# A Simulation Approach to Estimate the Efficacy of Meritor WABCO's Improved Roll Stability Control

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

October 2006

## Foreword

This report summarizes work performed to model, evaluate and verify the safety benefits of an improved version of the Roll Advisor and Controller (RA&C) on-board safety system.

A U.S. Department of Transportation (USDOT) Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT) led by Freightliner evaluated an RA&C on-board safety system. The RA&C system assists commercial vehicle drivers, especially drivers of tanker trucks, to avoid rollover crashes. The RA&C is comprised of two components that perform two distinct functions: to inform drivers when they have performed a maneuver with a high risk of rollover (the roll stability advisor [RSA] component), and to initiate autonomous braking to prevent a rollover (the roll stability control [RSC] component).

All of the data analyzed in this report came from the Freightliner IVI FOT. Data were collected on six Freightliner tractors pulling tank trailers of liquid nitrogen in revenue service during late 2000 through 2001. The methods for estimating the benefits of a safety system were developed by Battelle as part of the independent evaluation of the FOT. This report describes how the methods of the independent evaluation were applied to the data of the FOT to predict the benefits of an improved RSC, without conducting a new field test of the system.

Although the report can be helpful to the general public in understanding an on-board safety system, the report is primarily targeted towards commercial motor carriers and their drivers.

This publication is considered a final report and does not supersede another publication.

## Notice

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16. Abstract:

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## SI* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | ml |
| gal | gallons | 3.785 | liters | l |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lbs) | 0.907 | megagrams | Mg |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 or (F-32)/1.8 | Celsius temperature | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/m2 | cd/m2 |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | pound-force | 4.45 | newtons | N |
| psi | pound-force per square inch | 6.89 | kilopascals | kPa |

### APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | Yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| ml | milliliters | 0.034 | fluid ounces | fl oz |
| l | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.71 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg | megagrams | 1.103 | short tons (2000 lbs) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 1.8 C + 32 | Fahrenheit temperature | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/m2 | candela/m2 | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | pound-force | lbf |
| kPa | kilopascals | 0.145 | pound-force per square inch | psi |

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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# Executive Summary

This report summarizes work performed to model, evaluate, and verify the safety benefits of an improved version of the Roll Advisor and Controller (RA&C) on-board safety system.

The RA&C on-board safety system includes two major components consisting of the Roll Stability Advisor (RSA) and the Roll Stability Control (RSC). The RSA component informs drivers when they have performed a maneuver with a high risk of rollover; the RSC component initiates autonomous braking to prevent a rollover due to excessive speed in a curve. The combined RA&C constantly monitors cornering forces while the vehicle is in operation. An on-board computer in the RA&C processes the information received from the on-board sensors to detect when there is risk of a rollover. If a high risk of rollover is detected, the RSC component initiates braking automatically to slow the vehicle without driver intervention.

The RA&C on-board safety system was originally tested in the U.S. Department of Transportation (USDOT) Intelligent Vehicle Initiative (IVI) Freightliner Field Operational Test (FOT). In the FOT, the RSC version that performed autonomous braking used only the engine retarder (often referred to as the Jake Brake), which uses engine compression to slow the vehicle.

From the independent evaluation of the FOT, it was found that the RSC could provide greater safety benefits by engaging the service brakes, which provide faster and more positive braking forces to potentially increase the effectiveness of the system to reduce rollover and road departure crashes. Therefore, the vendor who manufactured the RSC subsequently developed an improved system that used the service brakes to slow the vehicle in response to detected critical events.

In order to estimate the effectiveness of the improved RSC without conducting another FOT or extensive track testing, an alternative evaluation approach was necessary. The approach used a computer simulation tool to model the improved RSC to predict how the RSC would have behaved in situations (i.e., driving conflicts) similar to those observed in the Freightliner FOT.

Using the simulations, the RSC was estimated to prevent about 53 percent of the rollovers resulting from excessive speed in a curve. To estimate the combined effect of using both the RSA and RSC, it was assumed that the RSA would prevent some near-rollover situations from occurring due to driver education, and that the RSC would prevent some of those that remain from actually leading to a rollover. Therefore, the combined RA&C was estimated to prevent 69 percent of heavy vehicle rollovers that are caused by excessive speed in a turn.

# 1.0 Introduction

This report summarizes work performed to model, evaluate and verify the safety benefits of an improved version of the Roll Advisor and Controller (RA&C) on-board safety system.

A U.S. Department of Transportation (USDOT) Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT) led by Freightliner evaluated an RA&C on-board safety system. The RA&C system assists commercial vehicle drivers, especially drivers of tanker trucks, to avoid rollover crashes. The RA&C is comprised of two components that perform distinct functions:

- The roll stability advisor (RSA) component – to inform drivers when they have performed a maneuver with a high risk of rollover.

- The roll stability control (RSC) component – to initiate autonomous braking to prevent a rollover.

All of the data analyzed in this report came from the Freightliner IVI FOT. Data were collected on six Freightliner tractors pulling tank trailers of liquid nitrogen during late 2000 through 2001. The methods for estimating the benefits of a safety system were developed by Battelle as part of the independent evaluation of the FOT. The methods are described in detail in the report on the independent evaluation [Battelle, 2003] and its appendices [Battelle, 2003a]. This report describes how the methods of the independent evaluation were applied to the data of the FOT to predict the benefits of an improved RSC, without conducting a new field test of the system.

On the basis of the analysis, about 53 percent of heavy vehicle rollover crashes caused by excessive speed in curves can be prevented by the Roll Stability Control. The analysis corroborated the manufacturer's claim that the device can be quite useful in preventing rollover crashes, but it also confirmed the manufacturer's caution that the device does not prevent all crashes.

# 2.0 Background

The RA&C includes two major components consisting of the Roll Stability Advisor (RSA) and the Roll Stability Control (RSC). RSA is a passive system that communicates with the driver about recent rollover conditions. The advisor system warns the driver after the event has occurred with the objective of changing driver performance in similar future driving situations. RSC is an active system that interacts with the vehicle to correct a current rollover situation. The RA&C constantly monitors cornering forces while the vehicle is in operation. An on-board computer in the RA&C processes the information received from the on-board sensors to detect when there is risk of a rollover. If a high risk of rollover is detected, the RSC component initiates braking automatically to slow the vehicle without driver intervention.

In the FOT, the RSC version that performed autonomous braking used only the engine retarder (often referred to as the Jake Brake). The engine retarder uses engine compression to slow the vehicle. Meritor WABCO, the RSC manufacturer involved in the FOT, recognized that greater safety benefits could be realized by engaging the service brakes. The service brakes provide faster and more positive braking forces to potentially increase the effectiveness of the system to reduce rollover and road departure crashes. Therefore, the vendor who manufactured the RSC subsequently developed an improved system that used the service brakes to slow the vehicle in response to detected critical events.

This RA&C Deployment Planning Project originally focused on the version of the RA&C that was tested in the Freightliner FOT. However, recognizing that the vendor did not intend to offer this early version as a commercial product, it became clear that any deployment plan for the RA&C system should focus on accelerating the availability and use of the improved RSC (i.e., the RSC that uses the service brakes).

In order to estimate the effectiveness of the improved RSC without conducting another FOT or extensive track testing, an alternative evaluation approach was necessary. The approach used a computer simulation tool to model the improved RSC and predict how the RSC would have acted in situations (i.e., driving conflicts) similar to those observed in the RA&C FOT.

The accuracy in simulating a physical system depends on understanding the dynamic operating characteristics of the system and mathematically representing those dynamic operating characteristics accurately in the computer model. The model was developed using a commercially available tool, Vehicle Dynamics Analysis, Non-Linear (VDANL).[1] This tool incorporates equations of motion that explicitly describe vehicle dynamics in the longitudinal, lateral, and vertical directions in addition to independent wheel spin modes. Section 4 describes the tool and model in greater detail.

As part of the project, the RSC vendor also performed track tests at the Transportation Research Center in East Liberty, OH to obtain input data needed to calibrate the VDANL model for the improved RA&C. These data included typical brake pressure and deceleration time histories.

## 3.0 Approach

In the independent evaluation of the FOT, vehicle simulations were used to provide an objective and quantitative calculation of crash probability. A similar approach was used to estimate the number of crashes that could be prevented by the improved RSC. Unique events from the FOT of a truck equipped with the improved RSC were simulated.

There were no rollovers in the FOT. However, the independent evaluation identified 137 “critical conflicts”. These were events that had dynamic characteristics that preceded a rollover crash. Specifically, the lateral acceleration measured during the event was a significant fraction of the estimated static rollover threshold of the vehicle at the time of the event. If each of these 137 events were to occur again many thousands of times, each occurrence would differ slightly. For example, the speed may be slightly higher, the load may be a little fuller, or the driving path may be slightly different. These differences can be considered to be perturbations of the actual

[1] The VDANL model, including the equations of motion, is documented in Allen, R.W., Szostak, H.T., Klyde, D.H., Rosenthal, T.J., and Owens, K.J., *Vehicle Dynamic Stability and Rollover,* DOT-HS-807 956, September 1992.

event in the FOT. A small fraction of the combinations of these perturbations will result in a rollover crash. It is this fraction that must be calculated to assess the improved RSC's ability to eliminate crashes.

In short outline form, the procedure is:

1. Simulate the conflict exactly as it was recorded in the FOT.
2. Simulate the conflict again with the speed 1 ft/s faster, but do not change other conditions.
3. Keep repeating Step 2 until the vehicle rolls over or can no longer maintain its path.

The result of these three steps is a measure of the severity of the conflict. These steps are carried out separately for each conflict. A statistical procedure then estimates the probability of a rollover crash if all the conflict scenarios were repeated, say, ten thousand times, each time with a small perturbation. This process is illustrated in greater detail under the heading, "Simulation Example" in Section 4.4.

The procedure was followed first using a simulation model of an ordinary truck—one without the RSC. The entire procedure was repeated with a simulation model of a truck equipped with the improved RSC. The reduction in probability of a rollover attributable to the RSC was calculated, and, from this, the expected number of rollovers prevented was calculated based on historical crash data [Battelle, 2003b].

# 4.0 Simulation

A commercially available computer model of a heavy vehicle was adapted to evaluate the improved RSC. The simulation focused on how a tractor pulling a cargo tank semitrailer, similar to the vehicles in the FOT, would behave if it were equipped with the improved RSC.

## 4.1 Basic Vehicle Model

As part of the independent evaluation, the FOT vehicles were modeled in Vehicle Dynamics Analysis, Non-Linear (VDANL) Version 6.0.[2] This tool has been in development since the 1980s. It has been applied by its developer in contracts for various administrations within the DOT, including light vehicle rollover work for National Highway Traffic Safety Administration (NHTSA), and in contracts for private companies. By selecting parameters to describe the vehicle, VDANL can be applied to vehicles from race cars to tractor-semitrailer combinations. This rigid-body model incorporates equations of motion that explicitly describe vehicle dynamics in the longitudinal, lateral, and vertical directions in addition to independent wheel spin modes. The sprung and unsprung mass motions are modeled separately in the pitch, roll, heave, and lateral modes. The longitudinal motions are for the total vehicle while the sprung and unsprung masses rotate together in yaw. The model also shows a two-axle trailer connected to the tractor through a compliant fifth wheel. The model integrates the nonlinear equations of

[2] VDANL, Systems Technology Inc., Hawthorne, CA. Phone 310-679-2281.

motion, incorporating driver actions and external inputs. The VDANL model, including the equations of motion and the methods for measuring parameters, is documented in Allen et al. [1992].

The description of a vehicle in VDANL for the independent evaluation is defined by several parameters. When possible, actual measured values were used in the model. For example, the wheelbase and track widths (see Table 1) of the truck used in the track testing were measured. Axle loads were also measured during the track test. However, the height of the vehicle's center of gravity and inertias had to be estimated. Other parameters such as roll stiffness, throttle and steering lags, and steering geometry were assumed to be typical of five-axle trucks.

**Table 1. Summary of Parameters in the VDANL Model for the Two Load Conditions**

| Vehicle Component | Mass | Sprung Mass Center of Gravity Height | Whole Unit Center of Gravity Height | Wheelbase | Track Width |
|---|---|---|---|---|---|
| Tractor | 16,600 lb | 2.92 ft | 3.34 ft | 15.5 ft | 7.5 ft |
| Trailer (partial load) | 45,000 lb | 5.7 ft | 6.1 ft | 34.0 ft | 7.5 ft |
| Trailer (full load) | 64,100 lb | 7.1 ft | 7.36 ft | 34.0 ft | 7.5 ft |

Vehicle weight and center of gravity are key parameters in determining the rollover thresholds of a heavy vehicle. The gross vehicle weight was not the same for all of the 137 conflict cases analyzed. The modeling accommodated this variability by establishing three groups according to Table 2. The mass of the modeled vehicle was always within about four tons of the mass of the FOT vehicle in the conflict being modeled. Appendix C contains a more complete description of the differences between the models of the full and partially loaded cases. The vehicle was not in danger of rolling over in the conflicts where the tank was empty or nearly empty, and those conflicts were not simulated in the present exercise. The primary differences in the parameters are in the vehicle sprung and unsprung mass weights, vehicle sprung mass center-of-gravity heights, and the vehicle inertias. Minor variation in some of the driver model feedback parameters was made between models to obtain good speed and curvature tracking.

**Table 2. Fill Levels of Conflicts Identified in the FOT Data**

| Condition of the Vehicle in the Conflict in the FOT | Number of Conflicts | Range of Vehicle Weights Measured in the FOT | Vehicle Weight in the Corresponding VDANL Model |
|---|---|---|---|
| Full or nearly full | 113 | 36 to 41 tons | 40 tons |
| Partially loaded | 13 | 26 to 35 tons | 31 tons |
| Empty or nearly empty | 11 | 17 to 24 tons | -- |

VDANL incorporates a driver model with access to the gains of the closed loop system. These can be modified to achieve the appropriate velocity, steering, or curvature input response.

During the FOT, vehicle speed and yaw rate of the tractor were measured. The ratio of the yaw rate to the speed is the curvature of the path being traversed by the truck. Hence, the vehicle speed and road curvature were used as inputs to the VDANL model.

## 4.2 Roll Stability Control Model

A model of the improved RSC safety system was incorporated in the VDANL model of the tractor-trailer combination. The basic vehicle model developed and validated in the independent evaluation was used as a starting point. The model was expanded to include the improved RSC that applies the service brakes.

The vehicle model simulates several levels of braking by the improved RSC depending on the vehicle weight and level of lateral acceleration during the maneuvers. The improved RSC provides for different levels of intervention according to the perceived severity of the situation. The lowest level calls for engine torque reduction, and the higher levels add the engine retarder or control pressure signals to apply the drive axle and trailer brakes.

Meritor WABCO provided Battelle with qualitative and quantitative descriptions of the brake pressures, vehicle decelerations, and time constants it had measured on an actual truck equipped with RSC. A description of the RSC was coded in the VDANL model by adjusting the braking torques and gear-shifting to provide braking characteristics similar to the Meritor WABCO system. The system must estimate the vehicle mass; the mass was assumed to be measured exactly in the simulation.

## 4.3 Model Validation

The original model and parameter set to describe the vehicle itself were validated through comparison with data from full-vehicle tests performed at the Transportation Research Center (TRC) in East Liberty, OH as part of the independent evaluation [Battelle, 2003a].

The VDANL models were exercised using inputs from several representative test track maneuvers and several representative FOT maneuvers. In addition, some of the FOT runs were simulated using the different gross vehicle weight models. The accuracy of the simulation results with the test track runs validated that the VDANL truck model responses are similar to an actual truck performing these maneuvers. Close agreement of the simulation and representative maneuvers from the FOT gave confidence that the simulation could be used for simulating the improved RSC for the 137 FOT conflict cases [Battelle, 2003, pages 5-25 to 5-35].

The ability of the RSC model to emulate the performance of the improved RSC product was demonstrated by simulating maneuvers that had been performed at TRC by Meritor WABCO. Quantitative and qualitative comparisons proved that the behavior of the RSC had been captured in the model. The actual truck used to validate the model of the vehicle in the independent evaluation was a nitrogen-style tanker filled with water; except for the load, it was nearly identical to those in the FOT. The vehicle used to validate the model of the RSC in the present effort was a flatbed loaded with blocks of concrete to provide a high center of gravity, which differed from the tanker used in previous experiments and described in the vehicle model. Its roll dynamics are somewhat different from those of a vehicle with a tank trailer; however, the RSC is contained entirely on the tractor, and its braking commands are similar for any fully loaded combination vehicle. The center column of Table 3 gives the peak deceleration recorded on the actual vehicle at TRC for cases of high and low rollover risk for a fully loaded vehicle and for a low rollover risk in a partially loaded vehicle. The right column gives the peak deceleration calculated in the model for similar maneuvers on fully and partially loaded vehicles.

**Table 3. Deceleration Achieved by the RSC in an Actual Vehicle on the Test Track and by the VDANL Model of the RSC in a Similar Situation**

| Condition | Peak Deceleration, g | |
|---|---|---|
| | Actual Vehicle at TRC, equipped with RSC | VDANL Model of vehicle with RSC |
| full vehicle, high risk | 0.22 | 0.24 |
| full vehicle, moderate risk | 0.12 | 0.125 |
| partially loaded vehicle, moderate risk | 0.12 | 0.12 |

## 4.4 Simulation Example

The 137 conflict cases identified in the FOT were used as the basis for a special simulation analysis to determine the efficacy of the RSC.[3] The table in Appendix A lists a summary of input and output information for each of the conflicts. The leftmost "input" columns in Appendix A give information that characterize the type of curve, vehicle information, and the initial speed of the maneuver. The columns to the right in the appendix present "output" results from the simulations such as the maximum lateral acceleration with and without the system, and the speed at which rollover occurs with and without the system. The introductory material to the appendix describes the columns more fully. There is one page for each conflict in Appendix B, where the maneuver path is displayed along with a time history of the speed lateral acceleration and other measurements.

For each conflict, vehicle speed was perturbed to induce a vehicle rollover. Starting with the speed profile recorded for the conflict, the speed was incremented by 1 ft/s (about 0.7 mph) for the entire maneuver, and the simulation was run. If no rollover was observed, the speed profile was incremented by an additional 1 ft/s and the simulation repeated. Increasing the speed in 1 ft/s increments, each conflict was perturbed until a vehicle rollover was observed.

The independent evaluation established the speed perturbations that could be tolerated by the vehicle in each of the conflict cases before it resulted in a rollover. With the introduction of the improved RSC, the exercise was repeated to determine if the dynamic envelope that separates the conflict case from a definite rollover could be widened (i.e., could the truck equipped with the

[3] The FOT had two phases. Of the 137 conflicts, 71 came from the first phase and 66 from the second. The analysis in the independent evaluation discerned no significant difference between conflicts from the two phases. Therefore, to provide a larger pool for analysis in the present study, all conflicts were studied together without regard to the phase in which they originated.

RSC enter a curve at speed perturbations higher than an identical truck without the RSC and not roll over).

Figures 1 through 4 illustrate how this process was carried out for one of the 137 conflict events. This conflict was recorded on Truck 4 during trip 1072 at approximately the time marker of 622. (This conflict is highlighted in Appendix A, and shown in Appendix B.7.) The first figure is a "bird's eye view" of the intended maneuver. The truck was coming from the upper left and turned right through two curves before driving off to the south. The black dot in Figure 1 indicates the point of interest—where the highest lateral acceleration was measured during the FOT. In Figure 2, the lower, lighter line is the speed history of the Praxair truck as it drove through the path in the FOT. It began around 17 mph, sped up gradually, slowed briefly again as it made the curve, and then accelerated out of the curve. In the first simulation of this maneuver, the simulated truck followed the path shown in Figure 1 at the speeds shown in the lower line of Figure 2—the same path and speed measured on the real truck in the FOT. The black dot on this trace at 18.2 mph indicates the speed at the moment where the peak lateral acceleration was observed. This is the reference speed for calculating the probability of a crash in Section 5.1

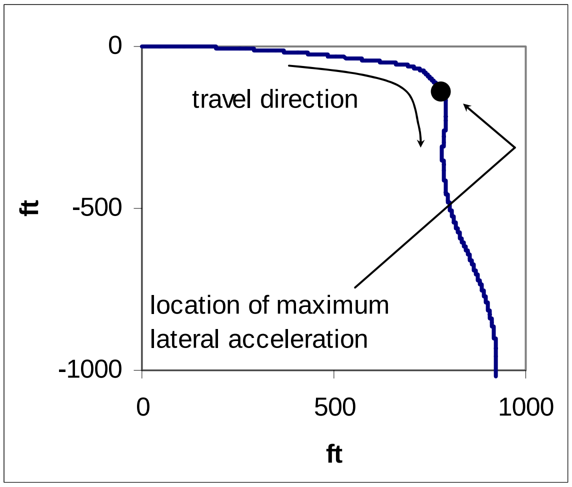


**Figure 1. Path of the Truck in One of the Critical Conflicts**

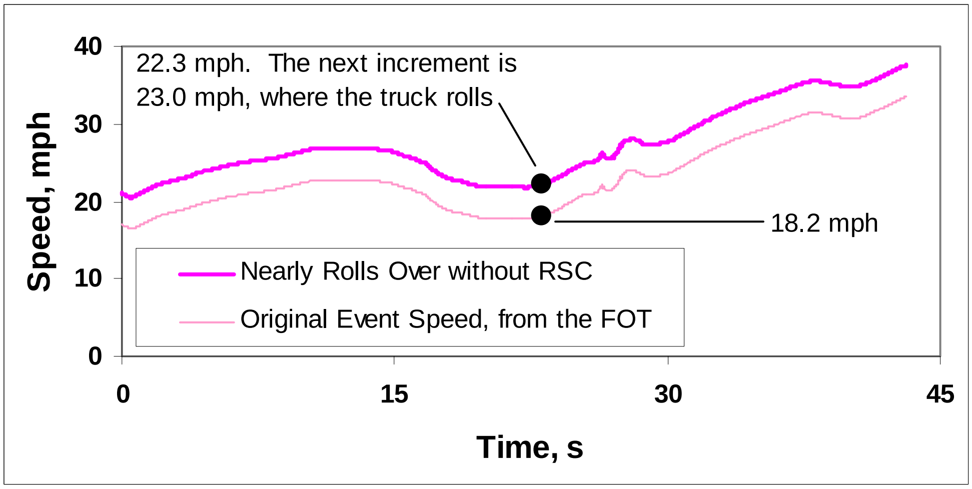


**Figure 2. Speed through the Path of Figure 1, as in the FOT and Increased Nearly to the Point of Rollover**

The simulation was then repeated with successively higher speed increments until the simulated truck rolled over. The upper, heavier trace in Figure 2 shows the speed of the truck when it was

4 mph faster than the original FOT speed. This was as fast as the truck could go through the path without rolling over. At the next speed increment, the simulated truck rolled over. That is the first piece of important information from the simulation: if everything were identical to the actual event observed in the FOT, except that the driver entered the maneuver 4.8 mph faster than the actual FOT speed, the truck (without the RSC) would have rolled over.

The model of the RSC was implemented for the next simulation of this maneuver. When the vehicle was about to roll over, the RSC called for the brakes to be applied, so an appropriate brake application was simulated. The truck slowed down and did not roll. Figure 3 shows how the RSC affects the speed of the simulated truck. The solid line is the speed of the truck without RSC, just below the rollover threshold. The dotted line indicates the speed of the truck equipped with RSC. Up to the point of intervention, the two trucks had the same speed. At the point indicated by the arrow, the brakes were applied, the simulated vehicle slowed down, and a rollover was avoided.

Figure 4 shows the lateral acceleration calculated at the trailer center of gravity during these simulations. As the acceleration reaches about 0.3 g, the RSC activates and reduces the rolling tendency of the trailer. The static rollover threshold of a filled FOT vehicle was measured to be about 0.37 g [Figure 4-6, Battelle, 2003]. At the next higher speed increment, the vehicle without the RSC would have reached a peak trailer lateral acceleration of 0.40 g (the value in Appendix A for this example case) and rolled over. When the vehicle with RSC was simulated at the next speed increment, the peak lateral acceleration was limited to 3.0 g, as noted in Appendix A.

Figure 5 compares the roll angles of the trailers on the unequipped and equipped vehicles. The plot with the wide swings in roll angle is on the truck without RSC. The roll angle reaches about 15 degrees, and our earlier work on the test track showed that this is well beyond the point of safe maneuvering. The roll angle of the trailer on the vehicle with RSC is limited to a much safer 5 degrees.

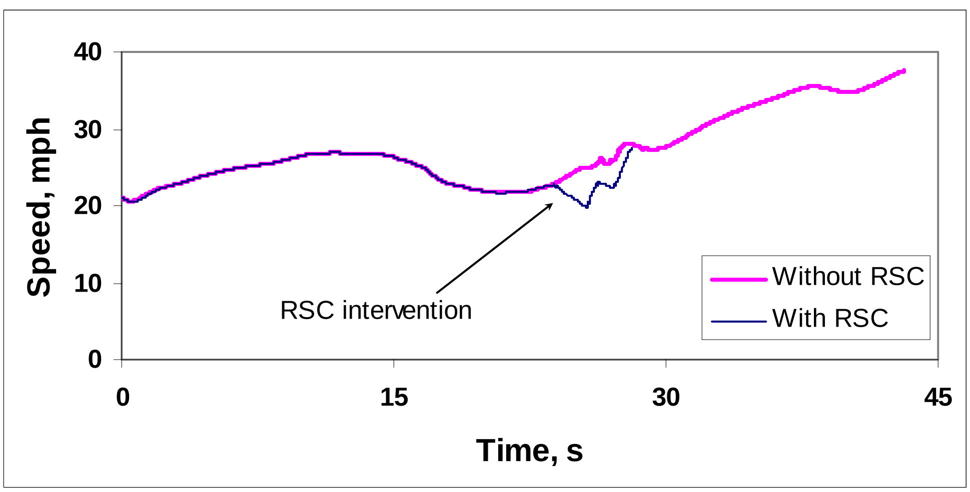


**Figure 3. Simulation of the RSC to Reduce Speed and Avoid a Rollover**

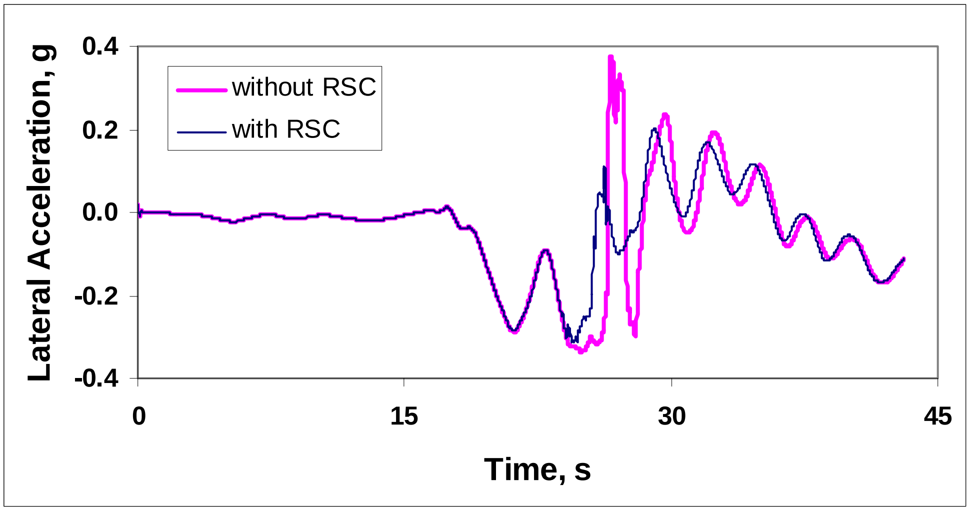


**Figure 4. RSC Limits the Lateral Acceleration of the Trailer**

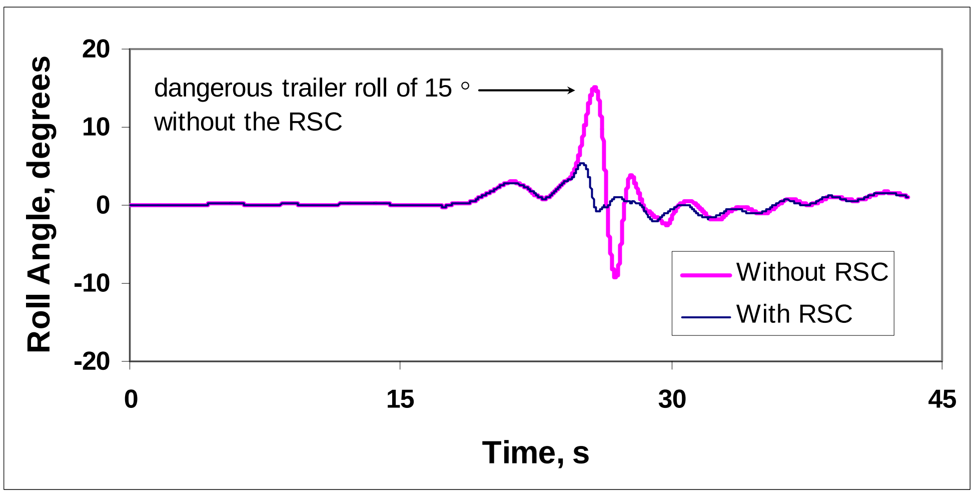


**Figure 5. RSC Limits the Roll Angle of the Trailer**

Finally, the simulated truck was launched into this same path at successively higher starting speeds until eventually the RSC could not prevent a rollover. This gave the second piece of necessary information for the conflict—how much faster than the actual FOT speed would the driver have had to enter the maneuver to roll the truck, had the truck been equipped with the RSC. In the maneuver of Figure 1, the driver would have had to begin the maneuver at 24.5 mph, 7.5 mph faster than the driver actually did in the FOT, to overcome the benefit of the RSC and roll the vehicle.

This simulation procedure was repeated for 126 of the 137 conflicts identified in the FOT. (The trailer was empty in the remaining 11 events and not in danger of rolling over, so they were excluded from this analysis.) The simulation exercise produced two data points for each of the 126 maneuvers. The first point is how much faster the driver would need to drive to roll the truck without the RSC (4.8 mph in the illustrated case), and the second is how much faster the driver would need to drive to roll the truck with the RSC (7.5 mph in the illustrated case). These data are tabulated in Appendix A.

In the 125 situations simulated, the RSC always intervened at a speed lower than the speed at which the unequipped truck would roll over. There were no cases where the truck rolled without triggering the RSC. The computer simulation's steering algorithm was developed for following smooth paths, and it does not have all the skills of a human driver to maintain stability of the vehicle in emergency handling situations. The algorithm occasionally responds inappropriately to the sudden braking applied by the RSC. This is why there are a few cases (e.g., case Tractor 4, Trip 685, Identifier 515 – page 21) where the probability of a crash was estimated to be higher with the RSC than without it. A human driver may have responded safely in these circumstances, but that question could not be pursued in the current study.

This example illustrates how the severity of a single conflict was characterized for two conditions—trucks with and without the RSC. The next section shows how these results were used to compute how the RSC reduces the probability of a crash and, from there, how many rollovers it can be expected to prevent.

## 5.0 Benefits Assessment

In order to determine the potential benefit of implementing the improved RA&C nationwide, the research team examined national crash statistics. The USDOT keeps statistics on the number of truck crashes, the events that precede them, and the number of resulting injuries and fatalities. Data for this project were taken from the General Estimates System (GES) and Fatality Analysis Reporting System (FARS) for the years 1995 through 2000. These data were analyzed and compared to the relatively small amount of data from the FOT and simulations to predict how many crashes could be avoided if the system were deployed nationwide.

### 5.1 Probability Estimates

The results of the simulations can be used to calculate the probability of a crash for the conflicts, which is a step toward estimating the overall benefits of the system.

Using simulations such as those just illustrated, the probability that each conflict would result in a crash was estimated, using the following equation:

$$P(C \mid S_{1,j}) = 1 - \Phi\left(\frac{\Delta v_{j,R}}{\sigma \times v_{j,M}}\right) \tag{1}$$

where $S_{1,j}$ indicates conflict number j,

$P(C \mid S_{1,j})$ is the probability of a crash resulting from conflict j

$\Delta v_{j,R}$ is the increase in speed of conflict j that results in a rollover,

$v_{j,M}$ is the speed during the FOT of conflict j at the peak lateral acceleration, and
$\Phi()$ is the Gaussian cumulative distribution.

The scaling factor, $\sigma$, was estimated to be 0.0010 in the independent evaluation [Battelle, 2003, pages 5-36 through 5-40]. As an example, Equation 1 can be applied to the conflict that served as an example in the previous section,

$$P(C \mid S_{1,j}) = 1 - \Phi(\frac{\Delta v_{j,R}}{\sigma \times v_{j,M}}) = 1 - \Phi(\frac{4.8}{0.0010 \times 1.1 \times 18.2}) = 1.53 \times 10^{-14}. \quad (1a)$$

The numerator in this equation, 4.8 mph, is the speed increment required for this maneuver to lead to a rollover. It was estimated by the simulation following the steps illustrated in Section 4.4. The value of 0.0010 is the variance scaling factor, and 1.1 is a units conversion factor[4]. The final value in the denominator, 18.2 mph, is the speed of the vehicle, measured during the FOT, at which the lateral acceleration of the tractor's steer axle reached a peak value. This quantity was read from one of the "input" columns of Appendix A. The probability of this conflict resulting in a crash even without the RSC is extremely small. Indeed, crashes are rare events, so the probabilities are expected to be remote, and this conflict is among the least likely to result in a rollover.

The second set of simulations, those where the truck was equipped with the RSC, yielded a second set of speed increments, $\Delta v'_{j,R}$. The formula in Equation (1) was computed again to determine the probability that a truck equipped with RSC would crash, given that it entered one of the 126 conflicts observed in the FOT. Again as an example, Equation 1 can be applied to this same conflict to calculate the probability of a crash given this conflict and that the truck is equipped with RSC:

$$P(C \mid S_{1,j}) = 1 - \Phi(\frac{\Delta v_{j,R}}{\sigma \times v_{j,M}}) = 1 - \Phi(\frac{7.5}{0.0010 \times 1.1 \times 18.2}) \approx 0. \quad (1b)$$

Thus, there were two numbers for each conflict—the probability of a truck without RSC rolling over and the probability of a truck with RSC rolling over. These pairs of probabilities are tabulated in Appendix A.

The difference between these probabilities is the reduction in probability of a crash that is attributable to the RSC. With the appropriate scaling factors, the probabilities can be summed to determine the total probability of a crash, and multiplied by the number of miles driven by a given fleet, to estimate the number of rollovers the RSC will prevent.

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[4] The scaling factor $\sigma$ itself is nondimensional. The FOT Evaluation was conducted mostly in metric units, but the present report is in English units. The difference in units between reports requires the units conversion factor. 1ft/s ≈ 1.1 kph.

## 5.2 Benefits Formula

The safety benefit of a countermeasure system is the number of crashes it is expected to prevent, when all factors are considered. It is calculated using Equation 5-13 of the independent evaluation final report [Battelle, 2003] or its simpler form, Equation 5-15 of the report,

$$B = N_{wo} \times App \times Eff. \qquad (2)$$

The first term in the formula is the average number of annual crashes without the system, $N_{wo}$, which is available from GES and FARS. The system's applicability, App, the proportion of crashes it is intended to address, is also calculated from national crash statistics. The effectiveness of the RA&C was discussed in the evaluation report [Battelle, 2003, Tables 4-2 and 4-3] and in the Task 5.2 report [Battelle, 2003b, Section 2.2]. The efficacy, Eff, is a measure of how close the system performs its intended function. The efficacy is calculated with data from a field operational test and from simulations. The efficacy depends on two quantities, which are termed the prevention ratio and the exposure ratio,

$$Eff = 1 - PR \times ER. \qquad (3)$$

The prevention ratio and the exposure ratio were mathematically defined in the evaluation report [Battelle, 2003, Equations 5-1 and 5-6]. Essentially, the exposure ratio measures the ability of the countermeasure system to prevent critical conflicts from happening, and the prevention ratio measures the ability of the countermeasure system to prevent a crash given that a conflict has occurred.

The primary component evaluated in the FOT was the RSA. The advisor, a driver education tool, is expected to reduce the number of times the driver makes a risky, near-rollover maneuver. It can be expected to affect the exposure ratio more than the prevention ratio. Calculations estimate that the RSA alone will prevent about 33 percent of the conflicts involving high speeds in turns that may result in trailer rollovers. This reduction in conflict rates was statistically significant. For the present analysis, the RSA is assigned a prevention ratio of 1.0.[5]

The controller's main benefit is to reduce the probability of a rollover after the vehicle enters a conflict. Therefore, the analysis assumes that, if the RSC were installed alone without the RSA, drivers would behave exactly the same with the RSC installed as they would without. Mathematically, this implies that the exposure ratio would be 1.0 and that all 137 conflicts observed in the FOT are representative of those that could occur if the RSC were installed alone.[6] This assumption would be true if RSC interventions were sufficiently rare that they do

[5] The original evaluation report [Battelle, 2003, pages 5-43 to 5-45] estimated the prevention ratio to be 1.2; that is, the conflicts occurring with the RSA are, on average, slightly more severe than those without. The efficacy of the RSA was estimated to be 20 percent (1-1.2×0.67). However, for the present analysis, the prevention ratio is taken to be 1.0, and the RSA (advisor) acting alone is estimated to prevent about 33 percent (1-1.0×0.67) of rollover crashes involving high speeds in turns. This is because (a) the estimated RSA prevention ratio of 1.2 was not statistically significant, and (b) the RSC, which intervenes when rollover is believed to be imminent, is expected to play the dominant role in reducing the number of near-rollover maneuvers that actually lead to rollover.

[6] An earlier version of the RSC was installed in the vehicles in the FOT. It activated only a few times during the FOT and in only 11 cases did it affect the vehicle dynamics. Not once did the drivers recognize the RSC

not have the training effect of the RSA advisories, and if drivers, knowing they had an extra safety device, resisted the temptation to drive faster or more recklessly.

Using the simulations of the RSC (controller) as described above, the RSC was estimated to prevent about 53 percent of the rollovers resulting from excessive speed in a curve (i.e., the prevention ratio was estimated to be 1-0.53=0.47). The prevention ratio is estimated as the ratio of the overall probability of a crash with the RSC to the overall probability of a crash without the RSC, both given that a driving conflict has occurred. The overall probability of a crash given a conflict is estimated as the average probability of a crash given the 126 specific conflicts considered as described in the following equation:

$$PR = \frac{P_w(C \mid S_1)}{P_{wo}(C \mid S_1)} = \frac{\frac{1}{126}\sum_{i=1}^{126} P_w(C \mid S_{1,i})}{\frac{1}{126}\sum_{i=1}^{126} P_{wo}(C \mid S_{1,i})} = 0.53 \tag{4}$$

The example illustrated in Section 4.4 is now one of the 126 elements in the sum. The value of Equation (1a) is one of the elements in the denominator, where the probability of a crash without the RSC is summed. The value of Equation (1b) is one of the elements in the numerator.

To estimate the combined effect of using both the RSA and RSC, we assume that the RSA would prevent some near-rollover situations from occurring, and that the RSC would prevent some of those that remain from actually leading to a rollover, and that the two effects would be independent of one another. Mathematically, because of the RSA, the exposure ratio would be 0.67, and because of the RSC, the prevention ratio would be 0.47. The combined efficacy is

$$\text{Eff} = 1 - \text{PR} \times \text{ER} \tag{5}$$

$$= 1 - .47 \times .67$$

$$= .69.$$

Therefore, the combined RA&C is estimated to prevent 69 percent of heavy vehicle rollovers that are caused by excessive speed in a turn.

## 5.3 Number of Rollovers Prevented

The analysis predicted what would happen if the RA&C were applied to four types of fleets nationwide:

- Tractors pulling tank trailers that display a hazardous material placard
- Tractors pulling any tank trailer

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intervention. Therefore, we feel justified in our assumption that the RSC's presence did not appreciably affect the behavior of the drivers of the FOT.

- Tractors pulling at least one trailing unit (almost always a semi-trailer)
- All heavy trucks (Class 3 through 8, or 10,000 lb and greater).

One significant finding of this undertaking was that the RSA can be expected to prevent a number of run-off-road (or single-vehicle roadway departure) crashes as well as rollovers. Many run-off-road crashes follow the same pattern as most rollovers—taking a curve too fast. Not as high a fraction of run-off-road crashes involve excessive speed in curves, but because there are many more of them than rollovers, the RA&C is actually expected to prevent more run-off-road incidents than rollover crashes.

In order to apply the results of the FOT, which involved one kind of vehicle in one type of business in one geographical area, some assumptions were made. For the purpose of calculation, the devices were assumed to be deployed throughout the fleets. Applying these results to the four fleet types examined as well as single-vehicle road departures yields the crash avoidance results shown in Table 4. The crash populations in this table are taken from Battelle [2003, Table 5-8, page 5-56; and 2003b, Table 4-1, page 24].

**Table 4. Crash Prevention Estimates**

| Type of Truck | Rollover (Fast Turn) | | | |
|---|---|---|---|---|
| | Number of Trucks in Crashes/Year | Number of Crashes Avoided | | |
| | | RSA (33%) | RSC (53%) | RA&C (69%) |
| HazMat Tankers | 4 | 1.4 | 2.3 | 3 |
| All Tankers | 46 | 15 | 24 | 32 |
| Tractor Trailers | 471 | 155 | 250 | 325 |
| Large Trucks | 787 | 260 | 417 | 543 |

## 5.4 Effect of Circumstances on Performance

The 137 critical conflicts identified in the FOT data occurred in a variety of road geometries, and they represent a variety of vehicle speeds and road curvatures. As these events occurred naturally during the FOT period, they constitute a representative sample of circumstances of possible rollovers, but not an exhaustive study of all circumstances of possible rollovers. The variety provided by these driving conflicts presents the opportunity to explore the question of whether the circumstances of the maneuver affect the performance of the RSC. To do so, the prevention ratios of individual events were considered as a function of four possible independent variables: road geometry, vehicle speed at the time of maximum lateral acceleration, path curvature at the time of maximum lateral acceleration, and vehicle fill (i.e., partial vs. full).

The prevention ratio for an individual driving conflict ($PR_j$) is calculated as the ratio of the probability of that driving conflict resulting in a crash with the RSC to that same probability without the RSC. Specifically,

$$PR_j = \frac{P_w(C \mid S_{1,j})}{P_{wo}(C \mid S_{1,j})} \qquad (6)$$

where $P(C \mid S_{1,j})$ is calculated as described in Equation 1 and the subscripts *w* and *wo* denote the conditions with the RSC and without the RSC, respectively. The probabilities in Equation 6 are functions of $\Delta v_{j,R}$, the increase in speed of conflict j that results in a rollover, with and without the RSC. Due to the non-linear nature of Equation 1, it is necessary to explore the prevention ratio directly; exploration of change in increase in conflict speed resulting in a rollover crash ($\Delta v_{j,R} - \Delta v'_{j,R}$) is not sufficient. This is problematic because the probabilities that individual conflicts result in a crash, which are intermediate quantities in the calculation of the prevention ratio, are very small quantities. These quantities vary from each other by orders of magnitude.[7]

Note that 93 of the 126 driving conflicts exhibit improvement due to the RSC, as measured by the increase in change of conflict speed resulting in a rollover crash; 8 exhibit detriment due to the RSC; and 25 exhibit no change.

There are cases where the RSC had an effect as measured by the change in speed increment but no effect as measured by the change in probability of a crash.[8] There were only 37 cases that exhibit measurable improvement due to the RSC as measured by the prevention ratio, 7 that exhibit measurable detriment, and 81 that exhibit no change. Thus, using either measure (change in speed increment or change in crash probability), a safety improvement due to the RSC is indicated. However, there is little data with which to explore factors associated with improvement using the prevention ratio.

The prevention ratio is characterized by a few influential values (i.e., values that are orders of magnitude larger than the rest). Due to these driving conflicts with large values, there is significant variability associated with comparisons made using this data. Sometimes influential values (outliers) are removed from a data set before analysis. This did not make sense in this case, because these are the exact driving conflicts that are most influential in the prevention ratio estimate made in the independent evaluation [Battelle, 2003]. Additionally, when the most extreme outliers are removed from this data set, new observations appear as outliers within the reduced data set; thus, it is difficult to decide exactly how many of these can be reasonably thrown out before analysis. Due to the variability observed in the prevention ratio values, no significant effect due to road geometry, vehicle speed at the time of maximum lateral acceleration, path curvature at the time of maximum lateral acceleration, or vehicle fill (i.e., partial vs. full) could be identified.

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[7] There were some conflicts where the RSC reduced the probability of a crash, but the probability of a crash was already very low, even without the RSC. A good example is the second entry in the table in Appendix A. The probability of that conflict becoming a rollover crash without the RSC is one in a hundred million. With the RSC, the probability of a crash is more remote than one in a billion. That is an improvement, but it does not significantly affect the overall probability because, for example, in the first and third conflicts in the table are a hundred times more likely to result in a crash than is the second entry.

[8] The second entry in the table of Appendix A is an example of a "measurable" improvement. The probability of a crash is substantially lower with the RSC than without. The fifth entry in the table is an example of a change that cannot be measured. The probability of a crash is approximately one in a billion, regardless of whether the RSC is present.

## 6.0 References

Allen, R. W., Szostak, H. T., Klyde, D. H., Rosenthal, T. J., and Owens, K. J., 1992 “Vehicle Dynamic Stability and Rollover,” DOT-HS-807 956, September 1992.

Battelle, 2003, “Final Report – Evaluation of the Freightliner Intelligent Vehicle Initiative Field Operational Test,” Contract No. DTFJ61-96-C-00077, Task Order 7718.

Battelle, 2003a, “Final Report – Evaluation of the Freightliner Intelligent Vehicle Initiative Field Operational Test,” Contract No. DTFJ61-96-C-00077, Task Order 7718, Appendices Volume, Appendix D.

Battelle, 2003b, “Review of Commercial Motor Vehicle Crash Data,” Contract DTFH61-96-C-00077, Task Order 32.

Battelle, 2003c, “Analysis and Documentation of Industry Benefits and Costs for the Improved Roll Advisor and Controller Technology,” Contract DTFH61-96-C-00077, Task Order 32.

# Appendix A

# Input and Output Data in Tabular Format

# Appendix A

## Input and Output Data in Tabular Format

The VDANL model inputs and outputs are summarized in the following table for each critical event analyzed. Each row in the following table represents one conflict that was studied. The first three columns identify the conflict; the next four describe the condition of the conflict; and the final six present the results of either the simulation study or the statistical analysis.

Tractor, Trip, and Identifier in the first three columns of the table uniquely identify a conflict. The input values, dynamic output values, and crash probability are described below.

### Input Values

**Initial Speed**: This is the speed measured on the truck during the FOT. It was recorded at the time of the peak in the lateral acceleration, measured by the accelerometer mounted on the steer axle of the tractor.

**Curvature**: The simulation path curvature at instant of maximum tractor acceleration. This is not the road curvature. As the vehicle is maneuvering to maintain a path in a severe roll, this curvature may be significantly different from the road curvature. A positive value indicates a left turn and a negative value, a right turn.

**Loading Condition**: The trailer loading condition – full or partial. Vehicles with a nearly full load at the time of the conflict (36 to 41 tons) were simulated with a vehicle weight of 40 tons. Vehicles with a partial load at the time of the conflict (26 to 35 tons) were assigned a weight of 31 tons in the simulation. See Table 2 of the text and the accompanying discussion. All vehicles in the FOT were Class 8 tractors pulling liquid nitrogen trailers, and all vehicles in the simulation were five-axle articulated vehicles.

**Curve Shape**: Gives a description of the type of curve being negotiated. Corresponds to the descriptions in Appendix B.

### Dynamic Output Values

The output columns have data sorted by whether the RSC was active or not active. They were calculated when the vehicle was simulated as going faster than in the FOT.

**Speed at Rollover**: The speed when the "initial speed" had been increased sufficiently to lead to a rollover. This first column is the maximum speed at which the maneuver could be taken without rolling over, when the RSC was not present. The second column is the maximum speed at which the RSC can prevent a rollover.

**Trailer Acceleration**: The lateral acceleration of the trailer at the instant of maximum tractor lateral acceleration. The simulation was conducted at the speed where the vehicle is predicted to roll over without the RSC. The cases with RSC were simulated beginning at the same speed as those without the RSC, but the RSC activated and changed the dynamics at the point of near-rollover. When the peak lateral acceleration is lower in the case with the RSC, it indicates that the RSC has reduced the rollover tendency of the trailer. (A positive value indicates a left turn and a negative value, a right turn.)

## Speed Increment to Crash and Crash Probability

**Speed Increment to Crash**: This is how much faster than the original FOT speed the vehicle would have to traverse the path to roll the vehicle. These speed increments are the change in speeds $\Delta v_{j,R}$ used to calculate the probability of a crash in Equation (1) of the main text.

**Probability of a Crash**: These columns indicate the probability of a rollover crash, given that the respective conflict occurred. These probabilities are summarized and combined to calculate the Prevention Ratio as in Equation (3) of the text. Because the probabilities vary over a wide range, they are expressed as a phrase instead of a number. For example, if the probability is listed as, "one in a . . . million," that means that the probability of a crash is approximately $10^{-6}$, or that if this same conflict were repeated a million times, each with slightly different perturbations, one of them would be expected to roll over. A blank entry indicates that the probability of a crash was quite remote, less than one in a billion.

The highlighted row, for Tractor 4, Trip 1072, and identifier 622 – page 24, is the one illustrated in Figures 1 through 4 of the text.

# VDANL Model Inputs and Outputs

| Identification | | | Input | | | | Output | | | | Implications for a Crash | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC |
| Tractor | Trip | Identifier | FOT Speed mph | Curvature 1/ft | Loading Condition | Curve Shape | Speed of the Rollover Simulation mph | | Trailer Max. Accel. g | | Speed Increment to Rollover mph | | Probability of a Crash one in a... | |
| 1 | 407 | 595 | 29.8 | 0.008 | Full | ? Turns | 34.5 | 35.9 | 0.38 | 0.36 | 4.8 | 6.1 | million | billion |
| 1 | 780 | 696 | 28.4 | 0.008 | Full | ? Turns | 33.9 | 35.9 | 0.47 | 0.43 | 5.5 | 7.5 | hundred million | -- |
| 1 | 1179 | 580 | 28.0 | 0.007 | Full | ? Turns | 32.7 | 34.8 | 0.38 | 0.38 | 4.8 | 6.8 | million | -- |
| 1 | 1678 | 511 | 29.5 | 0.008 | Full | ? Turns | 35.0 | 35.7 | 0.47 | 0.41 | 5.5 | 6.1 | ten million | billion |
| 2 | 1244 | 420 | 27.0 | 0.009 | Full | ? Turns | 32.4 | 32.4 | 0.39 | 0.44 | 5.5 | 5.5 | billion | billion |
| 3 | 77 | 578 | 29.6 | 0.007 | Full | ? Turns | 35.7 | 36.4 | 0.43 | 0.38 | 6.1 | 6.8 | billion | -- |
| 3 | 568 | 700 | 27.9 | 0.009 | Full | ? Turns | 33.3 | 33.3 | 0.46 | 0.41 | 5.5 | 5.5 | hundred million | hundred million |
| 4 | 1224 | 751 | 29.8 | 0.008 | Full | ? Turns | 33.9 | 33.9 | 0.39 | 0.40 | 4.1 | 4.1 | ten thousand | ten thousand |
| 4 | 1312 | 510 | 27.9 | 0.008 | Full | ? Turns | 32.7 | 35.4 | 0.39 | 0.37 | 4.8 | 7.5 | million | -- |
| 5 | 271 | 471 | 29.8 | 0.008 | Full | ? Turns | 34.5 | 35.2 | 0.39 | 0.38 | 4.8 | 5.5 | million | ten million |
| 5 | 1728 | 496 | 28.7 | 0.008 | Full | ? Turns | 33.5 | 32.8 | 0.40 | -- | 4.8 | 4.1 | million | hundred thousand |
| 6 | 282 | 634 | 29.4 | 0.007 | Full | ? Turns | 34.2 | 34.9 | 0.46 | 0.35 | 4.8 | 5.5 | million | ten million |
| 1 | 1693 | 381 | 22.8 | 0.009 | Full | Consecutive Opposite Turns | 30.3 | 34.4 | 0.42 | 0.35 | 7.5 | 11.6 | -- | -- |
| 2 | 758 | 474 | 20.5 | -0.009 | Full | Consecutive Opposite Turns | 25.2 | 29.3 | 0.32 | -0.29 | 4.8 | 8.9 | -- | -- |
| 2 | 811 | 523 | 15.8 | -0.015 | Full | Consecutive Opposite Turns | 20.6 | 19.2 | -0.38 | -- | 4.8 | 3.4 | -- | -- |
| 2 | 1468 | 558 | 15.7 | -0.016 | Full | Consecutive Opposite Turns | 19.1 | 22.5 | -0.31 | -0.30 | 3.4 | 6.8 | -- | -- |
| 3 | 83 | 425 | 16.0 | 0.014 | Full | Consecutive Opposite Turns | 21.4 | 22.8 | 0.32 | 0.32 | 5.5 | 6.8 | -- | -- |
| 3 | 98 | 551 | 16.5 | -0.016 | Full | Consecutive Opposite Turns | 19.2 | 19.2 | -0.34 | -0.34 | 2.7 | 2.7 | million | million |

# VDANL Model Inputs and Outputs

| Identification | | | Input | | | | Output | | | | Implications for a Crash | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tractor | Trip | Identifier | FOT Speed mph | Curvature 1/ft | Loading Condition | Curve Shape | Speed of the Rollover Simulation mph | | Trailer Max. Accel. g | | Speed Increment to Rollover mph | | Probability of a Crash one in a... | |
| | | | | | | | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC |
| 3 | 276 | 414 | 15.9 | -0.013 | Full | Consecutive Opposite Turns | 20.0 | 20.0 | 0.31 | -0.31 | 4.1 | 4.1 | -- | -- |
| 3 | 1211 | 310 | 16.6 | -0.011 | Full | Consecutive Opposite Turns | 20.1 | 22.8 | -0.36 | -0.29 | 3.4 | 6.1 | ten million | -- |
| 4 | 623 | 397 | 16.8 | -0.017 | Full | Consecutive Opposite Turns | 22.9 | 25.0 | 0.41 | 0.29 | 6.1 | 8.2 | -- | -- |
| 4 | 685 | 515 | 16.1 | -0.022 | Full | Consecutive Opposite Turns | 22.9 | 18.8 | 0.15 | -- | 6.8 | 2.7 | -- | million |
| 5 | 26 | 568 | 16.6 | -0.016 | Full | Consecutive Opposite Turns | 19.3 | 20.0 | -0.31 | -0.30 | 2.7 | 3.4 | million | billion |
| 5 | 526 | 635 | 15.1 | -0.014 | Full | Consecutive Opposite Turns | 19.2 | 19.9 | -0.34 | 0.26 | 4.1 | 4.8 | -- | -- |
| 5 | 922 | 331 | 20.2 | -0.010 | Full | Consecutive Opposite Turns | 23.6 | 26.4 | -0.36 | -0.33 | 3.4 | 6.1 | million | -- |
| 5 | 1304 | 421 | 16.0 | -0.015 | Full | Consecutive Opposite Turns | 19.4 | 19.4 | -0.32 | -0.32 | 3.4 | 3.4 | -- | -- |
| 6 | 523 | 446 | 15.9 | -0.013 | Full | Consecutive Opposite Turns | 20.7 | 23.4 | -0.34 | -0.33 | 4.8 | 7.5 | -- | -- |
| 3 | 508 | 250 | 34.9 | 0.005 | Full | Gradual Left | 56.0 | 55.3 | 0.57 | -- | 21.1 | 20.5 | -- | -- |
| 3 | 1052 | 427 | 38.9 | 0.005 | Full | Gradual Left | 59.3 | 59.3 | -0.56 | 0.71 | 20.5 | 20.5 | -- | -- |
| 1 | 777 | 416 | 15.4 | 0.014 | Full | Left Turn | 20.2 | 20.2 | 0.33 | 0.33 | 4.8 | 4.8 | -- | -- |
| 2 | 360 | 787 | 15.9 | 0.023 | Full | Left Turn | 28.2 | 19.3 | 0.08 | -- | 12.3 | 3.4 | -- | -- |
| 2 | 549 | 623 | 15.7 | 0.017 | Partial | Left Turn | 20.5 | 27.3 | 0.42 | 0.35 | 4.8 | 11.6 | -- | -- |
| 2 | 1839 | 522 | 16.4 | 0.015 | Full | Left Turn | 19.2 | 19.2 | 0.32 | 0.32 | 2.7 | 2.7 | million | million |
| 2 | 1844 | 356 | 16.3 | 0.012 | Full | Left Turn | 22.4 | 23.8 | 0.07 | 0.35 | 6.1 | 7.5 | -- | -- |
| 3 | 877 | 395 | 17.8 | 0.013 | Full | Left Turn | 21.2 | 22.6 | 0.31 | 0.29 | 3.4 | 4.8 | hundred million | -- |
| 3 | 1308 | 475 | 16.7 | 0.012 | Full | Left Turn | 20.8 | 27.6 | 0.36 | 0.34 | 4.1 | 10.9 | -- | -- |
| 4 | 449 | 444 | 15.8 | 0.017 | Partial | Left Turn | 21.2 | 30.8 | 0.44 | 0.39 | 5.5 | 15.0 | -- | -- |
| 4 | 1548 | 443 | 16.1 | 0.015 | Full | Left Turn | 20.2 | 22.3 | 0.32 | 0.31 | 4.1 | 6.1 | -- | -- |
| 4 | 1608 | 629 | 16.7 | 0.012 | Full | Left Turn | 22.8 | 24.9 | 0.33 | 0.31 | 6.1 | 8.2 | -- | -- |
| 4 | 1665 | 549 | 16.2 | 0.011 | Full | Left Turn | 21.6 | 23.0 | -0.31 | 0.32 | 5.5 | 6.8 | -- | -- |

# VDANL Model Inputs and Outputs

| Identification | | | Input | | | | Output | | | | Implications for a Crash | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Speed of the Rollover Simulation mph | | Trailer Max. Accel. g | | Speed Increment to Rollover mph | | Probability of a Crash one in a... | |
| Tractor | Trip | Identifier | FOT Speed mph | Curvature 1/ft | Loading Condition | Curve Shape | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC |
| 4 | 1682 | 674 | 18.2 | 0.010 | Full | Left Turn | 23.0 | 25.0 | 0.34 | 0.34 | 4.8 | 6.8 | -- | -- |
| 5 | 89 | 441 | 15.7 | 0.018 | Full | Left Turn | 19.1 | 19.1 | 0.33 | 0.32 | 3.4 | 3.4 | -- | -- |
| 5 | 126 | 376 | 15.7 | 0.016 | Full | Left Turn | 20.4 | 23.2 | 0.37 | 0.35 | 4.8 | 7.5 | -- | -- |
| 5 | 229 | 470 | 16.0 | 0.015 | Partial | Left Turn | 24.9 | 29.7 | 0.48 | 0.33 | 8.9 | 13.6 | -- | -- |
| 6 | 306 | 358 | 16.9 | 0.016 | Full | Left Turn | 20.3 | 21.6 | 0.34 | 0.34 | 3.4 | 4.8 | billion | -- |
| 6 | 454 | 535 | 15.2 | 0.021 | Partial | Left Turn | 18.6 | 17.2 | 0.42 | -- | 3.4 | 2.0 | -- | ten thousand |
| 1 | 766 | 774 | 19.7 | -0.011 | Full | Right Turn | 25.8 | 29.9 | -0.36 | -0.32 | 6.1 | 10.2 | -- | -- |
| 2 | 1155 | 466 | 20.4 | -0.009 | Full | Right Turn | 25.9 | 27.9 | -0.35 | -0.31 | 5.5 | 7.5 | -- | -- |
| 3 | 508 | 259 | 16.2 | -0.014 | Full | Right Turn | 19.6 | 19.6 | -0.32 | -0.32 | 3.4 | 3.4 | billion | billion |
| 3 | 1053 | 534 | 17.7 | -0.009 | Full | Right Turn | 21.8 | 21.1 | -0.31 | -- | 4.1 | 3.4 | -- | hundred million |
| 3 | 1211 | 310 | 19.0 | -0.013 | Full | Right Turn | 23.8 | 25.8 | -0.35 | -0.35 | 4.8 | 6.8 | -- | -- |
| 3 | 1566 | 261 | 15.9 | -0.013 | Full | Right Turn | 19.3 | 19.3 | -0.33 | -0.33 | 3.4 | 3.4 | -- | -- |
| 4 | 865 | 832 | 16.1 | -0.014 | Full | Right Turn | 21.6 | 21.6 | -0.35 | -0.33 | 5.5 | 5.5 | -- | -- |
| 4 | 1566 | 670 | 16.1 | -0.017 | Full | Right Turn | 18.9 | 19.5 | -0.30 | -0.30 | 2.7 | 3.4 | million | billion |
| 1 | 418 | 620 | 16.6 | -0.015 | Full | S-Curve | 22.1 | 23.4 | -0.36 | 0.28 | 5.5 | 6.8 | -- | -- |
| 1 | 974 | 367 | 17.2 | 0.013 | Full | S-Curve | 23.4 | 27.5 | 0.36 | 0.33 | 6.1 | 10.2 | -- | -- |
| 1 | 1000 | 361 | 19.3 | -0.009 | Full | S-Curve | 26.8 | 30.2 | -0.37 | 0.30 | 7.5 | 10.9 | -- | -- |
| 1 | 1228 | 504 | 17.2 | 0.011 | Full | S-Curve | 23.4 | 26.1 | 0.35 | 0.28 | 6.1 | 8.9 | -- | -- |
| 2 | 1143 | 313 | 17.8 | -0.011 | Full | S-Curve | 24.7 | 27.4 | -0.34 | 0.30 | 6.8 | 9.5 | -- | -- |
| 2 | 1616 | 508 | 15.7 | -0.017 | Partial | S-Curve | 21.8 | 25.2 | -0.43 | 0.36 | 6.1 | 9.5 | -- | -- |
| 3 | 551 | 380 | 19.5 | -0.011 | Full | S-Curve | 26.3 | 27.7 | -0.37 | 0.31 | 6.8 | 8.2 | -- | -- |
| 4 | 887 | 377 | 17.4 | 0.011 | Full | S-Curve | 25.6 | 26.9 | 0.37 | 0.33 | 8.2 | 9.5 | -- | -- |
| 4 | 1115 | 535 | 17.8 | -0.013 | Full | S-Curve | 23.2 | 25.3 | -0.35 | 0.31 | 5.5 | 7.5 | -- | -- |
| 5 | 76 | 497 | 20.0 | 0.013 | Full | S-Curve | 25.5 | 27.5 | 0.34 | 0.30 | 5.5 | 7.5 | -- | -- |
| 5 | 127 | 416 | 15.8 | -0.012 | Full | S-Curve | 22.0 | 26.1 | -0.35 | -0.32 | 6.1 | 10.2 | -- | -- |
| 5 | 1202 | 537 | 17.8 | 0.018 | Partial | S-Curve | 25.3 | 32.8 | 0.46 | 0.38 | 7.5 | 15.0 | -- | -- |

# VDANL Model Inputs and Outputs

| Identification | | | Input | | | | Output | | | | Implications for a Crash | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC |
| Tractor | Trip | Identifier | FOT Speed mph | Curvature 1/ft | Loading Condition | Curve Shape | Speed of the Rollover Simulation mph | | Trailer Max. Accel. g | | Speed Increment to Rollover mph | | Probability of a Crash one in a... | |
| 5 | 1630 | 560 | 16.8 | -0.018 | Full | S-Curve | 18.1 | 21.6 | -0.34 | 0.29 | 1.4 | 4.8 | hundred | -- |
| 6 | 459 | 396 | 21.0 | -0.012 | Full | S-Curve | 28.5 | 31.3 | -0.37 | 0.28 | 7.5 | 10.2 | -- | -- |
| 6 | 1139 | 447 | 17.0 | -0.014 | Full | S-Curve | 21.8 | 23.1 | 0.38 | 0.28 | 4.8 | 6.1 | -- | -- |
| 1 | 605 | 267 | 15.8 | 0.016 | Partial | Sharp Trumpet Turn | 22.6 | 29.4 | 0.44 | 0.36 | 6.8 | 13.6 | -- | -- |
| 1 | 1516 | 560 | 16.9 | 0.012 | Full | Sharp Trumpet Turn | 22.3 | 23.7 | 0.35 | 0.33 | 5.5 | 6.8 | -- | -- |
| 1 | 1680 | 282 | 16.8 | 0.013 | Full | Sharp Trumpet Turn | 20.9 | 23.0 | 0.32 | 0.32 | 4.1 | 6.1 | -- | -- |
| 2 | 633 | 410 | 18.2 | -0.004 | Full | Sharp Trumpet Turn | 23.7 | 24.4 | 0.33 | 0.32 | 5.5 | 6.1 | -- | -- |
| 2 | 634 | 444 | 17.7 | 0.014 | Partial | Sharp Trumpet Turn | 25.9 | 32.7 | 0.48 | 0.35 | 8.2 | 15.0 | -- | -- |
| 3 | 1412 | 425 | 17.2 | 0.016 | Partial | Sharp Trumpet Turn | 24.0 | 29.4 | 0.44 | 0.34 | 6.8 | 12.3 | -- | -- |
| 3 | 1735 | 452 | 18.1 | 0.012 | Full | Sharp Trumpet Turn | 22.2 | 26.3 | 0.34 | 0.32 | 4.1 | 8.2 | -- | -- |
| 4 | 653 | 630 | 15.8 | 0.022 | Partial | Sharp Trumpet Turn | 19.2 | 26.7 | 0.47 | 0.32 | 3.4 | 10.9 | -- | -- |
| 4 | 811 | 336 | 16.1 | 0.015 | Full | Sharp Trumpet Turn | 19.6 | 20.2 | 0.35 | 0.33 | 3.4 | 4.1 | billion | -- |
| 5 | 1298 | 384 | 15.5 | -0.015 | Partial | Sharp Trumpet Turn | 20.9 | 32.5 | -0.44 | -0.37 | 5.5 | 17.0 | -- | -- |
| 6 | 911 | 605 | 17.2 | 0.014 | Full | Sharp Trumpet Turn | 21.3 | 22.6 | 0.32 | 0.31 | 4.1 | 5.5 | -- | -- |
| 4 | 790 | 564 | 18.4 | -0.011 | Full | Slight Right at Stop | 27.9 | 27.9 | -0.33 | -0.34 | 9.5 | 9.5 | -- | -- |
| 4 | 1259 | 565 | 17.2 | -0.013 | Full | Slight Right at Stop | 27.4 | 27.4 | -0.33 | -0.33 | 10.2 | 10.2 | -- | -- |
| 4 | 1540 | 609 | 18.6 | -0.012 | Full | Slight Right at Stop | 28.1 | 28.8 | -0.35 | -0.34 | 9.5 | 10.2 | -- | -- |
| 5 | 1011 | 481 | 15.7 | -0.013 | Full | Slight Right at Stop | 26.0 | 26.6 | -0.35 | -0.33 | 10.2 | 10.9 | -- | -- |
| 6 | 1122 | 563 | 16.5 | -0.013 | Full | Slight Right at | 26.7 | 26.7 | -0.34 | -0.33 | 10.2 | 10.2 | -- | -- |

# VDANL Model Inputs and Outputs

| Identification | | | Input | | | | Output | | | | Implications for a Crash | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tractor | Trip | Identifier | FOT Speed mph | Curvature 1/ft | Loading Condition | Curve Shape | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC |
| | | | | | | | Speed of the Rollover Simulation mph | | Trailer Max. Accel. g | | Speed Increment to Rollover mph | | Probability of a Crash one in a... | |
| | | | | | | Stop | | | | | | | | |
| 3 | 256 | 641 | 29.9 | -0.010 | Full | Turn Over 180 | 34.7 | 34.7 | -0.36 | -0.43 | 4.8 | 4.8 | million | million |
| 3 | 877 | 335 | 28.9 | -0.006 | Full | Turn Over 180 | 34.3 | 34.3 | -0.39 | -0.33 | 5.5 | 5.5 | hundred million | hundred million |
| 5 | 707 | 316 | 18.4 | -0.013 | Full | Turn Over 180 | 22.5 | 25.9 | -0.35 | -0.35 | 4.1 | 7.5 | -- | -- |
| 1 | 397 | 471 | 18.2 | 0.011 | Full | Unique Curve | 26.4 | 27.1 | 0.33 | 0.33 | 8.2 | 8.9 | -- | -- |
| 1 | 676 | 622 | 24.1 | -0.008 | Full | Unique Curve | 34.3 | 35.7 | -0.47 | -0.45 | 10.2 | 11.6 | -- | -- |
| 1 | 690 | 635 | 24.2 | -0.006 | Full | Unique Curve | 34.4 | 35.1 | -0.40 | -0.42 | 10.2 | 10.9 | -- | -- |
| 1 | 787 | 489 | 51.7 | -0.005 | Full | Unique Curve | 64.0 | 62.6 | -0.47 | -- | 12.3 | 10.9 | -- | billion |
| 1 | 965 | 908 | 19.8 | 0.009 | Full | Unique Curve | 27.3 | 30.7 | 0.37 | 0.31 | 7.5 | 10.9 | -- | -- |
| 1 | 1043 | 461 | 17.7 | -0.006 | Full | Unique Curve | 29.3 | 29.9 | -0.41 | -0.40 | 11.6 | 12.3 | -- | -- |
| 1 | 1084 | 569 | 16.6 | 0.011 | Full | Unique Curve | 23.4 | 25.4 | 0.38 | 0.31 | 6.8 | 8.9 | -- | -- |
| 1 | 1119 | 508 | 17.1 | 0.014 | Full | Unique Curve | 21.9 | 23.9 | 0.38 | 0.33 | 4.8 | 6.8 | -- | -- |
| 1 | 1571 | 420 | 15.5 | 0.014 | Full | Unique Curve | 20.3 | 20.3 | 0.32 | 0.33 | 4.8 | 4.8 | -- | -- |
| 1 | 1687 | 569 | 17.1 | 0.005 | Full | Unique Curve | 22.6 | 24.0 | 0.39 | 0.38 | 5.5 | 6.8 | -- | -- |
| 3 | 332 | 616 | 41.2 | -0.005 | Full | Unique Curve | 50.0 | 50.0 | -0.58 | -0.48 | 8.9 | 8.9 | -- | -- |
| 3 | 508 | 298 | 16.8 | 0.014 | Full | Unique Curve | 22.2 | 25.0 | 0.33 | 0.34 | 5.5 | 8.2 | -- | -- |
| 3 | 813 | 415 | 16.0 | 0.011 | Full | Unique Curve | 21.4 | 22.8 | 0.37 | 0.35 | 5.5 | 6.8 | -- | -- |
| 3 | 850 | 368 | 16.1 | 0.015 | Full | Unique Curve | 18.1 | 18.8 | 0.32 | 0.31 | 2.0 | 2.7 | ten thousand | million |
| 3 | 1660 | 431 | 16.1 | 0.013 | Full | Unique Curve | 20.1 | 24.2 | 0.32 | 0.30 | 4.1 | 8.2 | -- | -- |
| 4 | 480 | 565 | 20.3 | -0.011 | Full | Unique Curve | 25.8 | 29.2 | -0.35 | -0.30 | 5.5 | 8.9 | -- | -- |
| 4 | 523 | 497 | 16.0 | -0.020 | Full | Unique Curve | 20.1 | 20.1 | -0.35 | -0.35 | 4.1 | 4.1 | -- | -- |
| 4 | 1072 | 622 | 18.2 | -0.014 | Full | Unique Curve | 23.0 | 25.7 | -0.40 | -0.30 | 4.8 | 7.5 | -- | -- |
| 4 | 1548 | 437 | 17.5 | -0.014 | Full | Unique Curve | 21.6 | 25.7 | -0.35 | -0.32 | 4.1 | 8.2 | -- | -- |
| 4 | 1587 | 445 | 16.9 | 0.012 | Full | Unique Curve | 22.4 | 25.8 | 0.33 | 0.34 | 5.5 | 8.9 | -- | -- |
| 4 | 1665 | 549 | 18.1 | -0.013 | Full | Unique Curve | 24.2 | 25.6 | -0.34 | -0.33 | 6.1 | 7.5 | -- | -- |
| 4 | 1689 | 622 | 22.0 | -0.009 | Full | Unique Curve | 30.9 | 32.9 | -0.41 | -0.36 | 8.9 | 10.9 | -- | -- |

# VDANL Model Inputs and Outputs

| Identification | | | Input | | | | Output | | | | Implications for a Crash | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Speed of the Rollover Simulation mph | | Trailer Max. Accel. g | | Speed Increment to Rollover mph | | Probability of a Crash one in a... | |
| Tractor | Trip | Identifier | FOT Speed mph | Curvature 1/ft | Loading Condition | Curve Shape | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC | Without RSC | With RSC |
| 5 | 86 | 534 | 16.1 | -0.013 | Full | Unique Curve | 20.9 | 24.3 | -0.38 | -0.28 | 4.8 | 8.2 | -- | -- |
| 5 | 126 | 375 | 17.8 | -0.013 | Full | Unique Curve | 21.8 | 28.7 | -0.39 | -0.34 | 4.1 | 10.9 | -- | -- |
| 5 | 482 | 579 | 15.9 | -0.014 | Full | Unique Curve | 20.0 | 20.0 | -0.34 | -0.34 | 4.1 | 4.1 | -- | -- |
| 5 | 688 | 432 | 22.1 | -0.007 | Full | Unique Curve | 34.4 | 35.8 | -0.45 | -0.39 | 12.3 | 13.6 | -- | -- |
| 5 | 1263 | 545 | 17.2 | 0.010 | Full | Unique Curve | 25.4 | 27.5 | 0.36 | 0.30 | 8.2 | 10.2 | -- | -- |
| 6 | 128 | 620 | 17.9 | 0.014 | Full | Unique Curve | 24.1 | 25.4 | 0.36 | 0.29 | 6.1 | 7.5 | -- | -- |
| 6 | 287 | 708 | 16.5 | 0.012 | Full | Unique Curve | 17.8 | 17.8 | 0.37 | 0.36 | 1.4 | 1.4 | hundred | hundred |
| 6 | 1090 | 488 | 15.8 | 0.015 | Partial | Unique Curve | 23.3 | 30.1 | 0.44 | 0.34 | 7.5 | 14.3 | -- | -- |
| 6 | 1222 | 661 | 17.1 | 0.008 | Full | Unique Curve | 20.5 | 20.5 | -0.37 | -0.28 | 3.4 | 3.4 | hundred million | hundred million |
| 1 | 787 | 548 | 16.9 | -0.013 | Full | Wiggle | 26.5 | 26.5 | -0.34 | -0.36 | 9.5 | 9.5 | -- | -- |
| 1 | 800 | 562 | 15.8 | -0.005 | Full | Wiggle | 26.0 | 26.7 | -0.39 | -0.39 | 10.2 | 10.9 | -- | -- |
| 1 | 1701 | 645 | 26.3 | 0.005 | Full | Wiggle | 42.0 | 43.4 | 0.43 | 0.40 | 15.7 | 17.0 | -- | -- |
| 3 | 1767 | 690 | 16.9 | 0.010 | Full | Wiggle | 27.1 | 27.8 | 0.37 | 0.34 | 10.2 | 10.9 | -- | -- |
| 5 | 469 | 413 | 17.9 | -0.011 | Full | Wiggle | 23.4 | 25.4 | 0.34 | 0.29 | 5.5 | 7.5 | -- | -- |
| 6 | 177 | 492 | 15.8 | -0.014 | Full | Wiggle | 25.3 | 26.7 | -0.36 | -0.33 | 9.5 | 10.9 | -- | -- |

# Appendix B

# Conflict Analysis Plots

# Appendix B

## Conflict Interpretation Example

In order to interpret individual conflicts, a tool was developed to plot the relevant information relating to a conflict. A screen capture of the tool's output is shown on the following page. This group of plots on this page provides the information needed to understand what took place during each of the conflicts.

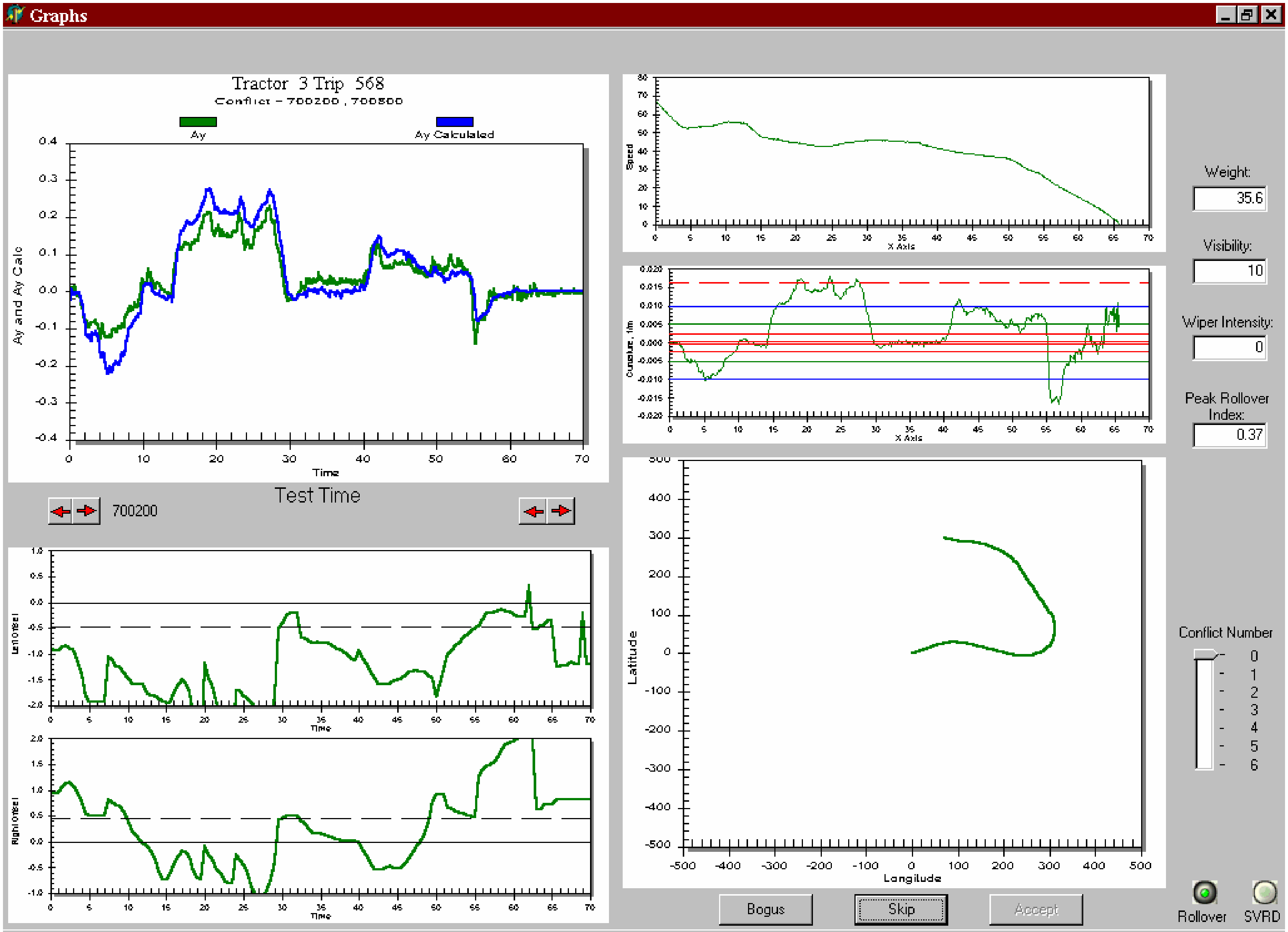
On each page, the plot in the upper left indicates the lateral acceleration of the vehicle, which is often referred to as Ay because it is the acceleration along the y axis perpendicular to the vehicle. The plot includes the tractor number (1-6), the trip number, and an identifier for the individual conflict. (These three indexes can be used to find the conflict in Appendix A. The first three digits of the identifier in this appendix correspond to the identifier in the third column of the table in Appendix A.) The plot includes both the lateral acceleration measured at the steer axle and the calculated lateral acceleration based on speed and yaw rate. The measured acceleration was used in the conflict analysis.

The two plots in the lower left corner are from the lane tracker that was on the trucks but not an official part of the FOT. The uppermost plot on the right side is the speed of the vehicle in kilometers per hour. These units can be converted into miles per hour by multiplying kilometers by 5/8.

The plot below the speed plot is the instantaneous path curvature as a function of time. This indicates how tight a turn the vehicle was making. Curvature is the inverse of the radius of the curve. As a turn gets tighter and its radius of curvature decreases, the curvature increases. In both the lateral acceleration and curvature plots, negative values indicate a turn to the right and positive values a turn to the left.

The plot in the lower right is the GPS data recorded by the vehicle during the conflict. It is important to note that the conflict always begins at the origin of this plot because, unlike the other plots, this plot does not move from left to right over time. This plot provides a bird's-eye view of the vehicle path during the conflict and is very helpful to understand what occurred during the conflict. The shapes into which the conflicts are grouped in this appendix and the Curve Shape column in Appendix A are characterizations of the shapes in this window.

Interpretation of the conflict requires relating what is taking place in several plots at the same time. A first step is to understand the state of the vehicle at the beginning of the plotted conflict. At the beginning of the plots shown on the following page, the vehicle is traveling fairly straight; the lateral acceleration and curvature both being near zero. The vehicle is also traveling at a relatively high rate of speed (approximately 66 kph or 41 mph), but is decelerating.



Graphs
Tractor 3 Trip 568
Conflict – 700200 , 700800
Ay
Ay Calculated
Ay and Ay Calc
Time
Test Time
700200
Speed
X Axis
Curvature, 1/m
Left Wheel
Right Wheel
Latitude
Longitude
Weight:
35.6
Visibility:
10
Wiper Intensity:
0
Peak Rollover Index:
0.37
Conflict Number
0
1
2
3
4
5
6
Bogus
Skip
Accept
Rollover
SVRD

The vehicle then makes a right turn while maintaining or slightly increasing its speed. This turn is shown in the GPS plot as only a slight turn of less than 90 degrees. The vehicle then makes a sustained left turn of nearly constant radius. This turn appears as a plateau from roughly 15 s to 30 s in both the lateral acceleration and the curvature plots. The speed during this left turn is relatively constant.

After the sustained left turn, the vehicle travels straight for a short distance. This is indicated in the curvature and lateral acceleration plots by a return of the plot to near zero values. This straight section occurs from roughly 30 s to 40 s. The speed plot during the time shows a slight deceleration of the vehicle.

The vehicle then makes another left turn, less severe than the previous one, both because the vehicle is traveling a little slower at this time as shown in the speed plot, and because the turn is not as tight as shown in the curvature plot. Both of these factors influence the lateral acceleration which is significantly lower than during the previous left turn. By the end of this second left turn which occurs from roughly 40 s to 55 s, the speed of the vehicle has decreased significantly. The speed of the vehicle continues to decrease as the vehicle straightens out and eventually stops at about 66 s as shown in the speed plot. This conflict took place on an off ramp at an interchange as the vehicle was leaving the freeway.

Other items on the figures are not relevant to the present report. At the right of the figures, “Weight” is the mass of the total vehicle in metric tons as calculated by the FOT partnership. “Wiper Intensity” indicates whether the tractor’s windshield wipers were operating at the time of the conflict. A value of 0 means they were off, 1 means they were on low speed, and 2 means they were on high speed. A fractional value indicates an intermittent setting. “Peak rollover index” is a preliminary measure of the conflicts severity, as defined in Equation (4-1) of the FOT evaluation report. The “Visibility” was intended to be an indication of weather conditions at the time of the conflict, but the data proved to be more difficult to gather than first expected, so the field was not used. The “Conflict Number” scroll bar, the two circular indicators in the lower right, and the three buttons under the GPS map were all intended for internal use by Battelle in classifying the conflicts, and they do not present any information about the conflicts.


USGS

# Appendix C

# VDANL Vehicle and Trailer Characterization Data

# Appendix C

## VDANL Vehicle and Trailer Characterization Data

Several input files are required for using VDANL for simulation of vehicles. These input files are described in a particular format and each file contains input information on one or more aspects of the vehicle that is being modeled. The standard vehicle and trailer files contain information that includes vehicle and trailer sprung and unsprung mass and inertia values, wheelbase, track width and center of gravity locations. A detailed description of the input parameters required for VDANL can been seen in (Allen, R.W., et al. (1992), "Vehicle Dynamics Stability and Rollover," Final Report on NHTSA Contract DTNH22-88-C-07384). The vehicle and trailer input files used in this program have been included in this appendix. The vehicle file (Table C-1) remains the same for the fully loaded and partially loaded cases. However, the trailer files (Tables C-2 and C-3) are different for the two cases and they are reflected in the sprung mass weights, inertias, and the center of gravity locations.

In addition to the vehicle and trailer files, the other input files are used for defining engine and drive train aspects of the vehicle, vehicle tire parameters, and vehicle driver model parameters. A complete description of the data parameters are provided in Table C-4.

## Table C-1. Vehicle Parameters

```
V.MASS = 515
V.SMASS = 350
V.UMASSF = 35
V.UMASSR = 130
V.VLENA = 4.5
V.VLENB = 11
V.IXS = 5076
V.IYS = 16023
V.IXZ = 0
V.IZZ = 30000
V.KSTR = 15.45
V.KSCF = 0.000038
V.KSCB = 0
V.DLADV = 0
V.DNADV = 0
V.DYADV = 0
V.DENSITY = 0.00237
V.REFAREA = 0
V.CDX = 0.4
V.AEROVEL = 44
V.KSAF = 1
V.KSAR = 1
V.KSF = 16000
V.KSR = 87800
V.KSDF = 423
V.KSDR = 864
V.TRWF = 7.5
V.TRWR = 7.5
V.HF = 0.225
V.HR = -0.117
V.HCG = 2.92
V.KTSF = 501340
V.KTSR = 1193300
V.KRASF = 120000
V.KRADPF = 3000 % 7000
V.KRADCFF = 0
V.KRADCFDF = 0
V.KRASR = 120000
V.KRADPR = 5000 % 7000
V.KRADCFR = 0
V.KRADCFDR = 0
V.HRAF = 1.6
V.HRAR = 2.56
V.HS = 3.34
V.IXUF = 500
V.IXUR = 1250
V.XACC = 0
V.ZACC = 0
V.KBTF = -57.21
V.KVB = 1.4
V.KMB = 1.4
V.FBPVL = 100
V.SWW = 100
V.SWZ = 0.9
V.KCF = -0.000001
V.LSO = 0
V.BRAKPROP1 = -80
V.BRAKPROP2 = -200
V.FXLIMIT = 0
V.DAMPCOMF = 800
V.DAMPEXTF = 800
V.DAMPCOMR = 2000
V.DAMPEXTR = 2000
V.AIRBRAKES = 1
V.BRAKLAG1 = 0.31
V.BRAKLAG2 = 0.35
V.ANTIBF = 0
V.ANTIBLIMF = 0
V.KANTIBF = 0
V.ANTIBR = 0
V.ANTIBLIMR = 0
V.KANTIBR = 0
```

## Table C-2.  Full Trailer Parameters

```
TR.MASS = 1990
TR.SMASS = 1890
TR.UMASSF = 50
TR.UMASSR = 50
TR.VLENA = -15
TR.VLENB = 19
TR.IXS = 18200
TR.IYS = 317200
TR.IXZ = 0
TR.IZZ = 320000
TR.KSCF = 0
TR.KSCB = 0
TR.DLADV = 0
TR.DNADV = 0
TR.DYADV = 0
TR.DENSITY = 0
TR.REFAREA = 0
TR.CDX = 0
TR.AEROVEL = 0
TR.KSF = 215840
TR.KSDF = 864
TR.KSR = 208000
TR.KSDR = 864
TR.TRWF = 7.5
TR.TRWR = 7.5
TR.HCG =7.1
TR.KTSF = 2568000
TR.KTSR = 2187000
TR.KRASF = 120000
TR.KRADPF = 7000
TR.KRADCFF = 0
TR.KRADCFDF = 0
TR.KRASR = 120000
TR.KRADPR = 7000
TR.KRADCFR = 0
TR.KRADCFDR = 0
TR.HRAF = 2.4
TR.HRAR = 2.28
TR.HS = 7.36
TR.IXUF = 570
TR.IXUR = 570
TR.XACC = 0
TR.ZACC = 0
TR.KCF = 0
TR.LSO = 0
TR.DAMPCOMF = 2200 %0
TR.DAMPEXTF = 2200 %0
TR.DAMPCOMR = 2200 %0
TR.DAMPEXTR = 2200 %0
%TR.BRAKPROP1 = 200
%TR.BRAKPROP2 = 200
TR.BRAKLAG3 = 0.42
TR.LEND = 10.5
TR.LENE = 17
TR.THH= 3.6
TR.HITCHSP = 600000
TR.HITCHSPD = 7000
TR.KTFIFTH = 1146000
TR.KFADE = 0.0005
TR.NDRWHL = 4
TR.NTRWHL = 2
TR.ANTIBF = 0
TR.ANTIBLIMF = 0
TR.KANTIBF = 0
TR.ANTIBR = 0
TR.ANTIBLIMR = 0
TR.KANTIBR = 0
TR.SUSPENSIONF = 1
TR.SUSPENSIONR = 1
TR.HF = 0.035
TR.HR = 0.169
TR.LF = 1
TR.LR = 1
TR.KSAF = 0
TR.KSAR = 0
TR.BF = 0
TR.BR = 0
TR.CF = 0
TR.CR = 0
TR.DF = 0
TR.DR = 0
TR.EF = 0
TR.ER = 0
TR.KSLF = 0
TR.KSLR = 0
TR.LSAF = 1
TR.LSAR = 1
TR.KSADF = 0
TR.KSADR = 0
TR.KSAD2F = 0
TR.KSAD2R = 0
TR.KBSCF = 600000
TR.HBSCF = 0.2
TR.SBSCF = 1E+20
TR.KBSEF = 600000
TR.HBSEF = 0.2
TR.SBSEF = 1E+20
TR.KBSCR = 600000
TR.HBSCR = 0.2
TR.SBSCR = 1E+20
TR.KBSER = 600000
TR.HBSER = 0.2
TR.SBSER = 1E+20
```

**Table C-3. Partial Trailer Parameters**

```
TR.MASS = 1400
TR.SMASS = 1300
TR.UMASSF = 50
TR.UMASSR = 50
TR.VLENA = -15
TR.VLENB = 19
TR.IXS = 12460
TR.IYS = 217160
TR.IXZ = 0
TR.IZZ = 218000
TR.KSCF = 0
TR.KSCB = 0
TR.DLADV = 0
TR.DNADV = 0
TR.DYADV = 0
TR.DENSITY = 0
TR.REFAREA = 0
TR.CDX = 0
TR.AEROVEL = 0
TR.KSF = 215840
TR.KSDF = 864
TR.KSR = 208000
TR.KSDR = 864
TR.TRWF = 7.5
TR.TRWR = 7.5
TR.HCG = 5.7
TR.KTSF = 2568000
TR.KTSR = 2187000
TR.KRASF = 120000
TR.KRADPF = 7000
TR.KRADCFF = 0
TR.KRADCFDF = 0
TR.KRASR = 120000
TR.KRADPR = 7000
TR.KRADCFR = 0
TR.KRADCFDR = 0
TR.HRAF = 2.4
TR.HRAR = 2.28
TR.HS = 6.1
TR.IXUF = 570
TR.IXUR = 570
TR.XACC = 0
TR.ZACC = 0
TR.KCF = 0
TR.LSO = 0
TR.DAMPCOMF = 2200 %0
TR.DAMPEXTF = 2200 %0
TR.DAMPCOMR = 2200 %0
TR.DAMPEXTR = 2200 %0
%TR.BRAKPROP1 = 200
%TR.BRAKPROP2 = 200
TR.BRAKLAG3 = 0.42
TR.LEND = 10.5
TR.LENE = 17
TR.THH= 3.6
TR.HITCHSP = 600000
TR.HITCHSPD = 7000
TR.KTFIFTH = 1146000
TR.KFADE = 0.0005
TR.NDRWHL = 4
TR.NTRWHL = 2
TR.ANTIBF = 0
TR.ANTIBLIMF = 0
TR.KANTIBF = 0
TR.ANTIBR = 0
TR.ANTIBLIMR = 0
TR.KANTIBR = 0
TR.SUSPENSIONF = 1
TR.SUSPENSIONR = 1
TR.HF = 0.035
TR.HR = 0.169
TR.LF = 1
TR.LR = 1
TR.KSAF = 0
TR.KSAR = 0
TR.BF = 0
TR.BR = 0
TR.CF = 0
TR.CR = 0
TR.DF = 0
TR.DR = 0
TR.EF = 0
TR.ER = 0
TR.KSLF = 0
TR.KSLR = 0
TR.LSAF = 1
TR.LSAR = 1
TR.KSADF = 0
TR.KSADR = 0
TR.KSAD2F = 0
TR.KSAD2R = 0
TR.KBSCF = 600000
TR.HBSCF = 0.2
TR.SBSCF = 1E+20
TR.KBSEF = 600000
TR.HBSEF = 0.2
TR.SBSEF = 1E+20
TR.KBSCR = 600000
TR.HBSCR = 0.2
TR.SBSCR = 1E+20
TR.KBSER = 600000
TR.HBSER = 0.2
TR.SBSER = 1E+20
```

## Table C-4. Table of Parameters, their Units and Definition

| Data Parameter | Units | Definition |
|---|---|---|
| V.VLENA | ft | X distance from $m_s$ c.g. to front axle |
| V.REFAREA | $ft^2$ | Frontal area of vehicle, used for longitudinal drag |
| V.VLENB | ft | X distance from $m_s$ c.g. to rear axle |
| V.BF, V.BR | 1/ft | First order coefficient for change in wheel steer angle with suspension deflection |
| V.CF, V.CR | $1/ft^2$ | Second order coefficient for wheel steer with suspension deflection |
| V.CDX | | Longitudinal drag coefficient |
| V.DF,V. DR | 1/ft | First order coefficient for change in wheel camber angle, with suspension deflection |
| V.EF, V.ER | $1/ft^2$ | Second order coefficient for wheel camber angle with suspension deflection |
| V.HF, V.HR | ft | $l_i$ times slope of trailing link in trailing arm suspension |
| V.HCG | ft | c.g. height of total mass |
| V.HRAF, V.HRAR | ft | Height of roll axis above ground for solid axle suspension |
| V.HS | ft | $m_s$ c.g. height above ground |
| V.IXS | lb-ft-$sec^2$ | Moment of inertia for sprung mass in roll |
| V.IXZ | lb-ft-$sec^2$ | Cross product of inertia for sprung mass about x-z axis |
| V.IXUF, V.IXUR | lb-ft-$sec^2$ | Moment of inertia for unsprung mass about X axis |
| V.IYS | lb-ft-$sec^2$ | Moment of inertia for sprung mass about y axis |
| V.IZZ | lb-ft-$sec^2$ | Moment of inertia for entire mass about z axis |
| V.KACK | ft/ft | Ackerman steer coefficient |
| V.KCF | rad/sec | Lateral force steering compliance for suspension and steer linkage |
| V.KRADPF, V.KRADPR | lb-sec/ft | Damping rate at compliant pin joint between $m_s$ and $m_u$ |
| V.KRASF, V.KRASR | lbs/ft | Lateral spring rate at compliant pin joint between $m_s$ and $m_u$ |
| V.KSAF, V.KSAR | | = 1.0 for solid axle, = 0.0 for independent suspension |
| V.KSADF, V.KSADR | ft/ft | Anti dive coefficient, or slope in side view of an equivalent single suspension arm |
| V.KSAD2F, V.KSAD2R | ft/ft | Special case for $k_{sadi}$ when there is positive $f_x$ with independent suspension |
| V.KSF, V.KSR | lbs/ft | Suspension spring rate equivalent at each wheel |
| V.KSCF, V.KSCB | rad-lbs/ft | Steering compliance for steering gear |
| V.KSDF, V.KSDR | lbs-sec/ft | Suspension damping rate equivalent at each wheel |

| Data Parameter | Units | Definition |
|---|---|---|
| V.KSLF, V.KLSR | ft/ft | Lateral slope of an equivalent single suspension arm, at curb load |
| V.KSTR | rad/rad | Overall steering ratio |
| V.KTSF, V.KTSR | ft-lbs/rad | Auxiliary torsional roll stiffness per axle, (normally negative) |
| V.LF, V.LR | ft | Length of trailing link, in a trailing arm suspension |
| V.LSAF, V.LSAR | ft | Length of the $k_{slj}$ arm |
| V.LSO | ft | Lateral steering axis offset from king pin to tire patch center (positive if tire c.l. is outside king pin axis) |
| V.MASS | slugs | Total vehicle mass |
| V.SMASS | slugs | Sprung mass |
| V.UMASSF, V.UMASSR | slugs | Front, or rear, unsprung mass |
| V.TRWF, V.TRWR | ft | Track width |
| V.SWW | rad/rad | Natural frequency for second order steering system lag |
| V.SWZ | | Damping ratio for steering system lag |
| V.DLADV | ft-lbs/ft/sec | Aerodynamic roll moment coefficient |
| V.DNADV | ft-lbs/ft/sec | Aerodynamic yaw moment coefficient |
| V.DYADV | lbs/ft/sec | Aerodynamic lateral force coefficient |
| V. DENSITY | lbs/ft$^3$ | Air density |
| V. AEROVEL | ft/sec | Aerodynamic reference speed |
| V. XACC | ft | Distance of accelerometer ahead of sprung mass c.g. |
| V. ZACC | ft | Distance of accelerometer above vehicle roll axis |
| V.KBTF | ft-lbs/psi | Front brake effectiveness |
| V.KVB | psi/lbs | Brake gain in vacuum boost range |
| V.KMB | psi/lbs | Brake gain in manual range |
| V.FBPVL | lbs | Pedal force where vacuum boost runs out |
| V.BRAKPROP1 | lbs/lbs, or ft-lbs/psi | Hydraulic: initial f/r brake force slope, air-front axle brake effectiveness |
| V.BRAKPROP2 | lbs/lbs, or ft-lbs/psi | Hydraulic: final f/r brake force slope, air-drive and trailer axle brake effectiveness |
| V.FXLIMIT | lbs | Hydraulic: front brake force at knee in rear vs. front brake force curve (entered as a negative number) |
| V. DAMPCOMF | lbs-sec/ft | Front shock compression damping |
| V. DAMPEXTF | lbs-sec/ft | Front shock rebound or extension damping |
| V. DAMPCOMR | lbs-sec/ft | Fear shock compression damping |
| V. DAMPEXTR | lbs-sec/ft | Fear shock rebound or extension damping |
| V.AIRBRAKES | 0 or 1 | Air brake model flag: 0 - off, 1 - on |
| V.BRAKLAG1 | sec | Front axle brake force time constant |

| Data Parameter | Units | Definition |
|---|---|---|
| V.BRAKLAG2 | sec | Drive axle brake force time constant |
| V.BRAKLAG3 | sec | Trailer axle brake force time constant |
| V.ANTIBF | 0 or 1 | Front axle anti-lock brake flag:  0 - off, 1 - on |
| V. ANTIBLIMF | - | Longitudinal slip ratio limit where the anti-lock braking routine for the front turns on and off |
| V. KANTIBF | ft-lbs/s | Anti-lock braking gain for front the brakes |
| V.ANTIBR | 0 or 1 | Rear axle anti-lock brake flag:  0 - off, 1 - on |
| V. ANTIBLIMR | - | Longitudinal slip ratio limit where the anti-lock braking routine for the rear turns on and off |
| V. KANTIBR | ft-lbs/s | Anti-lock braking gain for rear the brakes |
| TR. LEND | ft | Distance from vehicle sprung mass c.g. to hitch |
| TR. LENE | ft | Distance from trailer sprung mass c.g. to hitch |
| TR.THH | ft | Trailer hitch height above ground |
| TR. HITCHSP | lbs/ft | Hitch deflection spring stiffness |
| TR. HITCHSPD | lbs-sec/ft | Hitch deflection damping |
| TR.KTFIFTH | ft-lbs/rad | Hitch torsional stiffness |
| TR.KFADE | %/°f | Brake temperature fade parameter |
| TR.NDRWHL | # | Number of tires at each end of drive axle |
| TR.TDRWHL | # | Number of tires at each end of trailer axle |
| V.SUSPENSIONF | 0 or 1 | Front suspension type:  0 - solid axle, 1 - independent |
| V.SUSPENSIONR | 0 or 1 | Rear suspension type:  0 - solid axle, 1 - independent |
| $V.KBSC_j$ | lb/ft | Compression bump stop stiffness |
| $V.HBSC_j$ | ft | Compression bump stop contact point |
| $V.SBSC_j$ | - | Compression bump stop transition term |
| $V.KBSE_j$ | lb/ft | Extension bump stop stiffness |
| $V.HBSE_j$ | ft | Extension bump stop contact point |
| $V.SBSE_j$ | - | Extension bump stop transition term |
| TIRE(#).TWIDTH | ft | Tire contact patch width |
| TIRE(#).KA0 | lbs/rad | Cornering stiffness vs. load constant term |
| TIRE(#).KA1 | 1/rad | Cornering stiffness vs. load linear term |
| TIRE(#).KA2 | lbs | Cornering stiffness vs. load squared term |
| TIRE(#).KA3 | 1/rad | Camber stiffness vs. load linear term |
| TIRE(#).KA4 | lbs | Camber stiffness vs. load squared term |
| TIRE(#).KA | – | Contact patch elongation with fx |
| TIRE(#).KX | – | Change in cornering stiffness with fx |
| TIRE(#).KMUY | – | Decay in lateral friction with increasing slip angle |
| TIRE(#).TPRES | psi | Tire inflation pressure |
| TIRE(#).KB1Y | 1/lbs | Peak lateral friction vs. load linear term |
| TIRE(#).KB3Y | – | Peak lateral friction vs. load constant term |

| Data Parameter | Units | Definition |
|---|---|---|
| TIRE(#).KB4Y | $1/lbs^2$ | Peak lateral friction vs. load squared term |
| TIRE(#).KGAMMA | – | Falloff of camber thrust at high slip |
| TIRE(#).CSFZ | – | Normalized longitudinal tire force stiffness |
| TIRE(#).MUNOMY | – | Lateral friction of vehicle test surface |
| TIRE(#).MUNOMX | – | Longitudinal friction of vehicle test surface |
| TIRE(#).FZTRL | lbs | Tire design load |
| TIRE(#).KK1 | ft/lbs | Aligning torque stiffness vs. load |
| TIRE(#).C1 | – | Shaping coefficient, c1, for force saturation function (-) |
| TIRE(#).C2 | – | Shaping coefficient, c2, for force saturation function (-) |
| TIRE(#).C3 | – | Shaping coefficient, c3, for force saturation function (-) |
| TIRE(#).C4 | – | Shaping coefficient, c4, for force saturation function (-) |
| TIRE(#).C5 | – | Shaping coefficient, c5, for force saturation function (-) |
| TIRE(#).G1 | – | Aligning moment shaping parameter, g1 |
| TIRE(#).G2 | – | Aligning moment shaping parameter, g2 |
| TIRE(#).TLONGLAG | sec | Longitudinal slip ratio time constant |
| TIRE(#).PLYSTEER | rad | Slip angle offset for zero lateral tire force |
| TIRE(#).KB1X | 1/lbs | Peak longitudinal friction vs. load linear term |
| TIRE(#).KB3X | - | Peak longitudinal friction vs. load constant term |
| TIRE(#).KB4X | $1/lbs^2$ | Peak longitudinal friction vs. load squared term |
| TIRE(#).KMUX | – | Decay in longitudinal friction with increasing slip |
| TIRE(#).DRAGC | – | Rolling drag coefficient |
| TIRE(#).BRAKMULT | – | Brake torque multiplier |
| TIRE(#).STIFFNESS | lbs/ft | Vertical spring rate of tire |
| TIRE(#).DAMPING | lbs-sec/ft | Vertical damping rate of tire |
| TIRE(#).KTL | ft | Tire lag, expressed in rolling distance |
| TIRE(#).KLT | ft/lb | Lateral compliance rate, of tire, wheel, and suspension, per tire |
| TIRE(#).RR | ft | Effective wheel/tire radius, and same as c.g. height of $m_{ui}$ |
| DRT.KDC | – | Center differential gear ratio |
| DRT.KDF | – | Front differential gear ratio |
| DRT.KDB | – | Rear differential gear ratio |
| DRT. KCP | $\frac{ft \cdot lbs \cdot sec}{rad}$ | Center viscous coupling pressure coefficient |
| DRT. KCPF | $\frac{ft \cdot lbs \cdot sec}{rad}$ | Front viscous coupling pressure coefficient |

| Data Parameter | Units | Definition |
|---|---|---|
| DRT. KCPB | $\frac{ft \cdot lbs \cdot sec}{rad}$ | Rear viscous coupling pressure coefficient |
| DRT.KRF | - | Front torque split differential coefficient |
| DRT.KRB | - | Rear torque split differential coefficient |
| DRT.KE$_{K=1\ TO\ 6}$ | - | Coefficients for the engine torque curve |
| DRT.KTC0 | $\frac{rad}{ft \cdot lbs \cdot sec}$ | Torque converter coefficient |
| DRT.SR0 | - | Torque converter stall ratio |
| DRT.ENGINEI | ft-lbs-sec$^2$ | Engine rotary inertia |
| DRT. TRANSMISSIONI | ft-lbs-sec$^2$ | Transmission rotary inertia |
| DRT.SHIFTTIME | sec | Time interval for transmission gear shift |
| DRT.SPEEDK1 | $\frac{throttle}{\Delta V_{ERROR}}$ | Proportional automatic speed control gain |
| DRT.SPEEDK2 | $\frac{throttle}{\int \Delta V_{ERROR}}$ | Integral automatic speed control gain |
| DRT.IDLE | rad/sec | Engine idle speed |
| DRT.DIFFTYPE | - | Center differential type, choices: 1 - limited slip differential, 2 - locked differential |
| DRT.DG(K), $_{K=1\ TO\ 10}$ | - | If the center differential is locked, then dg(1) is the drive shaft spring stiffness in ft-lbs-sec^2, and dg(2) is the drive shaft damping in ft-lbs-sec/rad otherwise all are zero |
| DRT. TRANSMISSION | 0 or 1 | 0 - Automatic transmission, 1 - Manual transmission |
| DRT.NUMGEAR | - | Number of transmission gear ranges (max=20) |
| DRT. DOWNSHIFT | rad/sec | Downshift threshold |
| DRT.KGR(K), $_{K=-1\ TO\ 20}$ | - | Gear ratios (-1 is reverse) |
| DRT.KT1(K), $_{K=1\ TO\ 20}$ | rad/sec | Minimum upshift speed from gear k to k+1 |
| DRT.KT2(K), $_{K=1\ TO\ 20}$ | rad/sec | Maximum minus minimum upshift speed k to k+1 |
| DRT.GEARBYTE(K), $_{K=-1\ TO\ 20}$ | 0 to 255 | Byte value of input port used to read current gear number |
| DRI.TAUA | sec | The driver's look ahead distance reaction time delay |
| DRI.TAUR | sec | The motion feedback time delay |
| DRI.KY | 1/(ft-sec$^2$) | Trim loop gain |
| DRI.KR | - | Motion feedback gain (yaw rate feedback gain) |
| DRI.TL | sec | Driver curvature error lead compensation term |
| DRI.KPSI | ft/sec | Steering loop yaw rate command gain |
| DRI.ZN | - | The damping ratio of the driver's neuromuscular dynamics |

| Data Parameter | Units | Definition |
|---|---|---|
| DRI.WN | rad/sec | The frequency of the driver's neuromuscular dynamics |
| DRI.KA | 1/sec | The driver's look ahead distance constant ($x_a = k_a*u$) |
| DRI.KBDSW | - | Beta to steering wheel compensation gain |
| DRI.THROTTLEMAX | - | Maximum throttle input |
| DRI. KBDDSW | sec | Beta rate to steering wheel compensation gain |
| DRI.FBKAY | | Collision avoidance feedback loop gain |
| DRI.KYDOT | sec | Lane position rate feedback gain |
| DRI.KSTABF | rad/ft/sec$^2$ | Vehicle's stability factor |
| DRI.AYD | ft/sec$^2$ | 3d terrain desired cornering ay |
| DRI.SPEEDLIMIT | ft/sec | 3d terrain speed limit |
| DRI.KCPRIME | | 3d terrain trim integrator gain |
| DRI.KCVELM | | 3d terrain proportional throttle gain multiplied by mass |
| DRI.KSFF | | 3d terrain steering feed forward gain |
| DRI.TAUB | sec | 3d terrain braking time delay |
| DRI.KFBP | lbs/throttle | 3d terrain braking gain |
| DRI.KAS | sec | 3d terrain driver steering look ahead time |
| DRI.KAB | sec | 3d terrain driver speed control look ahead time |
| DRI.YC | ft | 3d terrain commanded lane position |
| NL.SMI | - | Wheel spin mode integration rate multiplier |
| NL.IYW | lb ft sec$^2$ | Wheel inertia about spin axis |
| NL.DSWMAX | rad | Maximum value the steering wheel may be turned in either direction |
| NL. BRAKTMAX | lbs | The maximum limiting brake pedal force |
| NL.SIUNITS | 0 or 1 | Flag for plotting and saving data in si units: 0 - u.s., 1 - si |
| NL.SAVERATE | Hz | Output data save rate |
| NL.ROLLOVER | rad | Vehicle roll angle where simulation stops |
| NL.DISTPLOT | 0 or 1 | Change plotting and saving data from time base to distance based: 0 - time, 1 - distance |
| NLSAVEtoDISK | 0 or 1 | Change variable storage from RAM (0) to DISK (1). Use disk for long runs to avoid using up memory |
| NL.TERLAGDIST | ft | Distance used for first order terrain height lag |

U.S. Department of Transportation
**Federal Motor Carrier Safety Administration**

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