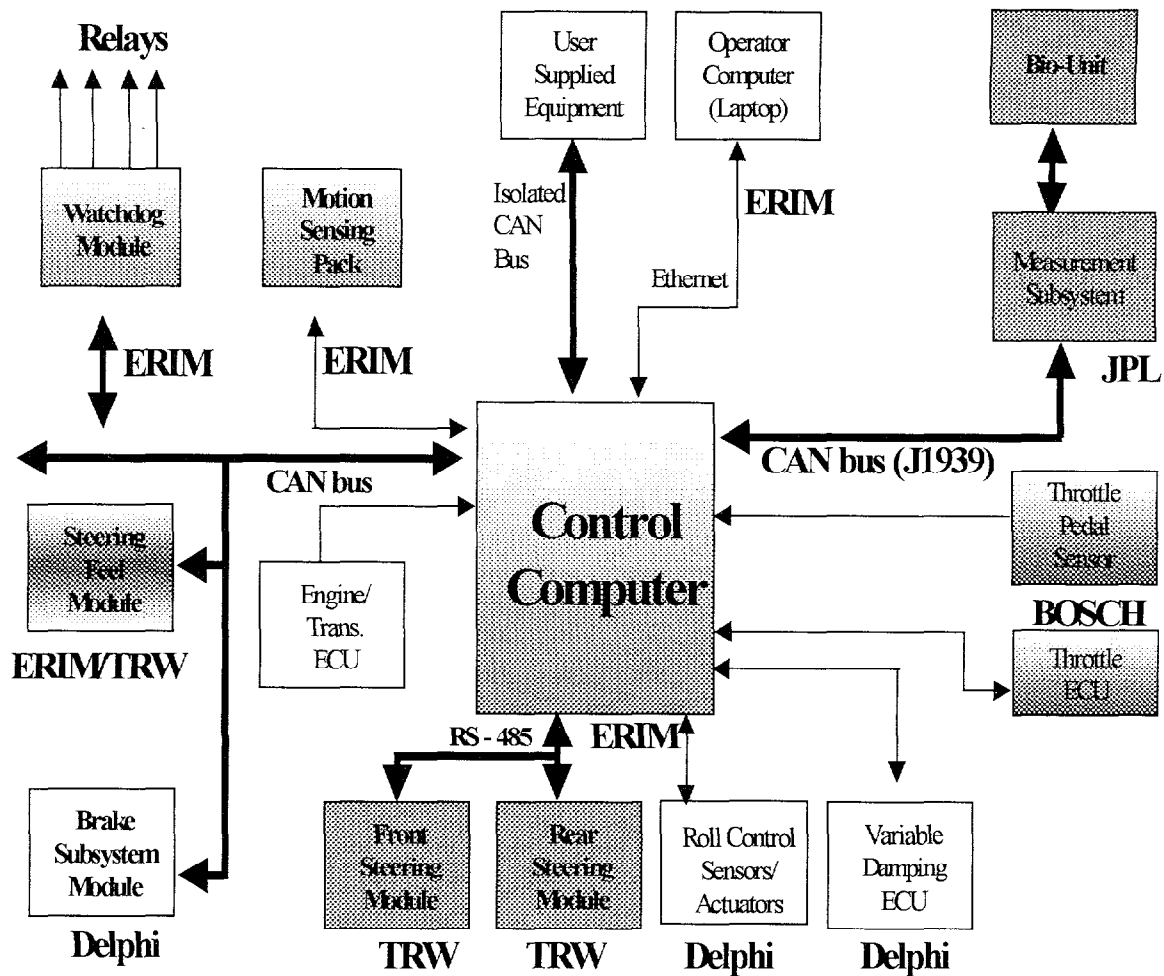
The Steering feel system uses an electric motor to provide force-feedback to the handwheel.

## VEHICLE DESIGN AND CONSTRUCTION

The VDTV could only meet the above performance requirements by having vehicle systems that are variable in performance and easily changed through active control by way of a laptop computer or a similar device. This requirement was designed to be attained by having control-by-wire vehicle systems. These control-by-wire type systems were not readily available and would have been very expensive and time consuming to develop from scratch. However, that proved to be unnecessary. The VDTV major contractor, ERIM Automotive International, was able to put together a consortium of tier one automotive component suppliers who offered their latest “ready for production, off-the-shelf”, “drive-by-wire” systems and components. The diagram in Figure 8 gives an overview of the VDTV by-wire systems, the major suppliers, and the general electronic relationships among these systems. The cooperation of the automotive industry greatly enhanced the affordability and relevancy of the VDTV to present and future technology.

A brief explanation of the elements contained in Figure 8 are presented in the following comments:

- i. Control Computer - this hardware supplied by dSpace. Acts as the vehicle-level Control computer and coordinates the activities of all of the other subsystems. Emulation and control strategies are implemented on this computer.
- ii. Operator Computer - Laptop computer interfaced to the control computer via an Ethernet link. This computer is used for data display and operator input.
- iii. Measurement Subsystem - Acts as the data storage device for the VDTV and records all of telemetry from the Control Computer. This Pentium PC computer also interfaces to the Bio-unit for measuring physiological data. Digital video will also be recorded by this subsystem.
- iv. Throttle Unit - This by-wire subsystem replaces the mechanical throttle linkage.
- v. Steering System - The front and rear steering racks are electrically driven and electronically controlled. They are interfaced to the steering wheel by a mechanical linkage as a back-up mechanism. Normally, the steering wheel is mechanically isolated from the steering system. The steering feel system uses an electric motor to provide force-feedback to the handwheel.
- vi. Brake System - This system is electrically controlled with hydraulic back-up. The systems includes four wheel ABS, traction control, and yaw control. Autonomous braking is engaged via the control computer.
- vii. Motion Sensing Pack - This unit serves as an inertial measurement unit for the VDTV. Utilizing micro-machined accelerometers and fiber-optic gyros, this unit measures body-frame and earth-frame accelerations and rotations.
- viii. Watchdog Module - Overseas the activities of the control computer and engages back-up systems when failures are detected.
- ix. Roll Control System - Provides for active control of body roll via electrically-controlled hydraulic pistons in the stabilizer bar connection to the vehicle struts. Front and rear stabilizer stiffness is independently controllable for maximum flexibility.
- x. Damping System - Continuously variable real-time damping system provides the capability to vary the ride characteristics of the vehicle so as to explore their influence on emergency driving performance.
- xi. User-Supplied Equipment - Subsystem for future testing on the vehicle. Examples include intelligent cruise control, collision warning, lane following, and other such systems.



**Figure 8.** VDTV Electronics.

The above control systems are being installed on a modified 1995 Ford Taurus SHO. The SHO was modified by Roush Technologies based on experience gained in modifying previous SHO vehicles for the Bob Bondurant school of high performance driving. This vehicle already contained a full roll cage, high performance springs, heavy duty subframe mounts, and a fire control system. This base vehicle has an experience history of proven high performance, low maintainability and high reliability.

A new approach for developing the VDTV control software was used to greatly reduce the amount of handwritten software development on the VDTV program, and to ease the modification of the VDTV to support a variety of research needs. The graphical programming tool SIMULINK from the Mathworks, Inc., was utilized to diagram the control system. A

special compiler was then used to convert this graphical description into C code (and ultimately machine code) compatible with the in-vehicle computer supplied by dSpace, Inc. This in-vehicle computer utilizes a TI 320C40 DSP and a DEC Alpha RISC processor to control and monitor the vehicle in real time.

The graphical control diagrams developed in SIMULINK are also integrated with a 17-DOF dynamics model of the VDTV for off-line simulation of control strategies and algorithms before implementation on the vehicle.

Milliken Research Associates (MRA) converted the Systems Technology, Inc., (STI) model developed for DOT in 1992 into the SIMULINK environment to serve as the basis of the VDTV model. MRA modified and extended the model to accommodate

the unique features of the VDTV. MRA also performed a series of simulations (using their own models and software) to evaluate the capabilities to vary the dynamics of the vehicle in real-time. This capability in real-time is the cornerstone of the vehicle's ability to simulate different classes of vehicles and to vary the dynamic properties individually. The MRA simulation work led to the control algorithms being used in the VDTV.

The following is a brief description of the VDTV "by-wire" control systems chosen for incorporation into the VDTV.

### Front and Rear Steering Racks

The front and rear steering racks were supplied by TRW. They are driven by an electric motor from electronic signals coming from either the steering wheel or the algorithm computer. The front steering rack is mechanically connected to the steering wheel through a clutch which is always disengaged except during a system failure. The rear steering rack is also driven by an electric motor from electronic signals coming from the algorithm computer. The fail-safe position of the rear steering rack has not yet been determined. There are basically two choices at the present time, either return to zero steer angle or freeze the steering angle at the point of failure. However, safety algorithms can be constructed to handle different situations. The VDTV steering subsystem is diagrammed in Figure 9.

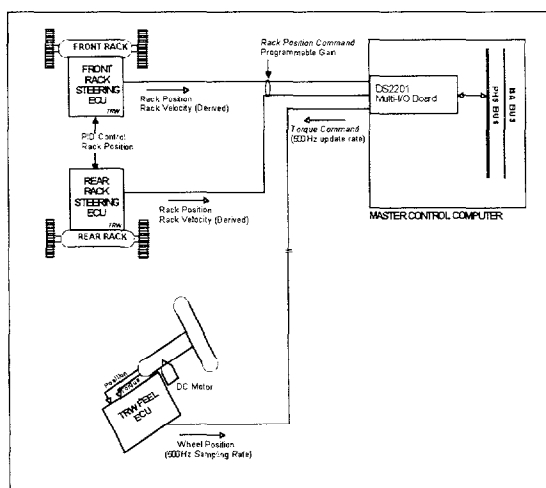


Figure 9. Steering Subsystem.

The steering racks have programmable gains and inputs controlled by the laptop computer. They also have a programmable steering feel capability.

### Brake System

The VDTV is being equipped with an advanced brake-by-wire system supplied by GM-Delphi that is production ready. The front brake caliper has been upgraded from a 10 inch diameter one to a 12 inch one to enhance the braking capability of the vehicle. The braking system is an advanced four-wheel ABS system with traction control and a four-wheel yaw control system. All of these systems will have on-and-off switches for ease of testing. The VDTV brake and brake feel subsystem is shown in Figure 10.

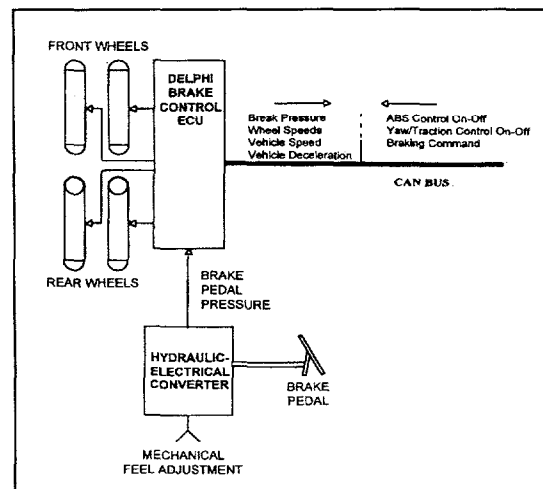
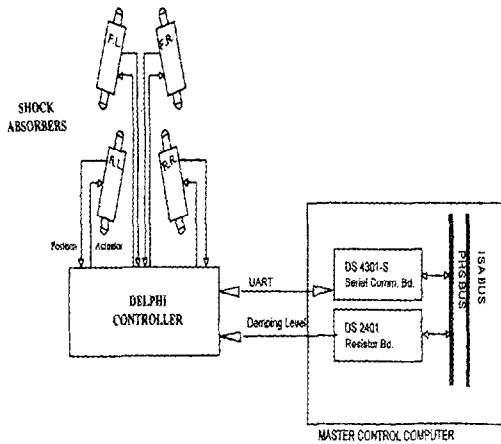


Figure 10. Braking System.

### Variable Rate Suspension System

The VDTV is being equipped with a variable rate suspension system produced and supplied by GM-Delphi. The system is programmable from the laptop computer and will provide a wide variety of suspension stiffness for performing human factors and vehicle dynamics research. The system is shown in Figure 11.

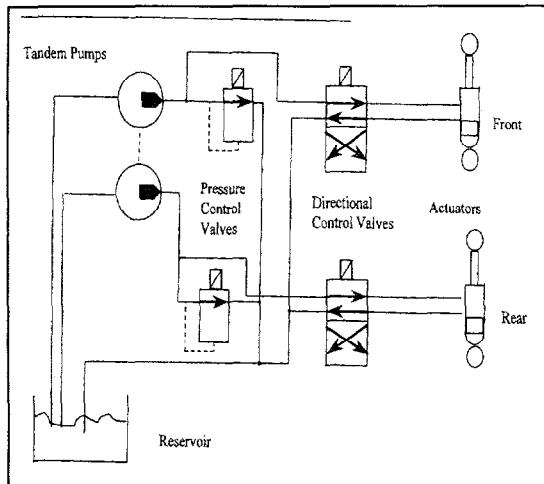




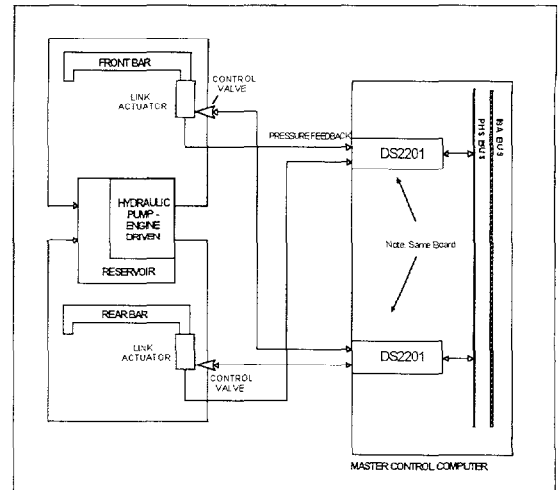
**Figure 11.** Damper Subsystem.

Front and Rear Anti-Roll Bars

The VDTV is being equipped with fully adjustable front and rear anti-roll bars supplied by GM-Delphi which can be controlled by the laptop computer. The bars can be readily changed to provide more or less roll stiffness. This capability will allow the research to vary the total vehicle roll stiffness, as well as the percentage front-to-rear stiffness distribution. The variable front-to-rear stiffness distribution capability will greatly enhance the ability of researchers to control and change the VDTV understeer coefficient. The active roll control system is shown in Figures 12 and 13.



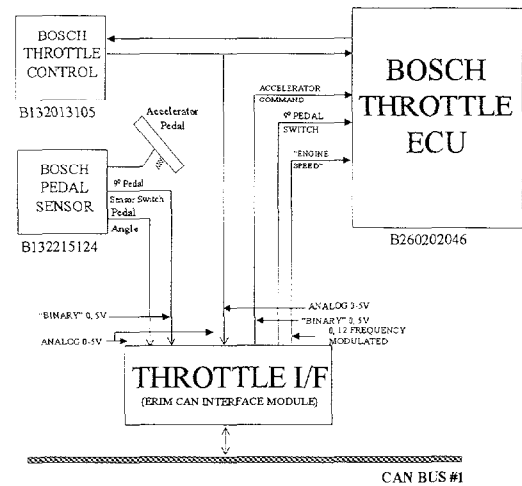
**Figure 12.** Active Roll Control.



**Figure 13.** Roll Control System.

Throttle-by-wire System

The VDTV is being equipped with a throttle-by-wire system supplied by Bosch. The system will be completely programmable from the laptop computer. The throttle feel system will be a set of changeable springs. The VDTV throttle-by-wire system is shown in Figure 14.



**Figure 14.** Throttle-By-Wire Subsystem.

**PROGRAM RESULTS**

The VDTV is scheduled to begin shakedown tests at the Vehicle Research and Test Center in Ohio on June 8, 1998. The control systems, safety systems, and data measurement systems will all be thoroughly checked out before a series of VDTV acceptance

tests are begun. The vehicle has been designed to meet certain specifications for performance and safety. After the VDTV has passed the acceptance tests, it will be used as a test tool in planned research programs.

## **REFERENCES**

**Marriott, A.T.**, *“Variable Dynamic Testbed Vehicle Study”*, Department of Transportation Contract Technical Report Numbers DOT HS 808 178, (Volume I) Technical Summary; DOT HS 808 179, (Volume II) Technical Results; DOT HS 808 180 (Volume III) Appendixes

**VDTV Contract Document** entitled *“Exhibit I - Variable Dynamic Testbed Vehicle Functional Requirements”*