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Safety Performance and Robustness of Heavy Vehicle AVCS

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Final Report for Task Order 4211

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Final Report
TO 4211
Safety Performance and Robustness of Heavy Vehicle AVCS

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1 Introduction

Dynamically, heavy trucks are inherently different than passenger cars. In addition to the increase rollover risk arising from an elevated center of gravity height, heavy trucks possess additional failure modes such as jackknifing and excessive trailer swing. As a response to these issues, significant research has been performed in the last three decades to establish safety metrics for heavy trucks based on dynamic testing. This research has had an impact on determining acceptable size and weight restrictions for heavy vehicles and on the actual design of heavy trucks for increased safety.

Yet despite the focus placed on heavy truck safety by the truck size and weight community, research in heavy truck automation has not yet embraced these issues. The control models developed for heavy trucks and their controllers have generally treated the truck as a planar model without roll. When roll has been included, it has taken the form of a simply-sprung model without the inherent complexity of real suspension and steering geometry and effects such as roll steer. The potential for problems in such an approach is clear: if the models assume that roll and suspension kinematics are unimportant, it is impossible to use these models to assess the impact of heavy truck lateral control on roll dynamics. Thus the impact of existing lateral control designs on heavy truck safety, particularly with respect to roll, is unknown.

In TO 4211 and its predecessor, MOU 390, the goal of the research was to develop a more detailed heavy truck dynamic model for the purpose of evaluating the effects of lateral controllers on safety and roll dynamics. MOU 390 laid the groundwork for this evaluation through a literature review of evaluation methods from the truck size and weight community and a characterization of typical parameters for heavy trucks. In addition, work under MOU 390 initiated the development of a more complete vehicle model comparable to those used in industry for ride and handling studies. The parameters chosen for this model were taken from the existing tractor belonging to the California PATH Program. In TO 4211, the truck model was completed and integrated into a complete simulation environment where multiple trajectories and controller designs could be compared.

The results of the project both underscore the importance of considering roll and provide some encouraging insight into the performance of existing PATH control schemes. By using the lane change maneuver methodology proposed in MOU 390, different control gains that produce comparable lane tracking behavior can be shown to produce vastly different roll responses. Thus consideration of roll excitation is indeed an important criterion for the development of heavy truck lateral controllers. Furthermore, the ability to discriminate among these controllers provides support for the lane change maneuver as an effective tool for evaluating vehicle roll effects. Most encouragingly, there exist choices of gains within the existing PATH control scheme that produce low levels of vehicle roll. Thus, while roll has not been explicitly considered in previous work, there appears to be sufficient flexibility within the control scheme to ensure that roll dynamics are not heavily excited. The simulation study did not find any cases where the existing control structure could not be tuned to provide acceptable tracking and safety.

While the objectives of the project were therefore fulfilled and the model proved useful as a design tool, the specific implementation of the vehicle model using commercial software proved somewhat challenging to use. This report concludes with suggestions for improving the software environment for future use as a design tool.

2 Background – Work Completed Under MOU 390

The work described here under TO 4211 represents the second year of a two-year project initiated under MOU 390. The research contributions from MOU 390 are described in the separate report for MOU 390 but are briefly summarized here to put the work of the second year in perspective. These tasks consisted of developing ranges of parameter variation for heavy trucks, identifying standard maneuvers and metrics that could be used to evaluate heavy truck safety and beginning to develop a detailed multi-body dynamic model of the Freightliner truck used by the California PATH program.

Parameter Study

A list of mechanical properties was compiled for heavy truck components such as tires and suspension. Tire properties included cornering stiffness and longitudinal stiffness. Suspension properties included roll stiffness, roll center height, and lateral stiffness. UMTRI's Mechanical Properties Factbook (Fancher et al, 1986) proved to be a valuable reference for many of these parameters. In addition, the study included information about the types of vehicles found on the road in California. The California Vehicle Code, which stipulates legal limits for truck size, weight, and axle load, served as the main source of information for possible truck, tractor, trailer, and semitrailer configurations.

A literature review cataloging parameter values typically used by researchers was also completed. This work provides a basis for developing models with physically realistic parameter values. For example, a tire's cornering stiffness is heavily influenced by the vertical load on the tire. Several papers (Pottinger et al, 1998) have developed formulas to calculate cornering stiffness based on vertical load and the literature review cataloged these efforts. Similarly, heavy trucks employ a wide variety of suspension types. Another paper (Winkler et al, 1992) tabulates experimental suspension data gathered from nearly a hundred trucks of different makes and models, giving a wealth of information for researchers developing truck models. The final report for MOU 390 includes a full annotated bibliography of the papers found during the literature search.

Performance Measures Study

Another literature search was performed to compile the different tests and performance measures used in evaluating safety of heavy trucks. Some of the more common measures include braking efficiency, friction demand, static rollover threshold, and load transfer ratio. Benchmark values for these performance measures were also documented.

Based on the desire to evaluate heavy truck lateral controllers for their effects on vehicle safety, particularly roll, the report proposed concentrating on the SAE standard lane change maneuver as a relevant test. The lane-change maneuver defined by SAE is a high-speed (55 mph) test requiring 4.8 feet of lateral displacement over a distance of 200 feet. This maneuver is similar to the RTAC-b evasive maneuver developed by Ervin, et. al. (1986). In reality, it represents a distance comparable to half of a lane change and not a full lane change. The reason for this is to avoid producing excessive roll that would necessitate the use of outriggers when testing heavy trucks. The maneuver is designed to trigger roll and trailer swing to enable judgments to be made about the safety of the truck in a rapid maneuver. This seemed like a natural choice for evaluating lateral controllers since the connection to lateral control was clear (the test is simply a trajectory for the controller to follow) and it provides an evaluation of how the controller may amplify frequencies that are harmful in roll or trailer swing.

The test can simply be evaluated in terms of the roll or roll rate produced in the vehicle or several standard performance metrics can be generated from the data. These include:

- **Dynamic load-transfer ratio –** the fractional change in load between left and right side tires in an evasive maneuver
- **High-speed transient offtracking –** the lateral overshoot of the last axle with respect to the path of the first axle in an evasive maneuver
- **Rearward amplification –** the ratio of the highest lateral acceleration of the last trailer to the highest lateral acceleration of the tractor during evasive maneuver (primarily of concern for multi-trailer units)

One of the main goals of the second year of the project was to determine if this maneuver was indeed informative in assessing the safety of heavy truck lateral controllers. The results obtained in this respect are very encouraging and suggest that the maneuver can be as effective for analyzing the closed-loop behavior of a lateral controller as it can be in evaluating the truck by itself.

Development of Heavy Truck Model

Under MOU 390, physical dimensions were obtained from the PATH truck, the most critical dimensions being values related to the steering and suspension systems. From these values, the research team began to develop a multi-body dynamic model of the PATH truck using ADAMS dynamics simulation software. The model went through further revision in the second year as suspension stiffness values were tuned to match the observed behavior of the PATH truck. The model was therefore completed under TO 4211. The full description of the final model used in the simulations follows in the next section.

3 ADAMS truck model

The following sections detail the modeling assumptions necessary to develop the multi-body dynamic model of the PATH truck.

3.1 Model description

The California PATH Association heavy truck is a Freightliner FLD120 Conventional Class 8 vehicle. Physical dimensions, particularly those belonging to the steering and suspension systems, have been taken from the PATH truck. A preliminary dynamic model of this vehicle has been completed using the *Automatic Dynamic Analysis of Mechanical Systems* (*ADAMS*) modeling package distributed by Mechanical Dynamics, Inc. The ADAMS software is used to simulate the dynamics of systems consisting of rigid-bodies and/or flexible parts. ADAMS is commonly used within the automotive community to study suspension or ride and handling performance of full vehicle models. A snapshot of the full vehicle ADAMS model of the California PATH Association heavy truck is shown in Figure 1.

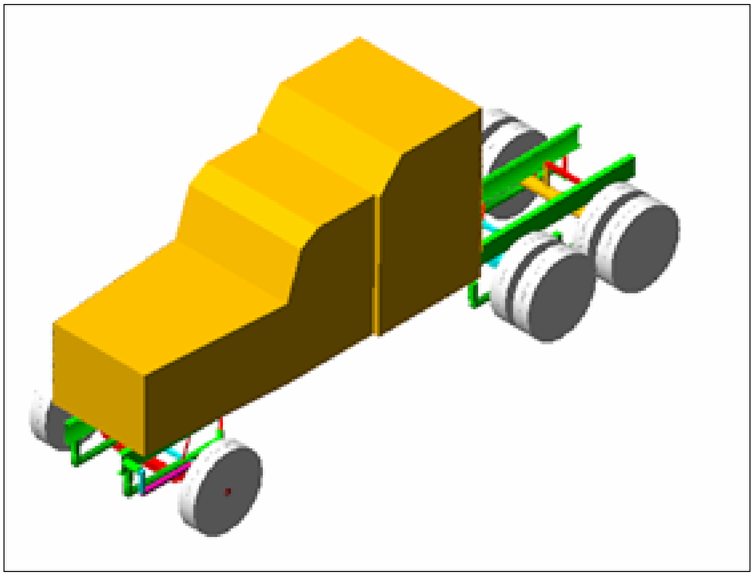

Figure 1: ADAMS model of Freightliner Conventional.

The ADAMS model of the PATH truck was created using only rigid-body components; i.e., there are no flexible parts besides spring and damper elements. Figure 2 depicts the modeled front suspension and steering linkage of the PATH truck. The front axle is primarily suspended by leaf springs directly attached to the frame. While a real leaf spring derives its characteristics from deformation of the leaves and friction between the leaves, this type of behavior is difficult to model. Instead, each leaf spring has been modeled as a rigid link attached at its forward end to the frame via a revolute joint and at the other end by a spring. The spring constants will approximate the roll stiffness and vertical stiffness provided by the leaf springs. The dampers attaching the leaf springs to the frame are representative of the dampers found on the PATH truck. However, the damping values must account for the additional damping provided by the leaf springs. In the model, the leaf springs are attached to the axle via bushings to allow for some twisting motion of the axle with respect to the frame.

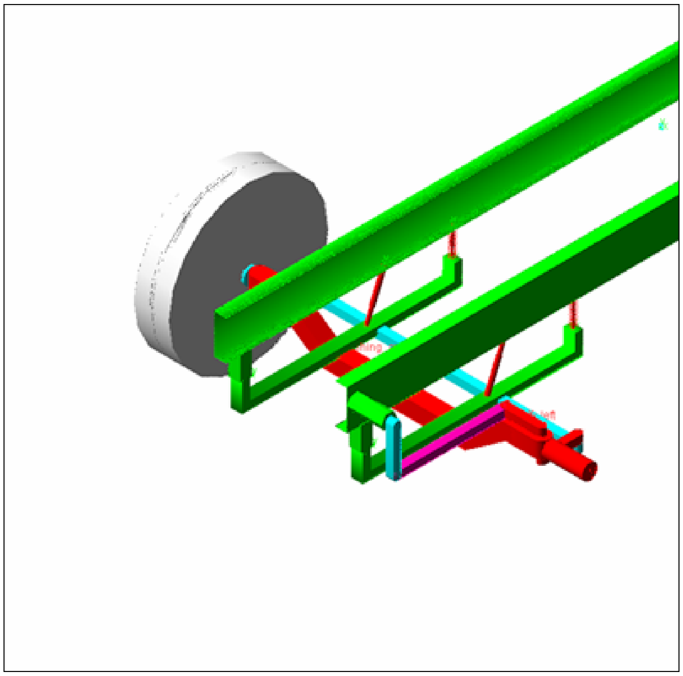

Figure 2: Front suspension and steering linkage.

The front wheels are steered by the motion of the pitman arm against the left wheel assembly, with the steering action transmitted to the right wheel by the tie rod (Figure 2). The pitman arm (blue in color) rotates with respect to the truck frame via a revolute joint. The horizontal linkage (magenta in color), which is connected to the pitman arm and runs parallel to the truck frame, is attached to the pitman arm and left spindle (red in color) via spherical joints. The right and left spindles are both joined to the axle through revolute joints. The tie rod (blue in color) is attached to the left and right spindles using spherical joints. It should be noted that the joints that have been modeled as spherical joints are in reality revolute joints with bushings. These joints have been modeled as spherical joints instead of revolute joints to eliminate redundant constraints and to simulate the rotations that are allowed by the compliance of the bushings.

The rear suspension (Figure 3) differs from the front suspension in that the rear leaf springs are partially suspended by airbags. However, a rear leaf spring with air bag can be modeled in the same way as the front leaf spring — a rigid link located by revolute joint and spring element — since the spring approximates the behavior of the airbag. The spring constants will be different, of course, since the air suspension at the rear is softer than the front suspension with leaf springs only. An additional feature of the rear suspension is the pair of horizontal track rods that locate the rear axles with respect to the frame. The track rods lie directly over the axles, and are connected to the truck frame by way of revolute joints. A spherical joint connects the track rods to the axles to allow for roll steer effects.

The final major component of the model is the tires. The tires are modeled as Delft tires using the ADAMS *Tire* algorithm (further details on tire modeling and published tire models for heavy trucks can be found in the report for MOU 390). The algorithm solves for tire forces based on interaction with a road surface. The tires are attached to the axles by revolute joints.

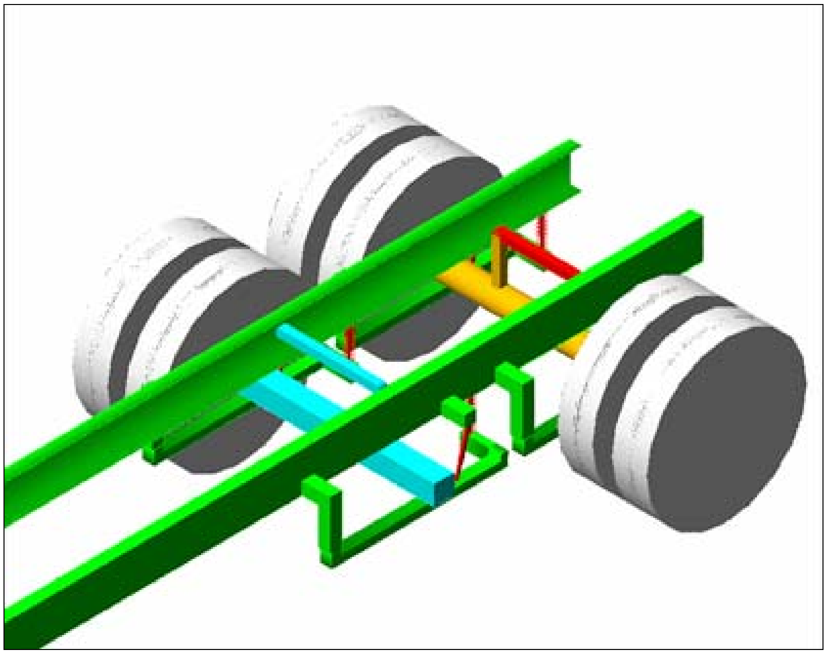

Figure 3: Rear suspension.

The high center of gravity and the narrow track width cause roll dynamics to greatly affect heavy-duty vehicles more so than passenger cars. Suspension properties must be accurate in order to adequately capture roll dynamics. Roll stiffness, roll center height, and the vertical stiffness are the most important suspension properties when analyzing roll. The roll stiffness of the suspension is defined as the torsional stiffness measured about the roll center. The vertical stiffness is the spring rate associated with the deflection of the suspension. The correct modeling of these parameters results in accurate analysis of roll rates and yaw rates.

Table 1 contains a listing of the stiffness values used in the model. Heavy truck suspensions often possess auxiliary roll stiffness beyond that attributable to the effect of the vertical stiffness and spring spacing. To tune the roll stiffnesses appropriately for a given vertical stiffness, the stiffnesses of the suspension bushings at the joints in the linkage were tuned appropriately. The values of these bushings are also included in Table 1.

Spring Stiffness and Damping Values by Axle		
	Suspension Stiffness ***lb_f/inch***	**Suspension Damping** ***lb_f-sec/inch***
Steer Axle	3260	300
Leading Drive Axle	3055	611
Trailing Drive Axle	3400	680
Leading Trailer Axle	5750	1150
Trailing Trailer Axle	8000	1600

Bushing Values			
	x	**Y**	**Z**
Damping (*lb_f-sec/inch)*	1000	1000	1000
Stiffness (*lb_f/inch)*	12000	10000	10000
Torsional Damping (*lb_f-inch-sec/deg)*	0	0	2000
Torsional Stiffness (*lb_f-inch/deg)*	0	0	35000

Table 1: Suspension and bushing properties.

4 Experimental Testing

While not in the original project proposal, the research team decided that it could be valuable to take advantage of some scheduled testing of the PATH truck at Crow's Landing in order to obtain some experimental data for validation purposes. Since there was not time to outfit the truck with additional sensing, the stock inertial and speed sensors, together with the steer angle measurement, formed the basis of the sensor suite. Similarly, since there was not an opportunity to place additional magnets in the runway area to create the SAE standard test maneuver, we chose to perform the tests in a manually driven mode.

Several important observations can be made based on the results of this testing:

- **The SAE standard lane change maneuver is rather mild.** We found that using the specified lateral distance, the tests produced very little roll and yaw rate signal at all. It was therefore necessary to increase the separation over the 200 foot distance to approximately 12.5 feet to generate a meaningful signal.

- **There is a high degree of driver dependence on the shape of the actual maneuver.** One of the reasons for the observed mildness in the maneuver was the tendency of the driver to smooth or filter certain parts of the steering command – driving a heavy truck in a manner that intentionally excites the dynamics is simply not a comfortable or intuitive process. Part of this effect could be controlled by using a greater number of cones to outline shape of the maneuver, leaving less interpolation to the driver. Note that this problem is not an obstacle to using the SAE maneuver to evaluate lateral controllers but it does make it hard to compare manually driven tests with simulations of either a model driver or a lateral controller.

- **The surface at Crow's Landing is problematic for this sort of testing.** As Figure 4 below illustrates, the unevenness of the runway surface at Crow's Landing induces a lot of roll and yaw motion in the vehicle. The dashed red line represents the roll rate in degrees per second and the solid blue line represents the steering input angle in degrees. Thus the effective signal to noise ratio in the roll rate is quite small. Since the SAE standard lane change maneuver is at its core a transient maneuver, these bumps make it difficult to quantitatively capture transient values such as the peak roll rate (or angle). Coupled with the variability in the driver input, particularly with respect to the timing and rate of the steering input reversal that produces the most roll, this makes Crow's Landing a poor location for running tests designed to evaluate transient roll or load transfer.

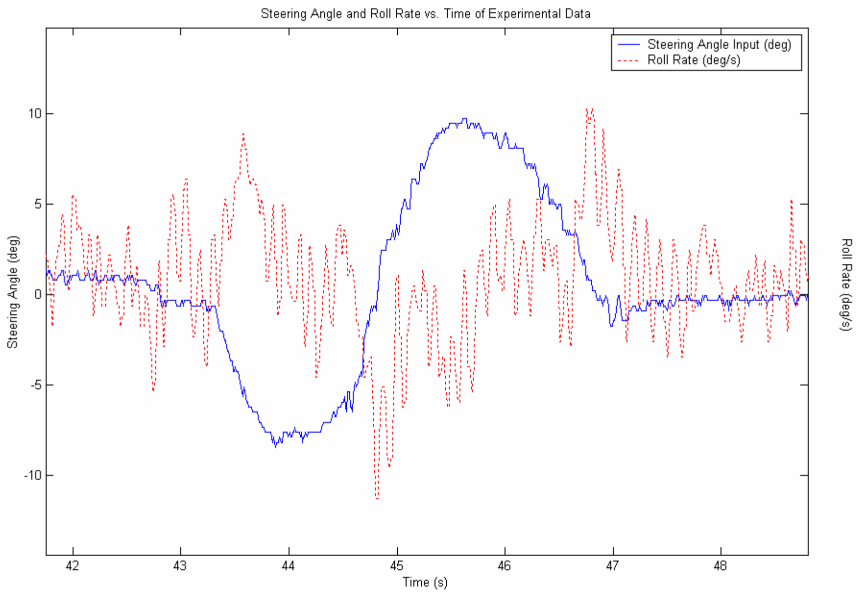

Figure 4: Experimental lane change maneuver.

Despite these challenges, the experimental testing did prove useful to the project. The values of roll rate measured enabled the stiffnesses of the suspension components to be tuned so that the overall roll behavior of the truck model matched that of the PATH truck. While not strictly necessary for the simulations (since the goal was to be able to simulate a representative truck and not necessarily reproduce the PATH truck precisely), this compatibility makes the conclusions of the simulation study more immediately relevant to other PATH researchers.

5 Integration of ADAMS and MATLAB

Evaluating controllers requires that the multi-body dynamic model be linked to the control algorithm defining the desired vehicle behavior and to the trajectory defining the desired motion of the vehicle. This involves challenges both in coupling software packages and in converting from the global frame of reference used by ADAMS for the multi-body dynamics to the path-centered frame of reference needed to implement and evaluate the controller. While such transformation is not necessary on the current PATH truck since magnetometers give measurements relative to the desired trajectory as defined by the magnets, this is required for the ADAMS model or for global location schemes such as those based on the Global Positioning System (GPS).

The following steps were required to connect the multi-body model to the controller and the environment:

- **Connect the ADAMS model to the MATLAB/Simulink environment.** While ADAMS has its own package for implementing control systems, a relatively new feature enables a model in ADAMS to be linked as a subsystem in a Simulink simulation. In this process, Simulink calls the ADAMS solver at each time step when updated information is required from the block, the ADAMS solver runs for the specified time step and updated information is imported into Simulink. The other processes in Simulink then run. The entire process is, unfortunately, very slow, given the need for both programs to run integration routines separately. In addition, some effort is required to identify outputs of interest in ADAMS and make these available to Simulink (Figure 5 illustrates graphically how the ADAMS block appears in Simulink). However, given the near-ubiquity of the MATLAB/Simulink environment in control development efforts in the California PATH program, it made sense to develop a model that could be used by a variety of researchers without having to modify their existing control algorithms substantially. As discussed later in the conclusions section, the lack of robustness of this interface and the difficulty with developing truck models in ADAMS makes the adoption by other researchers challenging. However, other solutions for incorporating more advanced truck dynamic models into Simulink have been identified and are available to PATH researchers wishing to adopt this approach.

- **Transform the ADAMS output into lane position error for the controller.** The ADAMS software generates the position of the vehicle with respect to a global frame of reference. To generate control signals, however, it is necessary to determine the distance between the vehicle and the lane center, comparable to what the magnetometers measure on the physical truck. This, in turn, requires specifying the lane or trajectory information in global coordinates either in ADAMS or in the

MATLAB/Simulink environment. Specifying this information in ADAMS has an advantage in that the calculation of the distance from lane center to the center of the bumper (or magnetometer location) is reasonably straightforward using pre-defined functions in ADAMS. Entry of the path information, however, is considerably more difficult than in Simulink. For ease of use, therefore, it was decided to put the path information in Simulink as opposed to ADAMS, making it very easy to switch, for instance, between the SAE standard lane change maneuver and a model of the test track at Crow's Landing. This required writing a Simulink function that would determine the shortest distance between the global location of the magnetometer position sent from ADAMS and the lane centerline defined in Simulink. Such a function is fairly straightforward to derive under the reasonable assumption that the tracking error is very small relative to the curvature of the test track. Under this assumption, the problem of multiple solutions can be eliminated.

- **Implement the controller in MATLAB/Simulink.** Once the vehicle has been located relative to the track, the offset from lane center can be calculated. Similarly, the relative heading error between the vehicle and the lane can be calculated using the yaw angle information from ADAMS and the road heading direction determined from the tangent to the curve specified in Simulink. Although this project did not consider specific sensor configurations such as a trailer mounted magnetometer or the determination of heading error from magnetometers on the front and rear of the truck chassis, such virtual measurements could be easily added in a similar manner. With these pieces of information, the control inputs can be calculated within the Simulink program using any desired control algorithm. Control inputs can be specified as a steering torque or steering angle depending upon the desired level of detail and sent through the interface to ADAMS. This completes the necessary integration of ADAMS and Simulink.

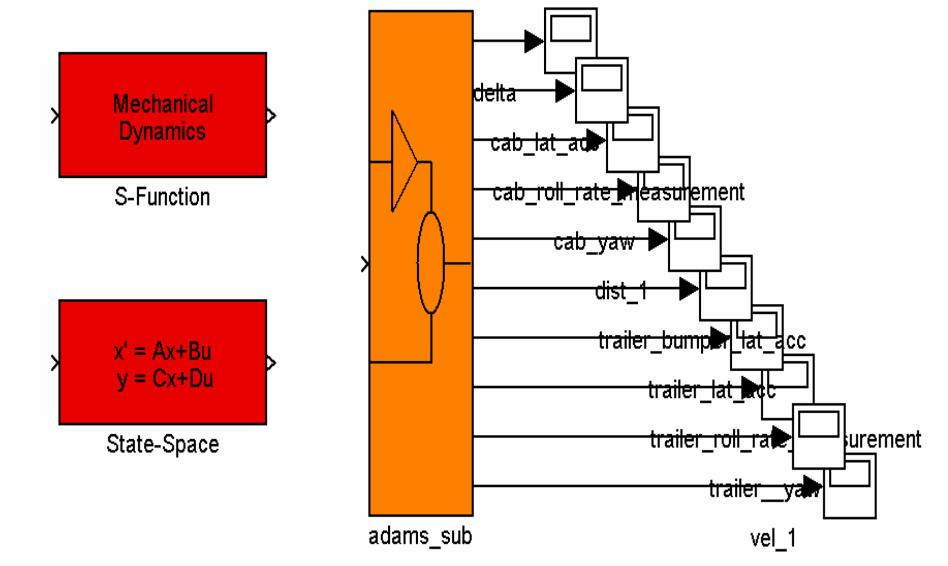

Figure 5: Incorporating the ADAMS model as a Simulink block.

Following this basic procedure, the ADAMS truck model was linked with Simulink to produce a single simulation capable of emulating a controlled heavy truck with suspension kinematics and roll motion. On the positive side, the combined simulation was able to produce realistic results of this complex integrated system. Unfortunately, the link between ADAMS and Simulink suffered from a lack of both speed and robustness. Simulations in this environment took considerable time to execute and would, without apparent repeatability, sometimes terminate unexpectedly. While the basic goal of the project could still be accomplished, the combined simulation fell short of a tool that could be easily transferred to other researchers. However, the research team reached an agreement with a corporate sponsor that could provide a similar system with vastly improved speed and robustness but the same overall structure. This option is described in the conclusions section of the report.

6 Results of Controller Simulation

With the ADAMS model connected to the Simulink environment, the next step was to implement a control algorithm and judge the impact of that algorithm on the vehicle roll behavior. To make these results most relevant, the controller chosen was the H-infinity algorithm developed by Hingwe and Tomizuka and already implemented in the PATH truck. Figure 6 illustrates this controller in the context of the overall simulation environment developed for the project.

The goal of the simulation was to determine whether or not this algorithm displayed any potential safety issues with respect to vehicle roll. In order to determine this, two different maneuvers were considered:

- **Variants on the SAE standard lane change maneuver**. For these tests, both 12.5 foot lateral motion over 200 feet (comparable to the Crow's Landing testing) and the standard 4.8 foot distance were used to excite the vehicle, Since in both cases the vehicle stayed well below saturation and serious nonlinear effects, the same conclusions about the control algorithms held. Obviously, the overall levels of roll were much lower for the 4.8 foot distance. Thus for this study the choice of amplitude was essentially arbitrary; for actual testing or as a standard procedure, the 4.8 foot distance may be better for avoiding large excitation while the 12.5 foot distance is better in terms of signal to noise ratio.

- **A trajectory consisting of two curves**. Both curves had radii of 800m and the total track length was 2205m. This was chosen to give an idea of how the controllers would fare in a normal highway environment, in contrast to a maneuver specifically designed to excite roll and trailer swing.

The simulation methodology involved finding several sets of controller gains that produced roughly the same lateral tracking error performance and then comparing the effect of these gains on the roll behavior of the vehicle. The conclusions of the study can be summarized succinctly with a few representative plots of simulation output.

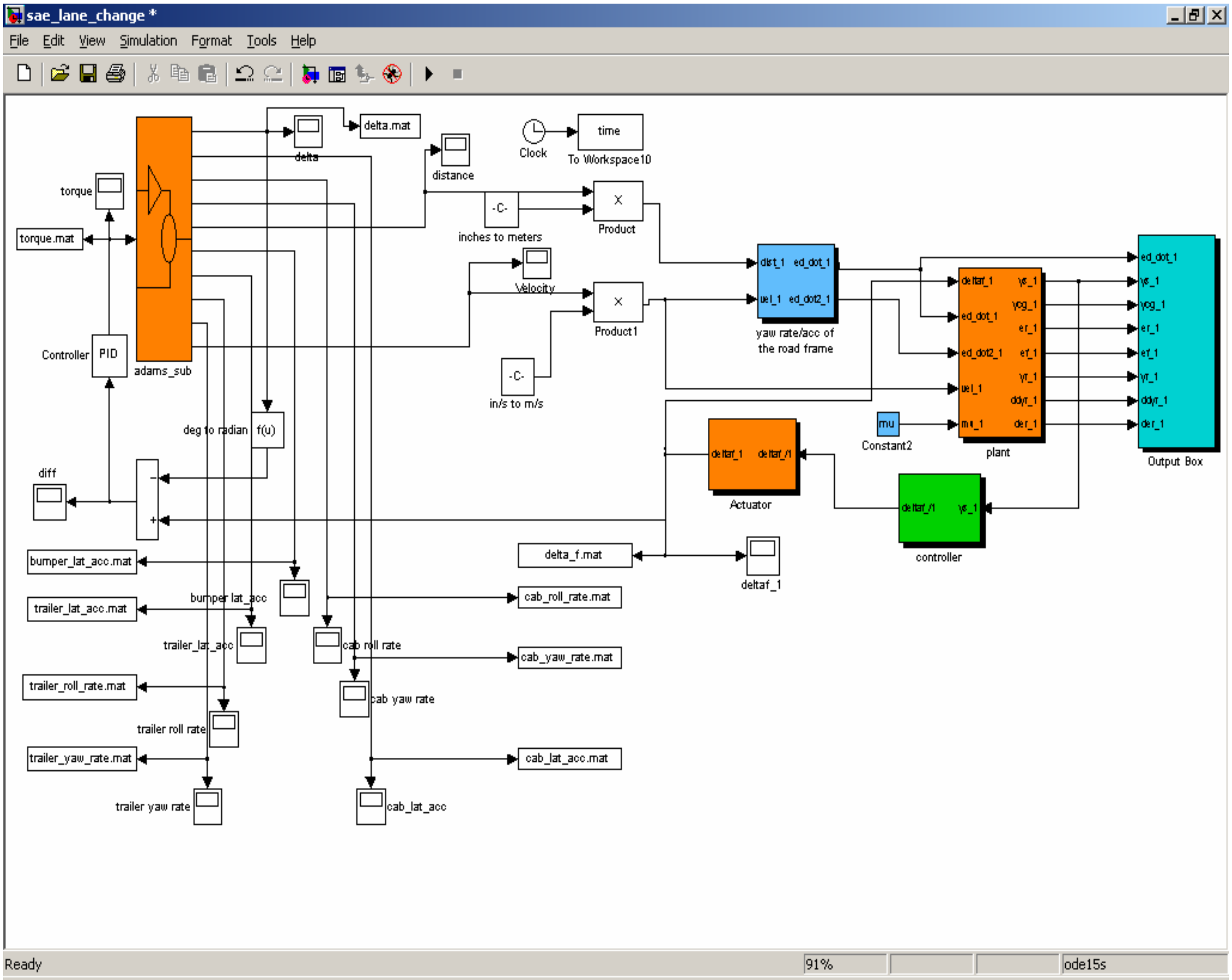

Figure 6: The PATH controller integrated in the combined simulation environment.

Figure 7 shows a representative plot of steer angle and roll rate during the lane change maneuver. In contrast to the results for the manually driven test, this particular choice of gains produces a steering input with additional high frequency input content. However, the steering reversal has been smoothed to a certain degree by the controller, resulting in a lower roll rate.

Figure 8 contrasts three different choices of gains. Clearly, different choices of gains produce both different amplitudes of roll response and result in roll initiation at different points in time. Again, this can be interpreted as a filtering effect, with the gains proceeding to use progressively less lookahead information and place more emphasis on the immediate lane deviation. As Figure 8 demonstrates, it is possible to find different choices of gains that produce similar levels of tracking accuracy yet have decidedly different impact on the roll behavior of the vehicle and, ultimately, the level of safety. This confirms the central thesis of the project that roll behavior should be taken into account when defining controllers for lateral control of heavy trucks.

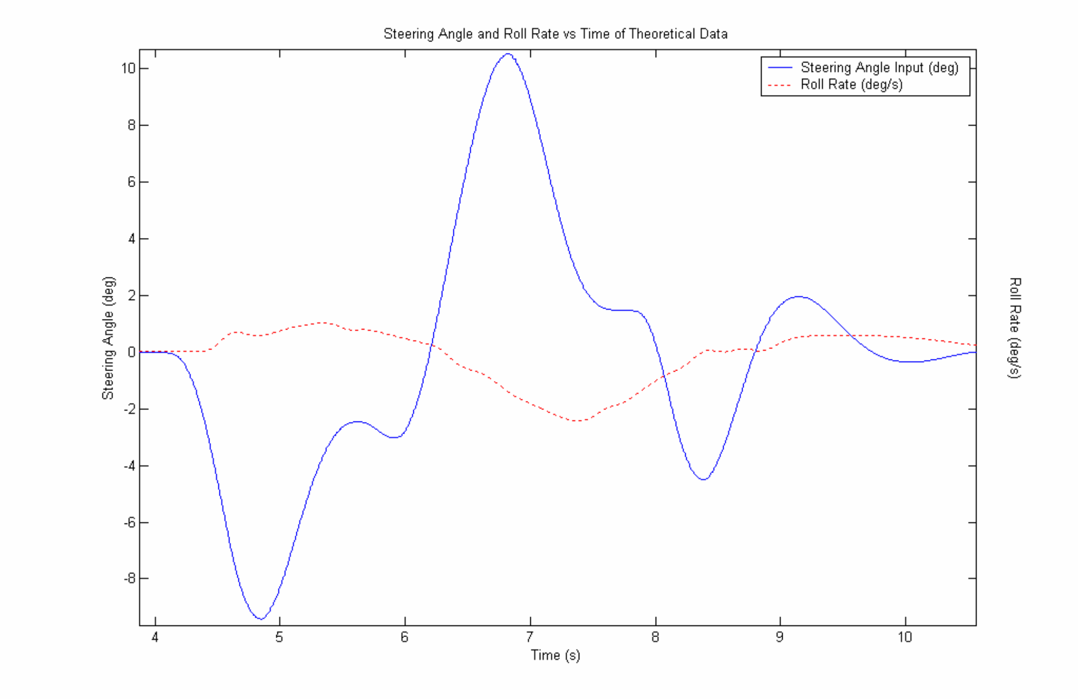

Figure 7: Representative steer angle and roll rate during lane change.

Another significant result from this plot is that there exist choices of gains for the existing heavy truck control architecture that do not excite much roll even in the lane change maneuver. Thus, while these results provide a cautionary warning that roll cannot and should not be ignored when designing a lateral controller, they also demonstrate that, with some care, existing control structures can be quite safe. The desire to reduce the impact of the lateral controller on the roll behavior of the vehicle does not, in fact, require an entirely new control design. It merely requires attention to gain choice.

The effectiveness of the lane change maneuver in amplifying and isolating potential problems with roll dynamics can be seen by comparing the results in Figure 8 to those of the much milder double curve maneuver shown in Figure 9. Not only are the roll rates significantly reduced in the double curve maneuver, but the difference in response between the two sets of gains is also reduced. Thus the lane change maneuver appears to be fulfilling exactly its desired role. The maneuver excites significantly higher levels of roll than are commonly encountered in highway driving and, as a result, serves to magnify differences between different choices of control gains. While other factors such as road superelevation can contribute to vehicle rollover and are not included in this analysis, the lane change maneuver does appear to identify control gains that can induce roll. Consequently, the simulations support the hypothesis presented in the report for

MOU 390 that the lane change maneuver can be used as a design tool for lateral controllers with increased safety.

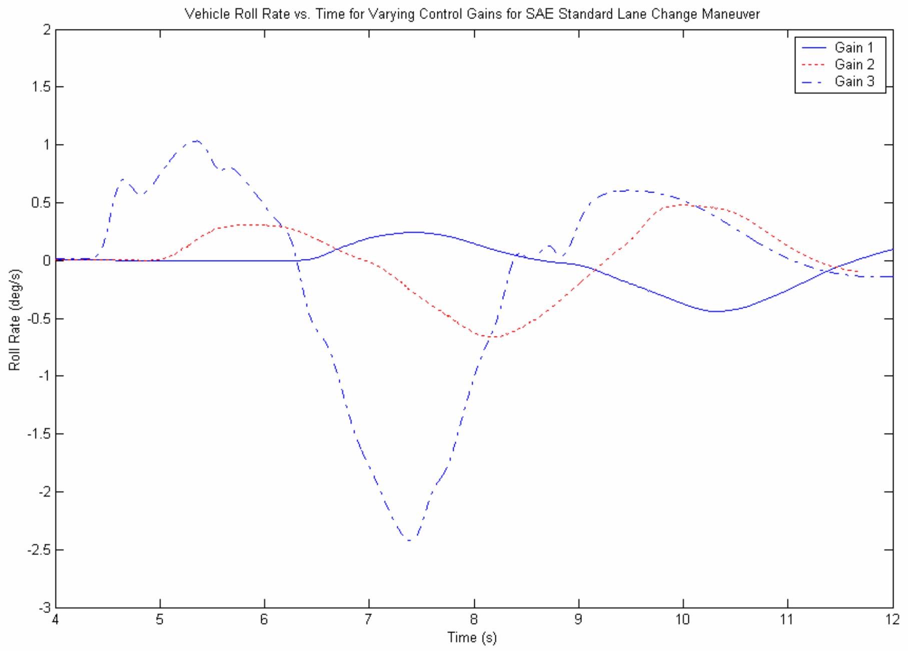

Figure 8: Roll rates during lane change for three different gain choices.

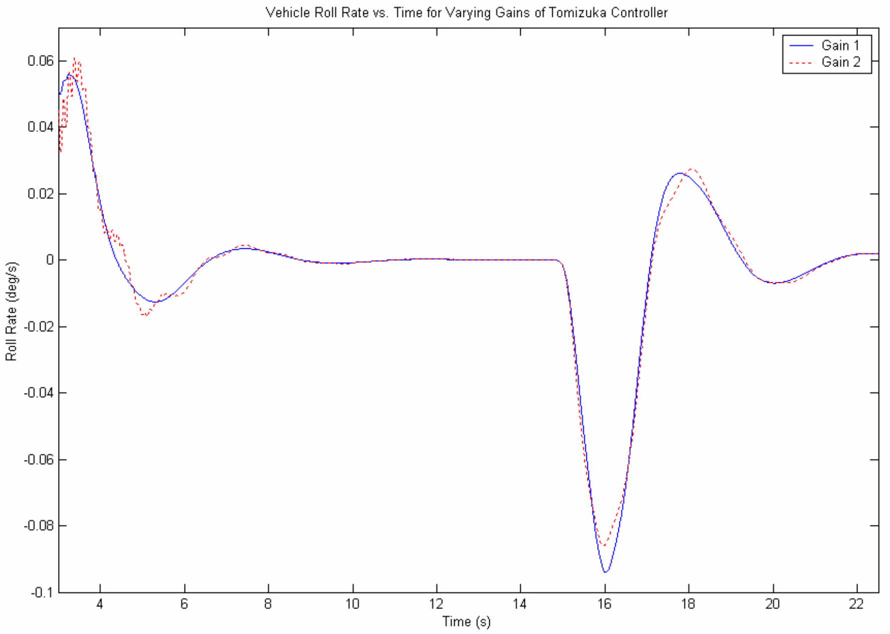

Figure 9: Roll rates during curve tracking for different gain choices.

Given the success of the existing PATH lateral controller in this safety evaluation when proper care is paid to the choice of gains, the simulation study does not provide any evidence that a redesign of the controller structure is necessary. This result can be interpreted in a qualitative manner to provide a general insight. The roll dynamics are excited by characteristic frequencies in the lateral motion of the vehicle. Similarly, the frequency content of the steering input is directly related to the gain choices made in the controller. The control structure developed previously is sufficiently flexible to enable shaping of the frequency content of the steering input while still maintaining acceptable lane tracking behavior. Thus the controller can be tuned to avoid triggering the roll dynamics. While obviously further study is warranted before concluding that gains could always be successfully chosen to avoid excessive roll excitation, this result seems both quantitatively and intuitively to possess some robustness.

7 Energy-Based Model Reduction

As originally conceived, the second year of the project split between developing the combined multi-body dynamic model and control algorithm simulation environment and developing a theoretical basis for energy-based model reduction. The objective was to link these research directions at the end of the project and propose a way to design safe control schemes based on systematic reduction of the models. This was intended to be a direction for future research. As described previously, analysis of the existing PATH control schemes did not indicate a need for controller redesign. Thus the link between the two parts of the project did not materialize as expected.

The project did indeed fulfill its objective to provide an energy theoretic basis for reduced-order models of Lagrangian systems. In the interest of keeping this report accessible to a broad audience and given the reduced significance of these results to controller redesign for the PATH program, only a brief summary of this work is presented here. Full details can be found in Chang et al. (2001) for those desiring a more technical treatment of these results.

The basic result can best be illustrated through use of an example. Consider, for instance, the swinging spring in Figure 10. This is a simple example of a system described by Lagrangian dynamics with two coupled modes – the pendulum mode and the spring mode. If the spring is stiff enough and reasonably damped, intuitively, and the pendulum motion does not excite the spring natural frequency, the system should act as a pendulum with some bounded disturbance corresponding to the oscillation of the spring mode. The analogy to the heavy truck problem is that we would expect the truck to act as a planar model without roll (within some bounded disturbance) assuming that the suspension is sufficiently stiff and damped. The challenge, then, is to determine a means of calculating these bounds.

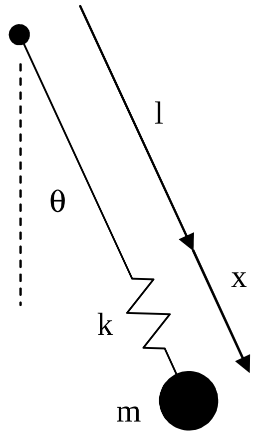

Figure 10: A swinging spring

In order to do this, consider an energy interpretation of the problem. In effect, the spring acts as an energy storage device. As the spring stretches, its tendency to return energy to the pendulum mode increases and only a sufficiently large force from the pendulum mode can prevent this energy exchange from taking place. In other words, if the behavior of the pendulum mode is known, the force from that mode on the spring mode can be bounded and the motion of the spring can, in turn, be bounded. This last bound requires that the energy of the system be modified to produce a strict Lyapunov function with a negative definite derivative. This ensures that the bounded input from the pendulum can be turned into a bounded deflection in the spring. The research developed under this project provides a systematic approach for determining these strict Lyapunov functions for certain classes of Lagrangian systems.

Computationally, the approach is not yet prepared to handle a vehicle dynamics model of the level of complexity as the one developed here. Simple models are feasible and the next step toward implementation in a vehicle framework would be to apply this to the roll dynamics in a simpler passenger car (or straight truck) model. Given the PATH focus on heavy trucks and the lack of an immediate need for these results to address changes in the PATH controllers, this work is not being proposed as a follow-on project to TO 4211 but will be performed under other sponsorship.

8 Conclusions and Recommendations

The work completed under TO 4211 (and, earlier, under MOU 390) has covered a broad range of issues from identifying appropriate parameters for heavy trucks, ascertaining which safety metrics and tests might be appropriate for evaluating lateral controllers, developing a multi-body dynamic model of the PATH truck, integrating this model with control software, evaluating existing lateral controllers and developing model reduction techniques. As might be expected with such a range of activities, the conclusions and recommendations also span a large range.

8.1 Roll Dynamics and Heavy Truck Lateral Control

A key goal of this research project has been to determine the extent to which roll dynamics of heavy trucks can be excited by lateral controllers and, if necessary, suggest modified controllers that produce less vehicle roll. To ensure that we did not oversimplify the problem, we chose to model the heavy truck using a multi-body dynamics package so that all of the kinematic and dynamic aspects of the actual suspension geometry could be considered in this analysis.

From our simulation results, we were able to demonstrate that different choices of controller gains produced very different amounts of roll when the truck proceeded through the SAE standard lane change maneuver. Thus the roll behavior of the vehicle can indeed be influenced by the lateral control scheme. Interestingly, the behavior of these different gain choices on the truck roll when moving on a path comparable to the test track at Crow's Landing or normal highway geometry was not very pronounced. This stands to reason since the SAE lane change maneuver was specifically designed to excite roll dynamics and rearward amplification.

Thus, in conclusion, the impact of the lateral controller on vehicle roll should be considered when developing automated highways. The proposed lane change maneuver appears to be an effective means for performing this evaluation. The existing control structure, with proper choice of gains, could be designed to avoid excessive roll excitation. Thus, no immediate need has been identified to redesign the existing control structure for safety in roll.

8.2 Modeling Software for Heavy Truck Dynamics

In terms of software for analyzing the interaction of vehicle controllers with the complex roll dynamics of heavy trucks, it is hard to recommend ADAMS for this purpose. Unlike passenger car simulations, for which ADAMS has numerous pre-defined templates, heavy truck simulation requires that each suspension element, wheel or chassis component be built up from primitives. This includes invoking the tire element in ADAMS which, at the time of this report, was an unsupported feature of the software. As detailed in the quarterly reports from MOU 390 and TO 4211, we were unable to obtain any technical support for the tires, bringing our modeling efforts to a halt until we were able to locate an engineer at the PACCAR Technical Center willing to help. Given the importance of the tires in a simulation of vehicle handling, this lack of support presents a serious obstacle.

Similarly, the link between ADAMS and MATLAB (a relatively new feature in the ADAMS software) was, in our experience, rather fragile. When running the combined simulation, we encountered a series of seemingly random errors that caused the program execution to stop prematurely. These errors were not completely repeatable and often running the same simulation a second time would result in successful execution. As a result of these issues, generating simulation results for the multi-body dynamic model in conjunction with a control system was a difficult process. This severely limits the number of simulations that can be performed and reduces the usefulness of the ADAMS model as a tool for controller development.

At the end of the project, we learned that Mechanical Dynamics was considering releasing a series of templates for heavy trucks, comparable to the ADAMS/Car package available for passenger cars. This would enable users to develop suspension models for trucks by merely specifying parameters instead of building the suspension models up from individual links and tuning parameters such as bushing stiffnesses to give the overall suspension stiffness. In addition, certain analyses for suspension kinematic motion could be performed with the touch of a button and dynamic maneuvers such as the SAE standard lane-change could be obtained by setting parameters in macros. If such a package is released for ADAMS in the future and future versions of the MATLAB interface show an increase in robustness, this could be a suitable approach for future use in the PATH program.

In addition, towards the end of the project, we received an offer from the Vehicle Systems Technology Center of DaimlerChrysler Research and Technology North America in Portland, OR, to use their software package for heavy truck simulation. They recently compiled a heavy truck model representing Freightliner trucks (with a variety of suspension types) into a block capable of executing in MATLAB. This block could then be linked directly to any vehicle controller previously developed in MATLAB since it takes the steering wheel angle directly as an input. This model has been distributed within the Freightliner Corporation and tested extensively and, therefore, represents a more robust solution than the one developed in ADAMS. Similarly, the execution time represents an improvement of more than an order of magnitude over the ADAMS solution. Since this offer was received at the end of the project, we did not have an opportunity to take this new direction (note also that this had not been developed at the beginning of the project and so was not a possible alternative approach for this project). However, should other researchers at the PATH program be interested in incorporating advanced models of heavy truck dynamics in a simulation environment, we believe this would be the best solution at the current time.

Therefore, in conclusion, we cannot recommend that other researchers interested in adding multi-body dynamic simulation to their evaluation of heavy truck controllers reproduce the ADAMS system developed here. Instead, we would suggest cooperating with DaimlerChrysler and incorporating their Simulink model in an environment comparable to the one developed here.

8.3 Energy-Based Model Reduction

The conclusions with respect to the model reduction work in this project are decidedly mixed. We were able to meet the objectives of the original project and develop a systematic method for reducing certain classes of Lagrangian systems based upon the amount of energy stored in different modes. Thus, in terms of the project objectives, this activity was quite successful. The basic reduction techniques appear to have relatively broad applicability to mechanical systems with fairly consistent configurations. Ironically, the problem of lateral control design for heavy vehicles does not seem to immediately require these model reduction results.

On the one hand, this is somewhat disappointing from the standpoint of project consistency. However, the implication is that previous PATH research can be applied to develop lateral controllers that are not only accurate in tracking the lane but avoid excessive roll excitation. While further work would be required to be definitive about the ability to always successfully parameterize a controller, the research did not demonstrate a need for modification to the control structure. Thus disappointment over the need for additional theory must yield to the practical advantages of this result for the PATH program.

In the original conception of the two-year project completed under MOU390 and TO 4211, we planned to develop model reduction techniques, identify robustness problems through our heavy truck simulations and begin to address these concerns by applying the model reduction techniques. A more detailed meshing of the model reduction ideas and controller redesign was envisioned as a follow-on activity. Given the lack of immediate need in the lateral control area, we intend to pursue the model reduction ideas further in the area of passenger car control. Specifically, the interaction of stability control and rollover avoidance seems a logical application for these ideas. Should they prove successful in the passenger car arena, a future step would be to extend them further to the complexity of heavy trucks and examine control of heavy vehicles near the handling limits.

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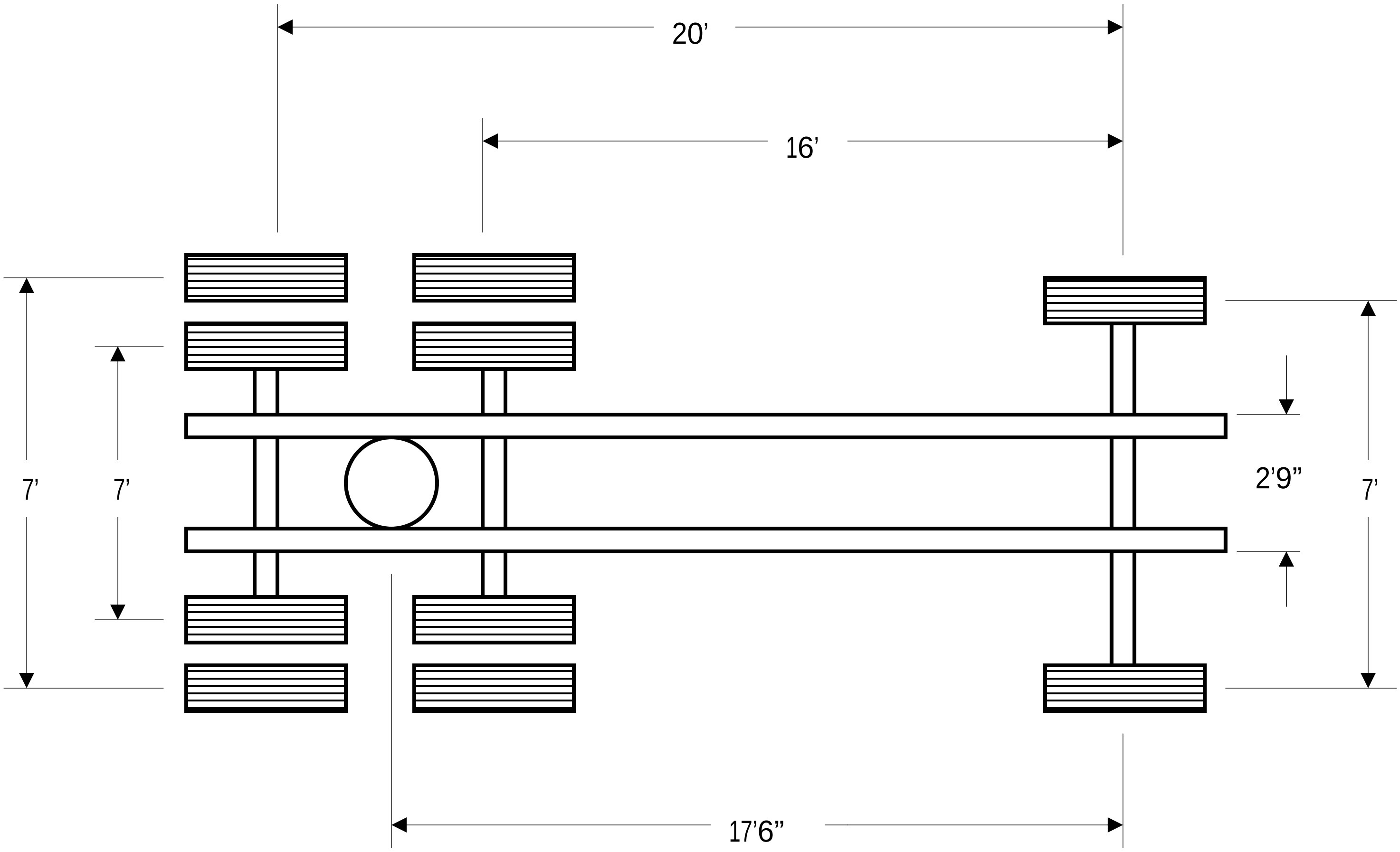
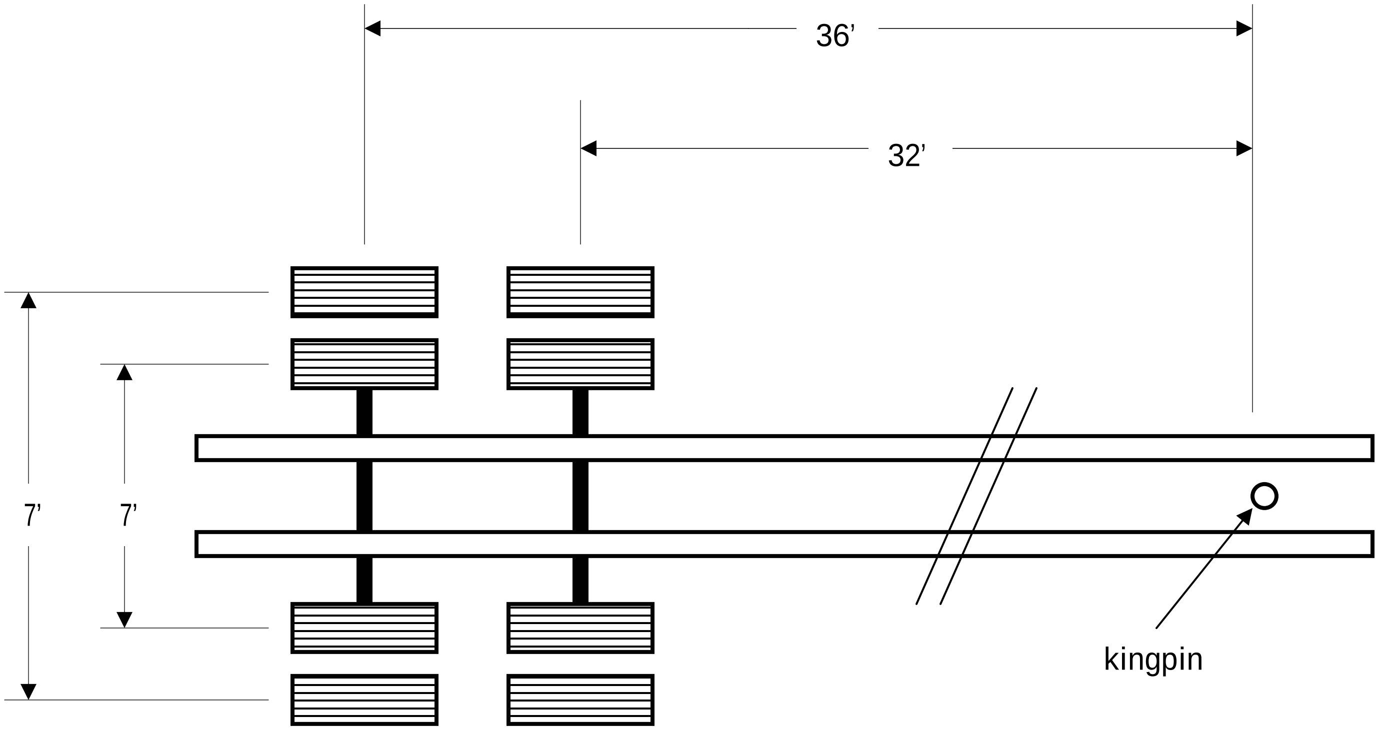
Appendix: PATH experimental heavy vehicle dimensions

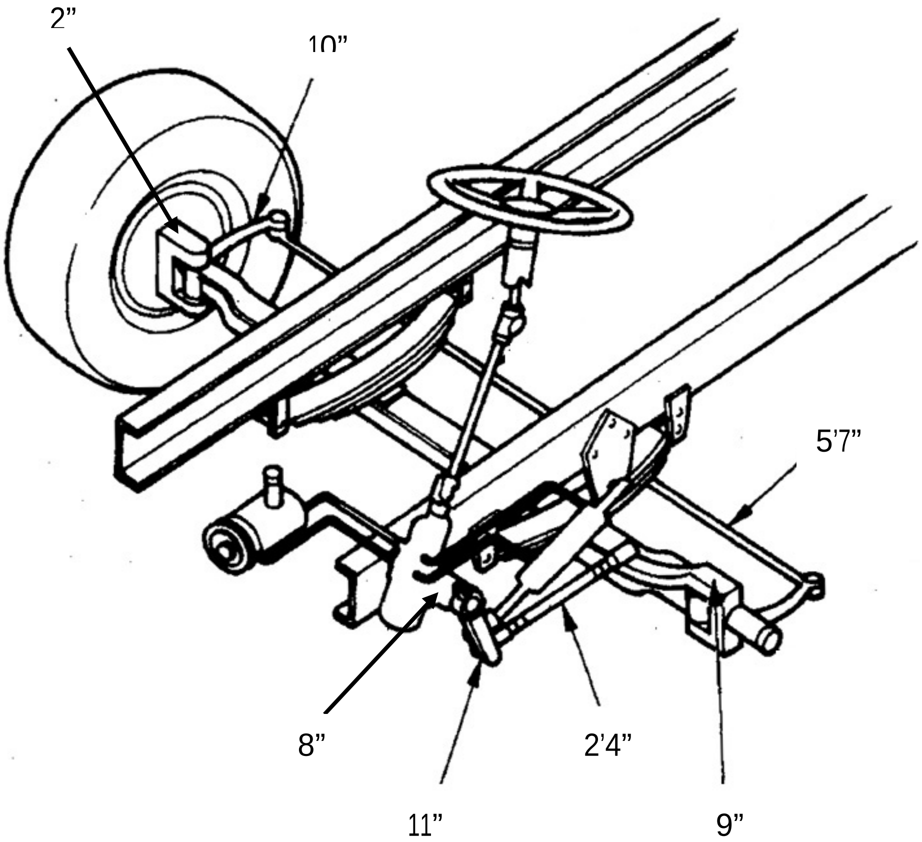
Tractor dimensions



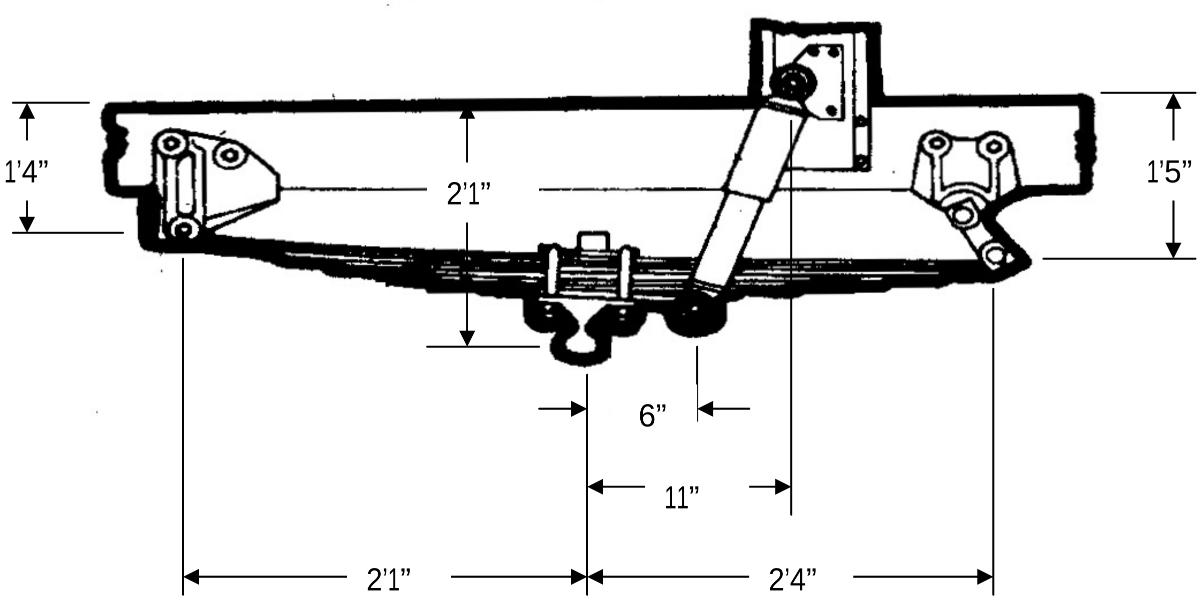
Semitrailer dimensions



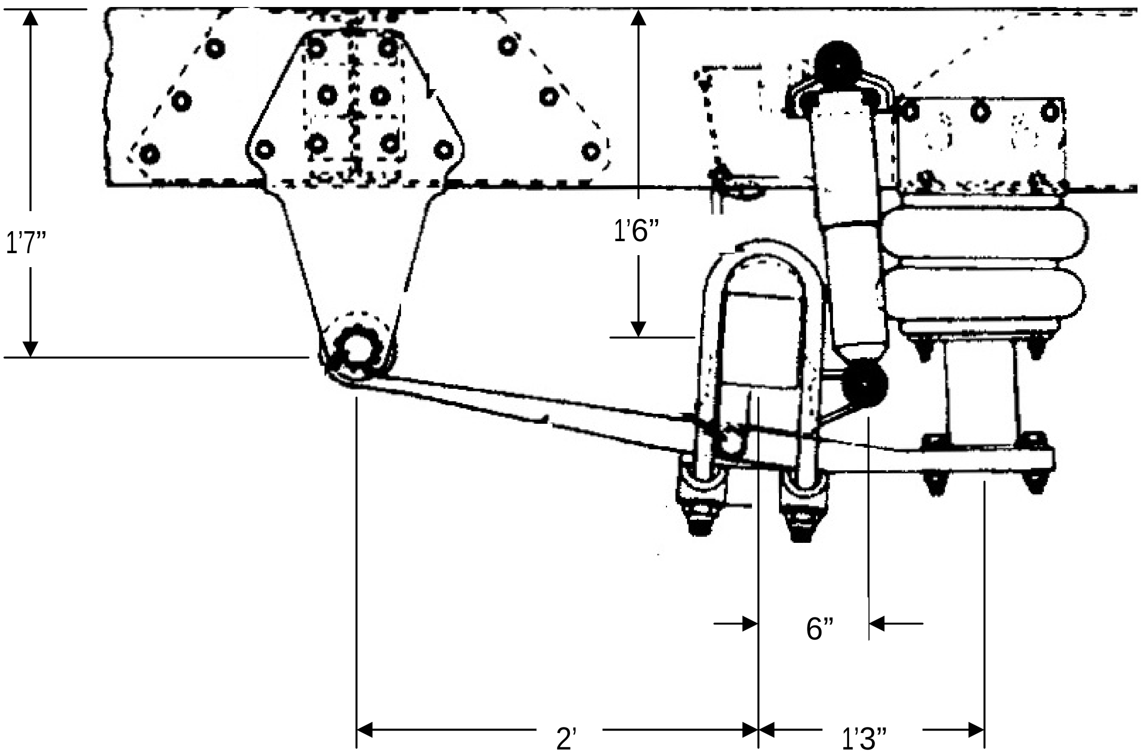
Steering component dimensions



Front suspension dimensions



Air suspension dimensions



Track rod dimensions