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Stability of Tank Truck Combinations On Curved Road Segments In the Yukon

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16. Abstract

Computerized analyses were conducted to evaluate roll stability issues involving the operation of heavy tanker combinations on two segments of curved roadway. Two vehicle configurations were examined, representing a tanker currently in service in the Yukon Territory of Canada and a reference tanker used in many parts of the U.S. and Canada for transporting petroleum products. The analyses show the comparison in static stability between the selected vehicles and the performance of these vehicles on an existing and a proposed road segment. Recommendations are offered for setting maximum speed values for trucks operating on the subject curves.

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1.0 INTRODUCTION

This document constitutes the final report on a study sponsored by the Yukon Community and Transportation Services. The study sought to examine the dynamic stability of fuel-carrying tanker truck combinations at a specific roadway intersection in the vicinity of Whitehorse, Yukon. This project involved the conduct of computerized simulation of vehicle dynamic response, using detailed descriptions of the vehicles and the road geometries of interest. The results of the study provide specific guidance for highway engineering practice in the Yukon, and generally serve to illustrate the remarkably low tolerance level which loaded truck combinations have for overspeeding in tight-radius turns.

The report presents the study methodology in Section 2.0 and results and conclusions in Sections 3.0 and 4.0, respectively. Appendices are provided to document vehicle-descriptive data as well computed performance.

2.0 METHODOLOGY

The methodology employed in this project involved the application of computer simulation techniques and existing parametric data which have been developed at The University of Michigan Transportation Research Institute (UMTRI) over a period of fifteen years. The effort involves, primarily, the determination of parametric data describing the vehicle and its components and the computation of vehicle performance by means of a digital computer. Two computer models were employed here; namely, the UMTRI Static Roll Model [1] which determines a basic rollover threshold measure for the vehicle, assuming a steady turn, and a comprehensive simulation program called the UMTRI Phase IV Model [2] which represents the instantaneous motion responses of the vehicle while it travels over the specific road segment in question.

Vehicles

A particular design of 5-axle tractor-semitrailer combination was defined through drawings and specifications provided by the sponsor. The mechanical properties of this vehicle were then determined by hand calculation and through identification of components such as tires, suspensions, and steering systems, by brand name, whose properties had been previously measured by UMTRI. The Yukon vehicle of immediate interest incorporated a relatively short (8.2 m) semitrailer having an abnormally high center of gravity (2.49 m for height of the composite sprung mass center of the loaded semitrailer above the ground). The gross weight of the combination vehicle was 38.6 m-tons. The full set of parameters used to represent this vehicle in the Phase IV program are listed in Appendix A.

A second vehicle was also selected to serve as a "reference" 5-axle tanker—having a roll stability threshold of 0.32 g's—such as is common in the U.S. and certain parts of Canada. This vehicle was represented with a gross weight of 36.4 m-tons. The height of the composite sprung mass of the loaded semitrailer in this configuration is 2.1 m. Although both of the selected vehicles were configured as tankers, the tank vessel was assumed to be sufficiently full that the liquid load was non-sloshing (although roll moments of inertia of the trailer were determined recognizing that the tank can rotate in the roll direction without significantly rotating the fluid mass). The full set of parametric values used to represent this vehicle in the Phase IV program are presented in Appendix B.

Roadways

Two right-turn intersection roadways were represented. The first of these road sections is shown in Figure 1, representing an existing T-type intersection between Industrial Road and the Alaska Highway, in the Yukon Territory of Canada. At this site, the Alaska Highway is on a steep upgrade toward the right side of the figure and is curved

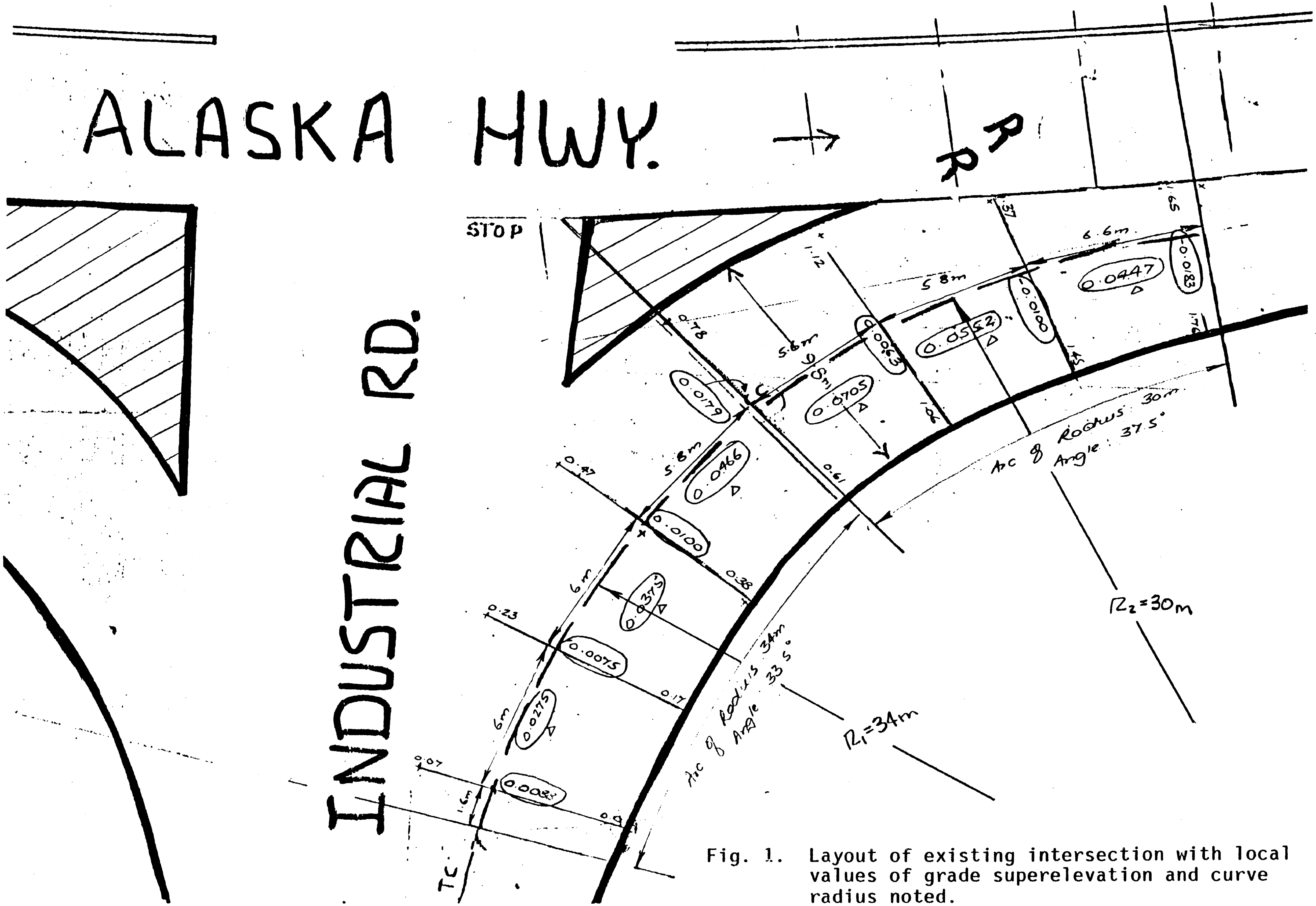

Fig. 1. Layout of existing intersection with local values of grade superelevation and curve radius noted.

away from the intersecting road. The intersection was of interest because of truck rollover accidents which suggested an unusually high level of cornering severity, given the advisory speed of 50 km/h. The Figure shows the superelevation and grade values (with numbers layed out laterally and longitudinally to the roadway, respectively) at selected stations along the right-turning lane. Because the right-turning lane merges with the Alaska Highway along the outside of a curve, this turning lane becomes reverse-superelevated near the merge point in order to eventually match the superelevation value of the major highway. The right-turn lane also comprises a slightly compounded curve, with an initial radius of 34 m and a final radius of 30 m. This road segment was represented in the computer simulation with superelevation values, as shown, although the grade condition was omitted, for simplicity, as inconsequential to roll stability.

A second road segment was examined as a prospective alternative to the existing right-turning lane. This proposed design involved a curve of 75 m radius which was transitioned by 40 m-long spirals at each end. The maximum superelevation rate of this curve was 0.06. Both of the selected curve layouts were studied by computing the dynamic response of both the Yukon and reference tanker configurations using the Phase IV simulation model.

3.0 RESULTS

The computed results will be presented in terms of the static roll stability of the two vehicles, themselves, and then using the simulated responses of these vehicle on each of the two road segments.

Static Stability of the Tanker Configurations

Appendix C presents a listing of the input parameters employed in the computation of the static roll stability of both tankers. The Appendix also includes a detailed explanation of each parameter. The reader will note that the data needed to describe each vehicle in the static roll computation is considerably less than that employed in the comprehensive simulation.

The roll behavior of the vehicle, up to its point of roll instability, is computed by the static roll program so as to reveal the maximum steady level of lateral acceleration which the vehicle can tolerate without rollover. The results for both vehicles are as follows:

Vehicle	Rollover Threshold	Roll Angle at Threshold
Yukon Tanker	0.28 g's	9.5 degrees
Reference Tanker	0.32 g's	11.0 degrees

These data show that the Yukon vehicle is substantially lower in roll stability than is the reference tanker. The observed difference in performance levels (that is, 0.28 vs. 0.32 g's) derives from the net difference in two distinctions between the vehicles. Namely, we see that the Yukon vehicle has (a) a higher profile tank layout, yielding a considerably higher placement of the center of gravity, but (b) a substantially stiffer set of suspensions at the tractor and trailer tandem sets, thus accounting for the lower roll angle at the point of instability. Although the stiffer suspensions tend to improve the stability of the Yukon tanker, the high placement of the mass center overpowers this benefit such that a net lower static stability level is achieved relative to the selected reference case.

Vehicle Response on the Selected Road Segments

The Yukon tanker was studied in simulated travel over the existing right-turning roadway at each of five speeds, shown below together with the nominal value of lateral acceleration which is implied at each speed.

Speed (Kmh)	Lateral Acceleration (G's)
50.0	0.58
41.6	0.40
32.9	0.25
29.4	0.20
25.5	0.15

Since the represented roadway employs a small level of superelevation (less than 0.02, at its maximum) and since the superelevated condition vanishes and even reverses slightly toward the end of the curve, the nominal values of lateral acceleration shown above closely approximate the so-called "side friction factor" which rates the geometric design of the curve. The first speed value, 50 km/h, represents the speed which had been posted at the right-turning lane of the existing intersection at the time that truck rollover accidents had occurred. Successively lower values of speed were examined in order to illustrate the degree of improvement in vehicle response that would accompany a speed reduction. The computed results for the *existing roadway* show the following:

At 50 km/h, the Yukon vehicle rolls over very quickly in the turn, with the inboard tires on both tandem axle sets lifting off of the ground when the tractor has gone only 12 meters into the turn (that is, with the tractor's mass center 12 meters beyond the point of curvature, TC). The roll response then builds up such that the tank body strikes the ground an estimated 20 to 30 meters further along the turn. The roll response of the vehicle beyond the liftoff point is only estimated here, however, since the Phase IV model does not produce an accurate portrayal of vehicle motions at high roll angles. Moreover, a 50 km/h speed on this turn is patently excessive since the nominal 0.58 g level of lateral acceleration dramatically exceeds the stability thresholds of most loaded commercial vehicles.

At 41.6 km/h, the Yukon vehicle rolls over decisively, with all inboard tires on the tandem axles lifting from the roadway when the tractor is 15 meters into the turn.

At 32.9 km/h, the Yukon tanker approaches rollover, with the inboard tires on the tractor tandem set reaching an essentially zero-load condition, but retains sufficient roll reaction capability at the trailer axles that complete rollover is averted. The nominal 0.25 g level of lateral acceleration is clearly so close to the 0.28 g threshold value for this vehicle, however, that a marginally stable condition is observed.

At 29.4 km/h, the Yukon tanker travels in a moderately stable manner through the intersection, with 70% of the load on the inside tires being transferred to the outside tires late in the turn. One could say that the vehicle is being operated, under these conditions, at "70% of its performance limit."

At 25.5 km/h, the Yukon tanker transfers approximately 50% of the load on its inside tires to the outside. This nominal lateral acceleration level of 0.15 g's, corresponding to a side friction factor of approximately 0.15, is seen as an upper bound representative of most highway designs in North America.

At the same 25.5 km/h speed, the reference tanker transfers some 44% of the load on its inside tires to the outside and, thus, enjoys a slightly larger margin of safety at this velocity on the subject roadway.

Appendix D contains plots of selected response variables showing the behavior of (a) the Yukon tanker on the existing roadway at speeds of 32.9 and 25.5 km/h and (b) the reference tanker at the lower speed of 25.5 km/h. The plots serve to illustrate characteristic time histories for lateral acceleration, roll angles, and suspension and tire loads.

Regarding the *proposed* roadway, results were obtained for a speed value of 37.6 km/h, which yields a centripetal acceleration level of 0.15 g's. Given the 0.06 superelevation level employed in this proposed design, the side friction factor associated with the simulated conditions was a nominal 0.09. This condition was selected to demonstrate the higher level of conservatism that the authors deem to be advisable in designing and signing new roadways, recognizing the generally poor stability levels of commercial vehicles [3]. The simulated responses of both tankers under these conditions, which are plotted in Appendix D, indicate that only 25% of the load on the inside tires has been transferred to the outside, thus providing a substantial margin for error.

A corresponding vehicle speed of 20 km/h would be needed on the *existing* roadway in order to yield this more conservative 0.09 value of side friction factor.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The computations, together with the results of prior research, support the findings that:

1) The Yukon tanker is relatively low in roll stability, although not as low as the most extreme cases of tank vehicles which are known to operate in North America. For the transportation of hazardous liquids, the high profile of the tank vessel on this vehicle constitutes a less-than-desirable layout.

2) Rollover of this vehicle will occur on the existing roadway, at the intersection of Industrial Road and the Alaska Highway, at all speeds above approximately 35 km/h.

3) The safety margin, relative to rollover risks, can be kept within the bounds of those prevailing at most curved roadways in the U.S. and Canada if speeds on the existing roadway are kept within approximately 25 km/h.

4) A safety margin which, in the opinion of the authors, is more suitable for the operation of heavy duty truck combinations, would require that speeds on the existing roadway are kept within approximately 20 km/h.

5) The proposed right-turning road segment would yield this preferable level of safety margin if speeds were kept within a value of approximately 38 km/h.

5.0 REFERENCES

1. Dill, P.A. Static Roll Model User's Manual. Transp. Research Inst., Univ. of Mich., December 1985.

2. MacAdam, C.C., et al. A Computerized Model for Simulating the Braking and Steering Dynamics of Trucks, Tractor-Semitrailers, Doubles, and Triples Combinations, User's Manual, Phase IV. Final Rept., MVMA Project 1197, Rept. No. UM-HSRI-80-58, September 1, 1980.

3. Ervin, R.D., et al. Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges. Final Rept., Contract No. DTFH61-82-C-00054, Transp. Res. Inst., Univ. of Mich., Rept. No. UMTRI-85-33, August 1985.

APPENDIX A

COMPREHENSIVE INPUT DATA REPRESENTING THE YUKON TANKER AND THE EXISTING ROADWAY IN UMTRI'S PHASE IV SIMULATION

Yukon's 3 axle tractor and tandem axle tanker.

SIMULATION OPERATION PARAMETERS:

VEHICLE CONFIGURATION (NUMBER OF TRAILERS - ENTER 0 FOR A STRAIGHT TRUCK)	1
INITIAL VELOCITY (FT/SEC)	37.90
STEER TABLE (NUMBER OF LINES): POSITIVE -STEER ANGLE TABLE, NEGATIVE - PATH FOLLOWER TABLE	-82

CLOSED-LOOP PATH FOLLOWING MODE

X-Y PATH COORDINATES :

X (FEET)	Y (FEET)
0.0	0.0
100.00	0.0
101.50	0.01
103.00	0.05
104.50	0.10
106.00	0.17
107.49	0.27
108.99	0.38
110.48	0.52
111.98	0.67
113.47	0.85
114.95	1.04
116.44	1.25
117.92	1.49
119.40	1.74
120.87	2.02
122.34	2.31
123.81	2.63
125.27	2.96
126.73	3.31
128.18	3.68
129.63	4.08
131.07	4.49
132.51	4.92
133.94	5.37
135.37	5.84
136.78	6.33
138.20	6.83
139.60	7.36
141.00	7.91
142.39	8.47
143.77	9.05
145.14	9.65
146.51	10.27
147.87	10.91
149.22	11.57
150.56	12.24

151.89	12.93
153.21	13.64
154.52	14.37
155.82	15.12
157.11	15.88
158.39	16.66
159.67	17.46
160.92	18.27
162.17	19.11
163.40	19.96
164.62	20.83
165.83	21.72
167.02	22.63
168.20	23.56
169.37	24.51
170.52	25.47
171.65	26.45
172.77	27.45
173.88	28.46
174.97	29.49
176.04	30.54
177.10	31.61
178.14	32.69
179.16	33.78
180.17	34.89
181.16	36.02
182.13	37.16
183.09	38.32
184.03	39.49
184.95	40.67
185.85	41.87
186.73	43.08
187.60	44.31
188.44	45.55
189.27	46.80
190.08	48.06
190.87	49.34
191.64	50.62
192.39	51.92
193.12	53.23
193.83	54.56
194.51	55.89
195.18	57.23
195.83	58.58
238.10	150.31

DRIVER TRANSPORT LAG (SEC) : 0.0
END OF PREVIEW INTERVAL (SEC) : 0.30
END OF CLOSED LOOP CONTROL (SEC) : 18.00
RAMP-STEER RATE (DEG/SEC) : 0.0

TREADLE PRESSURE TABLE (NUMBER OF LINES) 0
* ZERO ENTRY INDICATES NO FURTHER TABLE DATA IS NECESSARY - THE FOLLOWING TABLE IS ASSIGNED INTERNALLY *
TABLE ENTRIES:

TIME (SEC)	PRESSURE (PSI)
0.0	0.0

MAXIMUM SIMULATION TIME (SEC) 8.00
TIME INCREMENT OF OUTPUT (SEC) 0.10

ROAD KEY = -1 : USER-DEFINED ROAD SURFACE (SUBROUTINE ROAD).

OUTPUT PAGE OPTION KEYS: O DELETES PAGES

SPRUNG MASS POSITION	SPRUNG MASS VELOCITY	SPRUNG MASS ACCELERATION	TIRE FORCES PAGES	BRAKE SUMMARY PAGES	LATERAL PAGES	UNSPRUNG MASS PAGES	TEMP PAGES
1	1	1	1	1	1	1	1

Yukon's 3 axle tractor and tandem axle tanker.

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TRACTOR PARAMETERS
------------------

     WHEELBASE - DISTANCE FROM FRONT AXLE TO CENTER  OF REAR SUSPENSION (IN)            186.00
     BASE VEHICLE CURB WEIGHT ON FRONT SUSPENSION (LB)                                 7941.93
     BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)                                  7358.07
     SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)                                            44.00
     SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                20000.00
     SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)                              120000.00
     SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)                                120000.00
     PAYLOAD WEIGHT (LB)                                                                  0.0
          *** ZERO ENTRY INDICATES NO PAYLOAD ***
          *** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***
     FIFTH WHEEL LOCATION (IN. AHEAD OF REAR SUSP. CENTER)                               13.00
     FIFTH WHEEL HEIGHT ABOVE GROUND (IN)                                                50.00
     TRACTOR FRAME STIFFNESS (IN-LB/DEG)                                              40000.00
     TRACTOR FRAME TORSIONAL AXIS HEIGHT ABOVE GROUND (IN)                               38.00

TRACTOR FRONT SUSPENSION AND AXLE PARAMETERS                          LEFT SIDE        RIGHT SIDE
-------------------------------------------                           ---------        ----------

     SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                          -101.00          -101.00
          *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
          *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
     SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                    22.26            22.26
     COULOMB FRICTION (LB/SIDE/AXLE)                                      0.0              0.0
                                                                      ---------------------------
     AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                 3700.00
     ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                        18.25
     ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                 0.0
     AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                  3824.00
     LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                             32.00
     TRACK WIDTH (IN)                                                             80.00
     UNSPRUNG WEIGHT (LB)                                                       1200.00
     STEERING GEAR RATIO (DEG STEERING WHEEL/DEG ROAD WHEEL)                      30.00
     STEERING STIFFNESS (IN-LB/DEG)                                            11000.00
     TIE ROD STIFFNESS (IN-LB/DEG)                                             11000.00
     MECHANICAL TRAIL (IN)                                                         1.00
     TORSIONAL WRAP-UP STIFFNESS (IN-LB/IN)                                   150000.00
     LATERAL OFFSET OF STEERING AXIS (IN)                                          3.00

TRACTOR FRONT TIRES AND WHEELS                                        LEFT SIDE        RIGHT SIDE
------------------------------                                        ---------        ----------

     CORNERING STIFFNESS  (LB/DEG/TIRE)                                  -1.00            -1.00
          *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
          *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
     LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                             -51.00           -51.00
          *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
          *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
     CAMBER STIFFNESS (LB/DEG/TIRE)                                       0.0              0.0
     ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                -1320.84         -1320.84
       *** NEGATIVE ALIGNING MOMENT ENTRY ***
```

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  *** ALIGNING MOMENT CURVE FIT PARAMETERS:  (  0.0      8.0000  5.0000  0.8000) (  0.0      8.0000  5.0000  0.8000)
TIRE SPRING RATE (LB/IN/TIRE)                                                    4500.00                 4500.00
TIRE LOADED RADIUS (IN)                                                            20.00                   20.00
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                      103.00                  103.00
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Yukon's 3 axle tractor and tandem axle tanker.

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TRACTOR REAR SUSPENSION  AND AXLE PARAMETERS                          LEADING TANDEM AXLE         TRAILING TANDEM AXLE
                                                                    LEFT SIDE   RIGHT SIDE      LEFT SIDE   RIGHT SIDE

  SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM        2
      TANDEM AXLE SEPARATION (IN BETWEEN LEADING AND TRAILING AXLES)                   50.00
      STATIC LOAD TRANSFER (PERCENT LOAD ON LEAD AXLE)                                 50.00
      DYNAMIC LOAD TRANSFER (% BRAKE TORQUE REACTED AS TANDEM AXLE LOAD TRANSFER)       0.0
  SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                          -102.00     -102.00          -102.00     -102.00
      *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
      *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
  SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                     0.0         0.0              0.0         0.0
  COULOMB FRICTION (LB/SIDE/AXLE)                                      0.0         0.0              0.0         0.0

  AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                        5100.00                                 5100.00
  ROLL CENTER HEIGHT (IN. ABOVE GROUND)                               33.00                                   33.00
  ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                        0.0                                     0.0
  AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                        30000.00                                30000.00
  LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                    38.00                                   38.00
  TRACK WIDTH (IN)                                                    72.00                                   72.00
  UNSPRUNG WEIGHT (LB)                                              2300.00                                 2300.00

TRACTOR REAR TIRES  AND WHEELS                                               LEFT SIDE               RIGHT SIDE

  DUAL TIRE SEPARATION (IN)                                                    13.00                   13.00
  CORNERING STIFFNESS  (LB/DEG/TIRE)                                           -1.00                   -1.00
      *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
      *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
  LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                      -51.00                  -51.00
      *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
      *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
  CAMBER STIFFNESS (LB/DEG/TIRE)                                                0.0                     0.0
  ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                         -1320.84                -1320.84
    *** NEGATIVE ALIGNING MOMENT ENTRY ***
    *** ALIGNING MOMENT CURVE FIT PARAMETERS:  ( 0.0  8.0000  5.0000  0.8000) ( 0.0  8.0000  5.0000  0.8000)
  TIRE SPRING RATE (LB/IN/TIRE)                                              4500.00                 4500.00
  TIRE LOADED RADIUS (IN)                                                      20.00                   20.00
  POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                103.00                  103.00

*** ZERO LINES IN TREADLE PRESSURE TABLE INDICATES NO BRAKING ***
*** THREE BRAKE PARAMETERS PER AXLE ARE DELETED AT THIS POINT ***
```

Yukon's 3 axle tractor and tandem axle tanker.

TRAILER NO. 1 PARAMETERS

WHEELBASE - DISTANCE FROM KINGPIN TO CENTER OF REAR SUSPENSION (IN)	232.00
BASE VEHICLE KINGPIN STATIC LOAD (LB)	30337.45
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)	39262.55
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)	98.10
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	52500.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)	757000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)	757000.00
PAYLOAD WEIGHT (LB)	0.0

*** ZERO ENTRY INDICATES NO PAYLOAD ***
*** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***

TRAILER NO. 1 REAR SUSPENSION AND AXLE PARAMETERS

	LEADING TANDEM AXLE LEFT SIDE	LEADING TANDEM AXLE RIGHT SIDE		TRAILING TANDEM AXLE LEFT SIDE	TRAILING TANDEM AXLE RIGHT SIDE
SUSPENSION KEY - O INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM			1		
TANDEM AXLE SEPARATION (IN BETWEEN LEADING AND TRAILING AXLES)			48.00		
STATIC LOAD TRANSFER (PERCENT LOAD ON LEAD AXLE)			50.00		
DYNAMIC LOAD TRANSFER (% BRAKE TORQUE REACTED AS TANDEM AXLE LOAD TRANSFER)			0.0		
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)	-103.00	-103.00		-103.00	-103.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***					
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***					
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)	0.0	0.0		0.0	0.0
COULOMB FRICTION (LB/SIDE/AXLE)	0.0	0.0		0.0	0.0

	LEADING TANDEM AXLE	TRAILING TANDEM AXLE
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	4100.00	4100.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)	27.00	27.00
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)	0.0	0.0
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)	9000.00	9000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)	38.00	38.00
TRACK WIDTH (IN)	72.00	72.00
UNSPRUNG WEIGHT (LB)	1500.00	1500.00

TRAILER NO. 1 REAR TIRES AND WHEELS

	LEADING TANDEM AXLE LEFT SIDE	LEADING TANDEM AXLE RIGHT SIDE	TRAILING TANDEM AXLE LEFT SIDE	TRAILING TANDEM AXLE RIGHT SIDE
DUAL TIRE SEPARATION (IN)	13.00	13.00	13.00	13.00
CORNERING STIFFNESS (LB/DEG/TIRE)	-1.00	-1.00	-1.00	-1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
LONGITUDINAL STIFFNESS (LB/SLIP/TIRE)	-51.00	-51.00	-51.00	-51.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
CAMBER STIFFNESS (LB/DEG/TIRE)	0.0	0.0	0.0	0.0
ALIGNING MOMENT (IN-LB/DEG/TIRE)	-1320.84	-1320.84	-1320.84	-1320.84
*** NEGATIVE ALIGNING MOMENT ENTRY ***				

```
*** ALIGNING MOMENT CURVE FIT PARAMETERS:  (  0.0     8.0000  5.0000  0.8000) (  0.0     8.0000  5.0000  0.8000)
                                           (
*** NEGATIVE ALIGNING MOMENT ENTRY ***
*** ALIGNING MOMENT CURVE FIT PARAMETERS:  (  0.0     8.0000  5.0000  0.8000) (  0.0     8.0000  5.0000  0.8000)
                                           (
TIRE SPRING RATE (LB/IN/TIRE)                              4500.00     4500.00            4500.00     4500.00
TIRE LOADED RADIUS (IN)                                      20.00       20.00              20.00       20.00
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                103.00      103.00             103.00      103.00
```

Yukon's 3 axle tractor and tandem axle tanker.

*** ZERO LINES IN TREADLE PRESSURE TABLE INDICATES NO BRAKING ***
*** THREE BRAKE PARAMETERS PER AXLE ARE DELETED AT THIS POINT ***

ANTILOCK KEY: 1 INDICATES ANTILOCK WILL BE USED   0

Yukon's 3 axle tractor and tandem axle tanker.

TRAILER NO. 1 PAYLOAD = 0.0 LBS.

	EMPTY	LOADED
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO REAR SUSPENSION (IN)	105.680	105.680
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO GROUND (IN)	98.100	98.100
ROLL MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	52500.000	52500.000
PITCH MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	756999.938	756999.936
YAW MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	756999.938	756999.938

TRACTOR PAYLOAD = 0.0 LBS

	EMPTY	LOADED
DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO REAR SUSPENSION (IN)	132.000	132.000
DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO GROUND (IN)	44.000	44.000
ROLL MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	19999.996	19999.996
PITCH MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	120000.000	120000.000
YAW MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	120000.000	120000.000

THE STATIC LOADS ON THE AXLES ARE:

AXLE NUMBER	LOAD
NS(1,1,1)	10062.293
NS(1,2,1)	17787.578
NS(1,2,2)	17787.578
NS(2,2,1)	19631.273
NS(2,2,2)	19631.273
TOTAL	84899.938

THE TRACTOR TOTAL MASS CENTER IS 89.451 INCHES BEHIND THE FRONT AXLE
THE TOTAL YAW MOMENT OF INERTIA IS 308241.688 IN-LB-SEC**2

THE FIRST TRAILER TOTAL MASS CENTER IS 130.875 INCHES BEHIND THE KINGPIN
THE TOTAL YAW MOMENT OF INERTIA IS 852734.250 IN-LB-SEC**2

Yukon's 3 axle tractor and tandem axle tanker.

SPRING TABLES

NO. OF LINES	FORCE (LB)	DEFLECTION (IN)	TABLE NO.
9			-101.00
	-20400.00	-15.00	
	-1020.00	-0.75	
	0.0	0.0	
	1550.00	1.00	
	2900.00	2.00	
	4200.00	3.00	
	7700.00	5.50	
	11750.00	8.50	
	21200.00	15.50	
	(SPRING COMPRESSION ENVELOPE)		
	-20700.00	-15.00	
	-1320.00	-0.75	
	-300.00	0.0	
	950.00	1.00	
	2200.00	2.00	
	3450.00	3.00	
	6780.00	5.50	
	10505.00	8.50	
	18953.00	15.50	
	(SPRING EXTENSION ENVELOPE)		

SUSPENSION DEFLECTION CONSTANTS = 0.17000 INCHES COMPRESSION, 0.15000 INCHES EXTENSION.

SPRING STATIC EQUILIBRIUM CONDITION: 4431.14 LB, 3.44 INCHES. UNIT 1 SUSP 1 AXLE 1

NO. OF LINES	FORCE (LB)	DEFLECTION (IN)	TABLE NO.
9			-102.00
	-15980.00	-2.00	
	200.00	-0.25	
	900.00	0.0	
	1800.00	0.25	
	3600.00	0.50	
	5900.00	0.75	
	11000.00	1.00	
	44750.00	2.25	
	119000.00	5.00	
	(SPRING COMPRESSION ENVELOPE)		

-16450.00	-2.00
-300.00	-0.25
0.0	0.0
700.00	0.25
1820.00	0.50
3600.00	0.75
6900.00	1.00
31593.50	2.25
84014.00	5.00

(SPRING EXTENSION ENVELOPE)

SUSPENSION DEFLECTION CONSTANTS = 0.15000 INCHES COMPRESSION, 0.15000 INCHES EXTENSION.

SPRING STATIC EQUILIBRIUM CONDITION: 15487.58 LB, 1.28 INCHES. UNIT 1 SUSP 2 AXLE 1

7 -103.00

-26562.50	-10.00
0.0	-1.50
0.0	0.0
1600.00	0.25
4000.00	0.50
6750.00	0.75
48000.00	4.50

(SPRING COMPRESSION ENVELOPE)

-26757.81	-10.00
-195.31	-1.50
-100.00	0.0
700.00	0.25
2000.00	0.50
4000.00	0.75
31085.70	4.50

(SPRING EXTENSION ENVELOPE)

SUSPENSION DEFLECTION CONSTANTS = 0.15000 INCHES COMPRESSION, 0.15000 INCHES EXTENSION.

SPRING STATIC EQUILIBRIUM CONDITION: 9065.64 LB, 1.16 INCHES. UNIT 2 SUSP 2 AXLE 1

SPRING STATIC EQUILIBRIUM CONDITION: 9065.64 LB, 1.16 INCHES. UNIT 2 SUSP 2 AXLE 2

Yukon's 3 axle tractor and tandem axle tanker.

MU-Y VS ALPHA TABLES

NO. OF LOADS	NO. OF VELOCITIES	TABLE NO.
3	1	-1

VELOCITY = 58.70 FT/SEC LOAD = 1983.00 LB

ALPHA (DEG)	MU - Y
0.0	0.0
1.00	0.18
2.00	0.32
4.00	0.54
8.00	0.77
12.00	0.91

VELOCITY = 58.70 FT/SEC LOAD = 5967.00 LB

ALPHA (DEG)	MU - Y
0.0	0.0
1.00	0.14
2.00	0.27
4.00	0.47
8.00	0.66
12.00	0.73

VELOCITY = 58.70 FT/SEC LOAD = 9441.00 LB

ALPHA (DEG)	MU - Y
0.0	0.0
1.00	0.10
2.00	0.19
4.00	0.36
8.00	0.55
12.00	0.61

ROLL-OFF TABLE

	SLIP						
ALPHA	0.0	0.04	0.10	0.24	0.25	0.50	1.00
0.0	1.00	1.00	0.87	0.40	0.38	0.17	0.06
1.00	1.00	1.00	0.83	0.40	0.38	0.17	0.06
2.00	1.00	1.00	0.81	0.39	0.38	0.17	0.06

4.00	1.00	0.97	0.75	0.39	0.38	0.17	0.06
6.00	1.00	0.96	0.79	0.45	0.44	0.21	0.07
8.00	1.00	0.97	0.84	0.52	0.50	0.25	0.09
12.00	1.00	0.97	0.89	0.63	0.62	0.33	0.12
16.00	1.00	0.98	0.92	0.71	0.70	0.40	0.15

Yukon's 3 axle tractor and tandem axle tanker.

MU-X VS. SLIP TABLES

NO. OF LOADS	NO. OF VELOCITIES	TABLE NO.
3	3	-51

VELOCITY = 29.30 FT/SEC LOAD = 3020.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.58
0.10	0.81
0.21	0.86
0.25	0.86
0.50	0.79
1.00	0.62

VELOCITY = 58.70 FT/SEC LOAD = 3020.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.51
0.10	0.79
0.21	0.85
0.25	0.85
0.50	0.77
1.00	0.56

VELOCITY = 80.70 FT/SEC LOAD = 3020.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.46
0.10	0.78
0.21	0.84
0.25	0.84
0.50	0.76
1.00	0.52

Yukon's 3 axle tractor and tandem axle tanker.

VELOCITY = 29.30 FT/SEC LOAD = 6040.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.37
0.10	0.71
0.24	0.80
0.25	0.80
0.50	0.74
1.00	0.54

VELOCITY = 58.70 FT/SEC LOAD = 6040.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.33
0.10	0.69
0.24	0.79
0.25	0.79
0.50	0.72
1.00	0.48

VELOCITY = 80.70 FT/SEC LOAD = 6040.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.30
0.10	0.67
0.24	0.79
0.25	0.78
0.50	0.70
1.00	0.44

VELOCITY = 29.30 FT/SEC LOAD = 9060.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.24
0.10	0.59
0.24	0.74
0.25	0.74
0.50	0.69
1.00	0.46

Yukon's 3 axle tractor and tandem axle tanker.

VELOCITY = 58.70 FT/SEC LOAD = 9060.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.22
0.10	0.55
0.24	0.73
0.25	0.73
0.50	0.67
1.00	0.41

VELOCITY = 80.70 FT/SEC LOAD = 9060.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.20
0.10	0.52
0.24	0.73
0.25	0.73
0.50	0.65
1.00	0.36

ROLL-OFF TABLE

	SLIP						
ALPHA	0.0	0.04	0.10	0.24	0.25	0.50	1.00
0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00
2.00	1.00	1.00	0.96	0.99	0.99	1.00	1.00
4.00	1.00	0.93	0.87	0.96	0.97	0.99	1.00
6.00	0.79	0.78	0.77	0.92	0.93	0.98	0.99
8.00	0.64	0.65	0.67	0.87	0.88	0.96	0.99
12.00	0.44	0.47	0.52	0.77	0.78	0.92	0.98
16.00	0.34	0.37	0.41	0.66	0.68	0.87	0.96

APPENDIX B

COMPREHENSIVE INPUT DATA REPRESENTING THE REFERENCE TANKER AND THE PROPOSED ROADWAY IN UMTRI'S PHASE IV SIMULATION

Michigan 3 axle tractor and tandem axle tanker.

SIMULATION OPERATION PARAMETERS:

VEHICLE CONFIGURATION (NUMBER OF TRAILERS - ENTER 0 FOR A STRAIGHT TRUCK)	1
INITIAL VELOCITY (FT/SEC)	34.47
STEER TABLE (NUMBER OF LINES): POSITIVE -STEER ANGLE TABLE, NEGATIVE - PATH FOLLOWER TABLE	-87

CLOSED-LOOP PATH FOLLOWING MODE

X-Y PATH COORDINATES :

X (FEET)	Y (FEET)
0.0	0.0
100.00	0.0
110.00	0.01
115.00	0.02
120.00	0.05
125.00	0.09
130.00	0.15
135.00	0.24
140.00	0.35
145.00	0.50
149.99	0.68
154.99	0.90
159.98	1.16
164.97	1.47
169.96	1.83
174.94	2.25
179.92	2.72
184.89	3.26
189.85	3.86
194.81	4.53
199.75	5.28
204.68	6.10
209.60	7.01
214.50	7.99
219.38	9.07
224.25	10.24
229.08	11.50
233.90	12.85
238.68	14.31
243.43	15.86
248.15	17.51
252.84	19.25
257.49	21.09
262.10	23.02
266.67	25.05
271.20	27.16
275.69	29.37

280.13	31.67
284.52	34.06
288.86	36.54
293.15	39.11
297.39	41.76
301.57	44.50
305.70	47.32
309.77	50.23
313.78	53.21
317.73	56.28
321.61	59.43
325.43	62.66
329.18	65.96
332.87	69.34
336.48	72.80
340.03	76.32
343.50	79.92
346.90	83.59
350.22	87.32
353.47	91.13
356.64	94.99
359.73	98.92
362.74	102.92
365.68	106.96
368.54	111.06
371.32	115.21
374.04	119.41
376.67	123.66
379.24	127.95
381.74	132.28
384.17	136.65
386.54	141.05
388.85	145.49
391.11	149.95
393.31	154.44
395.47	158.95
397.57	163.49
399.63	168.04
401.66	172.61
403.64	177.20
405.59	181.80
407.52	186.42
409.41	191.05
411.29	195.68
413.14	200.33
414.98	204.98
416.80	209.63
418.62	214.29
420.44	218.95
601.99	685.90

DRIVER TRANSPORT LAG (SEC) : 0.0
END OF PREVIEW INTERVAL (SEC) : 0.30
END OF CLOSED LOOP CONTROL (SEC) : 23.00
RAMP-STEER RATE (DEG/SEC) : 0.0

TREADLE PRESSURE TABLE (NUMBER OF LINES) 0
* ZERO ENTRY INDICATES NO FURTHER TABLE DATA IS NECESSARY - THE FOLLOWING TABLE IS ASSIGNED INTERNALLY *
TABLE ENTRIES: TIME (SEC) PRESSURE (PSI)

0.0 0.0

MAXIMUM SIMULATION TIME (SEC)	18.00
TIME INCREMENT OF OUTPUT (SEC)	0.10

ROAD KEY = -1 : USER-DEFINED ROAD SURFACE (SUBROUTINE ROAD).

OUTPUT PAGE OPTION KEYS: 0 DELETES PAGES

SPRUNG MASS POSITION	SPRUNG MASS VELOCITY	SPRUNG MASS ACCELERATION	TIRE FORCES PAGES	BRAKE SUMMARY PAGES	LATERAL PAGES	UNSPRUNG MASS PAGES	TEMP PAGES
1	1	1	1	1	1	1	1

Michigan 3 axle tractor and tandem axle tanker.

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TRACTOR PARAMETERS
------------------

     WHEELBASE - DISTANCE FROM FRONT AXLE TO CENTER  OF REAR SUSPENSION (IN)              136.50
     BASE VEHICLE CURB WEIGHT ON FRONT SUSPENSION (LB)                                   5800.00
     BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)                                    9200.00
     SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)                                              40.00
     SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                  18200.00
     SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)                                 65000.00
     SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)                                   65000.00
     PAYLOAD WEIGHT (LB)                                                                    0.0
          *** ZERO ENTRY INDICATES NO PAYLOAD ***
          *** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***
     FIFTH WHEEL LOCATION (IN. AHEAD OF REAR SUSP. CENTER)                                 27.30
     FIFTH WHEEL HEIGHT ABOVE GROUND (IN)                                                  50.00
     TRACTOR FRAME STIFFNESS (IN-LB/DEG)                                                40000.00
     TRACTOR FRAME TORSIONAL AXIS HEIGHT ABOVE GROUND (IN)                                 38.00

TRACTOR FRONT SUSPENSION AND AXLE PARAMETERS                          LEFT SIDE       RIGHT SIDE
--------------------------------------------                          ---------       ----------

     SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                           -101.00         -101.00
          *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
          *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
     SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                     22.26           22.26
     COULOMB FRICTION (LB/SIDE/AXLE)                                       0.0             0.0
                                                                     ------------------------------
     AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                3700.00
     ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                       18.25
     ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                0.0
     AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                 3824.00
     LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                            32.00
     TRACK WIDTH (IN)                                                            80.00
     UNSPRUNG WEIGHT (LB)                                                      1200.00
     STEERING GEAR RATIO (DEG STEERING WHEEL/DEG ROAD WHEEL)                     30.00
     STEERING STIFFNESS (IN-LB/DEG)                                           11000.00
     TIE ROD STIFFNESS (IN-LB/DEG)                                            11000.00
     MECHANICAL TRAIL (IN)                                                        1.00
     TORSIONAL WRAP-UP STIFFNESS (IN-LB/IN)                                  150000.00
     LATERAL OFFSET OF STEERING AXIS (IN)                                         3.00

TRACTOR FRONT TIRES AND WHEELS                                        LEFT SIDE       RIGHT SIDE
------------------------------                                        ---------       ----------

     CORNERING STIFFNESS  (LB/DEG/TIRE)                                   -1.00           -1.00
          *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
          *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
     LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                              -51.00          -51.00
          *** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
          *** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
     CAMBER STIFFNESS (LB/DEG/TIRE)                                        0.0             0.0
     ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                 -1320.84        -1320.84
       *** NEGATIVE ALIGNING MOMENT ENTRY ***
```

```
 *** ALIGNING MOMENT CURVE FIT PARAMETERS:  (  0.0     8.0000  5.0000  0.8000) (  0.0     8.0000  5.0000  0.8000)
TIRE SPRING RATE (LB/IN/TIRE)                                                    4500.00              4500.00
TIRE LOADED RADIUS (IN)                                                            20.00                20.00
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                      103.00               103.00
```

Michigan 3 axle tractor and tandem axle tanker.

TRACTOR REAR SUSPENSION AND AXLE PARAMETERS

	LEADING TANDEM AXLE		TRAILING TANDEM AXLE	
	LEFT SIDE	RIGHT SIDE	LEFT SIDE	RIGHT SIDE
SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM	1			
TANDEM AXLE SEPARATION (IN BETWEEN LEADING AND TRAILING AXLES)	50.00			
STATIC LOAD TRANSFER (PERCENT LOAD ON LEAD AXLE)	50.00			
DYNAMIC LOAD TRANSFER (% BRAKE TORQUE REACTED AS TANDEM AXLE LOAD TRANSFER)	0.0			
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)	-102.00	-102.00	-102.00	-102.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)	0.0	0.0	0.0	0.0
COULOMB FRICTION (LB/SIDE/AXLE)	0.0	0.0	0.0	0.0

	LEADING TANDEM AXLE	TRAILING TANDEM AXLE
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	4458.00	4458.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)	29.00	29.00
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)	0.0	0.0
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)	8000.00	8000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)	38.00	38.00
TRACK WIDTH (IN)	72.00	72.00
UNSPRUNG WEIGHT (LB)	2300.00	2300.00

TRACTOR REAR TIRES AND WHEELS

	LEADING TANDEM AXLE		TRAILING TANDEM AXLE	
	LEFT SIDE	RIGHT SIDE	LEFT SIDE	RIGHT SIDE
DUAL TIRE SEPARATION (IN)	13.00	13.00	13.00	13.00
CORNERING STIFFNESS (LB/DEG/TIRE)	-1.00	-1.00	-1.00	-1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
LONGITUDINAL STIFFNESS (LB/SLIP/TIRE)	-51.00	-51.00	-51.00	-51.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
CAMBER STIFFNESS (LB/DEG/TIRE)	0.0	0.0	0.0	0.0
ALIGNING MOMENT (IN-LB/DEG/TIRE)	-1320.84	-1320.84	-1320.84	-1320.84
*** NEGATIVE ALIGNING MOMENT ENTRY ***				
*** ALIGNING MOMENT CURVE FIT PARAMETERS:	(0.0 8.0000 5.0000 0.8000)	(0.0 8.0000 5.0000 0.8000)		
*** NEGATIVE ALIGNING MOMENT ENTRY ***				
*** ALIGNING MOMENT CURVE FIT PARAMETERS:	(0.0 8.0000 5.0000 0.8000)	(0.0 8.0000 5.0000 0.8000)		
TIRE SPRING RATE (LB/IN/TIRE)	4500.00	4500.00	4500.00	4500.00
TIRE LOADED RADIUS (IN)	20.00	20.00	20.00	20.00
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)	103.00	103.00	103.00	103.00

*** ZERO LINES IN TREADLE PRESSURE TABLE INDICATES NO BRAKING ***
*** THREE BRAKE PARAMETERS PER AXLE ARE DELETED AT THIS POINT ***

Michigan 3 axle tractor and tandem axle tanker.

TRAILER NO. 1 PARAMETERS

WHEELBASE - DISTANCE FROM KINGPIN TO CENTER OF REAR SUSPENSION (IN)	407.60
BASE VEHICLE KINGPIN STATIC LOAD (LB)	31000.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)	34000.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)	84.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	34570.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)	2763000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)	2763000.00
PAYLOAD WEIGHT (LB)	0.0

*** ZERO ENTRY INDICATES NO PAYLOAD ***
*** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***

TRAILER NO. 1 REAR SUSPENSION AND AXLE PARAMETERS

	LEADING TANDEM AXLE		TRAILING TANDEM AXLE	
	LEFT SIDE	RIGHT SIDE	LEFT SIDE	RIGHT SIDE
SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM		1		
TANDEM AXLE SEPARATION (IN BETWEEN LEADING AND TRAILING AXLES)		50.00		
STATIC LOAD TRANSFER (PERCENT LOAD ON LEAD AXLE)		50.00		
DYNAMIC LOAD TRANSFER (% BRAKE TORQUE REACTED AS TANDEM AXLE LOAD TRANSFER)		0.0		
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)	-103.00	-103.00	-103.00	-103.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)	0.0	0.0	0.0	0.0
COULOMB FRICTION (LB/SIDE/AXLE)	0.0	0.0	0.0	0.0

	LEADING TANDEM AXLE	TRAILING TANDEM AXLE
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	4100.00	4100.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)	29.00	29.00
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)	0.0	0.0
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)	8000.00	8000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)	38.00	38.00
TRACK WIDTH (IN)	72.00	72.00
UNSPRUNG WEIGHT (LB)	1500.00	1500.00

TRAILER NO. 1 REAR TIRES AND WHEELS

	LEADING TANDEM AXLE		TRAILING TANDEM AXLE	
	LEFT SIDE	RIGHT SIDE	LEFT SIDE	RIGHT SIDE
DUAL TIRE SEPARATION (IN)	13.00	13.00	13.00	13.00
CORNERING STIFFNESS (LB/DEG/TIRE)	-1.00	-1.00	-1.00	-1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
LONGITUDINAL STIFFNESS (LB/SLIP/TIRE)	-51.00	-51.00	-51.00	-51.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***				
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***				
CAMBER STIFFNESS (LB/DEG/TIRE)	0.0	0.0	0.0	0.0
ALIGNING MOMENT (IN-LB/DEG/TIRE)	-1320.84	-1320.84	-1320.84	-1320.84

*** NEGATIVE ALIGNING MOMENT ENTRY ***

```
*** ALIGNING MOMENT CURVE FIT PARAMETERS:  (  0.0      8.0000  5.0000  0.8000) (  0.0      8.0000  5.0000  0.8000)
                                           (
*** NEGATIVE ALIGNING MOMENT ENTRY ***
*** ALIGNING MOMENT CURVE FIT PARAMETERS:  (  0.0      8.0000  5.0000  0.8000) (  0.0      8.0000  5.0000  0.8000)
                                           (
TIRE SPRING RATE (LB/IN/TIRE)                                4500.00     4500.00        4500.00     4500.00
TIRE LOADED RADIUS (IN)                                        20.00       20.00          20.00       20.00
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                  103.00      103.00         103.00      103.00
```

Michigan 3 axle tractor and tandem axle tanker.

*** ZERO LINES IN TREADLE PRESSURE TABLE INDICATES NO BRAKING ***
*** THREE BRAKE PARAMETERS PER AXLE ARE DELETED AT THIS POINT ***

ANTILOCK KEY: 1 INDICATES ANTILOCK WILL BE USED . 0

Michigan 3 axle tractor and tandem axle tanker.

TRAILER NO. 1 PAYLOAD = 0.0 LBS.	EMPTY	LOADED
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO REAR SUSPENSION (IN)	203.800	203.800
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO GROUND (IN)	84.000	84.000
ROLL MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	34569.996	34569.996
PITCH MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	2763000.000	2763000.000
YAW MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	2763000.000	2763000.000

TRACTOR PAYLOAD = 0.0 LBS	EMPTY	LOADED
DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO REAR SUSPENSION (IN)	68.250	68.250
DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO GROUND (IN)	40.000	40.000
ROLL MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	18199.996	18199.996
PITCH MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	64999.969	64999.969
YAW MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	64999.969	64999.969

THE STATIC LOADS ON THE AXLES ARE:

AXLE NUMBER	LOAD
NS(1,1,1)	12000.000
NS(1,2,1)	17000.000
NS(1,2,2)	17000.000
NS(2,2,1)	17000.000
NS(2,2,2)	17000.000
TOTAL	80000.000

THE TRACTOR TOTAL MASS CENTER IS 83.720 INCHES BEHIND THE FRONT AXLE
THE TOTAL YAW MOMENT OF INERTIA IS 145755.625 IN-LB-SEC**2

THE FIRST TRAILER TOTAL MASS CENTER IS 213.206 INCHES BEHIND THE KINGPIN
THE TOTAL YAW MOMENT OF INERTIA IS 3083963.000 IN-LB-SEC**2

Michigan 3 axle tractor and tandem axle tanker.

SPRING TABLES

NO. OF LINES	FORCE (LB)	DEFLECTION (IN)	TABLE NO.
9			-101.00
	-20400.00	-15.00	
	-1020.00	-0.75	
	0.0	0.0	
	1550.00	1.00	
	2900.00	2.00	
	4200.00	3.00	
	7700.00	5.50	
	11750.00	8.50	
	21200.00	15.50	
	(SPRING COMPRESSION ENVELOPE)		
	-20700.00	-15.00	
	-1320.00	-0.75	
	-300.00	0.0	
	950.00	1.00	
	2200.00	2.00	
	3450.00	3.00	
	6780.00	5.50	
	10505.00	8.50	
	18953.00	15.50	
	(SPRING EXTENSION ENVELOPE)		

SUSPENSION DEFLECTION CONSTANTS = 0.17000 INCHES COMPRESSION, 0.15000 INCHES EXTENSION.

SPRING STATIC EQUILIBRIUM CONDITION: 5400.00 LB, 4.15 INCHES. UNIT 1 SUSP 1 AXLE 1

NO. OF LINES	FORCE (LB)	DEFLECTION (IN)	TABLE NO.
9			-102.00
	-11562.50	-10.00	
	-5312.50	-5.00	
	0.0	-0.75	
	0.0	0.0	
	1750.00	0.50	
	6550.00	1.50	
	9250.00	2.00	
	33550.00	6.50	
	41650.00	8.00	
	(SPRING COMPRESSION ENVELOPE)		

-11662.50	-10.00
-5412.50	-5.00
-100.00	-0.75
-100.00	0.0
1050.00	0.50
4550.00	1.50
6950.00	2.00
24827.00	6.50
30821.00	8.00

(SPRING EXTENSION ENVELOPE)

SUSPENSION DEFLECTION CONSTANTS = 0.05000 INCHES COMPRESSION, 0.05000 INCHES EXTENSION.

SPRING STATIC EQUILIBRIUM CONDITION: 7350.00 LB, 1.85 INCHES. UNIT 1 SUSP 2 AXLE 1

SPRING STATIC EQUILIBRIUM CONDITION: 7350.00 LB, 1.85 INCHES. UNIT 1 SUSP 2 AXLE 2

7 -103.00

-34062.50	-20.00
-300.00	-1.75
250.00	0.0
1650.00	0.50
4250.00	1.00
7250.00	1.50
31750.00	5.00

(SPRING COMPRESSION ENVELOPE)

-34162.50	-20.00
-400.00	-1.75
0.0	0.0
950.00	0.50
2900.00	1.00
5750.00	1.50
26193.80	5.00

(SPRING EXTENSION ENVELOPE)

SUSPENSION DEFLECTION CONSTANTS = 0.03000 INCHES COMPRESSION, 0.03000 INCHES EXTENSION.

SPRING STATIC EQUILIBRIUM CONDITION: 7750.00 LB, 1.69 INCHES. UNIT 2 SUSP 2 AXLE 1

SPRING STATIC EQUILIBRIUM CONDITION: 7750.00 LB, 1.69 INCHES. UNIT 2 SUSP 2 AXLE 2

Michigan 3 axle tractor and tandem axle tanker.

MU-Y VS ALPHA TABLES

NO. OF LOADS	NO. OF VELOCITIES	TABLE NO.
3	1	-1

VELOCITY = 58.70 FT/SEC LOAD = 1983.00 LB

ALPHA (DEG)	MU - Y
0.0	0.0
1.00	0.18
2.00	0.32
4.00	0.54
8.00	0.77
12.00	0.91

VELOCITY = 58.70 FT/SEC LOAD = 5967.00 LB

ALPHA (DEG)	MU - Y
0.0	0.0
1.00	0.14
2.00	0.27
4.00	0.47
8.00	0.66
12.00	0.73

VELOCITY = 58.70 FT/SEC LOAD = 9441.00 LB

ALPHA (DEG)	MU - Y
0.0	0.0
1.00	0.10
2.00	0.19
4.00	0.36
8.00	0.55
12.00	0.61

ROLL-OFF TABLE

	SLIP						
ALPHA	0.0	0.04	0.10	0.24	0.25	0.50	1.00
0.0	1.00	1.00	0.87	0.40	0.38	0.17	0.06
1.00	1.00	1.00	0.83	0.40	0.38	0.17	0.06
2.00	1.00	1.00	0.81	0.39	0.38	0.17	0.06

4.00	1.00	0.97	0.75	0.39	0.38	0.17	0.06
6.00	1.00	0.96	0.79	0.45	0.44	0.21	0.07
8.00	1.00	0.97	0.84	0.52	0.50	0.25	0.09
12.00	1.00	0.97	0.89	0.63	0.62	0.33	0.12
16.00	1.00	0.98	0.92	0.71	0.70	0.40	0.15

Michigan 3 axle tractor and tandem axle tanker.

MU-X VS. SLIP TABLES

TABLE NO. -51

NO. OF LOADS	NO. OF VELOCITIES
3	3

VELOCITY = 29.30 FT/SEC LOAD = 3020.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.58
0.10	0.81
0.21	0.86
0.25	0.86
0.50	0.79
1.00	0.62

VELOCITY = 58.70 FT/SEC LOAD = 3020.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.51
0.10	0.79
0.21	0.85
0.25	0.85
0.50	0.77
1.00	0.56

VELOCITY = 80.70 FT/SEC LOAD = 3020.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.46
0.10	0.78
0.21	0.84
0.25	0.84
0.50	0.76
1.00	0.52

Michigan 3 axle tractor and tandem axle tanker

VELOCITY = 29.30 FT/SEC LOAD = 6040.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.37
0.10	0.71
0.24	0.80
0.25	0.80
0.50	0.74
1.00	0.54

VELOCITY = 58.70 FT/SEC LOAD = 6040.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.33
0.10	0.69
0.24	0.79
0.25	0.79
0.50	0.72
1.00	0.48

VELOCITY = 80.70 FT/SEC LOAD = 6040.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.30
0.10	0.67
0.24	0.79
0.25	0.78
0.50	0.70
1.00	0.44

VELOCITY = 29.30 FT/SEC LOAD = 9060.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.24
0.10	0.59
0.24	0.74
0.25	0.74
0.50	0.69
1.00	0.46

Michigan 3 axle tractor and tandem axle tanker.

VELOCITY = 58.70 FT/SEC LOAD = 9060.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.22
0.10	0.55
0.24	0.73
0.25	0.73
0.50	0.67
1.00	0.41

VELOCITY = 80.70 FT/SEC LOAD = 9060.00 LB

SLIP	MU - X
0.0	0.0
0.04	0.2C
0.10	0.52
0.24	0.73
0.25	0.73
0.50	0.65
1.00	0.36

ROLL-OFF TABLE

	SLIP						
ALPHA	0.0	0.04	0.10	0.24	0.25	0.50	1.00
0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00
2.00	1.00	1.00	0.96	0.99	0.99	1.00	1.00
4.00	1.00	0.93	0.87	0.96	0 97	0.99	1.00
6.00	0.79	0.78	0.77	0.92	0.93	0.98	0.99
8.00	0.64	0.65	0.67	0.87	0.88	0.96	0.99
12.00	0.44	0.47	0.52	0.77	0.78	0.92	0.98
16.00	0.34	0.37	0.41	0.66	0.68	0.87	0.96

APPENDIX C

INPUT AND RESULTS FOR STATIC ROLL COMPUTATION

Yukon's 3 axle tractor and tandem axle tanker.

```
WU1 =   1200.  WU2 =   4600.  WU3 =   3000.  WAXL1 =   10062.  WAXL2 =   35575.  WAXL3 =   39263.

T1 =  40.00 A1 =    0.0  T2 =  29.50 A2 =  13.00 T3 =  29.50 A3 =  13.00 S1 =  16.00 S2 =  19.00 S3 =  19.00

ZS1 =  46.45 ZS2 =  38.00 ZS3 =  98.10 R1 =  20.00R2 =  20.00 R3 =  20.00

HR1 =  18.25 HR2 =  33.00 HR3 =  27.00 Z5 =  50.00 ZFR =  38.00

KT11 =     4500.0 KT21 =     9000.0 KT31 =     9000.0 KRS1 =       3824. KRS2 =      60000. KRS3 =      18000.

MFR =    40000.0 COULFR =     5000.0 M5 =  1000000.0 MOMSEP = 546074.1

LASH5 =     3.0 W5 =  30337.4 WS2 =    1000.0

KYT1 =     5000.0 KYT2 =    10000.0 KYT3 =    10000.0

KOVT1 =      352.2 KOVT2 =      704.4 KOVT3 =      704.4
DELPH =    0.02 XPRINT =    0.50
```

SPRING TABLE: 1
NO. OF DATA POINTS IN TABLE : 9

FORCE	DEFLECTION
-20550.000	-15.000
-1170.000	-0.750
-150.000	0.0
1250.000	1.000
2550.000	2.000
3825.000	3.000
7240.000	5.500
11127.500	8.500
20076.500	15.500

SPRING TABLE: 2
NO. OF DATA POINTS IN TABLE : 9

FORCE	DEFLECTION
-16215.000	-2.000
-50.000	-0.250
450.000	0.0
1250.000	0.250
2710.000	0.500
4750.000	0.750
8950.000	1.000
38172.000	2.250
101507.000	5.000

SPRING TABLE: 3
NO. OF DATA POINTS IN TABLE : 7

FORCE	DEFLECTION
-53320.301	-10.000
-195.300	-1.500
-100.000	0.0
2300.000	0.250
6000.000	0.500
10750.000	0.750
79085.688	4.500

DATA FROM:

LATERAL ACC	SPRUNG MASS 1	SPRUNG MASS 2	SPRUNG MASS 3	UNSPRG MASS 1	UNSPRG MASS 2	UNSPRG MASS 3	V DEFL T1 AX2	V DEFL T2 AX2	V DEFL T3 AX2	V DEFL T4 AX2	V DELF T1 AX3	V DEFL T2 AX3	V DEFL T3 AX3	V DEFL T4 AX3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.99	0.99	0.99	0.99	1.09	1.09	1.09	1.09
0.032	0.45	0.44	0.52	0.05	0.17	0.15	0.87	0.90	1.07	1.11	0.98	1.01	1.17	1.20
0.064	0.93	0.89	1.04	0.10	0.33	0.31	0.74	0.82	1.16	1.23	0.86	0.93	1.25	1.32
0.096	1.45	1.33	1.56	0.16	0.50	0.46	0.62	0.73	1.24	1.36	0.75	0.86	1.33	1.43
0.127	1.96	1.79	2.08	0.21	0.65	0.61	0.51	0.65	1.32	1.47	0.64	0.78	1.40	1.54
0.158	2.48	2.24	2.60	0.27	0.81	0.77	0.39	0.57	1.40	1.59	0.52	0.70	1.48	1.66
0.184	2.98	2.70	3.12	0.32	0.94	0.91	0.29	0.51	1.47	1.68	0.42	0.62	1.56	1.76
0.209	3.48	3.17	3.64	0.37	1.06	1.05	0.20	0.44	1.53	1.77	0.32	0.55	1.63	1.87
0.230	3.97	3.64	4.16	0.41	1.17	1.17	0.12	0.39	1.59	1.85	0.23	0.49	1.69	1.95
0.240	4.28	3.98	4.68	0.44	1.23	1.24	0.08	0.36	1.62	1.90	0.17	0.45	1.73	2.01
0.234	4.21	3.93	5.20	0.43	1.22	1.25	0.09	0.37	1.61	1.89	0.17	0.45	1.73	2.01
0.227	4.13	3.87	5.72	0.42	1.20	1.26	0.10	0.37	1.60	1.88	0.16	0.45	1.73	2.02
0.221	4.06	3.82	6.24	0.41	1.19	1.26	0.11	0.38	1.59	1.86	0.16	0.45	1.73	2.02
0.214	3.98	3.77	6.76	0.40	1.17	1.27	0.12	0.39	1.59	1.85	0.16	0.44	1.74	2.02
0.219	4.04	3.81	7.28	0.41	1.18	1.34	0.11	0.38	1.59	1.86	0.10	0.40	1.78	2.08
0.232	4.42	4.21	7.80	0.44	1.25	1.43	0.06	0.35	1.63	1.91	0.03	0.36	1.82	2.15
0.246	4.88	4.69	8.32	0.48	1.33	1.56	0.00	0.31	1.67	1.97	-0.08	0.28	1.87	2.22
0.262	5.33	5.16	8.84	0.52	1.52	1.71	-0.18	0.17	1.72	2.07	-0.23	0.16	1.91	2.30
0.278	5.78	5.62	9.36	0.56	1.71	1.87	-0.36	0.02	1.77	2.16	-0.38	0.04	1.95	2.37
0.281	5.87	5.72	9.46	0.57	1.75	1.90	-0.40	-0.00	1.78	2.18	-0.41	0.02	1.96	2.39
0.281	5.97	5.84	9.58	0.57	1.88	1.93	-0.58	-0.15	1.77	2.19	-0.44	-0.00	1.96	2.40

999.000

Michigan 3 axle tractor and tandem axle tanker.

WU1 = 1200. WU2 = 4600. WU3 = 3000. WAXL1 = 12000. WAXL2 = 34000. WAXL3 = 34000.

T1 = 40.00 A1 = 0.0 T2 = 29.50 A2 = 13.00 T3 = 29.50 A3 = 13.00 S1 = 16.00 S2 = 19.00 S3 = 19.00

ZS1 = 42.00 ZS2 = 38.00 ZS3 = 84.00 R1 = 20.00R2 = 20.00 R3 = 20.00

HR1 = 18.25 HR2 = 29.00 HR3 = 29.00 Z5 = 50.00 ZFR = 38.00

KT11 = 4500.0 KT21 = 9000.0 KT31 = 9000.0 KRS1 = 3824. KRS2 = 16000. KRS3 = 16000.

MFR = 40000.0 COULFR = 5000.0 M5 = 1000000.0 MOMSEP = 558000.0

LASH5 = 3.0 W5 = 31000.0 WS2 = 1000.0

KYT1 = 5000.0 KYT2 = 10000.0 KYT3 = 10000.0

KOVT1 = 352.2 KOVT2 = 704.4 KOVT3 = 704.4
DELPH = 0.02 XPRINT = 0.50

SPRING TABLE: 1
NO. OF DATA POINTS IN TABLE : 9

FORCE	DEFLECTION
-20550.000	-15.000
-1170.000	-0.750
-150.000	0.0
1250.000	1.000
2550.000	2.000
3825.000	3.000
7240.000	5.500
11127.500	8.500
20076.500	15.500

SPRING TABLE: 2
NO. OF DATA POINTS IN TABLE : 9

FORCE	DEFLECTION
-23225.000	-10.000
-10725.000	-5.000
-100.000	-0.750
-100.000	0.0
2800.000	0.500
11100.000	1.500
16200.000	2.000
58377.000	6.500
72471.000	8.000

SPRING TABLE: 3
NO. OF DATA POINTS IN TABLE : 7

FORCE	DEFLECTION
-68225.000	-20.000
-700.000	-1.750
250.000	0.0
2600.000	0.500
7150.000	1.000
13000.000	1.500
57943.801	5.000

DATA FROM:

LATERAL ACC	SPRUNG MASS 1	SPRUNG MASS 2	SPRUNG MASS 3	UNSPRG MASS 1	UNSPRG MASS 2	UNSPRG MASS 3	V DEFL T1 AX2	V DEFL T2 AX2	V DEFL T3 AX2	V DEFL T4 AX2	V DELF T1 AX3	V DEFL T2 AX3	V DEFL T3 AX3	V DEFL T4 AX3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
0.028	0.49	0.49	0.52	0.05	0.10	0.12	0.87	0.89	1.00	1.02	0.86	0.88	1.01	1.03
0.055	0.98	0.98	1.04	0.11	0.20	0.24	0.80	0.84	1.05	1.09	0.77	0.82	1.07	1.12
0.082	1.48	1.47	1.56	0.16	0.30	0.35	0.72	0.79	1.10	1.16	0.68	0.76	1.13	1.21
0.108	2.00	1.96	2.08	0.22	0.39	0.47	0.66	0.74	1.14	1.23	0.60	0.70	1.19	1.29
0.134	2.52	2.45	2.60	0.27	0.48	0.58	0.59	0.70	1.19	1.30	0.51	0.64	1.24	1.38
0.158	3.04	2.94	3.12	0.33	0.57	0.69	0.52	0.65	1.24	1.37	0.43	0.59	1.30	1.46
0.182	3.55	3.44	3.64	0.38	0.66	0.80	0.45	0.60	1.29	1.44	0.36	0.54	1.35	1.53
0.206	4.06	3.93	4.16	0.44	0.76	0.90	0.39	0.56	1.33	1.50	0.28	0.48	1.41	1.61
0.226	4.54	4.41	4.68	0.48	0.84	0.99	0.32	0.51	1.38	1.57	0.22	0.44	1.45	1.67
0.245	5.03	4.90	5.20	0.53	0.93	1.07	0.26	0.47	1.42	1.63	0.16	0.40	1.49	1.73
0.258	5.48	5.39	5.72	0.57	1.00	1.12	0.21	0.43	1.45	1.68	0.12	0.37	1.52	1.77
0.267	5.92	5.87	6.24	0.60	1.06	1.15	0.16	0.40	1.49	1.73	0.10	0.36	1.53	1.79
0.274	6.37	6.36	6.76	0.64	1.12	1.18	0.12	0.37	1.52	1.77	0.08	0.34	1.55	1.81
0.273	6.87	6.88	7.28	0.67	1.13	1.20	0.11	0.37	1.52	1.78	0.06	0.33	1.56	1.83
0.272	7.32	7.39	7.80	0.69	1.14	1.21	0.10	0.36	1.53	1.79	0.05	0.32	1.56	1.84
0.276	7.74	7.88	8.32	0.72	1.18	1.24	0.07	0.34	1.55	1.82	0.03	0.31	1.58	1.86
0.288	8.20	8.39	8.84	0.76	1.23	1.32	0.03	0.31	1.57	1.85	-0.04	0.26	1.61	1.91
0.299	8.66	8.89	9.36	0.80	1.29	1.43	-0.01	0.29	1.60	1.89	-0.15	0.18	1.64	1.96
0.309	9.11	9.39	9.88	0.83	1.38	1.54	-0.09	0.22	1.62	1.94	-0.25	0.10	1.67	2.02
0.319	9.57	9.89	10.40	0.87	1.46	1.65	-0.18	0.15	1.65	1.98	-0.36	0.01	1.70	2.07
0.321	9.63	9.97	10.48	0.88	1.48	1.67	-0.19	0.14	1.65	1.99	-0.38	-0.00	1.70	2.08
0.320	9.96	10.39	10.92	0.90	1.53	2.14	-0.25	0.10	1.66	2.01	-1.02	-0.54	1.65	2.13
0.320	10.35	10.88	11.44	0.92	1.60	2.70	-0.31	0.05	1.68	2.04	-1.79	-1.17	1.58	2.20
0.312	10.20	10.74	11.96	0.90	1.56	3.17	-0.28	0.08	1.67	2.03	-2.43	-1.71	1.53	2.25
0.305	10.05	10.60	12.48	0.89	1.53	3.64	-0.24	0.10	1.66	2.01	-3.07	-2.24	1.48	2.30
0.297	9.91	10.47	13.00	0.87	1.49	4.11	-0.21	0.13	1.65	1.99	-3.71	-2.78	1.42	2.36
0.290	9.76	10.33	13.52	0.85	1.46	4.58	-0.18	0.15	1.65	1.98	-4.35	-3.31	1.37	2.41
0.285	9.84	10.46	14.04	0.85	1.47	5.09	-0.19	0.15	1.65	1.98	-5.04	-3.88	1.31	2.47
0.285	10.23	10.95	14.56	0.88	1.53	5.65	-0.25	0.10	1.67	2.01	-5.80	-4.52	1.25	2.53
0.284	10.56	11.37	15.00	0.90	1.59	6.12	-0.30	0.06	1.68	2.04	-6.44	-5.05	1.20	2.58

999.000

INTRODUCTION

The Static Roll Model is a computer-based model which is useful for calculating the rollover threshold of articulated vehicles during steady turning maneuvers. The dynamics of roll motion are not included in the model. Instead, the roll response in a steady turn is computed by repeatedly solving, for small increments of roll angle, a set of equations which describe the static equilibrium of the vehicle in the roll plane. In reference [2], experimental evidence is used to show that the Static Roll Model is capable of predicting the rollover threshold of articulated vehicles with a high level of accuracy.

The likelihood that either maneuvering or accident-induced forces can cause a rollover is strongly influenced by the steady turning rollover threshold of the vehicle.[2] Hence, if the rollover immunity level of heavy vehicles is to be enhanced, it is essential to gain a broad understanding of the rollover process and to develop the analytical tools that can be used for evaluating the various methods by which the rollover threshold of a vehicle can be improved.

ENGINEERING UNITS AND COMPUTER REQUIREMENTS

Throughout the program, the English system of units is used. All input data are given in the units of pounds, inches, degrees, and seconds. Masses and weights are in units of pounds, with a gravitational constant of 386 in/sec/sec assumed.

The Static Roll model is written for use on any large-scale computer system, and requires only one input and one output device. The source code is written in the level-G FORTRAN IV language.

Copies of the program and documentation are available to the public through the Engineering Research Division, The University of Michigan Transportation Research Institute, 2901 Baxter Road, Ann Arbor, Michigan, 48109.

STATIC ROLL INPUT

The input to the Static Roll Model is submitted to the model in one text file, which is detailed below. This file is attached to the logical I/O unit 5, and is written in fixed format. (Depending on the system used, the model may also accept the data with only commas, no spaces, separating the values.)

This model is designed to only accept input for a tractor and semi-trailer. In order to simulate a conventional (A-type) double combination, two runs of the model are necessary. The first run should include input for the tractor and the first semi-trailer. The second run should represent the second semi-trailer as a full-trailer, with all variables that reference the tractor rear suspension replaced with information about the dolly attached to the front of the semi. In this run, the front end of the tractor is to be effectively ignored, so most values refering to this may remain the same as in the first run. The exceptions are the weight of the tractor's front axle (WU_1), and the front axle load of the tractor ($WAXL_1$), which should be assigned low values (1 to 20 lbs). Triples may be simulated by using three runs of the model. A straight three-suspension truck may be simulated by increasing the fifth wheel roll stiffness (M5) and the moment of separation (MOMSEP) to to a high value (999999.9). A straight two-suspension truck can be simulated by entering large values for M5 and MOMSEP and low values for WU_1 and $WAXL_1$. See sample runs in appendix for input and ouput file examples.

INPUT DATA FILE

Line #1

TITLE : The title line is an alpha-numeric string of up to 80 characters in length. This title is supplied by the user to identify the simulation run. The program reads the title in 20A4 format, and the program variable is HEAD.

Line #2

WEIGHT OF THE FRONT AXLE OF THE TRACTOR : This variable indicates the weight of the front axle of the tractor in lbs. In this context, "axle weight" comprises the sum of the elements constituting the front unsprung mass. This parameter is read by the program in F10.2 format, and the program variable is WU_1.

WEIGHT OF THE REAR AXLE OF THE TRACTOR : If the tractor has tandem rear axles, the weight of both axles in lbs are combined. It is read by the program in F10.2 format, and the program variable is WU_2.

WEIGHT OF THE TRAILER AXLES : For multiple axles, combine the weight of all trailer axles in lbs. The number is entered in F10.2 format, and the program variable is WU_3.

TRACTOR FRONT AXLE LOAD : This variable is the measure of the total load carried by ONLY the front axle of the tractor in lbs. It is read by the program in F10.2 format, and the program variable is $WAXL_1$.

TRACTOR REAR AXLE LOAD : If the tractor has tandem axles, then combine the load in lbs carried by both these axles. This number is entered in F10.2 format, and the program variable is $WAXL_2$.

TRAILER AXLE LOAD : This is a measure in lbs of the load carried by the trailer axles. For multiple axles, combine the load carried by all trailer axles. The format for this variable is F10.2, and the program variable is $WAXL_3$.

TRACTOR TIRE LATERAL SPACING : This variable is half the lateral distance between the inner tires (center to center) on the tractor's front axle. For the normal single tire installations, this variable is equal to half the lateral distance between the single tires. The single tire convention is used for all the following lateral spacing parameters. This variable is measured in inches, and is written in F10.2 format. The program variable is T_1.

TRACTOR DUAL SPACING : This parameter is a measure in inches of the spacing between dual tires, if they exist, on the front axle of the tractor. For normal single tires, this parameter is set to zero. The parameter is read by the program in F10.2 format, and the program variable is A_1.

TRACTOR REAR TIRE LATERAL SPACING : The value of this parameter is the measure in inches of half the lateral distance between the inner tires (center to center) on the tractor rear axles. It is written in F10.2 format, and the program variable is T_2.

TRACTOR REAR DUAL SPACING : The value of this parameter is a measure in inches of the spacing between dual tires, if they exist, on the rear axle of the tractor. For single tires, this parameter is set to zero. It is written in F10.2 format, and the program variable is A_2.

TRAILER TIRE LATERAL SPACING : This variable is half the lateral distance between the inner tires (center to center) on the trailer axle measured in inches. The program reads this variable in F10.2 format, and the program variable is T_2.

TRAILER DUAL SPACING : Trailer dual spacing is a measure in inches of the dual tire spacing on the rear axles of the trailer. For single tires, this parameter is set to zero. It is read in F10.2 format, and the program variable is A_3.

TRACTOR SPRING SPACING : This parameter is a measure in inches of half the lateral distance between the suspension springs on the front axle of the tractor. It is read in F10.2 format, and the program variable is S_1.

TRACTOR REAR SPRING SPACING : Half the lateral distance between the suspension springs on the rear axles of the tractor, in inches, is represented by this variable. It is read in F10.2 format, and the program variable is S_2.

TRAILER SPRING SPACING : This variable is half the lateral distance between the suspension springs on the axles on the trailer. It is measured in inches, and written in F10.2 format. The program variable is S_3.

Line #3

HEIGHTS : On this line height dimensions in inches are entered. Each entry is in F10.2 format, and the order of the entries is as follows.

>Height of tractor's front sprung mass above the ground - (ie. the portion of the tractor's sprung mass at the forward end of the spring frame). This and the following height dimensions apply to the condition when the vehicle is loaded as desired and the trailer is coupled. The program variable is ZS_1.

>Height of the tractor's rear sprung mass - (ie. the portion of the tractor's sprung mass at the aft end of the frame spring). Program variable is ZS_2.

>Height of the trailer's sprung mass - Program variable is ZS_3.

>Height of the tractor's front unsprung (or "axle") mass - Program variable is Z_1.

>Height of the tractor's rear unsprung mass - Program variable is Z_2.

>Height of the trailer's unsprung mass - Program variable is Z_3.

>Roll Center Height of tractor's front suspension - Program variable is HR_1.

>Roll Center Height of tractor's rear suspension - Program variable is HR_2.

>Roll Center Height of trailer's suspension - Program variable is HR_3.

>Fifth Wheel Height above the ground - Program variable is Z5.

>Tractor Frame Height above the ground - (ie. the height of the center line of the tractor frame.) Program variable is ZFR.

Line #4

VERTICAL STIFFNESSES : The next three entries are vertical stiffnesses of the tires on the vehicle. They are measured in lb/in. and are written in F10.2 format. The order of input is as follows.

>Vertical Stiffness of ONE tire on the front axle of the tractor. Note that the dual spacing parameter A_1 must have been set to zero in order to establish single tire installation on this axle. Program variable is KT_{11}.

>Vertical Stiffness of ONE tire on the rear axle of the tractor, multiplied by the number of axles on the rear suspension. The case of dual tires is automatically accomodated in the program when variable A_2 is entered as a nonzero value. Program variable is KT_{21}.

>Vertical Stiffness of ONE tire on the trailer axles, multiplied by the number of axles on the rear suspension. The case of dual tires is automatically accommodated when the variable A_3 is nonzero. Program variable is KT_{31}.

AUXILIARY ROLL STIFFNESSES : The last three entries on this line are auxiliary roll stiffnesses of the suspension of the vehicle. They are measured in in-lb/deg, and are written in F10.2 format. The order of input is as follows :

>Auxiliary Roll Stiffness of the tractor's front suspension Program variable is KRS_1.

>Combined Auxiliary Roll Stiffness of all the axles on the tractor's rear suspension. Program variable is KRS_2.

>Combined Auxiliary Roll Stiffness of all the axles on the trailer. Program variable is KRS_3.

Line #5

TRACTOR FRAME TORSIONAL STIFFNESS : This variable represents the torsional stiffness of the tractor frame in transmitting roll moments between the "front" and "rear" tractor sprung masses. It is measured in in-lb/deg, and is written in F10.2 format. The program variable is MFR.

COULOMB FRICTION : Coulomb friction in the torsional response of the tractor frame is represented by this parameter. It is measured in in-lbs, and written in F10.2 format. The program variable is COULFR.

FIFTH WHEEL ROLL STIFFNESS : This variable represents the torsional stiffness of the fifth wheel coupling in transmitting roll moment from the trailer to the frame of the tractor. It is measured in in-lb/deg, and is written in F10.2 format. The program variable is M5.

FIFTH WHEEL SEPARATION MOMENT: This parameter indicates the roll moment that is necessary to separate the fifth wheel from the trailer's upper coupler plate. It is measured in in-lbs, and is read by the program in F10.2 format. The program variable is MOMSEP.

FIFTH WHEEL SEPARATION: This parameter, measured in degrees, represents the angular separation which can be achieved between the fifth wheel and the trailer's upper coupler plate. This moment is generally equal to the fifth wheel load multiplied by the half-width of the fifth wheel plate. It is written in F10.2 format, and the program variable is LASH5.

FIFTH WHEEL LOAD: The vertical load carried by the fifth wheel is represented by this parameter. It is measured in lbs, and written in F10.2 format. The program variable is W5.

TRACTOR REAR SPRUNG WEIGHT: This variable indicates the sprung weight situated at the rear of the tractor frame spring. It is measured in lbs, and usually ranges from 500 to 1000 lbs. It is read by the program in F10.2 format, and the program variable is WS_2.

Line #6

LATERAL STIFFNESSES: The next three entries are the lateral stiffnesses of the tires on the vehicle. They are measured in lb/in, and written in F10.2 format. The order of the entries are as follows.

>Lateral Stiffness of ONE tire on the tractor's front axle. Program variable is KYT_1.

>Lateral Stiffness of ONE tire on the tractor's rear axle multiplied by the number of rear axles. Program variable is KYT_2.

>Lateral Stiffness of ONE tire on the trailer's axles multiplied by the number of axles on the trailer. Program variable is KYT_3.

OVERTURNING STIFFNESSES: The next three entries are the overturning stiffness of the tires on the vehicle. They are measured in in-lb/deg, and are written in F10.2 format. The order of the entries are as follows.

>Overturning Stiffness of ONE tire on the tractor's front axle. Program variable is $KOVT_1$.

>Overturning Stiffness of ONE tire on the tractor's rear axle multiplied by the number of rear axles. Program variable is $KOVT_2$.

>Overturning Stiffness of ONE tire on the trailer's axle multiplied by the number of axles on the trailer. Program variable is $KOVT_3$.

ROLL INCREMENT: This variable represents the increment of trailer roll angle used for computing roll response. A typical value for this is 0.02 degrees. Large values can result in significant errors in the computed roll response. The roll increment is measured in degrees and written in F10.2 format. The program variable is DELPH.

PRINT INCREMENT: This parameter indicates the frequency of data printed out. The print out is triggered by the roll angle, and thus a roll angle increment is entered. The value of 0.5 degrees is usually suitable. This parameter is measured in degrees and written in F10.2 format. The program variable is XPRINT.

Line #8 - To The End

SPRING TABLES: The last section of the data file consists of three spring tables, one each for the tractor front axle, tractor rear axle(s), and trailer axle(s). The first line of each table consists only of an integer, NUM_i in I2 format, indicating the number of lines in the table that follows. After this, the spring table is listed with the force [lbs], FOR_{ij}, in the first column, and deflection [in], DEL_{ij}, in the second column. Both of these values are written in **F10.3** format. The table should start at the tensile end of the force deflection characteristic.

SIGN CONVENTION: Tensil forces, and deflections in the tensile region of the force deflection characteristic, are assumed to be negative.

TANDEM AXLES: Only one spring table is included in the input file for each suspension. In the case of tandem axles on the tractor rear or trailer, the force values reflect the sum of the spring loads which derive on one side of the suspension, as a function of vertical deflection. In the case of a two-axle tandem having a spring over each axle, for example, the entered force values would be equal to twice those measured in the deflection of a single spring.

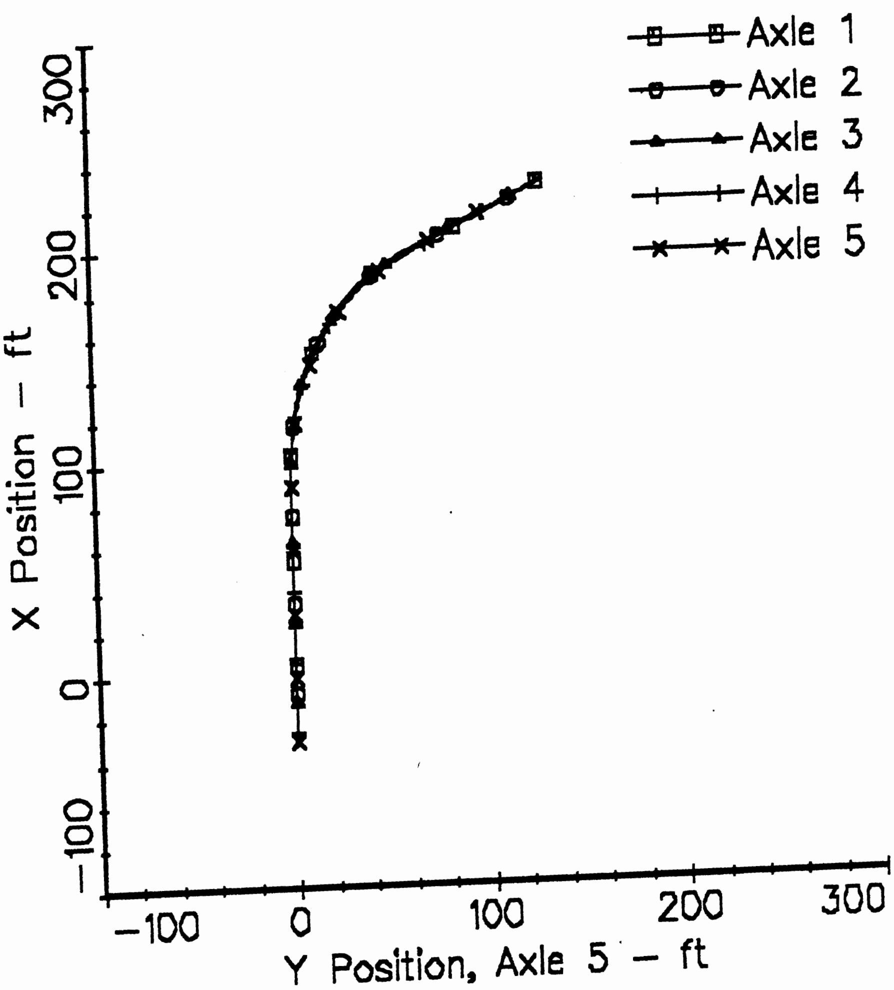
APPENDIX D

PLOTTED RESPONSE OF VEHICLE ON THE EXISTING AND PROPOSED ROADWAYS

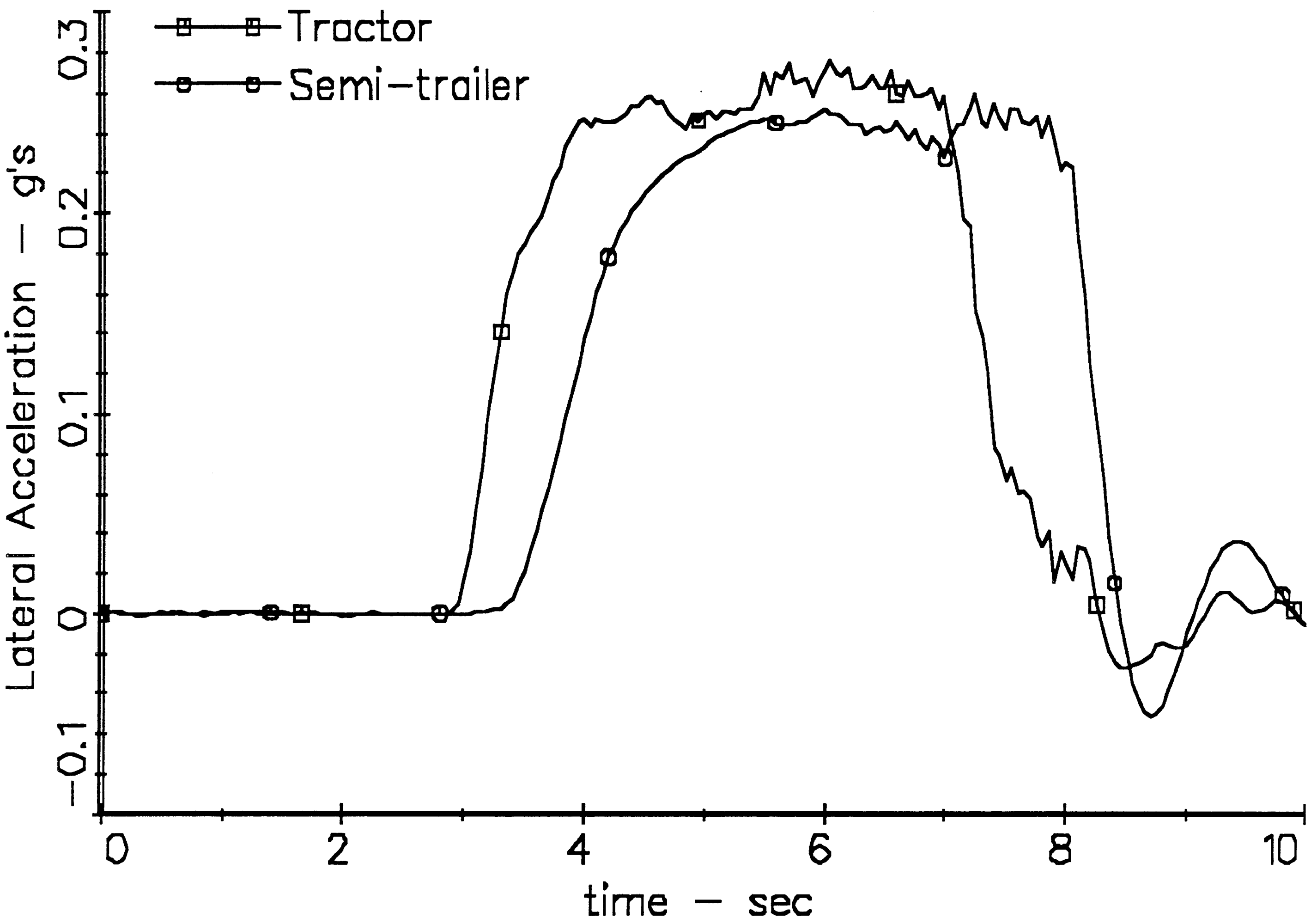
Yukon Tanker, Existing Roadway, 32.9 km/h

Jan 28, '87

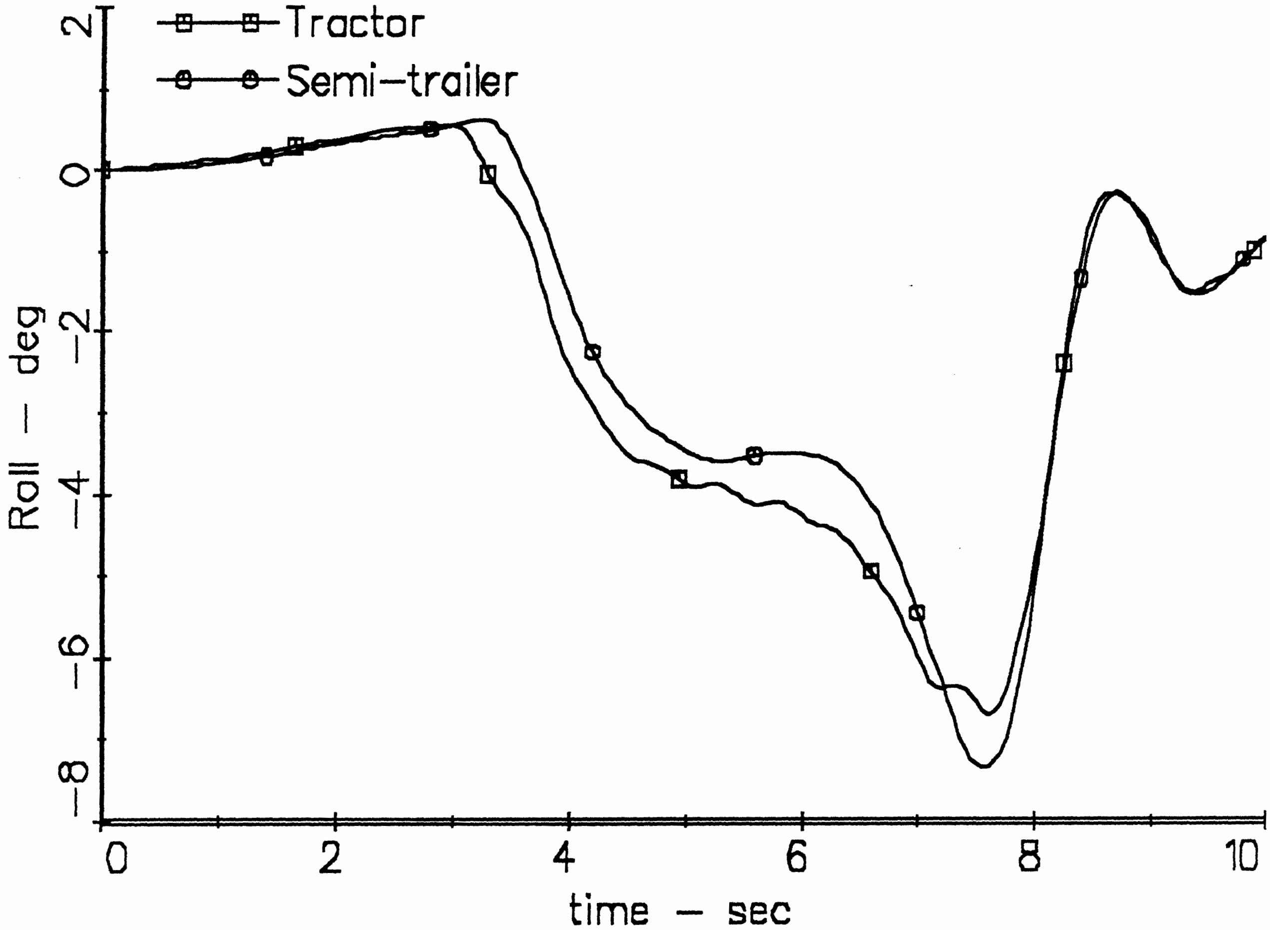
* Ay = 0.25 g's
* Existing intersection
* Yukon's vehicle
* With superelevation



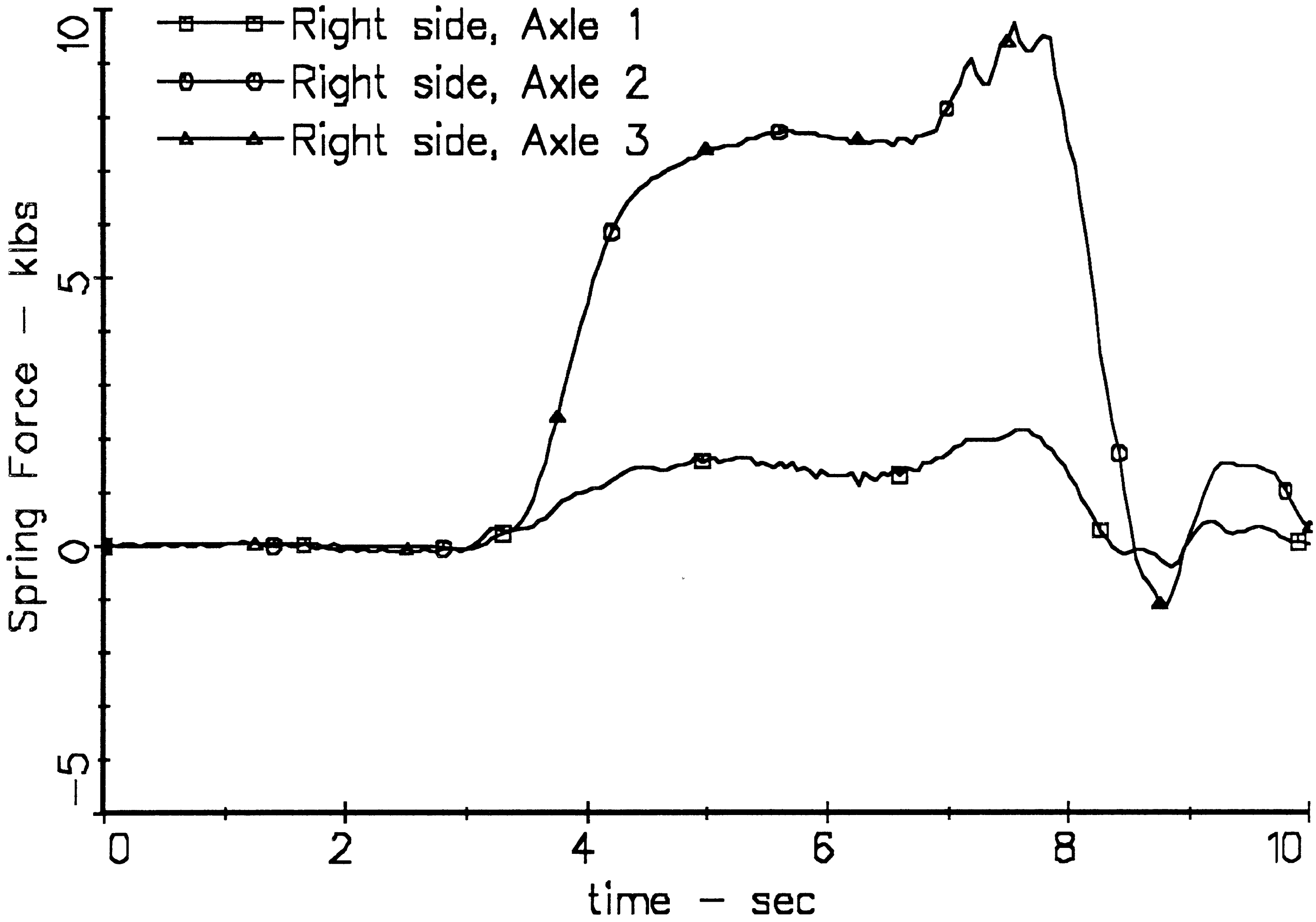
Yukon's 3 axle tractor and tandem axle tanker.



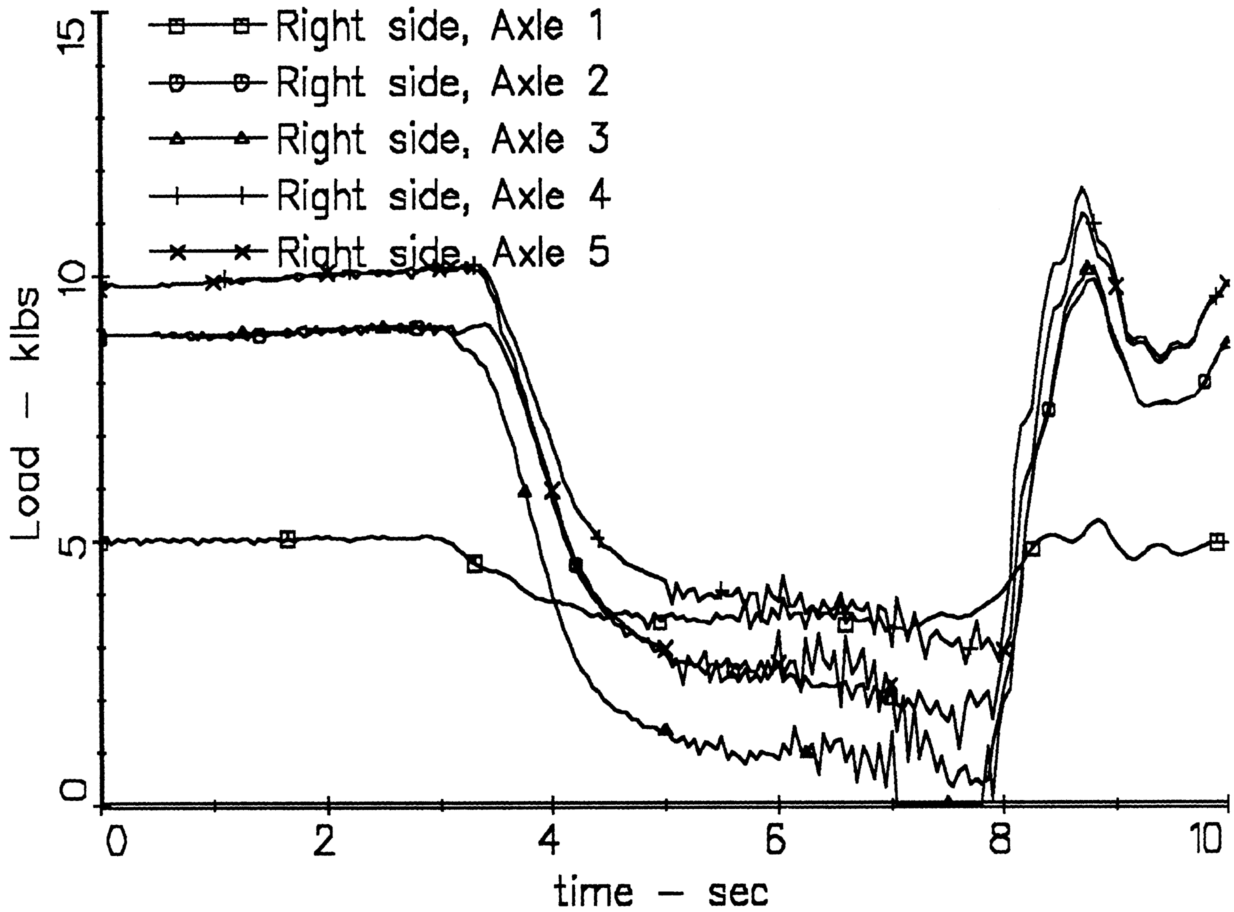
Yukon's 3 axle tractor and tandem axle tanker.



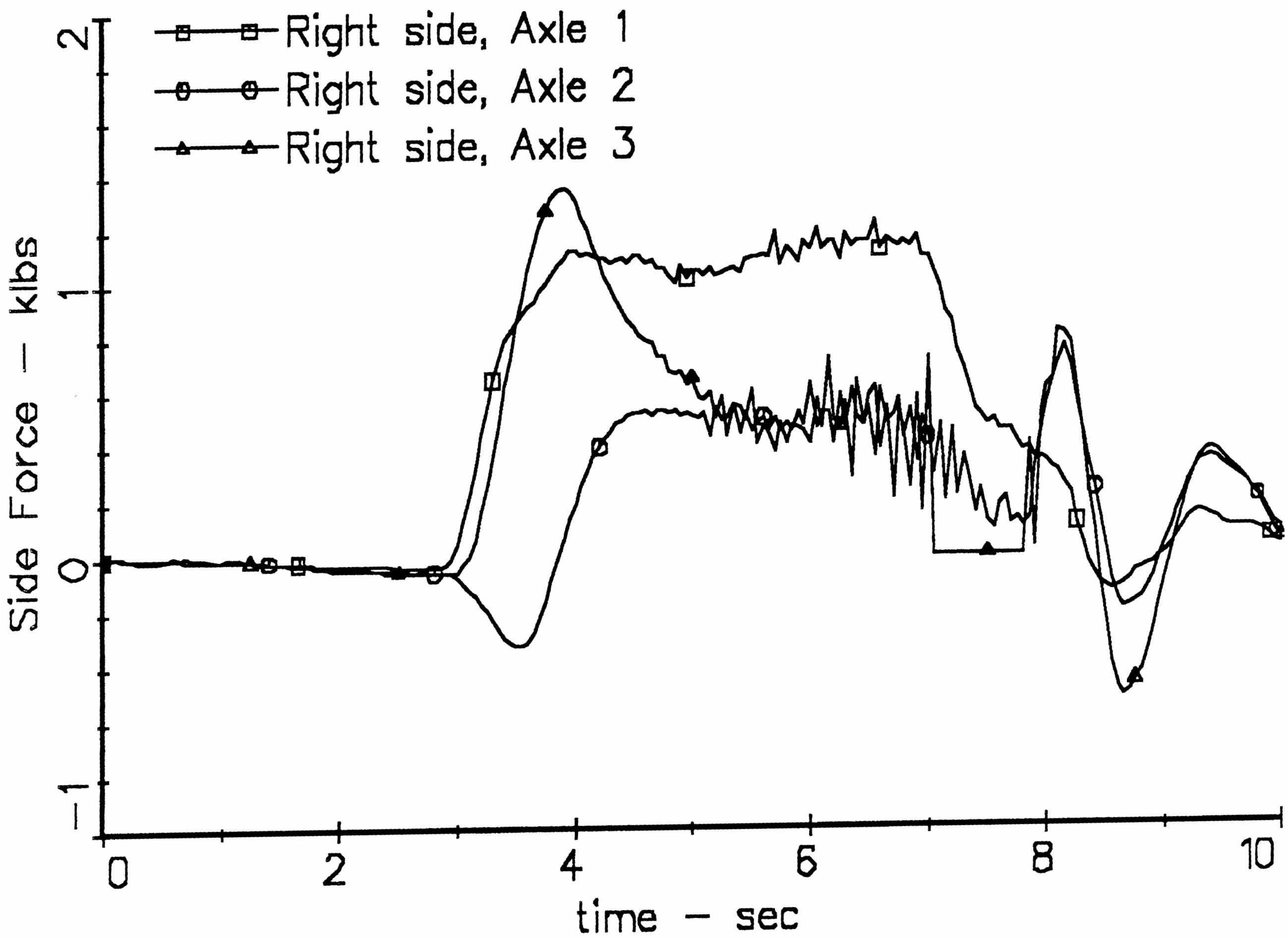
Yukon's 3 axle tractor and tandem axle tanker.



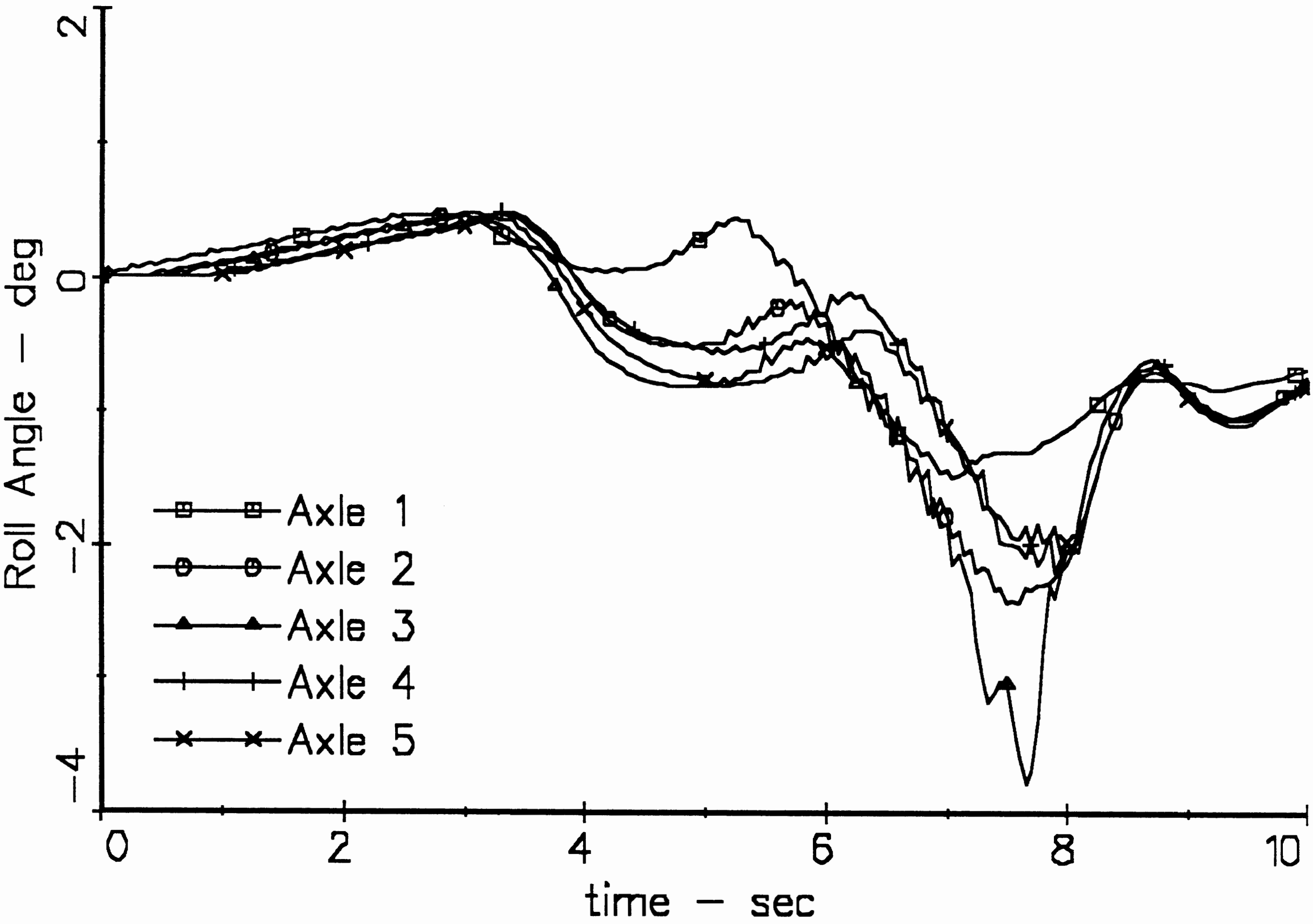
Yukon's 3 axle tractor and tandem axle tanker.



Yukon's 3 axle tractor and tandem axle tanker.



Yukon's 3 axle tractor and tandem axle tanker.

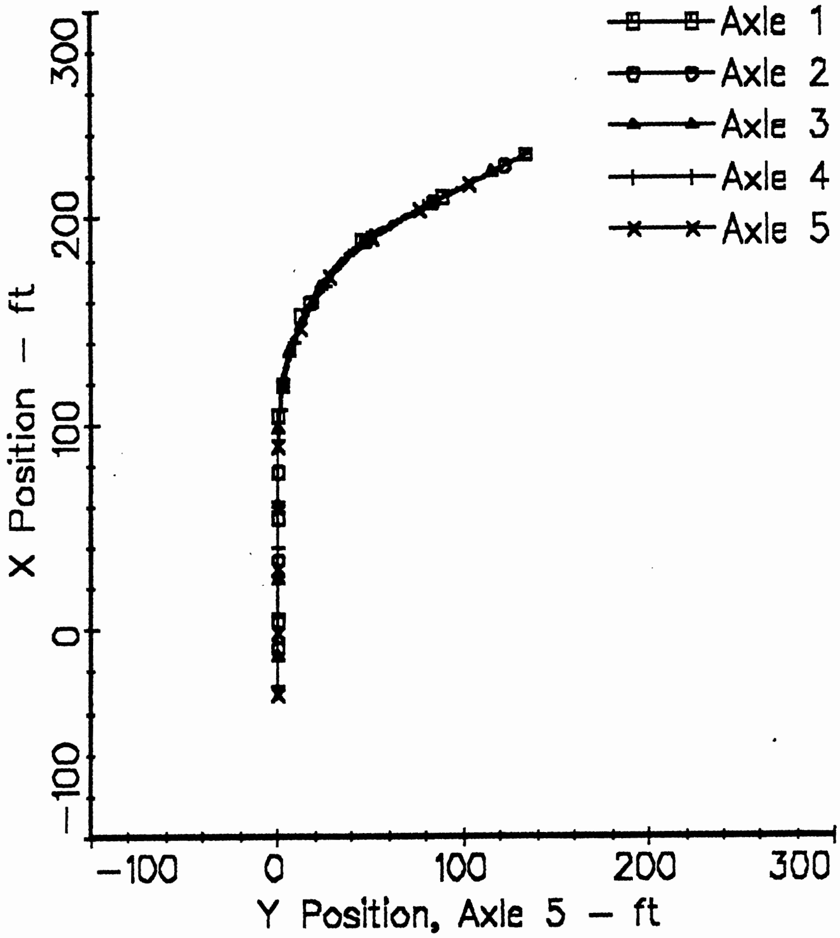


Yukon's 3 axle tractor and tandem axle tanker.

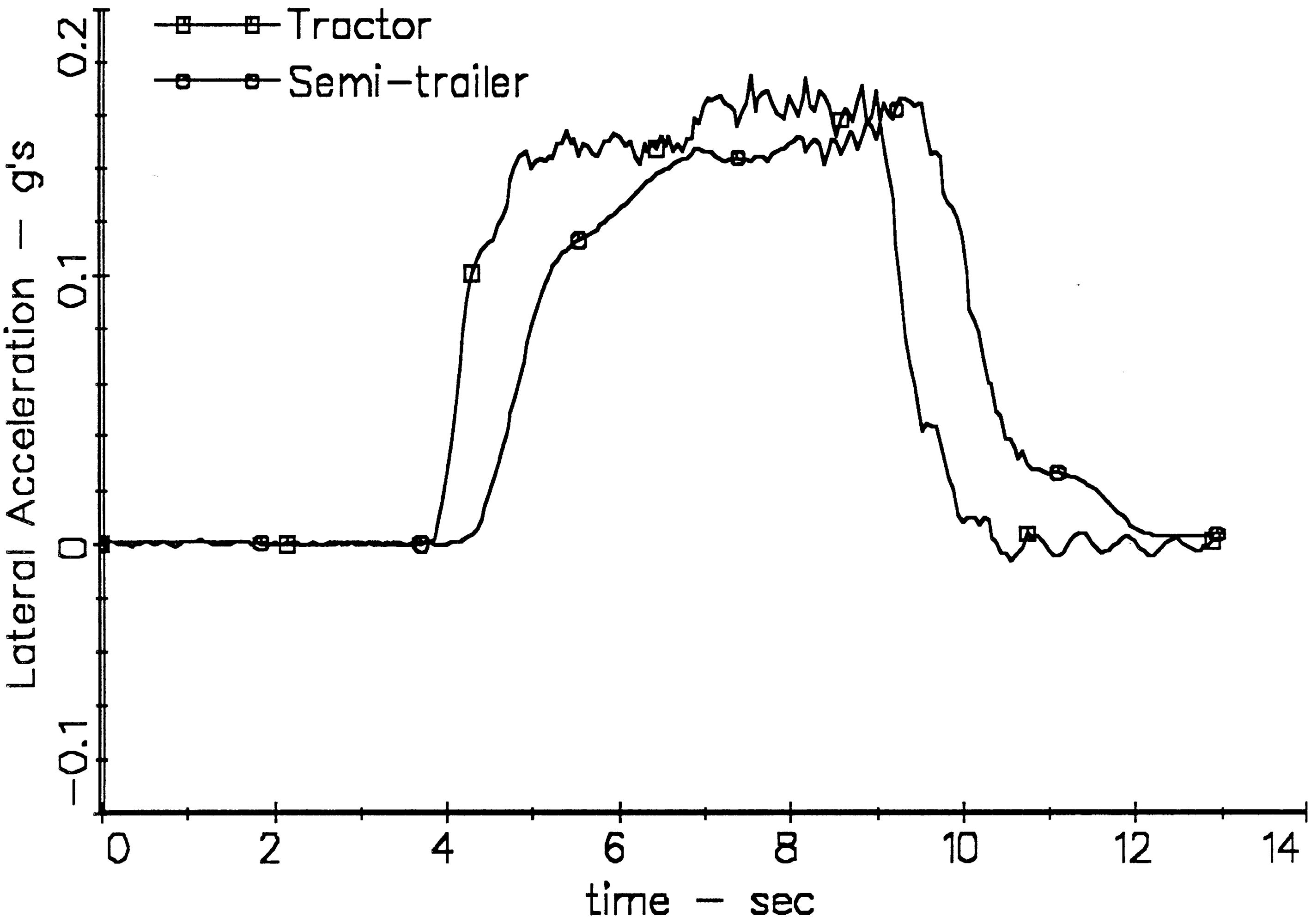
Yukon Tanker, Existing Roadway, 25.5 km/h

Jan 28, 87

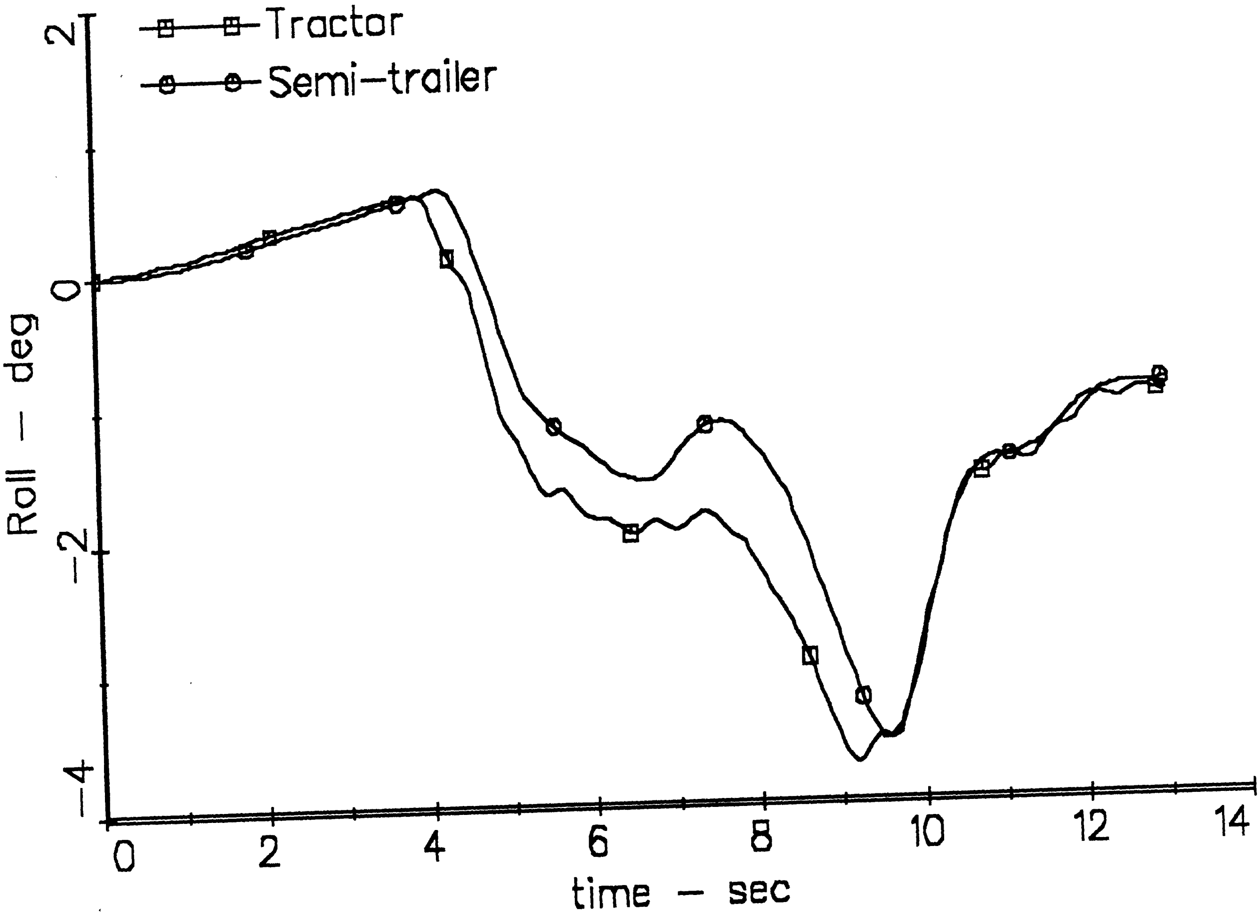
* A_y = 0.15 g's
* Existing intersect
* Yukon's vehicle
* With superelevat



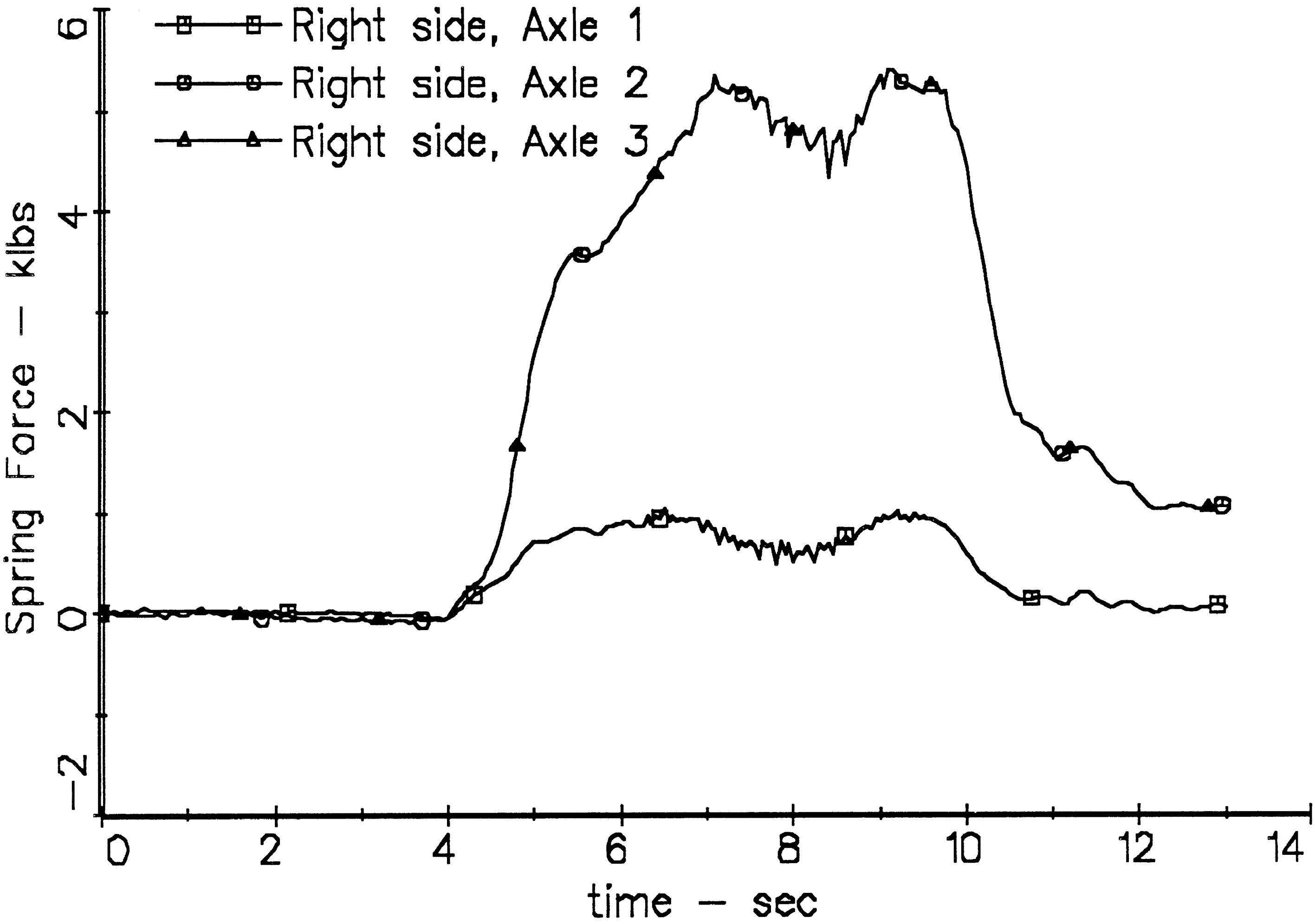
Yukon's 3 axle tractor and tandem axle tanker.



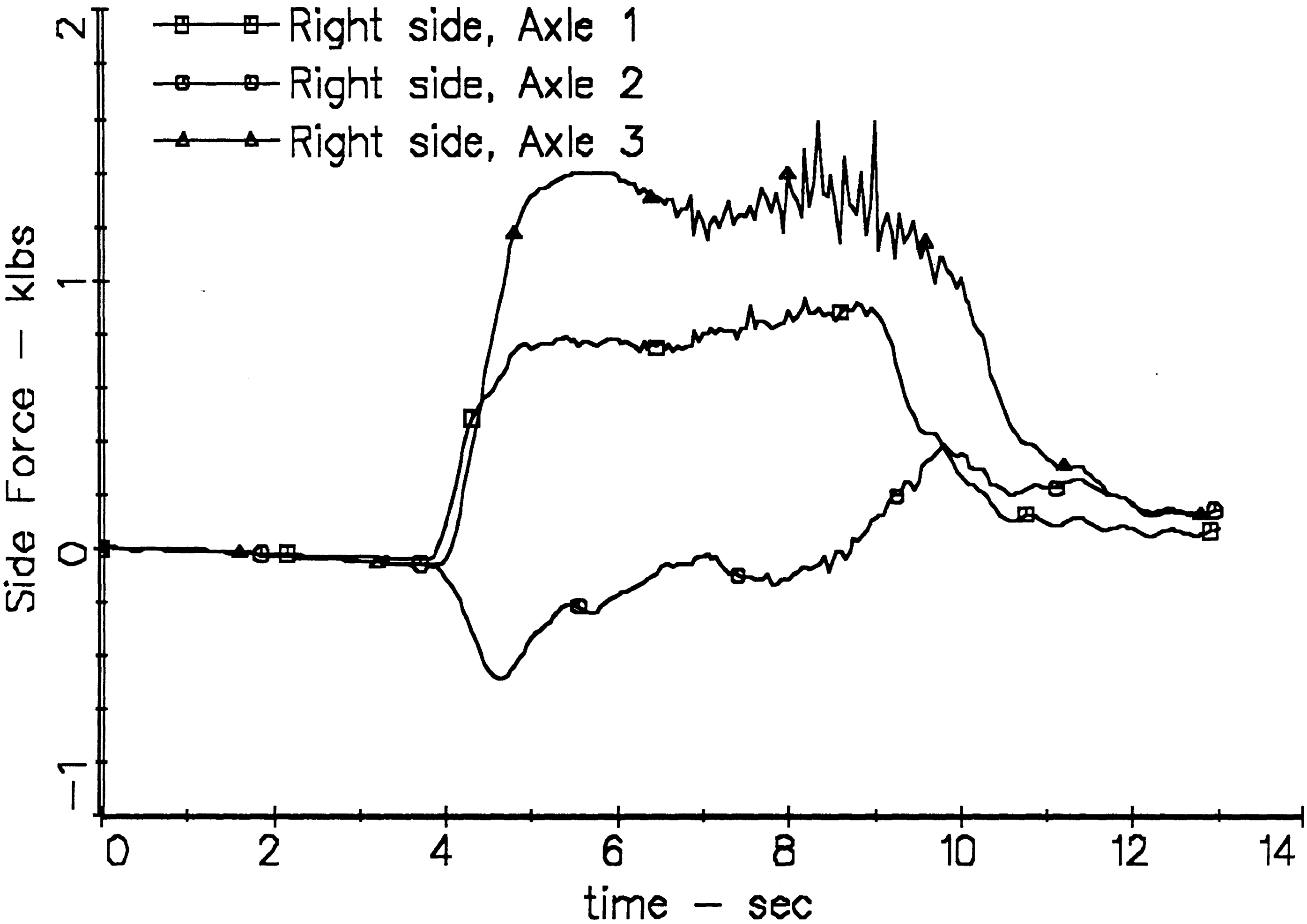
Yukon's 3 axle tractor and tandem axle tanker.



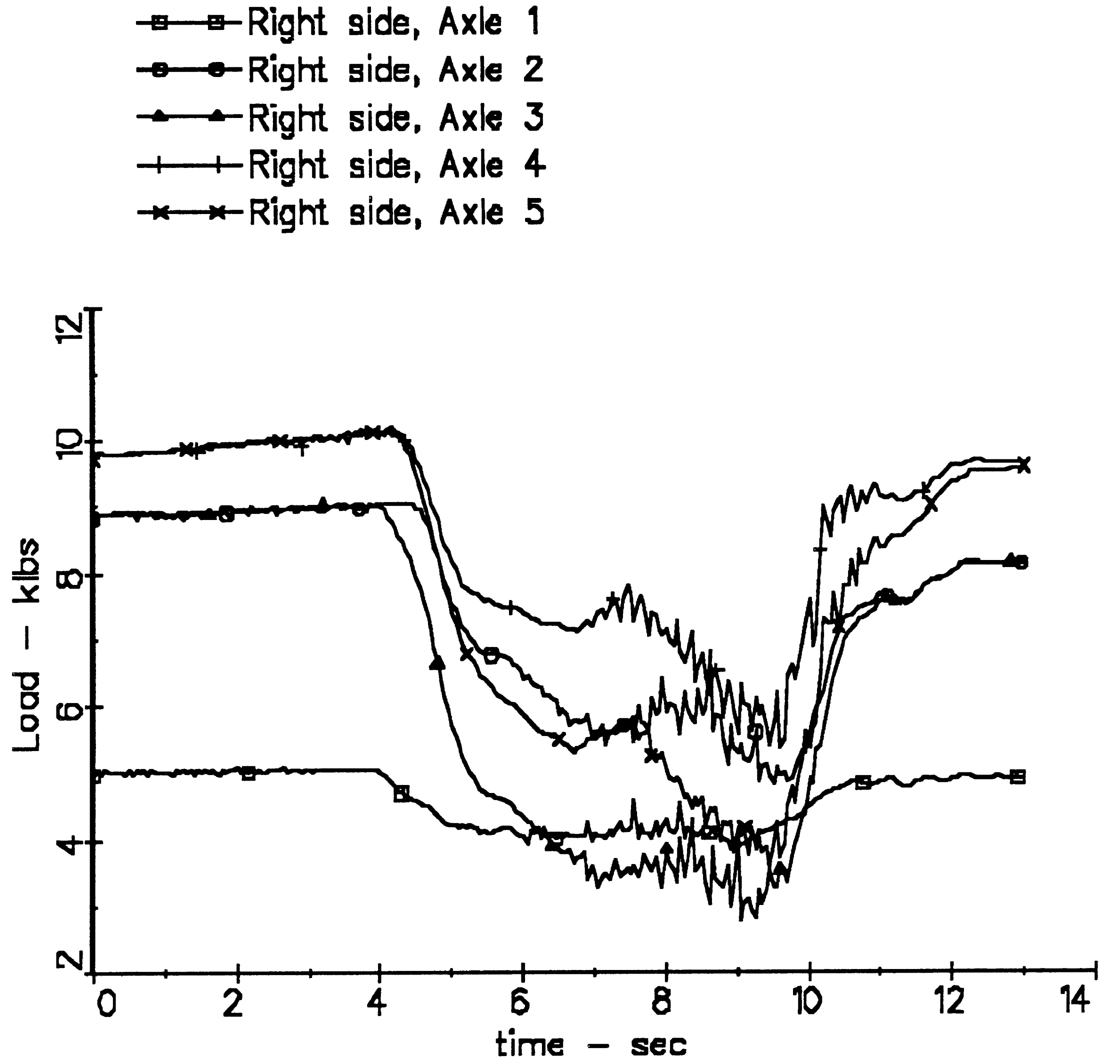
Yukon's 3 axle tractor and tandem axle tanker.



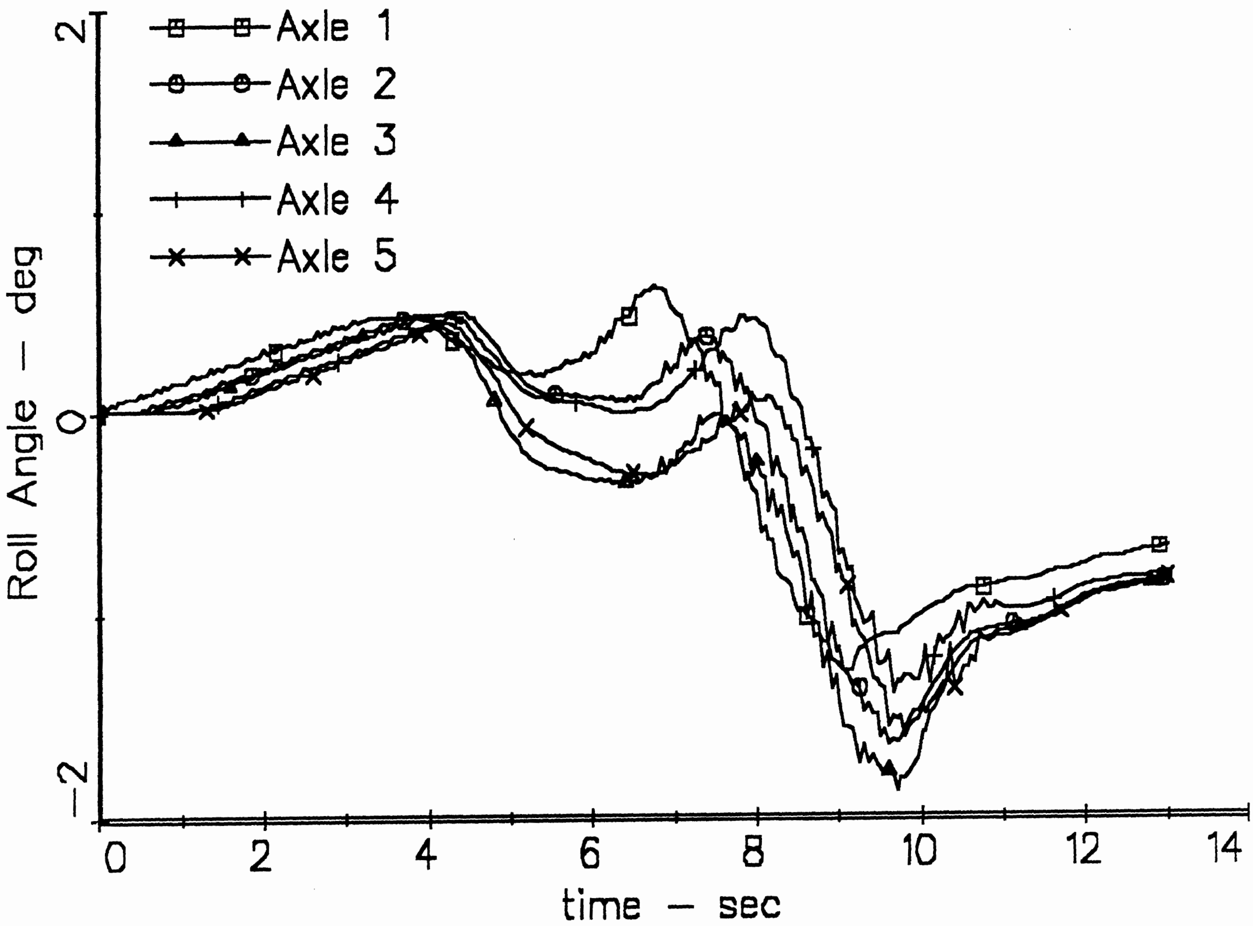
Yukon's 3 axle tractor and tandem axle tanker.



Yukon's 3 axle tractor and tandem axle tanker.



Yukon's 3 axle tractor and tandem axle tanker.

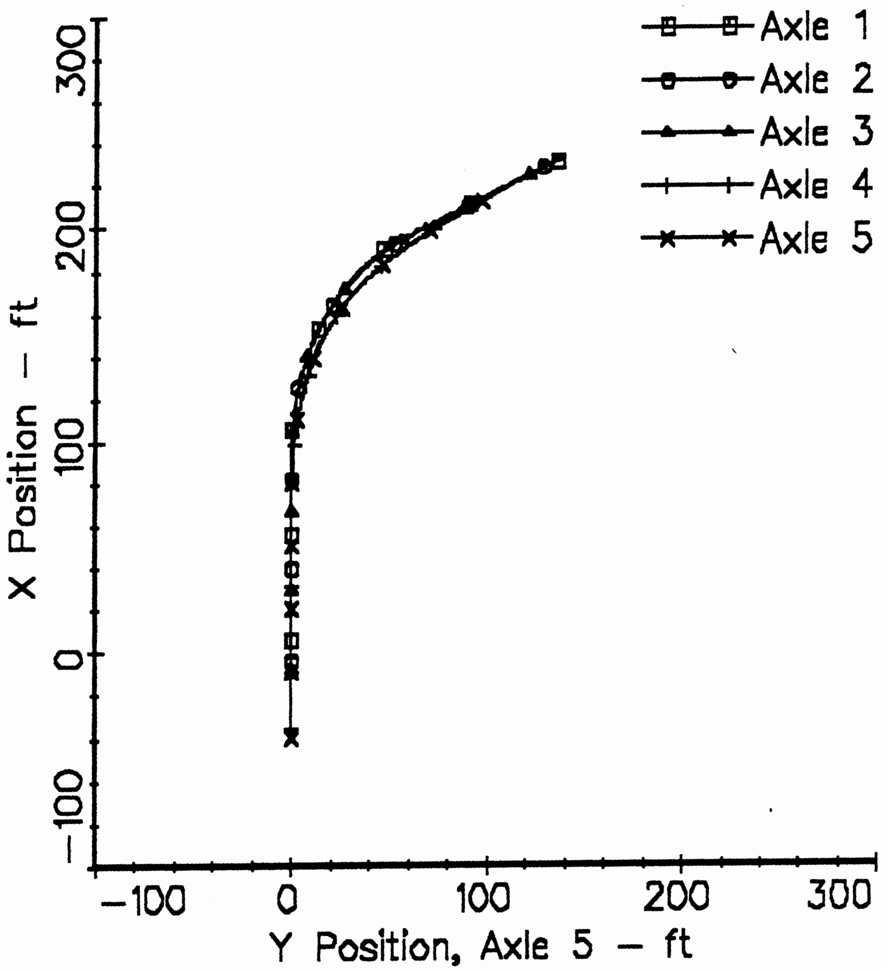


Yukon's 3 axle tractor and tandem axle tanker.

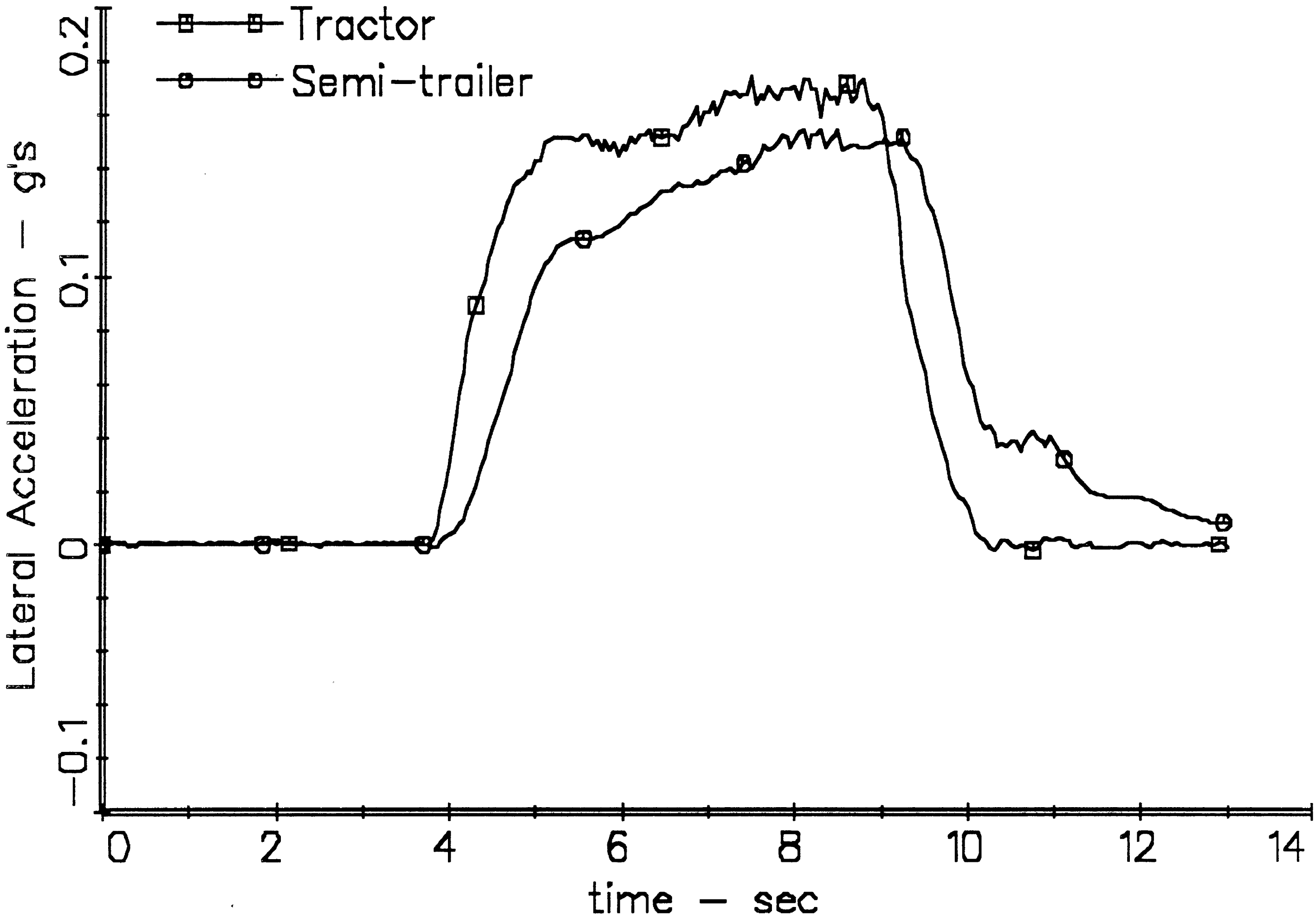
Reference Tanker, Existing Roadway, 25.5 km/h

Jan 31, '87

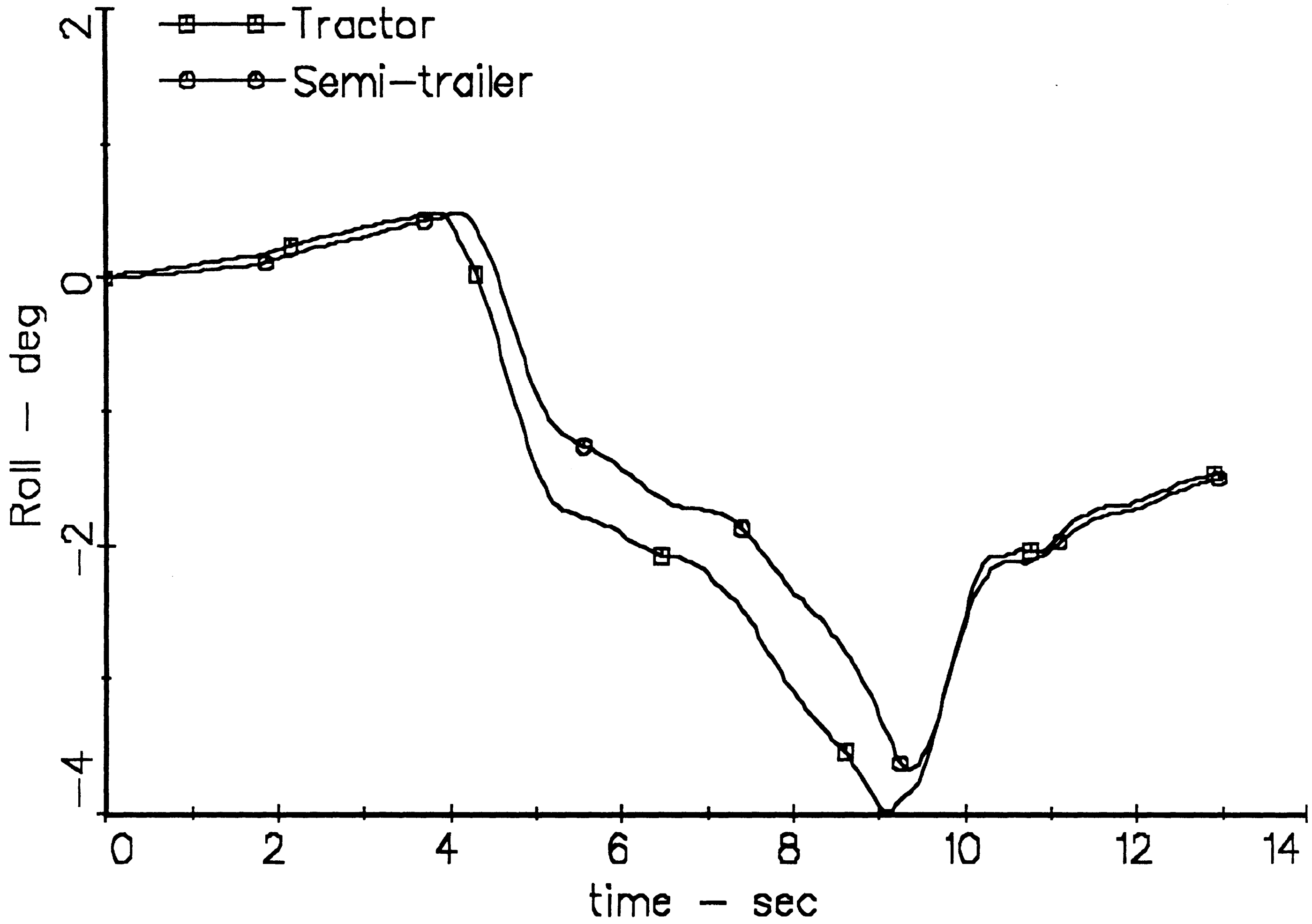
* Ay = 0.15 g's
* Existing intersection
* Baseline tanker (MC306)
* With Superelevation



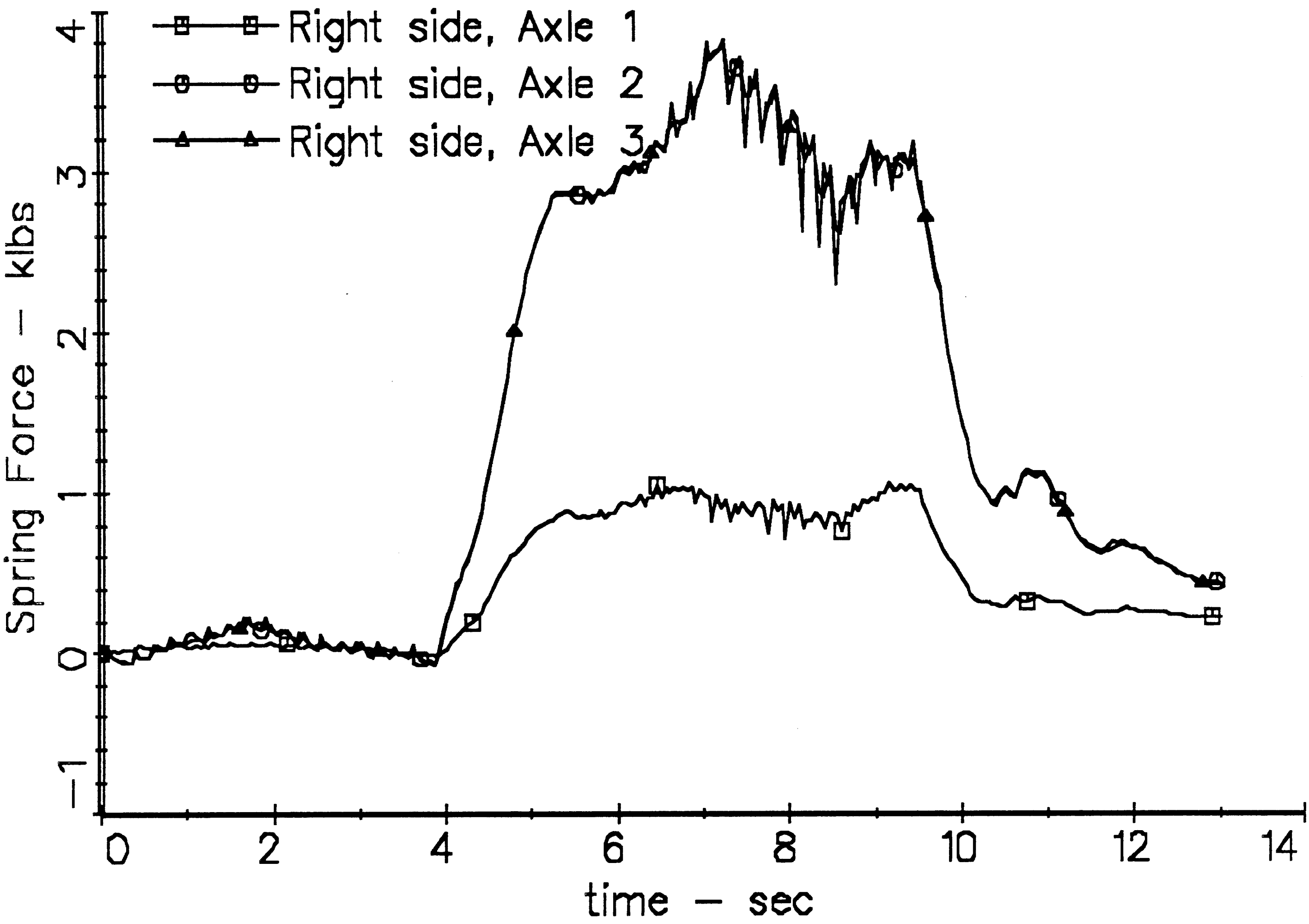
Michigan 3 axle tractor and tandem axle tanker.



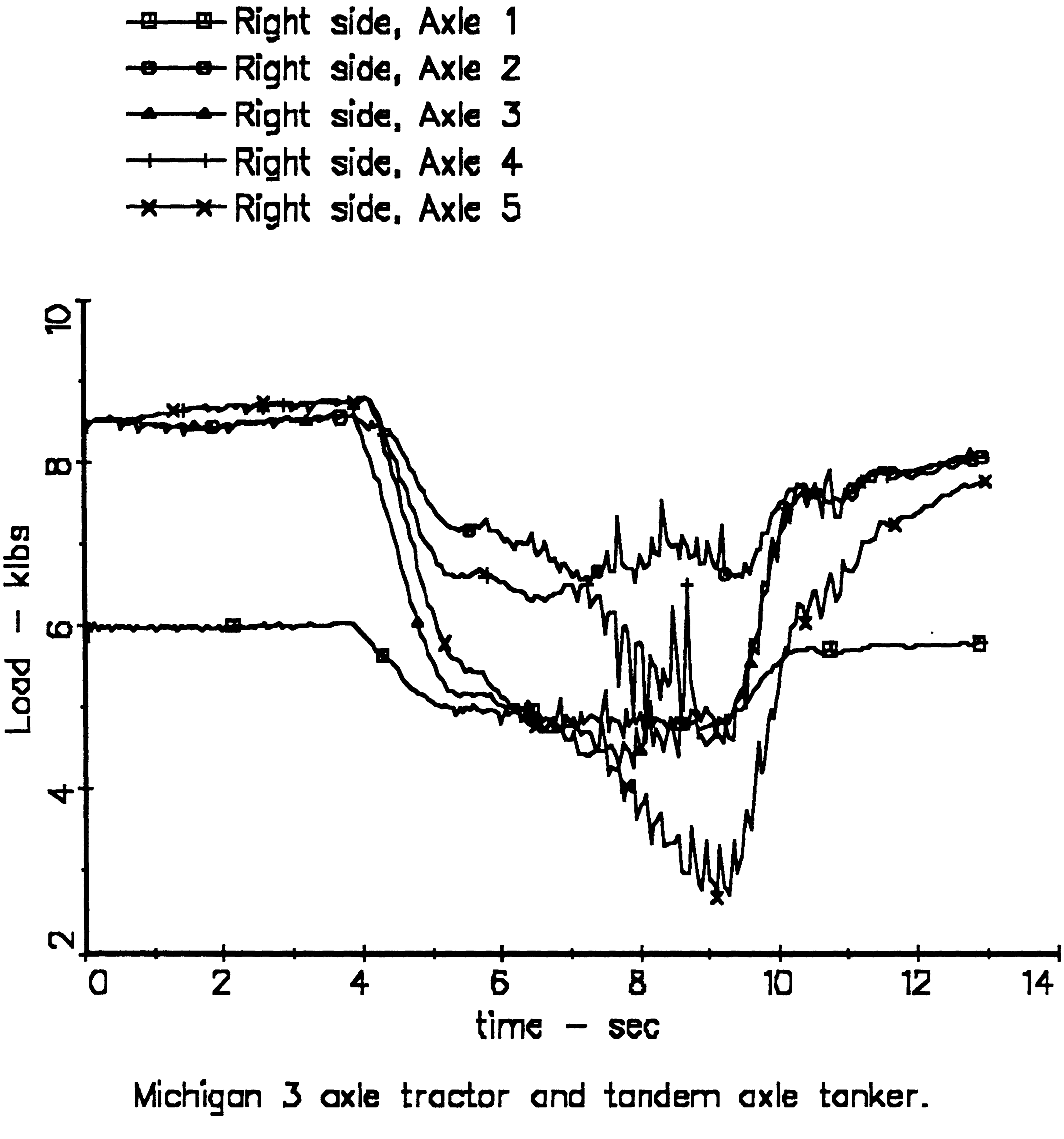
Michigan 3 axle tractor and tandem axle tanker.



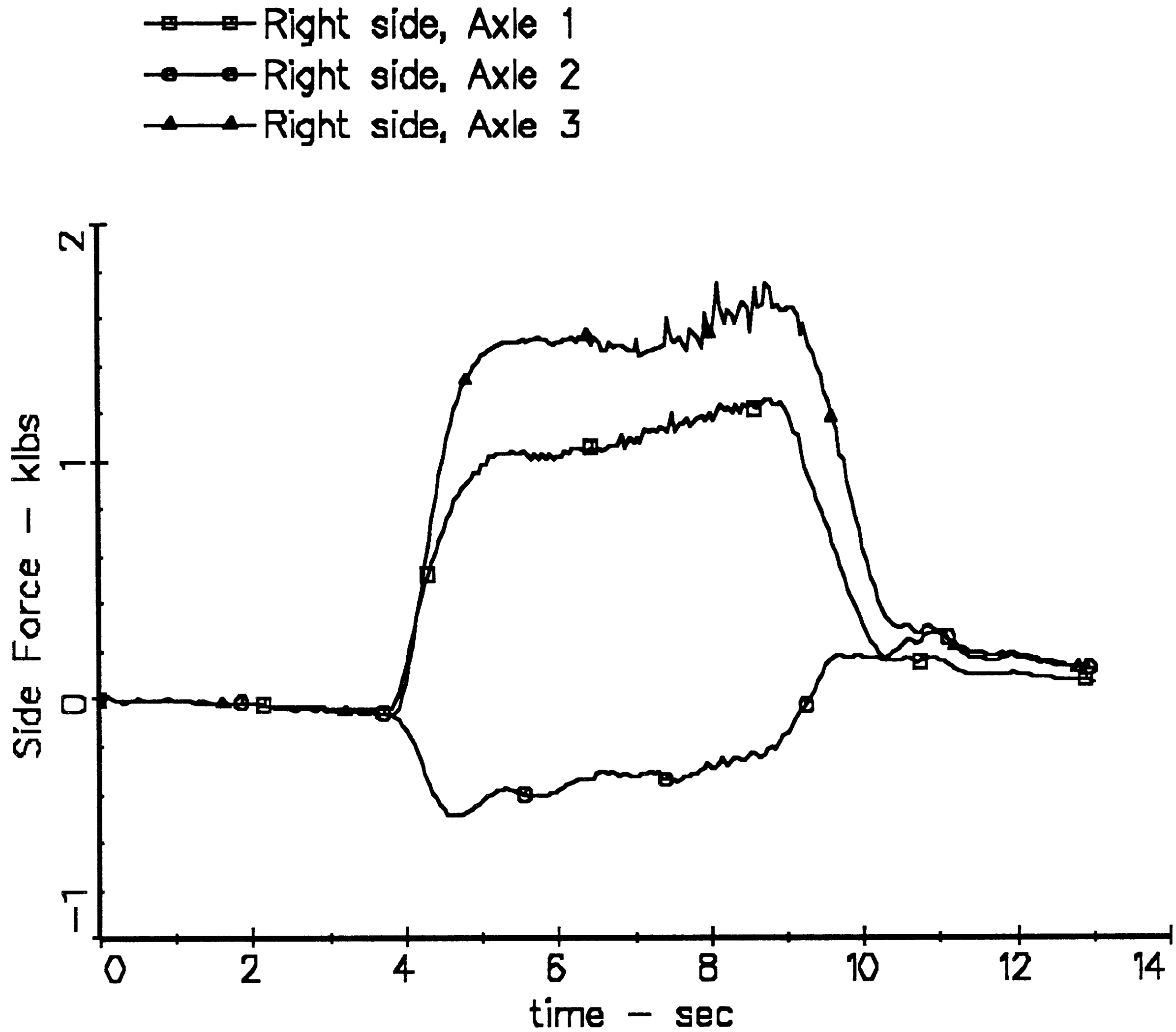
Michigan 3 axle tractor and tandem axle tanker.



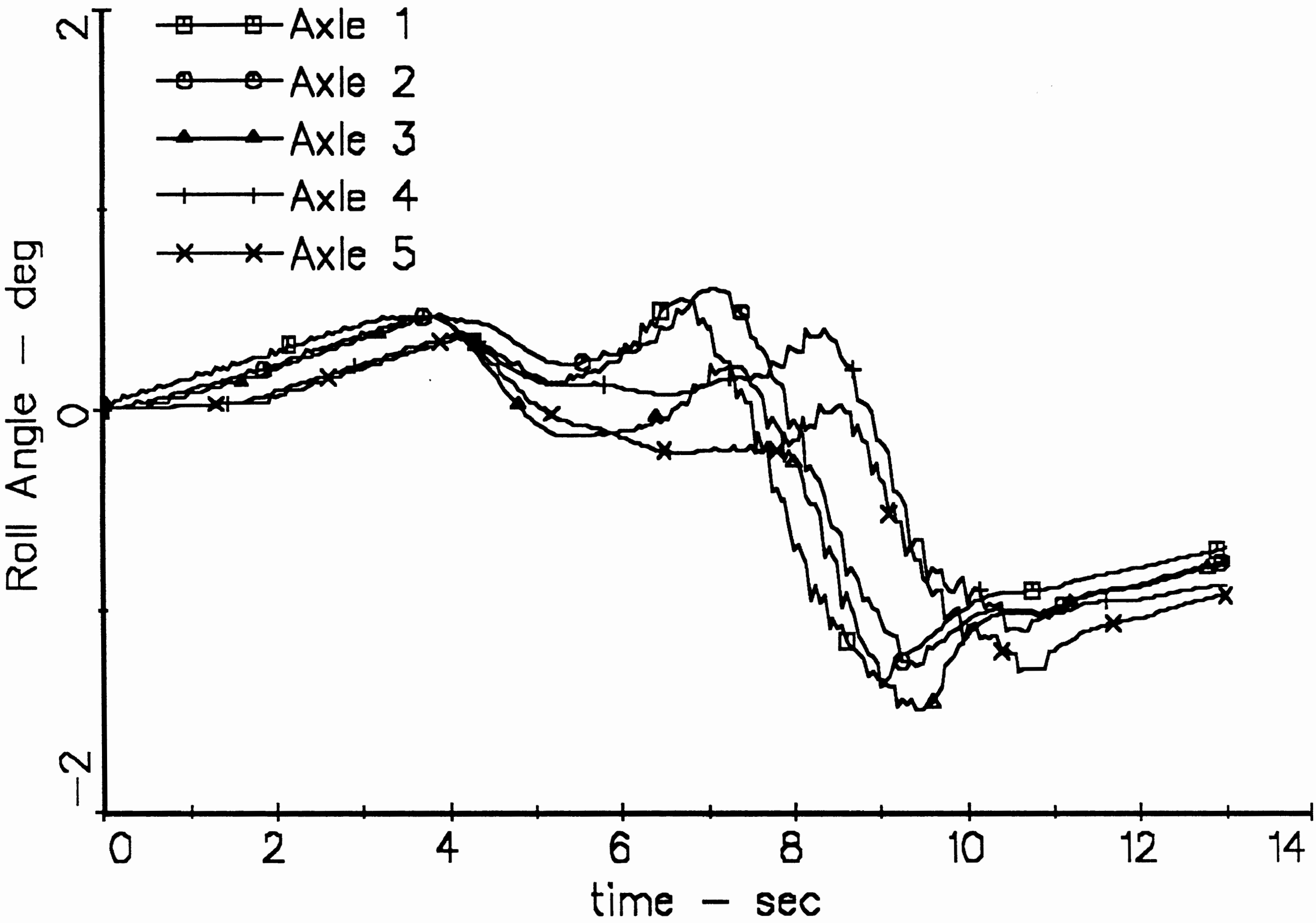
Michigan 3 axle tractor and tandem axle tanker.



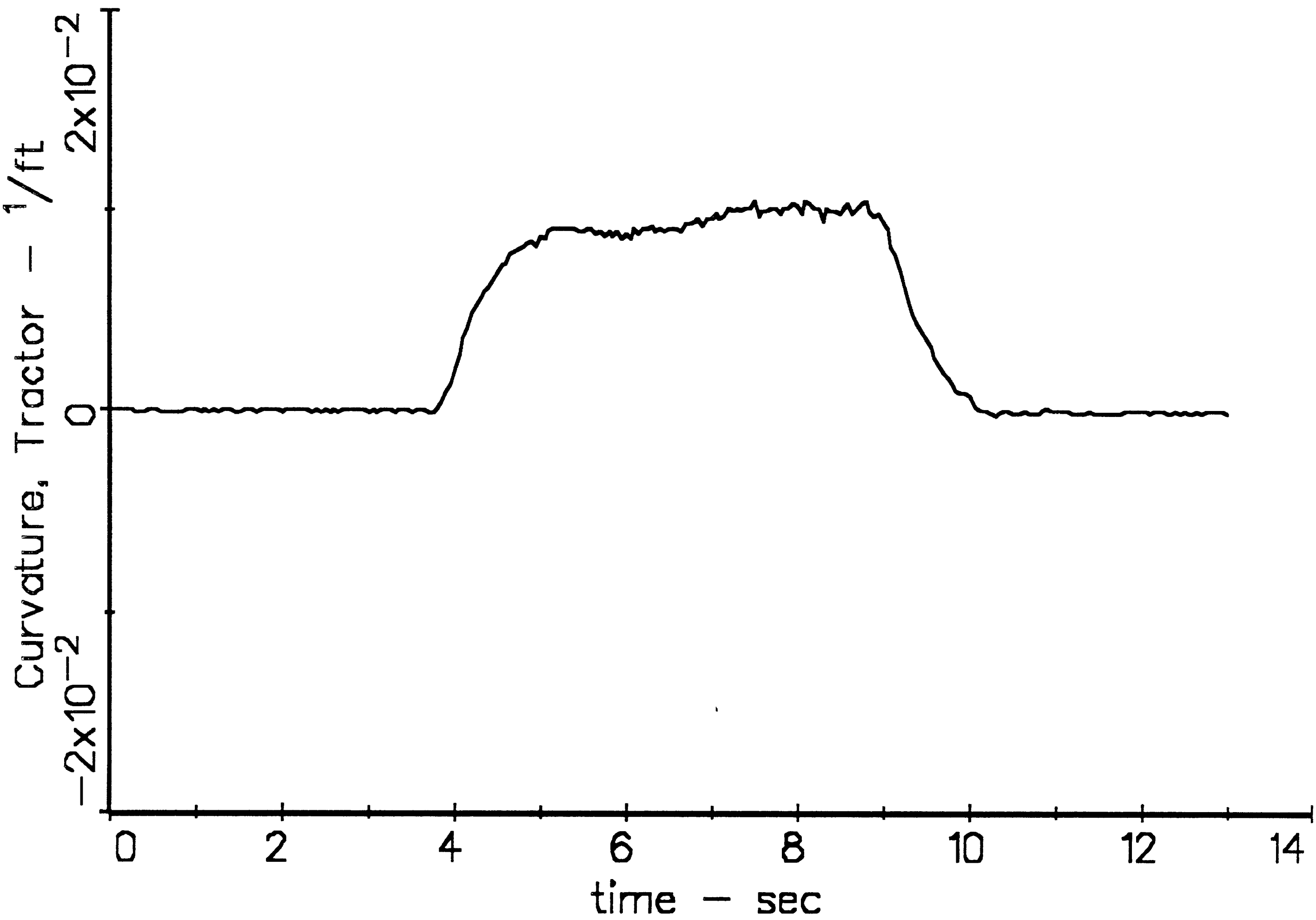
Michigan 3 axle tractor and tandem axle tanker.



Michigan 3 axle tractor and tandem axle tanker.



Michigan 3 axle tractor and tandem axle tanker.

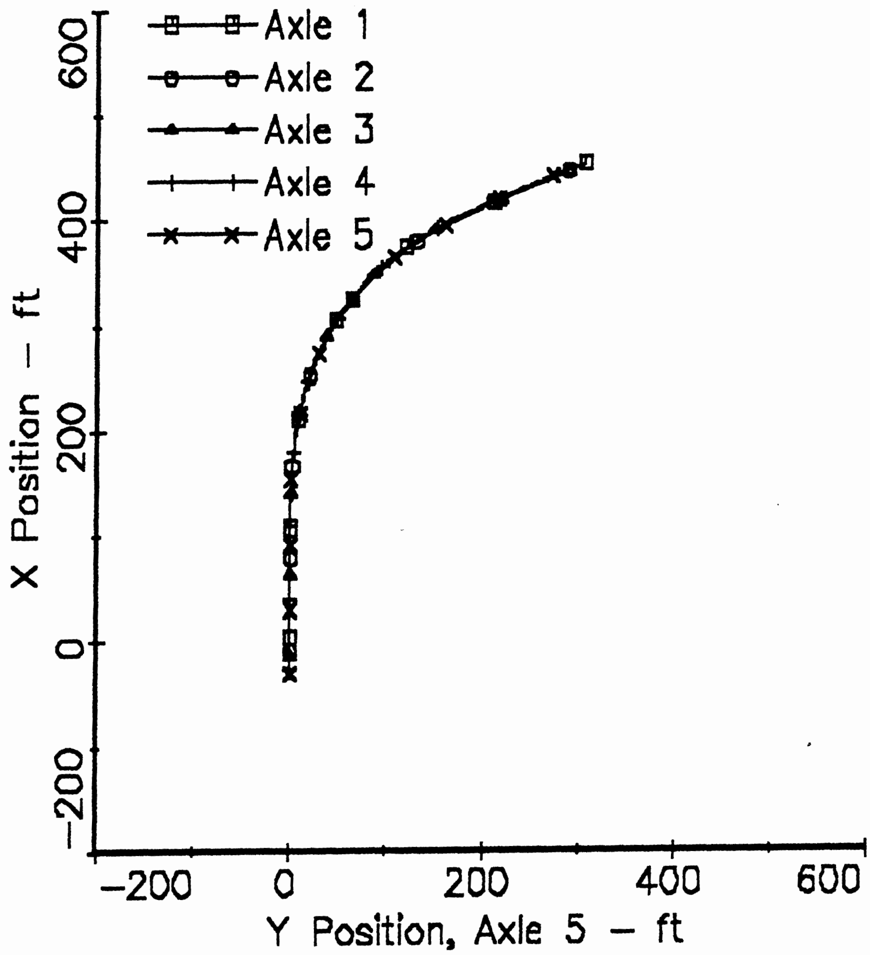


Michigan 3 axle tractor and tandem axle tanker.

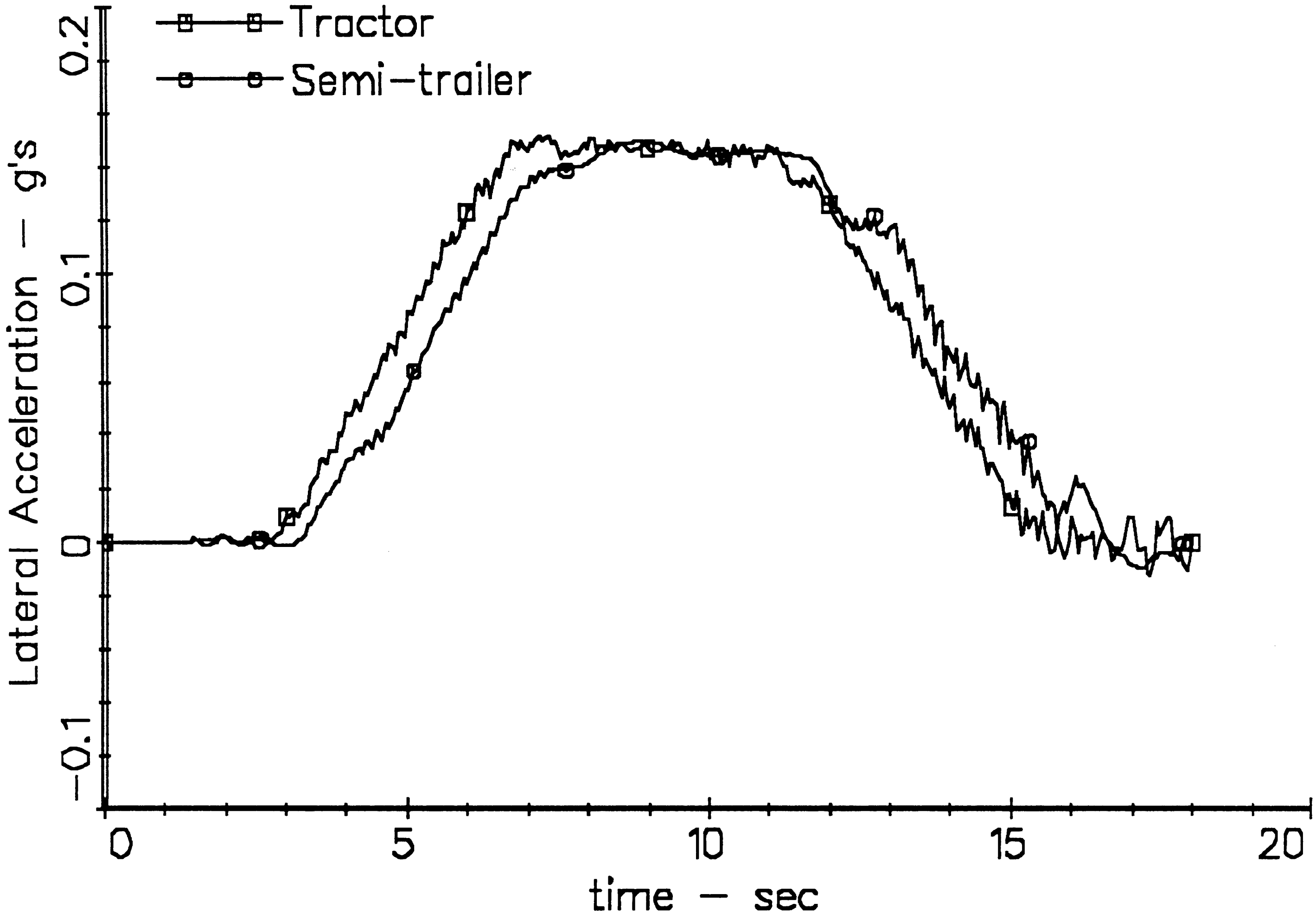
Yukon Tanker, Proposed Roadway, 37.6 km/h

Jan 31, '84

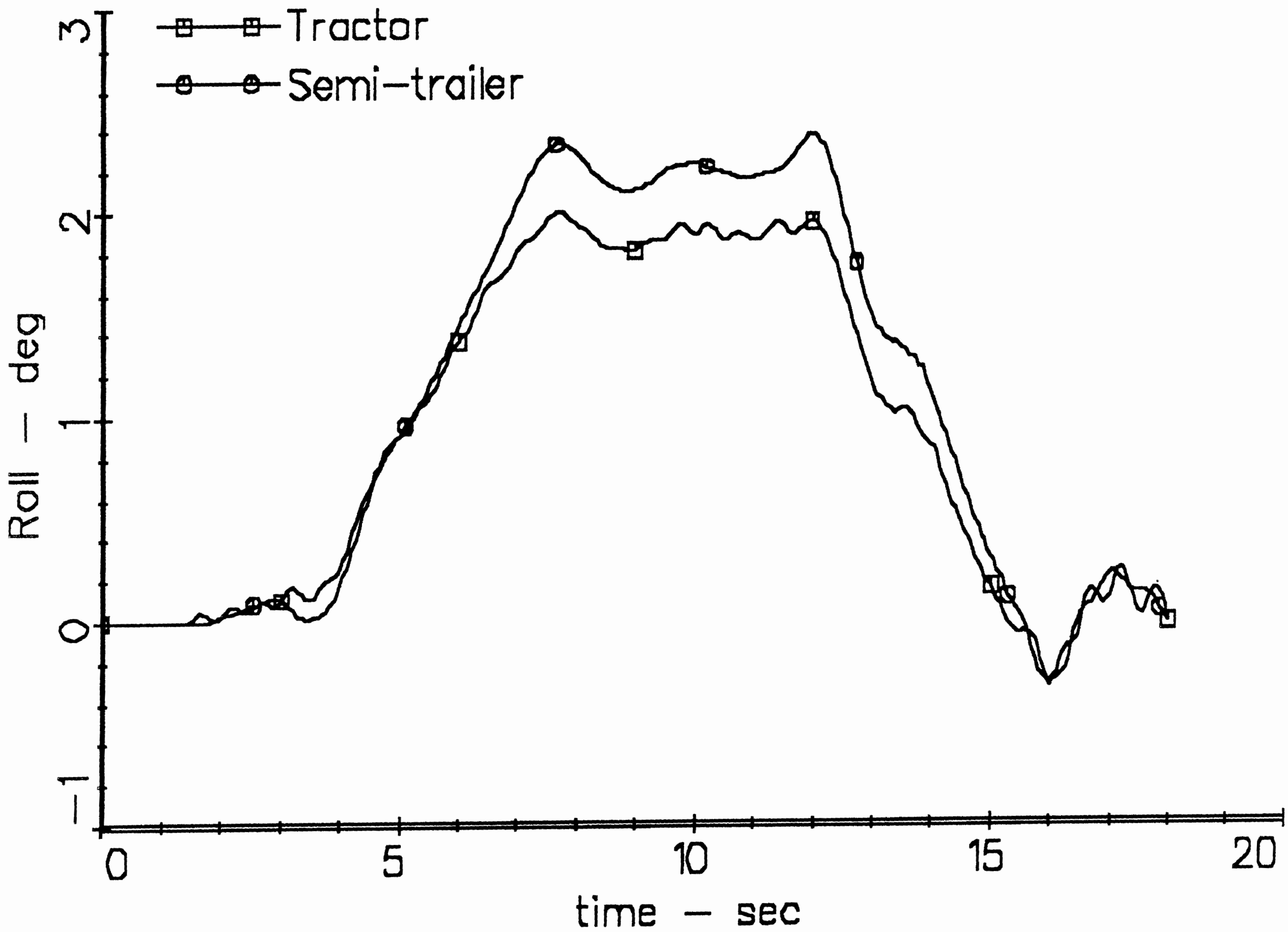
* Ay = 0.15 g's
* Proposed intersection
* Yukon's vehicle
* With superelevation



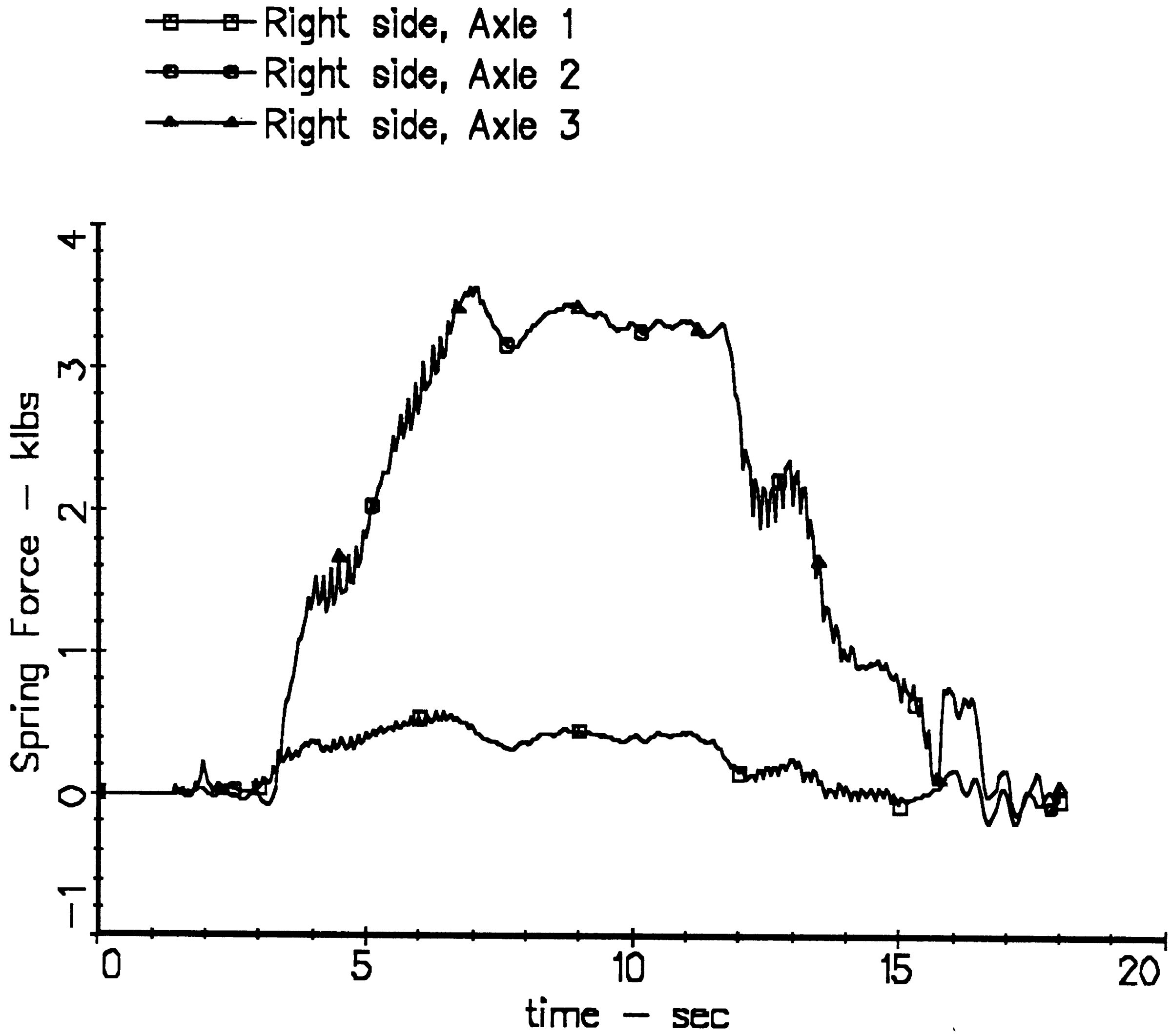
Yukon's 3 axle tractor and tandem axle tanker.



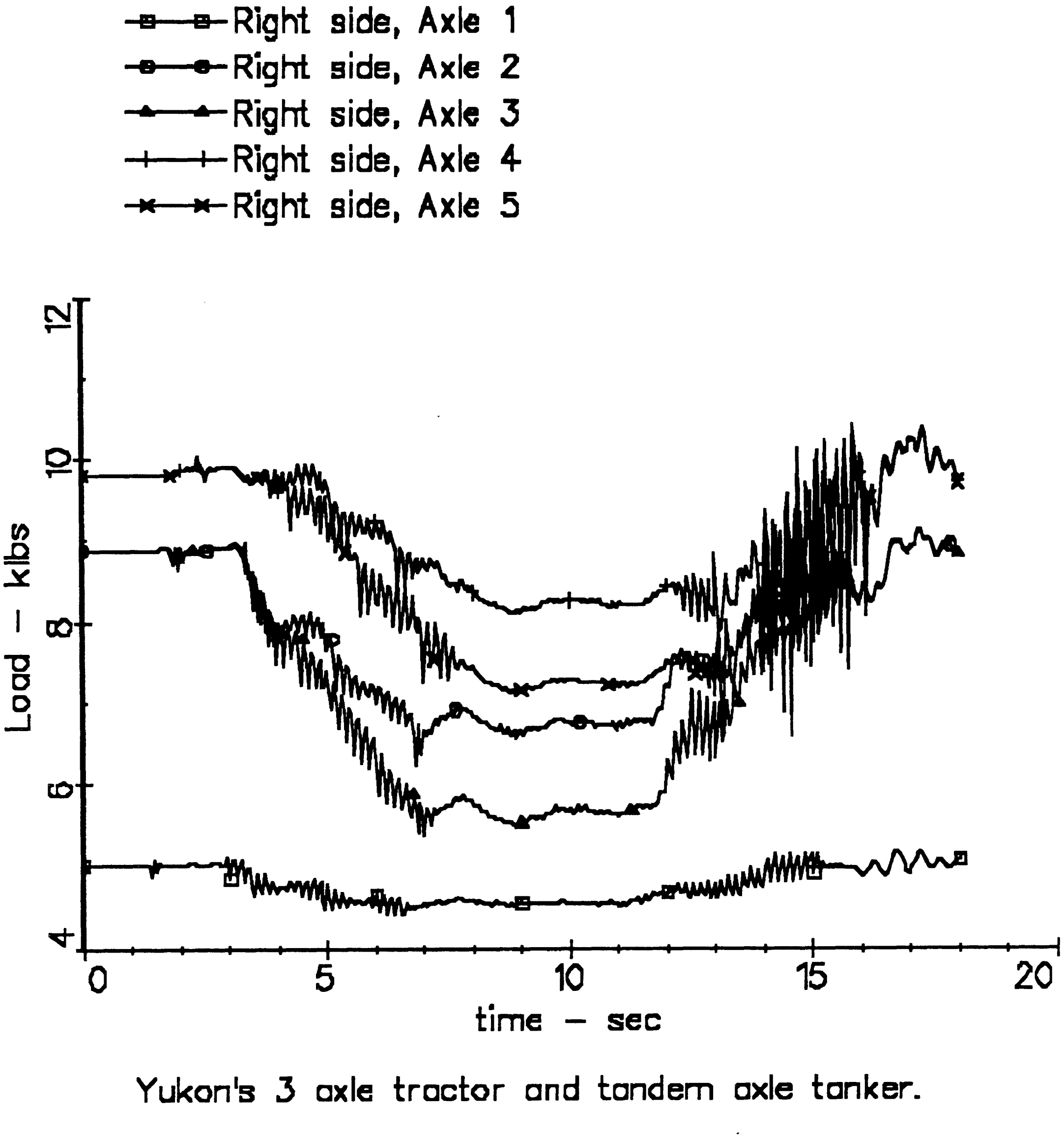
Yukon's 3 axle tractor and tandem axle tanker.



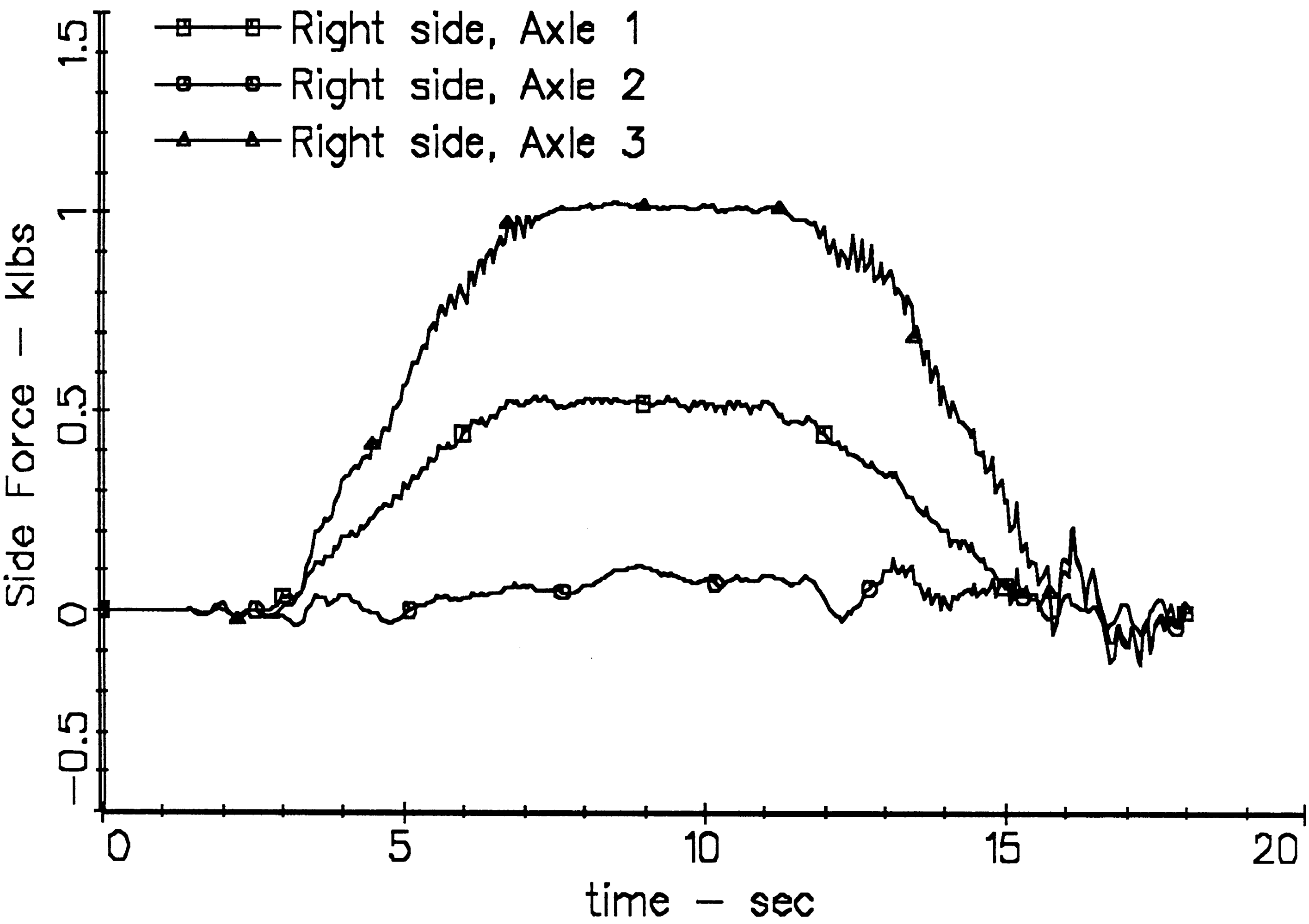
Yukon's 3 axle tractor and tandem axle tanker.



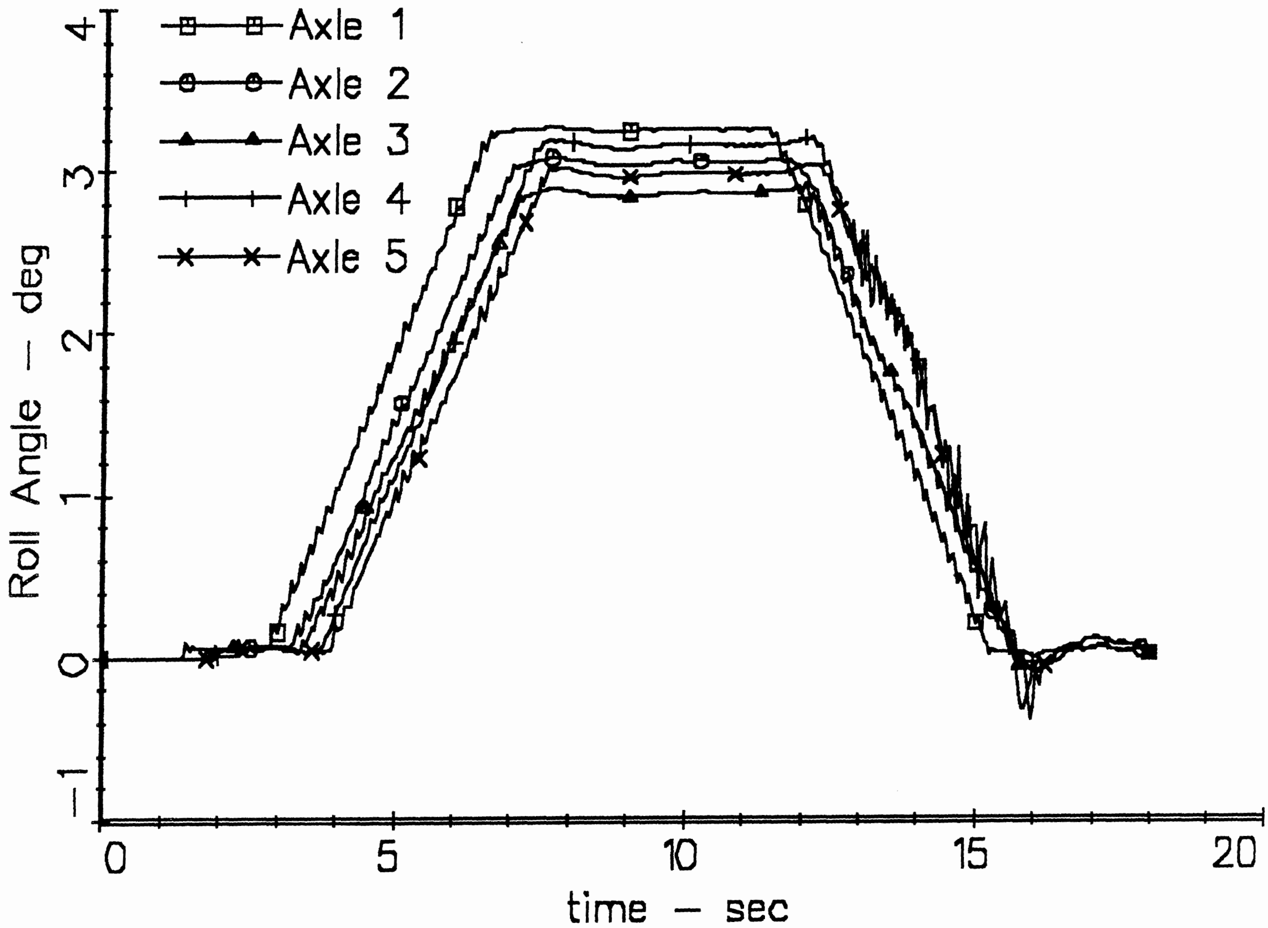
Yukon's 3 axle tractor and tandem axle tanker.



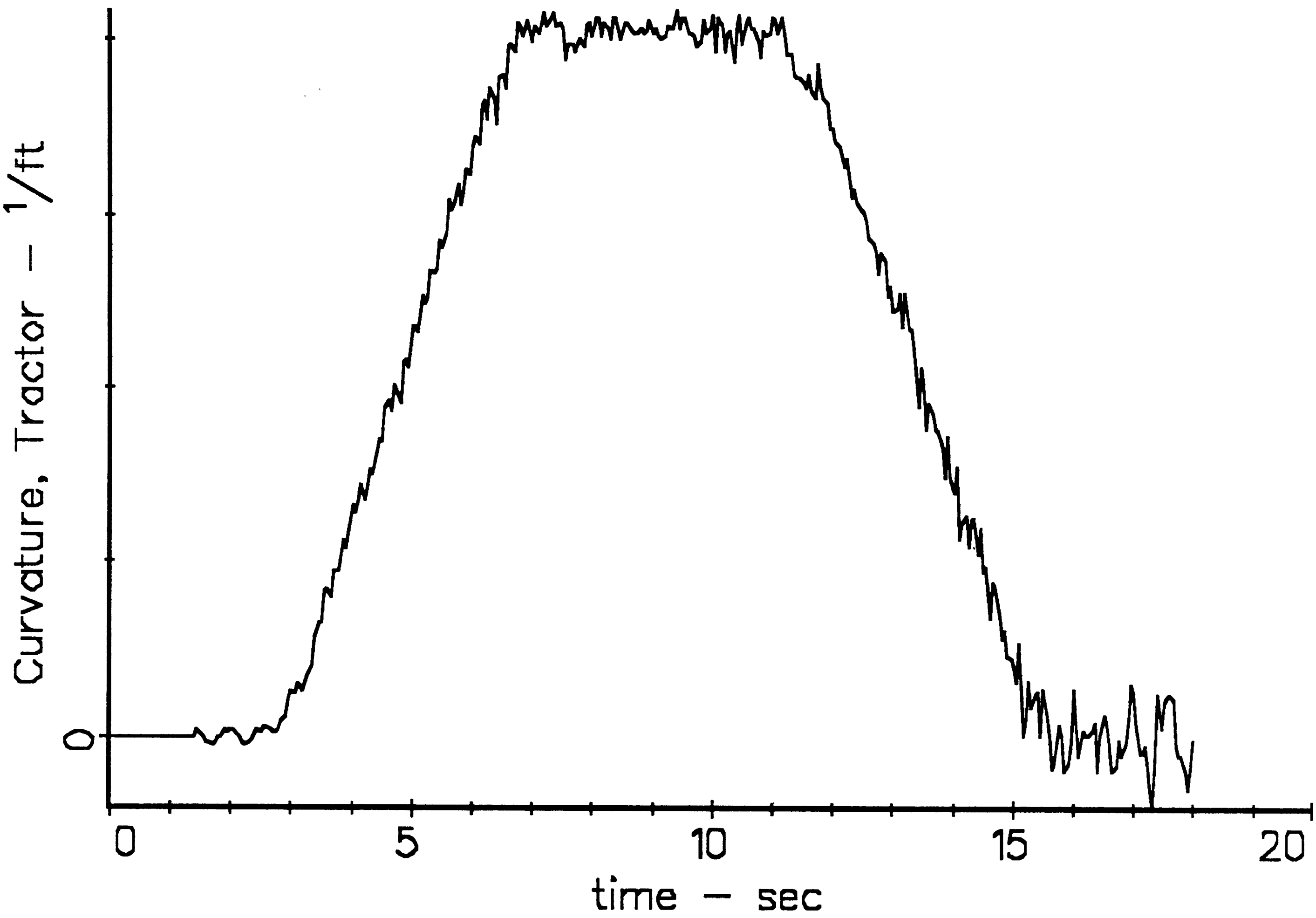
Yukon's 3 axle tractor and tandem axle tanker.



Yukon's 3 axle tractor and tandem axle tanker.



Yukon's 3 axle tractor and tandem axle tanker.

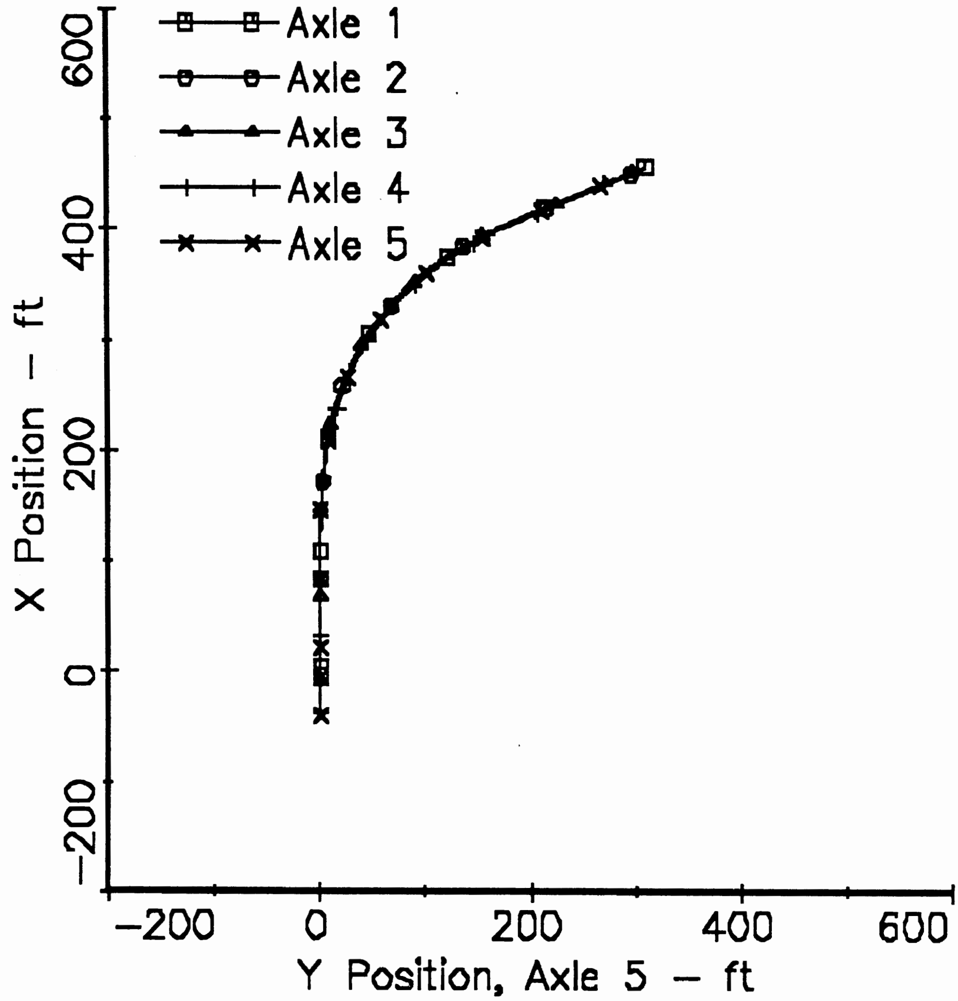


Yukon's 3 axle tractor and tandem axle tanker.

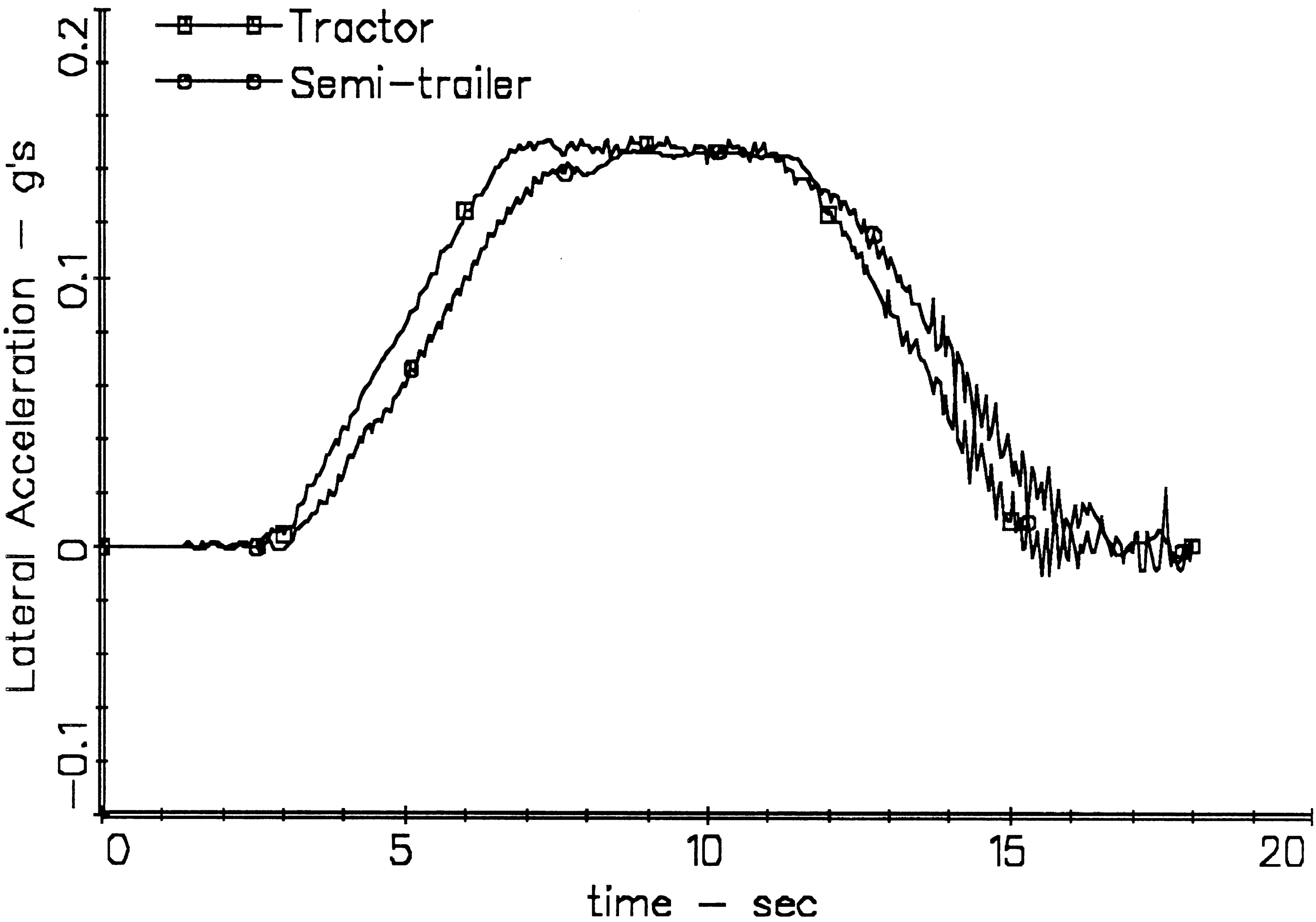
Reference Tanker, Proposed Roadway, 37.6 km/h

Jan 31, '87

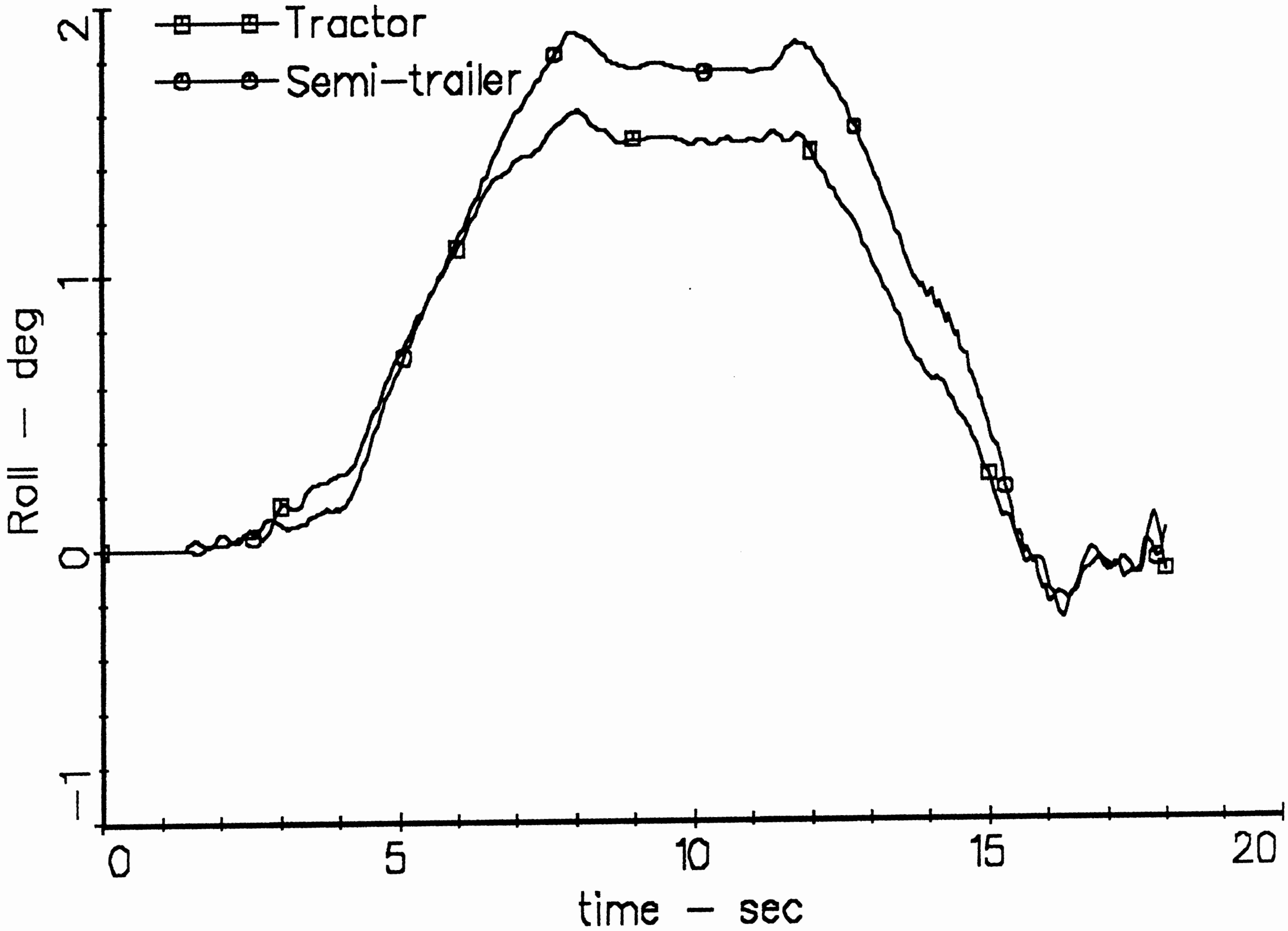
* Ay . 0.15 g's
* Proposed intersection
* Baseline tanker (MC 306)
* With superelevation.



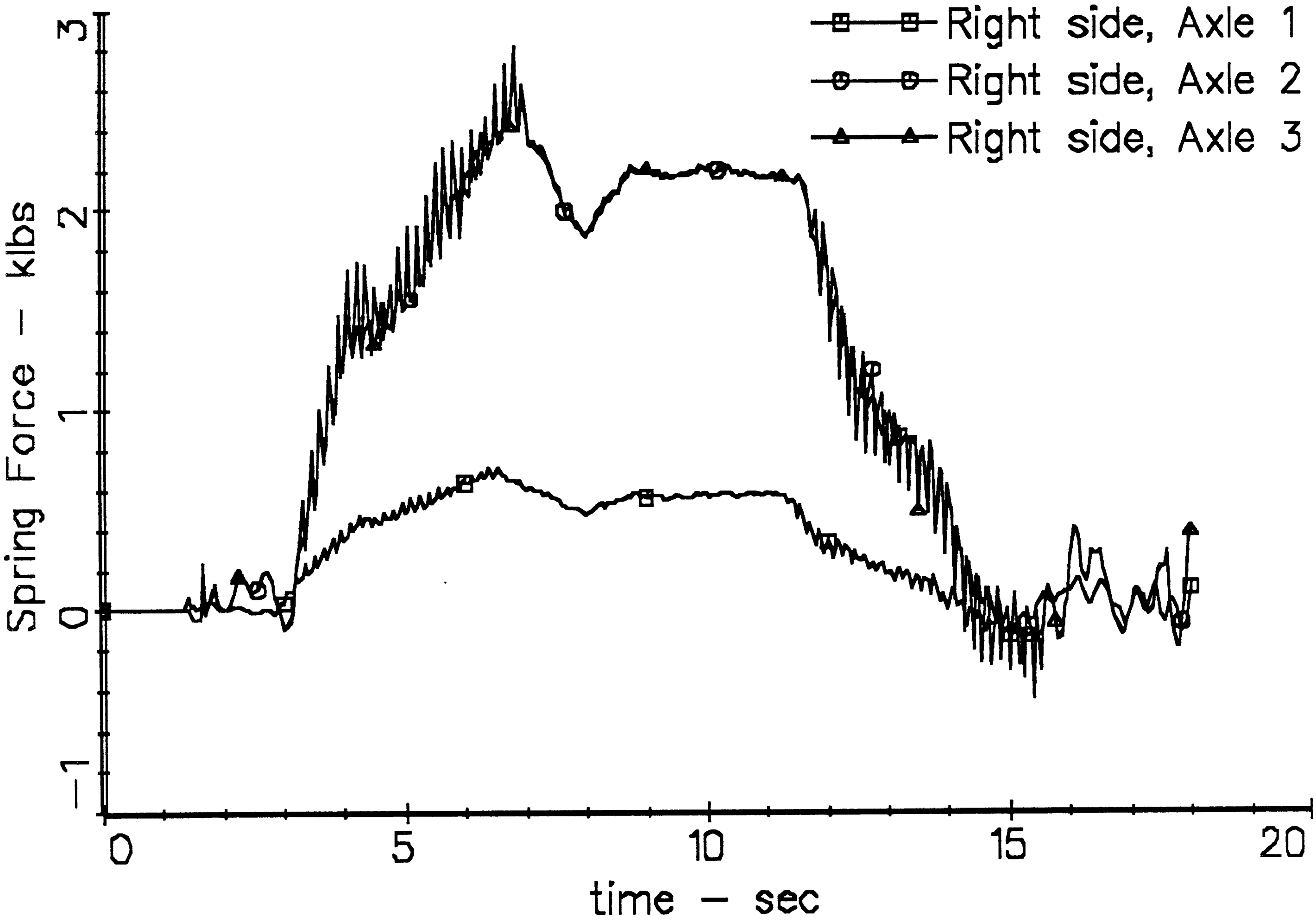
Michigan 3 axle tractor and tandem axle tanker.



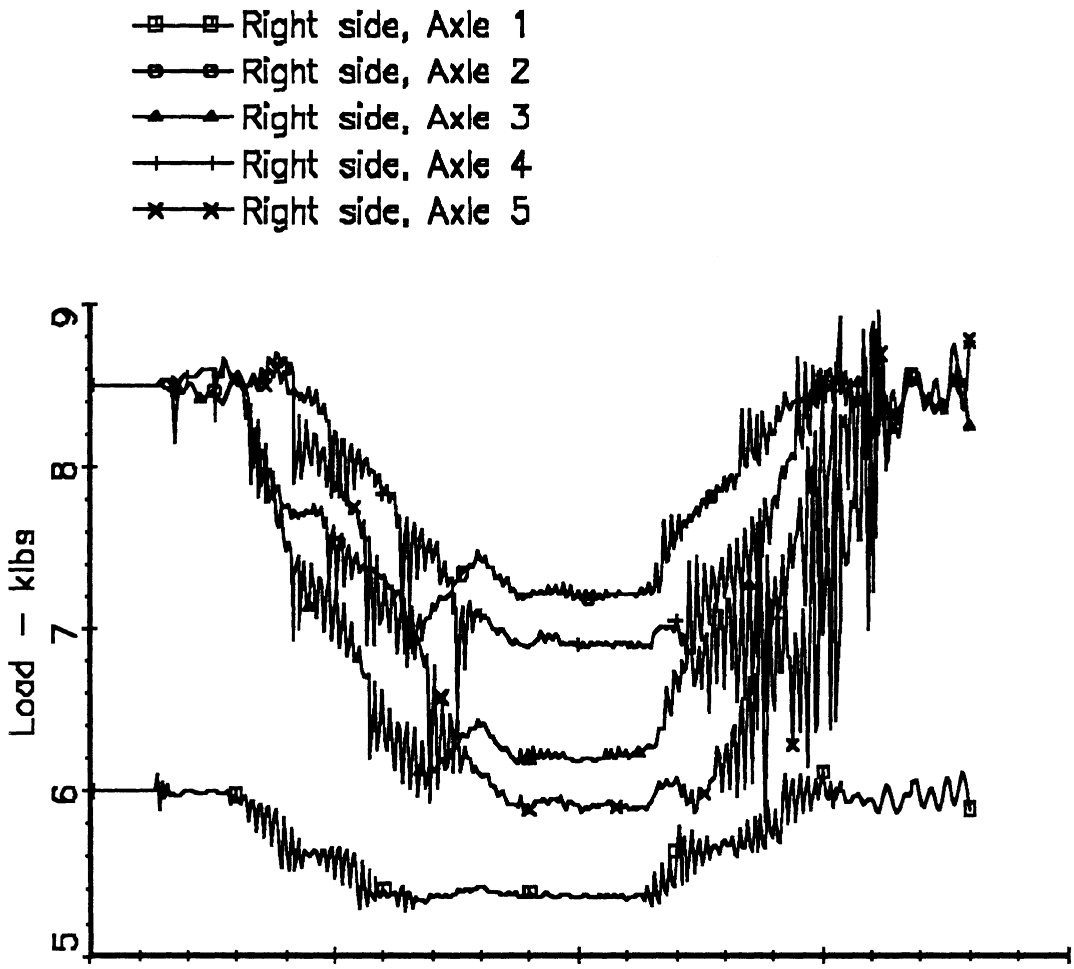
Michigan 3 axle tractor and tandem axle tanker.



Michigan 3 axle tractor and tandem axle tanker.



Michigan 3 axle tractor and tandem axle tanker.



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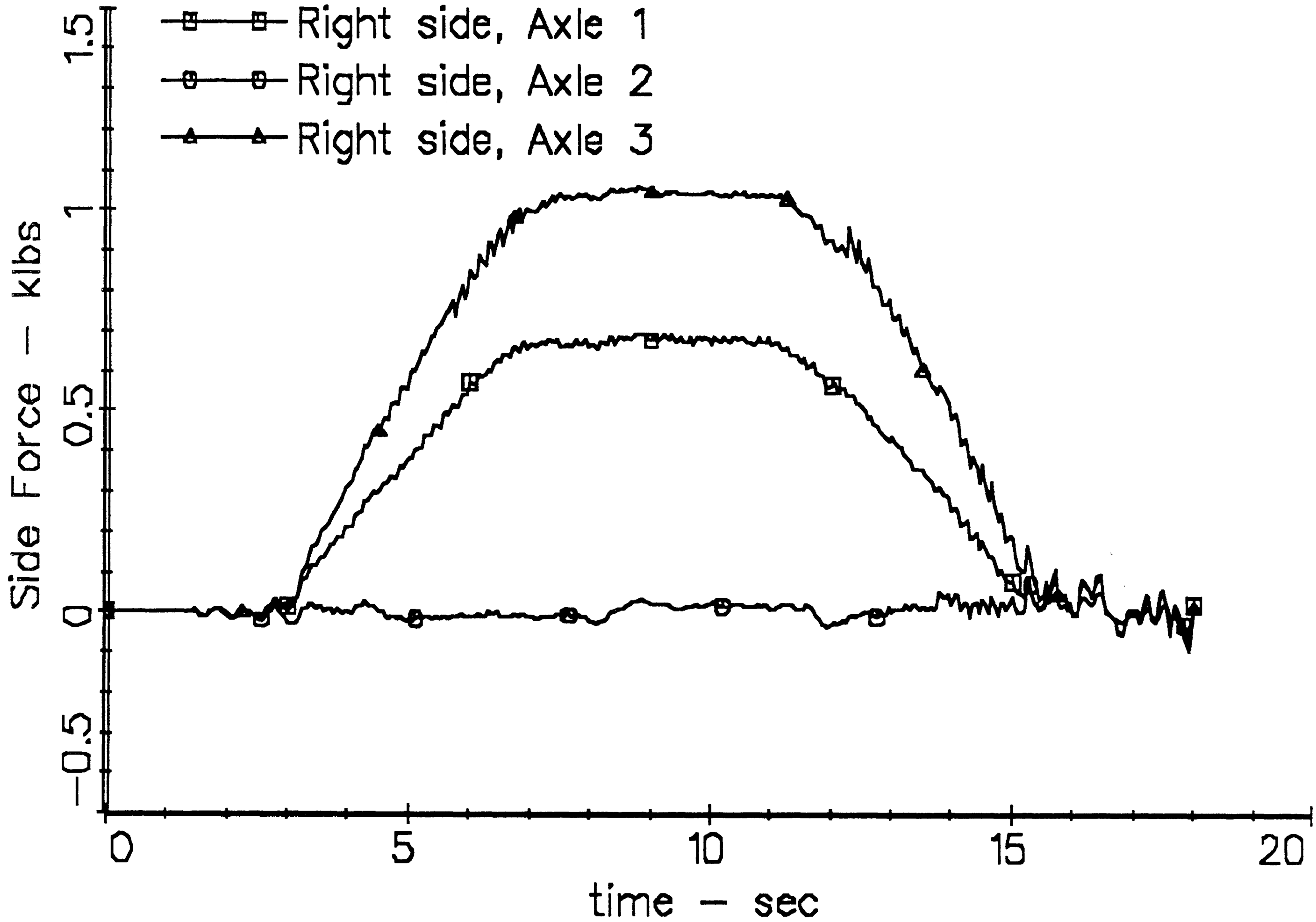
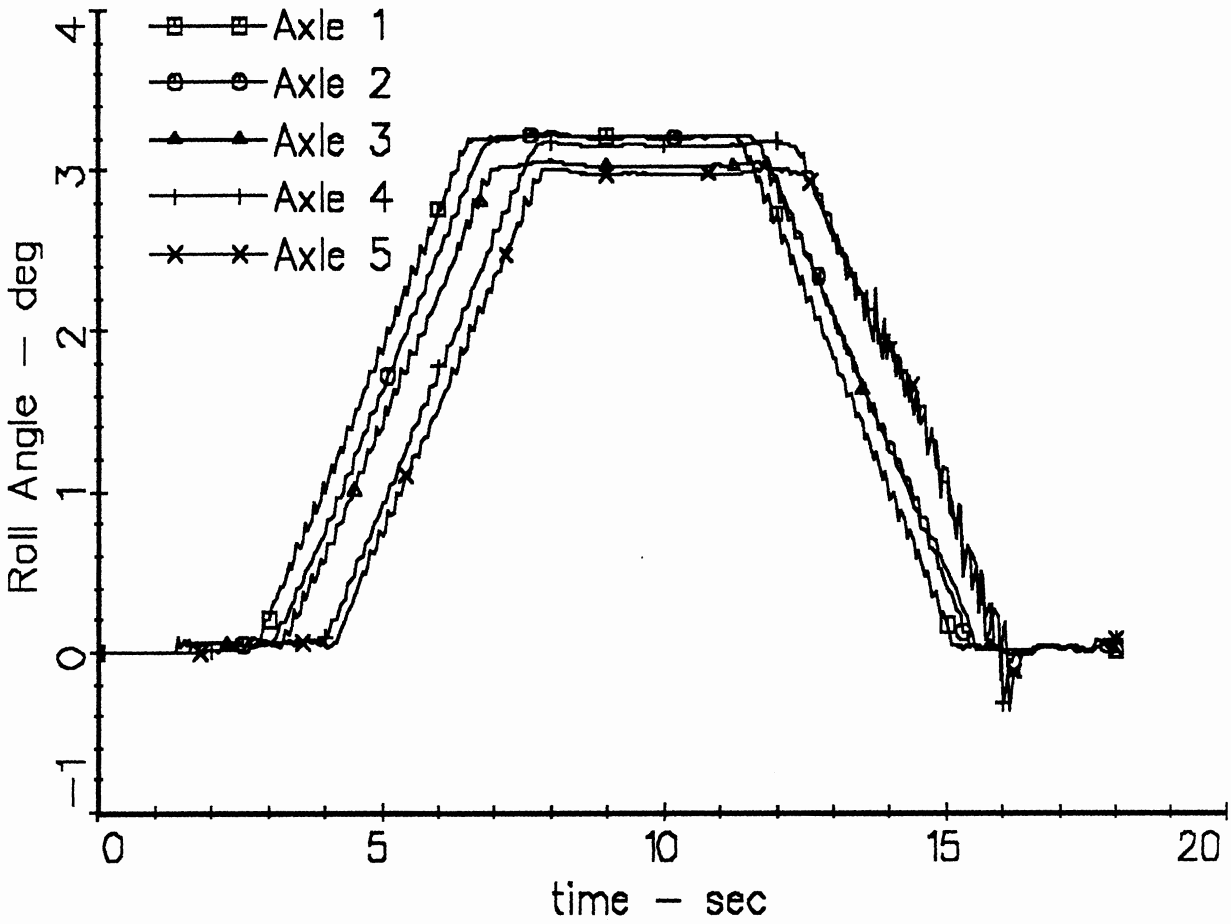
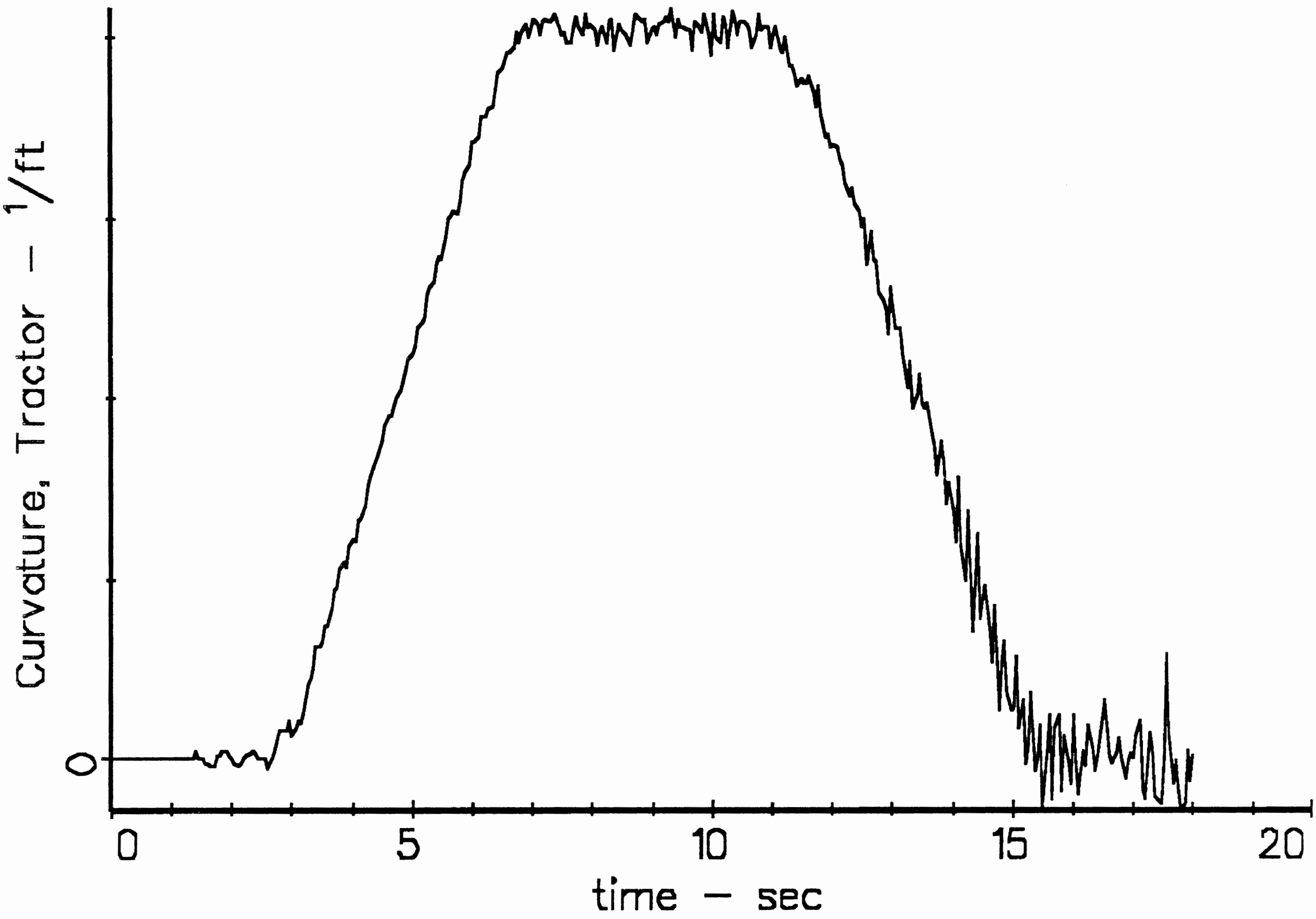


Michigan 3 axle tractor and tandem axle tanker.



Michigan 3 axle tractor and tandem axle tanker.



Michigan 3 axle tractor and tandem axle tanker.