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# VIRTUAL PROVING GROUND ENVIRONMENT FOR DESIGNING A ROLL-OVER DETECTION AND WARNING SYSTEM

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## ABSTRACT

A 24 degree-of-freedom full vehicle-driving simulator is proposed in this paper. The simulator provides a full immersive graphical virtual scenery and force/motion feedback cues for the driver. The simulator has been developed to provide an open architecture in a local network environment. Using Matlab/Simulink one can interface with the vehicle model through this environment, designing and testing vehicle sub models while evaluating the ride performance of the vehicle.

The development and implementation of a rollover detection and warning system is discussed, to illustrate the application of the driving simulator.

## INTRODUCTION

In the U.S., more than 35,000 people were killed in road accidents in 1997 [20]. About one fourth of these deaths were the result of non-collision crashes. The report also showed that rollover occurred in about 90% of the first harmful events of non-collision fatal crashes. Furthermore, the percentage of rollover occurrence in fatal crashes was significantly higher than other types of crash accidents. Compared to the other types of vehicles, sports utility vehicles (SUV) have the highest rollover rates in all crashes.

Recently, the National Highway Traffic Safety Administration (NHTSA) announced that it would provide additional information [6] about the rollover stability of vehicles in its future safety rating. One major thrust behind this new initiative is the well-publicized rollover incidents of several SUVs and passenger cars (Suzuki Samurai, Isuzu Trooper, Mercedes A-class, and the Mercedes/Swatch SmartCar). Since vehicle safety is a crucial factor influencing consumers' purchasing decisions and government regulations, it seems fair to say that rollover stability is becoming an important element in the overall vehicle safety performance.

Besides the particular solutions, also the design and development process of vehicle safety systems has gained much attention in the recent years. Due to emerging technologies in both computational and graphics display power of modern workstations, virtual vehicle systems simulation (VVSS) has become a useful tool at the design engineers' desktop.

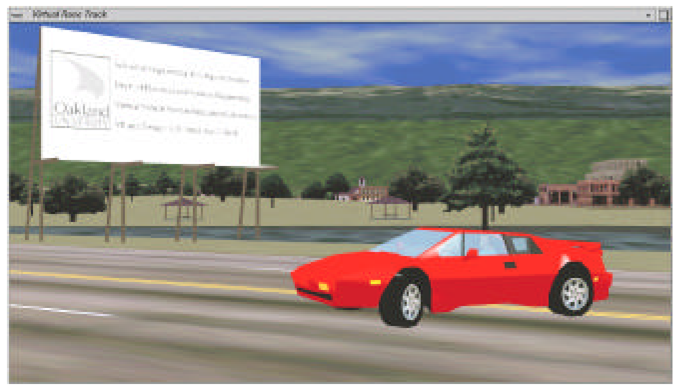

**Figure 1 Snapshot of Virtual Vehicle Simulation**

This paper details the design/modeling/simulation environment, VVSS, for developing and evaluating vehicle safety systems. It is a full vehicle simulation environment with virtual realistic rendering and a real-time interactive human interface. The engineering design interface is Matlab-Simulink based. The virtual simulation environment provides access to each state and parameter of the 24-degree-of-freedom vehicle model.

Multiple design stations can access the vehicle model during simulation, controlling the driver inputs, implementing prototype models of safety systems, and conducting diagnostics and data logging.

The simulation executes a real-time model of the full-vehicle dynamics. This allows driver-in-the-loop (DITL) and hardware-in-the-loop (HITL) simulation experiments. DITL provides the capability of subjective evaluation of prototype mathematical models (before building a prototype) in multiple (fatal) driving scenarios. HITL provides the capability of evaluating prototype subsystem performance before conducting field-experiments.

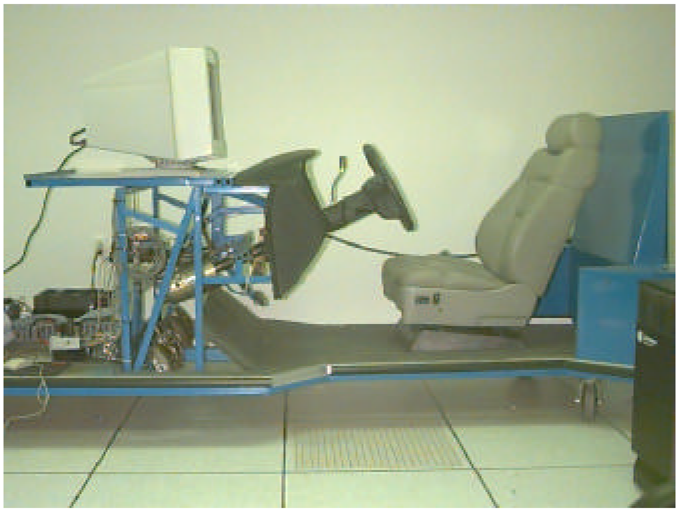

**Figure 3 Human Driver Interface**

Virtual prototyping has become a vital phase in the design and development process of vehicle systems. Especially, safety systems are evaluated in a non-destructive fashion, saving cost, human resources and turn-around time in iterative design stages.

This paper explains the requirements and construction of a virtual proving ground. The presentation will feature a live demonstration of the simulation environment for the development of a rollover warning system. The conclusions capture the applicability, demonstrate simulation results and present an overview of the virtual proving ground facility.

The capability of simulating the dynamics of a full-vehicle platform gives engineers the valuable option of conducting driving scenarios with concept vehicle subsystems before actual testing.

Commercial packages like ADAMS, DADS or VDANL [13] are available, as well as commercialized academic packages like TruckSim [15] and Madymo. However, generally they contain black-box simulators and are expensive. This means that a file of configuration parameters defines the simulation environment, but there is no easy access to the models. Also, these simulators will typically utilize a pre-defined scenario for the driver. This can be either a driving scenario (steering, throttle and brake trajectories) or a driving behavior characterization (delay, bandwidth, gain). The simulators will usually generate graphical output in the form of curves and plots on axes. Additional software needs to be acquired to visualize the data in 3D scenery. Hence, most of the commercial solutions will not be (or are expensive to be) customized and do not give the user the ability to run arbitrary interactive test scenarios, and do therefore not give the subjective feel of a systems performance. They are usually not designed for solving the vehicle dynamics model in real time or interactively.

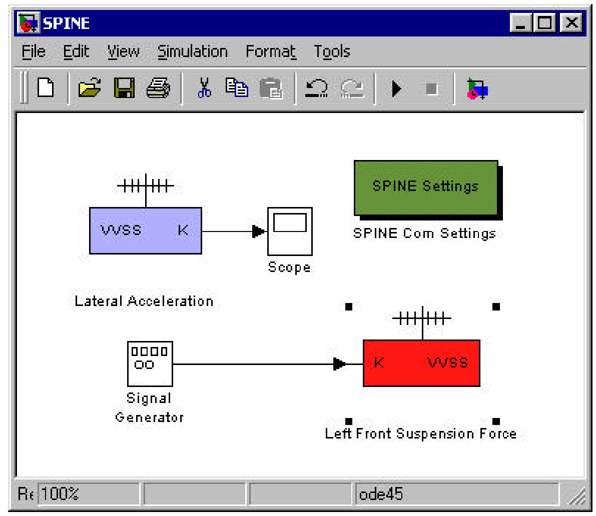


**Figure 2 Example Simulink Diagram for VVSS**

## VIRTUAL VEHICLE SIMULATION

A full vehicle simulation environment has been developed at Oakland University, which provides run-time access to all states and parameters in the mathematical model. The mathematical model of the vehicle contains 24 degrees of freedom. Generic models are used for power train and suspension systems. When higher fidelity models are needed, they can be employed through the collaborative simulation network. The details of the vehicle model have been published before in [16, 17, 18, 19].

A Silicon Graphics ONYX computer is used to evaluate the vehicle dynamics and to render the virtual realistic environment. The software contains features for various viewpoints, multiple vehicles multiple terrain characteristics and fog. A realistic driver interface is used for human in the loop operation. Figure 3 shows a picture of the driver interface. The driver interface is connected to the VVSS through a Pentium PC that is connected to the SGI computer. The next section explains in more detail about this collaborative simulation network.

## COLLABORATIVE SIMULATION ENVIRONMENT

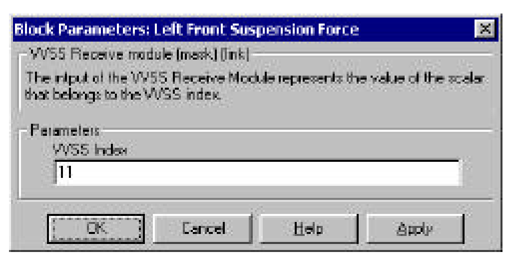


**Figure 4 Configuration Dialog Window for VVSS-link**

A collaborative simulation network environment has been developed in conjunction with the vehicle simulation model. This Simulation Platform with Integrated Network Environment (SPINE) provides access to the states and

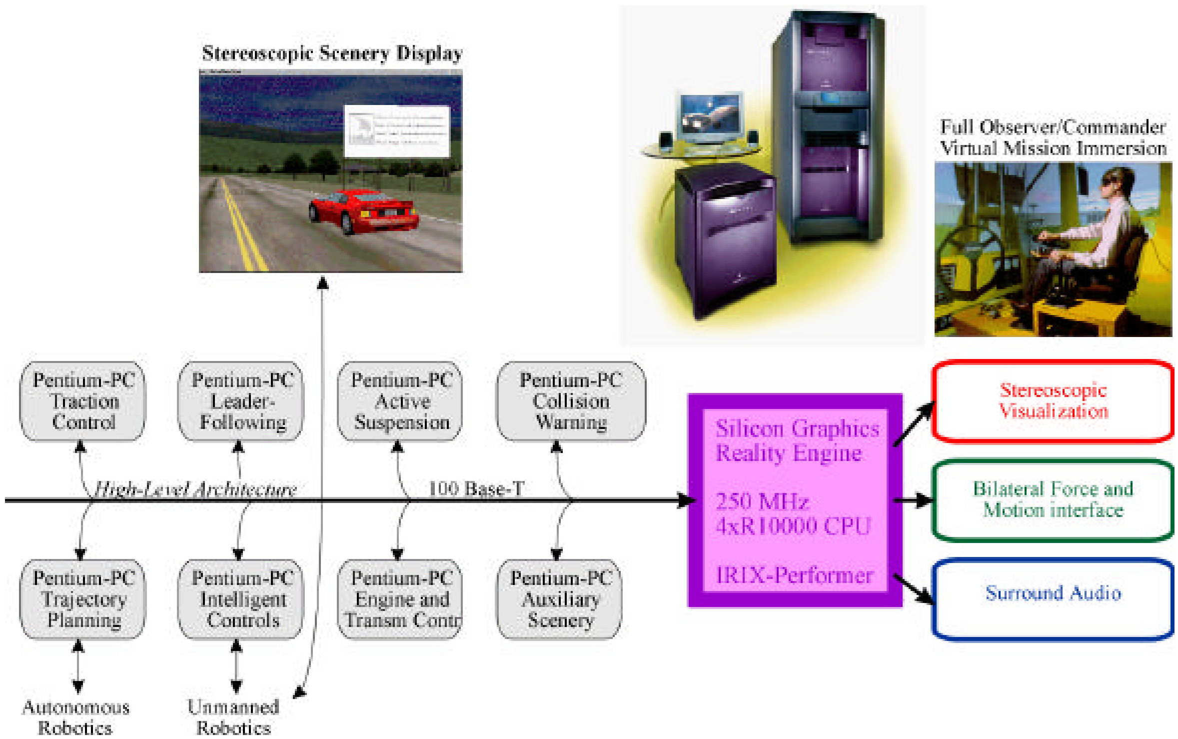


**Figure 5 Virtual Vehicle System Simulation Environment**

parameters of the vehicle model through Matlab/Simulink for Pentium PC's on the local network.

Figure 5 shows the topology of the network. The SGI ONYX computer is used to provide the virtual realistic interface for the VVSS. It hosts a service on the local area network for other workstations to interface with the runtime simulation model. These workstations will typically be Pentium PC's with Matlab/Simulink.

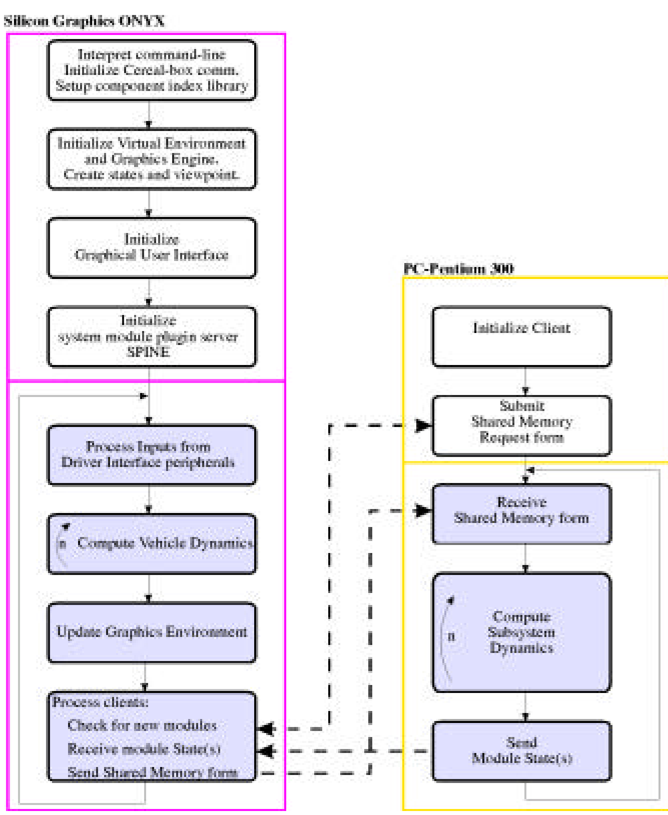


**Figure 6 Application Task Flow for Simulation.**

An interface library has been developed to provide capability within a Simulink diagram. It employs a client interface on the network and interface with the vehicle simulation model from Matlab. It is not necessary to compile or pre-process the Simulink model for executing the simulation. The library contains the index values that represent the states and parameters that are accessible through SPINE. All values are represented in SI units.

An example of a simple Simulink model as in Figure 2 illustrates the concept. By double clicking on the input port, a configuration window appears, as shown in Figure 4. The index number corresponds to the library entry for the desired state or parameter, in this case, 11 represents the vehicle lateral acceleration. The similar configuration is used for an output port.

The interface protocol for collaborative simulation through SPINE defines a strict timing management for the client/server models. A synchronization rate is defined in the VVSS, which is by default equal to the graphical frame rate. For each data-exchange time frame $t_p$, the vehicle dynamics model, and the simulation sub-model in the clients will be evaluated. For complex models this may require a higher rate sub-sampling for the individual models. At the end of each frame $t_p$, the values for the specific states and parameters that are used in the client model will be transferred. This concept is given in Figure 6.

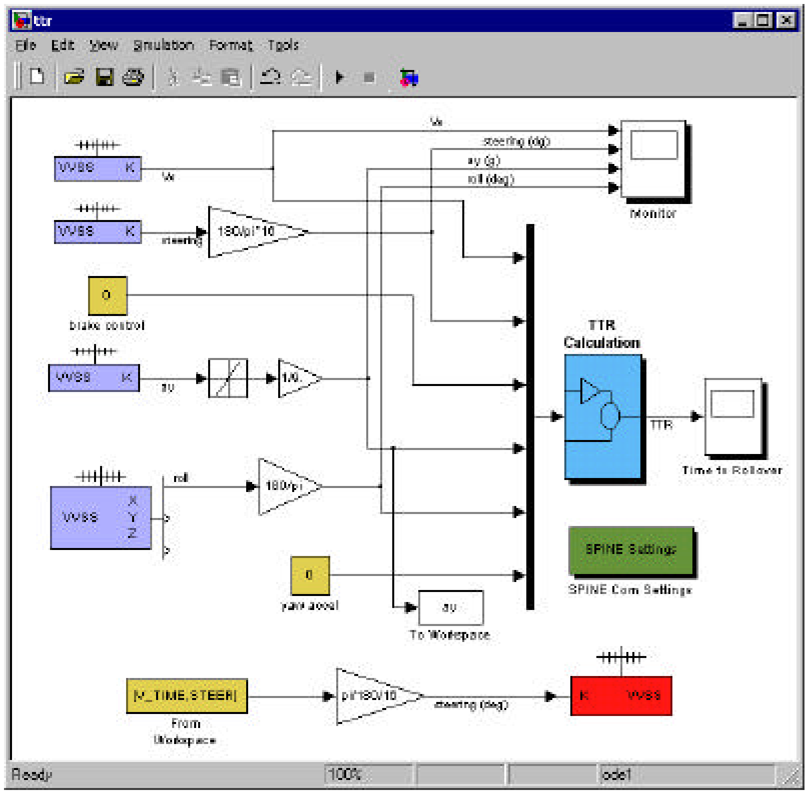


**Figure 7 Simulation model for Rollover Detection/Warning System in Simulink**

Since a regular 100 base-T TCP/IP network connection is used for the SPINE, there is a limitation to the data exchange rate in the system. The bandwidth of the signals that are communicated on SPINE as input and output ports of the Simulink model can currently go up to about 100 Hz.

## CONFIGURATION & CALLIBRATION

Now that the collaborative simulation environment has been setup, the actual application models can be designed and a Design of Experiment can be defined.

The first task is to tune and modify the vehicle system parameters, so that the simulation results correlate to the experimental data of a specific vehicle platform. Experimental data acquisition is often times expensive and time consuming. It is therefore desired to conduct a well-defined sequence of driving scenarios, which provide sufficient *exciting* data to uniquely calibrate the vehicle model.

The VVSS utilizes a vehicle definition file, which contains the vehicle characterization in ASCII format. The parameters define the vehicle geometry (e.g. lengths from CG to front and rear axels, inertia, masses, aerodynamic resistance), suspension anchor locations, damping and stiffness, tire geometry, damping, stiffness and damping, and tire model parameterization. It must be understood that higher detail models for suspension, chassis or power train can be applied through SPINE, when they are available.

## ROLLOVER APPLICATION APPROACH

The VVSS has been used for designing and evaluating the performance of a rollover detection and warning system. The research project was conducted in collaboration with the University of Michigan as part of the Automotive Research Center (ARC) Consortium.

Rollover prevention can be achieved by employing rollover warning and anti-rollover systems. Most existing rollover warning systems [14, 21, 22, 4, 23, 24, 25] are based on signal threshold techniques. These systems turn on the warning actions when the vehicle roll angle or the lateral acceleration exceeds a pre-selected threshold value. They are usually conservative and do not predict impending rollover danger in the future, which is very important for drivers to correct the dangerous maneuver and avoid the rollover accident before the threshold value is exceeded. To prevent/reduce rollover, one of the most important enabling techniques is the development of accurate rollover threat indices.

A rollover warning/control algorithm will work well only if the impending vehicle rollover threat can be accurately represented. The authors proposed a Time-To-Rollover (TTR) metric [1, 2] for rollover prevention. In theory, TTR provides a better assessment of impending rollover threat, and thus could be the basis for rollover warning and anti-rollover control algorithms. In [1], it was shown that the TTR for SUV's is too short for human drivers to respond. It is an indication that an active control may be necessary to assist the drivers for rollover prevention.

TIME-TO-ROLLOVER METRICS

The tire lift-off is defined as the unacceptable rollover event in this research. To be more precise, when we use the term "Time-To-Rollover" we actually mean "Time-To-Tire-lift-off'. This definition will not result in any major change in the overall algorithm development. A more aggressive or conservative roll event definition can be used and the overall design process to be described below will remain the same.

After a "rollover" (more precisely, tire-lift-off) has occurred, a true-TTR can be computed in an afterthought manner. In other words, whenever the vehicle roll angle exceeds the defined threshold value, we can roll back the clock and define a point 0.2 seconds before this tire-lift-off incident to have a "true-TTR" of 0.2 seconds. Ideally, if we can re-construct this TTR index in real-time, and in a predictive manner, the severity of rollover threat can be accurately represented and reported. Based on this index, various warning/control systems can be designed. A model-based TTR is defined as following: assuming the input (steering angle) stays fixed at its current level in the foreseeable future, the time it takes for the vehicle sprung mass to reach its critical roll angle is defined as the (model predicted) TTR. Under normal driving conditions, the model predictive TTR is usually quite large. For implementation considerations, we can saturate the model predicted TTR at X seconds. In other words, we will integrate the speed-dependent yaw-roll decoupled model for up to X seconds (see Figure 8). If it is found that the vehicle does not rollover, the model-predicted TTR is said to be X seconds.

Hence, for evaluating the time to rollover, the model will need the actual vehicle roll angle, lateral acceleration and current steering angle. The model output is only used for indication. It is not used for any return actuation on the vehicle.

For further detail on the TTR system, refer to [1, 2].

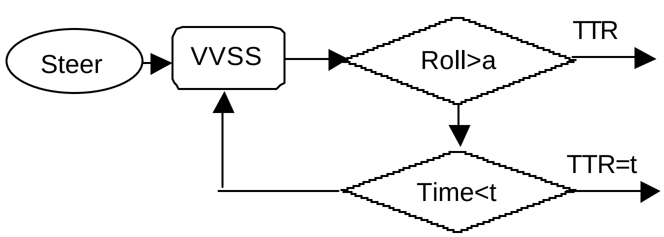


**Figure 8 Flowchart for TTR Calculation**

## CONCLUSION

The above application illustrates the use of the VVSS for virtual prototyping of automotive driving aid systems. A logical extension to this research effort would be to define a control law for the individual brakes on the vehicle corner, as to aid the desired yaw motion and to minimize the rollover threat. However, this aspect was outside of the scope of the project.

This application does demonstrate the accessibility of the VVSS virtual driving environment for prototyping concept models of subsystems. The ease of use in the familiar Matlab/Simulink environment eliminates the understanding of full-vehicle dynamics. It also avoids the need for compilation, while at the same time it provides open access to states and parameters, as we know from Simulink.

Current collaborations at Oakland University involve the application of Collision Warning and threat assessment, and performance evaluation of autonomous robotic vehicle systems, utilizing the VVSS environment.

Future efforts include automation algorithms for model calibration. Progress in this area will be reported in future publications.

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## REFERENCES

1. Chen, B. and Peng, H., "Rollover Warning for Articulated Vehicles Based on a Time-to-Rollover Metric," ASME International Mechanical Engineering Conference and Exhibition, November 1999.
2. Chen, B. and Peng, H., "A Real-time Rollover Threat Index for Sports Utility Vehicles", Automatic Control Conference, June 1999.
3. Dunwoody, A.B., "Active Roll Control of a Semi-Trailer," SAE Paper No. 933045, 1993.
4. Freedman, M., Olson, P. L. and Zador, P. L., "Speed Actuated Rollover Advisory Signs for Trucks on Highway Exit Ramps," Insurance Institute for Highway Safety and University of Michigan Transportation Research Institute, December 1992.
5. Furleigh, D.D., Vanderploeg, M.J. and Oh, C.Y., "Multiple Steered Axles for Reducing the Rollover Risks of Heavy Articulated Trucks," SAE Paper No. 881866, 1988.
6. Garrott, W. R., Howe, J. G., and Forkenbrock, G., "An Experimental Examination of Selected Maneuvers That May Induce On-Road Untripped, Light Vehicle Rollover -Phase II of NHTSA's 1997-1998 Vehicle Rollover Research Program, July 1999.

7. Koibuchi, K., Yamamoto, M., Fukada, Y., and Inagaki, S., "Vehicle Stability Control in Limit Coming by Active Brake," SAE Paper No. 960487.
8. Lin, R.C., "An Investigation of Active Roll Control for Heavy Vehicle Suspensions," Ph.D. Thesis, Cambridge University Engineering Department, 1994.
9. Lin, R.C., Cebon, D. and Cole D.J., "Optimal roll-control of a single-unit lorry," J. Auto. Eng., Proc. ImechE, D05294, pp. 45-55, 1996.
10. Lin, R.C., Cebon, D. and Cole D.J., "Active Roll Control of Articulated Vehicles," VSD, Vol. 26, No. 1, pp. 17-43, 1996.
11. Smid, G.E., "Virtual Vehicle Systems Simulation: A Modular Multi-CPU approach in Real-Time, "Ph.D. dissertation, Oakland University, Rochester, Michigan, 1999.
12. Strickland, R. and McGee, H., "Evaluation of Prototype Automatic Truck Rollover Warning Systems," FHWA-RD-97-124, 1997.
13. Vehicle Dynamics and Analysis Software. a comprehensive 6 degree of freedom vehicle simulation program for the PC.
14. Woodrooffe, J. H. F., "Practical Concepts In Heavy Truck Rollover Accident analysis," Heavy Vehicle Rollovers Conference, 29-30 April 1993, Atlanta, Ga.
15. Mechanical Simulation Corporation (MSC), "TruckSim User Reference Manual", February 1999.
16. K. Kobayashi, K. Watanabe, Ka C. Cheok, and G. E. Smid. A simple vehicle dynamics modeling by the object oriented approach. SICA, 1997.
17. G. E. Smid and Ka C. Cheok. Human integration in simulation. In Proceedings of Inter-national Workshop on Advanced Motion Control, pages 554–558, Coimbra, Portugal, June 29-31 1998.
18. G. E. Smid and Ka C. Cheok. Multi-computer real-time simulation of vehicle control systems. In Proceedings of International Conference on Intelligent Systems (ICIS), Paris, France, July 1998.
19. G. E. Smid, Ka C. Cheok, and K. Kobayashi. Simulation of vehicle dynamics using matrix-vector oriented calculation in Matlab. In Proceedings of CAINE (ISCA), pages 115–120, Orlando, FL, December 1996.
20. National Highway Traffic Safety Administration (NHTSA), "Traffic Safety Facts 1997: A Compilation of Motor Vehicle Crash Data from the fatality Analysis Reporting System and the General Estimates System", DOT-HS-808-806, November 1998.
21. Rakheja, S. and Piche, A., "Development of Directional Stability Criteria for an Early Warning Safety Device," SAE Paper No. 902265, 1990.
22. Preston-Thomas, J. and Woodrooffe, J. H. F., "A Feasibility Study of a Rollover Warning Device for Heavy Trucks," Transport Canada Publication No. TP 10610E, September 1990.
23. McGee, H. et al., "Feasibility of An Automatic Truck Warning System," FHWA-RD-93-039, June 1993.
24. Strickland, R. and McGee, H., "Evaluation of Prototype Automatic Truck Rollover Warning Systems," FHWA-RD-97-124, 1997.
25. Winkler, C. et al. "Cooperative Agreement to Foster the Deployment of a Heavy Vehicle Intelligent Dynamic Stability Enhancement System," University of Michigan Transportation Research Institute, Interim report, NHTSA - U.S. DOT Contract No. DTNH22-95-H-07002, January 1998.

## DEFINITIONS, ACRONYMS, ABBREVIATIONS

**ARC**: Automotive Research Center

**HITL**: Hardware In The Loop.

**VVSS**: Virtual Vehicle System Simulation

**SPINE**: Simulation Platform with Integrated Network Environment

**TTR**: Time To Rollover