Vehicle Weights and Dimensions Study

Volume 5

Comparison of Simulation and Tests of Baseline and Tractor Semitrailer Vehicles

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Abstract

A substantial program of full-scale heavy truck dynamic testing and computer simulation was undertaken in 1985 on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study by the Ontario Ministry of Transportation and Communications.

This report summarizes comparisons between simulation and test responses of six baseline vehicles: a 45 ft (13.72 m) tractor-trailer; A-, B-, and C-train doubles; A- and C-train triples; and three 48 ft (14.63 m) 5-, 6- and 7-axle tractor-trailer combinations.

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DISCLAIMER

This publication is produced under the auspices of the Technical Steering Committee of the Vehicle Weights and Dimensions Study. The points of view expressed herein are exclusively those of the authors and do not necessarily reflect the opinions of the Technical Steering Committee, Canroad Transportation Research Corporation or its supporting agencies.

This report has been published for the convenience of individuals or agencies with interests in the subject area. Readers are cautioned that the use and interpretation of the data, material and findings contained herein is done at their own risk. Conclusions drawn from this research, particularly as applied to regulation, should include consideration of the broader context of Vehicle Weights and Dimension issues, some of which have been examined in other elements of the research program and are reported on in other volumes in this series.

The Technical Steering Committee will be considering the findings of these research investigations in preparing its "Final Technical Report" (Volume 1 & 2), scheduled for completion in December 1986.

PREFACE

The report which follows constitutes one volume in a series of sixteen which have been produced by contract researchers involved in the Vehicle Weights and Dimensions Study. The research procedures and findings contained herein address one or more specific technical objectives in the context of the development of a consistent knowledge base necessary to achieve the overall goal of the Study; improved uniformity in interprovincial weight and dimension regulations.

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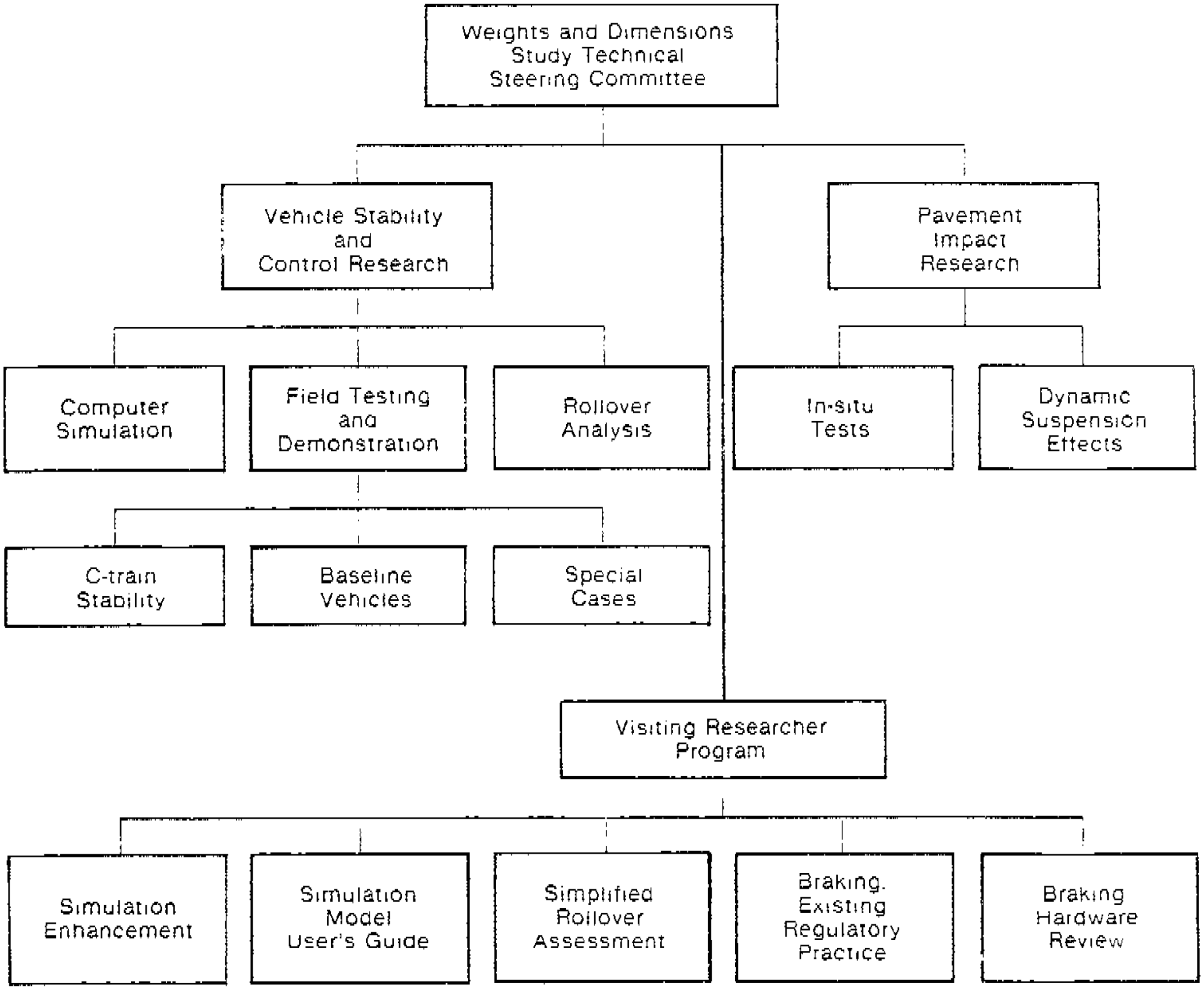
TECHNICAL WORK ELEMENTS OVERVIEW



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Volume 5

Comparison of Simulation and Tests of Baseline and Tractor Semitrailer Vehicles

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ABSTRACT

A substantial program of full-scale heavy truck dynamic testing and computer simulation was undertaken in 1985 on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study by the Ontario Ministry of Transportation and Communications.

This report summarizes comparisons between simulation and test responses of six baseline vehicles: a 45 ft (13.72 m) tractor-trailer; A-, B-, and C-train doubles; A- and C-train triples; and three 48 ft (14.63 m) 5-, 6-, 7-axle tractor-trailer combinations.

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EXECUTIVE SUMMARY

A substantial program of full-scale heavy truck dynamic testing and computer simulation was undertaken in 1985 on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study by the Ontario Ministry of Transportation and Communications. This test program provided the opportunity to see how computer simulation would represent a range of vehicle configurations in various manoeuvres and test conditions. This was not validation of the computer simulation, as the characteristics of vehicle components were not measured.

A minicomputer was used to capture and process the test data. The UMTRI yaw/roll vehicle dynamics simulation program was installed on this computer. The program was modified to run faster, resulting in time savings of 75 to 95% from the original program; to save the output in a form that was directly comparable with the test data; and to include a triples combination and the recent UMTRI B-dolly model. The equations of motion of the original UMTRI program were not changed. The modifications, thus, did not affect the function of the program; they were merely necessary to make it perform the required task within the limited capabilities of the minicomputer. The conversion of the UMTRI yaw/roll program to the minicomputer was validated by comparing results against the original mainframe version.

The test program covered six baseline vehicles: a 45 ft (13.72 m) semi; A-, B-, and C-train doubles; A- and C-train triples; and three additional 48 ft (14.63 m) 5-, 6-, 7-axle semitrailers. Each vehicle was subjected to 10 tests, but the simulation was restricted to only three of these: sinusoidal steer, lane change, and steady circular turn. All three of these tests were conducted with a loaded vehicle on a high-friction surface.

Vehicle data were obtained in various ways. Dimensions and axle loads were measured directly. Weights and inertias were estimated from a detailed component analysis of each vehicle unit. Suspension and tire properties were taken directly from UMTRI laboratory measurements performed on behalf of the study and were the same as used by UMTRI in their comprehensive simulation of vehicle configuration.

In spite of shortcomings in the input data, and other details that cannot

be or have not been represented in the model, the yaw/roll program was found to provide a reasonable prediction of the dynamic response of most of the vehicle configurations, namely, the 5-axle 45 ft (13.72 m) and 48 ft (14.63 m) semitrailers, A- and C-train doubles, and A- and C-train triples, in the sinusoidal steer and lane-change manoeuvres over a wide range of speeds and steer periods.

It was also demonstrated that if a better representation of the tire characteristics at the tractor drive axles was used, the yaw/roll program was capable of predicting a fairly accurate response of the B-train double and the 6- and 7- axle 48 ft (14.63 m) semitrailers in the sinusoidal steer and lane-change manoeuvres and all vehicles except the 7-axle 48 ft (14.63 m) semi in the steady circular turn.

This work was not a validation of the computer program, because the properties of the actual vehicles tested were not measured. Aside from the tire characteristics, no attempt was made to adjust component data to provide a better match to individual runs, although that evidently could have been done. Rather, the objective was to try and achieve reasonable agreement between test and simulation results using generic component data for individual runs and for the trend over a number of runs. This objective has been achieved, and the simulation, thus, may be used with confidence over at least the range of vehicle configurations and manoeuvres covered in this work. In many instances, in fact, it appears that the comparison between test and simulation raises more questions about the instrument responses than it does about the credibility of the simulation.

1/ INTRODUCTION

The effects of weight and dimension parameters on heavy truck stability and control and on pavement response are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The objective of the study is to compile technical information that, with an earlier study of the effects of heavy trucks on bridge loading [1], would provide a basis for the provinces to amend their truck weight and dimension regulations. The goal is to simplify interprovincial trucking through greater uniformity in these regulations.

The truck population of Canada was surveyed [2], and six generic families were defined, based on the number of trailers and hitching methods. One vehicle in common use in at least some provinces was selected as representative of each family and designated as the baseline vehicle configuration. Each baseline vehicle served as a yardstick against which variations in weight, dimension, or equipment were to be evaluated by means of a comprehensive series of computer simulations. The Ontario Ministry of Transportation and Communications (MTC) was asked to test the six baseline vehicles and three additional tractor-trailer combinations as part of its contribution to the study.

The primary objective of the test program was to assemble a body of technical and visual data that described the stability and control characteristics of the baseline vehicles with respect to certain performance measures. These tests would be used as a background to complement the findings of the computer simulation. Test manoeuvres were conducted to examine the following:

- turning performance;
- the air brake system;
- lateral/directional stability characteristics of an empty vehicle on a low-friction surface, with and without braking;
- lateral/directional response characteristics of a loaded vehicle on a high-friction surface;
- steady-state roll characteristics of a loaded vehicle on a high-friction surface;
- dynamic stability characteristics of a loaded vehicle on a high-friction surface;
- trailer sway.

A secondary objective was to conduct computer simulations using the measured test inputs and actual vehicle unit properties to demonstrate that simulation can represent vehicle responses for a wide range of vehicles and test manoeuvres. Simulations were conducted for the following test conditions:

- sinusoidal steer manoeuvre with loaded vehicle on a high-friction surface;
- lane change with a loaded vehicle on a high-friction surface;
- steady circular turn with a loaded vehicle on a high-friction surface.

This report summarizes the modifications made to the UMTRI yaw/roll program and the comparative study between computer simulation and test responses of the nine vehicles over a wide range of operating conditions.

Detailed descriptions of test procedures common to all vehicles [3], and test results [4-12], are presented elsewhere.

2/ TEST VEHICLES

The set of vehicles to be tested was defined and provided to MTC by the study.

The test vehicle consisted of the MTC Freightliner [3] and the trailer or trailer combination being tested. A 1976 Freightliner 6x4 was used for all tests. The MTC Freightliner, seen in Figure 1, has been used in many previous test programs and was already fully instrumented for the requirements of these tests. It was a cab-over-engine type with integral sleeper, powered by a Detroit Diesel V-12 engine rated at 465 bhp at 2100 rpm. The front axle was rated at 8182 kg (18 000 lb), and the tandem drive axles used a Hendrickson RTE-440 walking beam suspension rated at 20 000 kg (44 000 lb). The wheelbase was 3.50 m (138 in), the tandem axle spread was 1.83 m (72 in), and the drive axle wheel track was 2.44 m (96 in). The fifth wheel was installed 0.20 m (8 in) forward of the midpoint of the drive tandem. The normal operating weight of the Freightliner was about 9790 kg (21 540 lb), including driver and typical quantities of fluids. The Freightliner is somewhat atypical of late-model tractors used in interprovincial trucking, where the typical front axle rating is 5455 kg (12 000 lb), drive tandem spread is 1.52 m (60 in), and weight is 7730 to 8409 kg (17 000 to 18 500 lb) [2]. The Freightliner front axle used Michelin XZA radial tires, load range G, size 11R24.5, and the drive axles used Michelin XM+S4 radial tires, load range G, size 11R24.5.

2.1/ 45 ft Semi

The test vehicle consisted of the MTC Freightliner and a 45 ft (13.72 m) tandem-axle semitrailer. The combination is typical of equipment used in Atlantic and Western Canada and the US. Semitrailers used in Central Canada now typically have a tandem-axle spread of 1.83 m (72 in) or more, compared with the 1.37 m (54 in) of this trailer.

The trailer was manufactured by RAM Highway Trailers of Canada in June 1981 and bore the serial number 381-13648. The trailer had a nominal length of 13.72 m (45 ft) and a nominal width of 2.44 m (96 in). Suspension was a four-spring leaf suspension system with torque rods and equalizers. The spring centre width was 0.96 m (38 in), and the overall track width was 2.44 m (96 in). The trailer was rated at 8000 kg/axle (17 600 lb/axle). The axle spacing was 1.37 m (54 in). The combination had an overall length of 17.17 m (58.30 ft).

The test vehicle is shown in Figure 1, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 2. Empty weight of the combination in test condition was 18 299 kg (46 260 lb). Concrete blocks were used to obtain a loaded weight of 31 205 kg (68 650 lb). Axle loads in these conditions are given in Table 1. The legal gross weight for the vehicle tested varies between 36 500 and about 41 000 kg (80 300 and 90 200 lb), depending upon the province.

Table 1/ Axle Loads, 45 ft Semi

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	5 009	11 020	5 118	11 260
2	4 209	9 260	6 114	13 450
3	3 791	8 340	6 114	13 450
4	2 472	5 440	6 882	15 140
5	2 818	6 200	6 977	15 350
Total	18 299	40 260	31 205	68 650

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.24 m (9 in) below the top of the floor. The centre of gravity height was estimated as 0.17 m (7 in) above the top of the floor in the loaded condition.

2.2/ A-Train Double

The test vehicle consisted of the MTC Freightliner and two tandem-axle flatbed semitrailers with a single-axle A-type converter dolly. The combination is typical of equipment used in all regions of Canada, except the Atlantic provinces.

The trailers were manufactured by Fruehauf in Winnipeg and were model PB-F2-26-102-SF, with serial numbers DXT2796-08 and DXT2796-06. Each trailer had a nominal length of 7.93 m (26 ft) and a nominal width of 2.44 m (96 in). Each had two axles spaced 1.24 m (49 in) apart and suspended from a Reyco 21B four-spring leaf suspension system with torque rods and equalizer arms. The spring centre spacing for each trailer was 0.96 m (38 in), and the overall track width was 2.44 m (96 in). The

A-dolly comprised a standard A-dolly frame and a Reyco 21B four-spring leaf suspension system with a torque rod. The A-dolly had a spring centre width of 0.98 m (38.5 in), and the track overall width was 2.44 m (96 in). The fifth-wheel-to-hitch distance was 2.14 m (7 ft). The combination had an overall length of 21.07 m (69.13 ft).

The test vehicle is shown in Figure 3, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 4. Empty weight of the combination in test condition was 24 368 kg (53 610 lb). Concrete blocks were used to obtain a loaded weight of 47 699 kg (104 940 lb). Axle loads in these conditions are given in Table 2. Both trailers were loaded in the same fashion. The legal gross weight of the vehicle tested varies between 52 800 and 61 600 kg (116 160 and 135 520 lb), depending on the province.

Table 2/ Axle Loads, A-Train Double

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	5 082	11 180	5 127	11 280
2	3 845	8 460	5 327	11 720
3	3 027	6 660	5 486	12 070
4	2 205	4 850	5 250	11 550
5	2 277	5 010	6 882	15 140
6	3 323	7 310	7 400	16 280
7	2 950	6 490	6 936	15 260
8	1 659	3 650	5 291	11 640
Total	24 368	53 610	47 699	104 940

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.37 m (15 in) below the top of the floor. The centre of gravity height was estimated as 0.20 m (8 in) above the top of the floor in the loaded condition.

2.3/ B-Train Double

The test vehicle consisted of the MTC Freightliner [1] and a B-train double trailer combination with a centre triple axle and rear tandem axle. The combination is typical of equipment used in Central Canada in heavy-haul applications.

The trailers were manufactured by Pullman Trailmobile Canada in February 1980 and bore serial number 2.80.1110.1028.002. Both trailers had a nominal length of 7.92 m (26 ft) and a nominal width of 2.44 m (96 in). The lead trailer was provided with a triple-axle unit with an axle spacing of 1.52 m (60 in) and a Reyco six-spring suspension system with torque rods and equalizers. It had a fifth wheel mounted above the rear axle of the triple-axle unit. The tandem-axle rear trailer had an axle spacing of 1.79 m (70.5 in) and a Reyco four-spring suspension system with torque rods and equalizers. On both trailers, the spring centre spacing was 0.96 m (38 in); the overall track width, 2.44 m (96 in); and the axle rating, 9616 kg (21 155 lb). The combination had an overall length of 22.1 m (72.5 ft).

The test vehicle is shown in Figure 5, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 6. Empty weight of the combination in test condition was 26 155 kg (57 540 lb). Concrete blocks were used to obtain a loaded weight of 52 764 kg (116 080 lb). Axle loads in these conditions are given in Table 3. The legal gross weight of the vehicle tested is 56 600 kg (124 560 lb) in Quebec, 60 500 kg (133 100 lb) in Ontario, and would be about 52 000 kg (114 400 lb) where permitted in the prairie provinces.

Table 3/ Axle Loads, B-Train Double

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	4 650	10 230	4 991	10 980
2	3 996	8 790	6 082	13 380
3	3 500	7 700	5 723	12 590
4	3 386	7 450	7 864	17 300
5	2 918	6 420	7 827	17 220
6	2 664	5 860	7 232	15 910
7	3 077	6 770	7 536	16 580
8	1 964	4 320	5 509	12 120
Total	26 155	57 540	52 764	116 080

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.37 m (15 in) below the top of the floor. The centre of gravity height was estimated as 0.22 m (9 in) above the top of the floor in the loaded condition.

2.4/ C-Train Double

The test vehicle consisted of the MTC Freightliner and two tandem-axle flatbed semitrailers with a single-axle B-type converter dolly. The combination is typical of equipment used in provinces where C-train double trailer combinations operate.

The trailers were the same as those used in the A-train double (Section 2.3), but in the reverse order. The dolly was made up from the ASTL SSD frame, used in previous tests [13], and a Sauer model RLZ10041 self-steering axle rated at 10 000 kg (22 000 lb) and set for a speed of 80 km/h. Suspension was a Reyco two-spring leaf suspension system with a torque rod. The B-dolly had a spring centre width of 0.76 m (30 in), and the overall track width was 2.44 m (96 in). The fifth-wheel-to-hitch distance was 1.98 m (6.5 ft). The combination had an overall length of 20.97 m (68.8 ft).

The test vehicle is shown in Figure 7, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 8. Empty weight of the combination in test condition was 24 196 kg (53 230 lb). Concrete blocks were used to obtain a loaded weight of 48 668 kg (107 070 lb). Axle loads in these conditions are given in Table 4. Both trailers were loaded in the same fashion. The legal gross weight of the vehicle tested varies between 52 800 and 61 600 kg (116 160 and 135 520 lb), depending on the province.

Table 4/ Axle Loads, C-Train Double

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	4 832	10 630	5 127	11 280
2	3 700	8 140	5 445	11 980
3	3 218	7 080	5 464	12 020
4	2 073	4 560	5 664	12 460
5	2 355	5 180	6 536	14 380
6	3 518	7 740	7 727	17 000
7	2 445	5 380	6 814	14 990
8	2 055	4 520	5 891	12 960
Total	24 196	53 230	48 668	107 070

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.37 m (15 in) below the top of the floor. The centre of gravity height was estimated as 0.20 m (8 in) above the top of the floor in the loaded condition.

2.5/ A-Train Triple

The test vehicle consisted of the MTC Freightliner and three single-axle van-type semitrailers with single-axle A-type converter dollies. The combination is typical of equipment used in provinces where triple trailer combinations operate under special permit. The equipment was inspected before the test by a representative of the owner on behalf of the Canadian Trucking Association, with no deviations from specifications reported.

The trailers and dollies were brand new. They were manufactured by Trailmobile in February 1985. The trailers had serial numbers 2TCH281B6EA303117, 2TCH281B93A303130, and 25CH281B93A303127 and fleet numbers 7794, 7807, and 7804, from front to rear, respectively. The A-dollies had serial numbers 2TCT101AXEA303207 and 2TCT101A3EA303209 and fleet numbers 0747 and 0745 for front and rear, respectively.

Each trailer had a nominal length of 8.53 m (28 ft) and a nominal width of 2.59 m (102 in). Each trailer had a tapered nose section and a 1.22 m (4 ft) kingpin set back so that they could also be operated as a legal doubles combination in some provinces. The trailers were insulated, and a propane heater was installed at the front near the roof. The trailer suspension had a single tapered leaf spring and was rated at 9616 kg (21 155 lb). The spring spread was 1.09 m (43 in), and the overall track width was 2.59 m (102 in). The spring lash space was 38 to 41 mm (1.5 to 1.63 in). The trailers were equipped with an air-actuated no-slack pintle hook. The dollies had the same suspension as the trailers, a drawbar length of 2.13 m (84 in), and a fifth wheel set 25 mm (1 in) forward of the axle centreline. The combination had an overall length of 31.08 m (102 ft).

The test vehicle is shown in Figure 9, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 10. Empty weight of the combination in test condition was 33 087 kg (72 790 lb). Concrete blocks were used to obtain a loaded weight of 55 942 kg (123 070 lb). Axle loads in these conditions are given in Table 5. The loaded weight is somewhat greater than that allowed by provinces where this combination runs under special permit.

Typical loaded weights on the highway for such combinations are often much less than that allowed, by the nature of the cargo carried by the vehicle. All three trailers were loaded in the same fashion, consistent with normal practice. The tractor drive axles, therefore, were loaded less than each trailer axle, because their combined load was much less than 12 000 kg (26 400 lb) because of the empty vehicle.

Table 5/ Axle Loads, A-Train Triple

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	4 864	10 700	5 286	11 630
2	3 945	8 680	5 914	13 010
3	3 705	8 150	5 168	11 370
4	4 177	9 190	7 800	17 160
5	4 091	9 000	8 073	17 760
6	4 377	9 630	7 964	17 520
7	3 855	8 480	8 005	17 610
8	4 073	8 960	7 732	17 010
Total	33 087	72 790	55 942	123 070

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.40 m (16 in) above the top of the floor. The centre of gravity height was estimated as 0.33 m (13 in) above the top of the floor in the loaded condition.

2.6/ C-Train Triple

The test vehicle consisted of the MTC Freightliner and three single-axle van-type semitrailers with single-axle B-type converter dollies. The combination is typical of equipment used in provinces where triple trailer combinations operate under special permit.

The trailers were the same as those used for the A-train triple, described in Section 2.5. The B-dolly of the C-train double, described in Section 2.4, and another identical one were used to couple the trailers.

The test vehicle is shown in Figure 11, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 12. Empty weight of the combination in test condition was

33 997 kg (74 790 lb). Concrete blocks were used to obtain a loaded weight of 56 386 kg (124 050 lb). Axle loads in these conditions are given in Table 6. All three trailers were loaded in the same fashion, consistent with normal practice. The tractor drive axles, therefore, were loaded less than each trailer axle, because their combined load was much less than 12 000 kg (26 400 lb) because of the empty vehicle.

Table 6/ Axle Loads, C-Train Triple

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	5 014	11 030	5 286	11 630
2	4 114	9 050	5 914	13 010
3	3 523	7 750	5 168	11 370
4	4 305	9 470	7 800	17 160
5	4 286	9 430	8 295	18 250
6	4 409	9 700	7 964	17 520
7	3 223	9 290	8 227	18 100
8	4 123	9 070	7 732	17 010
Total	33 997	74 790	56 386	124 050

The loaded weight is somewhat greater than that allowed by provinces where this combination runs under special permit. Typical loaded weights on the highway for such combinations are often much less than that allowed, by the nature of the cargo carried by the vehicle.

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.40 m (16 in) above the top of the floor. The centre of gravity height was estimated as 0.33 m (13 in) above the top of the floor in the loaded condition.

2.7/ 5-Axle 48 ft Semi

The test vehicle consisted of the MTC Freightliner and a single 48 ft (14.63 m) tandem flatbed-type trailer. The combination is typical of equipment used in Central Canada, where additional weight can be carried on a widespread tandem axle.

The trailer was manufactured by Fruehauf and was a 48 ft (14.63 m) flatbed semitrailer with two fixed and two non-steering airlift axles that were raised for these tests. The trailer was manufactured in July 1984, bore the serial number 2H8P04843ER033601, and was model PBX4W 48102.

The trailer had a nominal length of 14.63 m (48 ft) and a nominal width of 2.59 m (102 in). The trailer suspension comprised a Reyco four-spring leaf system with long equalizer arms on the fixed axles, with a spacing of 2.77 m (109 in). The spring centre width was 0.96 m (38 in), and the overall track width was 2.44 m (96 in). The vehicle overall length was 18.69 m (61.32 ft). The trailer was rated at 9620 kg/axle (21 164 lb/axle).

The test vehicle is shown in Figure 13, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 14. Empty weight of the combination in test condition was 22 595 kg (49 710 lb). Concrete blocks were used to obtain a loaded weight of 34 409 kg (75 680 lb). Axle loads in these conditions are given in Table 7. The empty weight exceeds that which would normally be seen on the highway, because of the two lifted axles and the test equipment installed. The legal gross weight for the vehicle tested varies between 36 500 and about 44 000 kg (80 300 to 96 800 lb), depending upon the province.

Table 7/ Axle Loads, 5-Axle 48 ft Semi

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	4 918	10 820	5 055	11 120
2	5 368	11 810	7 336	16 120
3	4 686	10 310	6 827	15 020
4	4 082	8 980	7 618	16 760
5	3 541	7 790	7 573	16 660
Total	22 595	49 710	34 409	75 680

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.33 m (13 in) below the top of the floor. The centre of gravity height was estimated as 0.09 m (4 in) above the top of the floor in the loaded condition.

2.8/ 6-Axle 48 ft Semi

The test vehicle consisted of the MTC Freightliner and a single 48 ft (14.63 m) 3-axle flatbed semitrailer. The combination is typical of equipment used in Central Canada, where trailers with a widespread tandem axle and an airlift belly axle are permitted additional weight.

The trailer was the same as that for the 5-axle 48 ft (14.63 m) semi (Section 2.7), but with the aft airlift axle lowered. This non-steering axle had a Neway air suspension and was 2.74 m (108 in) ahead of the lead axle of the fixed tandem. Its air springs were on 0.76 m (30 in) centres, with shock absorbers in parallel on 0.30 m (12 in) centres.

The test vehicle is shown in Figure 15, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 16. Empty weight of the combination in test condition was 22 595 kg (49 710 lb). Concrete blocks were used to obtain a loaded weight of 41 543 kg (91 390 lb). Airlift axle pressure was 159 kPa (23 psi) for the empty vehicle and 345 kPa (50 psi) loaded. Axle loads in these conditions are given in Table 8. The empty weight exceeds that which would normally be seen on the highway because of the lifted axle and the test equipment. The legal gross weight of the vehicle tested is about 50 000 kg (110 000 lb) in Ontario and Quebec and 47 700 kg (105 000 lb) in B.C., where the belly axle is required to be steerable.

Table 8/ Axle Loads, 6-Axle 48 ft Semi

	Empty		Loaded	
Axle No.	(kg)	(lb)	(kg)	(lb)
1	4 918	10 820	5 373	11 820
2	4 554	10 019	7 505	16 510
3	4 554	10 019	6 809	14 980
4	2 856	6 284	7 396	16 270
5	2 856	6 284	7 714	16 970
6	2 856	6 284	6 746	14 840
Total	22 594	49 710	41 543	91 390

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.30 m (12 in) below the top of the floor. The centre of gravity height was estimated as 0.23 m (9 in) above the top of the floor in the loaded condition.

2.9/ 7-Axle 48 ft Semi

The test vehicle consisted of the MTC Freightliner and a single 48 ft

(14.63 m) four-axle flatbed-type semitrailer. The combination is typical of equipment used in Central Canada, where additional gross weight can be carried on a widespread tandem axle and belly axles.

The trailer was the same as that for the 5- and 6-axle 48 ft (14.63 m) semi (Sections 2.7 and 2.8), but with both non-steering airlift axles lowered.

The test vehicle is shown in Figure 17, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 18. Empty weight of the combination in test condition was 22 595 kg (49 710 lb). Concrete blocks were used to obtain a loaded weight of 49 898 kg (109 730 lb). Axle loads in these conditions are given in Table 9. Airlift axle pressure was 110 kPa (16 psi) in each axle for the empty vehicle and 345 kPa (50 psi) loaded. The legal gross weight for the vehicle tested is about 56 000 kg (123 200 lb) in Ontario.

Table 9/ Axle Loads, 7-Axle 48 ft Semi

	Empty		Loaded	
Axle No.	(kg)	(lb)	(kg)	(lb)
1	4 918	10 820	5 255	11 560
2	3 885	8 547	7 923	17 430
3	3 885	8 547	7 232	15 910
4	2 477	5 449	7 464	16 420
5	2 477	5 449	8 177	17 990
6	2 477	5 449	6 577	14 470
7	2 477	5 449	7 250	15 950
Total	22 595	49 710	49 878	109 730

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.26 m (10 in) below the top of the floor. The centre of gravity height was estimated as 0.27 m (11 in) above the top of the floor in the loaded condition.

3/ SIMULATION PROGRAM

3.1/ Yaw/Roll Model

The yaw/roll model is one of the simulation programs developed at UMTRI to study the directional and roll response of multi-articulated commercial vehicles in the time domain [14]. The model was designed to simulate a general truck-train combination of up to four vehicle units, with a total of 11 axles distributed in any arbitrary configuration, except with a single tractor front axle. The vehicle model was developed based on the following assumptions:

- Each vehicle unit consists of a rigid body sprung mass and a number of beam axles as unsprung masses connected to the sprung mass through compliant suspensions.
- The vehicle is moving at a constant forward speed on a horizontal surface with a uniform frictional characteristic.
- Each sprung mass has five degrees of freedom in the lateral, vertical, roll, pitch, and yaw directions, whereas each unsprung mass is capable only of roll and bounce with respect to the sprung mass.
- Pitch motion of the vehicle is assumed to be small, such that $\sin\theta$ and $\cos\theta$ can be approximated by θ and 1, respectively.
- The relative roll displacement between the sprung mass and the unsprung mass is small, such that $\sin(\phi_s-\phi_u)$ and $\cos(\phi_s-\phi_u)$ are approximated by $\phi_s-\phi_u$ and 1, respectively.
- The forces between the sprung mass and the unsprung mass are assumed to be transmitted through the roll centre of each axle, located directly underneath the sprung mass and free to move in the vertical axis of the unsprung mass.
- Each suspension is independent of other suspensions, such that inter-axle load transfer of load-sharing suspensions is neglected.
- The principal axes of inertia of the sprung and unsprung masses coincide with their respective body-fixed co-ordinate system.
- Sprung masses are connected by one of four hitch mechanisms: pintle hook, kingpin, fifth wheel, or inverted fifth wheel. With the pintle hook mechanism, the trailing unit is capable of bounce, roll, yaw, and pitch with respect to the lead unit. The kingpin connection allows only yaw motions between the leading and trailing units. Both the fifth wheel and inverted fifth wheel allow each unit to roll, pitch, and yaw with respect to one another.

Details of the mathematics of the equations of motion can be found in Reference 14.

State-of-the-art simulation techniques were implemented in the model, and the following special features were included in the yaw/roll program:

- non-linear tire characteristics of the tire-road interface in the form of cornering force and aligning moment as a function of slip angle and vertical axle load by lookup tables;
- non-linear suspension characteristics in the form of load versus deflection by lookup tables;
- simulation in either the open-loop mode using steer angle input or the closed-loop mode using a predefined vehicle trajectory as input data;
- self-steering axle and B-dolly configuration;
- four types of hitch mechanism: pintle hook, kingpin, conventional fifth wheel, and inverted fifth wheel.

With these features, the most complex configuration that can be simulated is a C-train double with a steerable axle at the B-dolly.

3.2/ Modification

Figure 19 shows a simplified flowchart of the UMTRI yaw/roll program, which consists of a main program and a number of subroutines within one program code. The original program operated on IBM mainframe equipment. To install the yaw/roll program on a modest minicomputer such as the HP-1000 A700 used by MTC for test data acquisition and processing, a substantial amount of modification was required to reduce program size and obtain a reasonable execution speed. The modifications made to the original yaw/roll program can be categorized under four different areas:

1/ I/O structure
2/ program size reduction
3/ computation changes
4/ program augmentation

3.2.1/ I/O Structure

The new program has a fixed field input format for all parameters so that the input data set is readable. The input data set was split into two, one for the vehicle parameters and the other for the vehicle operating conditions. The bulk of the original data remains intact in the vehicle parameter set. The purpose of this new arrangement was to facilitate simulation of test runs by defining the operating conditions of the vehicle in a separate file.

The output section of the yaw/roll program was completely restructured. Instead of printing all the simulation responses, the user now defines exactly which parameters are required, and the responses are stored in a file with the same format as the test data. Thus simulation and test responses can be compared readily. While the input data remain in imperial units, the output of the simulation has been converted to metric units.

3.2.2/ Program Size Reduction

The following steps were taken to reduce the core requirement of the yaw/roll program:

- Similar subroutines, such as FORTAB and ALTAB, were combined through code generalization.
- The closed-loop driver model, together with the supporting subroutines, was deleted from the program.
- Irrelevant subroutines and variables were deleted.
- The number of tire types allowed was reduced from 11 to 2.
- The output array dimensions were reduced from (18,14,45) to (18,14) by virtue of the I/O structural change.
- Program code was simplified to eliminate some variable arrays.
- Dimensions of the matrices were redefined to store only non-zero partitions.

As a result of all these changes, the size of the yaw/roll program was greatly reduced so that it could fit the limited memory of the HP-1000.

3.2.3/ Computation Coding

The changes described in this section were responsible for the improvement in execution speed of the yaw/roll program. The program code was simplified to minimize the number of computer operations because the FORTRAN compiler did not provide object code optimization. This reduced execution time and program size. The matrix arithmetic was modified to include only the non-zero calculations. Again, this reduced both size and execution time of the program. The hardware vector instructions of the HP-1000 A700 were also used throughout the computation, where appropriate. A search subroutine was added to "remember" the current index for the non-linear table lookups to minimize the amount of searching.

3.2.4/ Program Augmentation

Because of the changes made in the matrix computation, the program could be extended to allow simulation of an A-train triple combination, which has six sprung masses, without requiring a large increase in memory. Additional features such as a twin-steer front axle had previously been implemented. The pintle hook representation was modified to include a vertical constraint so that it was more representative of the actual physical system. A subroutine was included to convert lateral acceleration from the unit's centre of mass to any other location to facilitate comparison between test and simulation results.

With the latest improved version of the B-dolly model developed at UMTRI, the MTC version of the yaw/roll program can now be used to simulate a C-train triple with steerable axles. Flexibility of the program has been improved by changing the I/O structure so that direct simulation of a test condition is made trivial. The simulation output is data driven.

3.2.5/ MTC Yaw/Roll Program

Figure 20 shows the simplified flowchart of the improved yaw/roll program. Simulation is initiated by program SIMDA, which, in turn, starts program YAWRT and then waits for the simulation results. Program YAWRT has a similar function to the original yaw/roll program in that it reads in all the vehicle parameters and operating conditions by subroutine INPOT and performs the integration by HPCGT. However, upon completion of each time step, results of the simulation are sent to program SIMDA, which then puts the result into the appropriate array for eventual storage in a file on disk.

3.3/ Data Source

There are two types of data required as input to the simulation model: the vehicle parameters and the operating parameters. The vehicle parameters can further be broken down into two groups: the physical properties and dimensions of the vehicle and the mechanical properties of the suspension system and the tire-road interface.

As far as the vehicle parameters are concerned, all dimensions were measured from the vehicle on the test track.

Axle loads were obtained by a portable scale placed directly underneath the tires. Mass properties were estimated from the structural components and accessories of the vehicle unit, including the payloads.

The mechanical properties of the suspension system and the tire characteristics were taken from laboratory measurements performed by UMTRI on behalf of the Vehicle Weights and Dimensions Study [15] and were, thus, the same as those data used by UMTRI in their simulation work. The suspension compliance was represented by a non-linear force deflection table, whereas the tire characteristics were represented by non-linear cornering force and aligning torque with respect to sideslip and axle load, also in the form of lookup tables. Measured properties of the Sauer self-steering axle were not available, so those of the Ceschi axle were used instead, that axle appearing to be the closest, for which data were available, to the Sauer.

The vehicle operating parameters were chosen directly from the processed test data. The steer angle input was picked from the test data at a fixed time step, typically 0.1 s. The forward speed was determined as the average speed of the vehicle over a period of 1 s, immediately before the start of the steer input. The initial yaw angle and yaw rate were taken directly from the test data at the start of the steer input. Other initial conditions were assumed to be zero.

4/ SIMULATION RESULTS

4.1/ Sinusoidal Steer

In this manoeuvre, the driver approached an open high-friction test area at constant speed with a loaded vehicle and executed a sinusoidal steer input at the steering wheel. This created a sinusoidal lateral acceleration input at the tractor, which resulted in a sidestep to the left dependent on the speed and steer amplitude, a vehicle trajectory similar to the lane change. The sinusoidal steer was a standard input used to determine the vehicle's stability characteristics.

The test was run at speeds of 63, 84, and 94 km/h, which were the actual speeds in the gear that came closest to the target speeds of 60, 80, and 100 km/h. Steer periods within the range of 1 to 5 s were used.

The following sections describe comparisons between simulation and test responses for the nine vehicles.

4.1.1/ 45 ft Semi

Figures 21, 22, and 23 show the comparison of vehicle response between simulation and test results for the 45 ft (13.72 m) semi in the sinusoidal steer manoeuvre. In these and all subsequent similar figures, the test data are plotted as the solid line, and the simulation results, as the broken line.

Excellent agreement is evident in the directional and roll responses of both the tractor and trailer. Similar agreement was obtained with other steer periods.

4.1.2/ A-Train Double

Simulation of the sinusoidal steer manoeuvre of the A-train double was conducted at 63 and 94 km/h.

Figures 24 and 25 show excellent agreement between simulation and test results for the lateral acceleration and articulation responses of all the vehicle units. The difference in the dolly articulation angle is due to malfunction of the articulation measuring device at the pintle hook. Various degrees of agreement between test and simulation were obtained with different steer periods.

Figure 26 compares the rearward amplification of the A-train double as a function of steer period. In these and all subsequent similar figures, the test data are plotted as the "+" symbol, and the simulation results, as the "O" symbol. Both the test and simulation results show a similar trend in the rearward amplification as a function of steer period for both vehicle speeds.

4.1.3/ B-Train Double

Simulation was conducted for the B-train double at speeds of 63, 84, and 94 km/h in the sinusoidal steer manoeuvre with various steer periods. With the "standard" tire characteristics assumed for all the axles, the predicted responses did not agree well with the test responses for the B-train double. By using a tire characteristic of a "worn" tire, which has a somewhat higher cornering capability than the "standard" tire, at the tractor drive axles, the simulation gave much better agreement with the test.

Figures 27, 28, and 29 show good agreement between simulation and test results for the directional responses for all three vehicle speeds. Even though the simulation model did not predict the peak roll angle of the test response, there is still a good correlation between test and simulation in the roll responses of the three vehicle units.

Figure 30 shows the trends of the rearward amplification extracted from the simulation results superimposed on that of the test results as a function of steer period. There is excellent agreement between simulation and test.

4.1.4/ C-Train Double

Simulation was conducted for the C-train double in the sinusoidal steer manoeuvre at speeds of 84 and 94 km/h. For this C-train double and subsequent C-train configurations involving the self-steering B-dollies, the steering characteristics of a Ceschi steerable axle measured by UMTRI was used in the simulation because of a lack of data for the Sauer axle.

Figures 31 and 32 show good agreement for all the measured responses of the various vehicle units at both speeds, except for first trailer articulation. It can be observed that the simulation model gives a fairly good prediction of the dolly steer angle, except at the end of the manoeuvre. Similar agreement between test and simulation responses was found for the other steer periods.

A comparison of the rearward amplification between test and simulation is shown in Figure 33. There is close agreement in the trend of the rearward amplification as a function of steer period between test and simulation for the two vehicle speeds.

4.1.5/ A-Train Triple

Simulations were performed at the vehicle speeds of 63, 84, and 94 km/h in the sinusoidal steer manoeuvre for the A-train triple at different steer periods.

Figures 34, 35, and 36 show the comparison of the dynamic responses of the A-train triple between simulation and test results at these speeds, with a steer period between 2.0 and 2.5 s. Simulation results for the directional response of all the vehicle units agree well with the test responses, and there is good correlation for the roll responses below 84 km/h. At 94 km/h, the simulation model can still predict the dynamic responses of the test vehicle, except that the simulation predicted a higher damping at the end of the steering manoeuvre.

Figure 37 shows the rearward amplification superimposed on that of the test results as a function of steer period. There is a definite agreement between test and simulation results in the trend of rearward amplification as a function of steer period.

4.1.6/ C-Train Triple

Both computer simulation and test were conducted on the C-train triple in the sinusoidal steer manoeuvre at 63, 84, and 94 km/h.

Figures 38, 39, and 40 compare the dynamic responses of the vehicle between simulation and test at these speeds. Excellent agreement is seen in the lateral acceleration responses of all the vehicle units, as well as the articulation angles of the first and second trailers, for all three vehicle speeds. It is obvious from the figures that the third trailer articulation transducer malfunctioned at 63 and 84 km/h. There is also a good correlation between the roll angle responses. The steer angle at both dollies was small, as predicted by the simulation model. Similar agreement was obtained with the other steer periods.

Figure 41 shows good agreement in the trend of the rearward amplification as a function of steer period between test and simulation at the three test speeds.

4.1.7/ 5-Axle 48 ft Semi

Computer simulation of the sinusoidal steer manoeuvre was conducted for the 5-axle 48 ft (14.63 m) semi at 63, 84, and 94 km/h.

Figures 42, 43, and 44 show the simulated responses superimposed on the test results, at these speeds, with a steer period in the 2 to 3 s range. There is excellent agreement in the directional response of the vehicle units at 63 and 84 km/h. At 94 km/h, the simulation model predicts a somewhat different response than the test results. This is possibly caused by the difference in the tire characteristics between test and simulation, which shows up when the vehicle is operating at higher speeds. Similar agreement was obtained with other steer periods at the same speeds.

Figure 45 compares the trailer rearward amplification as a function of steer period between simulation and test results. There is excellent agreement in the trend of the rearward amplification with respect to steer period between test and simulation for the three speeds examined.

4.1.8/ 6-Axle 48 ft Semi

Due to failure of the computer disk drive, test data were lost for the 6-axle 48 ft (14.63 m) semi in the sinusoidal steer manoeuvre at 63 and 84 km/h, so computer simulation was conducted only for 94 km/h. With the 6-axle 48 ft (14.63 m) semi, the input data for the tire cornering capability at the tractor drive axles and the trailer tandem axles had to be modified to obtain a good match with test responses. The same tire characteristics were used as for the B-train double (Section 4.1.3).

Figure 46 compares the dynamic responses between simulation and test results at a speed of 94 km/h, with a 2.0 s steer period. There is a good agreement between test and simulation in the directional responses of both the tractor and the trailer unit. Although the simulation did not predict the same peak roll angles as that measured from the test responses, there is a good correlation in the roll responses.

Figure 47 shows the comparison in rearward amplification as a function of steer period. The trend of rearward amplification predicted by the simulation model is in close agreement with that obtained from the test results.

4.1.9/ 7-Axle 48 ft Semi

Both computer simulation and test were conducted for the 7-axle semi with the sinusoidal steer manoeuvre at 63, 84, and 94 km/h. With this configuration, the input data for the tire cornering capability at the tractor drive axles and the trailer tandem axles were modified to match the test responses, as was found necessary for the 6-axle 48 ft semi (14.63 m) (Section 4.1.8).

Figures 48, 49, and 50 compare the vehicle responses between test and simulation results at these speeds. Excellent agreement was found in the directional response of the vehicle units at 63 km/h. Similar agreement cannot be found for the vehicle responses at higher speeds. However, steer angle input for both the 84 and 94 km/h runs indicated that there was a large imbalance in the steer amplitude between the left and the right, and the simulation response reflects the steer input. Since the steer angles are small, the effect of toe-in and toe-out of the road wheel becomes significant at high speed. Together with the "treatment" of detrending in the calibrated data, the steer angle response appears to be unbalanced. This could explain why the test results indicate a balanced lateral acceleration response for the vehicle.

Figure 51 compares simulation and test results for the rearward amplification as a function of steer period. It can be observed that the simulated rearward amplification has a similar trend to that obtained from the test results.

4.2/ Lane Change

The lane change on a standard highway requires a steer input similar to the sinusoidal steer. The amplitude of the steer input must be such that a sidestep of 3.66 m (12 ft) or one lane is achieved. This test is representative of an obstacle avoidance manoeuvre on a multilane highway, where the sudden appearance of an obstacle necessitates a fast lane change to the left.

The test course was laid out on a high-friction surface, as shown in Figure 52. The 30 m (98 ft) gate was selected so that speeds at the limits of stability for all vehicles would be in the range of 70 to 90 km/h. The vehicle was loaded, and the driver approached the course at constant speed. The driver's task was to manoeuvre the vehicle through the gate while maintaining speed and control without contacting any of the marker cones. A sequence of runs was conducted at increasing speeds until the vehicle became unstable by rollover or there was 1 m (3.3 ft) swing out of lane. The test was terminated at 100 km/h, even if the vehicle was still able to complete the manoeuvre successfully.

4.2.1/ 45 ft Semi

Computer simulation was conducted for the 45 ft (13.72 m) semi executing the lane-change manoeuvre at various speeds ranging from 47 km/h to 100 km/h.

Figure 53 compares the responses of simulation and test at a speed of 72 km/h. There is, in general, good agreement in the directional responses of the vehicle units, even though there are some small differences between the peak responses of lateral acceleration of both the tractor and trailer. The roll angle responses of the tractor and trailer predicted by the simulation are slightly higher than the test responses, but the amplitudes are too small to be significant and the correlation is good. Similar agreement was found at other speeds.

4.2.2/ A-Train Double

No simulation was carried out for the A-train double because the test was not conducted.

4.2.3/ B-Train Double

The B-train double was simulated for speeds ranging from 47 km/h to 89 km/h.

With the "standard" tire characteristics, there was no agreement between the simulation and test responses for the three vehicle units, as shown in Figure 54, for a speed of 63 km/h.

By changing the tire characteristics at the tractor drive axle, as was found necessary in Section 4.1.3, the simulation agreed well with the test results, as shown in Figure 55, for the same run. There is excellent agreement in the directional responses and fairly good agreement in the roll responses of the first and second trailers. Similar agreement was found at other speeds.

4.2.4/ C-Train Double

Figure 56 shows the lane-change responses of the C-train double predicted by the simulation superimposed on the test results for a speed of 72 km/h. There is excellent agreement in all the measured responses of all vehicle units throughout the manoeuvre. The vehicle showed a significant amount of second trailer swing after the trailer reached the left lane, and the simulation model predicted a similar response. In particular, the simulation model produced an excellent prediction of the dolly steer angle throughout the lane-change manoeuvre. Similar results were found at higher speeds, although the level of agreement deteriorated at the end of the manoeuvre, possibly due to the change of tire characteristics as a function of speed.

4.2.5/ A-train Triple

A lane-change manoeuvre was conducted with the A-train triple from 47 km/h to 77 km/h, limited at that speed by an excessive third trailer swing. This was the least stable of the nine vehicles examined. Computer simulation was conducted with the same speed as in the test program.

Figure 57 shows the simulated responses of the A-train triple superimposed on the test responses for a speed of 63 km/h. The tractor vibrated greatly during the manoeuvre, as evident from the tractor lateral acceleration response signal. The agreement was good for the lateral acceleration and articulation angles of the vehicle units. Even though the roll responses predicted by the simulation model were somewhat higher than the actual measurements, the roll angles were small and there was a good correlation between the test and simulation. Thus, except for the roll angle responses, the yaw/roll program provides a fairly accurate prediction of the dynamic lane-change responses of the A-train triple. Similar agreement was found at other speeds.

4.2.6/ C-train Triple

Computer simulation of the lane-change manoeuvre for the C-train triple was conducted between speeds of 35 and 89 km/h, at which point the test vehicle responses became unacceptable.

Figure 58 compares the simulation and test responses at a speed of 63 km/h. There is close agreement in the lateral acceleration and articulation of all the vehicle units. The difference in peak roll angle responses is believed to result from transducer accuracy and the torsional rigidity of the vehicle units. Again, there is a good correlation in the roll angle responses between test and simulation. Similar agreement was found at other speeds.

4.2.7/ 5-Axle 48 ft Semi

Simulation of the 5-axle 48 ft (14.63 m) semi was performed between speeds of 47 km/h and 100 km/h in the lane-change manoeuvre. Results of the simulation indicated that there is, in general, good agreement in the directional responses for both the tractor and trailer between the simulation and test results.

Figure 59 compares the vehicle responses between simulation and test at a speed of 72 km/h. There is excellent agreement in the lateral acceleration responses as well as articulation, and although the predicted peak roll angle responses do not agree well with the test measurements, the differences are too small to be significant. Similar agreement was found at other speeds.

4.2.8/ 6-Axle 48 ft Semi

Due to failure of the computer disk drive, test data were lost for the 6-axle 48 ft (14.63 m) semi in the lane-change manoeuvre.

4.2.9/ 7-Axle 48 ft Semi

The 7-axle 48 ft (14.63 m) semi was tested for speeds from 47 km/h to 100 km/h.

With this vehicle configuration, simulation using the "standard" tire characteristics for all axles did not predict similar responses as the test measurements, as shown in Figure 60.

By changing the tire characteristics at the tractor drive axles and the third and fourth axle of the trailer, as mentioned in Section 4.1.9, the simulation responses were made to agree well with the test results. Figure 61 compares the simulation and test responses at a speed of 92 km/h. There is excellent agreement in the directional responses of both the tractor and trailer, and the only parameters that do not have complete agreement are the roll angle responses of the tractor and trailer. However, they are small and there is a good correlation between simulation and test responses. Similar agreement was found at other speeds.

4.3/ Steady Circular Turn

The steady circular turn course was laid out using traffic cones on a dry high-friction surface, as shown in Figure 62. The circle had a radius of 50 m (164 ft), with a 100 m (328 ft) long entry spiral. The vehicle was loaded, and the driver followed the approach at a specified constant speed, entered the circular turn as smoothly as possible, and followed on the outside for 90 to 180°, or as long as possible. A sequence of runs was conducted at increasing speeds until the vehicle became unstable by rollover or trailer swing or the driver could not maintain either the desired trajectory or the speed.

The outriggers were set such that the vehicle wheels on the inside of the turn would lift by 0.15 to 0.20 m (0.5 to 0.65 ft) at outrigger touchdown, which corresponds to about 6 to 7° of body roll. The A-trains could clearly roll over the rear trailer, but for the others, even if outrigger touchdown occurs, the entire vehicle could still be short of the point of rollover. Outrigger touchdown, therefore, simply denoted a point beyond which further testing was impractical. There would not necessarily be any relationship between these points for each vehicle.

It became evident after the simulation of a few vehicle configurations that the tire characteristics at the tractor drive axle had to be modified to achieve better agreement in the steady-state response between test and simulation of all the vehicles. The tire characteristics chosen for the drive axle of the tractor were the same as those used for the B-train double and 7-axle 48 ft (14.63 m) semi in the lane-change manoeuvre. The following sections describe the results of computer simulations of the nine vehicles.

4.3.1/ 45 ft Semi

Figure 63 compares the steady circular turn response between computer simulation and test results of the 45 ft (13.72 m) semi at a speed of 60 km/h. There is excellent agreement in the tractor's directional and roll responses throughout the entire manoeuvre and for the lateral acceleration and roll response of the semitrailer. Even though there is a significant difference in the steady-state articulation angle of the semitrailer, the correlation between test and simulation responses is good, and better agreement could be obtained by refining the tire characteristics of the trailer. Similar agreement between simulation and test responses was found at other speeds.

4.3.2/ A-Train Double

Simulation of the A-train double in the steady circular turn was conducted with the same speeds as that carried out in the tests, ranging from 35 to 63 km/h. Figure 64 compares the responses at a speed of 55 km/h. Good agreement is seen in the lateral acceleration responses of all the vehicle units, tractor yaw angle, trailer articulation angles, and roll angles. The difference in the dolly trailer articulation angle is believed to be caused by a malfunction of the articulation angle measurement. Similar agreement was obtained at other speeds.

4.3.3/ B-Train Double

The steady circular turn manoeuvre was conducted for the B-train double from 35 to 63 km/h. Computer simulation was performed in the same speed range. Figure 65 shows the simulation response superimposed on the test results for a speed of 47 km/h. The simulation model produced, in general, an accurate prediction of the directional and roll responses of the test vehicle. Similar agreement between test and simulation responses was obtained for other speeds until the vehicle approached the threshold of instability.

4.3.4/ C-Train Double

Figure 66 compares the steady circular turn response of the C-train double between simulation and test at a speed of 55 km/h. Excellent agreement is seen for lateral acceleration of all vehicle units, tractor yaw angle, first trailer articulation, and the roll responses. The differences between simulation and test in dolly steer and second trailer articulation angle for this particular vehicle and manoeuvre type are unknown at this stage. Similar agreement between simulation and test responses was found at other speeds.

4.3.5/ A-Train Triple

Simulation of the A-train triple for the steady circular turn was carried out with the same speeds as those conducted on the actual vehicle. Figure 67 compares responses at a speed of 55 km/h. The steer angle input shows that the driver had to make a number of steering adjustments to maintain the tractor on the circular path. The lateral acceleration responses predicted by the simulation model agree extremely well with the test responses for all the vehicle units, and the roll angles are also in good agreement. The differences in articulation angles between test and simulation are small. Better agreement could be obtained simply by refining the tire characteristics at respective units. Similar results were obtained at other speeds.

4.3.6/ C-Train Triple

Computer simulation was conducted for the C-train triple in the steady circular turn manoeuvre at each test speed. Figure 68 compares the vehicle responses at a speed of 47 km/h. There is excellent agreement for lateral acceleration of the six vehicle units and good agreement for the roll angle, except for the second and third trailer roll, which were drifting. Excellent agreement between test and simulation can also be observed in the trailer articulation angles as well as the first dolly steer angle. While the simulation model predicted a similar dolly steer at the second dolly, the tested data showed a different response, which was a bit doubtful. Similar agreement between test and simulation was obtained at other vehicle speeds.

4.3.7/ 5-Axle 48 ft Semi

Computer simulations of the steady circular turn manoeuvre for the 5-axle 48 ft (14.63 m) semi was carried out for speeds from 35 km/h to 63 km/h, during which the vehicle became unstable. Figure 69 compares the responses at a speed of 55 km/h. There is excellent agreement in directional and roll responses for both the tractor and the semitrailer. Similar agreement was found at other speeds, up to the limit of stability, at which point the driver was not able to hold the vehicle along the curve without either the trailer tipping on its outrigger or excessive trailer swing.

4.3.8/ 6-Axle 48 ft Semi

Computer simulations were conducted for the 6-axle 48 ft (14.63 m) semi undergoing steady circular turn for a number of vehicle speeds, ranging from 35 to 63 km/h, during which the trailer experienced a heavy touchdown of the outrigger. Tires squealed even at lower speeds, indicating that there was significant tire skidding along the circular path. Figure 70 compares the responses at a speed of 55 km/h. There was excellent agreement in the directional and roll responses of both the tractor and semitrailer. Test observation indicated that the inner wheels of one semitrailer axle were airborne. Similar agreement between simulation and test responses was obtained up to the threshold of instability.

4.3.9/ 7-Axle 48 ft Semi

Computer simulation of the 7-axle 48 ft (14.63 m) semi was conducted at speeds of 35, 40, 47, and 55 km/h for the steady circular turn manoeuvre. Results of the simulation indicated that, with the existing tire characteristics, the simulation model failed to produce a close prediction of the lateral acceleration response of the vehicle even at a low speed of 35 km/h. Figure 71 compares the vehicle response between test and simulation at 35 km/h. Test observation revealed that some of the tires at the trailer rearmost axle had developed an irregular wear pattern resulting from the earlier test of the 5- and 6-axle configurations of this combination. It is likely that these tires had a very different cornering characteristic than that used in the simulation, especially for this manoeuvre. Due to the scope of this work, no further attempt was made to refine the tire data for this vehicle. However, it is believed that better agreement between simulation and test response could be obtained by reducing the tire cornering capacity at the semitrailer's rearmost axle.

5/ DISCUSSION

One of the major concerns facing the transfer of a relatively large computer program from a mainframe to a minicomputer is the execution speed. With the original yaw/roll program, the execution speed was painfully slow. The speed ratio for an 8-axle tractor semitrailer was 400:1. In other words, the program required 400 s of computing time to generate 1 s of data. After all the code simplification, reduction in matrix algebra and use of vector instructions, the execution speed ratio was improved to about 100:1. Thus, the new version was four times faster than the original yaw/roll program on the HP-1000 minicomputer. Table 10 shows the execution speed ratio for the nine vehicle configurations simulated in this report. It ranges from a low of 74:1 for the 5-axle semi to a high of 250:1 for the triples combinations.

Table 10/ Simulation Speed Ratio of Various Configurations

Vehicle Configuration	Simulation Speed Ratio
5-axle 45 ft semi	74
5-axle 48 ft semi	74
6-axle 48 ft semi	82
7-axle 48 ft semi	90
B-train double	120
A-train double	144
C-train double	144
A-train triple	250
C-train triple	250

It was found during the course of modifying the UMTRI yaw/roll program that there was a problem with the modelling of the pintle hook mechanism. The analysis assumed that with the pintle hook arrangement, the trailing unit is free to bounce, roll, yaw, and pitch with respect to the towing unit. Using this assumption, simulation of an A-train double terminated after a few steps because of numerical problems in the integration process. Examination of the vehicle response revealed that there was an unstable pitch motion of the dolly, a direct result of the lack of a pintle hook vertical constraint. The problem could be avoided for the first 8 s if the dolly centre of mass, axle, and fifth wheel placement were all assumed at the same longitudinal position. However, if the simulation was extended further, an "unexpected" rollover of the trailing unit occurred due to the dolly pitch motion, as shown in Figure 72, for an A-train double undergoing a steady circular turn manoeuvre at 47 km/h. By imposing a vertical reaction at the pintle hook in the MTC program, the "unexpected" rollover was suppressed, as shown in Figure 73, for the same manoeuvre.

The result of this study has demonstrated the effect of tire wear on the directional response of the vehicle. It was observed that some of the tires at the rearmost axle of the 48 ft (14.63 m) semi developed an irregular wear pattern as a result of earlier tests in the 5- and 6-axle semi configurations. Thus, the tires of the 7-axle 48 ft (14.63 m) semi had a somewhat different characteristic than the original tire data. The effect of this was demonstrated in the steady circular turn manoeuvre, where the simulated response was higher than the test responses. Some vehicle configurations were found to be much more sensitive to the tire characteristics than others, such as the B-train double and the 7-axle 48 ft (14.63 m) semi. Proper data must be used to generate results that are representative of the actual vehicle responses.

Even though efforts were made to select input data that were representative of the physical component, it was not possible to get the precise characteristics of all components because of a lack of measured data. The tractor front suspension compliances and tractor drive axle tire characteristics are two examples where no data were available, and the input characteristics were selected from existing data that were considered to come closest to the actual component. Data for the other suspension compliances and tire characteristics were selected from the generic product [15]. All of these may affect, to a certain extent, the directional and roll responses of the vehicle.

Some vehicles experienced a significant drop in speed when they made the steady circular turn. Clearly, this affects the steer angle, lateral acceleration, yaw rate, and other responses. The simulations all assumed steady initial speed through the manoeuvre. It would have been possible to enter the forward speed as tabular input in the same way as the steer input. However, the Euler equations in the model assume a constant forward speed, and to permit longitudinal acceleration would have taken a great deal more effort than time permitted. Since longitudinal acceleration was low, it might have been a reasonable approximation to interpolate the "constant" speed in the same way as the steer input, but this was not tried. Because of these differences, the path followed by the vehicle in the simulation often diverged quite far from the actual path. Also, the path followed by the vehicle in the simulation diverged from the actual path in the lane-change manoeuvre. In this case, however, the divergence was due to small differences in initial yaw angle and yaw rate, as well as vehicle slide, integrated over a fairly long period. Both of these divergences are a consequence of using the measured steer input. When it is necessary to simulate a vehicle following a specific path, the yaw/roll program permits the path to be specified and requires the use of its driver model in a closed-loop mode of operation [14]. This feature was not used in this work and was actually omitted from the program to reduce memory requirements.

When simulation of a given test run was conducted using the measured steer input, certain responses were obtained which depended upon the model, its implementation as a computer program, and the input data which represent the subsystem and components. While the test responses may be different for the same operating condition because of small variations in steer input and random and non-random variables, such as wind effect, tire wear, road friction characteristics, etc., the computer program should give precisely the same results with the same input data. If the computer program is numerically stable, it is expected that a series of simulations, each using the steer input of a test run, would have similar variations to the variation between test responses if the model and data are reasonably representative of the actual vehicle. There remain, however, sample variations between tires and suspensions, for instance, and, possibly, assumptions regarding quantities such as hitch and frame stiffnesses. It is legitimate to suppose that variation in such data, over a range reasonable to represent the production and wear differences between these components, will result in differences in responses that are not large when compared to the gross response.

This type of comparison was not investigated in this work. Most test conditions were only run twice, with further repetitions only when earlier runs were obviously deficient. This was necessary to maintain schedule with a test program of this scope. There was, then, no clear need to conduct parametric variations in the simulation, except as appeared necessary where assumed values were adjusted to improve the match between test and simulation in an overall sense. This work has been concerned more with an overall impression resulting from nine vehicles in three manoeuvres and various test conditions than with a detailed and precise match for just a few conditions. It is evident that simulation results can be made to match test data from individual runs if the proper data are used, whether those data are obtained by direct measurement or deduced, as necessary, to achieve a match. However, if generic data result in a reasonable agreement for individual runs, say within the repeatability of individual test runs, and they also give the trend observed in test over a number of runs, then this work creates confidence that the simulation is broadly applicable.

The many comparisons between test and simulation results showed a large measure of agreement. Nevertheless, there were anomalies, either occasional or systematic. An example, perhaps, is in the roll angle measurement for the sinusoidal steer and lane-change manoeuvres, where the transducers do not appear to be responding properly to the transient manoeuvre, although their response to the steady-state turn is good. In general, it is considered that these anomalies are the result of a combination of the torsional flexibility of the vehicle units and the behaviour of the transducer.

6/ CONCLUSIONS

The UMTRI yaw/roll program has been successfully installed on the HP-1000 minicomputer at MTC. Simplification of the program code and utilization of the computer system's vector instructions enabled the modified program to execute in a reasonable time.

The program was extended to allow simulation of triple trailer combinations up to a maximum of six vehicle units. By including the improved version of the B-dolly model developed at UMTRI, the MTC version is capable of simulating a C-triple train with steerable axles.

In spite of shortcomings in the input data, and other details that cannot be or have not been represented in the model, the yaw/roll program still provided a reasonable prediction of the dynamic responses for most of the vehicle configurations, namely, the 5-axle 45 ft (13.72 m) and 48 ft (14.63 m) semitrailers, A- and C-train doubles, and A- and C-train triples, in the sinusoidal steer and lane-change manoeuvres over a wide range of speeds and steer periods.

It was also demonstrated that if a better representation of the tire characteristics at the tractor drive axles was used, the yaw/roll program was capable of predicting a fairly accurate response of the B-train double and the 6- and 7-axle 48 ft (14.63 m) semitrailers in the sinusoidal steer and lane-change manoeuvres and all vehicles except the 7-axle 48 ft (14.63 m) semi in the steady circular turn.

This study has shown that, with the proper input data, the yaw/roll program can provide fairly accurate prediction of the directional and roll responses of a wide range of vehicle configurations under various steering manoeuvres and operating conditions.

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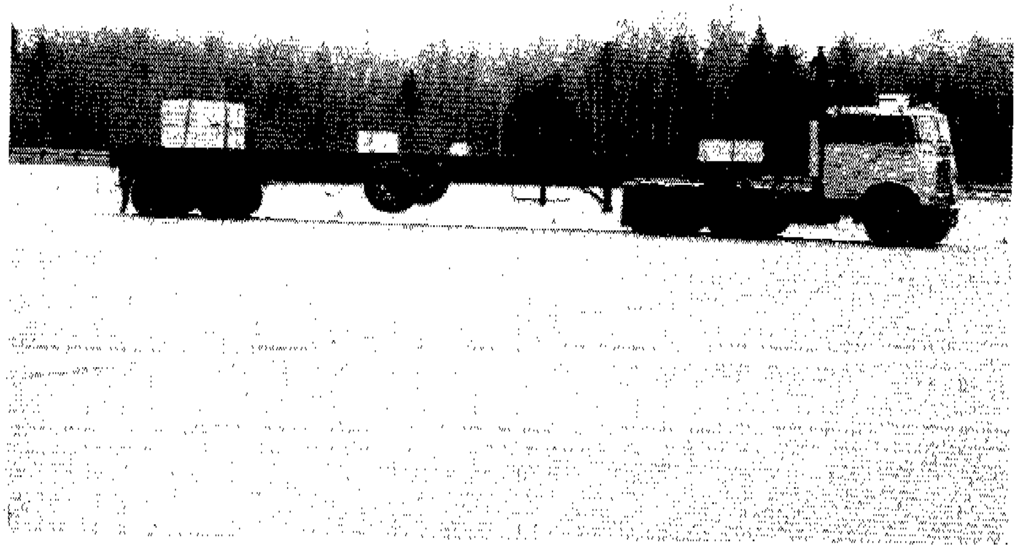


Figure 1/ 45 ft Semi, View of Vehicle

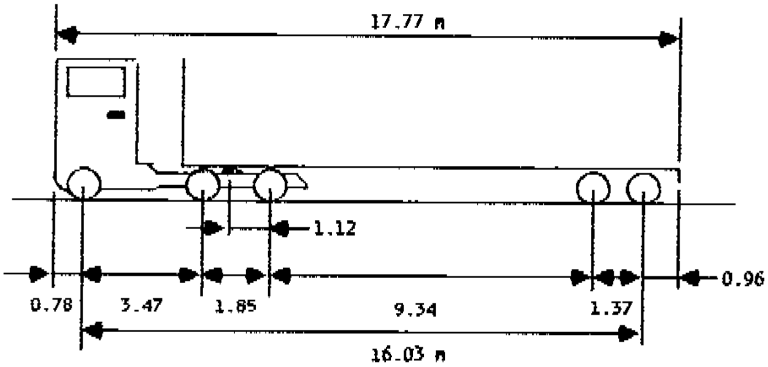


Figure 2/ 45 ft Semi, Vehicle Dimensions

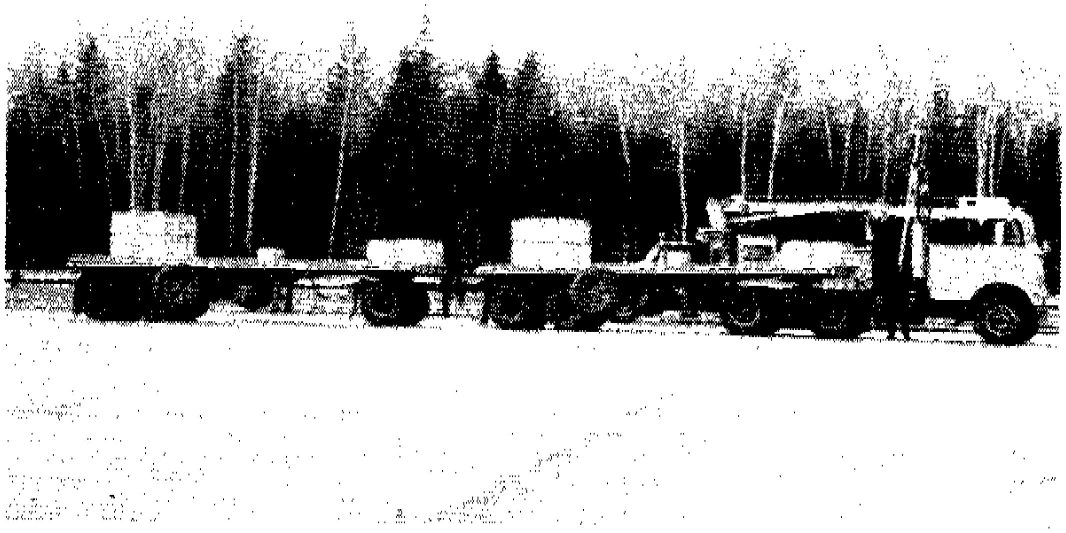


Figure 3/ A-Train Double, View of Vehicle

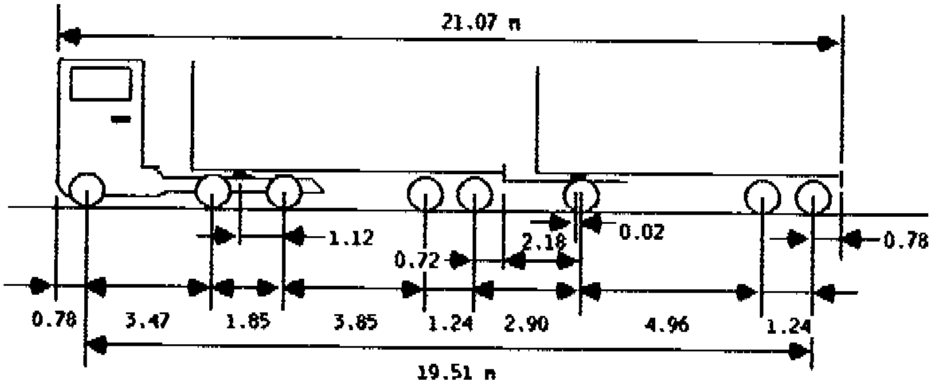


Figure 4/ A-Train Double, Vehicle Dimensions

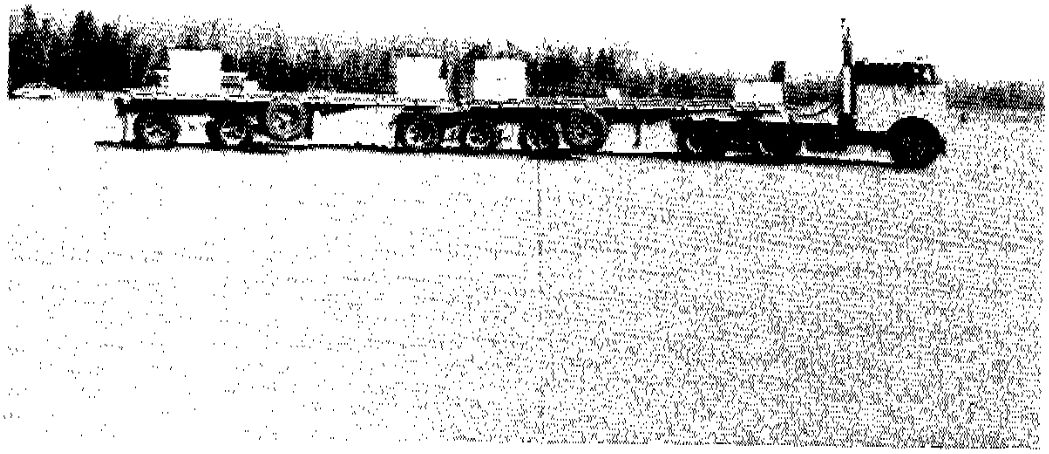


Figure 5/ B-Train Double, View of Vehicle

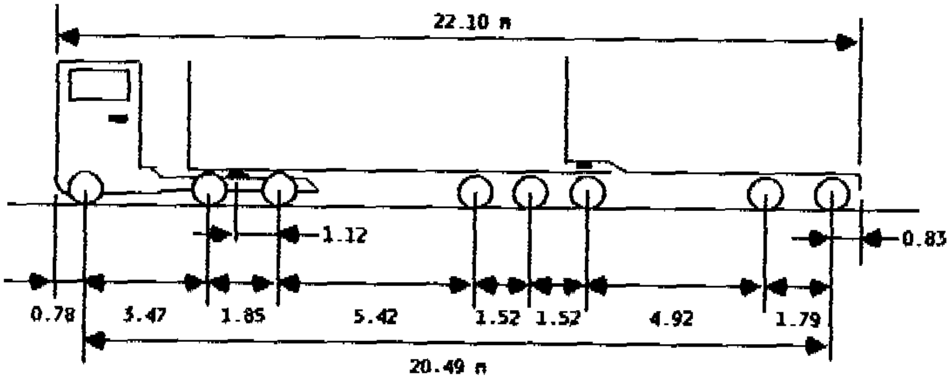


Figure 6/ B-Train Double, Vehicle Dimensions

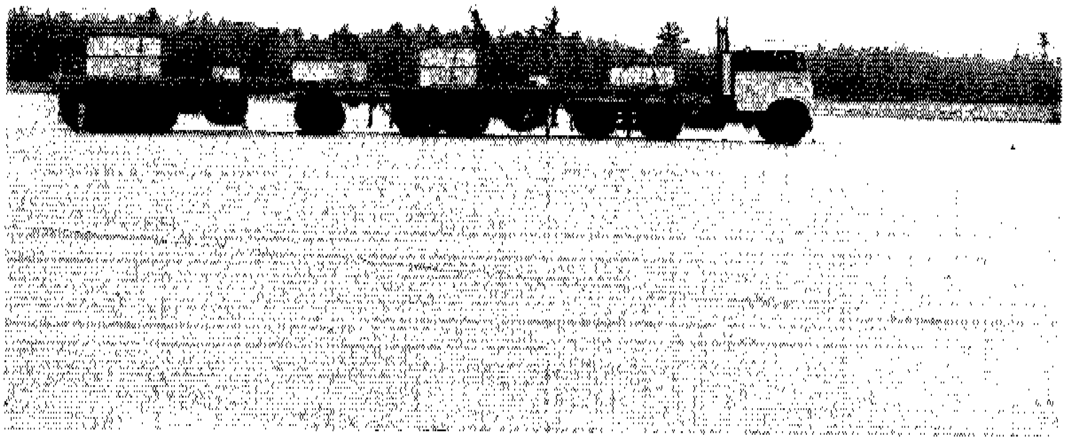


Figure 7/ C-Train Double, View of Vehicle

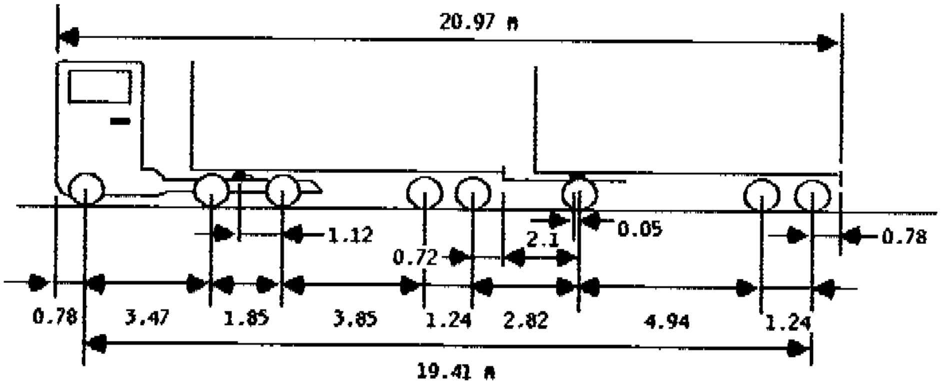


Figure 8/ C-Train Double, Vehicle Dimensions

Figure 9/ A-Train Triple, View of Vehicle

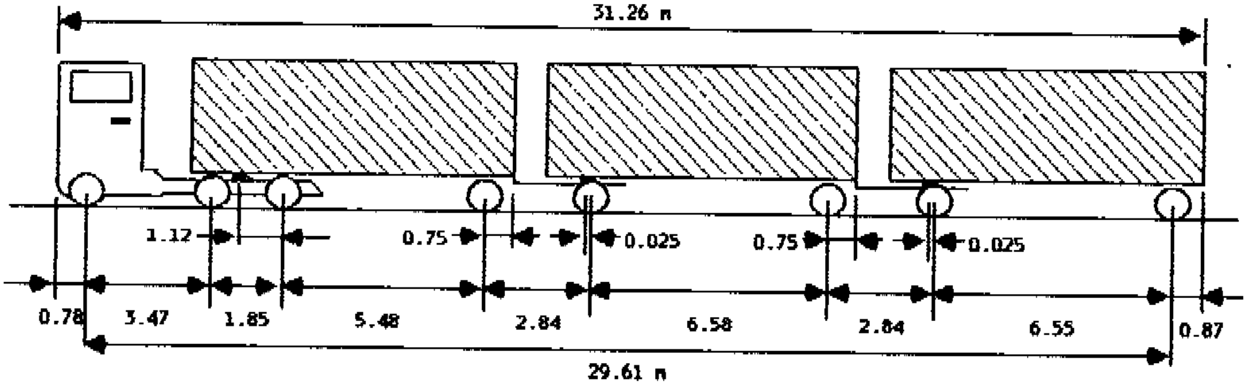


Figure 10/ A-Train Triple, Vehicle Dimensions

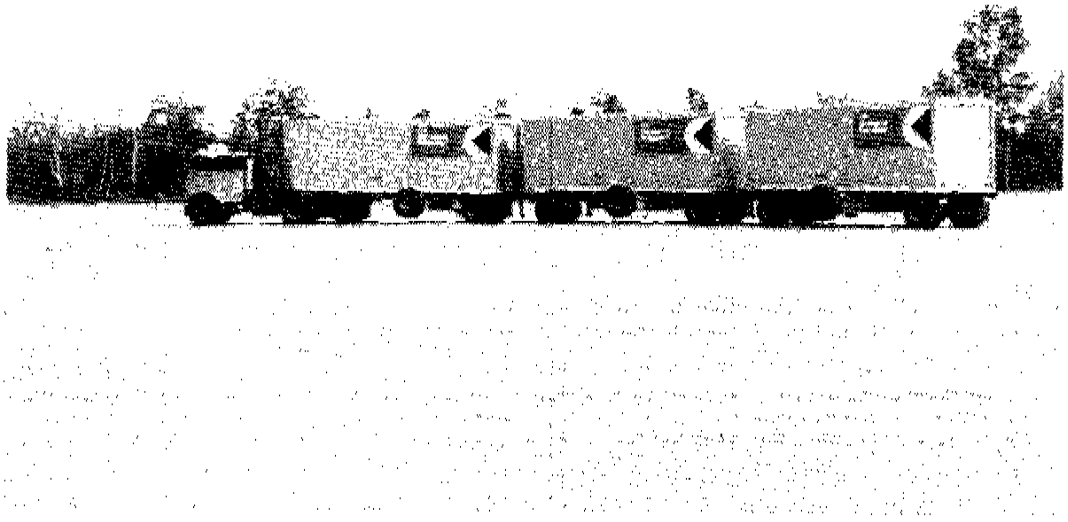


Figure 11/ C-Train Triple, View of Vehicle

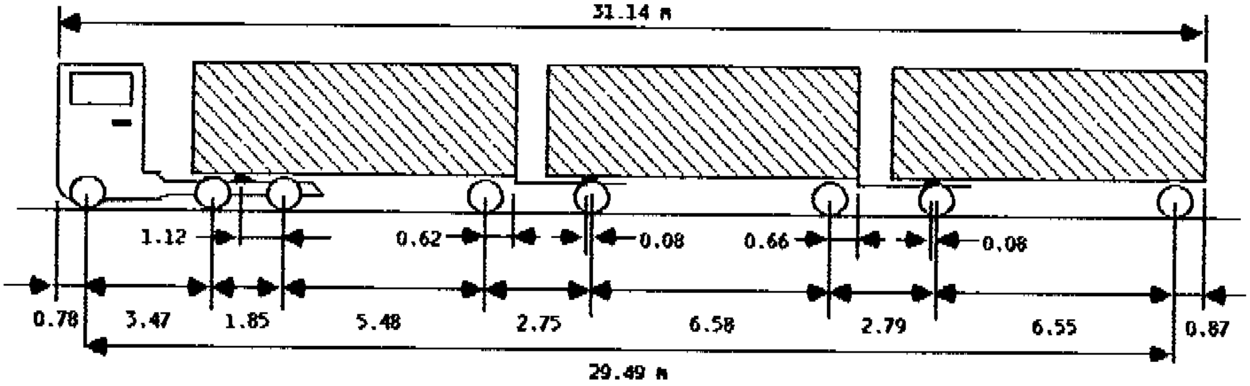


Figure 12/ C-Train Triple, Vehicle Dimensions

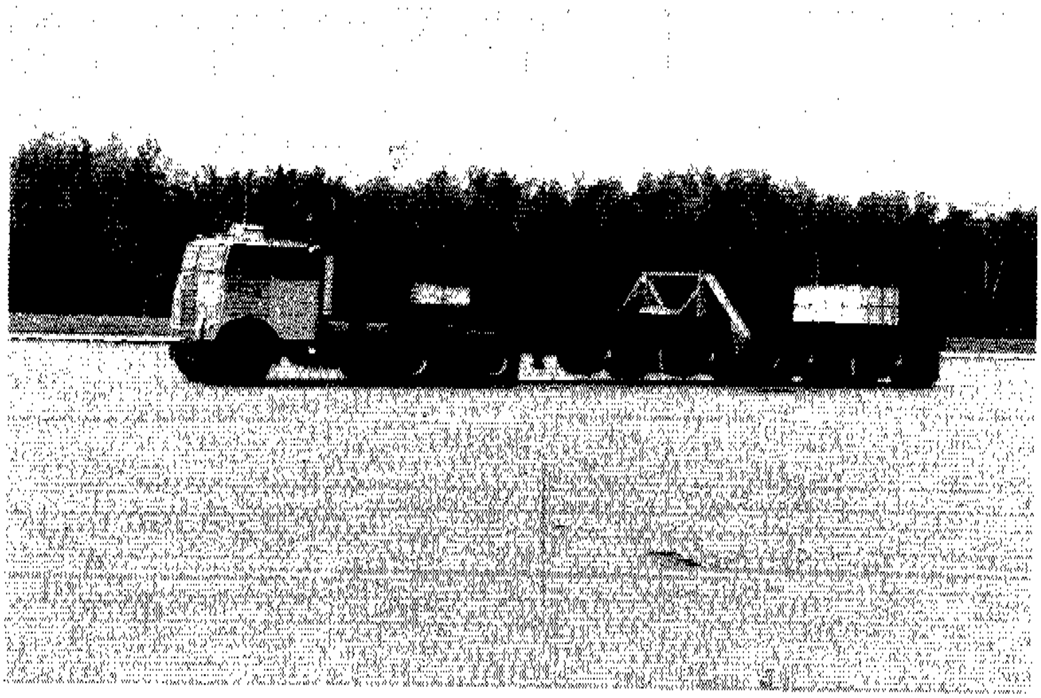


Figure 13/ 5-Axle 48 ft Semi, View of Vehicle

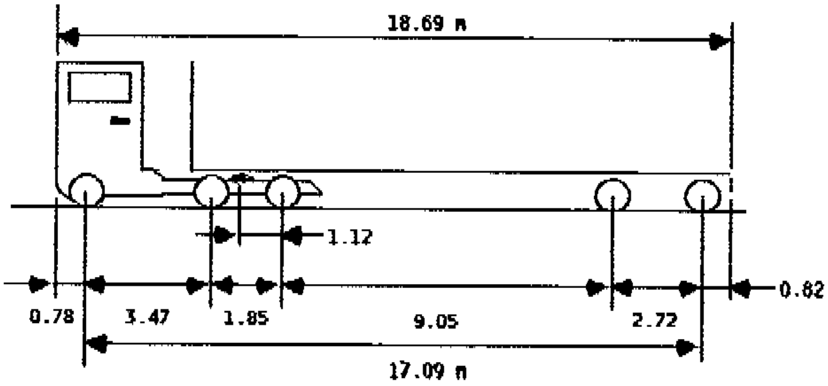


Figure 14/ 5-Axle 48 ft Semi, Vehicle Dimensions

Figure 15/ 6-Axle 48 ft Semi, View of Vehicle

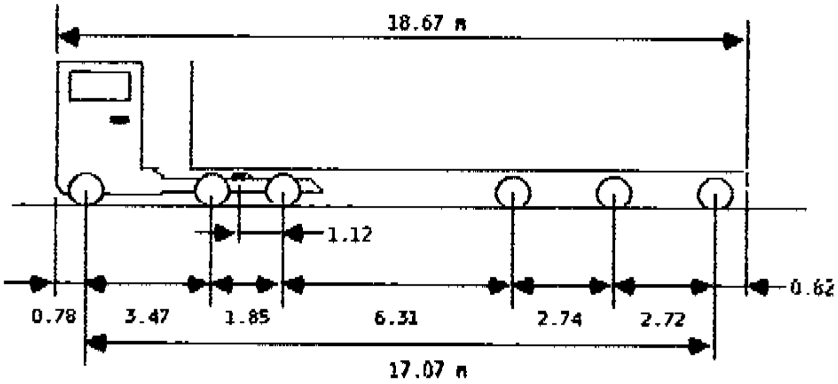


Figure 16/ 6-Axle 48 ft Semi, Vehicle Dimensions

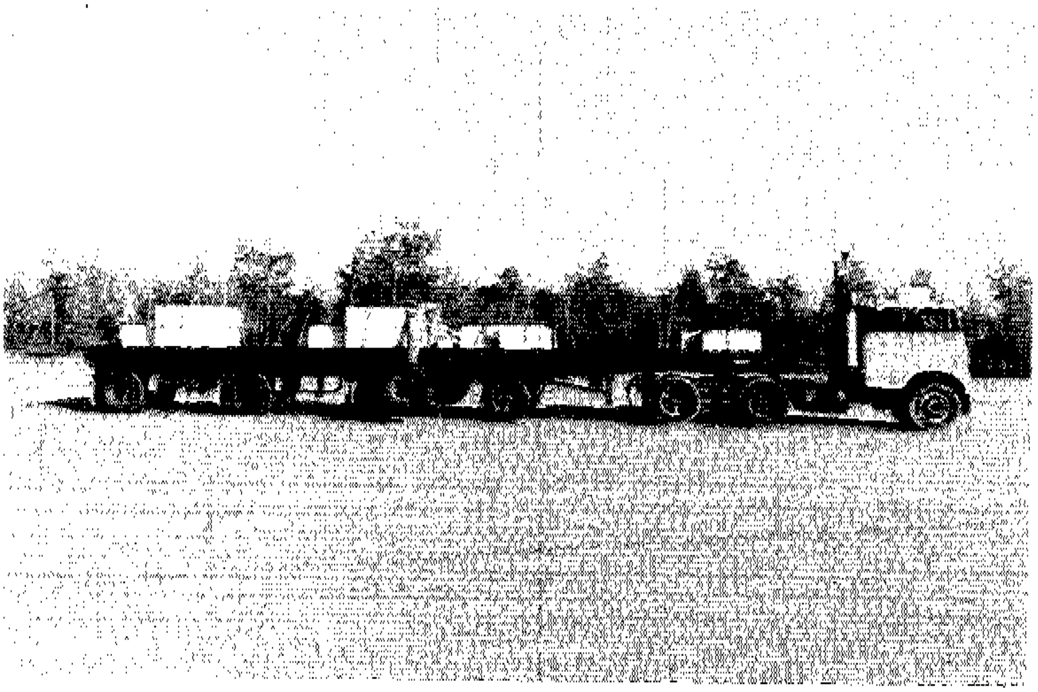


Figure 17/ 7-Axle 48 ft Semi, View of Vehicle

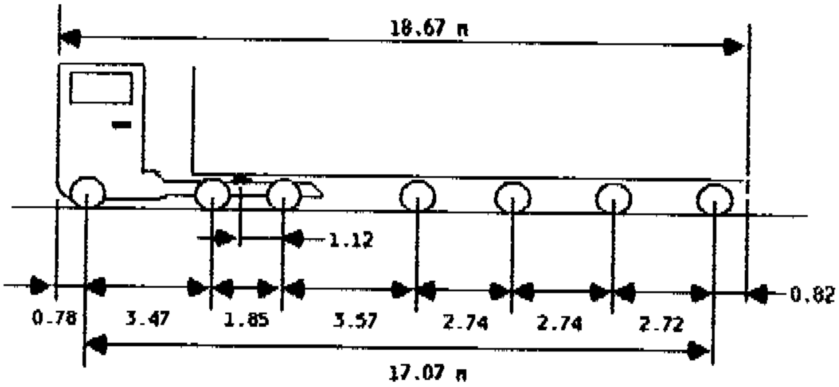


Figure 18/ 7-Axle 48 ft Semi, Vehicle Dimensions

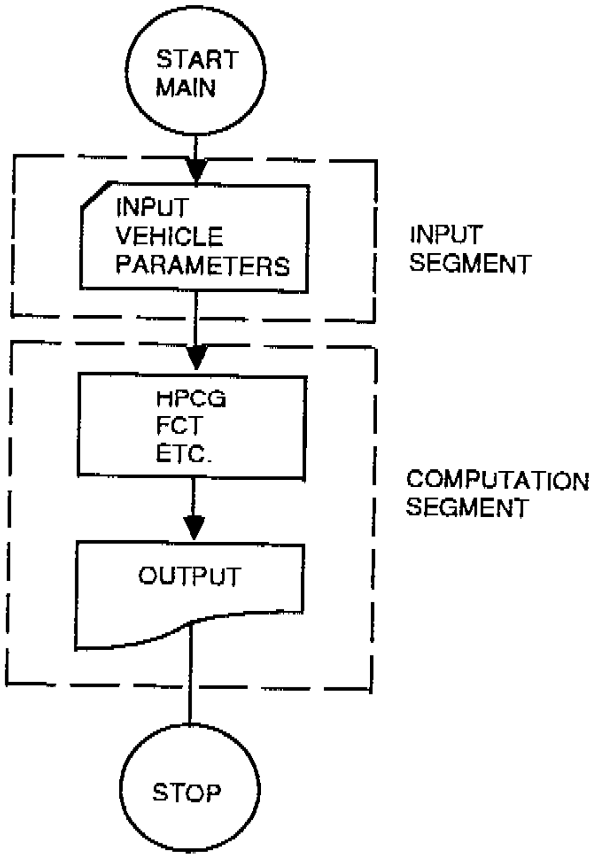


Figure 19/ UMTRI Yaw/Roll Program, Simplified Flowchart

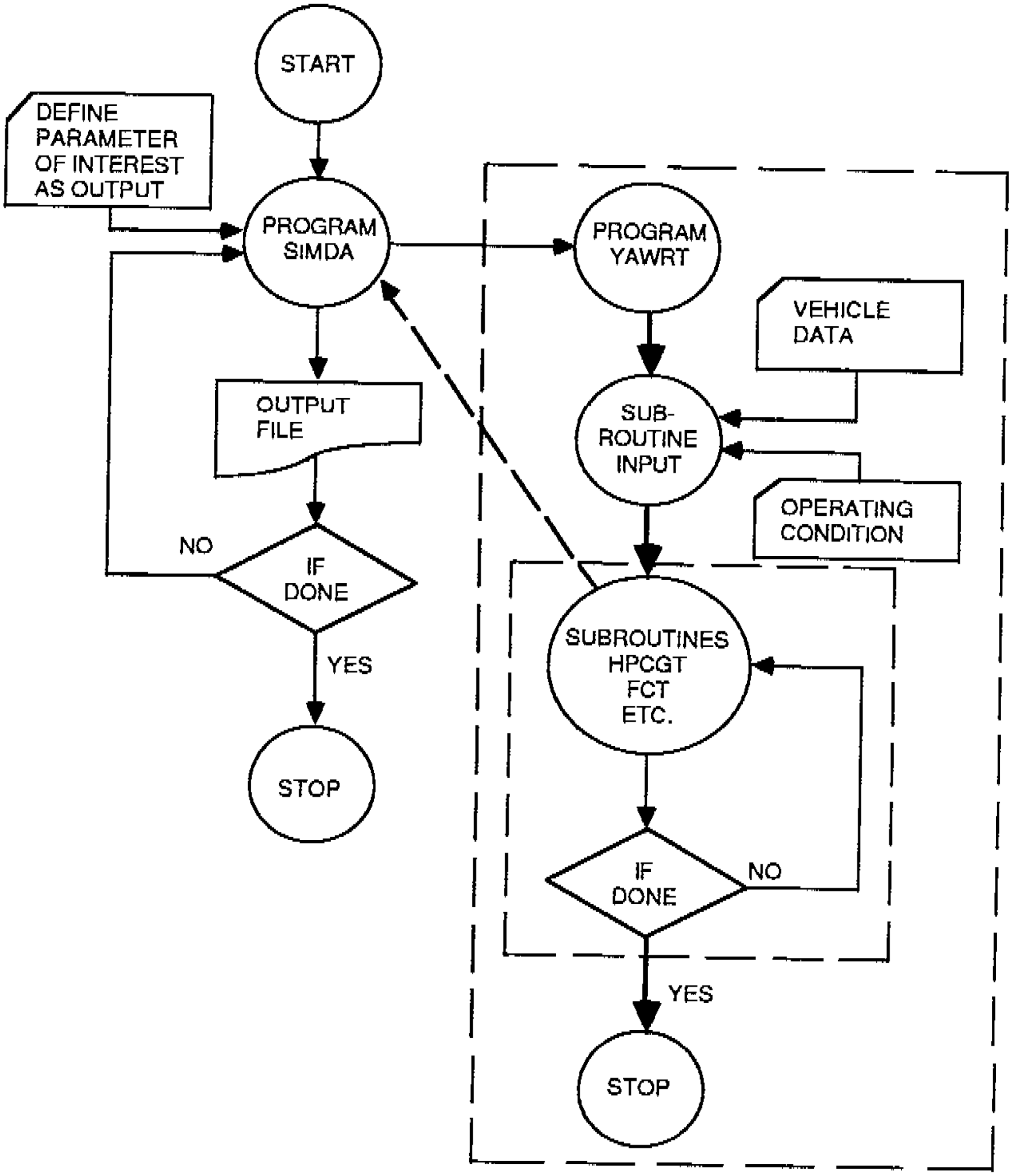


Figure 20/ MTC Yaw/Roll Program, Simplified Flowchart

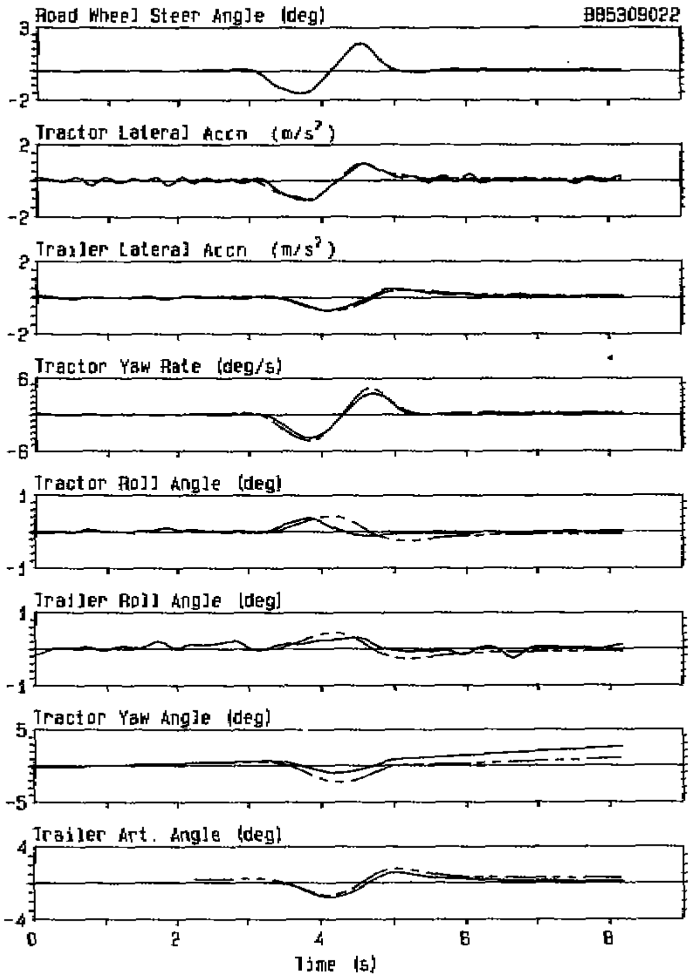


Figure 21/ 45 ft Semi, Sinusoidal Steer Responses at 63 km/h, 2.0 s Steer Period

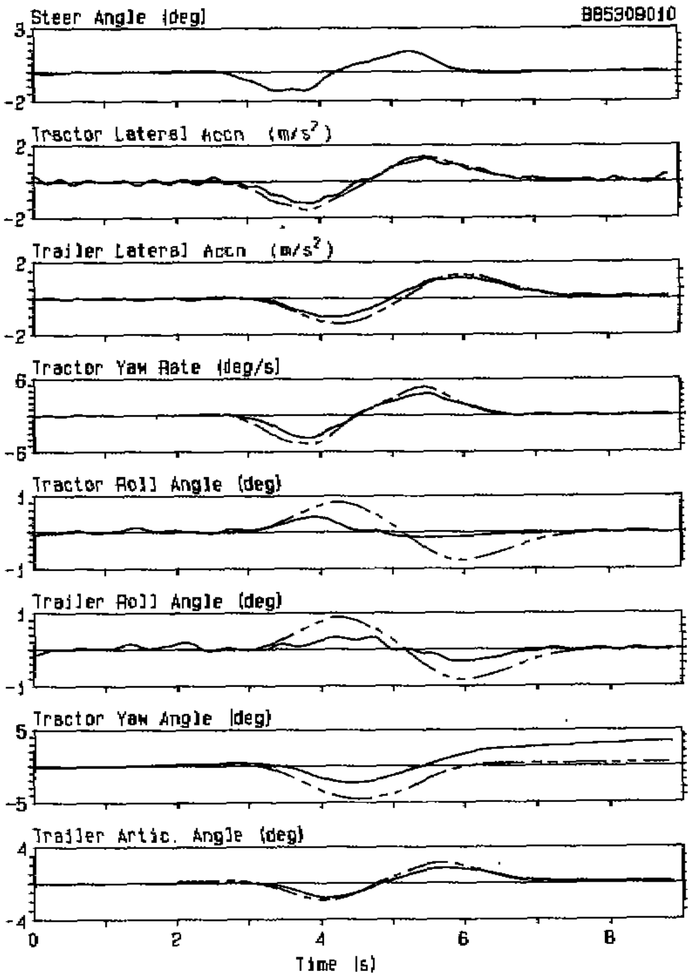


Figure 22/ 45 ft Semi, Sinusoidal Steer Responses at 84 km/h, 3.5 s Steer Period

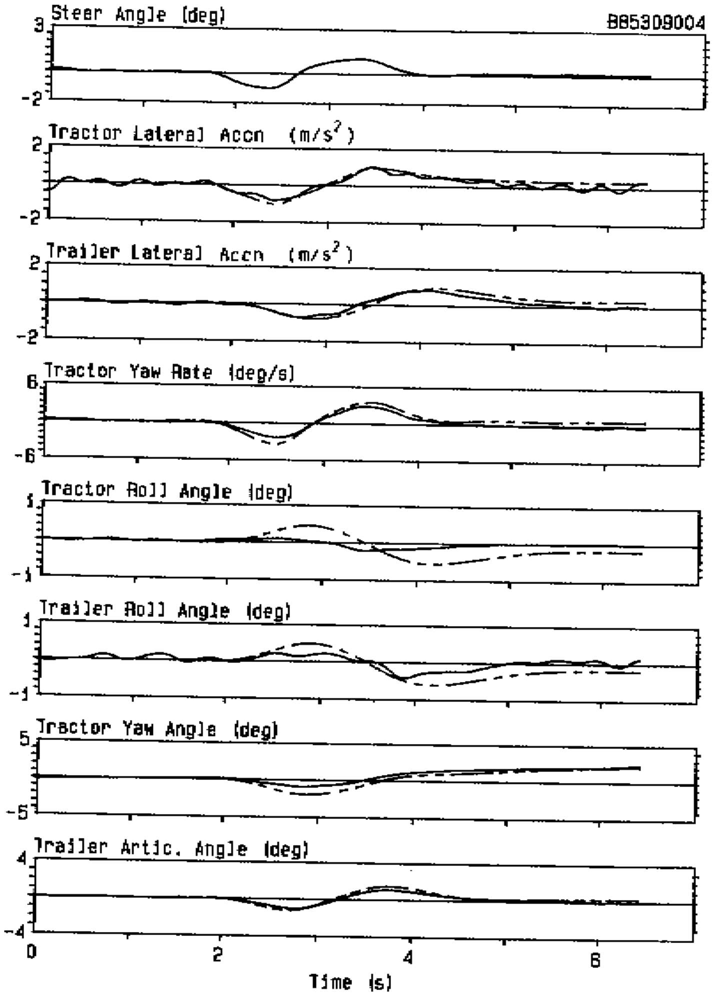


Figure 23/ 45 ft Semi, Sinusoidal Steer Responses at 94 km/h, 2.24 s Steer Period

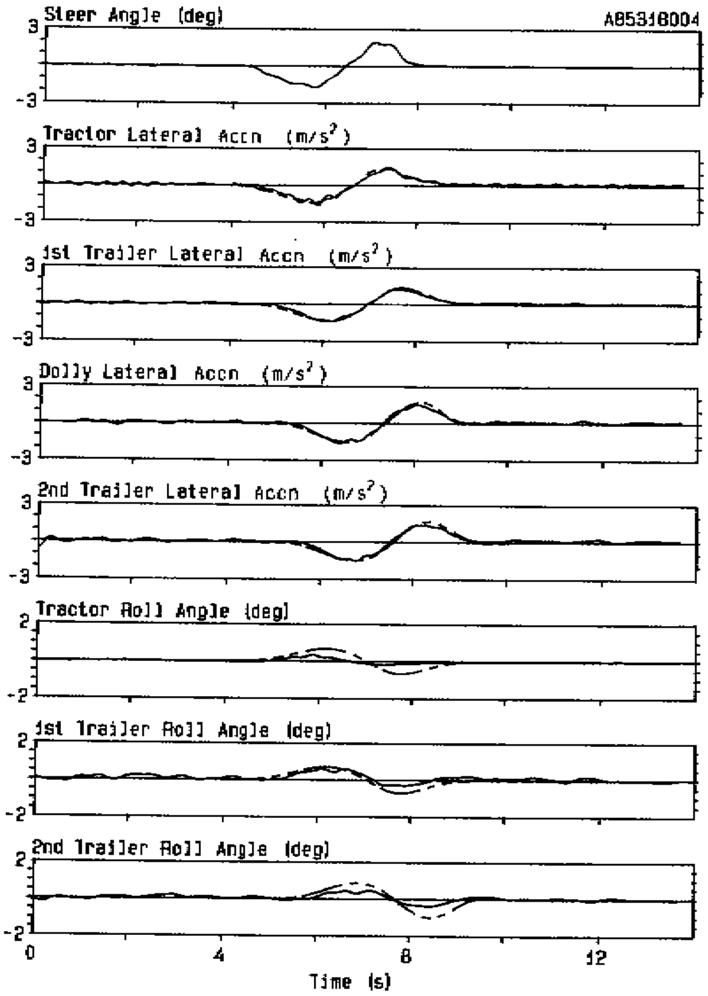
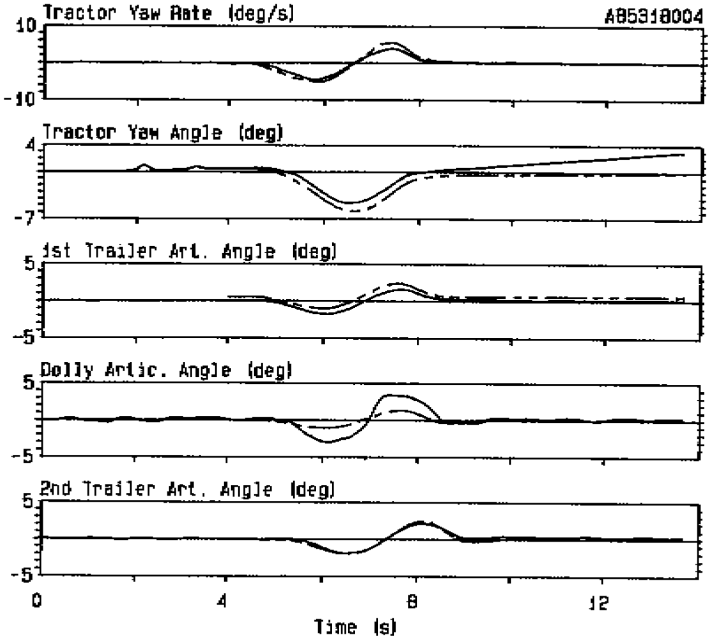


Figure 24/ A-Train Double, Sinusoidal Steer Responses at 63 km/h, 3.8 s Steer Period



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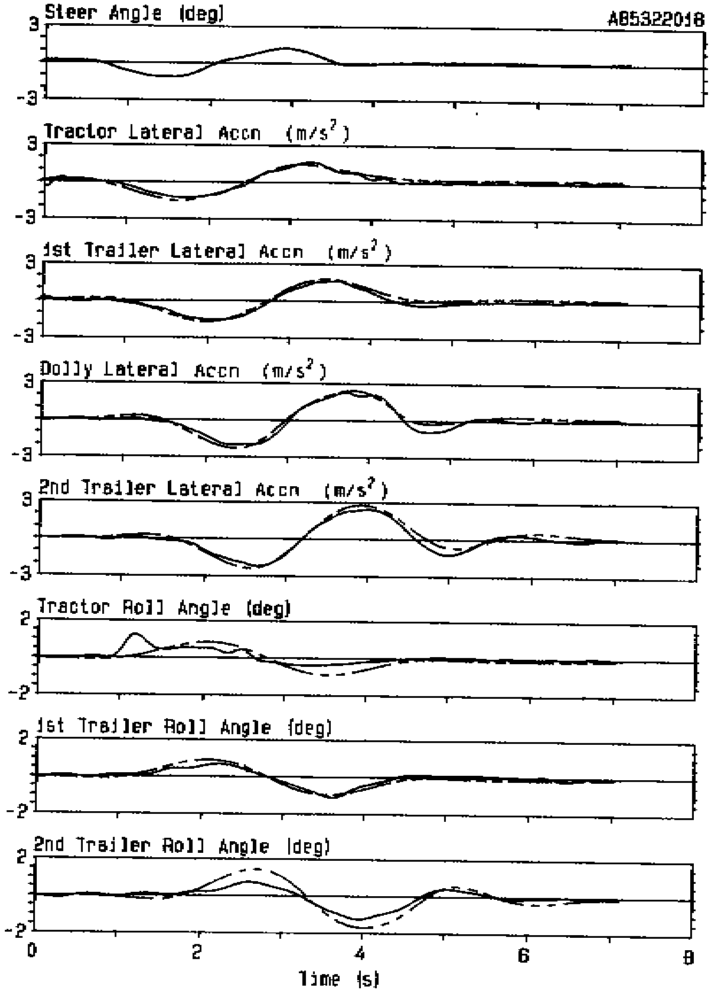
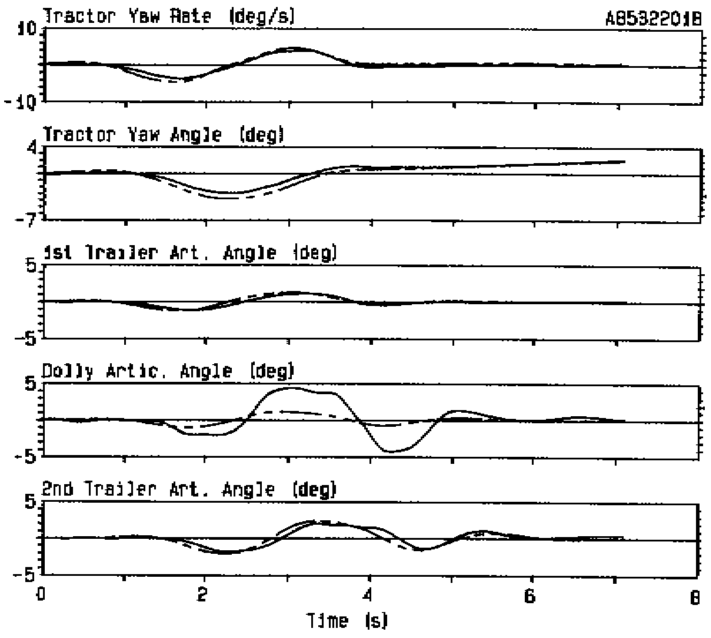


Figure 25/ A-Train Double, Sinusoidal Steer Responses at 94 km/h, 3.1 s Steer Period



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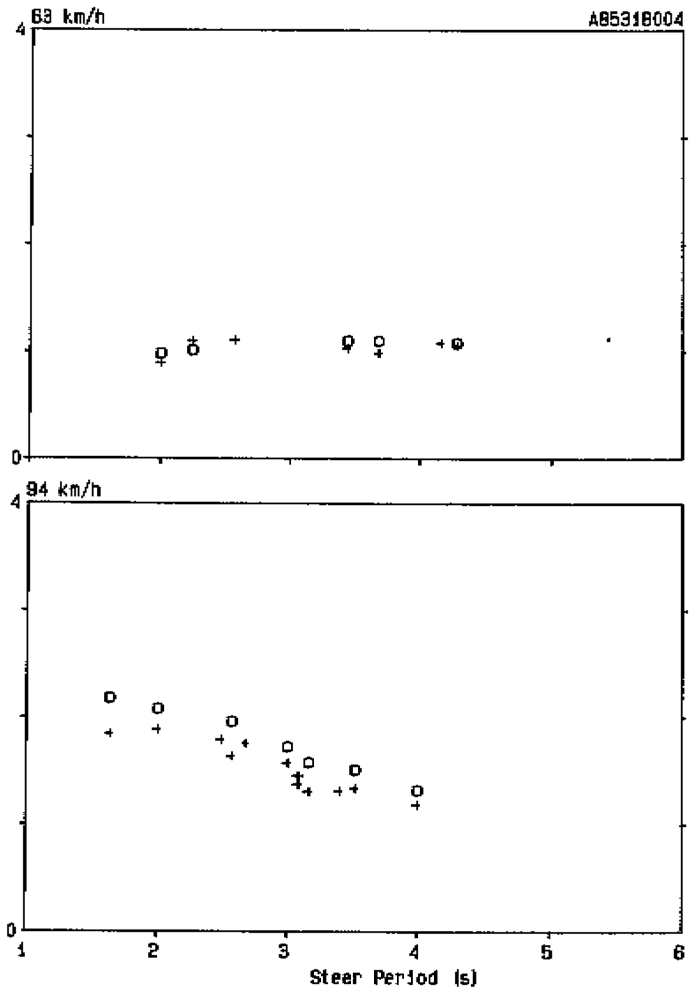


Figure 26/ A-Train Double, Rearward Amplification vs Steer Period

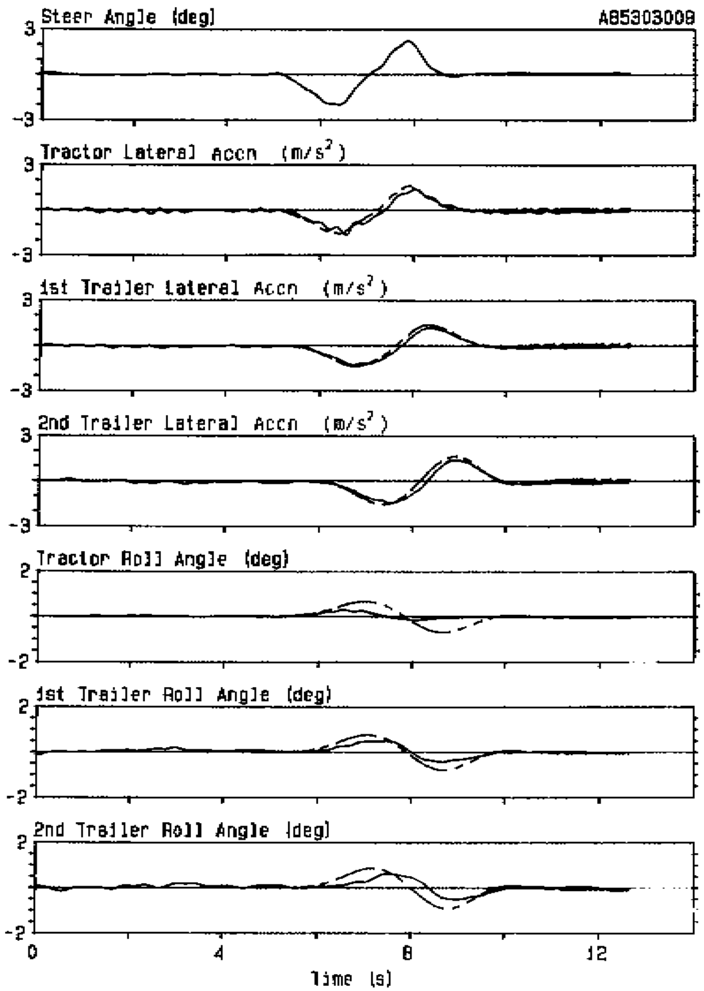
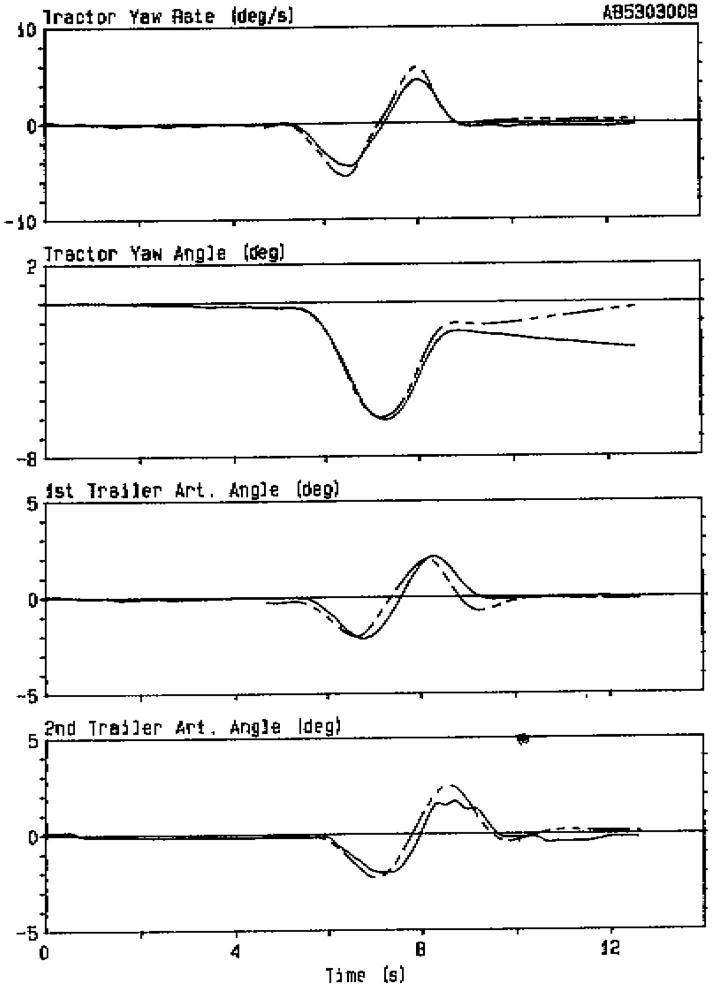


Figure 27/ B-Train Double, Sinusoidal Steer Responses at 63 km/h, 3.4 s Steer Period



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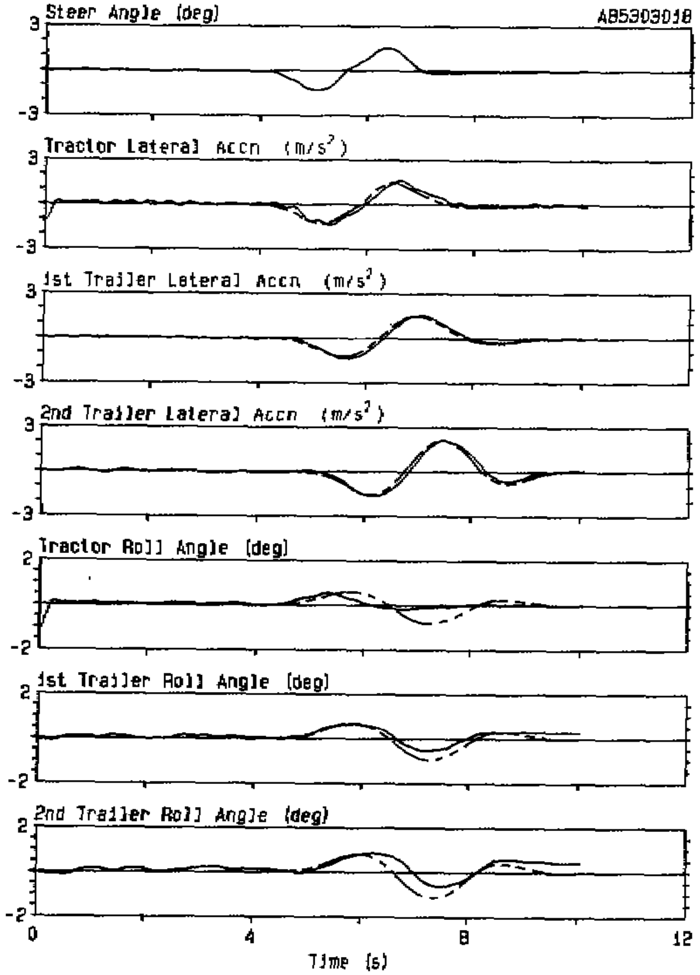
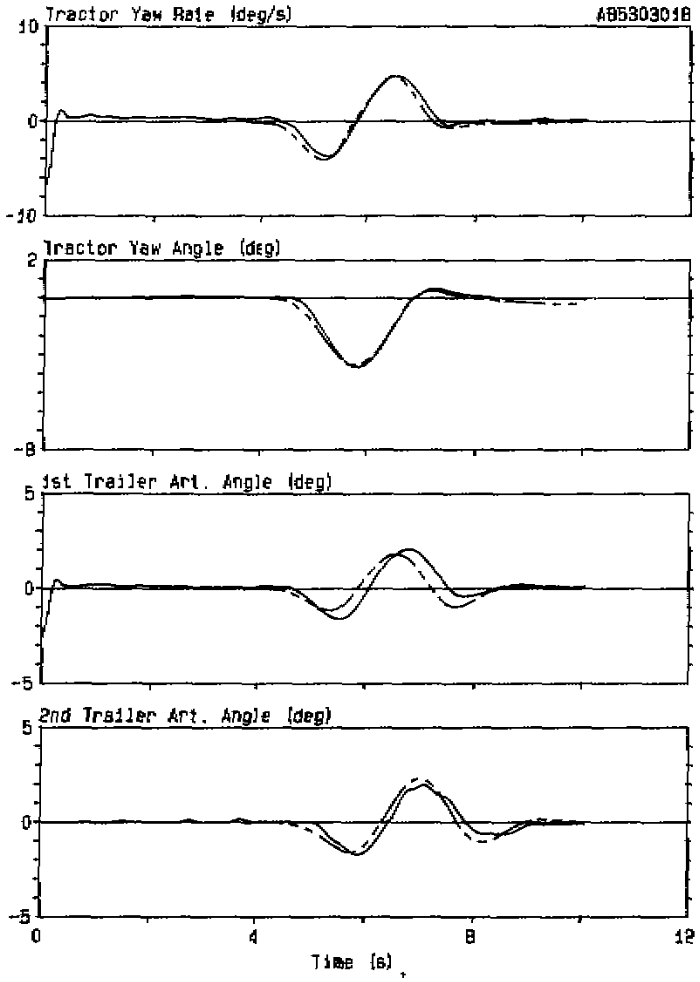


Figure 28/ B-Train Double, Sinusoidal Steer Responses at 84 km/h, 2.76 s Steer Period



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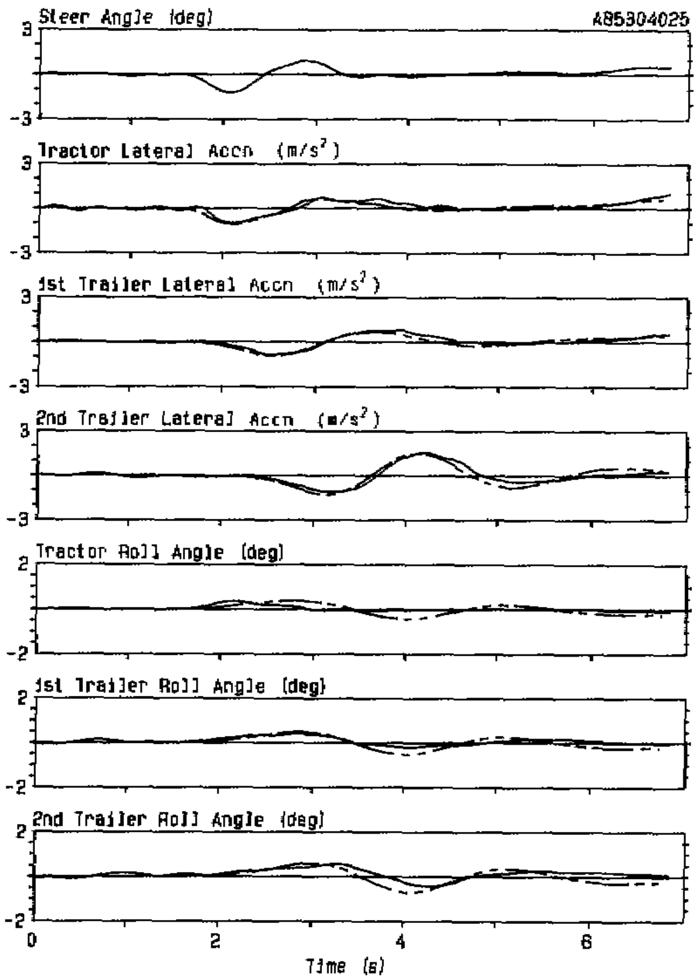


Figure 29/ B-Train Double, Sinusoidal Steer Responses at 94 km/h, 1.64 s Steer Period

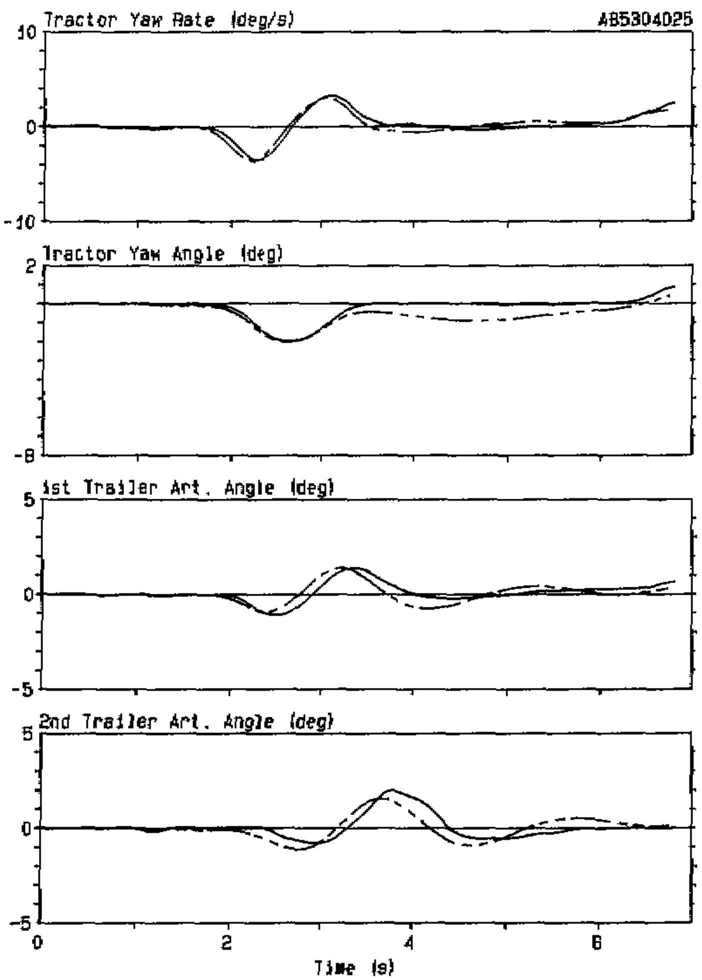


Figure 29/ Cont'd

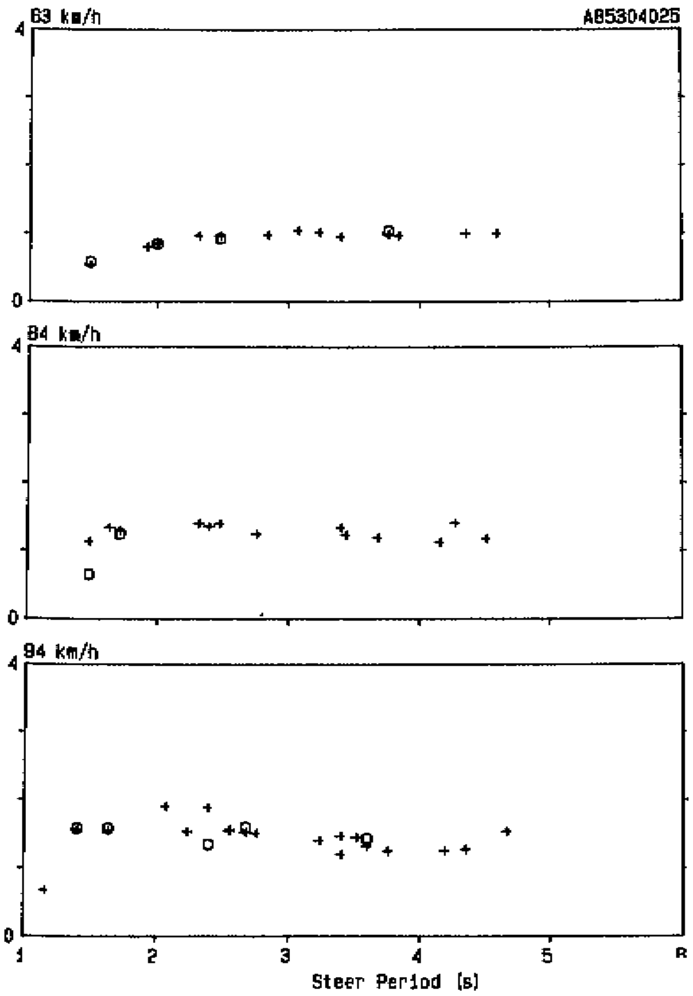


Figure 30/ B-Train Double,
Rearward Amplification vs
Steer Period

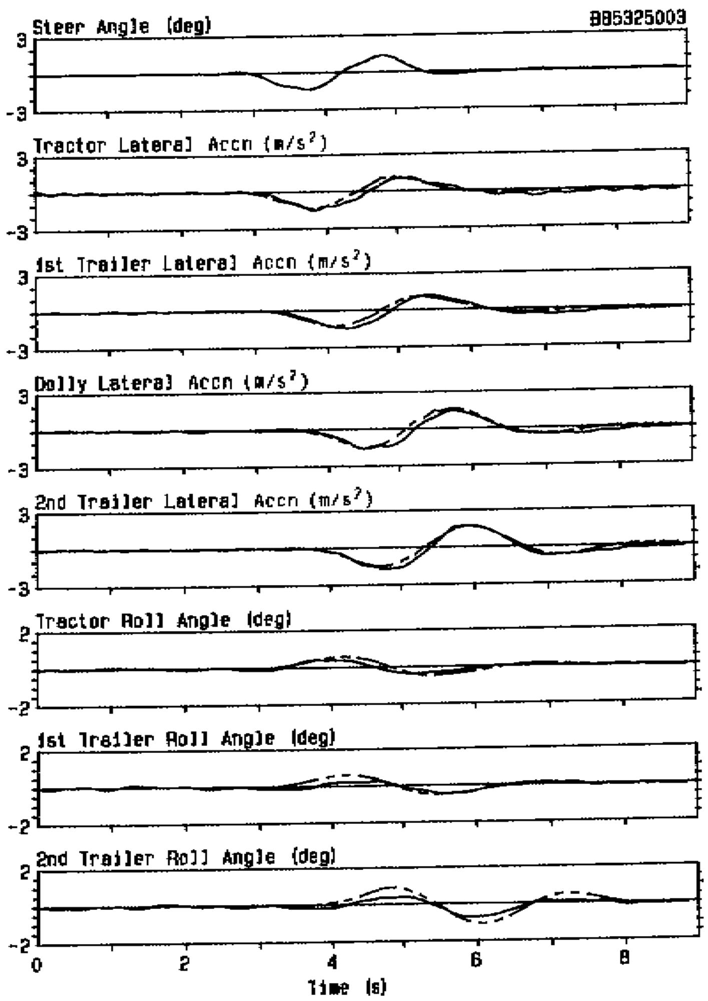
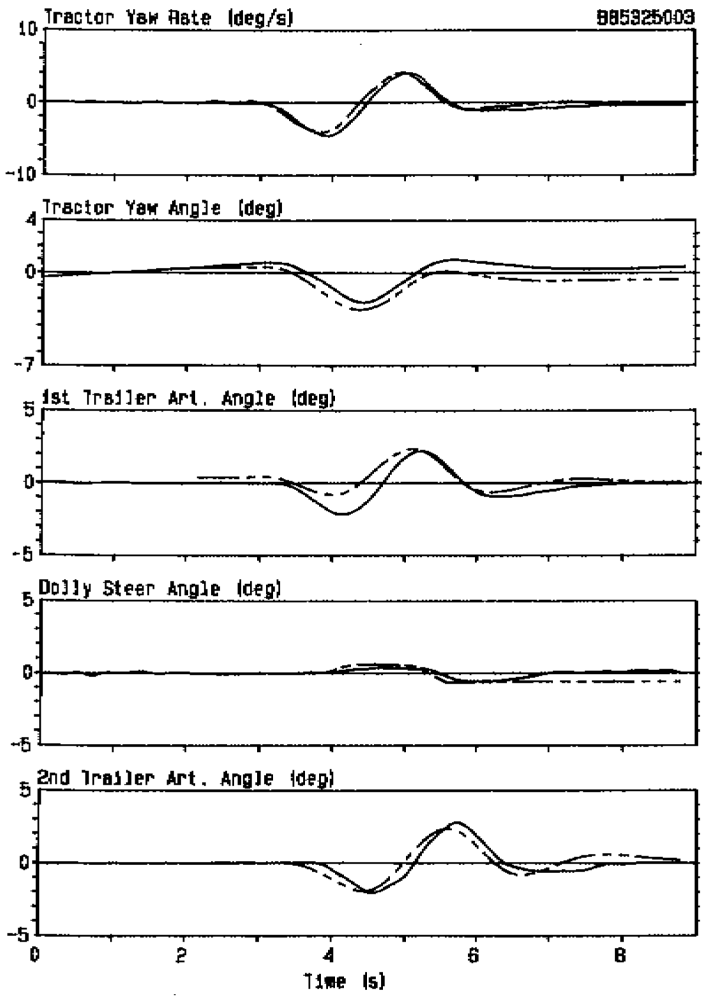


Figure 31/ C-Train Double, Sinusoidal Steer
Responses at 84 km/h,
2.5 s Steer Period



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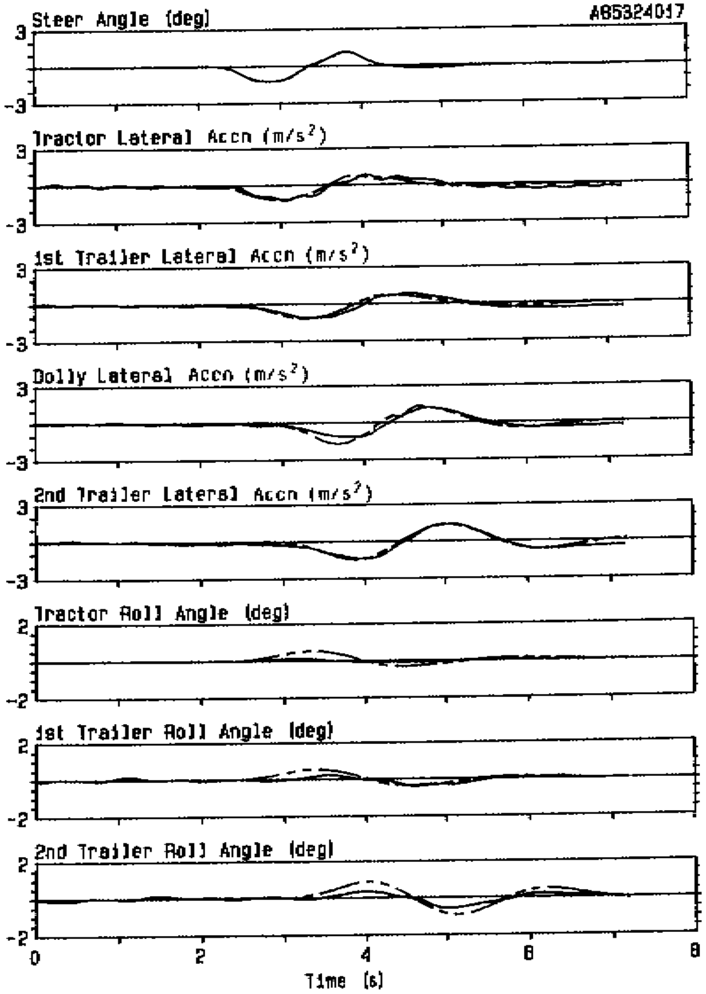
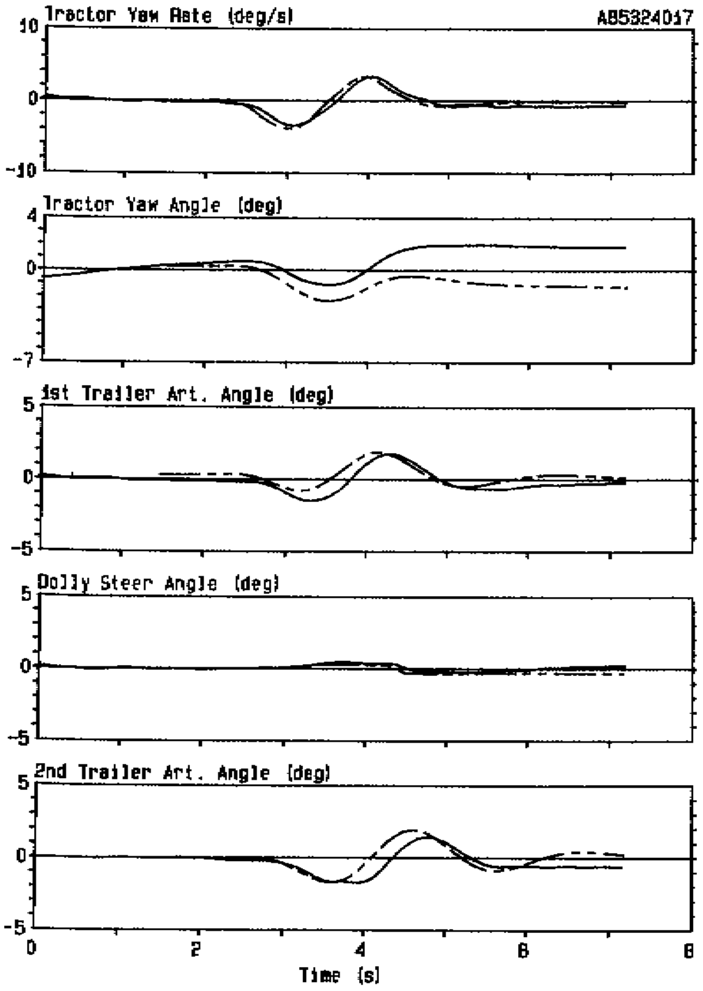


Figure 32/ C-Train Double, Sinusoidal Steer Responses at 94 km/h, 2.16 s Steer Period



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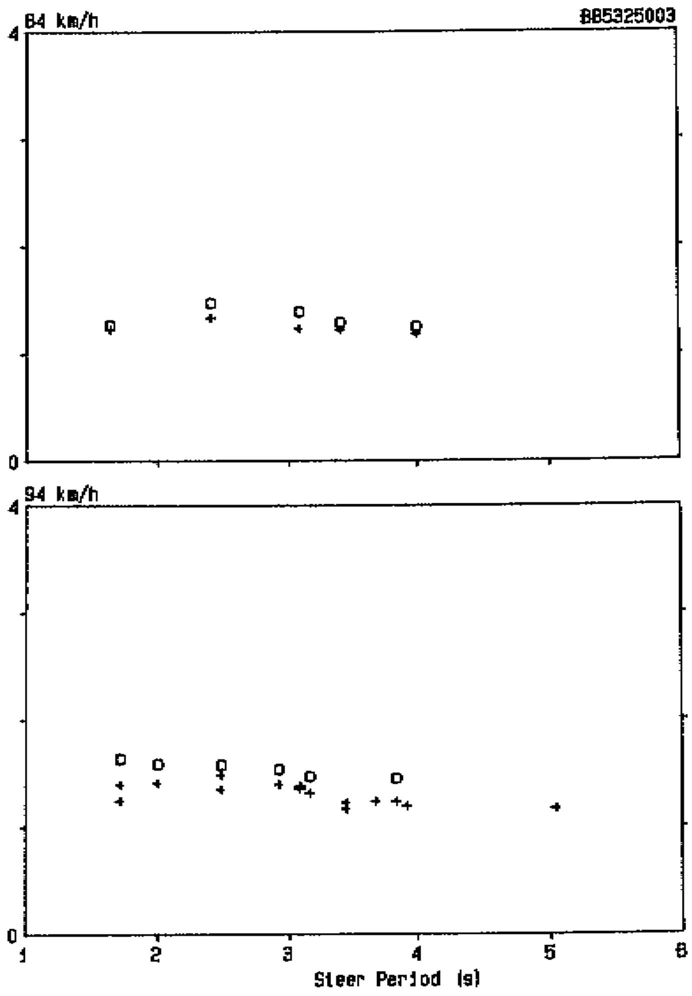


Figure 33/ C-Train Double, Rearward Amplification vs Steer Period

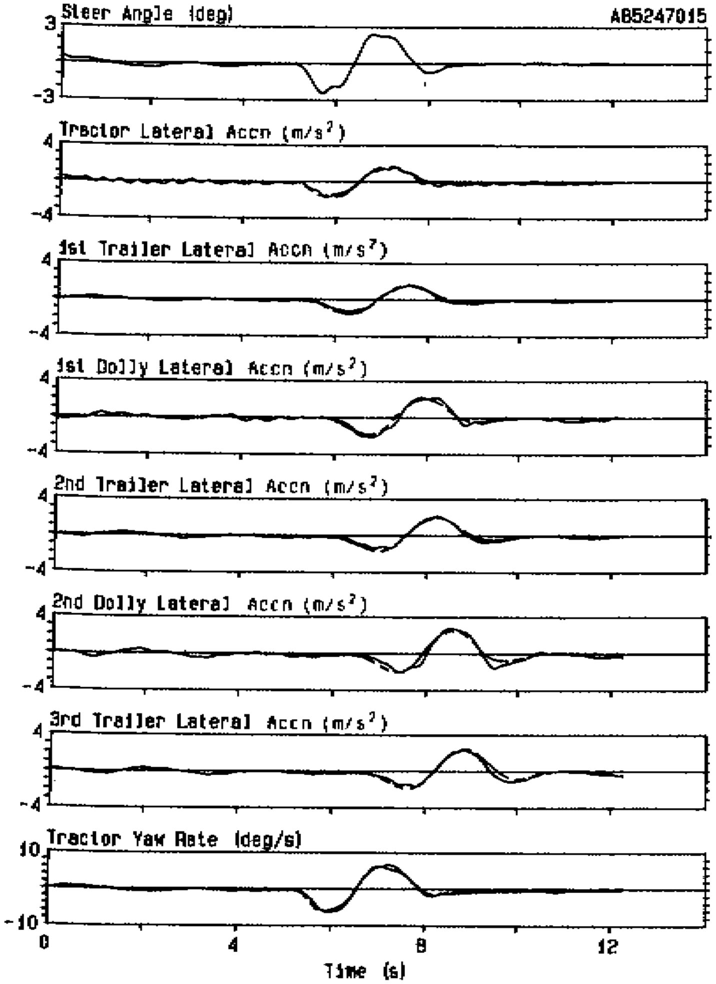
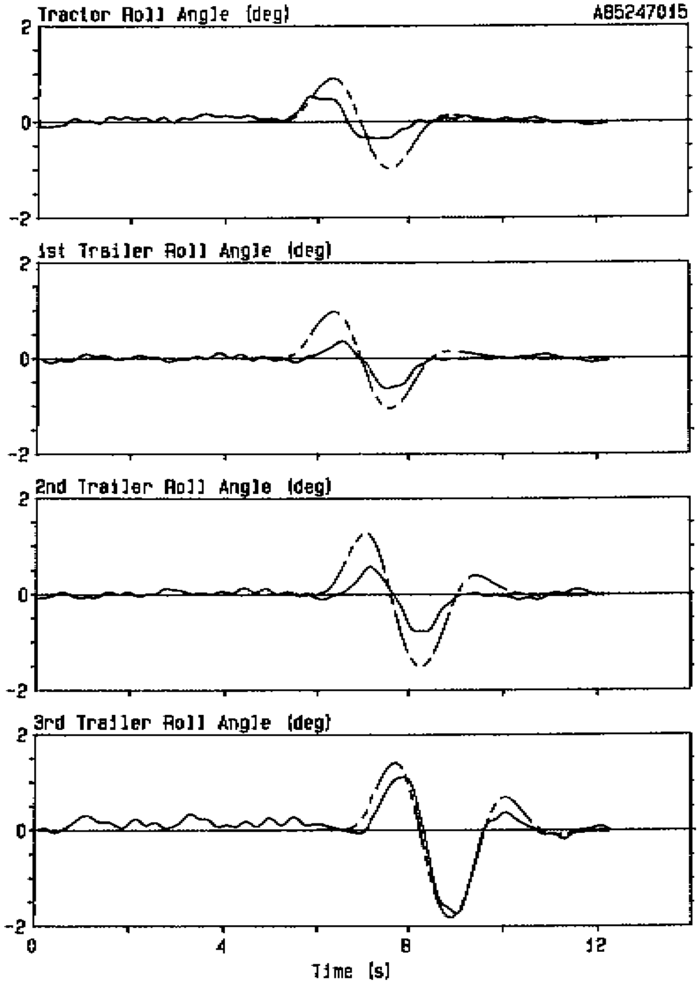


Figure 34/ A-Train Triple, Sinusoidal Steer Responses at 63 km/h, 2.56 s Steer Period



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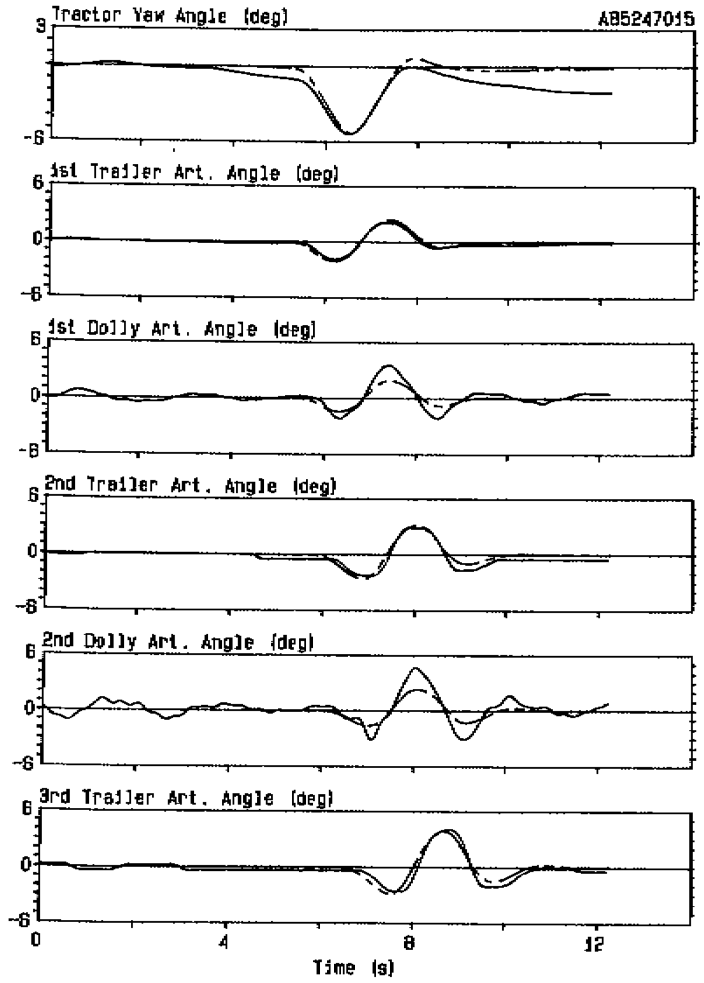

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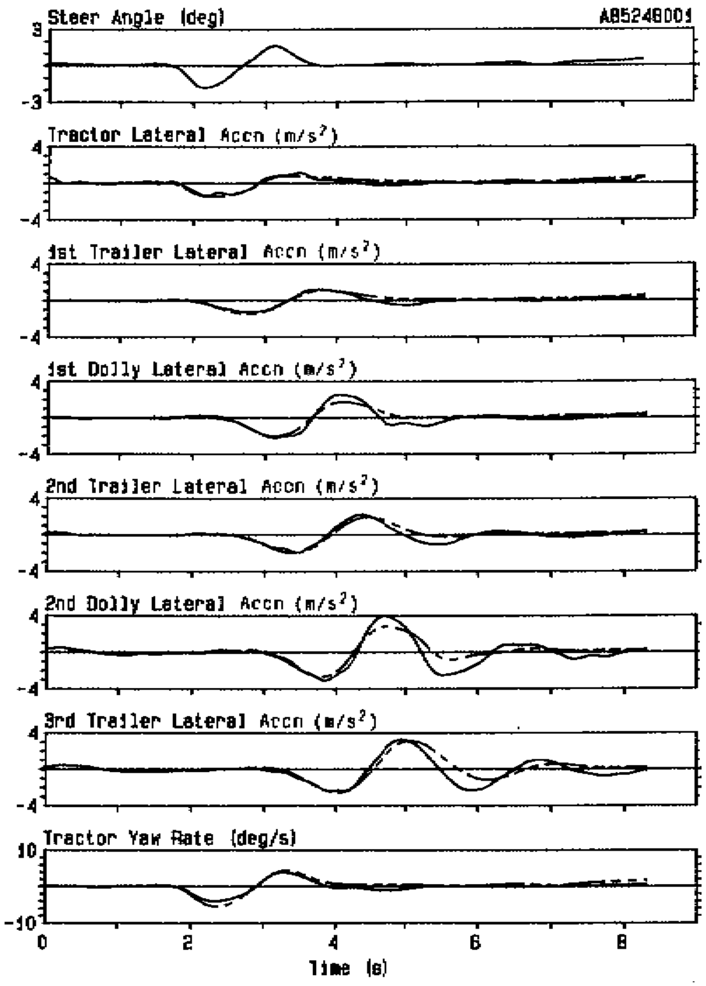
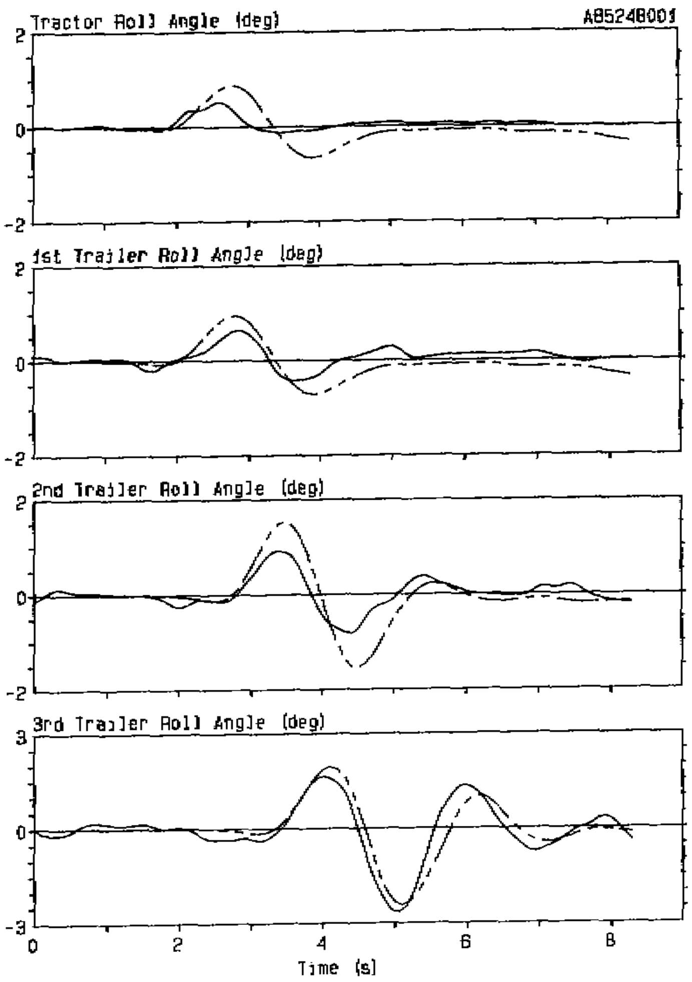


Figure 35/ A-Train Triple, Sinusoidal Steer Responses at 84 km/h, 2.0 s Steer Period



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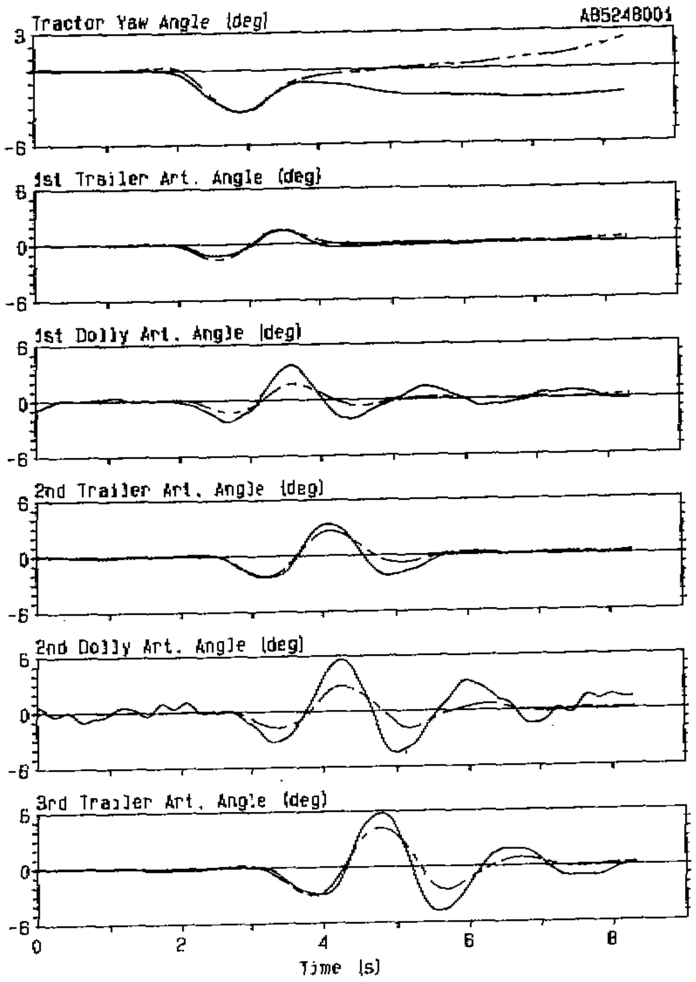

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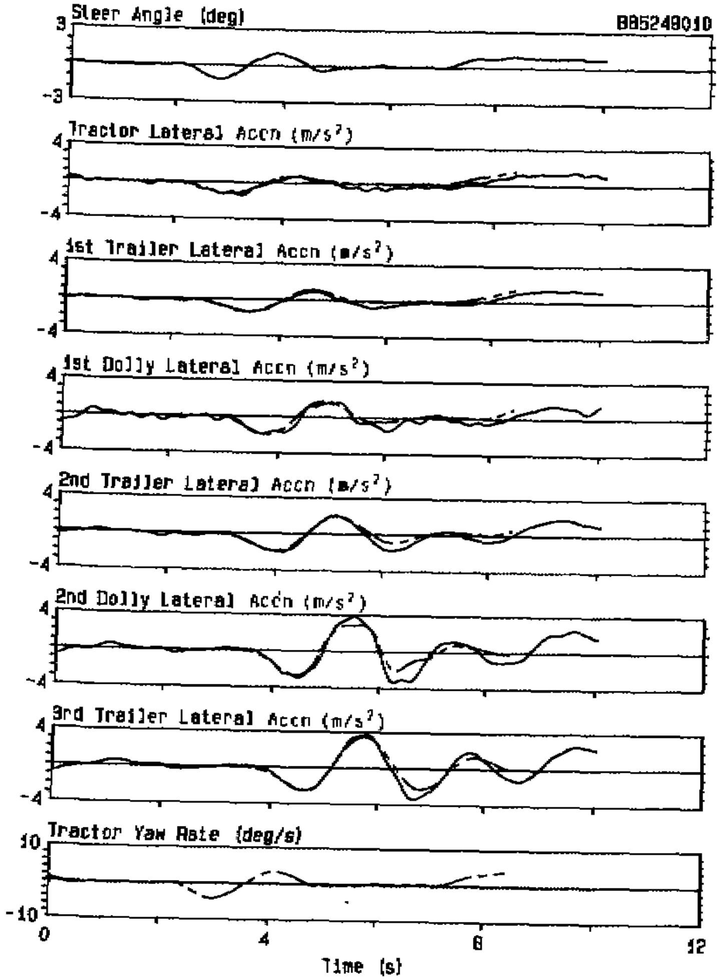
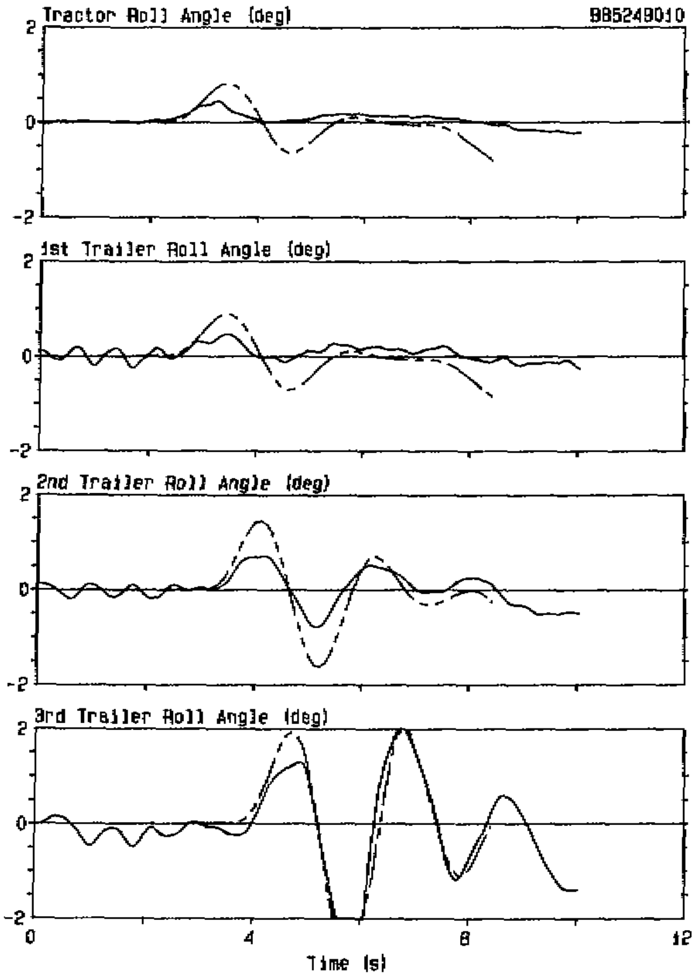


Figure 36/ A-Train Triple, Sinusoidal Steer
Responses at 94 km/h,
2.24 s Steer Period



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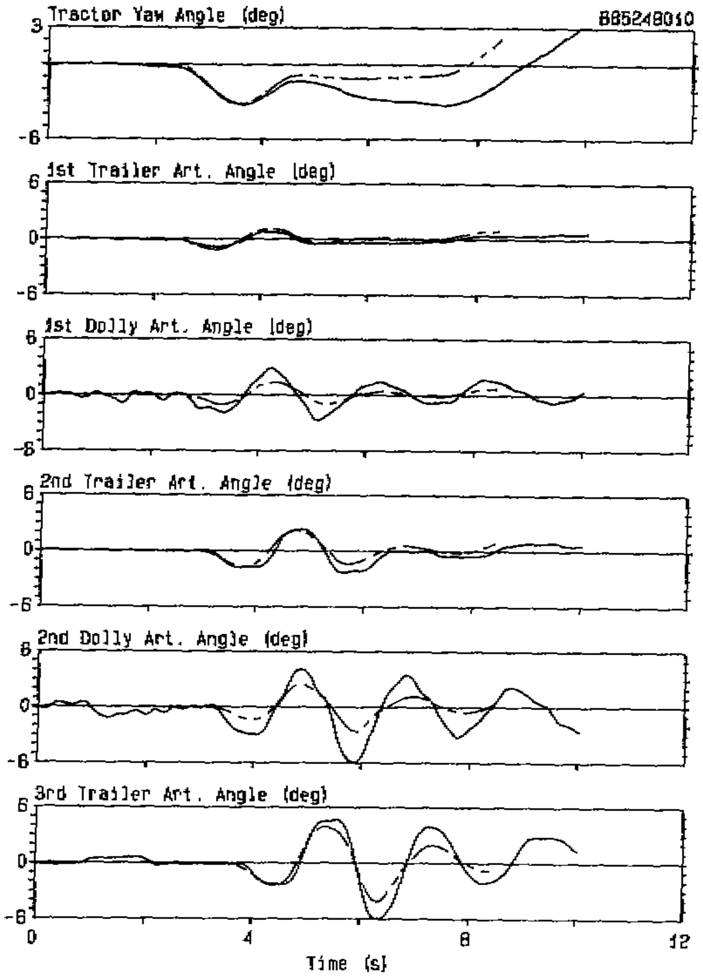

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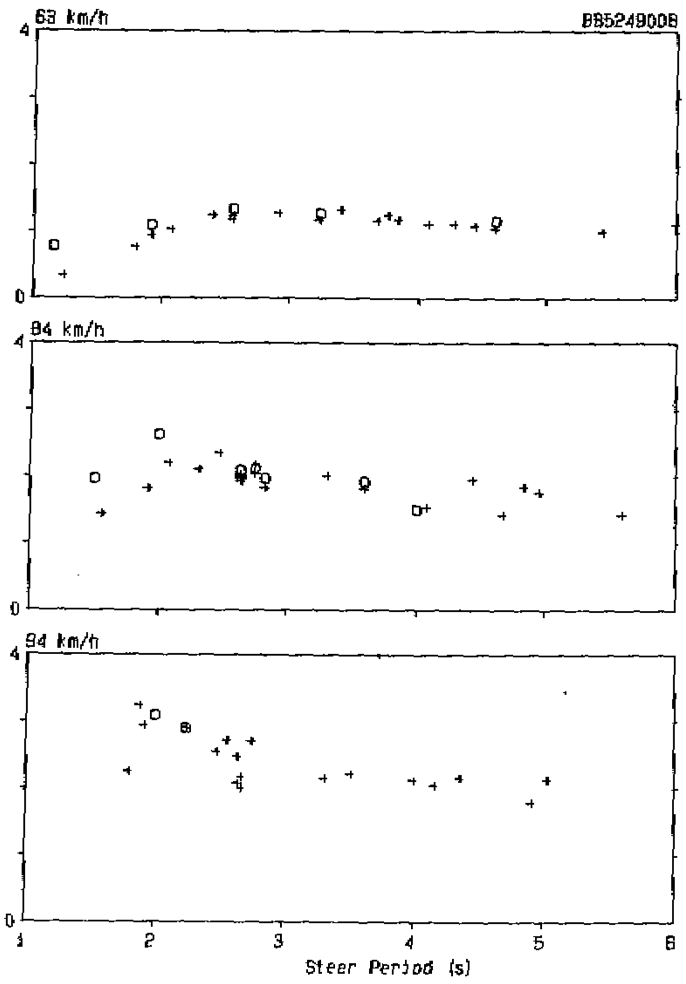


Figure 37/ A-Train Triple, Rearward Amplification vs Steer Period

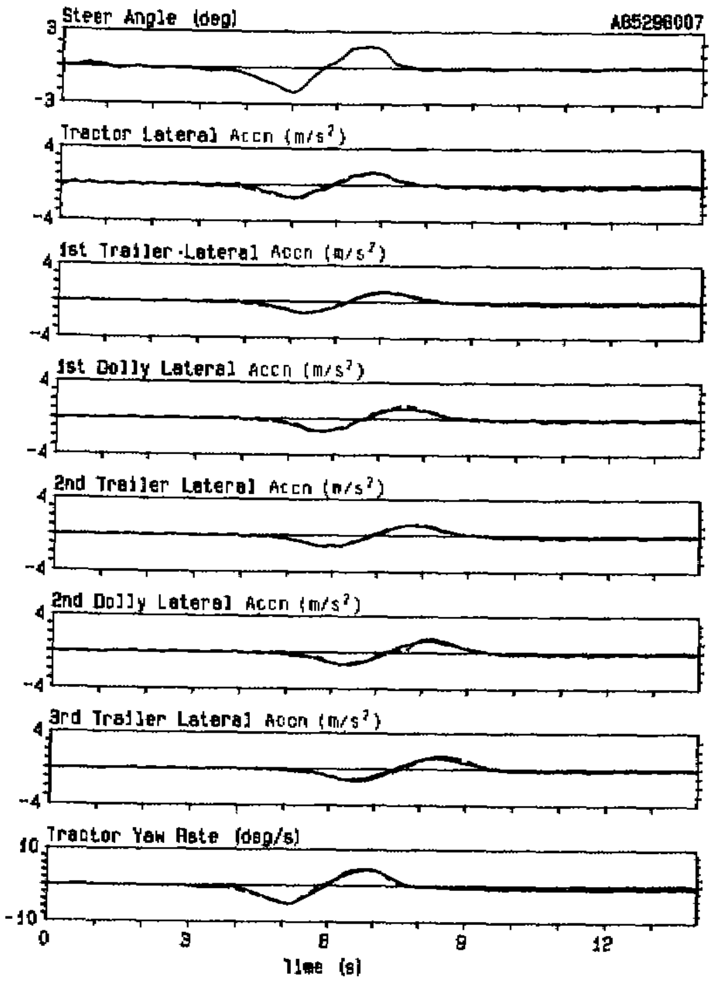
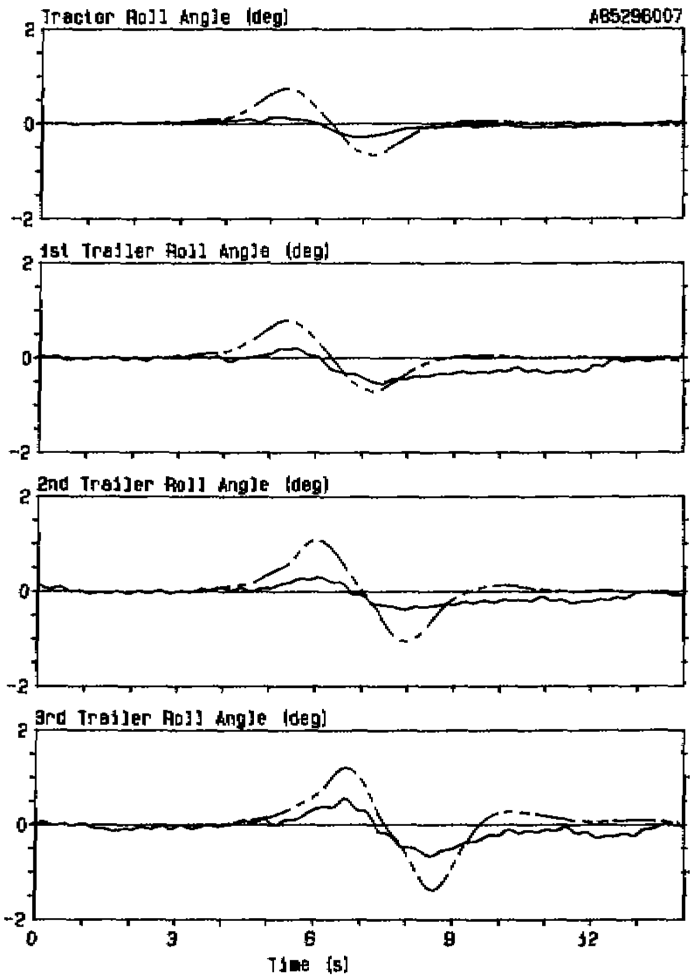


Figure 38/ C-Train Triple, Sinusoidal Steer Responses at 63 km/h, 3.84 s Steer Period



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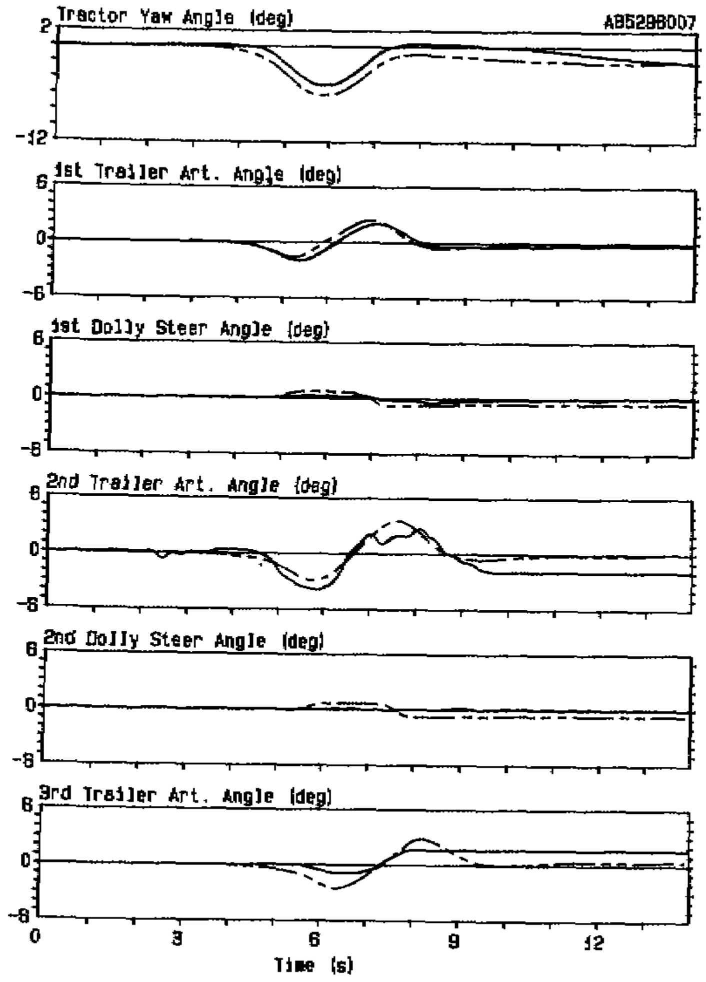

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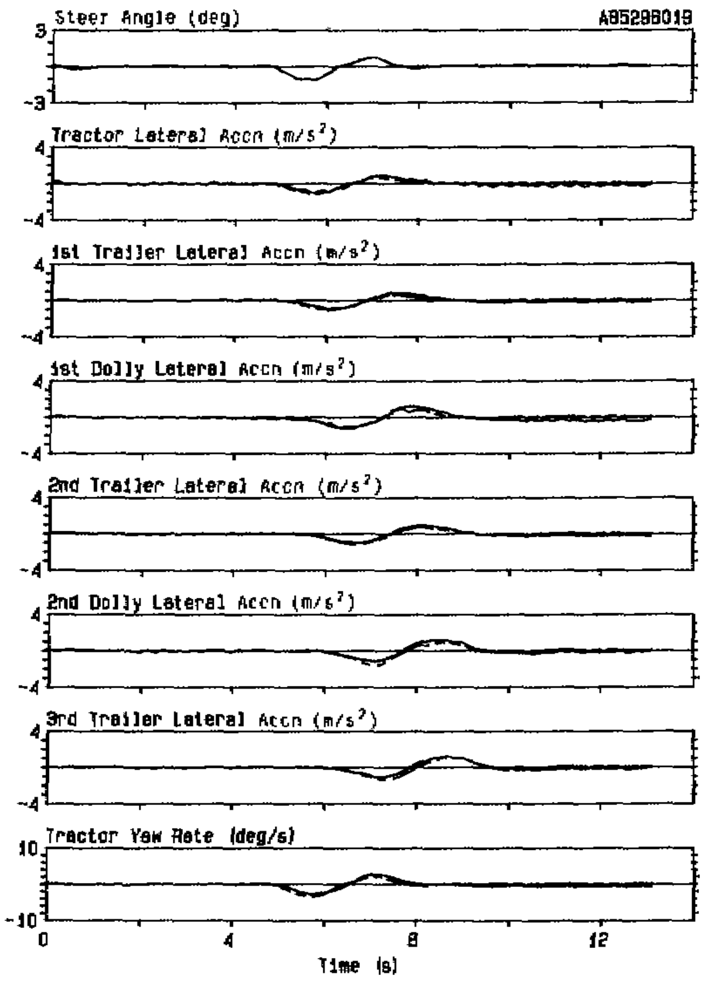
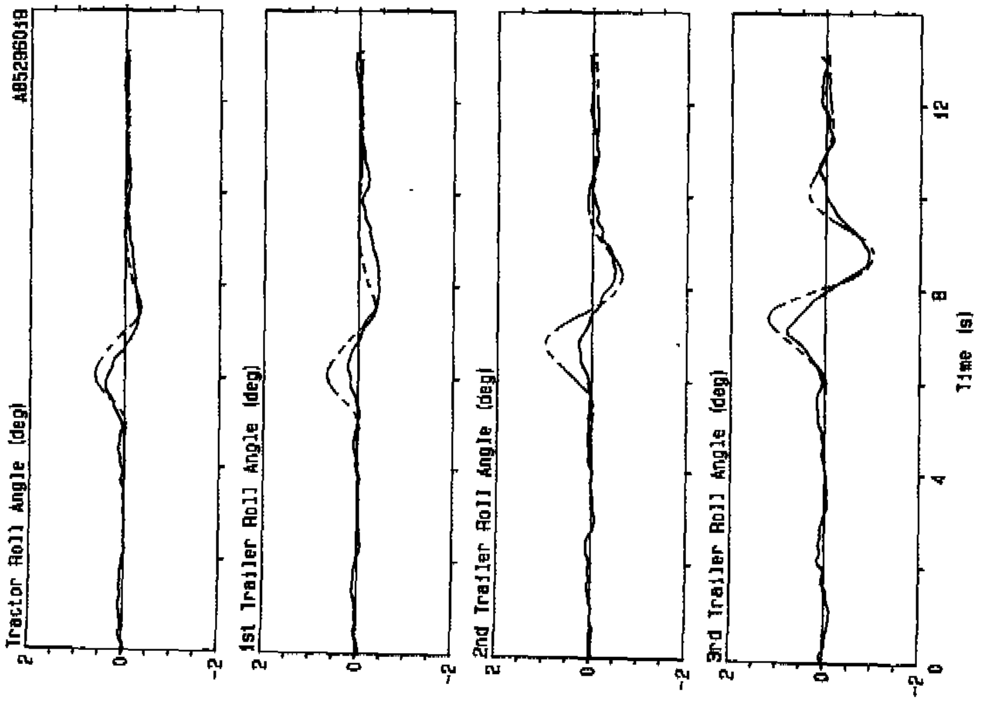


Figure 39/ C-Train Triple, Sinusoidal Steer Responses at 84 km/h, 2.76 s Steer Period



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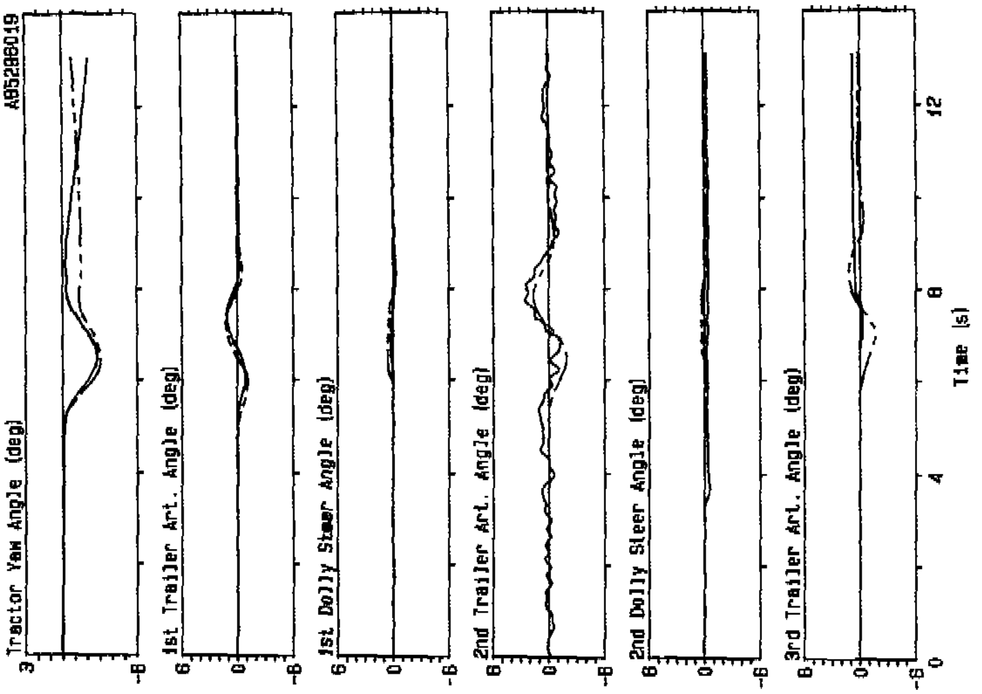

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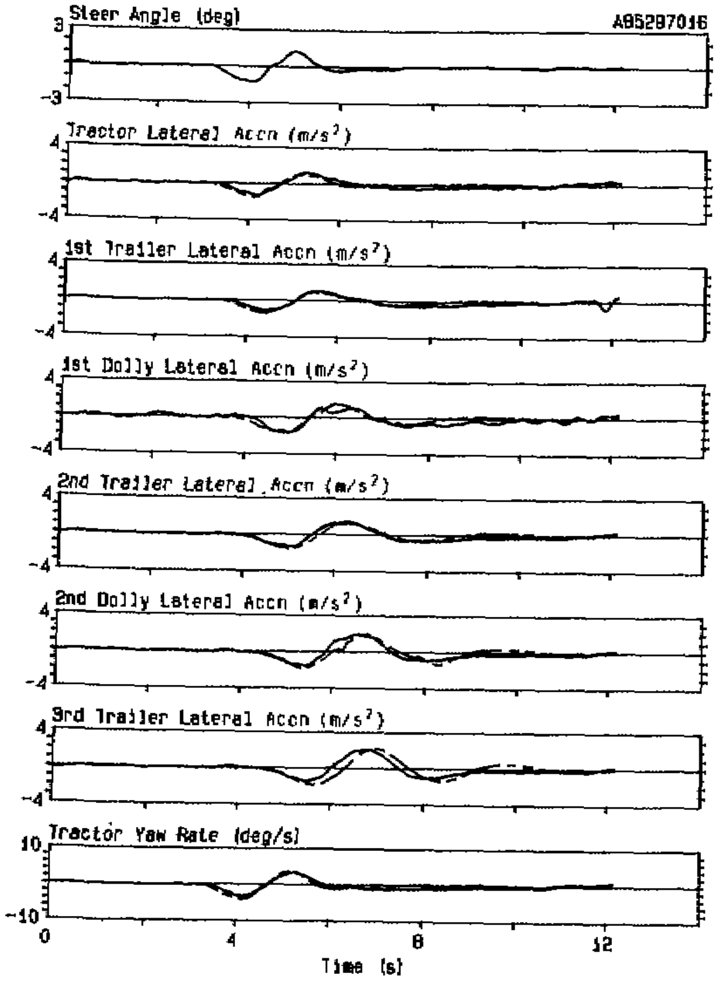
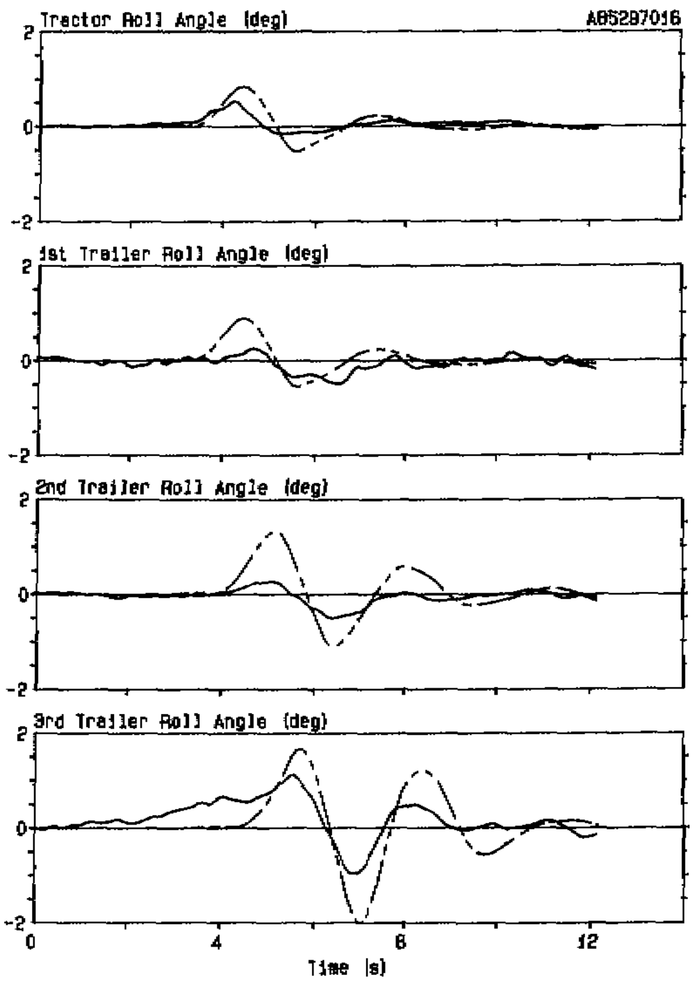


Figure 40/ C-Train Triple, Sinusoidal Steer
Responses at 94 km/h,
2.4 s Steer Period



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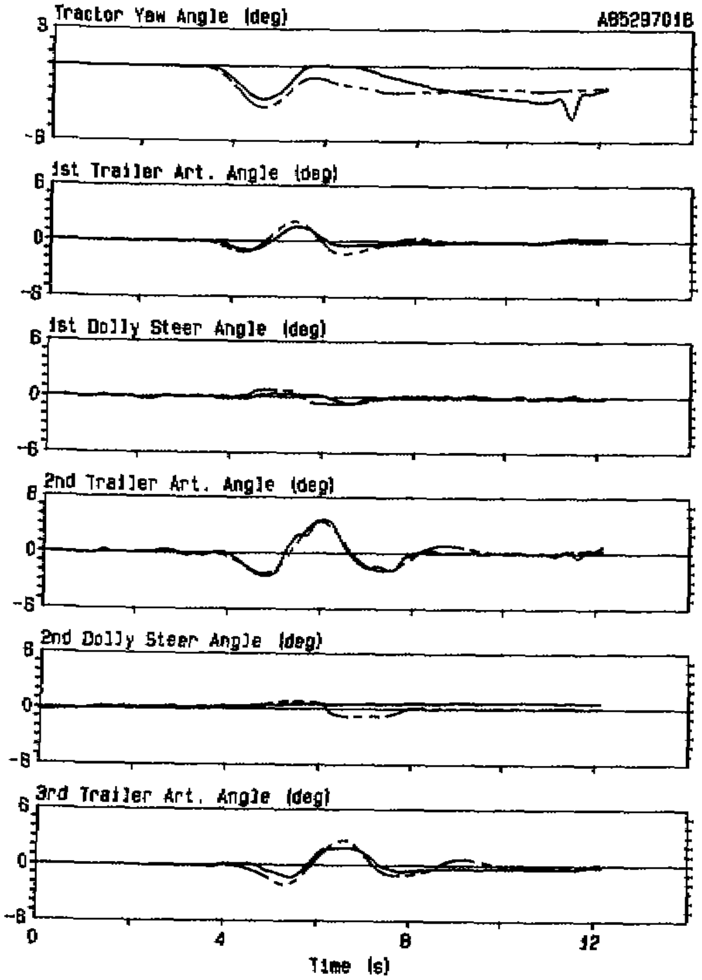

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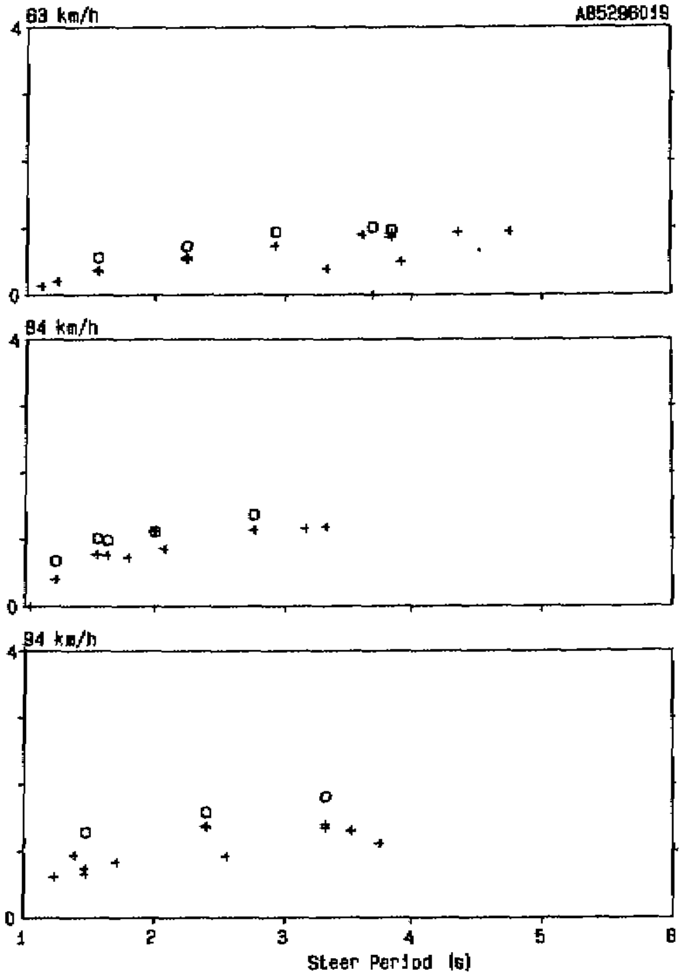


Figure 41/ C-Train Triple,
Rearward Amplification vs
Steer Period

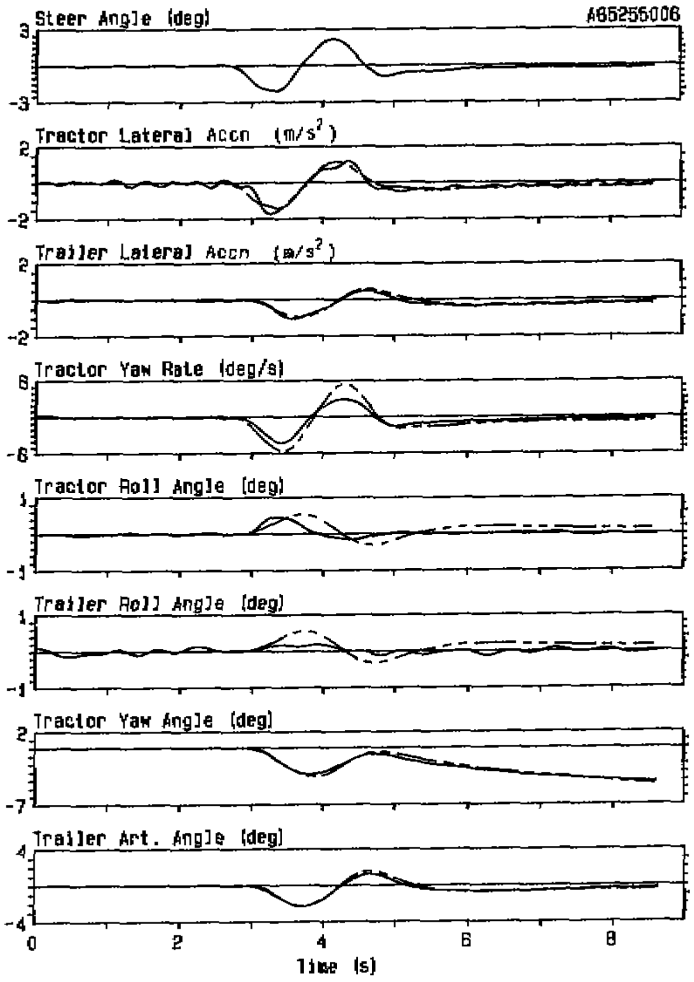


Figure 42/ 5-Axle 48 ft Semi, Sinusoidal Steer Responses at 63 km/h, 2.0 s Steer Period

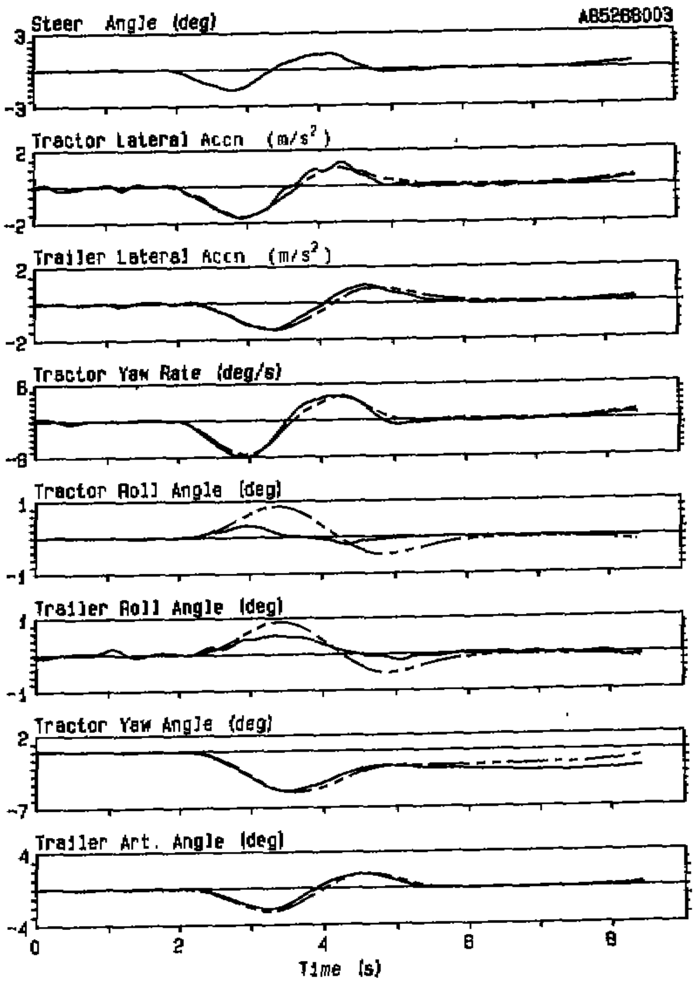


Figure 43/ 5-Axle 48 ft Semi, Sinusoidal Steer Responses at 84 km/h, 2.7 s Steer Period

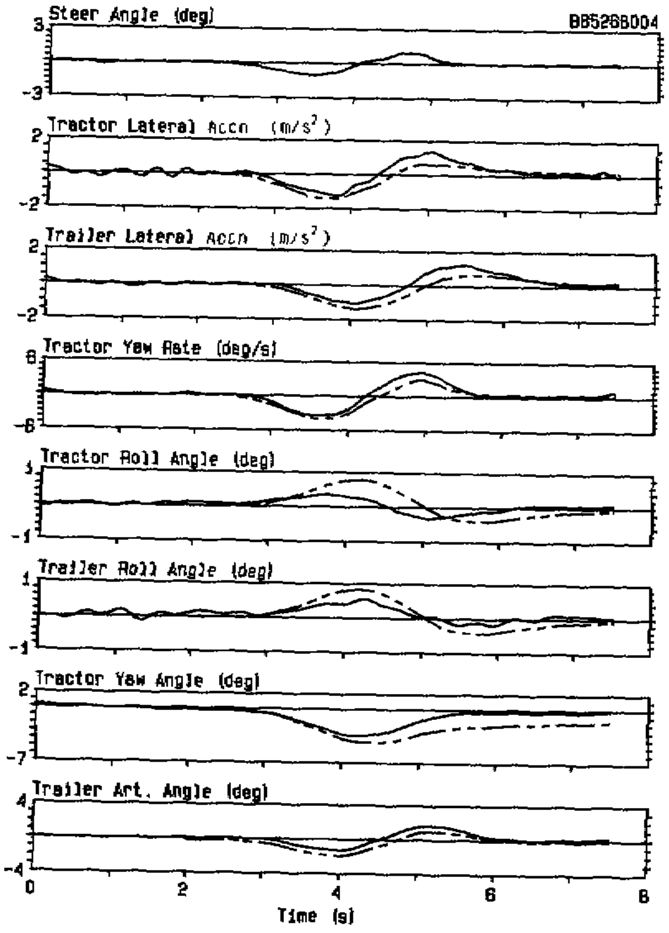


Figure 44/ 5-Axle 48 ft Semi, Sinusoidal Steer Responses at 94 km/h, 3.0 s Steer Period

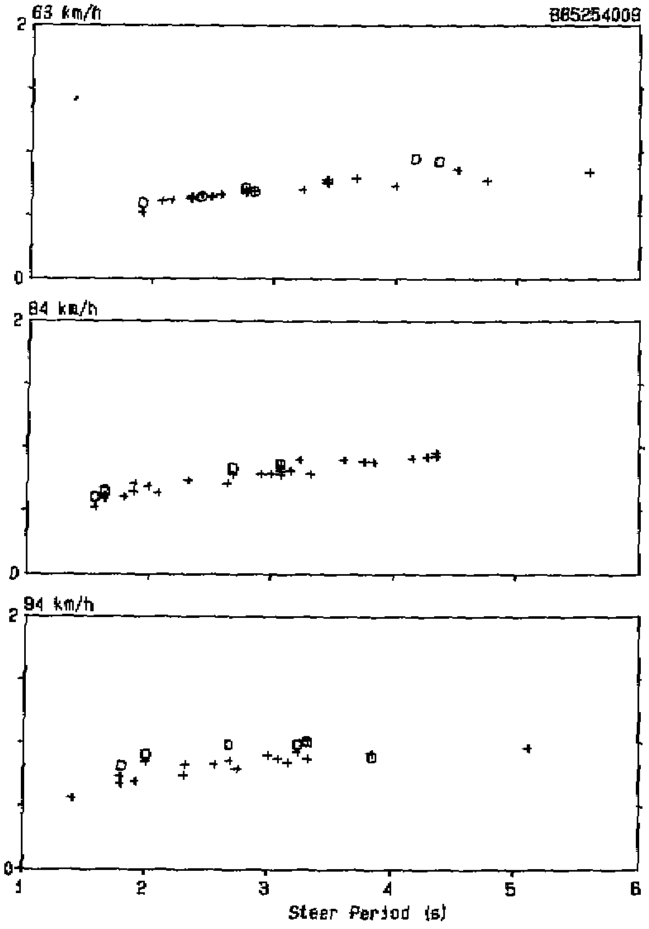


Figure 45/ 5-Axle 48 ft Semi, Rearward Amplification vs Steer Period

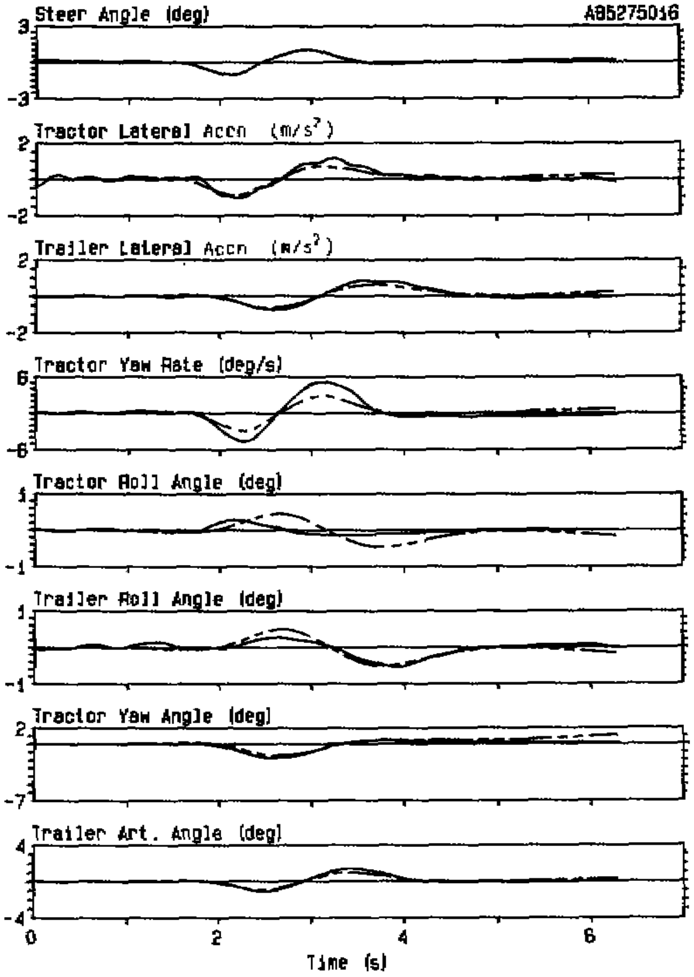


Figure 46/ 6-Axle 48 ft Semi, Sinusoidal Steer Responses at 94 km/h, 2.0 s Steer Period

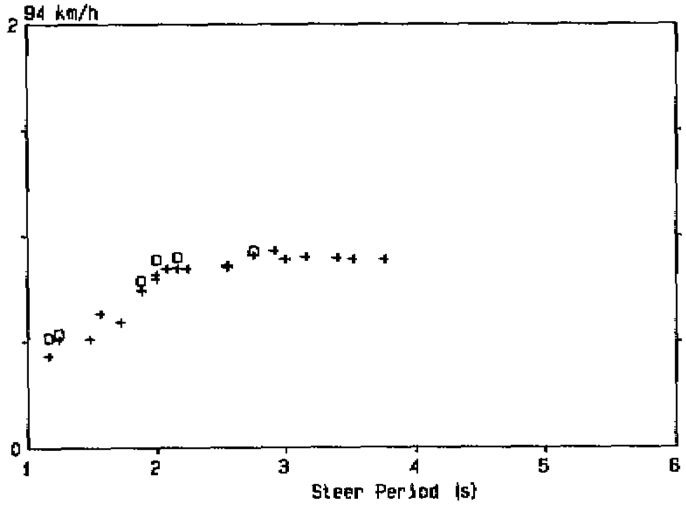


Figure 47/ 6-Axle 48 ft Semi, Rearward Amplification vs Steer Period

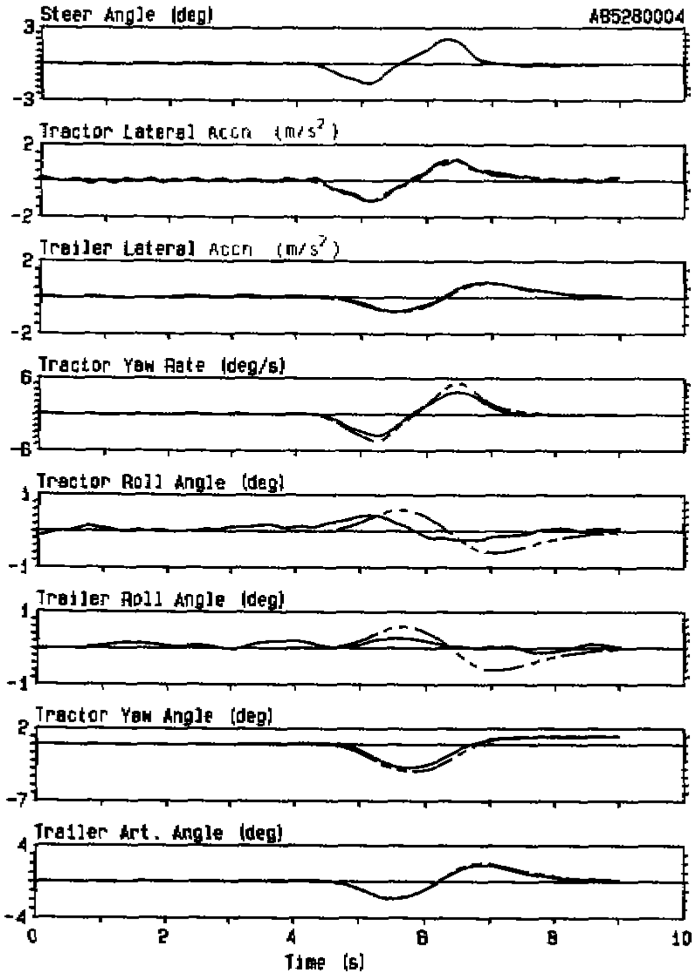


Figure 48/ 7-Axle 48 ft Semi, Sinusoidal Steer Responses at 63 km/h, 2.84 s Steer Period

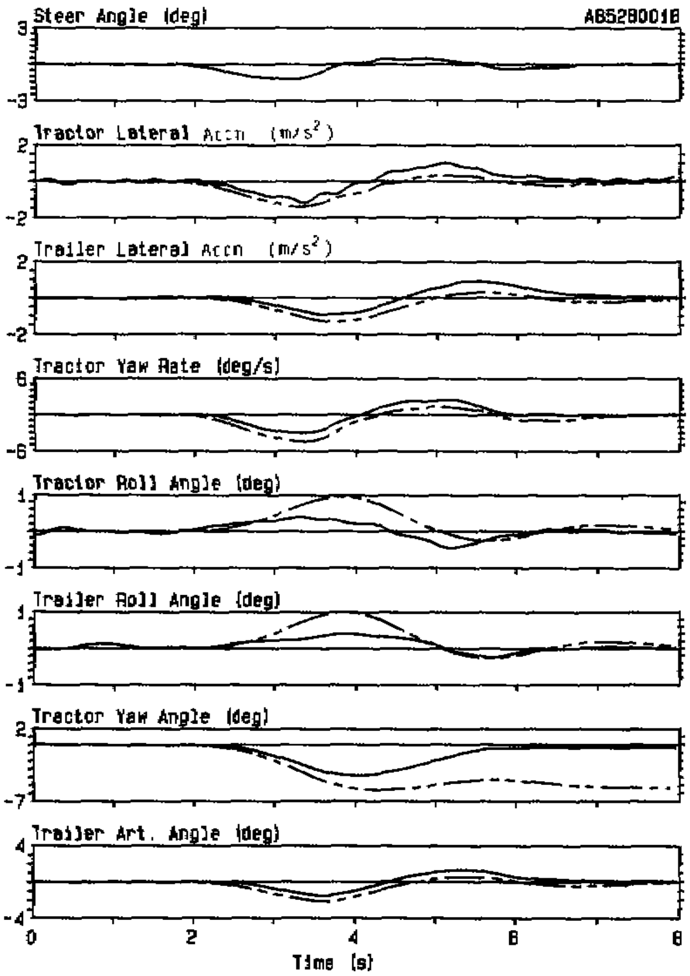


Figure 49/ 7-Axle 48 ft Semi, Sinusoidal Steer Responses at 84 km/h, 4.0 s Steer Period

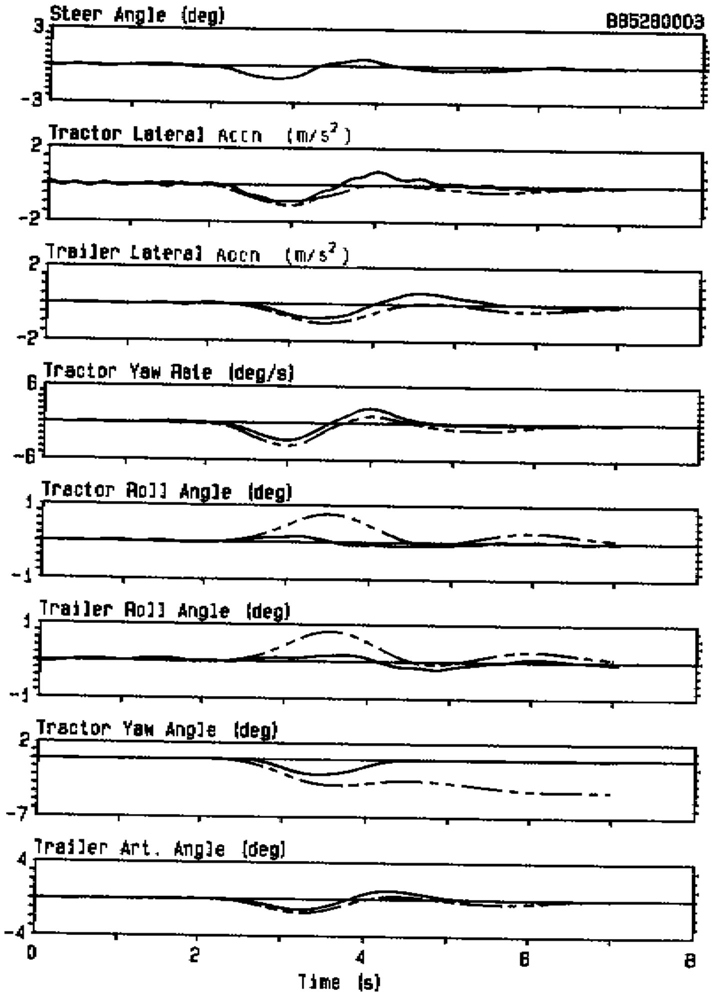


Figure 50/ 7-Axle 48 ft Semi, Sinusoidal Steer Responses at 94 km/h, 2.5 s Steer Period

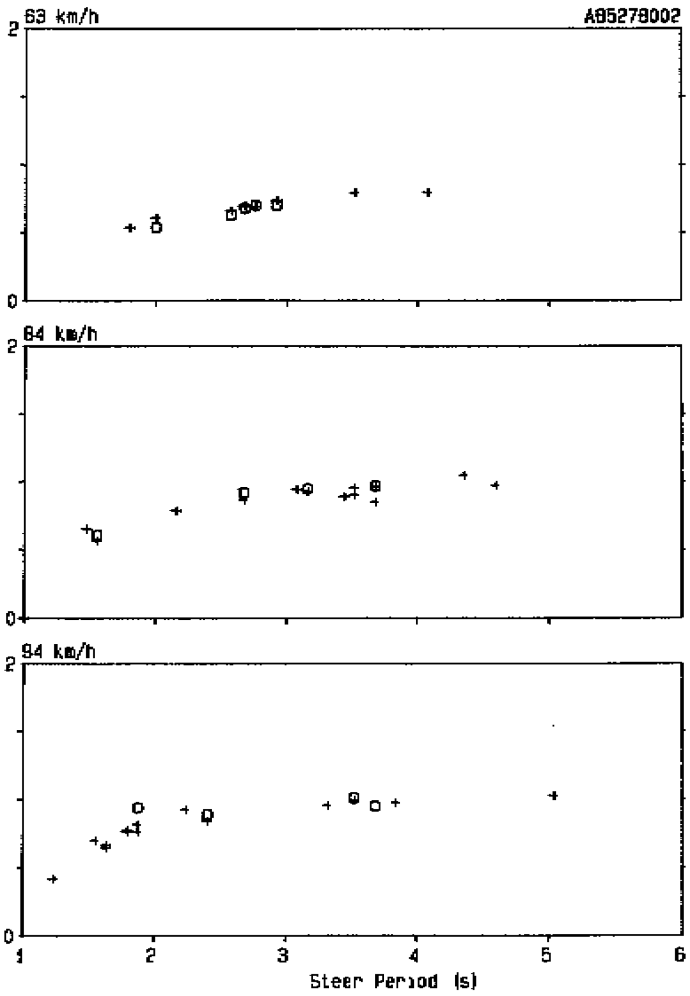


Figure 51/ 7-Axle 48 ft Semi, Rearward Amplification vs Steer Period

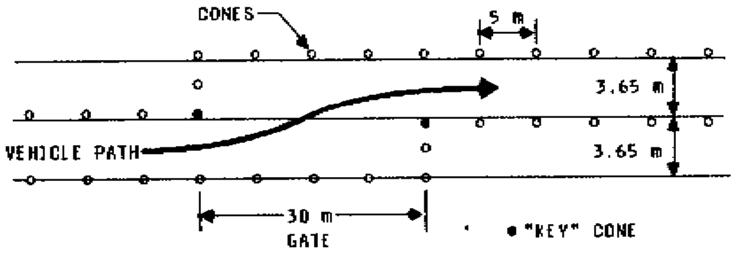


Figure 52/ Lane-Change Manoeuvre Course

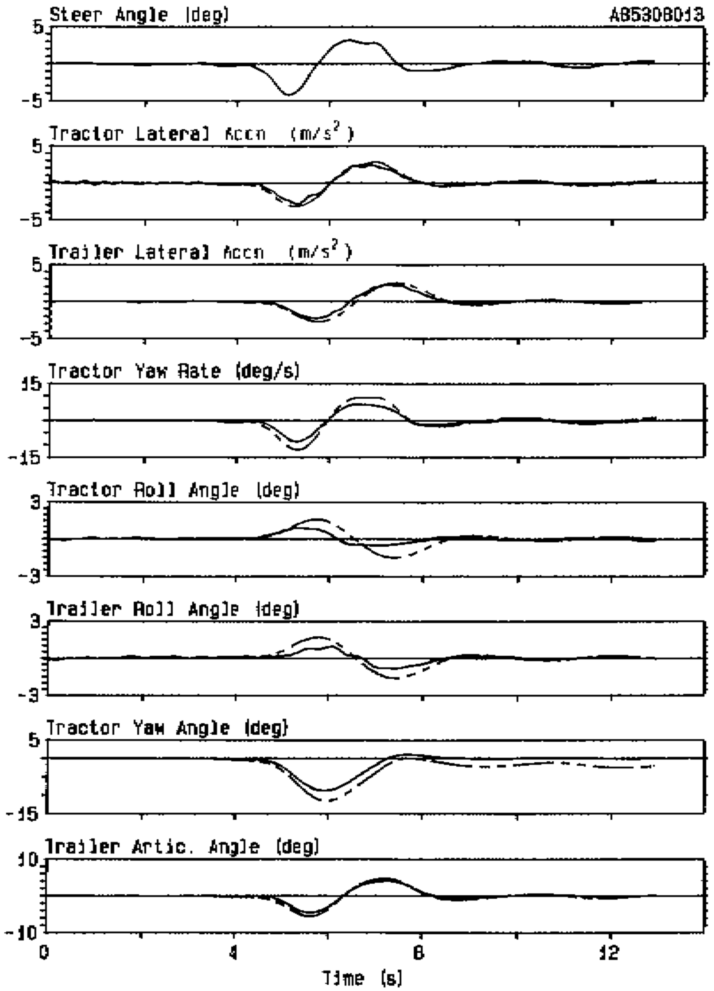


Figure 53/ 45 ft Semi,
Lane-Change Responses at 72 km/h

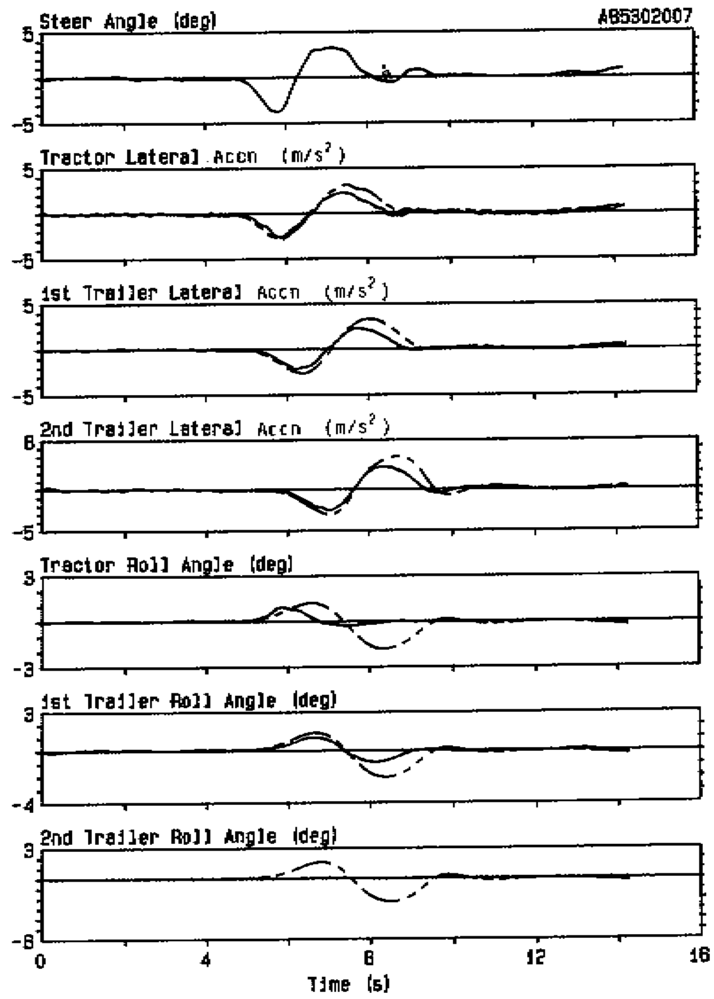


Figure 54/ B-Train Double,
Lane-Change Responses at 63 km/h

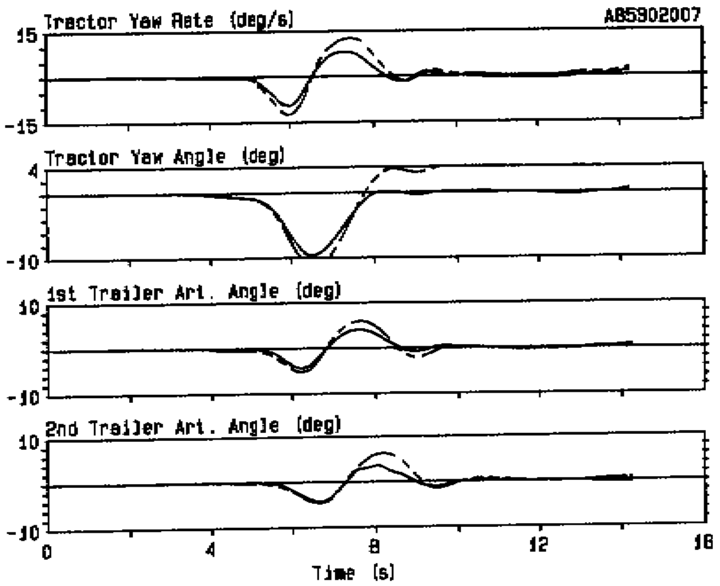


Figure 54/ Cont'd

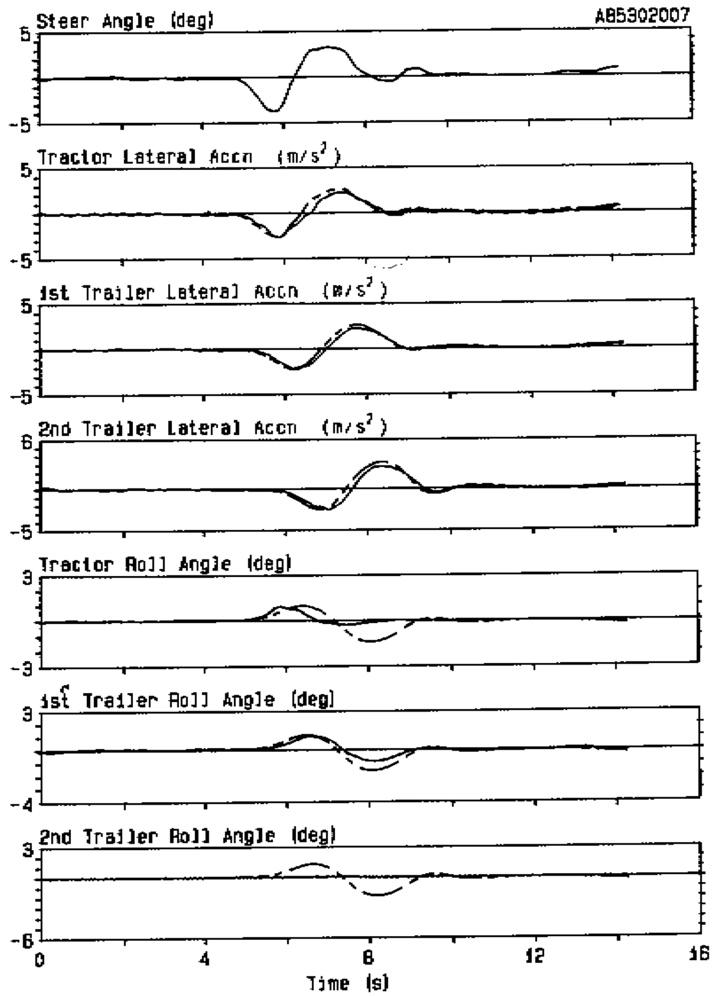


Figure 55/ B-Train Double,
Lane-Change Responses at 63 km/h
(Refined Tire Characteristics)

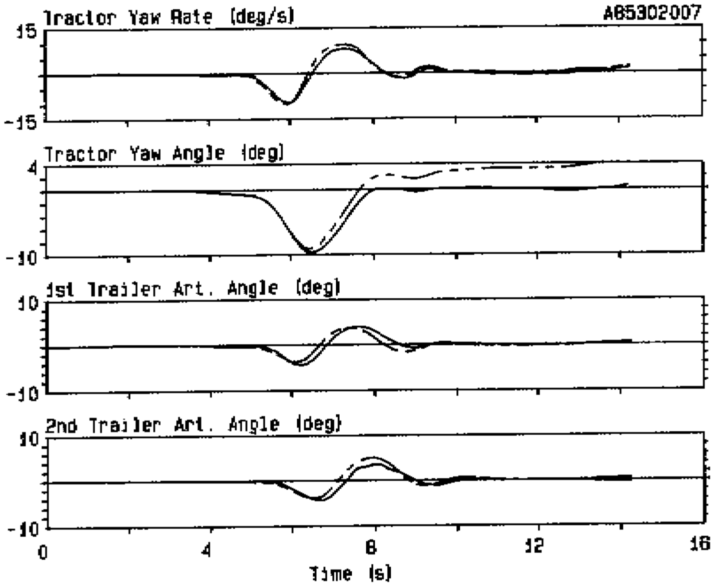


Figure 55/ Cont'd

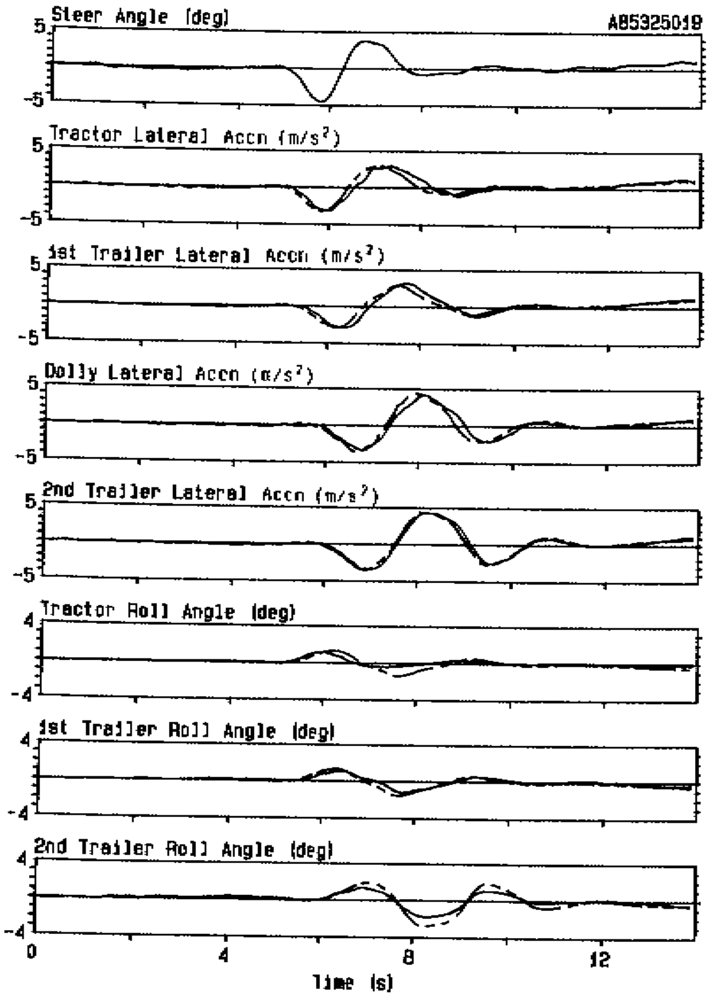
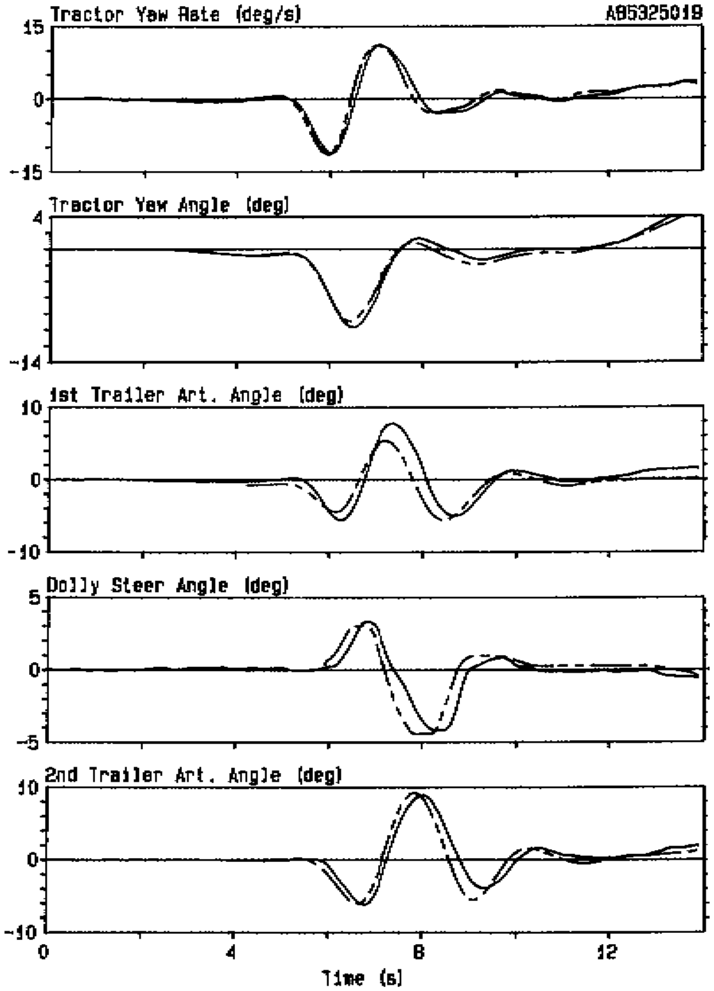


Figure 56/ C-Train Double,
Lane-Change Responses at 72 km/h



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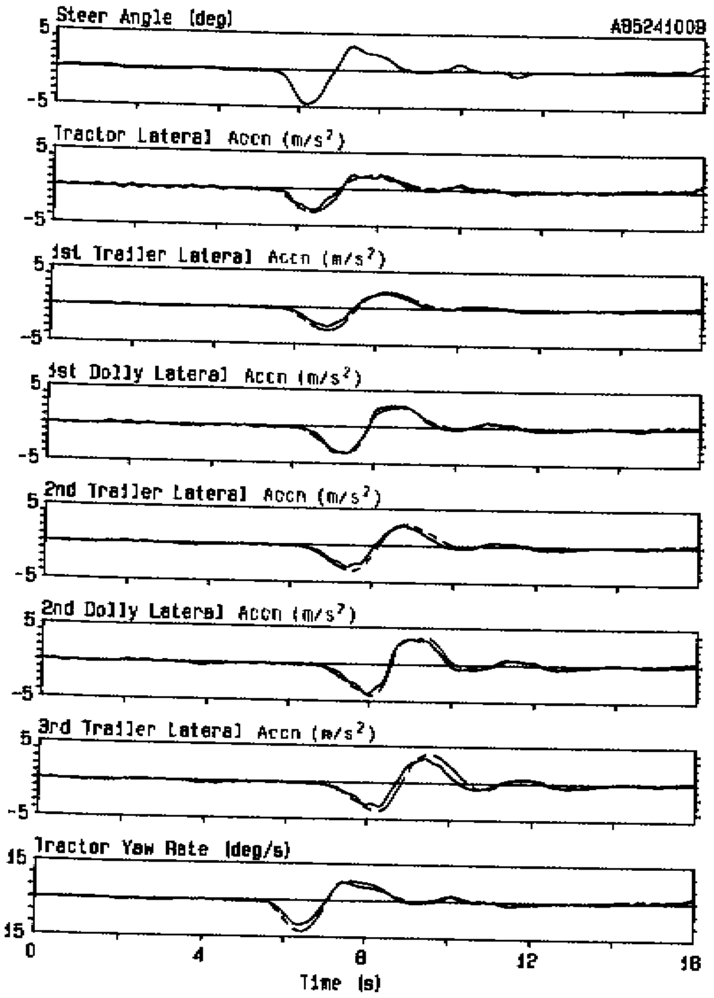
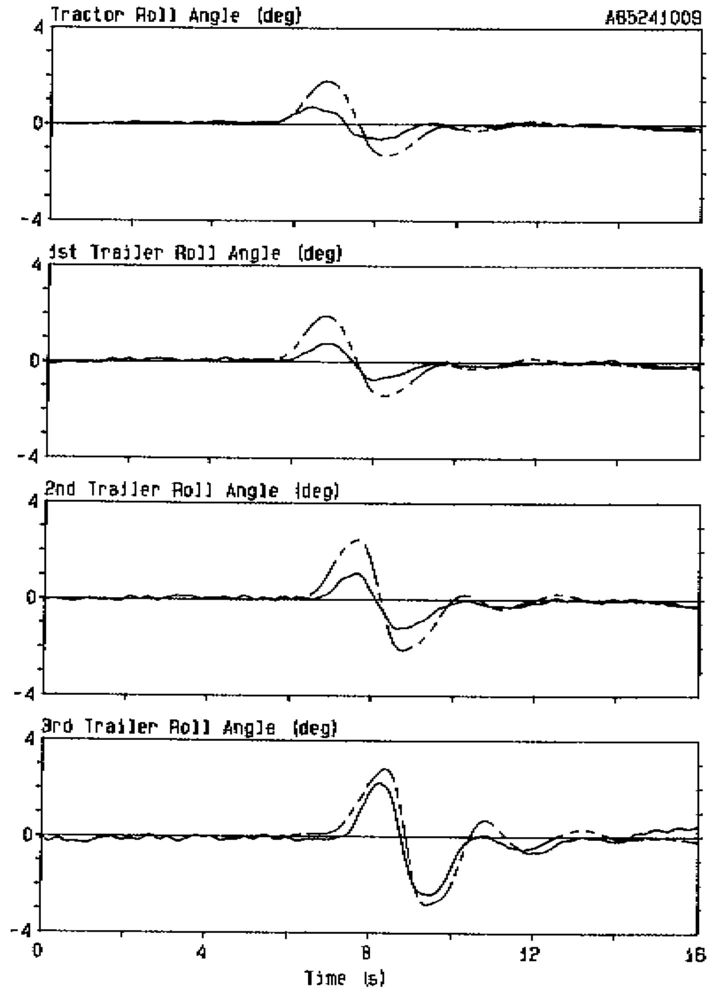


Figure 57/ A-Train Triple,
Lane-Change Responses at 63 km/h



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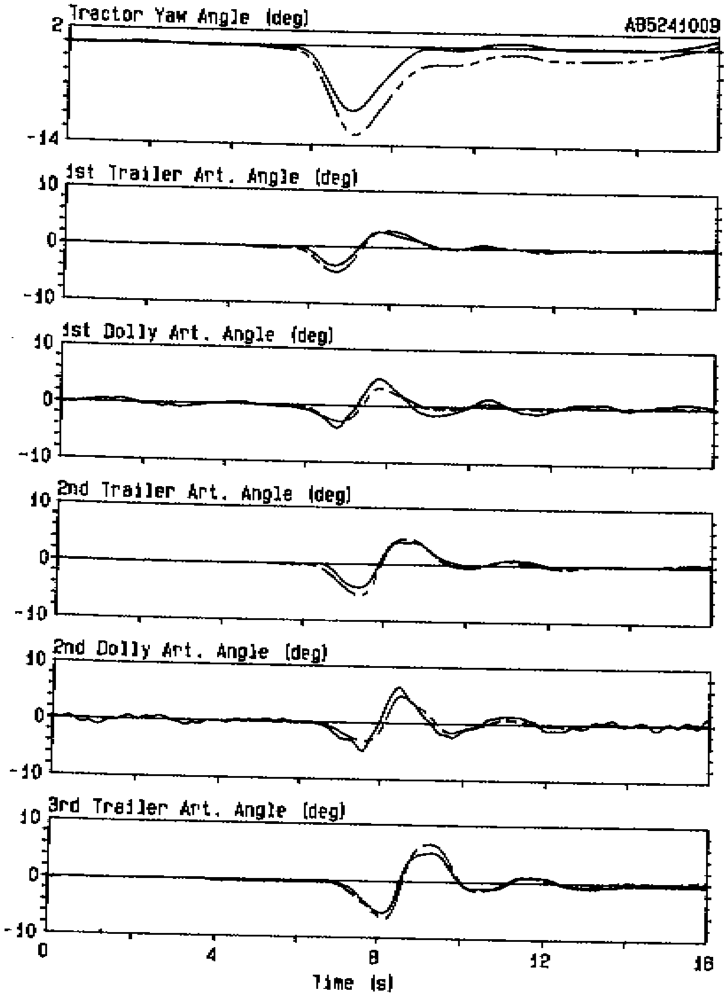

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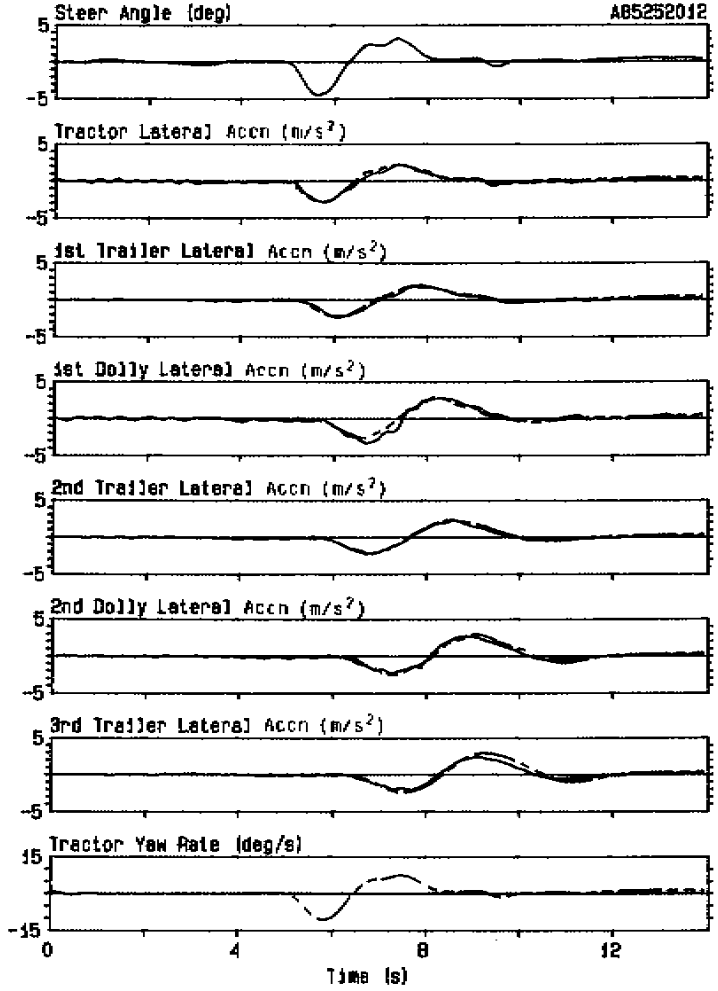

Figure 58/ C-Train Triple,
Lane-Change Responses at 63 km/h

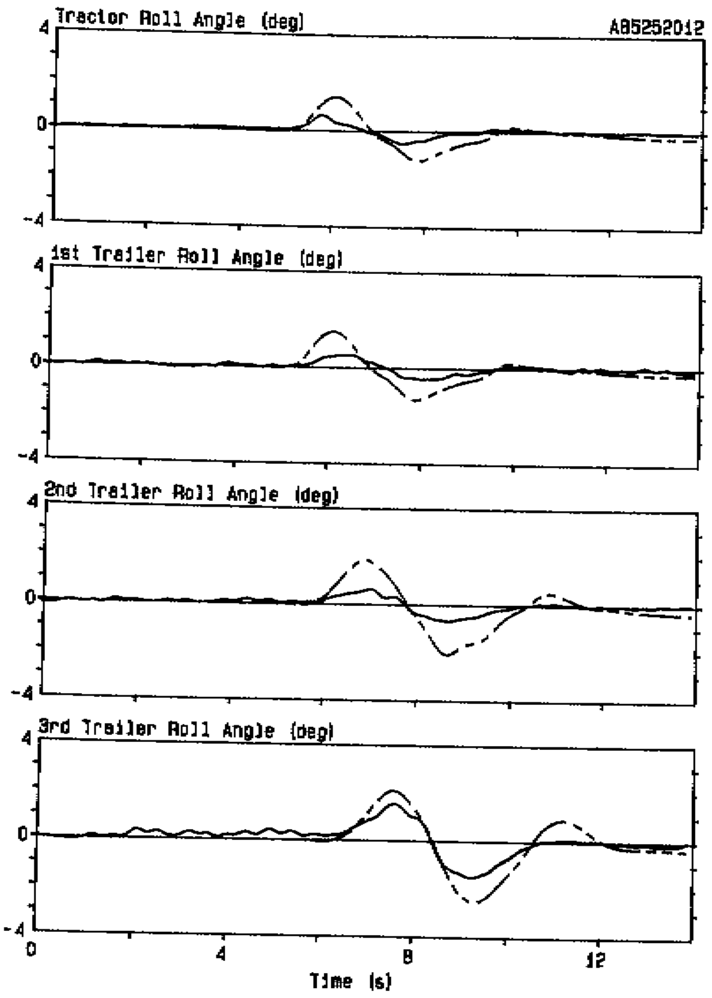

Figure 58/ Cont'd

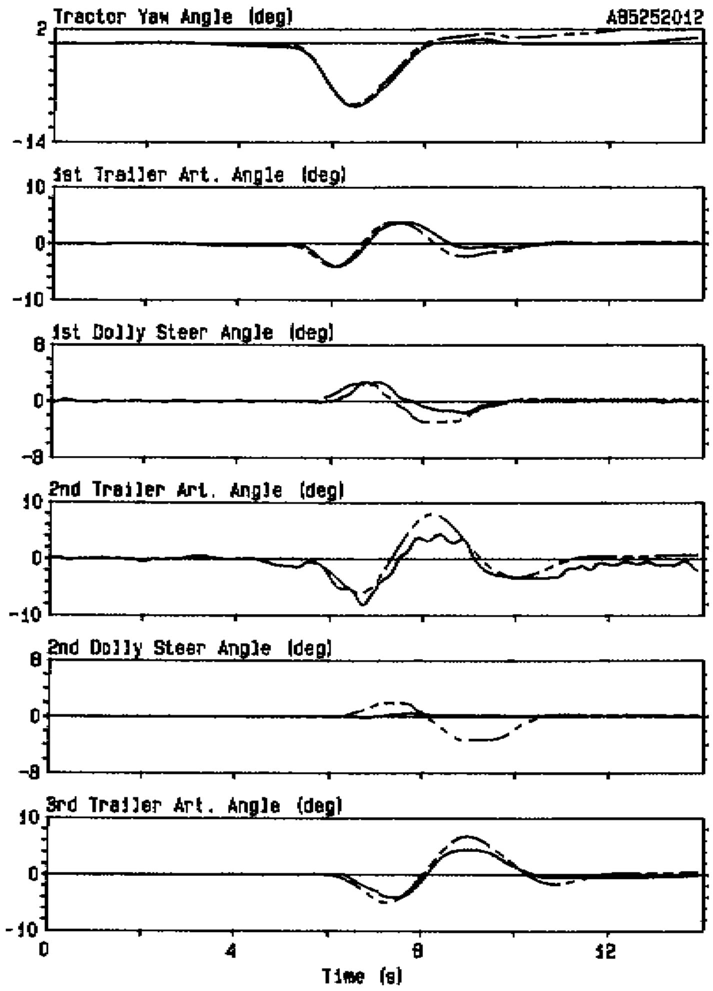

Figure 58/ Cont'd

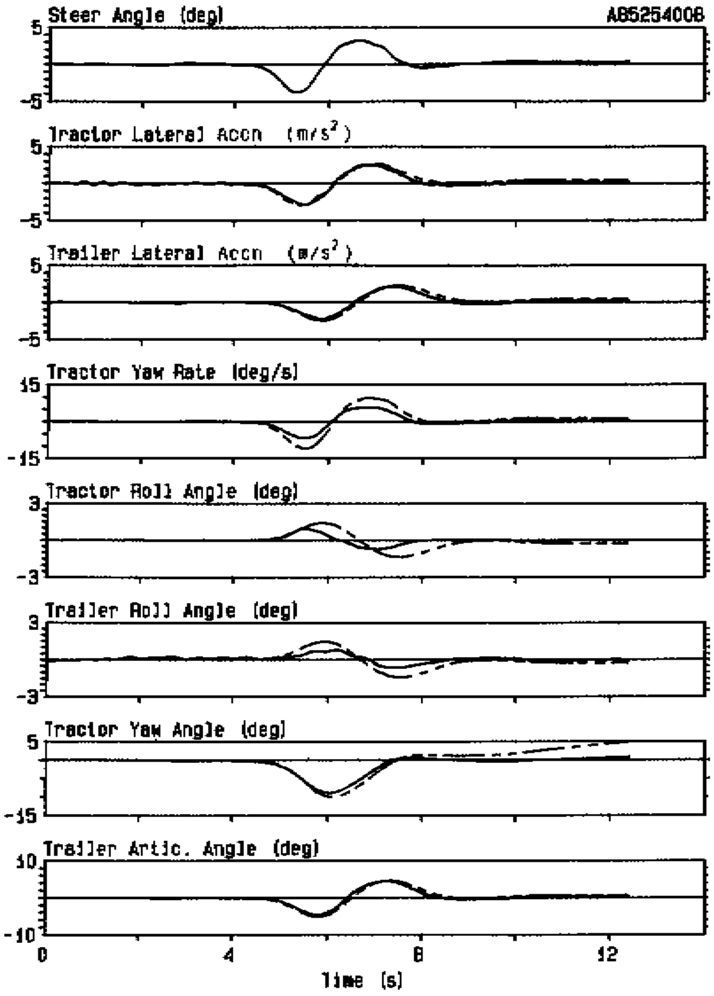

Figure 59/ 5-Axle 48 ft Semi,
Lane-Change Responses at 72 km/h

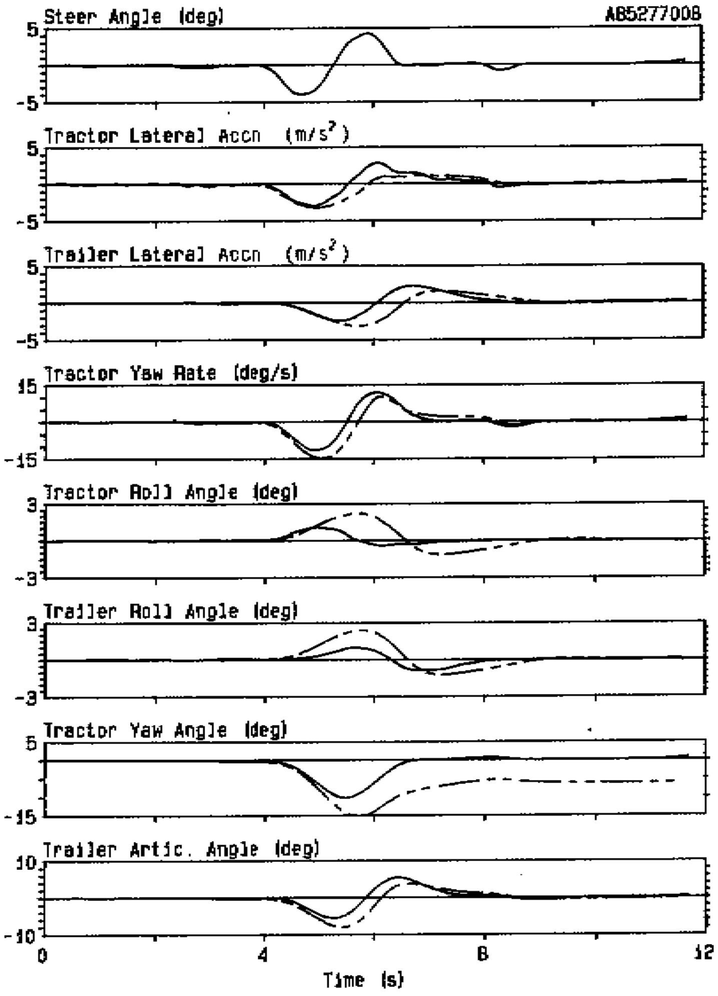

Figure 60/ 7-Axle 48 ft Semi,
Lane-Change Responses at 72 km/h

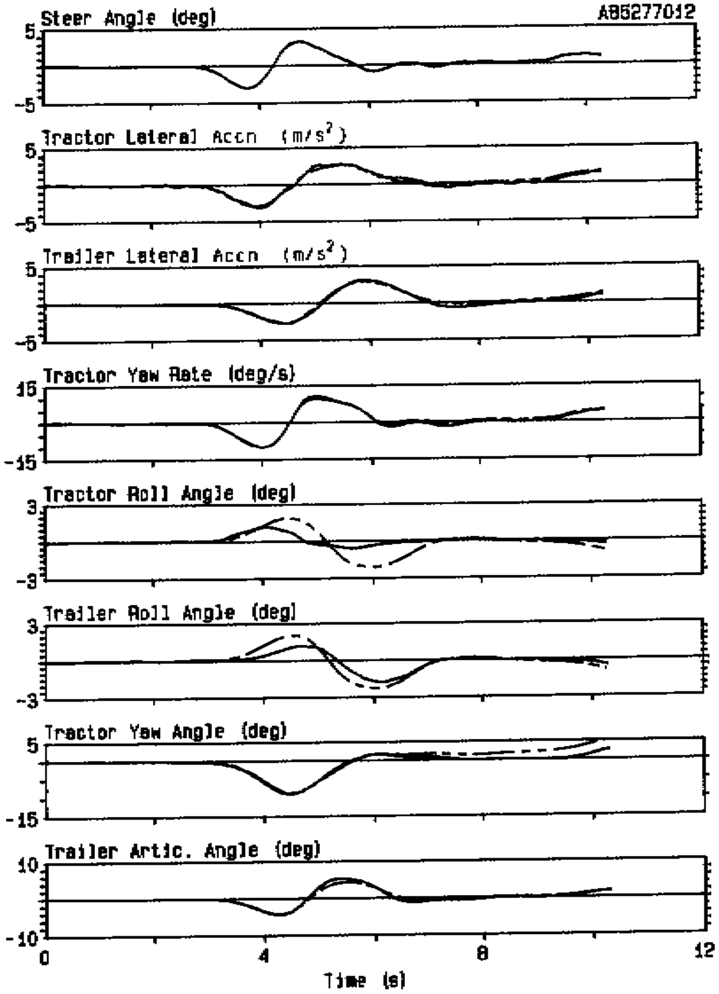

Figure 61/ 7-Axle 48 ft Semi,
Lane-Change Responses at 92 km/h

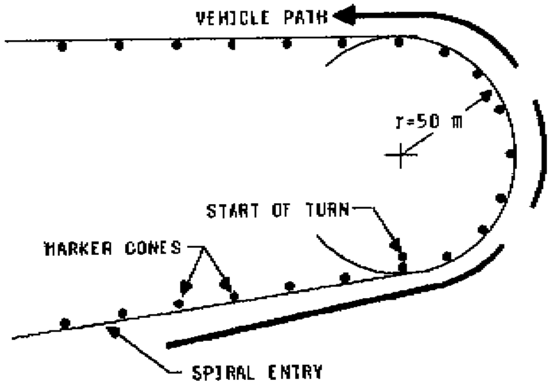

Figure 62/ Steady Circular Turn Course

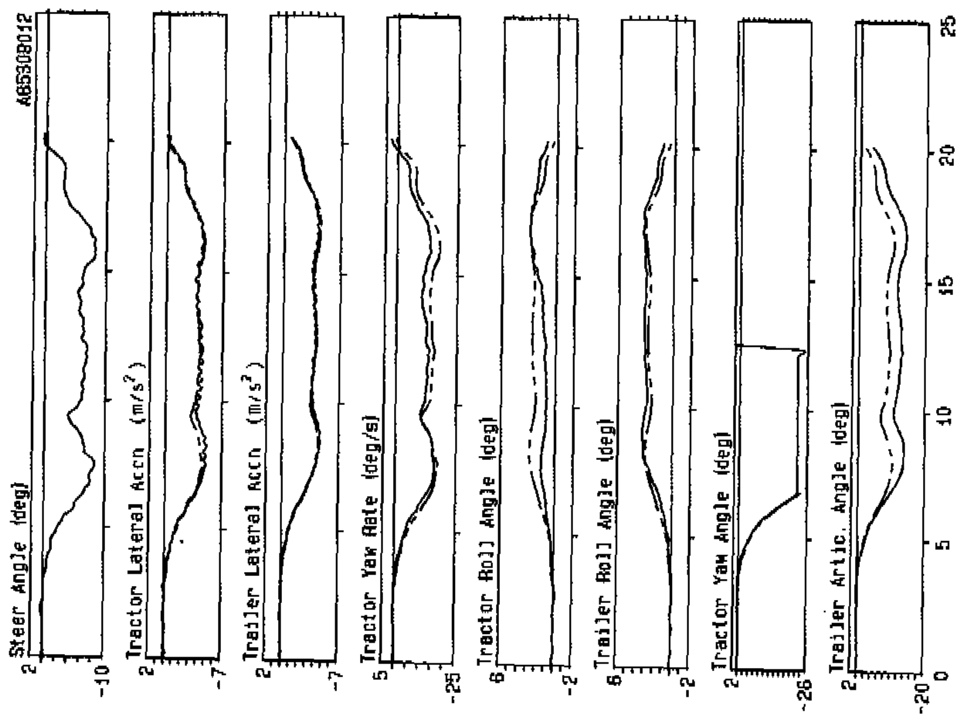

Figure 63/ 45 ft Semi, Steady Circular Turn Responses at 60 km/h

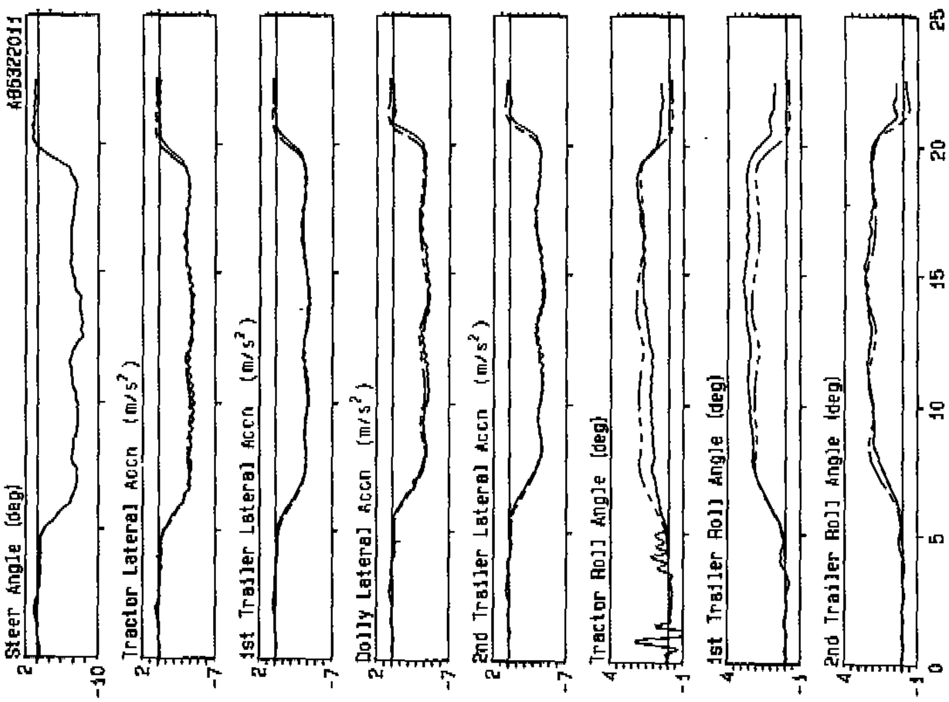

Figure 64/ A-Train Double, Steady Circular Turn Responses at 55 km/h

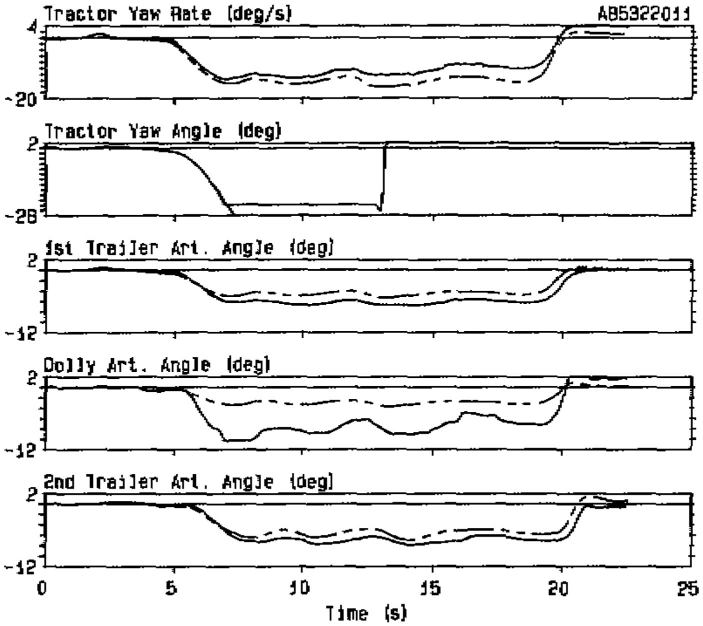

Figure 64/ Cont'd

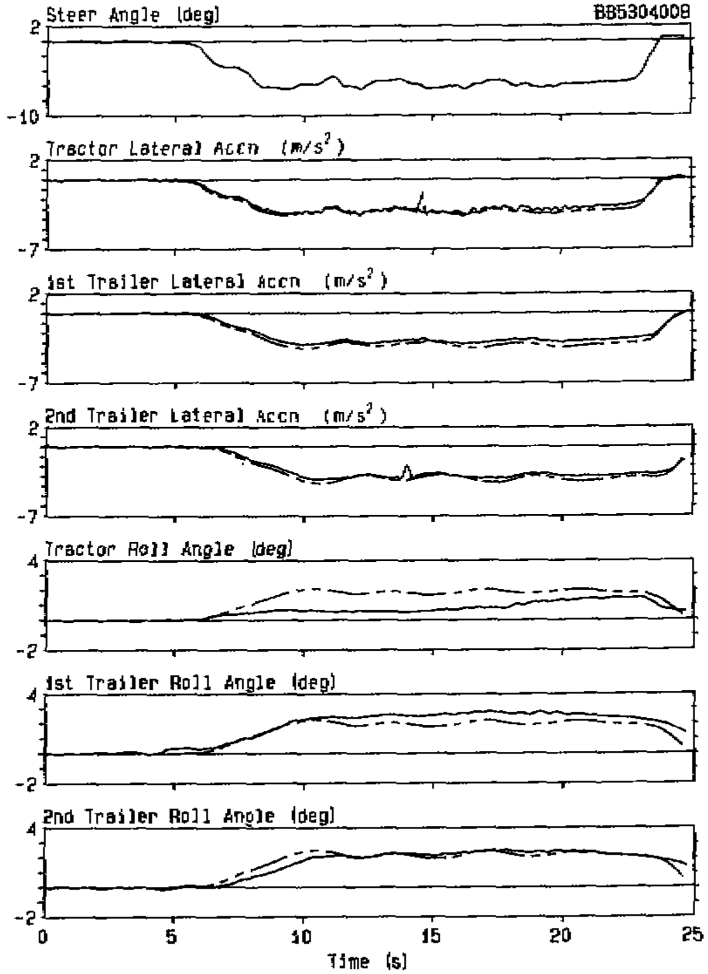

Figure 65/ B-Train Double, Steady Circular Turn Responses at 47 km/h

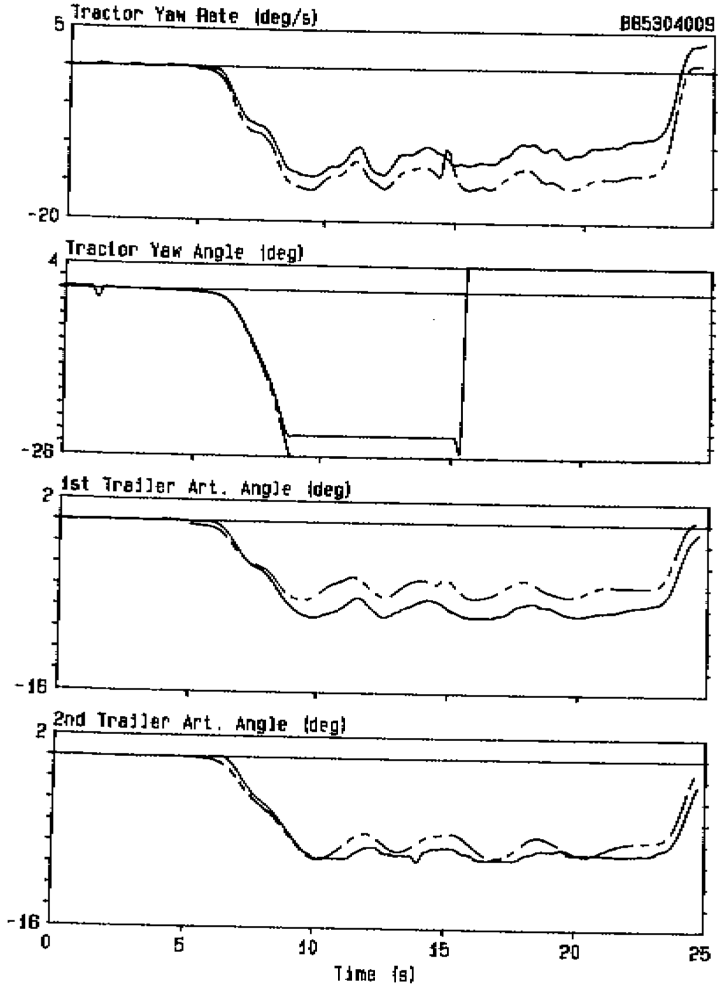

Figure 65/ Cont'd

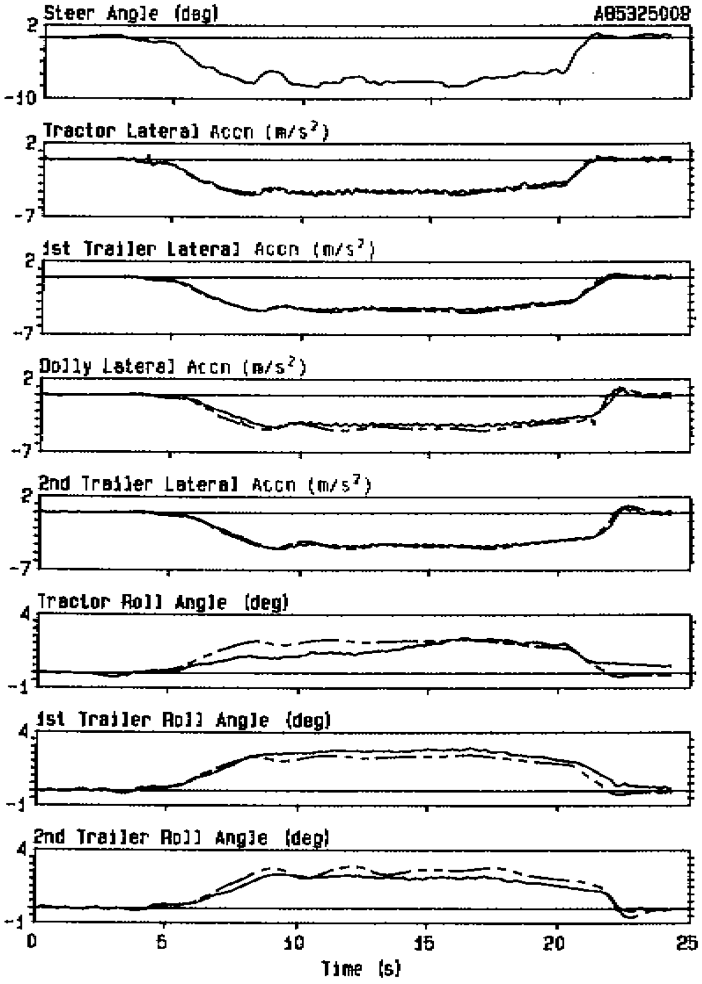

Figure 66/ C-Train Double, Steady Circular Turn Responses at 55 km/h

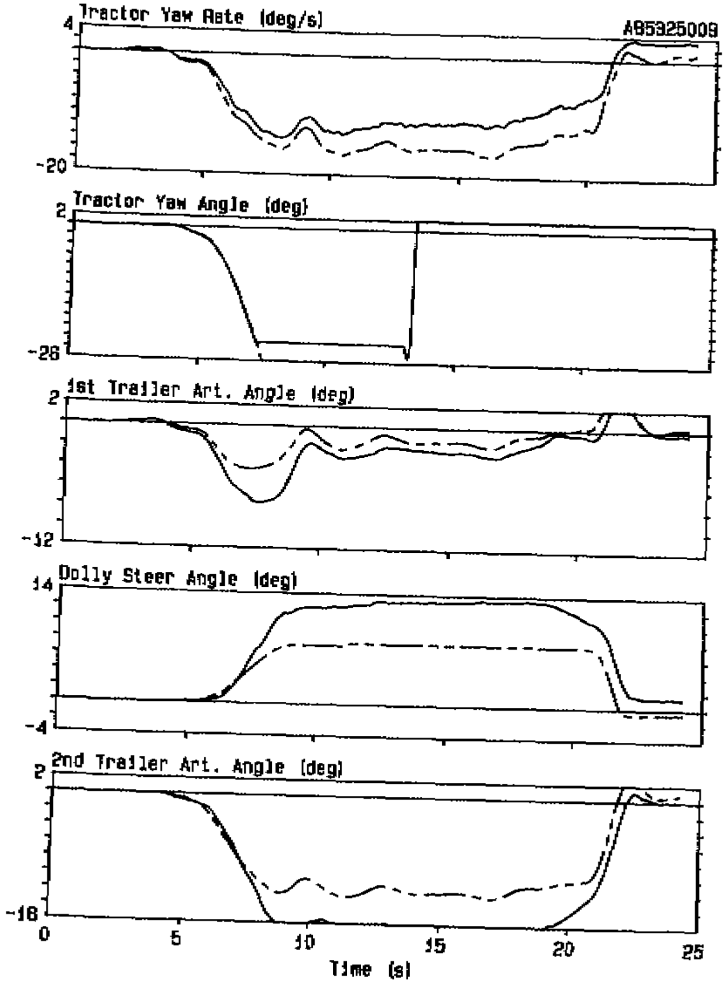

Figure 66/ Cont'd

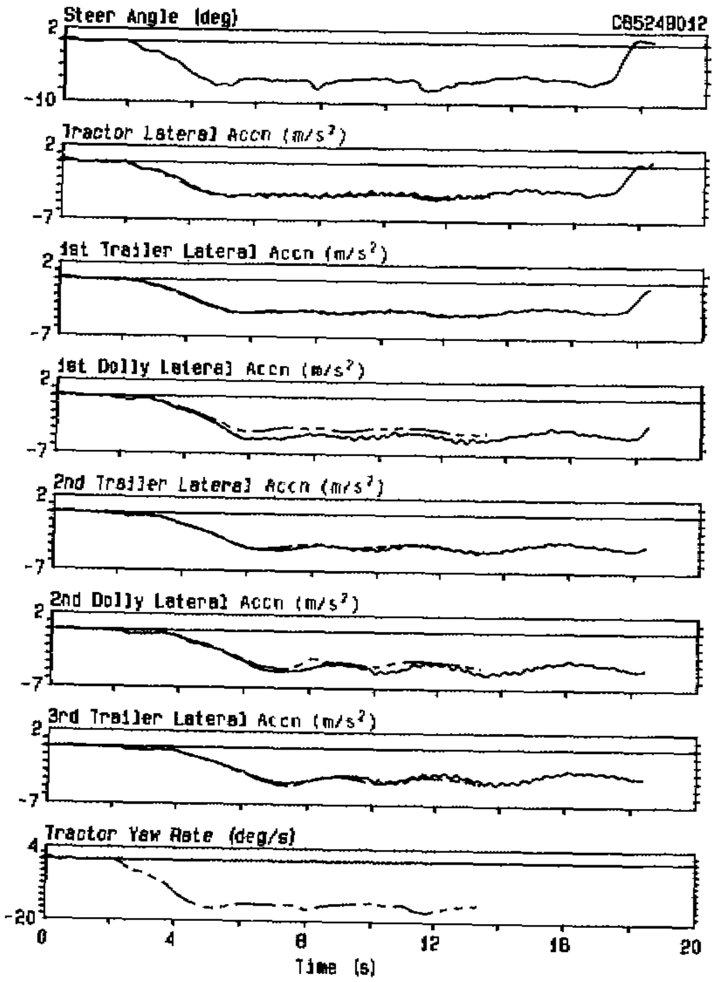

Figure 67/ A-Train Triple, Steady Circular Turn Responses at 55 km/h

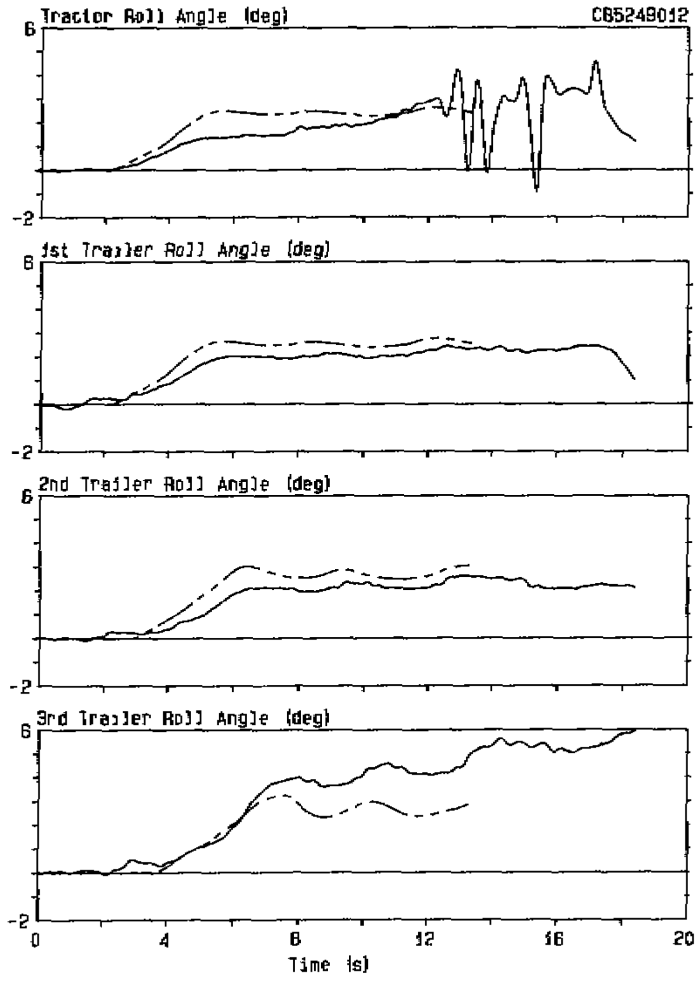

Figure 67/ Cont'd

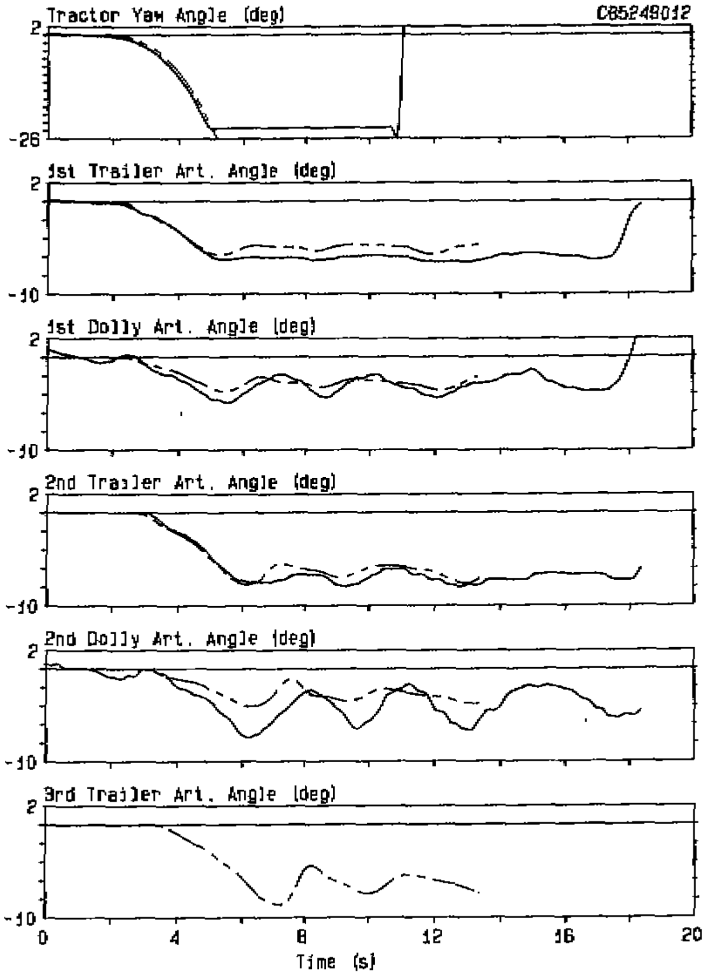

Figure 67/ Cont'd

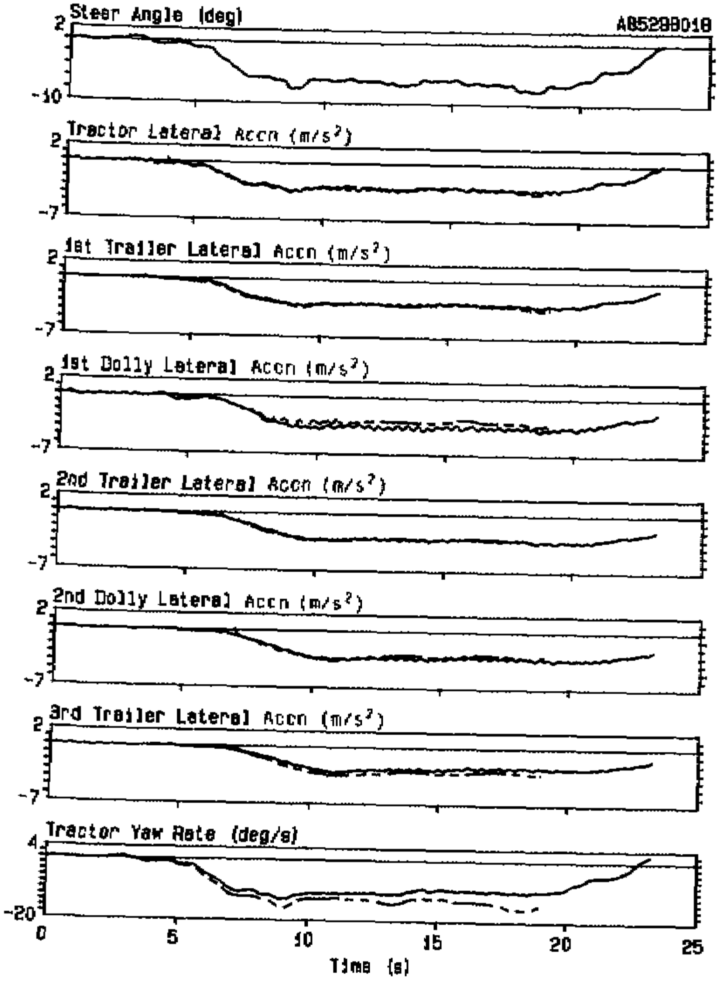

Figure 68/ C-Train Triple, Steady Circular Turn Responses at 47 km/h

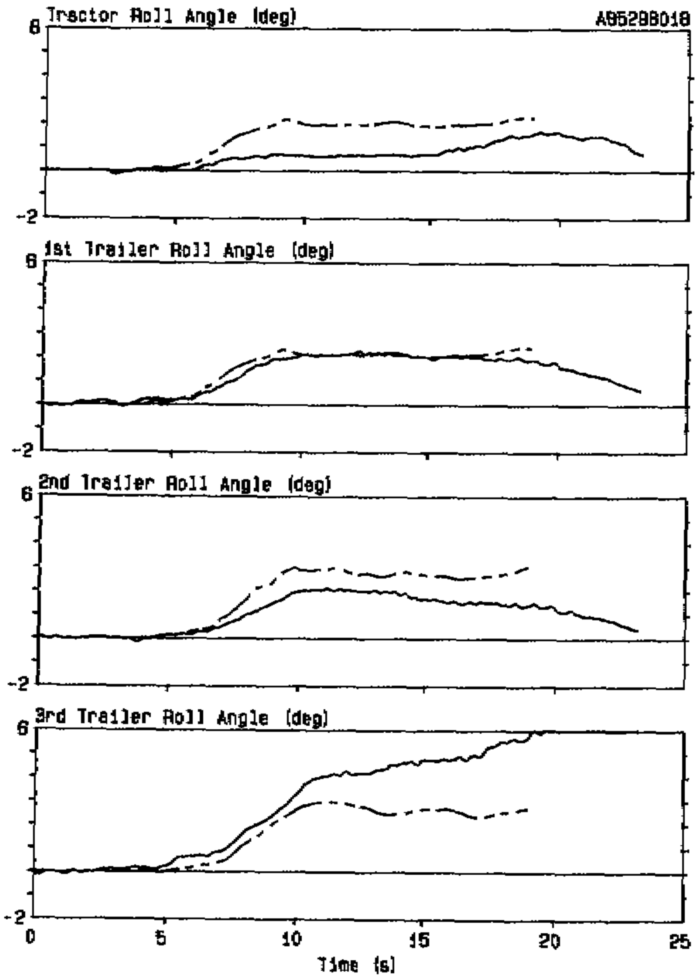

Figure 68/ Cont'd

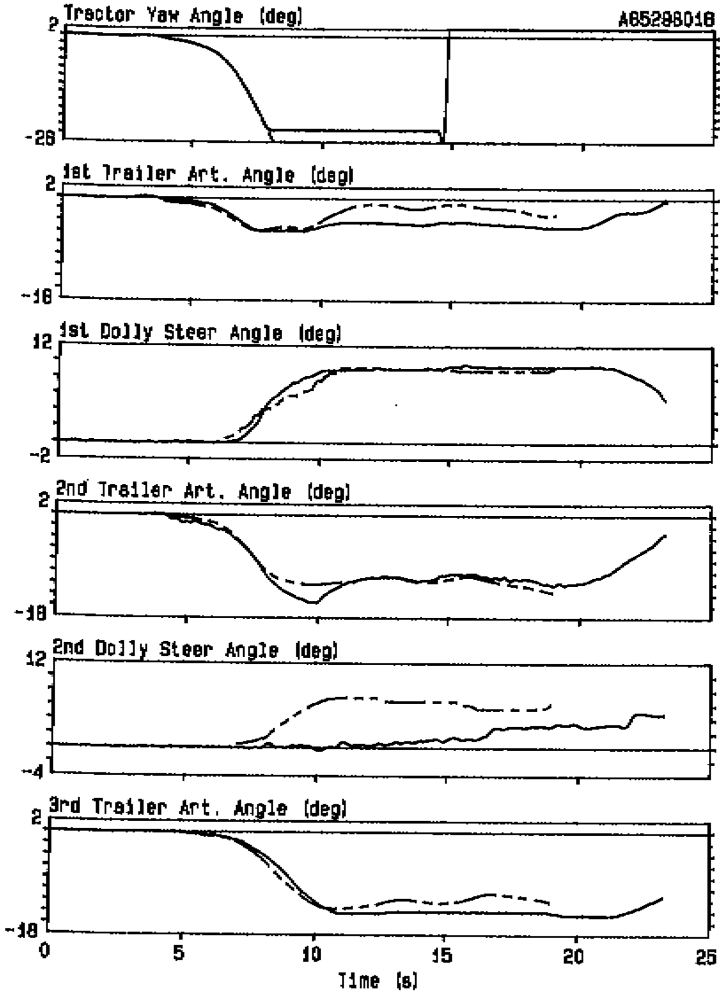

Figure 68/ Cont'd

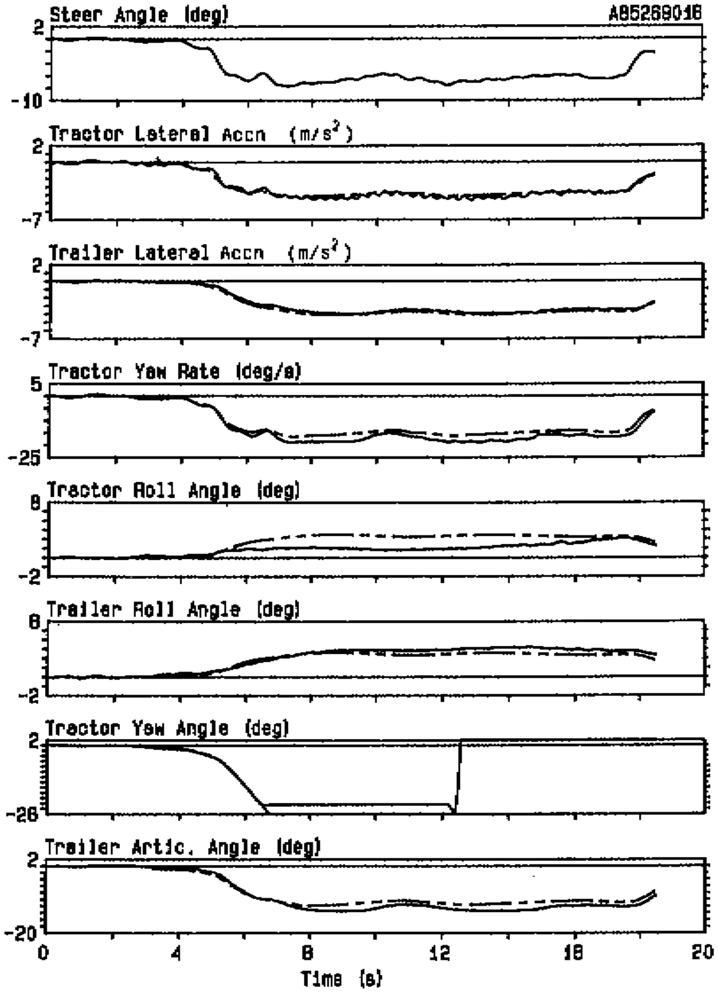

Figure 69/ 5-Axle 48 ft Semi, Steady Circular Turn Responses at 55 km/h

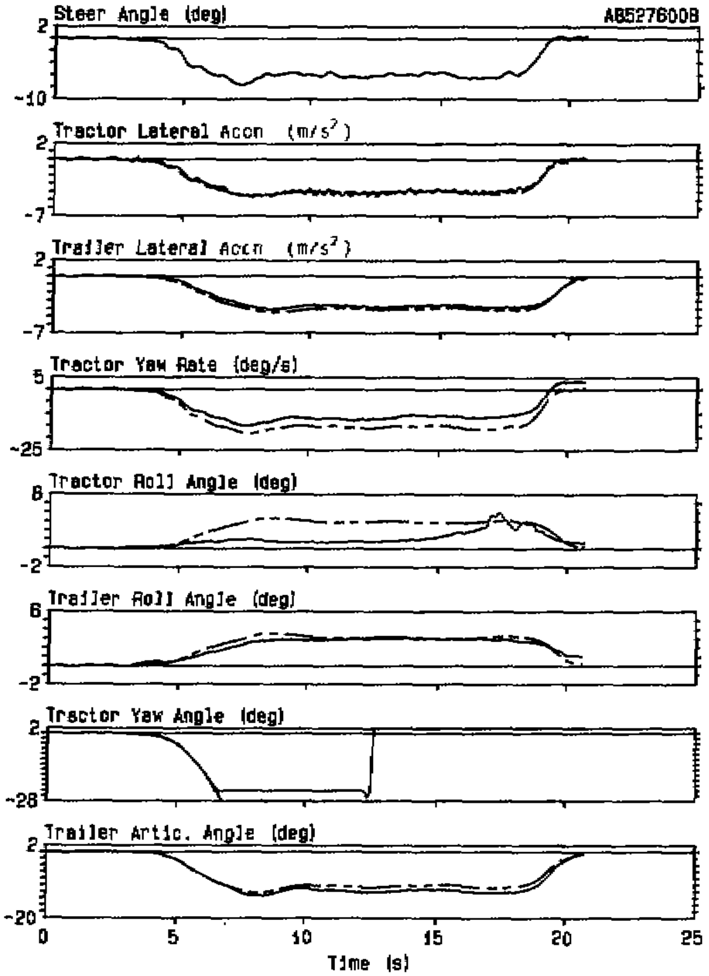

Figure 70/ 6-Axle 48 ft Semi, Steady Circular Turn Responses at 55 km/h

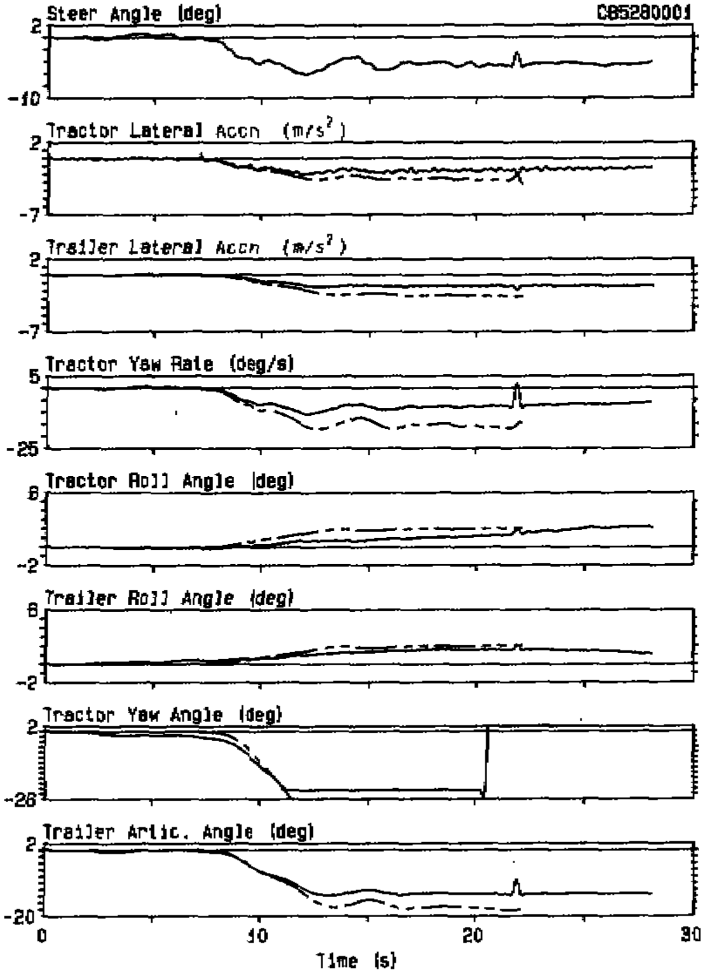

Figure 71/ 7-Axle 48 ft Semi, Steady Circular Turn Responses at 35 km/h

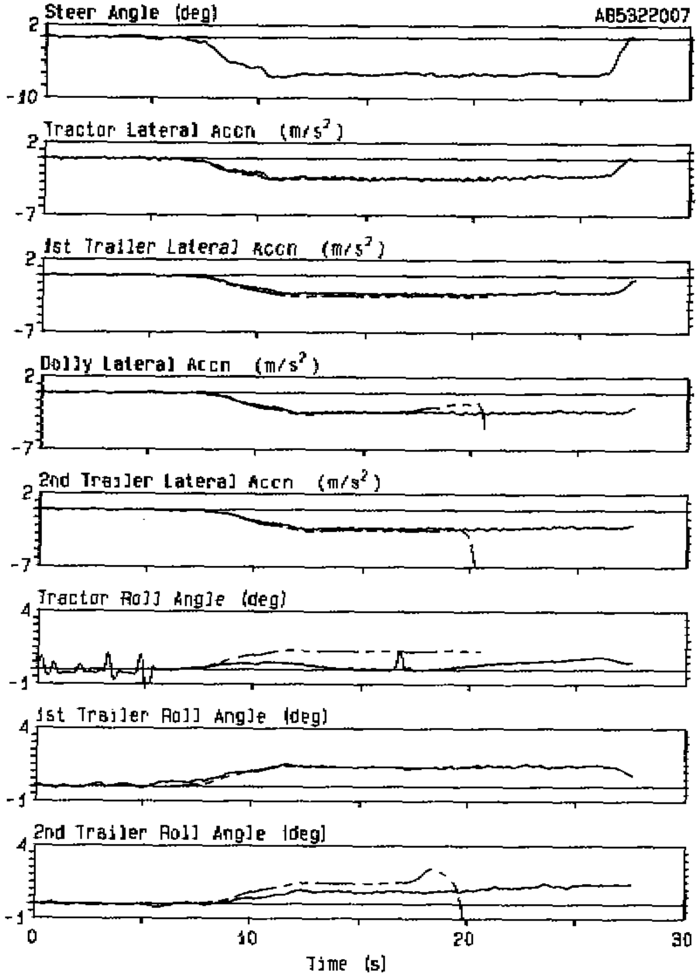

Figure 72/ A-Train Double, Steady Circular
Turn Responses at 47 km/h
(No Vertical Restraint)

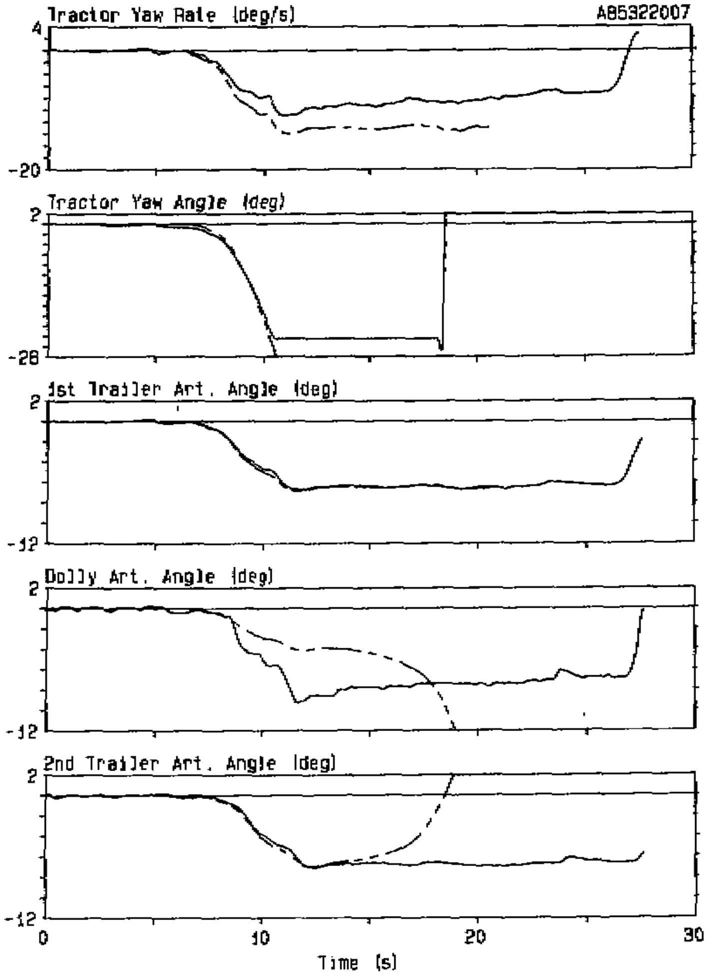

Figure 72/ Cont'd

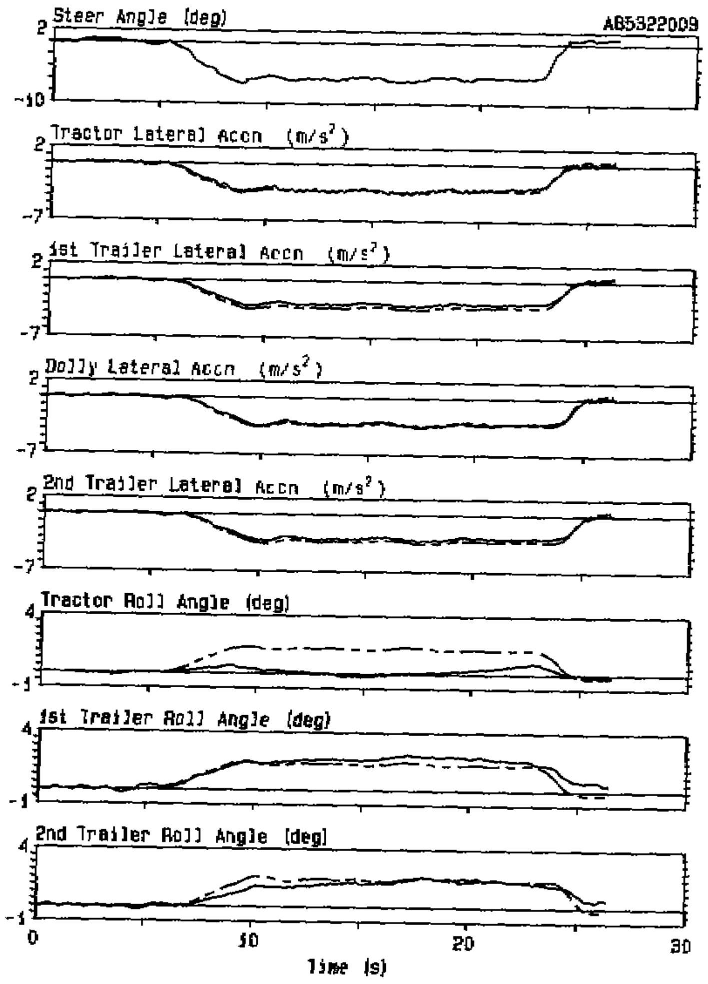

Figure 73/ A-Train Double, Steady Circular Turn Responses at 47 km/h (with Vertical Restraint)

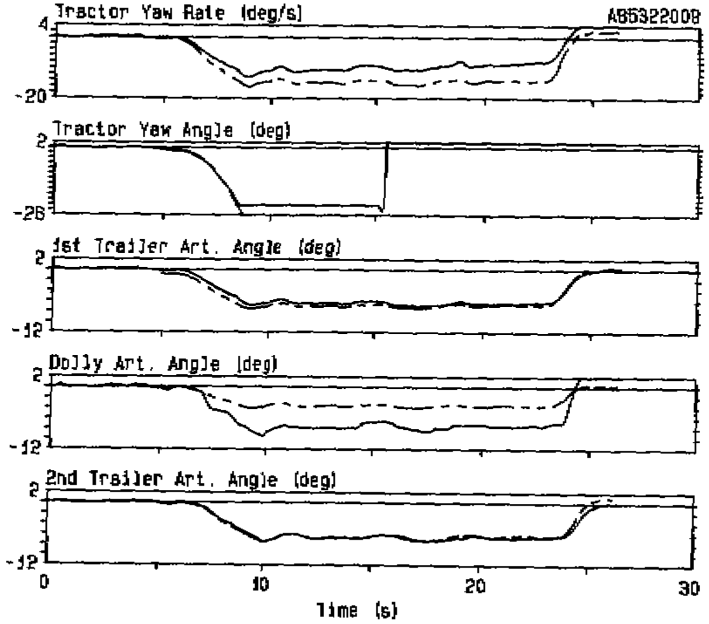

Figure 73/ Cont'd