Observational Validation of the SIMON Steer Degree-of-Freedom Model: A Case Study

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INTRODUCTION

An accident occurred near Eureka Springs, AR, in which a motorhome rolled out of control down an embankment, across a flat basin, and into a vertical cliff face, resulting in a total loss of the vehicle. The owner had been driving the motorhome eastbound through difficult and hilly terrain on a US highway. He claims to have experienced some problems with the brakes and was barely able to bring the vehicle to a stop on the eastbound shoulder. He decided to take his Jeep, which was attached to the rear of the motorhome, into Eureka Springs to look for a mechanic to repair his brakes. Shortly after setting his parking brake and detaching his Jeep from the motorhome the brakes were claimed to have failed completely and the motorhome rolled freely down the embankment. Numerous photographs were taken documenting the position of the Jeep at the detachment location and the position of the motorhome at point of rest.

Upon further inspection, the motorhome's brakes, which were S-Cam air brakes with springs, were found to be functioning normally. Furthermore, there was a southbound roadway which formed a T-intersection with the aforementioned eastbound road. The point of rest of the motor home was directly opposite the extended centerline of the southbound road. The owner's story of brake failure described that of a hydraulic system, which was not on the motorhome. Thus the police, wrecker driver, and claims agent all suspected that the vehicle had been started into the drainage basin deliberately from the southbound road with nobody inside to attempt braking. In other words, there was every reason to believe that was a case of insurance fraud.

The office of Cline Young, Consulting Engineer was contacted and asked to determine how a driverless vehicle would perform under the various slopes and grades. More specifically, the question that was posed dealt directly with determining if the motor home were indeed initially parked parallel to the drainage basin, on the eastbound shoulder of the US highway, or had it begun its travel on the intersecting southbound roadway.

BACKGROUND

Sir Isaac Newton's Second Law is the foundation of vehicle dynamics and numerical analysis regarding the three dimensional motion of rigid bodies. There are six degrees of freedom for each mass in the model. Constraints can be applied to reduce the number of degrees of freedom such as a given steering wheel angle. The model being used in this paper is explained elsewhere so it will not be explained here. The reader is referred to [1]. For a more simplified explanation in two dimensions, complete with the development of the equations of motion and the necessary subroutines for tire forces, the reader might reference [2].

In most cases when SIMON is being used, steering input is done in the form of a table and is under the control of the "driver". In this situation there was no driver onboard, so the steering angle then becomes a result of the applied forces and moments. In short, it needs to be calculated as a new degree-of-freedom, hence the name, "Steer Degree-of-Freedom" or SDOF. If it were not for the steering inertias and internal frictions, it could be described as the "Steer Path-of-Least-Resistance."

TECHNIQUE

First, the police report, witness statements and the scene photographs were studied to identify important topographical features that needed to be mapped. Those included road signs, intersection of two roads, surface grades, slope discontinuities and impact point.

Second, a site inspection was performed and the site was photographed and mapped with a TOPCON GPS Total Station paying due attention to the aforementioned topographical features.

Third, the motor home was inspected and wheelbase measured with overhangs front and rear. The crush too was measured. The crush on the driver's side measured to be 4 inches. On the passenger's side it was 20 inches. There was no displacement of the front axle on the driver's side but about 5 inches of displacement on the passenger's side. The tires were type Michelin X Pilote XZA1 295/80R22.5. Extensive measuring and testing of the brakes (the primary purpose for the inspection) took place but since that has no contribution to make to the purpose of this paper the data and discussion will be omitted. The rear overhang was also damaged due to the sudden and steep change in the topography at the bottom of the slope.

Fourth, a three dimensional terrain model was created using the TOPCON GPS data and AutoCAD 2006.

Figure 1: *Jeep in spot where motorhome was unhitched and motorhome at point of rest*

Figure 2: *View from the east of the vehicles at POR*

Figure 3: *View of the southbound centerline at intersection with eastbound road*

Figure 4: *Front damage on motorhome due to impact with cliff face*

Figure 5: *Rear overhang damage due to discontinuity between slope and basin bottom*

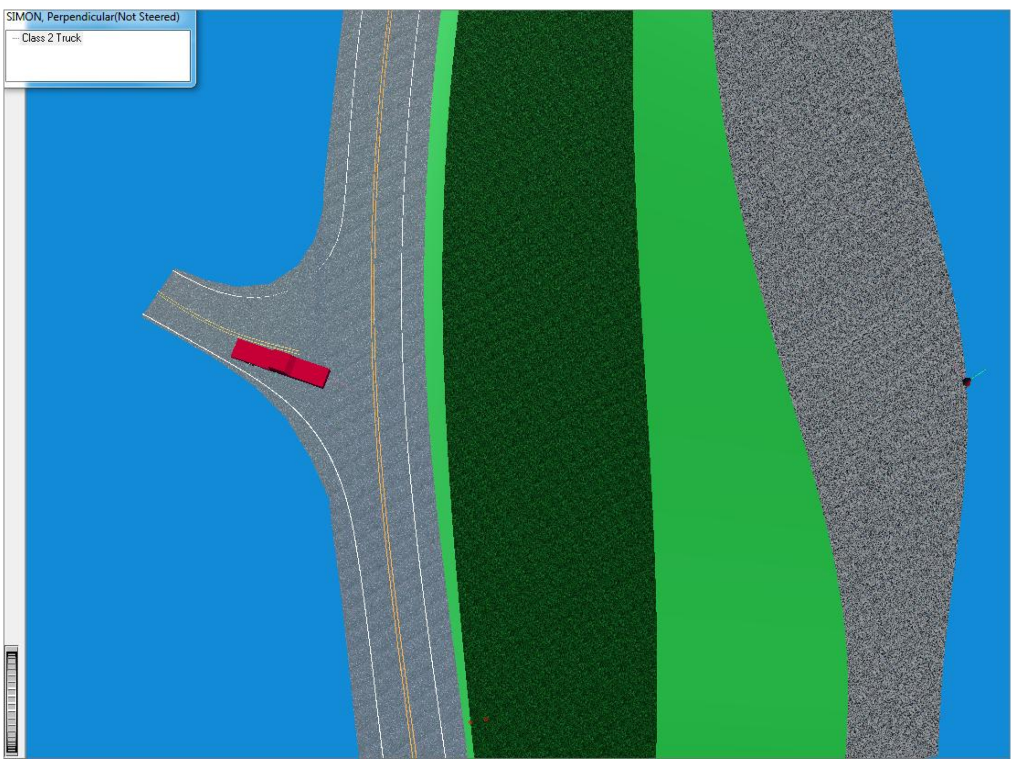

Figure 6: *Aerial view of the intersection with the RV on the intersecting roadway, with cone on the far right marking the point of impact of the RV with the cliff face*

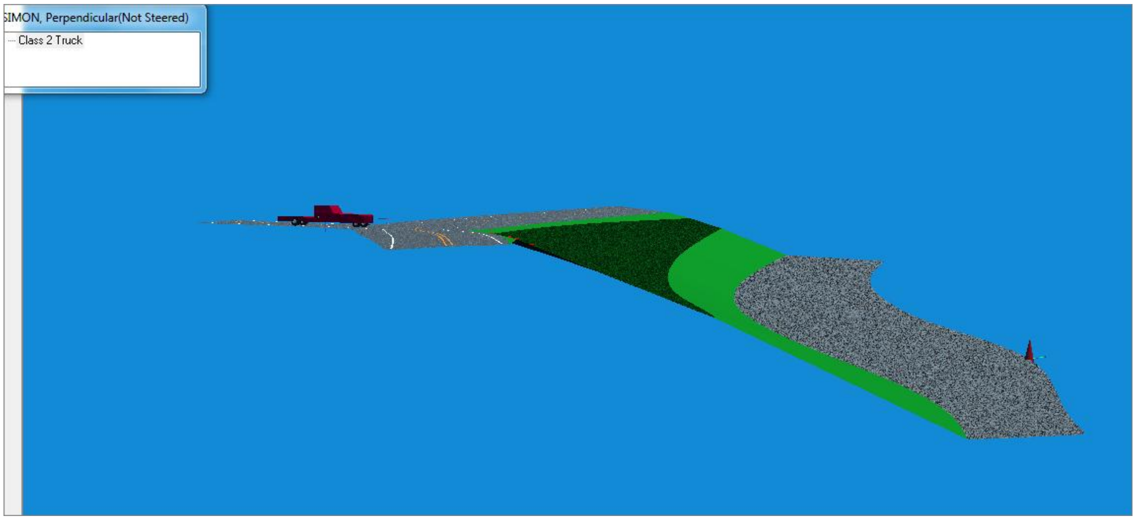

Figure 7: *Ground level view from the roadway showing elevation change of the slope to the basin*

The terrain model may be described as follows:
The cross slope grade from the intersecting roadway to the point of cliff impact at the "cone" varied from 34% to 47% over a distance of roughly 180 feet.
The total elevation change was approximately 66 feet.
The basin had a downstream slope of 0.8% and the roadway had a 7.8% downgrade.

Since there are no preset Recreational Vehicle models currently in HVE, the motorhome was modeled using a generic Class 2 Truck body. All values were left at default except for the following modifications:

CG to Front Axle (in): 191.99
Front Overhang (in): 48.01
CG to Back Axle (in): 144.00
Rear Overhang (in): 96.00
Wheelbase (in): 335.99

The complete set of Vehicle Data parameters can be found in the Appendix.

Since this particular case happened to be one where no driver was involved, the use of the Steer Degree-of-Freedom (SDOF) model in SIMON was clearly the best option. Three simulations were created in order to test the potential starting point for the motorhome: (1) motorhome begins motion at intersecting street, (2) motorhome begins motion at the road sign and parallel to the US highway, and (3) motorhome begins motion at three degrees right from parallel to the US highway. The purpose of the first was to test the police theory of the accident. The second was to check the feasibility of the owner's story. The third and final was to see what was needed to match the final impact spot perfectly. For each of the three simulations the SDOF was set at "normal" so that the steering table was completely ignored and the steering angle became a calculated value.

RESULTS

When the motorhome was placed at the intersecting southbound roadway and then allowed to free roll, the downgrade of the slope turned the motorhome to its left (eastward) and away from the desired impact area with the cliff. The simulation shows the motorhome striking the cliff about 131 feet east of the cone.

When the motorhome was allowed to free roll from a position parallel to the eastbound roadway, the cross slope of 34% to 47% dominated the motion by turning the vehicle to the right (southward). The 7.8% downgrade of the roadway also directs the vehicle a little too far eastward before it hits the cliff face, missing the cone by about 49 feet to the east.

When the motorhome was angled 3 degrees to the right at its starting position and then allowed to free roll almost parallel to the eastbound roadway, it turned in the same manner as described in #2 but impacted the cliff face in the correct spot on top of the cone.

CONCLUSIONS

The scene photographs clearly show the position from which the motorhome started and its position at point of rest. There was no observable path of travel in between the two points but a high level of accuracy was not required in this case in order to answer the question of starting position.

Contrary to the beliefs of the police, wrecker driver, and claims agent, the motorhome clearly did not start from the intersecting roadway headed straight south in a driverless fashion. The only way it could have arrived at the correct impact spot from there was if it had been steered, but there was clear evidence that no one was aboard the vehicle as it traversed the various slopes.

The “Steer Degree-of-Freedom” model within SIMON answered the question of “from which direction did the vehicle come” with an unexpectedly high level of accuracy. A heading angle of 3 degrees on the eastbound shoulder was all that was needed to make the vehicle strike the impact area spot. This is consistent with what one would expect of a vehicle that had been driven off of the roadway and brought to a complete stop in a controlled fashion before being allowed to free roll into the basin.

The 3 degree Off Parallel simulation shows the motorhome striking the cliff face at about 38 mph. Since a crush data database regarding Recreational Vehicles does not currently exist, it is difficult to confirm this speed with the damage seen in the photographs. However, this final velocity is not unreasonable to assume given the downgrade of the slope and lack of any braking. It could be useful for EDC to being collecting anecdotal data from cases such as this involving crush on heavy vehicles.

Our goal was to use the SDOF model to make an initial determination, not necessarily with a high degree of accuracy, of whether the motorhome's initial position was on the southbound or eastbound road. In a somewhat surprising result, we actually did achieve a high level of accuracy using the SDOF model and a 3 degree offset, which resulted in a simulation of the motorhome striking the cliff in precisely the correct spot.

REFERENCES

1. Day, T.D., Roberts, S.G. and York, A.R., "SIMON: A New Vehicle Simulation Model for Vehicle Design and Safety Research," SAE Paper No. 2001-01-0503, 2001.

2. Young, C.T., "A Preliminary Study of the Effects of a Front Wheel Steering Stabilizer and of Fifth Wheel Anti-Jackknifing Devices on Articulated Vehicle Response Characteristics," (M.S. Thesis, Oklahoma State University, 1976.)

APPENDIX

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                                                        Thu 10/31/13 10:30:13
Vehicle Data-SIMON, Perpendicular                            HVE Version 9.12
Licensed User: Cline Young                                             PAGE 1

                                 VEHICLE DATA

     General Information ---
                               Vehicle Name:          Class 2 Truck
                               Vehicle Type:             Truck
                               Vehicle Make:             Generic
                              Vehicle Model:             Generic
                               Vehicle Year:             Generic
                         Vehicle Body Style:             Class 2
                                 Version No:   V  5.20 (RCS $Revision: 2.2
                            Number of Axles:                2
                            Driver Location:            Left Side
                            Engine Location:          Front Engine
                              Drive Axle(s):             Axle 2

     Steady-State Handling Properties ---
           Total Understeer Gradient (deg/g):              3.14
          Steering Wheel Sensitivity (deg/g):            274.68
                       Roll Gradient (deg/g):              2.31
       Roll Couple Distribution, F/R (%/100):              0.31
            Weight Distribution, F/R (%/100):              0.41
             Static Weight, Front Tires (lb):           5724.18
              Static Weight, Rear Tires (lb):           8275.82

     Sprung Mass Dimensional Data ---
                        Overall Length (in):             480.00
                         Overall Width (in):              96.00
                        Overall Height (in):             103.35
                      Ground Clearance (in):              21.35
                             Wheelbase (in):             335.99
                      CG to Front Axle (in):             191.99
                       CG to Back Axle (in):            -144.00
                             CG Height (in):              45.35
                        Front Overhang (in):              48.01
                         Rear Overhang (in):              96.00

     Sprung Mass Inertial Data ---
                          Total Weight (lb):           14000.00
                         Sprung Weight (lb):           10666.06
                  Sprung Mass (lb-sec^2/in):              27.60
  Sprg Mass Rot Inertia (lb-sec^2-in) - Roll:           21000.00
                                      Pitch:           50000.00
                                        Yaw:           50000.00
                                 XZ Product:               0.00

     Sprung Mass Aerodynamic Parameters ---
                               Surface Name:              Front
                           Drag Coefficient:             0.7500
                  Proj. Surface Area (in^2):            7084.00
                    Center of Pressure (in) - x:          102.68
                                          y:               0.00
                                          z:               0.00

     Brake System Data ---
                 Brake Pedal Ratio (psi/lb):               1.00

                                 ABS System:         None Installed

     Steering System Parameters ---
      Steering System Friction Lag (deg/sec):              4.30
            Steering Column Friction (in-lb):           1400.00
       Steering Column Inertia (lb-sec^2-in):              0.00
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                                                                Thu 10/31/13 10:30:13
Vehicle Data-SIMON, Perpendicular                                    HVE Version 9.12
Licensed User: Cline Young                                                     PAGE 2

                                  First Axle:            Steerable
               Steering Gear Ratio (deg/deg):              28.00
                   Ackermann Steering Option:               On

                                         Right Side       Left Side
                                         ----------       ----------
                             Caster (deg):       0.00             0.00
                 Inclination Angle (deg):       0.00             0.00
                    Steering Offset (in):       0.00             0.00
                   Stub Axle Length (in):       0.00             0.00
      Initial Steer Axis Coord (in) - x:     191.99           191.99
                                      y:      39.75           -39.75
                                      z:      24.00            24.00
     Steer Axis Friction Torque (in-lb):     300.00           300.00
Total Wheel Steer Inertia (lb-sec^2-in):      73.43            73.43

                         Steering Stops:   (Right)   (Left)  (Right)   (Left)
                       Stop Angle (deg):    35.00   -35.00    35.00   -35.00
             Stop Stiffness (ft-lb/deg):     3.64     3.64     3.64     3.64
                     Stop Damping Ratio:     0.00     0.00     0.00     0.00

                                 Second Axle:          Not Steerable

     Drivetrain Parameters ---
                         Engine Description:       Generic Drivetrain
                          Maximum Power (HP):              350
                      Maximum Torque (ft-lb):             1350
                 Transmission Forward Speeds:               6
                         Differential Speeds:               3

   Wide-open Throttle, Speed (RPM):    200    800   1000   1200   1400   1600   1800   2200
                        Power (HP):     23    183    248    308    350    350    326    168
                    Torque (ft-lb):    600   1200   1300   1350   1313   1149    950    400

      Closed Throttle, Speed (RPM):    200    800   1200   1600   2200
                        Power (HP):     -1    -11    -24    -43    -82
                    Torque (ft-lb):    -26    -71   -107   -142   -196

                 Transmission Type: Manual

                 Transmission Gear:   Rev    1st    2nd    3rd    4th    5th    6th
                   Numerical Ratio:  -4.80   3.51   1.91   1.43   1.00   0.74   0.64

                 Differential Gear:  High   Mid    Low
                   Numerical Ratio:   3.08   3.36   3.58

     Electronic Stability Systems Properties ---

                         (No ESS Systems Installed.)

     Wheel Location Information, First Axle ---
                                         Right Side       Left Side
                                         ----------       ----------
     Initial Wheel Coordinates (in) - x:     191.99           191.99
                                      y:      39.75           -39.75
                                      z:      24.00            24.00

     Suspension Information, First Axle ---
                            Suspension Type:         Solid Axle
         Axle Roll/Yaw Inertia (lb-sec^2-in):           5000.00
              Axle Roll Ctr Ht Below CG (in):             21.00
                   Axle Roll Steer (deg/deg):              0.00
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Lateral Spring Spacing (in):	36.00
Nominal Track Width (in):	79.50
Total Unsprung Weight (Axle+Wheels, lb):	1152.94
Auxiliary Roll Stiffness (in-lb/deg):	0.00

	Right Side	Left Side
Spring Rate (lb/in):	1125.00	1125.00
Viscous Damping (lb-sec/in):	5.00	5.00
Coulomb Friction (lb):	500.00	500.00
Friction Null Band (in/sec):	5.00	5.00
Deflection to Jounce Stop (in):	-5.00	-5.00
Stop Linear Rate (lb/in):	500.00	500.00
Stop Cubic Rate (lb/in^3):	5000.00	5000.00
Stop Energy Ratio (%/100):	0.50	0.50
Deflection to Rebound Stop (in):	5.00	5.00
Stop Linear Rate (lb/in):	500.00	500.00
Stop Cubic Rate (lb/in^3):	5000.00	5000.00
Stop Energy Ratio (%/100):	0.50	0.50
Camber Constant (deg):	0.00	0.00

Tire Information, First Axle ---

	Right Side	Left Side
Tire Name:	Generic	Generic
Tire Manufacturer:	Generic	Generic
Tire Model:	Generic	Generic
Tire Size:	11.00R20H	11.00R20H
Version No:	V 5.20	V 5.20
Unloaded Radius (in):	21.35	21.35
Static Loaded Radius (in):	20.78	20.78
Nominal Width (in):	11.00	11.00
Tread Width (in):	9.90	9.90
Init. Radial Stiffness (lb/in/tire):	5000.00	5000.00
2nd Radial Stiffness (lb/in/tire):	50000.00	50000.00
Defl. @ 2nd Stiffness (in):	9.08	9.08
Max Deflection (in):	11.35	11.35
Rebound Energy Ratio (%/100):	1.00	1.00
Spin Inertia (Tire+Whl+Brk, lb-sec^2-in/	182.21	182.21
Steer Inertia (Tire+Whl+Brk, lb-sec^2-in	73.43	73.43
Weight (Tire+Whl+Brk, lb/tire):	249.00	249.00
Roll Resistance Const:	0.01	0.01
Roll Resististance Linear Coef (sec/in):	0.00	0.00
Min Fz For Skidmark (lb):	1900.00	1900.00
Pneumatic Trail (in):	-2.10	-2.10

Cornering Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):	704.0			704.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	321.9	581.0	823.0	321.9	581.0	823.0

Camber Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):	704.0			704.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	40.0	60.0	80.0	40.0	60.0	80.0

Tire Friction Table:	Right Side			Left Side		
Loads (lb):	3900.0	7200.0	10800.0	3900.0	7200.0	10800.0

Speeds (in/sec):	352.0	704.0		352.0	704.0	
Speed No. 1, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7600	0.7300	0.8000	0.7600	0.7300
Slide Mu:	0.6000	0.5500	0.5000	0.6000	0.5500	0.5000
Slip @ Peak Mu (%/100):	0.3500	0.3000	0.2500	0.3500	0.3000	0.2500
Long. Stiffness (lb/slip):	18000.0	35000.0	60000.0	18000.0	35000.0	60000.0
Speed No. 2, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7400	0.6800	0.8000	0.7400	0.6800
Slide Mu:	0.5000	0.4400	0.3900	0.5000	0.4400	0.3900
Slip @ Peak Mu (%/100):	0.2500	0.1800	0.1600	0.2500	0.1800	0.1600
Long. Stiffness (lb/slip):	29800.0	69220.0	119850.0	29800.0	69220.0	119850.0

Brake Information, First Axle ---

	Right Side	Left Side
Brake Assembly Type:	Generic Brake	Generic Brake
Brake Time Lag (sec):	0.1000	0.1000
Brake Time Rise (sec):	0.2000	0.2000
Pushout Pressure (psi):	0.00	0.00
Nominal Brake Torque Ratio (in-lb/psi):	1000.00	1000.00

Wheel Location Information, Second Axle ---

	Right Side	Left Side
Initial Wheel Coordinates (in) - x:	-144.00	-144.00
y:	36.00	-36.00
z:	24.00	24.00
Inter-dual Spacing (in):	13.50	13.50

Suspension Information, Second Axle ---

Suspension Type:	Solid Axle
Axle Roll/Yaw Inertia (lb-sec^2-in):	12230.00
Axle Roll Ctr Ht Below CG (in):	21.00
Axle Roll Steer (deg/deg):	0.00
Lateral Spring Spacing (in):	41.00
Nominal Track Width (in):	72.00
Total Unsprung Weight (Axle+Wheels, lb):	2181.00
Auxiliary Roll Stiffness (in-lb/deg):	0.00

	Right Side	Left Side
Spring Rate (lb/in):	6000.00	6000.00
Viscous Damping (lb-sec/in):	5.00	5.00
Coulomb Friction (lb):	1050.00	1050.00
Friction Null Band (in/sec):	5.00	5.00
Deflection to Jounce Stop (in):	-5.00	-5.00
Stop Linear Rate (lb/in):	300.00	300.00
Stop Cubic Rate (lb/in^3):	600.00	600.00
Stop Energy Ratio (%/100):	0.50	0.50
Deflection to Rebound Stop (in):	5.00	5.00
Stop Linear Rate (lb/in):	300.00	300.00
Stop Cubic Rate (lb/in^3):	600.00	600.00
Stop Energy Ratio (%/100):	0.50	0.50
Camber Constant (deg):	0.00	0.00

Tire Information, Second Axle ---

	Right Side	Left Side
Tire Name:	Generic	Generic
Tire Manufacturer:	Generic	Generic
Tire Model:	Generic	Generic
Tire Size:	11.00R20H	11.00R20H
Version No:	V 5.20	V 5.20

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Unloaded Radius (in):	21.35	21.35
Static Loaded Radius (in):	20.94	20.94
Nominal Width (in):	11.00	11.00
Tread Width (in):	9.90	9.90
Init. Radial Stiffness (lb/in/tire):	5000.00	5000.00
2nd Radial Stiffness (lb/in/tire):	50000.00	50000.00
Defl. @ 2nd Stiffness (in):	9.08	9.08
Max Deflection (in):	11.35	11.35
Rebound Energy Ratio (%/100):	1.00	1.00
Spin Inertia (Tire+Whl+Brk, lb-sec^2-in/	182.21	182.21
Steer Inertia (Tire+Whl+Brk, lb-sec^2-in	73.43	73.43
Weight (Tire+Whl+Brk, lb/tire):	249.00	249.00
Roll Resistance Const:	0.01	0.01
Roll Resististance Linear Coef (sec/in):	0.00	0.00
Min Fz For Skidmark (lb):	1900.00	1900.00
Pneumatic Trail (in):	-2.10	-2.10

Cornering Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):	704.0			704.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	321.9	581.0	823.0	321.9	581.0	823.0

Camber Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):	704.0			704.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	40.0	60.0	80.0	40.0	60.0	80.0

Tire Friction Table:	Right Side			Left Side		
Loads (lb):	3900.0	7200.0	10800.0	3900.0	7200.0	10800.0
Speeds (in/sec):	352.0	704.0		352.0	704.0	
Speed No. 1, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7600	0.7300	0.8000	0.7600	0.7300
Slide Mu:	0.6000	0.5500	0.5000	0.6000	0.5500	0.5000
Slip @ Peak Mu (%/100):	0.3500	0.3000	0.2500	0.3500	0.3000	0.2500
Long. Stiffness (lb/slip):	18000.0	35000.0	60000.0	18000.0	35000.0	60000.0
Speed No. 2, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7400	0.6800	0.8000	0.7400	0.6800
Slide Mu:	0.5000	0.4400	0.3900	0.5000	0.4400	0.3900
Slip @ Peak Mu (%/100):	0.2500	0.1800	0.1600	0.2500	0.1800	0.1600
Long. Stiffness (lb/slip):	29800.0	69220.0	119850.0	29800.0	69220.0	119850.0

Brake Information, Second Axle ---

	Right Side	Left Side
Brake Assembly Type:	Generic Brake	Generic Brake
Brake Time Lag (sec):	0.1000	0.1000
Brake Time Rise (sec):	0.2000	0.2000
Pushout Pressure (psi):	0.00	0.00
Nominal Brake Torque Ratio (in-lb/psi):	1500.00	1500.00