Vehicle Weights and Dimensions Study

Volume 3

Demonstration Test Program: Summary of Tests of Baseline Vehicle Performance

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Summary of Tests of Baseline Vehicle Performance

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Abstract

A substantial program of full-scale heavy truck dynamic testing 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 tests of six baseline vehicle configurations: a tractor-semitrailer; A-, B-, and C-train doubles; and A-and C-train triples configurations.

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DISCLAIMER

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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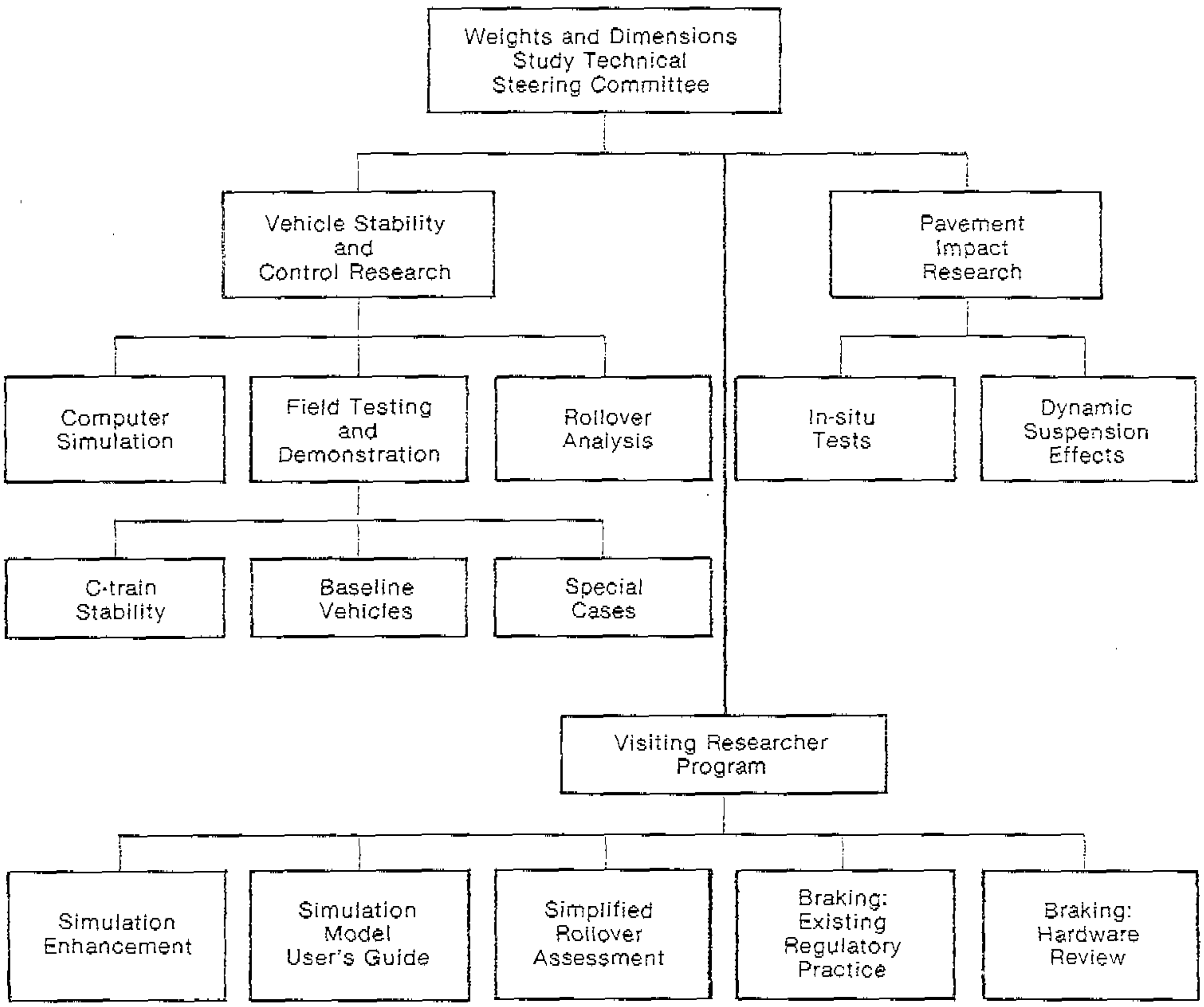
TECHNICAL WORK ELEMENTS OVERVIEW



Volume 3

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Summary of Tests of
Baseline Vehicle Performance

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This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson.

Test vehicles, tires, some vehicle movements, vehicle repairs, refurbishment, and other services were arranged by Mr. Pearson in support of this work.

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EXECUTIVE SUMMARY

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 Dimension Study. The objective of the study is to compile technical information to 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.

A baseline vehicle was selected to represent each of six major configurations: the tractor-trailer; A-, B- and C-train doubles; and A- and C-train triples. The Ontario Ministry of Transportation and Communications subjected each of these baseline vehicles to a standard series of tests for turning; the brake system; lateral/directional and roll stability; trailer sway; and a demonstration of straight-line braking.

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 a comprehensive computer simulation that was used to evaluate variations in weight, dimension, and equipment for the six configurations.

Vehicle turning performance depends primarily on trailer length and the number of trailers. It is not strongly dependent on the method of hitching. As trailer length or number of trailers increases, so does the space required to make turns.

Air brake system performance depends upon the number of vehicle units and selection and installation of components.

Lateral stability is strongly dependent upon vehicle configuration. The semi was the most stable, doubles were more stable than triples of similar configuration, and B- or C-trains were more stable than the A-train. This ranking follows the number of articulation points -- the more articulation points, the lower the stability.

EXECUTIVE SUMMARY (CONT'D)

Roll stability in a steady turn is essentially independent of vehicle configuration where vehicles have the same suspension, axle load, and centre of gravity height. The roll thresholds found for the steady turn were in good agreement with the roll thresholds found in a tilt test of the vehicle.

An extensive computer simulation using measured test inputs, actual vehicle dimension and mass properties, and generic suspension and tire data showed that responses of all vehicles could be predicted quite well both for individual runs and as a trend over a number of runs. Differences between simulation and test results often raised more questions about the interpretation of the measurement than the credibility of the simulation.

The specific results presented here apply to the vehicles tested for the particular test conditions. Results different in some respect might be expected for other vehicles or test conditions.

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 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.

This report presents a summary of the baseline vehicle tests. It will refer to reports describing test procedures common to all six vehicles [3], to the test results of the six baseline vehicles [4-9], and to a report describing the computer simulation results in comparison with the test data [10]. The content of this report is also summarized in a companion videotape, with narration, which illustrates the vehicle responses.

2/ TEST VEHICLES

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

The tractor-trailer family was represented by a 45 ft (13.72 m) semi. The A-, B-, and C-train doubles families were all represented by 8-axle combinations with two trailers, each with a bed length of 7.92 m (26 ft). Two triples families, the A- and C-trains, were represented by 8-axle combinations with three 8.53 m (28 ft) trailers. All equipment was typical of that used in at least one region of the country. The 45 ft (13.72 m) semi is a utility vehicle. The three doubles are all used for heavy haul and are closely comparable with each other from a usage standpoint. They are not comparable to the semi, because all provinces allow a higher gross weight for a combination with a greater number of axles. An operator whose primary business is moving heavy loads would tend to select the vehicle with the highest possible gross weight over a 5-axle semi. The triples are used only by special permit at relatively low gross weights, primarily for volume-limited cargo. While they are comparable with each other, they are not comparable either with the semi or the doubles by current usage. Clearly, if the triples were permitted higher gross weights than the doubles, they might be used in heavy-haul applications.

The test vehicle consisted of an MTC tractor [3] and the trailer or trailer combination being tested. The 1976 MTC Freightliner 6x4 was used for all except two turning tests. The 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 consists of a cab-over-engine chassis 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 4.40 m (174 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 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. 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].

A 1974 4x2 International Loadstar was used for two turning tests because it allowed the Freightliner to be available for other tests and vehicle preparation activities critical to the test schedule. This tractor is not typical at all of tractors which would haul the test trailers in interprovincial trucking. However, with a 3.81 m (150 in) wheelbase, and a fifth wheel 0.15 m (6 in) forward of the drive axle, its turning characteristics were regarded as sufficiently close to those of the Freightliner that the substitution was acceptable. Other specifications of this tractor are irrelevant to the test program, so are not presented.

No modifications were made to any equipment except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were slightly affected.

The empty weight of the vehicle as tested exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. The study set a target load of 8000 kg (17 600 lb) for all axles except for the steer axle.

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 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 17.77 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 (40 260 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 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 two-spring leaf suspension system with a torque rod. It had a spring centre width of 0.97 m (38.5 in), and the overall track 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 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 and 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 B-dolly was made up from an ASTL SSD frame, used in previous tests [11], and a Sauer model RLZ10041 automotive-type self-steering axle rated at 10 000 kg (22 000 lb) and placarded for a speed of 80 km/h. Suspension was a Reyco two-spring leaf 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 the specifications reported.

The trailers and dollies were manufactured by Trailmobile in February 1985 and were new. 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 line. 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 31.26 m (102.6 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 because of the nature of the cargo. All three trailers were loaded in the same fashion, consistent with normal practice. This caused the tractor drive axles to be less loaded than each trailer axle.

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 those used for the A-train triple, described in Section 2.5. The B-dolly from 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.

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

3/ TEST PROGRAM

3.1/ Test Facilities

Empty vehicle, low-friction surface tests were conducted at the Ministry of Transportation and Communications (MTC) Commercial Vehicle Test Facility (Centralia). This test facility is located at Huron Industrial Park, Centralia, 45 km (28 mi) north of London, Ontario. The test area includes a low-friction surface 200 m (656 ft) long with a wet skid number of about 18 to 24. A sprinkler system is used for continuous wetting of this surface. The test facility also has about 2000 m^2 (21 529 ft^2) of work space which was used for vehicle preparation and storage. It includes basic shop facilities, an electronics lab, office space, and a ground station for data acquisition and processing [3].

Loaded-vehicle, high-friction surface tests were conducted at the Transport Canada Motor Vehicle Test Centre, located at Blainville, Quebec, 35 km (22 mi) Montreal [3]. This facility was made available for the study by Transport Canada. In addition, tilt tests were conducted on the 45 ft (13.72 m) semi and the three doubles by others, using a tilt table installed for the study [12].

3.2/ Vehicle Preparation

The test trailers were equipped with the following:

- new tires
- outriggers
- safety cables
- instrument packages
- load

The trailers and dollies were fitted with new Michelin XZA radial tires, in load range H and size 11R22.5. These tires were run a nominal distance before any testing and were then, subsequently, used for all tests. Tire pressure was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load on all tires. This was used for all tests and represents the common operating practice of not reducing tire pressure when running empty.

Detachable beam-type underslung outriggers were specially designed, and three sets were fabricated for these tests, as can be seen in Figure 9. The outriggers were set with a ground clearance of 0.25 to 0.30 m

(10 to 12 in), which corresponds to a trailer roll angle of 6 to 7° at outrigger touchdown. Some local strengthening of flatbed trailers was conducted so that the structure could resist touchdown loads without permanent deformation.

High-speed dynamic testing of combination vehicles on a low-friction surface carries the hazard of tractor or dolly jackknife, or trailer swing. To prevent damage from such loss of control, safety cables were installed between each consecutive pair of vehicle units to limit articulation angles to about 20°.

Each vehicle was tested nominally empty, without payload, but equipped with instrumentation, outriggers, and safety cables. Each trailer therefore weighed about 1500 to 1800 kg (3300 to 4000 lb) more than it would on the highway.

Each vehicle was also tested at one nominal gross weight. This gross weight was achieved by loading trailers with concrete blocks, weighing about 936 kg (2060 lb) each. Blocks were tightly secured with chains.

Before testing, the vehicle was assembled in its test configuration, and the following additional measures were taken:
- The vehicle was checked for general mechanical fitness.
- Brake slack was checked and adjusted as necessary.
- Tire inflation pressure was set.
- Relevant vehicle dimensions were measured.
- The vehicle was weighed by axle, empty and loaded.
- Detailed measurements and an inventory of trailer structural numbers, fittings, and other components were made.
- Instrumentation was installed, as described in Section 5.2.
- The vehicle as a whole, parts thereof, and instrumentation installations were photographed and videotaped.

Detailed descriptions of vehicle preparation are presented elsewhere [3].

3.3/ Instrumentation

The MTC Freightliner has been used in many previous test programs. It was already equipped to measure the following driver inputs and vehicle responses:
- road wheel steer angle;

- speed;
- distance travelled;
- brake on/off;
- brake treadle valve pressure;
- brake chamber pressures;
- roll, pitch, and yaw angles;
- roll, pitch, and yaw rates;
- longitudinal, lateral, and vertical accelerations measured from an inertial platform;
- lateral load at the fifth wheel;
- an optical sensor for precise speed and position measurements;
- others, not required for this test program, such as steering wheel angle and rate, other wheel speeds, etc.

The tractor was equipped to control the instrumentation either by an automatic or a manual start that uncaged the gyroscope package, initialized the distance counter, commanded the data acquisition system through a calibration sequence, and finally returned it to data status. The automatic start was triggered by means of a downward facing optical sensor mounted beneath the tractor, which responded to a highly reflective tape marker placed on the ground a suitable distance ahead of the point where the test manoeuvre was to be made. This created a common start point, which simplified the development of computer data processing. Since the optical sensor would trigger on any light colour, it was normally inactive and was armed by the driver on the approach just before the starting marker.

Each trailer was instrumented to measure the following basic responses:
- articulation angle
- lateral acceleration
- roll angle
- outrigger touchdown
- brake chamber pressures

A single self-contained package housing the accelerometer and roll gyroscope, signal conditioning, multiplex system, and power supply formed the bulk of the instrumentation for each trailer. This package was mounted on the deck of the trailer midway between the kingpin and the centre of the trailer axles.

Each A-dolly was instrumented to measure the hitch articulation angle. Each B-dolly was instrumented to measure its axle steer angle by means of a rotary potentiometer. Each dolly also had an accelerometer installed to measure lateral acceleration at a point close to the trailer kingpin. A pressure transducer was also installed in a brake chamber for the brake tests.

Detailed descriptions of instrumentation are described elsewhere [3].

3.4/ Definition of Tests

The tests and demonstration conducted on all vehicles are broken down into four categories:

1/ Stationary
- Air brake system
- Tilt test

2/ Low-Speed Turns
- Steady-state offtracking
- Right-hand turn
- Channelized right turn

3/ Low-Friction Dynamic, Empty Vehicle
- Straight-line braking demonstration
- Evasive manoeuvre

4/ High-Friction Dynamic, Loaded Vehicle
- Sinusoidal steer
- Lane change
- Straight-line driving
- Steady circular turn

The following subsections present the rationale for each test and outline the procedure followed. Detailed procedures are presented elsewhere [3].

For all driving tests where a sequence of runs at increasing speeds was required, speeds were selected that resulted from the driver using full throttle in the appropriate gear. The engine speed control then acted as a limiter to hold speed to the required value. This was beneficial, as manual speed control at the stability thresholds proved to be difficult to maintain because of vehicle cab vibration, high drag during an aggressive manoeuvre, and driver work load. The actual speeds used in the various tests were 34, 40, 47, 55, 63, 72, 77, 80, 84, 89, and 94 km/h. The nominal speeds used by the driver were in miles per hour and differed somewhat from the actual values at the highest speed.

All tests except for the two right turns were conducted with outriggers and safety cables installed.

3.4.1/ Offtracking

The interaction of large trucks with highway geometrics was not specifically included in the study. It is, however, perhaps the most evident manifestation of increasing truck size to the motoring public in urban communities. Large trucks take more space and time to make turns than smaller trucks and, thus, appear to impede traffic. Three tests, therefore, were added to illustrate the space requirements needed for turns and to demonstrate the swept paths.

Steady-state offtracking is the most widely understood measure of the turning capability of large trucks. In normal driving, however, a steady-state offtracking situation would only likely be encountered in a 270° cloverleaf turn on a freeway ramp. In many cases these ramps are made up not of a principal circular arc with entry and exit spirals, but of several spirals and curves to accommodate the local space and terrain requirements. Trucks using these less regular ramps may not reach a true steady state. Nevertheless, steady-state offtracking provides a useful ranking of the space required to turn a large truck, though it may be somewhat misleading for some turns.

Steady-state offtracking was determined by driving the loaded vehicle on a high-friction surface at low speed, less than 5 km/h, in a circle of radius 29.87 m (98 ft). The turn was made with the truck on the inside of the circle with the tractor outer front wheel following the circumference. The vehicle traversed the circle until steady-state offtracking had been achieved and continued to about one full revolution. The distance from the centre of the circle to each axle's innermost tire was measured using a steel tape. The test was repeated in the opposite direction to determine if axle or chassis misalignment affected the results. The test course is shown in Figure 13. This test was conducted at Blainville.

3.4.2/ Right-Hand Turn

The 90° right-hand turn is probably the most demanding turning manoeuvre for large trucks. In urban areas, or where there are low truck volumes, small curb radii are often found. When a long truck comes to such an intersection, where the truck is too large to make the turn with a simple steady steer input by the driver, there are two strategies available to create more space for the turn. Either the driver can move to the left of the entry lane to increase the radius or ahead and intrude into lanes beside the exit lane in the roadway into which the turn is being made. In either case, the driver is using the space of other vehicles, which increases the hazard of the turn. In the first case, it is possible that the driver of a small vehicle also intending to turn right could misunderstand the truck driver's intention in the initial move to the left and become trapped to the right of the truck as the vehicle started to turn to the right. This strategy is, therefore, considered undesirable. The second strategy also uses the space of other vehicles, but at least the presence and intention of the truck are clear throughout, and the truck driver would not normally enter that space if oncoming vehicles were too close.

Vehicle trajectory in a right-hand turn was evaluated using a 15 m (49 ft) curb radius, with entry and exit lane widths of 3.66 m (12 ft), as shown in Figure 14. This has been used in highway geometric design standards for many years for turns from a two-lane two-way road into a four-lane two-way road, where the vehicle may exit in the left-hand lane rather than the right-hand lane. The drivers task is to approach the turn in the entry lane and make the "best" turn possible to exit ultimately in the right-hand exit lane. The "best" turn is a turn that in the opinion of the driver and the test director caused the rearmost axle right wheel to track parallel and as close to the circumferential curb as possible. The swept path of the tractor left front wheel, and rear trailer right rear wheel, were marked with marker cones on the rays shown in Figure 14. When the "best" turn was achieved, the positions of the cones were measured, and hence, the turn swept path was recorded. This test was conducted at Centralia. The MTC International tractor was used as the power unit for all vehicles, and the trailers were empty.

3.4.3/ Channelized Right Turn

Vehicle trajectory in a channelized right-hand turn was evaluated using a 25 m (82 ft) curb radius with a channel width of 5.5 m (18 ft). Entry and exit lane widths were 3.66 m (12 ft), and deceleration and acceleration taper lengths were 75 and 50 m (246 and 164 ft), respectively. The overall course, with island geometry, is shown in Figure 15. This is a typical highway geometric design standard for use in urban areas, where property presents a constraint problem and speeds are low. The taper lengths assume entry and exit roadway speed limits of 60 km/h. The turn might be superelevated and would have an advisory speed limit of 25 or 30 km/h.

This test was conducted at Centralia, with the MTC International used as the power unit for all vehicles and the test trailers empty.

This procedure results in measurement of the transient offtracking of the vehicle during passage through the channel, with the tractor following the most favourable line. In practice, there would be a gutter, perhaps 0.30 m (1 ft) wide on the left-hand side, which the driver would not normally use, and the turn might well be made at a speed when the lateral acceleration would tend to reduce the offtracking. Of course, in a congested traffic situation the turn could also be taken at a very low speed.

3.4.4/ Air Brake System

Balanced braking of a combination vehicle requires that the brake systems of all vehicle units be compatible so that pneumatic and torque balance can be achieved at each axle. In addition, short brake application and release times provide a brake system responsive to the driver's needs and reduce stopping distance and fuel consumption. Pneumatic balance and brake timing are both determined by the details of the air brake system, valves, and plumbing. Torque balance is determined by the foundation brake characteristics and axle loads and is a much more complex subject. A comprehensive treatment of the braking characteristics of combination vehicles was beyond the scope of the study. The issues of air brake system compatibility, however, are much more straightforward and could be illustrated by two tests.

1/ The first test follows the style of SAE Standard J982a for timing of the air brake system of a single vehicle unit. The test was, however, applied to the entire vehicle as an operational combination. It uses a maximum rate brake application, with a regulated air supply at 689 kPa (100 psi), and the time for the air pressure at each axle to reach 413 kPa (60 psi) is determined. The individual pressures at each axle are also found. Pressure differentials can cause differences in torque between axles, affecting the overall brake balance. Brake release times, which affect the drag on combination vehicles, were also determined. This test is very aggressive, as the high airflow rate might, for instance, overcome "sticky" valves that would take a significant pressure differential to crack. This test represents the rare emergency brake situation where maximum performance is demanded.

2/ The second test was a service brake application, with treadle valve travel limited to provide about 118 kPa (20 psi) with a 689 kPa (100 psi) supply and a normal rate brake application. The timing and pressure differentials in this test illustrate how the air system behaves in normal use, the usual case.

This test was conducted at Centralia with the vehicle stationary.

3.4.5/ Straight-Line Braking Demonstration

The action of braking an empty combination vehicle to a halt on a low-friction surface may result in loss of vehicle control if the wheels are locked. The physical characteristics of current braking systems make it extremely difficult to conduct rigorous tests and obtain repeatable results that can be generalized to other vehicles. A series of straight-line stops was therefore conducted to demonstrate modes in which vehicles may become unstable.

In this demonstration the vehicle was driven onto the wet low-friction test area at 47 km/h and braked to a halt. A series of runs was conducted with increasing brake application until all wheels of an axle group locked. The driver was allowed to steer as necessary to keep the tractor within the traffic lane. The speed was high enough that incipient unstable behaviour was always evident but not so high as to cause violent behaviour.

The primary results of this test were videotapes showing the vehicle's response to the braking input.

This test was conducted at Centralia.

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3.4.6/ Evasive Manoeuvre

This test is representative of an obstacle avoidance manoeuvre on a two-lane, two-way highway, where the sudden appearance of an obstacle necessitates a fast lane change to the left, then return to the original lane to avoid oncoming traffic. The test course was laid out on a wet low-friction surface, using marker cones as shown in Figure 16. The driver was instructed to negotiate the course at constant speed and manoeuvre the empty vehicle through the gates, without loss of control or contact of any of the cones by the vehicle. A sequence of runs was conducted at increasing speeds until the vehicle became unstable due to tractor jackknife, trailer swing, dolly jackknife, or trailer response resulted in a 1 m (3.3 ft) slide out of lane. Runs were repeated when responses were found to be inconsistent with the trend established by preceding runs, or when any marker cone was struck. When a run was made in which the vehicle response was unstable or undesirable, corroborating runs, varying by no more than 3 km/h, were conducted to bracket the stability boundary.

This test was conducted at Centralia. It was originally proposed as a lane-change manoeuvre, which is described in Section 3.4.8. However, this task did not sufficiently exercise most vehicles because the critical gate size for the most challenged vehicle had to be used. In the experience of ministry test staff, speeds in excess of 63 km/h were unduly hazardous for an empty vehicle equipped with safety cables on the wet low-friction surface. While the test area was provided with a high-friction shoulder, it was considered that the energy and momentum in total loss of control of a double or triple at any higher speed would be unnecessarily hazardous. Experience has shown that while the test driver is able to duplicate such manoeuvres consistently, the mode of loss of control may not be predictable, so speeds had to be limited for reasons of safety and preservation of equipment. A symmetrical gate arrangement was selected, and the gate size was the minimum that could be negotiated by the most critical vehicle at a speed below the 63 km/h safety limit.

3.4.7/ 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, a vehicle trajectory similar to the lane change described in Section 3.4.8. The lane change is constrained within a 3.66 m (12 ft) lane, whereas the sinusoidal steer results in a variable sidestep depending upon the speed and steer amplitude. The object was to achieve a tractor lateral acceleration of about 0.15 g.

This steer input is a standard method by which lateral/directional response of the vehicle could be excited. The input was chosen to be large enough to get a reasonable response from the vehicle, but not so large that units of the most responsive vehicles would be sliding or rolling excessively. This steer input permitted the lateral acceleration of each trailer of a combination vehicle to be examined, relative to the tractor lateral acceleration. These acceleration ratios, properly known as rearward amplification of lateral acceleration, are an important inherent dynamic characteristic of combination vehicles. An acceleration ratio no greater than unity means the trailer has a lower acceleration than the tractor, so the driver may be considered aware of vehicle response as he is in a position to sense the greatest acceleration in the vehicle. An acceleration ratio greater than unity means a trailer has a higher lateral acceleration than the tractor, and if the ratio and tractor lateral acceleration are high enough, the trailer may slide or roll over even though the driver feels the tractor is still fully under control.

A vehicle that has a higher rearward amplification than another has greater response per unit steer input. This means that it is more sensitive, or less stable, in its lateral/directional dynamic characteristics. This test, then, examines the inherent dynamic stability of the vehicle, an important property.

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 of 4, 3.5, 3, 2.5, and 2 s were used. A true-tracking, sinusoidal input computer program for the Freightliner, using a 37.5:1 steer ratio, provided the necessary steer amplitudes to generate approximately 0.15 g lateral acceleration at the tractor for each speed and steer period tested. These amplitudes were provided to the driver by means of indicators on the steering wheel.

Since it was considered somewhat difficult for the driver to estimate and perform a steer input of specific period, an electronic cueing device was developed. The steer period generator (SPG) permitted the driver to select the desired steer period by means of a switch, in increments of 0.5 s. Immediately after the gyroscope was uncaged, the driver would start the SPG and follow a light sequence given by a display module to achieve the correct steer period. This allowed the driver to conduct the test in an orderly manner without the need for wasted runs to achieve a particular period by a series of trials.

This test was conducted at Blainville.

3.4.8/ Lane Change

The lane change on a standard highway requires a steer input by the driver that is 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 17. 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 gates 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 trailer swing, or trailer response resulted in a 1 m (3.3 ft) swing out of lane. The sinusoidal steer test described in Section 3.4.7 is a subcritical test, designed to display the dynamic characteristics of a vehicle. This test takes basically the same manoeuvre as the sinusoidal steer, executed at the limits of stability of the vehicle to demonstrate the mode by which it becomes unstable. The cone layout imposes a limit on the driver and ensures repeatable results.

Runs were repeated when responses were found to be inconsistent with the trend established by preceding runs or when any cone was struck. When a run was made in which the response was unstable or undesirable, corroborating runs, varying by no more than 3 km/h, were conducted to bracket the stability boundary. The test was terminated if the vehicle reached 100 km/h, a typical maximum legal speed in provinces of Canada, and was still able to make the manoeuvre successfully.

This test was conducted at Blainville.

3.4.9/ Normal Straight-Line Driving

The trailers of combination vehicles tend to sway a small amount in straight-line driving due to road roughness, aerodynamics, suspension characteristics, and normal small steer corrections by the driver. This sway is related to vehicle configuration in the same way as rearward amplification of lateral acceleration. Some jurisdictions impose a 75 mm (3 in) sway amplitude limit on trailers. The limit, however, is non-specific because it is not related to the input to the vehicle. It is also difficult, if not impossible, to enforce because the sway cannot be realistically measured with current technology.

This test was conducted at Blainville.

3.4.10/ Steady Circular Turn

A loaded vehicle can roll over in a steady turn if its speed and adhesion is high enough. Such a situation typically occurs for vehicles with a high centre of gravity when driven at excessive speed on a freeway ramp. Dynamics are involved in such accidents, due to braking, steering, or both, as the driver attempts to negotiate the ramp. However, the essential mechanism involved is that of rollover in a steady turn, which is an important inherent stability characteristic of a vehicle. This test examined that characteristic.

Static rollover characteristics of all vehicles tested, except the triples, were examined in a parallel part of the Vehicle Weights and Dimensions Study conducted by Centre de Recherche Industrielle du Quebec (CRIQ), using a tilt table built for this purpose. The tilt test provides static roll characteristics of a vehicle. Vehicles were provided to CRIQ staff, loaded to MTC specifications. Outrigger outer sections were removed to get the vehicle onto the tilt table. The tilt table was equipped with load cells located strategically beneath wheel groups on each side of the vehicle. Axles and the vehicle body were suitably restrained, and tilt meters were attached. The table was then tilted until enough axles on the high side of the vehicle had lifted for the vehicle to be deemed to have reached the rollover point. Results of the tilt tests have been presented separately by CRIQ [12]. It may be presumed that these results would be related to the rollover characteristics obtained in a circular turn.

The steady circular turn course was laid out using traffic cones on a dry high-friction surface, as shown in Figure 18. The circle had a radius of 50 m (164 ft) and was approached along a tangent leading to a 100 m (328 ft) long 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 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. Sufficient runs were made to characterize the vehicle roll response as a function of 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 outrigger clearance settings varied somewhat between vehicle units and vehicles, because of attachment and adjustment limitations. More important, however, were the differences in suspension stiffness and longitudinal stiffness between vehicles. The A-trains could clearly roll over the rear trailer. In others, outrigger touchdown may occur, but the entire vehicle could still be short 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 was, therefore, considered more informative to characterize responses as a function of speed rather than simply establishing an arbitrary outrigger touchdown point.

This test was conducted within the vehicle dynamics area at Blainville.

3.5/ Data Capture

The data acquisition system consisted of multiplex systems mounted in the sleeper portion of the MTC Freightliner and instrumentation boxes on the trailers. Electrical signals produced by the transducers were conditioned by individual plug-in-type adapter cards within the multiplex unit. The conditioned output signals were transmitted from each multiplex system to a control unit in the tractor, where they were digitized at a rate of 100 samples/s for each channel and transformed into a pulse-code modulated (PCM) data stream in a standard IRIG format. The PCM data stream was broadcast by a radio telemetry system from the tractor to a ground station, using a radio frequency licensed to the ministry for use at both Centralia and Blainville.

The ground station was located in the MTC building at Centralia. All of the essential elements of the ground station were subsequently installed in a bus, which served as the ground station during tests at Blainville.

The ground station received the PCM data stream and recorded it in analog form on an instrumentation tape recorder. IRIG B time code was recorded on a second track of the recorder so that the location of a particular run could be found easily if data playback was required. This recording was for archival and backup purposes.

The PCM data stream was processed by a decommutator, which formatted it into a bit parallel, word serial, input stream for an Hewlett-Packard HP-1000 A700 computer in the ground station. The computer read each run in real time and created a raw data file on disk for subsequent processing. The project engineer at the computer graphics terminal had access to a quick-look display that provided an overview of system status functioning and data quality while the run was in progress. The raw data were reviewed by the project engineer on a graphics display, to determine whether all critical data channels were functioning correctly and whether the run appeared to meet the specified test conditions. The raw data file was then read, electronic calibrations were applied, each channel was converted to engineering units, and a calibrated data file was created. Characteristic responses were derived, and those critical to the test were displayed to the project engineer. These were used to radio recommendations for the next run to the test director on the track.

Before each test session, an electronic calibration of the entire data acquisition system was conducted. Any system requiring adjustments was identified and corrections made, and a second calibration was recorded. Before each test run, the control unit on the tractor was made to step automatically through a calibration sequence. This was recorded as part of the run data, to permit current system calibrations to be used for each run.

Each run was recorded on colour videotape, from the vantage point of a cherry picker parked adjacent to the manoeuvre approach, from other vantage points of interest, or both. Each videotape showed the day and run numbers, so that it was positively identifiable. The audio track of the video system was used to record ambient noise during testing, including incidental radio transmissions and comments.

Still colour photographs and colour slides of the vehicles, equipment, and activities were also taken. Manual notes and logs of all test conditions and observations were made. A log of all test runs was maintained within the computer.

A detailed description of data capture is presented elsewhere [3].

3.6/ Data Processing

At the beginning of each day, certain data files and procedures were initialized within the HP-1000 computer system. Data from each run were captured in real time by the HP-1000 and processed concurrent with testing, as described previously. After each test session, all raw data files; other files created in support of the data processing process; and all data input files which controlled the data processing were archived to a tape. The archived tape was indexed and complete, so that the processing of any particular run could be reconstructed.

Upon completion of the test program, all data processing procedures and supporting data files were exhaustively reviewed, and necessary enhancements were implemented and validated. Every run was also carefully reviewed, and those runs that did not meet the particular test objective, or were otherwise so flawed that the data could not be processed, were discarded.

Data processing proceeded in four phases:
1/ raw data correction
2/ calibration
3/ treatment
4/ extraction of results

The first phase, raw data correction, corrected any data frames in which telemetry dropout occurred. This resulted in partial loss of the frame during which dropout occurred, total loss of an unknown number of complete frames, and capture of one or two scrambled frames while the computer data acquisition was regaining synchronization with the decommutator. Runs were rejected in which there occurred frequent dropouts or dropouts during the manoeuvre.

Calibration proceeded in two phases. As previously mentioned, the onboard data acquisition system was commanded through an electronic calibration sequence at the beginning of data acquisition for each run. The calibration sequence consisted of approximately 0.5 s of each of negative full scale, zero, and positive full scale. This calibration was used on every run to modify the value used for conversion to engineering units, the second phase of calibration.

The term "treatment" is used for the sequence of operations whereby the calibrated data were processed so that specific quantities of interest for a particular test could be derived. Some of these operations were applied to the output of a particular instrument, while others were used rather generally on various types of data. The following treatments were used in data processing:

1/ transformation of speeds of all instrumented wheels to the speed of the tractor right front wheel;
2/ transformation of the sawtooth wave distance measurement to actual distance;
3/ correction of trailer lateral accelerations for the gravitational effect of roll angle;
4/ integration of yaw and roll rates to yaw and roll angles, respectively;
5/ detrending of data to remove zero offsets and drift;
6/ filtering of data to remove unwanted frequency content.

The final phase of data processing was extraction of results. The method used depended entirely on the test being processed. Details of the methods are presented elsewhere [3].

4/ PERFORMANCE MEASURES

The various vehicle configurations are evaluated across the entire study, using various performance measures. Some of these performance measures are addressed by simulation or analysis of various kinds, others by test, and some by both.

The following performance measures provide the basis of what will be considered from tests:

1/ steady-state roll characteristics, derived from circular turn manoeuvres for loaded vehicles;
2/ dynamic roll threshold, derived from lane-change manoeuvres for loaded vehicles;
3/ roll mode characteristics, from the manoeuvres of 1 and 2;
4/ rearward amplification of lateral acceleration, from sinusoidal steer and lane-change manoeuvres;
5/ yaw/directional stability (jackknife and trailer swing), derived from evasive manoeuvres with an empty vehicle on a low-friction surface;
6/ straight-line trailer sway for loaded vehicles;
7/ vehicle stability characteristics in straight-line emergency braking, empty on a low-friction surface;
8/ high-speed offtracking, derived from the steady circular turn;
9/ lateral loads at the tractor fifth wheel, derived from the steady circular turn, lane-change manoeuvres, and the sinusoidal steer input;
10/ yaw response gains and lag times;
11/ vehicle speed at lateral/directional and rollover stability thresholds;
12/ steady-state offtracking;
13/ swept paths in typical right-hand turns;
14/ air brake system application, release timing, and pneumatic balance.

These performance measures were computed from the measured data by the HP-1000 computer, as described previously. The values were stored in a file indexed by run, making it possible to display vehicle response characteristics against input parameters, for purposes of test management and data analysis.

5/ RESULTS

5.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [3]. A typical situation is shown in Figure 19.

The results are shown in Table 7. The 45 ft (13.72 m) semi has large offtracking because of the length of the trailer and the rear placement of the bogie. The three doubles all have much less offtracking because of their short trailers and additional articulation points. The B-train has greatest offtracking of the three because of the rearward location of the turn centre of its lead trailer. The C-train has slightly less offtracking than the comparable A-train, as found previously [11], and the same result pertains for the two triples. The differences within the three doubles, and the two triples, which are attributable to the method of hitching, are not regarded as of great practical significance in their turning requirements.

The measured data for all vehicles, shown in Table 7, were compared to data generated by a simple offtracking formula [13]. The difference between actual and computed values was always less than 0.5% for all axles, which is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

Table 7/ Offtracking at Rear Axle

Vehicle	Offtracking (m)
45 ft semi	2.65
A-double	1.45
B-double	1.69
C-double	1.35
A-triple	2.77
C-triple	2.52

5.2/ Right-Hand Turn

A right-hand turn at an intersection is a demanding manoeuvre for a large truck. The vehicle's swept path was measured according to the standard test procedure [3], in a 90° right-hand turn of 15 m (49 ft) radius. This radius is typical in an urban area or in areas of limited truck traffic. The driver was asked to make the best turn possible, without moving to the left out of the entry lane, and ending ultimately in the curb lane of the exit roadway. The driver manoeuvred the tractor to make the turn with the inner wheels of the last axle of the vehicle tracking closely around the curb. This required the driver to pull forward into available space beside the exit lane to create room for the turn. The driver then made a complex steer input to accomplish the turn. A typical vehicle is shown in Figure 20 during the turn.

The maximum excursion out of lane and the length of that excursion are presented in Table 8. The doubles barely intruded into the lane adjacent to the exit lane, whereas the semi required more than half of it, and the triples required all that lane and a little more. While this turn is very different than offtracking, the ranking of vehicles is the same for both. This test was conducted at a creep speed and represents the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

Table 8/ Right-Hand Turn

Vehicle	Maximum Excursion Out of Lane (m)	Length of Excursion (m)
45-ft semi	2.20	19.20
A-double	0.40	7.50
B-double	0.90	18.00
C-double	0.80	8.40
A-triple	3.80	19.40
C-triple	3.70	22.00

5.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [3]. The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. Such roadway geometrics may restrict access of the largest vehicles.

A typical vehicle is shown during the turn in Figure 21. The minimum clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Table 9. The doubles made it easily through the channel, the semi had less clearance, and the triples had very little clearance. The tractor left front wheel was following the curb, whereas a driver would normally leave some clearance on this side. This would cause the triples to be very close to running over the inside curb.

The test was run at creep speed, the worst condition, as the effect of lateral acceleration is to reduce the geometric offtracking measured in this test. However, this roadway geometry is used at busy intersections where traffic may not always be free-flowing, so the test may be considered realistic.

Table 9/ Channelized Right Turn

Vehicle	Curb Clearance (m)
45-ft semi	0.89
A-double	1.85
B-double	1.55
C-double	1.66
A-triple	0.51
C-triple	0.18

5.4/ Air Brake System

The air brake system of the combination was evaluated according to the standard test procedure [3].

The trailer air brake system was inspected; slack adjusters were adjusted to the minimum, about 32 mm (1.25 in) stroke on each axle; and pressure transducers were installed at all trailer and dolly axles. The tractor was supplied with shop air, regulated at 689 kPa (100 psi).

The SAE J982a style test was performed on the A- and C-train triples. The tractor-trailer was evaluated when air to the first dolly was shut off; the double, when air to the second dolly was shut off; and the full triple combination, when opened. The results of these tests are presented in Tables 10, 11, and 12. The results are the average of several tests in each case, with a time resolution of 0.02 s. A typical time history response of application and release for each triple is presented in Figure 22.

Table 10/ Air Brake Timing, Semi of Triples

Location	Application Timing 0-60 psi (s) A-Train	C-Train	Release Timing to 5 psi (s) A-Train	C-Train
Treadle	0.02	0.05	0.18	0.14
Axle 2	0.36	0.37	0.58	0.57
Axle 4	0.37	0.37	0.78	0.75

Table 11/ Air Brake Timing, Double of Triples

Location	Application Timing 0-60 psi (s) A-Train	C-Train	Release Timing to 5 psi (s) A-Train	C-Train
Treadle	0.03	0.08	0.17	0.16
Axle 2	0.37	0.38	0.57	0.56
Axle 4	0.55	0.76	1.41	2.06
Axle 5	0.59	0.96	1.47	2.19
Axle 6	0.67	0.85	1.51	2.12

Table 12/ Air Brake Timing, Triples

Location	Application Timing 0-60 psi (s) A-Train	C-Train	Release Timing to 5 psi (s) A-Train	C-Train
Treadle	0.07	0.11	0.18	0.16
Axle 2	0.37	0.39	0.58	0.56
Axle 4	0.54	0.96	1.42	3.68
Axle 5	0.57	1.25	1.50	3.78
Axle 6	0.85	1.52	1.92	3.98
Axle 7	0.95	1.70	1.95	4.00
Axle 8	0.97	1.57	2.05	4.08

Two interesting comparisons arise from these three tables. The first arises when examining the effect of adding trailers progressively for the A-train. As a semi (Table 10), application times for tractor and trailer were both 0.37 s, an ideal situation. When the second trailer was added (Table 11), the first trailer application time was prolonged to 0.55 s. When the rear trailer was added (Table 12), the second trailer application time was increased from 0.67 to 0.85 s. As each trailer was added, only the preceding trailer was affected. The plumbing and valves limited feedback to one trailer only. Similar results pertain for the release times.

The A-train dollies both had booster relay valves to speed the signal to the subsequent trailers. The C-train was not so equipped. Table 10 shows that application times for the A- and C-trains are the same within test errors, as these were the same combination tested at different times. When additional trailers were added, however, the benefits of the booster relay valve becomes apparent. Brake application time for the C-train double is 0.85 s, 27% longer than for the A-train, and it is 1.57 s for the C-train triple, 62% longer than for the A-train. Not only does the booster relay valve decrease both application and release times, it inhibits the third trailer slowing the first, as happens for the C-train. Figure 22 shows that the C-train application pressure was slightly less than for the A-train. If it had been higher, the C-train application times would have been longer.

Note in Table 12 that axle 5 on the first dolly is faster than axle 6 on the second trailer, for both vehicles. This means that as the brakes are applied and the vehicle starts to slow, the inertia of the last two trailers bears momentarily on the first dolly. This occurs before the brakes on the last two trailers become effective. This provides potential for a dolly jackknife in an aggressive braking situation with an empty vehicle on a low-friction surface. However, the timing of the corresponding axles 7 and 8 on the rear trailer are very close for the A-train and are reversed for the C-train, with the dolly axle reaching full braking after the trailer axle. This latter situation is considered desirable if it can be achieved without an excessive brake application time, which was not the case with the C-train. This vehicle was created from available vehicle units, the three trailers, and the two B-dollies. It was not originally intended as a combination as was the A-train. The desirable rear trailer brake timing came as a result of a hasty assembly of the second B-dolly from available parts. While recent work has shown that a big difference in timing between a tractor and trailer has little practical effect on the tendency to jackknife [14], no such work is known for dolly jackknife on doubles or triples.

The application times for both these vehicles are comparable with those obtained from tests conducted previously by MTC on other triples combinations [15,16]. The release times are considered long, however, especially as it was shown that a quick-release valve operating with a booster relay valve could halve the release time [16]. Not only can a faster or more responsive braking system be created at little, if any, cost difference to an "ordinary" system, but if a fast release can also be obtained, then a modest amount of fuel can be saved by reducing the need to accelerate against momentarily dragging brakes. An elementary calculation shows that a quick-release valve can pay for itself through fuel saving in a fraction of the life of the trailer.

The application and release timing for the other four vehicles is summarized in Tables 13 and 14. These results are typical of other tests on similar combinations [14,16]. As noted previously, the timings for the doubles would all have been improved if each combination had used a booster relay valve. The B-train was faster than the A- or C-train because it lacked a converter dolly, allowing simpler plumbing, and it was equipped with an anti-lock braking system, which requires less restrictive components. The release times of the A- and C-train doubles are both considered excessive.

Table 13/ Air Brake Application Timing Summary, 0-60 psi (s)

Location	45 ft Semi	A-Double	B-Double	C-Double
Treadle	0.07	0.04	0.04	0.03
Axle 2	0.41	0.39	0.40	0.43
Axle 4	0.49	0.57	0.56	0.54
Axle 5	0.45	0.56	0.62	0.53
Axle 6	-	0.81	-	0.85
Axle 7	-	0.79	-	0.83
Axle 8	-	0.77	0.68	0.83

Table 14/ Air Brake Release Timing Summary, to 5 psi (s)

Location	45 ft Semi	A-Double	B-Double	C-Double
Treadle	0.19	0.19	0.12	0.18
Axle 2	0.64	0.65	0.54	0.64
Axle 4	0.94	3.02	1.46	1.65
Axle 5	0.88	3.04	1.50	1.59
Axle 6	-	2.26	-	1.96
Axle 7	-	2.31	-	2.39
Axle 8	-	2.28	1.56	2.43

The greatest pressure differential between axles of a vehicle just before brake release ranged between 21 and 48 kPa (3 and 7 psi); the differential for most axles was not more than 21 kPa (3 psi). No clear patterns emerged from this.

A service brake application test was also conducted, where treadle valve travel was limited to keep the final pressure to about 138 kPa (20 psi). In general, application times were similar to those previously reported, because the brake application was not nearly so rapid. Release times were faster, as would be expected, and for most, there were no significant pressure differentials between axles.

This test has illustrated that the air brake system performance depends upon the number of vehicle units -- trailer and dollies. It has also shown that performance depends upon the selection and installation of components. Fast application and release times provide the driver with a responsive brake system. Proper pneumatic balance and low pressure differentials between axles are part of obtaining proper distribution of braking to all axles of the combination.

5.5/ Straight-Line Braking

It is difficult to achieve consistent results when conducting rigorous braking tests. A demonstration of modes of instability in straight-line braking was, therefore, conducted. A series of runs was made with the empty vehicle on the low-friction test area at 47 km/h. The driver braked using the treadle valve, with a regulated application pressure. Application pressure was increased on each run, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [3].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit.

The vehicles all remained fully under control when application pressure was insufficient to lock all braked axles. The results of the last run for each vehicle are presented in Table 15. In most cases, the limiting friction of the surface, a deceleration of about 0.15 g, was reached at a brake application pressure of 159 to 173 kPa (23 to 25 psi). At this pressure, most of the braked wheels were locking. The A-train double and the two triples became unstable at pressures little more than this, whereas the 45 ft (13.72 m) semi and the B- and C-train doubles required considerably harder braking before they became unstable.

Table 15/ **Instability in Straight-Line Braking**

Vehicle	Brake Pressure (psi)	Mode of Instability
45 ft Semi	50	Tractor jackknife
A-Double	32	Dolly jackknife
B-Double	41	Tractor jackknife
C-Double	45	Tractor jackknife
A-Triple	30	Tractor jackknife, driver recovered
C-Triple	34	Tractor jackknife, driver recovered

The tractor of the 45 ft (13.72 m) semi jackknifed to the right, as illustrated in Figure 23 and shown in Figure 25 in its final stopped condition. The dolly of the A-train double jackknifed to the right, as shown in Figure 24. While the whole vehicle remained within the lane during this stop, the dolly actually was unstable. The combination of speed, brake application pressure, and surface friction was such that the instability was demonstrated quite gently. If either speed or brake application pressure had been greater, or the friction had been lower, the dolly jackknife could have been much more violent. The dolly would have rotated until it struck the rear of the lead trailer, and presuming the hitch did not fail, the trailer would then have swung around. The test condition was selected so that the mode of instability was demonstrated but that this violent and hazardous consequence was avoided. The B- and C-train doubles and the triples all experienced tractor jackknife.

In the case of both triples, the driver released the brakes, steered to recover control of the tractor, and drove out of the manoeuvre without coming to a full stop. The tractor jackknifes were predominantly to the left, the direction of the crossfall of the test area. However, some were to the right, possibly due to the local surface characteristics and steer.

The demonstration was conducted without front axle brakes on the tractor. When a braked wheel locks and slides, it has no sideforce capability. However, if all wheels except those at the steer axle lock, the steer axle can still develop the substantial sideforces that are required to manoeuvre the vehicle in normal driving. Further, as the front axle is steered, a drag is created, and if the inertia of the trailer or trailers is enough to overcome the limited sideforce capability of the locked tractor drive axles, it attempts to push the rear of the tractor sideways, as shown in Figure 23. If front axle brakes had been used, the sideforce capability of the locked front wheels would have been very low, and the likelihood of tractor jackknife would have been greatly reduced. The vehicle would slide to a stop, not necessarily entirely under control of the driver, but generally straight and possibly within the lane. Of course, with the addition of the front axle brakes, the inertial effect of towed units is increased, and there remains the possibility of trailer swing on B- or C-train combinations or dolly jackknife as seen in the A-train double.

5.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. The runs were made in accordance with the standard test procedure [3]. For most vehicles, gates of 22.5 m (73.8 ft) were used for the lane change to the left and the return to the original lane, separated by 20 m (65.6 ft) in the left lane. However, the B-train double used gates of 20 m (65.6 ft), and the C-train triple used gates of 25 m (82 ft), as shown in Table 16. A typical test run for the B-train double is illustrated in Figure 26.

Table 16/ Instability in the Evasive Manoeuvre

Vehicle	Gate (m)	Limit Speed (km/h)	Mode of Instability
45 ft Semi	22.5	63	Reached limit of tractor control
A-Double	22.5	63	None
B-Double	20.0	54	Rear trailer swing
C-Double	22.5	63	Tractor pushed laterally through return to original lane
A-Triple	22.5	58	Dolly jackknife and rear trailer swing
C-Triple	25.0	63	Tractor pushed laterally through return to original lane, and rear trailer swing

The vehicles were evaluated primarily in terms of the yaw responses of their units.

The evasive manoeuvre is complex and subtle. The form of the steer input depends upon the layout of the course, the speed, and the handling characteristics of the vehicle. At a very low speed the steer input consists of two distinct sinusoidal steer inputs of opposite sign, the first for the lane change to the left and the second for the return to the original lane. As speed is increased, the two sine curves merge into a complex wave form, because the time in the left-hand lane is now insufficient for the driver to straighten out the tractor, so it follows a continuous curved path. As speed is increased further, the second half-wave of the first sinusoidal steer and the first half-wave of the second sinusoidal steer merge completely and the manoeuvre is accomplished in three continuous sinusoidal half-waves. As speed is increased even further the amplitude of the second of the three half-waves must be reduced.

Unlike some other manoeuvres, the evasive manoeuvre can actually get easier for the driver as speed is increased, because the number of steering wheel movements decreases from five to three. It is actually easiest when the two distinct sinusoidal steers have merged into three continuous half-waves, each of the same period, as this steer input can be done in one smooth flowing motion. Beyond this point, the steer input gets more difficult as the amplitude of the half-waves changes. The frequency content of the steer input, therefore, changes with speed, and is more complex than the basically sinusoidal steer required by the lane change, discussed in Section 5.8. Because of the complexity of the manoeuvre, it is sometimes difficult to get consistent results, especially since each vehicle has different frequency response characteristics and the frequency content of the input varies. For instance, a small steer error at a lower speed may result in an apparent unstable condition when, in fact, the driver might be able to make the manoeuvre rather easily at a higher speed, where the steer input can be made more smoothly.

In summary, the speed at which this manoeuvre can be made may be a little misleading as a ranking of the stability characteristics of the vehicle. Rather, attention should be given to the mode of instability, summarized in Table 16:

- The 45 ft (13.72 m) semi was clearly the most stable. It remained stable to the limit speed of 63 km/h, but at that speed the tractor was close to the limits of control and with the best steer that the driver could achieve, the trailer was just too long to go through the lane return gate.

- With both the A-train double and A-train triple, the driver had excellent control of the tractor, because the short trailer exerts little force on the tractor. The A-train double barely accomplished the manoeuvre at 63 km/h, but the dolly was sliding through the return gate and was on the verge of a dolly jackknife, which would have resulted in rear trailer swing and total loss of control. In contrast, there was greater lateral acceleration at the rear trailer of the A-train triple, due to rearward amplification, as discussed in Section 5.3.7. The second dolly jackknifed in the lane return, and the rear trailer swung out of lane to the right.

- The B-train double experienced rear trailer swing at only 54 km/h, but it performed the manoeuvre with a gate of only 20 m (65.6 ft).

- The tractor of the C-train double was "pushed" laterally through the original lane as it returned through the second gate. The tractor was at the limits of control, but the trailers remained stable. "Pushed," in this context, refers to a lateral and longitudinal tractor slide with a high degree of understeer and little directional control. It is likely that the mode of instability would have been tractor jackknife, as occurred in a previous test of a C-train in such a manoeuvre [11].

- The tractor of the C-train triple was also pushed laterally through the original lane as it returned through the second gate, and there was also trailer swing.

There was insufficient lateral traction to cause steering of any B-dolly in this manoeuvre.

5.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for each combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 63, 84, and 94 km/h, with steer input periods between about 2 and 5 s.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. The maximum lateral acceleration gain, or rearward amplification, of the rear trailer of each vehicle is presented in Table 17 for the three test speeds. Each gain is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless [3]. The maximum value was estimated by scribing a line by French curve through the gains obtained from runs at the various steer periods at each speed. This procedure was not exact but was adequate to illustrate the major differences between vehicles. The final column in Table 17 contains the approximate steer period at which the peak rearward amplification occurred at 94 km/h.

Table 17/ Rearward Amplification of Lateral Acceleration at the Last Trailer

Vehicle	63 km/h	84 km/h	94 km/h	Steer Period (s)
45 ft Semi	0.85	1.00	1.05	3
A-Double	1.10	--	1.85	2
B-Double	1.05	1.30	1.80	2.5
C-Double	--	1.30	1.50	2.5
A-Triple	1.50	2.60	3.30	2
C-Triple	1.15	1.30	1.70	3

It is evident from Table 17 that rearward amplification increases with speed. It also increases rearward by trailer and is somewhat sensitive to steer period, as seen in Figure 27 for the A-train triple. The results, as seen in Figure 27 and Table 17, show that at highway speed, the A-train triple is a highly responsive vehicle. The reason for this is that its inherent stability is rather low. Stability and response of mechanical systems have an inverse relationship. High stability means low response to input and vice versa. Figure 28 shows the rear trailer response of the A-train triple in a typical run for a steer period of about 2.5 s at each test speed. At 63 km/h the response is nearly dead-beat; at 84 km/h the rear trailer is clearly oscillating; and at 94 km/h the rear trailer is oscillating strongly. These three time histories clearly depict the reduction in damping of the vehicle's lateral/ directional response as speed is increased. Figure 29 shows the three comparable conditions for the C-train triple. These are evidently much more highly damped. At 94 km/h, the C-train triple's response is similar to the A-train triple's response at only 63 km/h.

The responsiveness of the A-train triple made this and other tests difficult to conduct for the following reasons:

1/ On approach, small steer corrections made by the driver were amplified rearward so that a desired steady period before the manoeuvre was rarely achieved. This made data detrending difficult [3] and may account for a certain amount of scatter in the data.
2/ The response to the manoeuvre itself continued to the point where the driver had to exit the test area; a complete response could not be obtained because the test area was simply not large enough.
3/ The steer inputs were very small, typically 25 to 35° of steering wheel angle, which is less than 1° steer at the front axle. This small steer resulted in a tractor lateral acceleration of about 0.1 to 0.15 g.

A rearward amplification of 3.0 did, on occasion, result in substantial trailer roll and sometimes trailer swing, even on the high-friction surface. However, tempering the steer input to avoid excessive rear trailer response resulted in such a small steer input that while it was closely sinusoidal at the steering wheel, it was often rather poorly balanced at the front axle. Responses, therefore, were often not well balanced, which means that the steer input contained, perhaps, substantial other periodic content besides the intended steer period.

For this reason, the rearward amplifications were computed as the ratio of peak-to-peak trailer lateral acceleration response to peak-to-peak tractor lateral acceleration. This significantly reduced the scatter in the results and avoided the issue of whether the first, second, or highest input and response peaks should be used as the basis for these ratios. Nevertheless, because the input was often unbalanced and not a pure sine wave, the response was likely attenuated compared to what would result from a pure sine wave. The data in Table 17 are considered optimistic, as they are probably lower than would arise from a perfect steering system or a computer simulation of the vehicle using a pure sine wave steer input.

Tests were only conducted to 94 km/h. The stability of the A-train triple decreased with an increase in speed. This vehicle would be less stable at a typical highway speed limit of 100 km/h and even more unstable if actual speeds exceeded 100 km/h, as they often do. These data are considered a powerful argument in favour of the comparable C-train configuration. A less effective alternative would be a restriction of A-train triples to a maximum speed of 80 km/h.

The results presented in Table 17 are reasonably consistent with other test and simulation findings [17], though those results were obtained for somewhat different vehicles and loadings and a different definition of rearward amplification was used.

5.8/ Lane Change

The objective of this test was to evaluate vehicle stability characteristics in a dynamic manoeuvre. A series of runs was made where the driver made a lane-change manoeuvre, which is considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [3].

A gate of 30 m (98.4 ft) was used for the lane change. This allowed a vehicle speed of about 80 km/h, which is a typical speed limit, and some comparison of the results of this test with those described in the preceding sections.

The limit speed at which each vehicle became unstable in this manoeuvre, and the mode of instability, are presented in Table 18.

Table 18/ Instability in the Lane-Change Manoeuvre

Vehicle	Limit Speed (km/h)	Mode of Instability
45 ft Semi	95	None
A-Double	83	Rear trailer rollover
B-Double	88	Violent rear trailer swing and outrigger touchdown
C-Double	95	Lead trailer slide
A-Triple	74	Rear trailer swing
C-Triple	89	Second trailer slide and rear trailer swing

The 45 ft (13.72 m) semi was able to negotiate the course at the maximum test speed of 95 km/h and was the most stable vehicle.

While this test was not conducted for the A-train double, it was conducted for a very similar vehicle in a previous test program, which resulted in slide and violent rollover of the rear trailer [11]. The rear trailer of the B-train double swung violently, and its outrigger touched down on both sides (Figure 30). The vehicle may not have rolled over, but the response was undesirable. When the C-train double reached a sufficiently high speed, the B-dolly steered out. This transferred lateral load from the rear trailer to the lead trailer tandem axles. As these became overloaded, the lead trailer slid left towards the edge of the lane, and the rear trailer tracked behind. The response of this vehicle was mild compared to the B-train double.

The A-train triple had such a high rearward amplification that at only 74 km/h the second dolly slid and the rear trailer swung violently out of lane, as shown in Figure 31. No outrigger touchdown occurred. Three factors provide a tendency to trailer swing rather than rollover:

1/ The centre of gravity was low because of the method of loading and the underslung outriggers. Typical similar trailers in operation would have a considerably higher centre of gravity.
2/ The overall wheel track width was 2.59 m (102 in), whereas for the 45 ft (13.72 m) semi and all three doubles, it was 2.44 m (96 in).
3/ The sideforce capability of a single axle in such a manoeuvre is expected to be less than for a tandem axle.

If the trailer centre of gravity had been at a more typical height, the rear trailer would have rolled over violently, as it did for the A-train double. While rollover was the "expected" mode of instability, this test shows that another mode of instability is possible. The response of the C-train triple was mild compared to the A-train and it reacted the same as the C-train double, except that both B-dollies steered out, and because of the extra trailer, the vehicle reached the edge of lane at only 72 km/h. The response was not violent, and testing continued until 89 km/h, when as a consequence of the second trailer slide, the rear trailer swung violently out of lane.

The sinusoidal steer test ranked the six vehicles in terms of stability; the higher the rearward amplification, the lower the stability. When the rearward amplifications of Table 17 are compared with the limit speeds of Table 18, it is seen that there is an inverse relationship between the speed at which this manoeuvre could be conducted and the rearward amplification. Rearward amplification, therefore, can be directly related to the likelihood of loss of control in a fast steer input such as might be made in an accident avoidance situation.

5.9/ Normal Straight-Line Driving

The objective of this test was to evaluate lateral motion of the rear trailer of the combination, the phenomenon known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [3].

Trailer sway is simply a low-level vehicle response. Sway amplitude is related to vehicle configuration and speed in the same way as the rearward amplification of lateral acceleration, and it may also involve free play at the hitches.

The slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in rear trailer sway that was evaluated by root mean square (RMS) lateral acceleration of the rear trailer and RMS sway of the rear of the rear trailer relative to the tractor steer axle, per degree of RMS steer angle.

The responses were all, in general, very small, no more than 2% of full scale on the data acquisition system. In some cases, the data must have been below the resolution of the transducers and system. It was not considered necessary to conduct a full frequency domain analysis, but the simple ratio of RMS response to RMS steer would be adequate to illustrate the principal differences between vehicles.

The results are summarized in Table 19, as RMS rear trailer lateral acceleration divided by RMS steer input.

Table 19/ Trailer Sway in Straight-Line Driving

Vehicle	Rear Trailer Lateral Acceleration (g/°)
45 ft Semi	0.63
A-Double	1.74
B-Double	1.49
C-Double	1.46
A-Triple	3.37
C-Traiple	2.05

The lateral acceleration ratios are roughly in proportion to the rearward amplifications of Table 17, though the similarity of the actual values is coincidental. The results for sway depend, in particular, upon the articulation measurements, which were very small. These results were noted, but are not presented. There is no doubt, however, that there was no perceptible sway to observers in a chase vehicle with the 45 ft (13.72 m) semi. For the doubles and the C-train triple, some other reference, such as a lane edge stripe, was necessary to observe the vehicle sway -- it was otherwise hardly perceptible. However, for the A-train triple, sway was continuous and very perceptible, with a distinct component of about 2 s period and 0.05 g lateral acceleration at the rear trailer.

5.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics to determine the high-speed offtracking of the vehicle and examine the side loads exerted on the tractor by the trailers. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The 45 ft (13.72 m) semi experienced a smooth outrigger touchdown at 0.52 g in this test, as shown in Figure 32. The trailer twisted due to the load distribution, leaving the impression that the entire vehicle may not have rolled over. The A-train double's rear trailer rolled over independently of the rest of the vehicle at a lateral acceleration of 0.53 g and caused the dolly to slide out. This was a violent response, unlike the smooth rollover of the 45 ft (13.72 m) semi and a similar A-train in an earlier test [11]. The B- and C-train doubles both had so much configuration drag in this manoeuvre that speed dropped off significantly after they entered the circular turn. On both vehicles the outriggers of both trailers touched down, at 0.49 g for the B-train and 0.54 g for the C-train. Whether these vehicles would actually have rolled over entirely may be questionable. All wheels except those of the tractor lifted for the B-train (Figure 33), but since speed was dropping off fast at this point, it was difficult to predict exactly what would have happened. Both of these vehicles would roll over entirely, in contrast to the A-train double, which would only roll the rear trailer. For both A- and C-train triples the low trailer centre of gravity previously mentioned and the 2.59 m (102 in) overall wheel track width elevated the roll threshold above the threshold of lateral/directional stability. The rear trailer swung out on entry to the circular turn, achieving a maximum of 0.50 g for the A-train and 0.46 g for the C-train. If the trailer centre of gravity had been higher, the A-train's rear trailer would have rolled over, and presumably the entire C-train triple vehicle would have rolled over. While rollover was the "expected" consequence of this test, the actual result illustrates that other modes of instability are possible, as seen in the lane change, discussed in Section 5.8, for these vehicles.

The 45 ft (13.72 m) semi and the three doubles are all similar with respect to suspension roll stiffness, axle loads, and centre of gravity height. Therefore, it is not surprising that they have similar roll thresholds. In a manoeuvre at the limits of stability in an A-train, the driver has little, if any, feel for the rear trailer's attitude, and that trailer can roll over while the rest of the vehicle remains upright. However, in the semi or either of the other two doubles, the driver can feel roll moment transmitted forward from the rear trailer and, knowing that the entire vehicle will roll over, may have an opportunity to stabilize. Drivers would be expected to prefer the A-train, as the likelihood of death or serious injury in a heavy truck rollover is high. However, with the feel provided by a B- or C-train, it might be expected that the driver would respond to the vehicle and be better able to avoid the marginal situation. From this point of view, the B- or C-train double may be preferred to the A-train, though this opinion may not be shared by all drivers.

A static tilt test was conducted on the 45 ft (13.72 m) semi and the three doubles [12]. The two triples were too long to fit on the tilt table. The outer sections of the outrigger were removed for this test, which raised the centre of gravity of each trailer about 0.06 m (2.5 in) from the values quoted in Section 2. The table was tilted until a vehicle rollover condition was achieved, as indicated by the loads on critical high-side wheel pads becoming zero. For the A-train double the critical axles were those on the rear trailer only, as this trailer was free to roll independently of the rest of the vehicle as the dolly hitch offers no roll restraint. For the other three vehicles, all high-side wheel pad loads, except, possibly, those at the steer axle, were required to reach zero, as roll moment was transmitted between all vehicle units of these combinations. A typical rollover condition is shown in Figure 34, with the A-train double. The angles at which rollover occurred in the tilt test are compared in Table 20, with the peak lateral acceleration at which the vehicle unit rolled over in the steady circular turn. These tilt angles include all appropriate corrections, discussed elsewhere [12].

Table 20/ Comparison of Roll Thresholds, Tilt Test and Steady Circular Turn

Vehicle	Tilt Angle (deg)	Tangent of Tilt Angle	Lateral Acceleration at Outrigger Touchdown in Steady Circular Turn (g)	Centre of Gravity Height Above Table (m)
45 ft Semi	28.4	0.54	0.52	1.78
A-Double	29.1	0.56	0.53	1.69
B-Double	26.9	0.51	0.49	1.75
C-Double	28.0	0.53	0.54	1.73

The agreement here seems quite good, but the data are sparse and are based on a single test in each case. It is, therefore, difficult to ascribe much significance to the differences.

The closeness of the tilt test results for these four vehicles bears out the observation that these vehicles all have similar suspensions, axle loads, and centre of gravity heights. Because their centres of gravity were quite low, it was necessary to make a very aggressive turn to achieve rollover: 0.5 g or higher would require the advisory speed on a freeway ramp to be exceeded by 80% or more, which may be done in a car but is far beyond typical driving in a truck. The 1.75 m (70 in) centre of gravity height of Table 20 is typical of a load of steel or bricks. However, tankers, vans, and flatbeds of lumber can often have a centre of gravity more than 2.5 m (100 in) above the ground, which for the vehicles tested would reduce their rollover threshold to 0.3 g or so, a substantial decrease [17]. Such an elevated centre of gravity would have resulted in rollover of the triples in this test. It would also have resulted in rollover of all vehicles in the lane-change test (Section 5.8).

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6/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailers were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal because of the underslung outriggers.

The test program started in early June at Centralia, transferred to Blainville in August, and returned to Centralia at the end of November for two more weeks of testing. A test program of such duration encountered a variety of weather conditions. The summer months, with air temperatures of 25 to 30°C, resulted in high-friction surface temperatures up to 55°C and low-friction surface temperatures about the same as the air temperature. However, in the final four weeks, air temperatures were -3 to +5°C, and surface temperatures were about 3 to 5°C. The low-friction surface was less slippery in cold conditions. It also appeared less slippery to the test driver than during a previous series of A- and C-train tests [11], though those tests used different tires. The B-train and A- and C-train triples were tested in similar warm conditions, whereas the 45 ft (13.72 m) semi and A- and C-train doubles were tested in cold conditions. While temperature may affect tire traction characteristics, there should be little effect for comparisons within these groups.

New tires were installed on the Freightliner at the start of the test program and were replaced once when half the usable tread had worn. New tires were installed on each trailer and dolly. The C-triple was tested after the A-triple and used the same trailers. The C-double was tested after the A-double and also used the same trailers. When the tires were used for the second series of tests, they could still be described as "nearly new" and without evident unusual wear patterns.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results, except for centre of gravity height, which has been mentioned already where it may have affected the results. The results presented pertain to the particular vehicles tested, and results different in some respects might be obtained for other vehicles at another time.

The test program was the largest undertaken by the ministry, and it was planned with the expectation that there would be delays. The expectation was fulfilled, though the delays were unscheduled. As autumn was trying to become winter, there were often extended periods when such inclement weather as rain, ice pellets, and snow prevented testing. Some time was lost because contracted work took longer than promised. Various pieces of equipment failed at various times, requiring repair, replacement from spares, or a change in the test sequence. Fortunately, no unduplicated piece of equipment failed and caused an extended delay. Finally, telemetry dropouts wasted many runs at Blainville. The source of the dropouts could never be established because the pattern changed with time and was not responsive to changes in transmitter or receiver antennae, ground station location, signal levels, or a number of other variables. As a consequence of these delays, tests on vehicles were done with varying depth to maintain schedule. Some were exhaustive, but others only completed the test objective. Only one test was omitted, the lane change on the A-train double, and this was done to maintain schedule only because the same test had previously been conducted with an almost identical vehicle [11].

The 45 ft semi was considered an easy vehicle to drive by the test driver. It tracked well, manoeuvred well, and was very stable. It just took much more space to turn than the three doubles, due to the trailer length and the rearward placement of the axles. The test driver also considered the A-train double an easy vehicle to manoeuvre and drive, particularly in the evasive manoeuvre on the low-friction surface. The trailers had little influence on vehicle handling, whereas the trailers of both B- and C-train doubles were pushing the tractor laterally through the return to the original lane. The tendency to push was also noticeable on the high-friction surface, particularly in the steady circular turn, where simply following the turn required considerably greater effort in the B- and C-trains than in the A-train. It was of interest, though, that the driver was very satisfied with the handling of the C-train double on the highway in snow and ice when the vehicle was being returned from Blainville to Centralia. The short trailer wheelbase and single axle made the A-train triple easy to manoeuvre in both low-speed turns and dynamic tests, as the trailer imposed rather modest forces on the tractor. It was also particularly easy in the evasive manoeuvre on a low-friction surface, where the rear two trailers and dollies appeared to slide through the gates. However, because it was so responsive it was very easy for the driver to create a trailer swing situation, and this would have been a rollover situation with a higher trailer centre of

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gravity. The driver had no feedback of second- or third-trailer response once a manoeuvre had started, because the A-dolly hitch does not transmit trailer roll moment forward. The responsiveness of this vehicle in normal driving, particularly when empty, was a concern because rough roads excited considerable trailer sway. Even hauling two trailers to the test site on delivery was not a pleasant experience. By contrast, the C-train triple was rather stable, but again it tended to push the tractor laterally in manoeuvres. With regard to the C-trains, the driver felt that the axle used was preferable to the axle tested previously [11] because the force required to break out the self-steering mechanism was lower, so the axle appeared to steer almost continuously in a dynamic manoeuvre. In the earlier test, the steer would break out suddenly and unexpectedly during the manoeuvre, affecting performance of the manoeuvre by the driver.

In absolute terms there is no question that the 5-axle 45 ft (13.72 m) semi was the most stable of the six baseline vehicles. This is attributable simply to its single point of articulation and the long wheelbase of the trailer. However, this is a utility vehicle and is not the vehicle of choice for heavy-haul applications, where double trailer combinations with more than five axles can carry higher gross weights. There is also no question that the B- or C-train doubles tested were more stable than the A-train double, simply because these two vehicles have one less point of articulation. However, the issue was by no means clear-cut. In the evasive manoeuvre on the wet low-friction surface, the A-train double might be judged to have performed better than the B- or C-train. It was certainly the easiest for the driver to put through the course, but this was because the A-dolly makes a combination that is easier to turn than the other two configurations. However, from previous experience [11], the dolly jackknife/trailer swing mode of loss of control of the A-train is judged potentially more hazardous to other road users than the loss of tractor control that is most apparent with the B- or C-trains. On the high friction surface the A-train had the highest rearward amplification. Because all three vehicles had similar roll thresholds, the A-train double is the most vulnerable to rear trailer swing or rollover in a dynamic manoeuvre. Again, because of a lack of feedback from the rear trailer to the driver, it is more likely that the driver of an A-train will approach the point where loss of control is likely than will the driver of a B-train or the corresponding C-train.

7/ COMPUTER SIMULATION

The University of Michigan Transportation Research Institute (UMTRI) yaw/roll model [18] was installed on the HP-1000 computer used in the ground station for data processing. The program was extended to simulate a triple trailer combination and was updated to include an improved B-dolly model developed by UMTRI, so that all vehicles tested could be simulated with the same program. Details of the internal computation were also modified to achieve run times no more than 25% the duration of those for the original program, and in most cases much less.

The properties of vehicle unit suspensions were available from parametric measurements made by UMTRI, as were tire properties [19]. The geometric properties of vehicles were measured, and mass properties were determined by a process of weighing and calculation. By this means, data sets were prepared that were representative of the vehicles as they were actually tested.

The program was also modified to read the steer input measured during a test run and the initial conditions for some other model degrees of freedom from the test data. It then integrated the equations of motion, computed responses of interest at the measurement locations on the test vehicle, and stored those responses in a data file having the same format as that containing the responses measured in the test. The test and simulation results could, then, be directly compared.

This test program consisted of standardized tests of nine vehicles of different configurations. It provided an opportunity to exercise computer simulation techniques over a wide range of cases. The objective was to demonstrate that computer simulation could represent a vehicle's response in a specific manoeuvre and the trend in response characteristics over a range of manoeuvres. The program data were set up to be as representative as possible of the actual vehicle tested, using generic data where directly measured data were not available. This work was not a validation of the computer model.

Computer simulation was conducted for all vehicles in the loaded condition for the following tests on a high-friction surface:

1/ sinusoidal steer
2/ lane change
3/ steady circular turn

All vehicles showed good agreement between the simulation and test results in the sinusoidal steer. However, it was found necessary to modify the tractor drive axle tire characteristics for the B-train simulation to match the test results as well as the other five vehicles did. This modification was considered acceptable because no measured data were available for these tires, so essentially the simulation provided a tool whereby the tire characteristics could be approximated. This tire modification was found essential for all vehicles if the simulation was to match the test results in the steady circular turn.

This work showed that the computer simulation could produce quite reasonable agreement with test results for this range of vehicle configurations and conditions, both for individual runs and as a trend over a number of runs. This agreement was obtained using generic tire and suspension data with accurate geometric and mass data. Better agreement with individual runs could, perhaps, have been achieved by "tuning" the data. However, since many of the deviations were of the same order as differences between test runs, such effort did not appear warranted. If anything, differences between simulation and test results for individual runs raised more questions about interpretation of the test data than the credibility of the simulation.

A detailed summary of this work is presented elsewhere [10].

8/ CONCLUSIONS

The CCMTA/RTAC Vehicle Weights and Dimensions Study selected a baseline vehicle to represent each of six major truck configurations: the tractor-trailer; A-, B- and C-train doubles; and A- and C-train triples. The Ontario Ministry of Transportation and Communications subjected each of these baseline vehicles to a standard series of tests for turning; the air brake system; lateral/directional and roll stability; trailer sway; and a demonstration of straight-line braking.

Vehicle turning performance depends primarily on trailer length and the number of trailers. It is not strongly dependent on the method of hitching. As trailer length or number of trailers increases, so does the space required to make turns.

Air brake system performance depends on the number of vehicle units and selection and installation of components.

Lateral/directional stability is strongly dependent upon vehicle configuration. The semi was the most stable, doubles were more stable than triples of similar configuration, and B- or C-trains were more stable than the A-train. This ranking follows the number of articulation points -- the more articulation points, the lower the stability.

Roll stability in a steady turn is essentially independent of vehicle configuration where vehicles have the same suspension, axle load, and centre of gravity height. Roll thresholds in the steady turn agreed well with those found in a tilt test.

An extensive computer simulation showed that responses of all vehicles could be predicted quite well, both for individual runs and as a trend over a number of runs.

The specific results presented here apply to the vehicles tested for the particular test conditions. Results different in some respects might be expected for other vehicles or test conditions.

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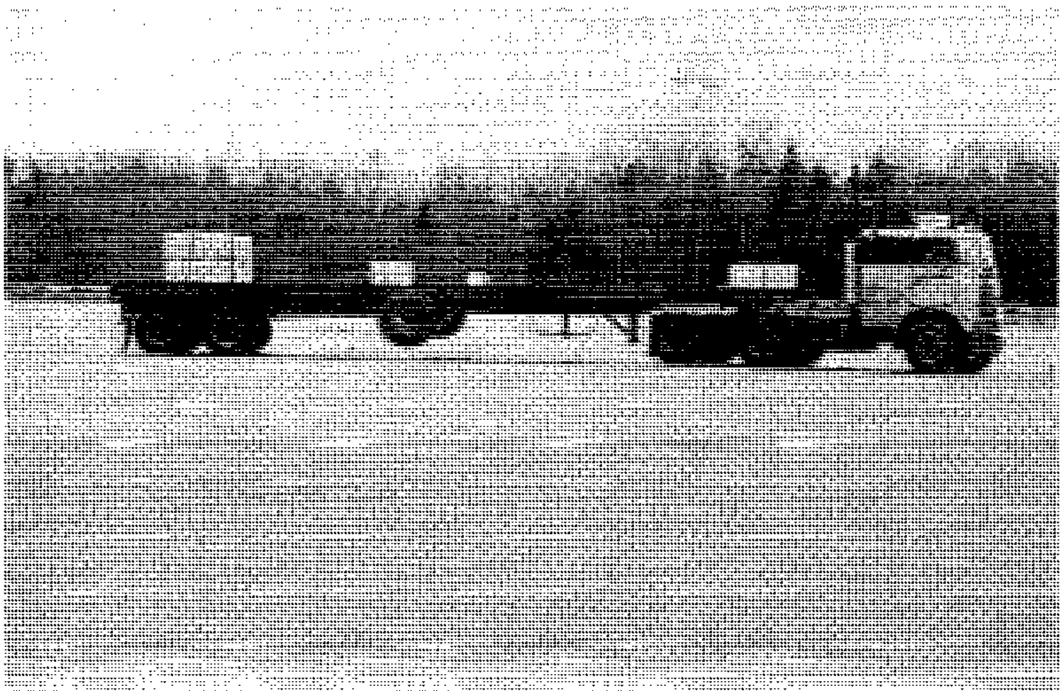


Figure 1/ 45 ft Semi, View of Vehicle

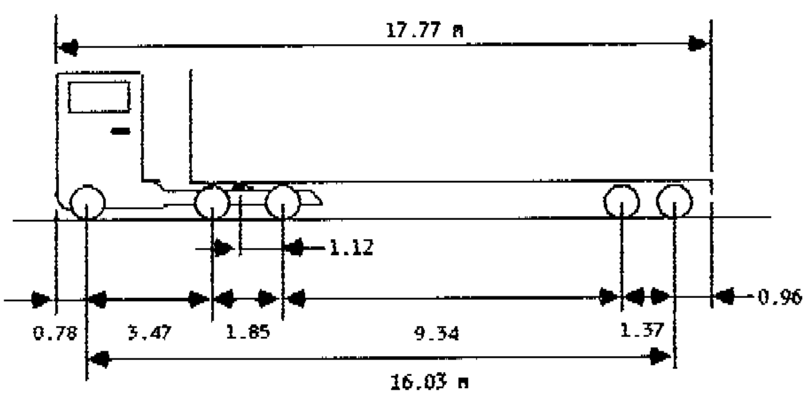


Figure 2/ 45 ft Semi, Vehicle Dimensions

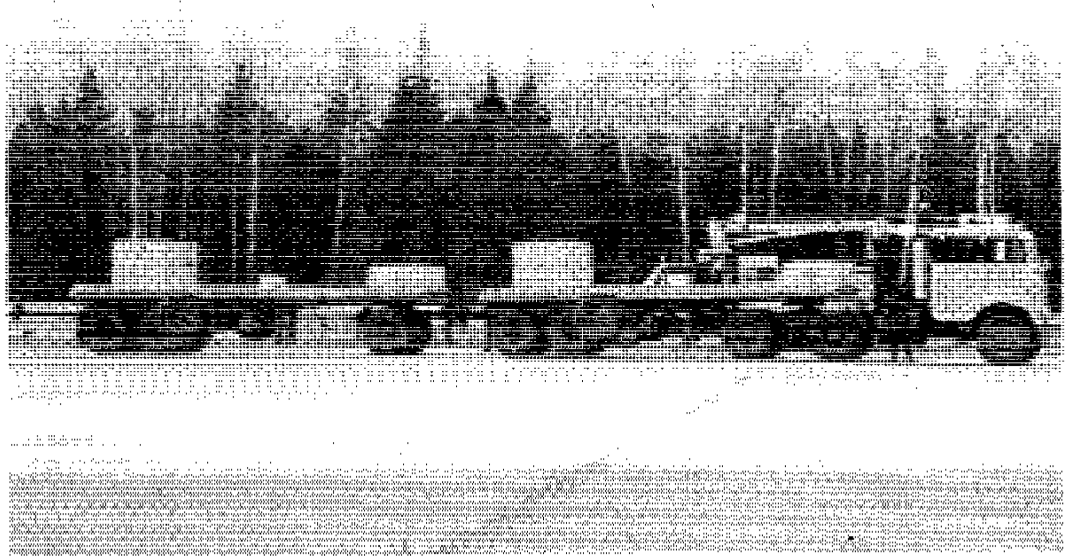


Figure 3/ A-Train Double, View of Vehicle

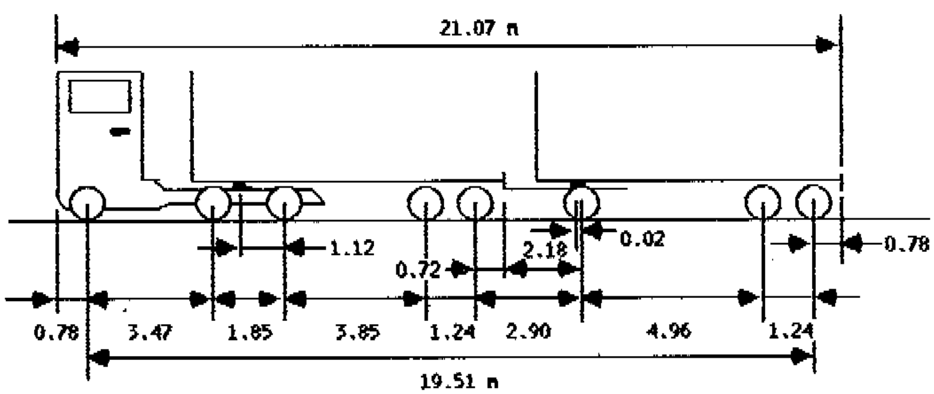


Figure 4/ A-Train Double, Vehicle Dimensions

Figure 5/ B-Train Double, View of Vehicle

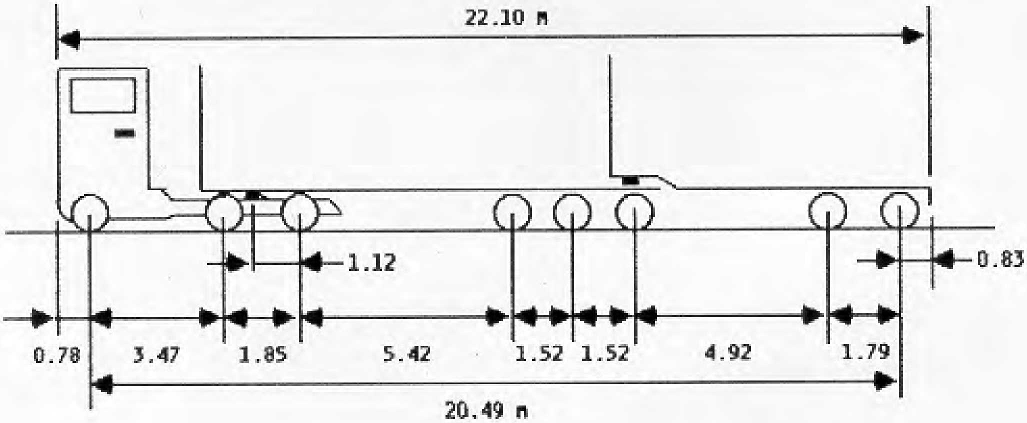


Figure 6/ B-Train Double, Vehicle Dimensions

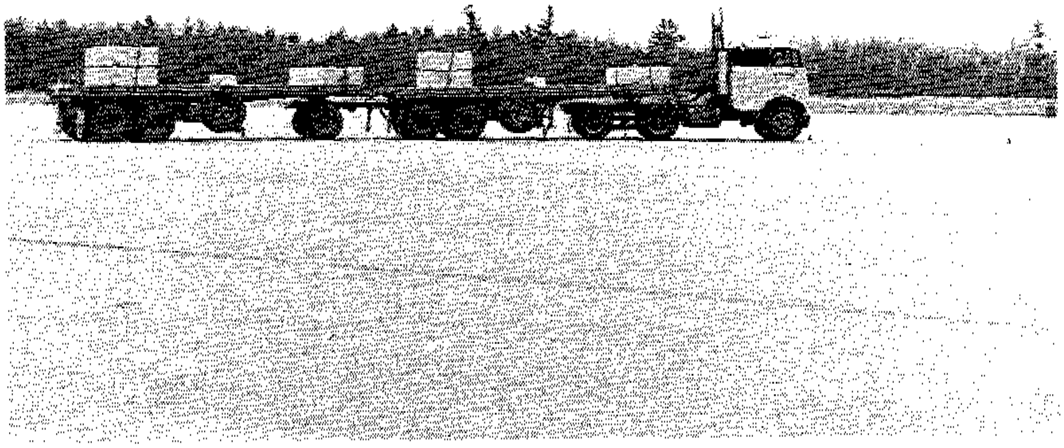


Figure 7/ C-Train Double, View of Vehicle

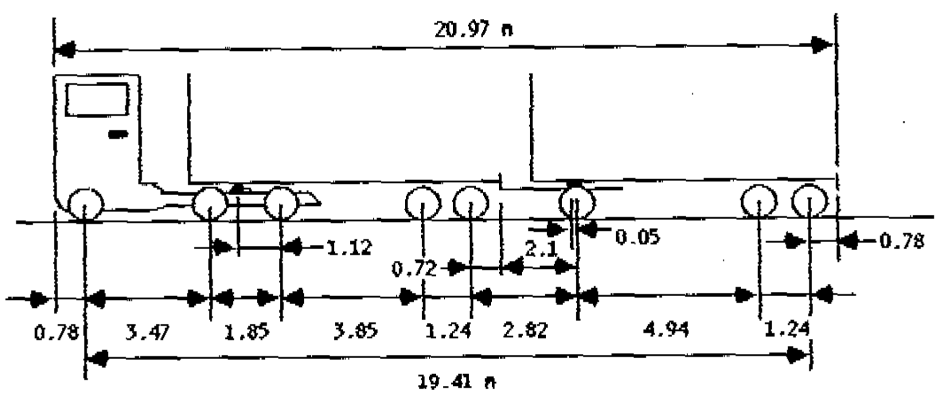


Figure 8/ C-Train Double, Vehicle Dimensions

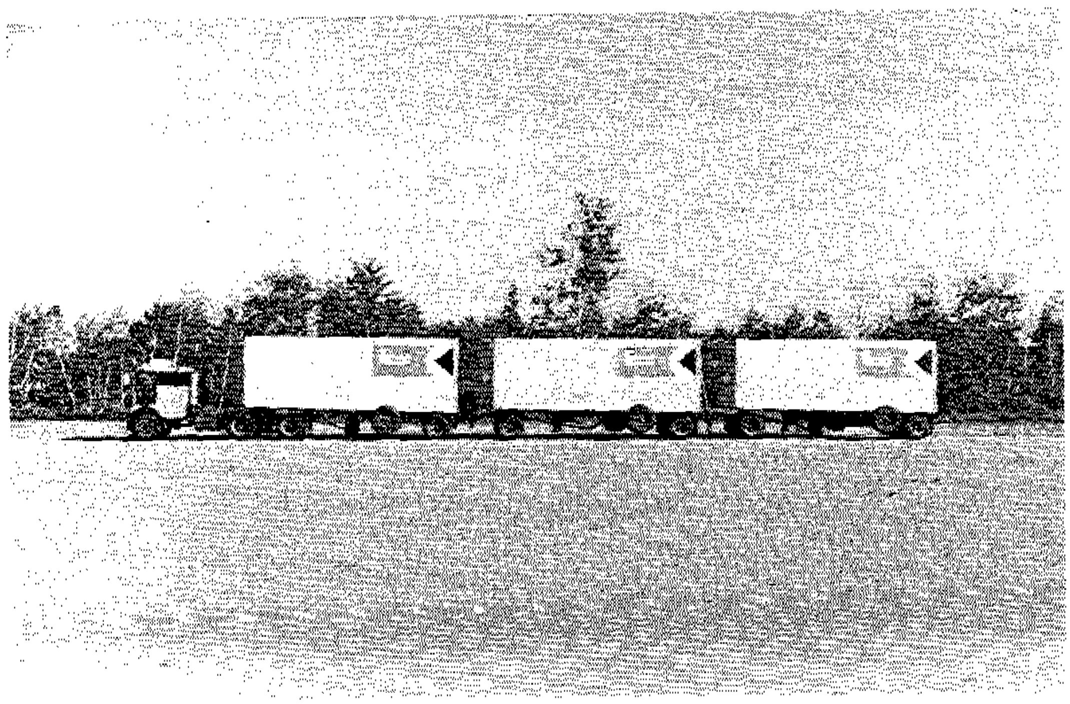


Figure 9/ A-Train Triple, View of Vehicle

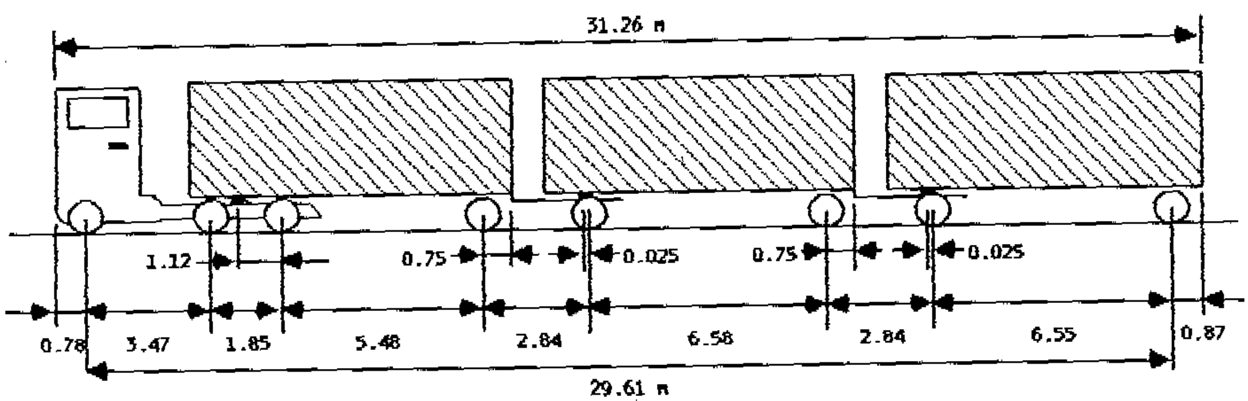


Figure 10/ A-Train Triple, Vehicle Dimensions

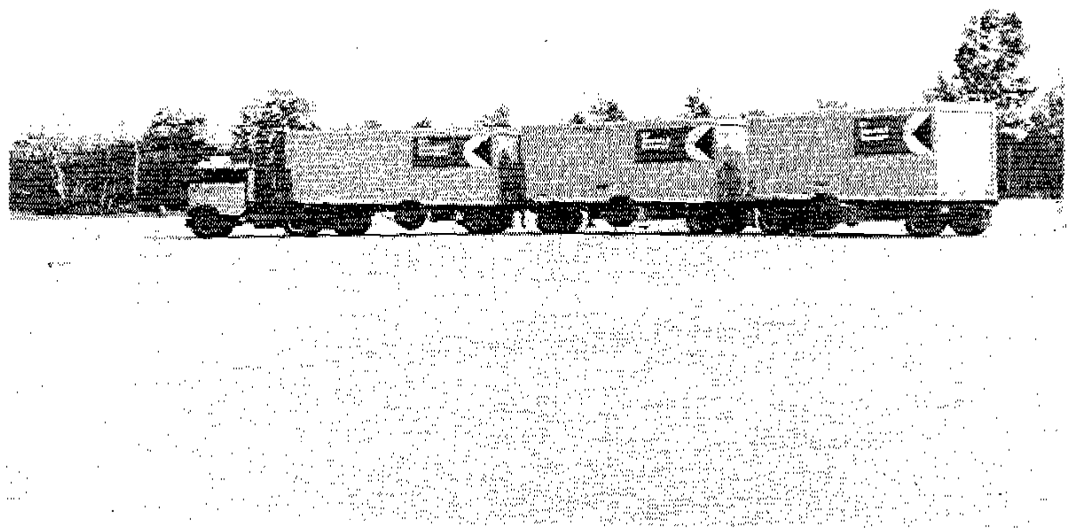


Figure 11/ C-Train Triple, View of Vehicle

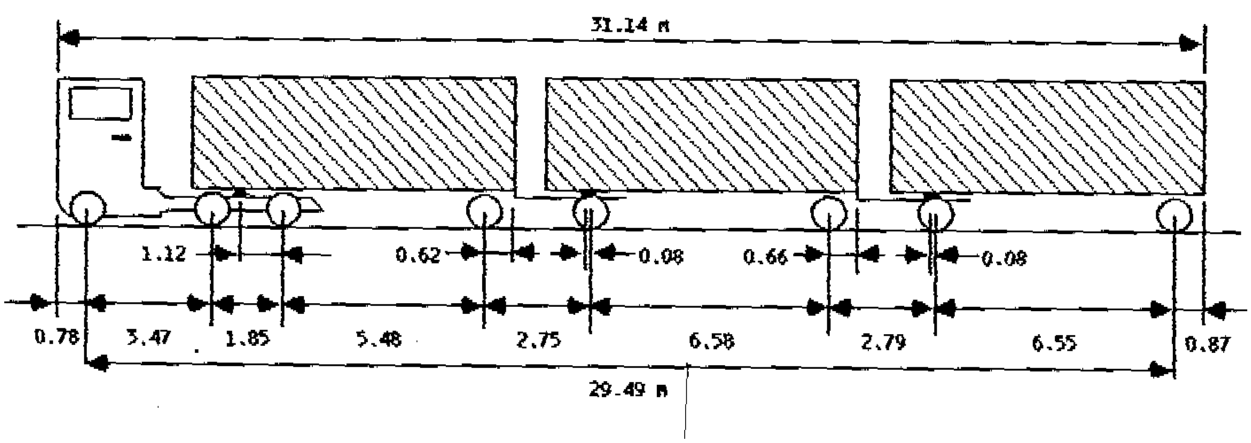


Figure 12/ C-Train Triple, Vehicle Dimensions

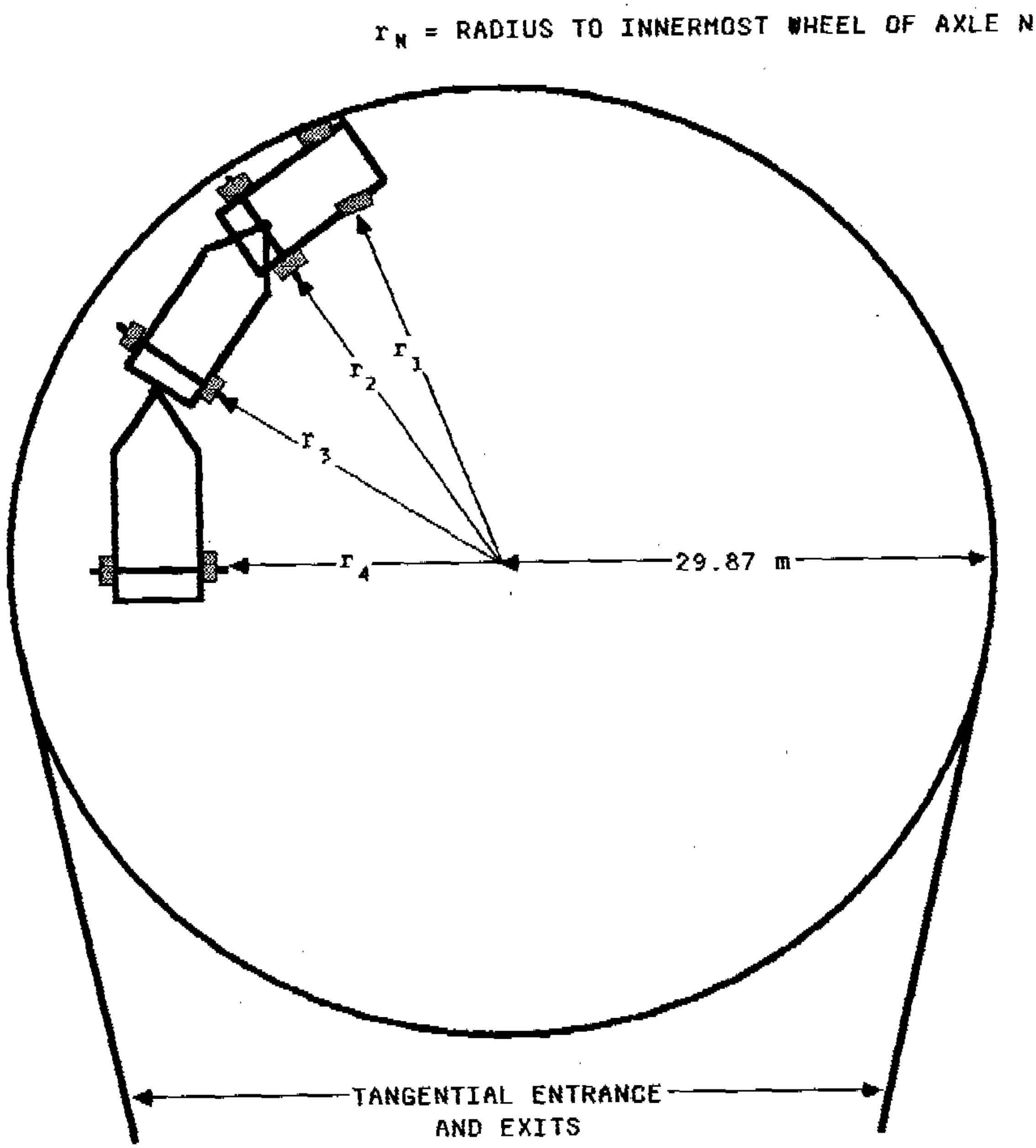


Figure 13/ Offtracking Course

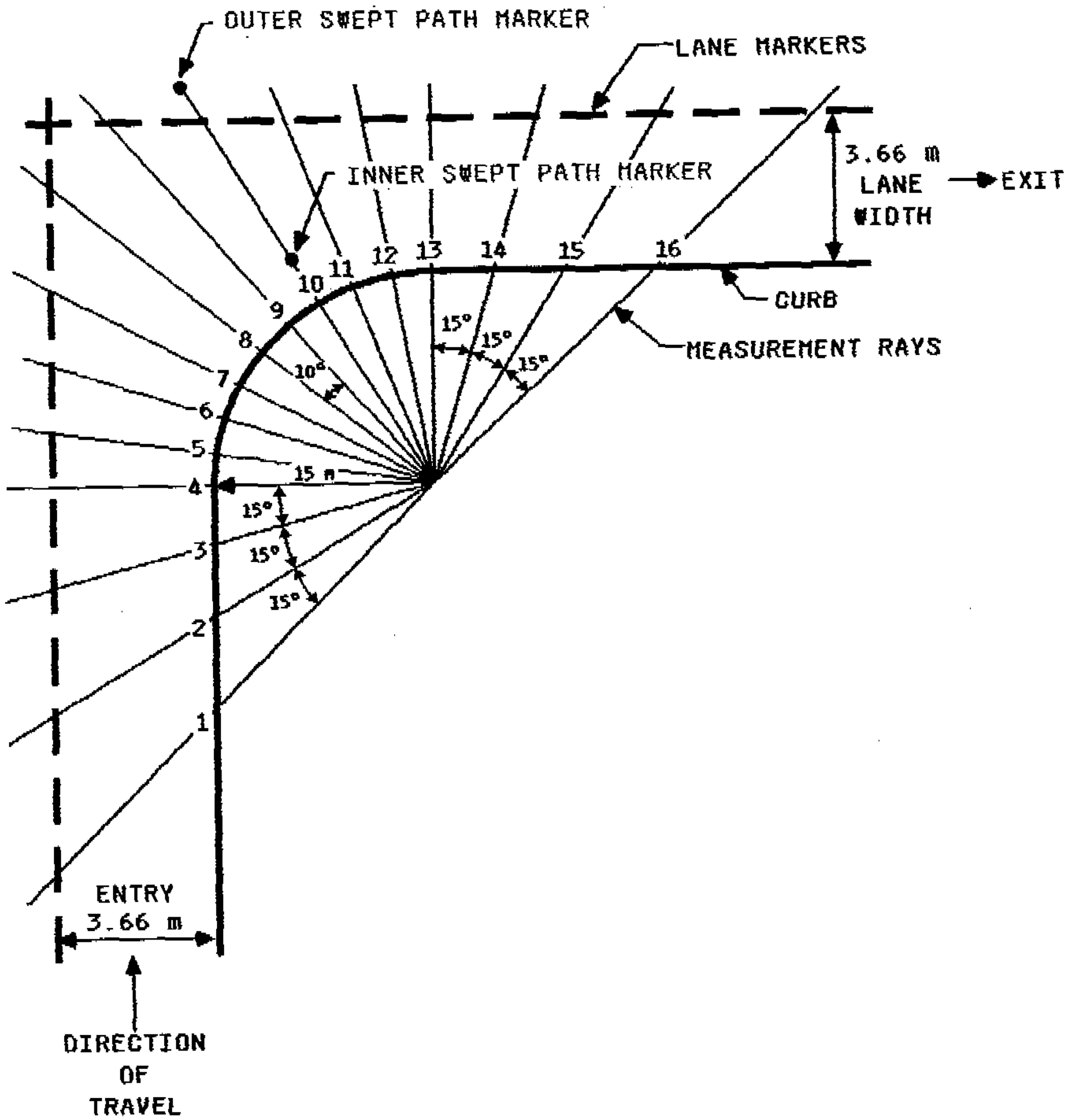
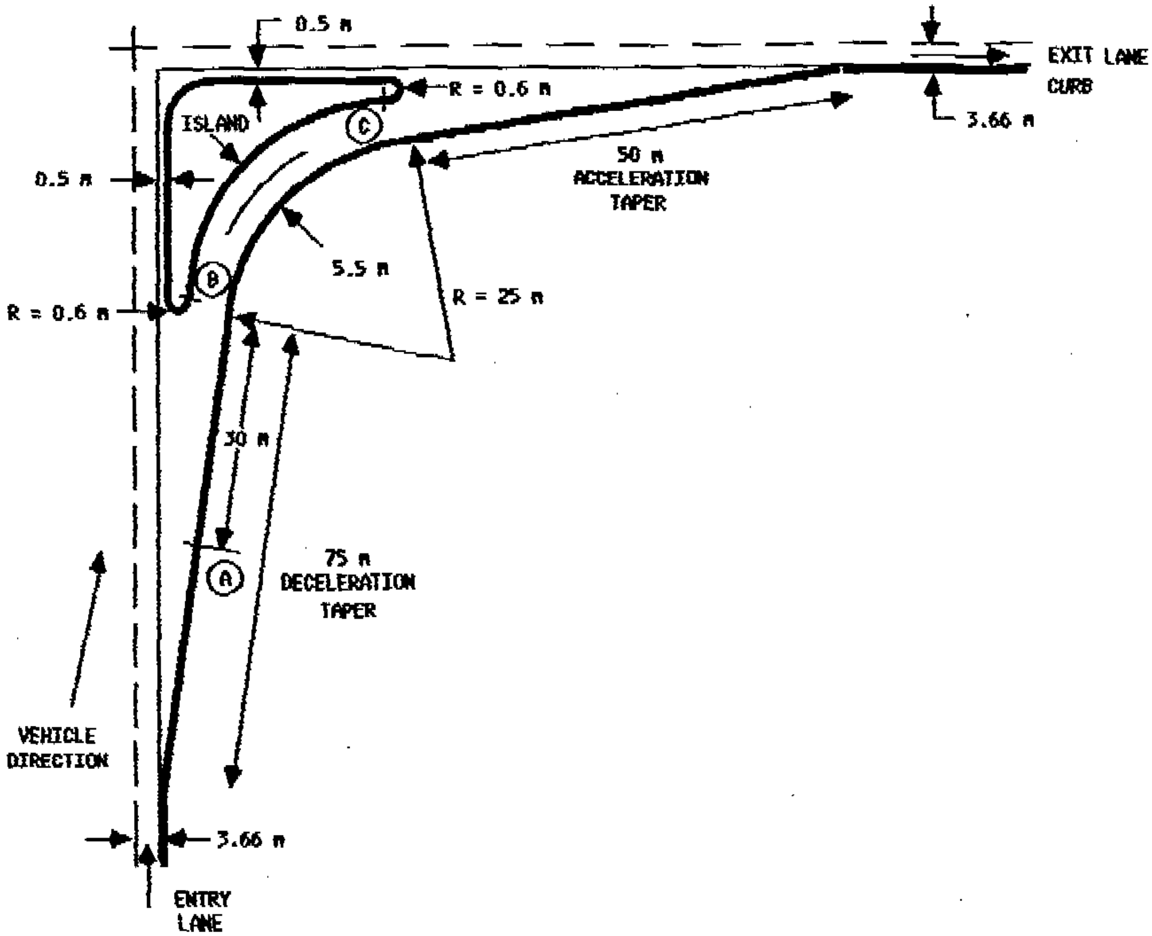
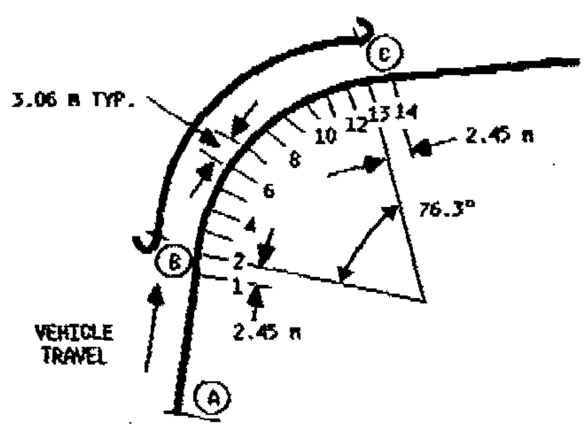


Figure 14/ Right-Hand Turn Course



(a) Geometry



(b) Measurement Reference Points

Figure 15/ Channelized Right Turn Course

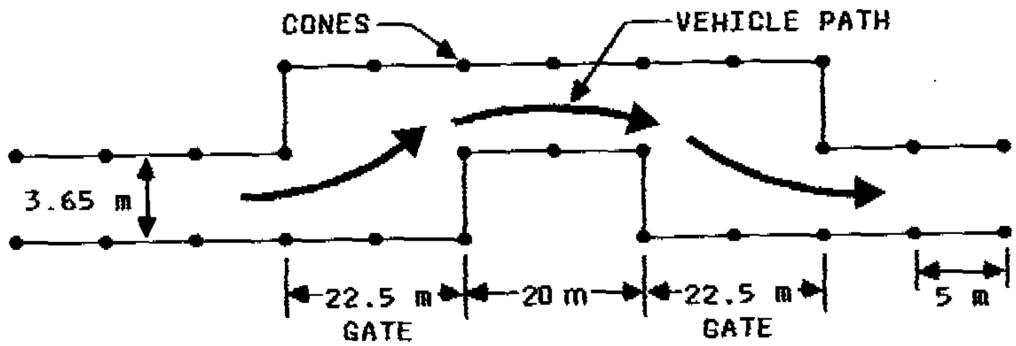


Figure 16/ Evasive Manoeuvre Course

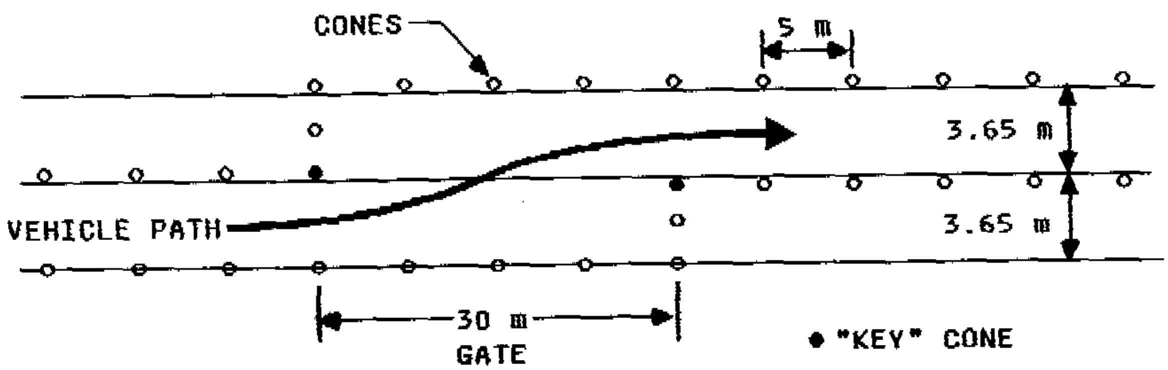


Figure 17/ Lane-Change Manoeuvre Course

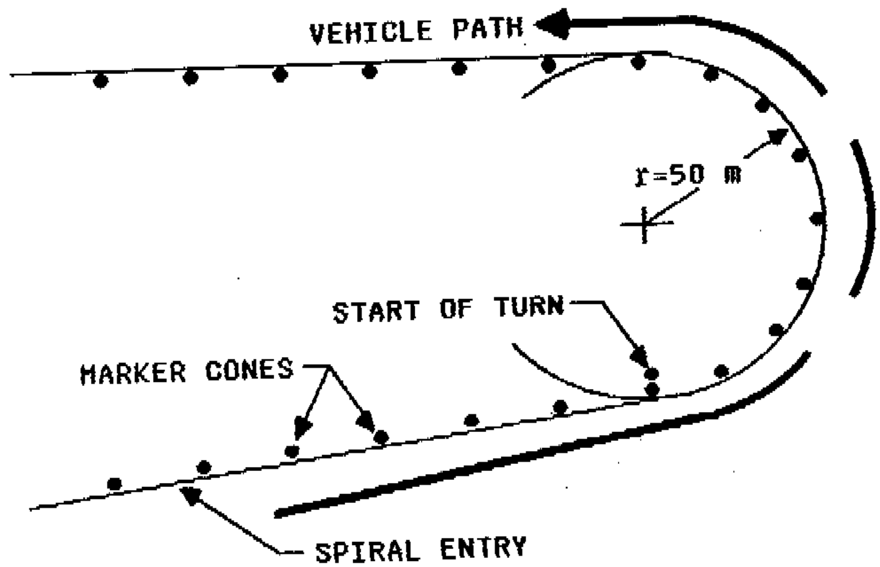


Figure 18/ Steady Circular Turn Course

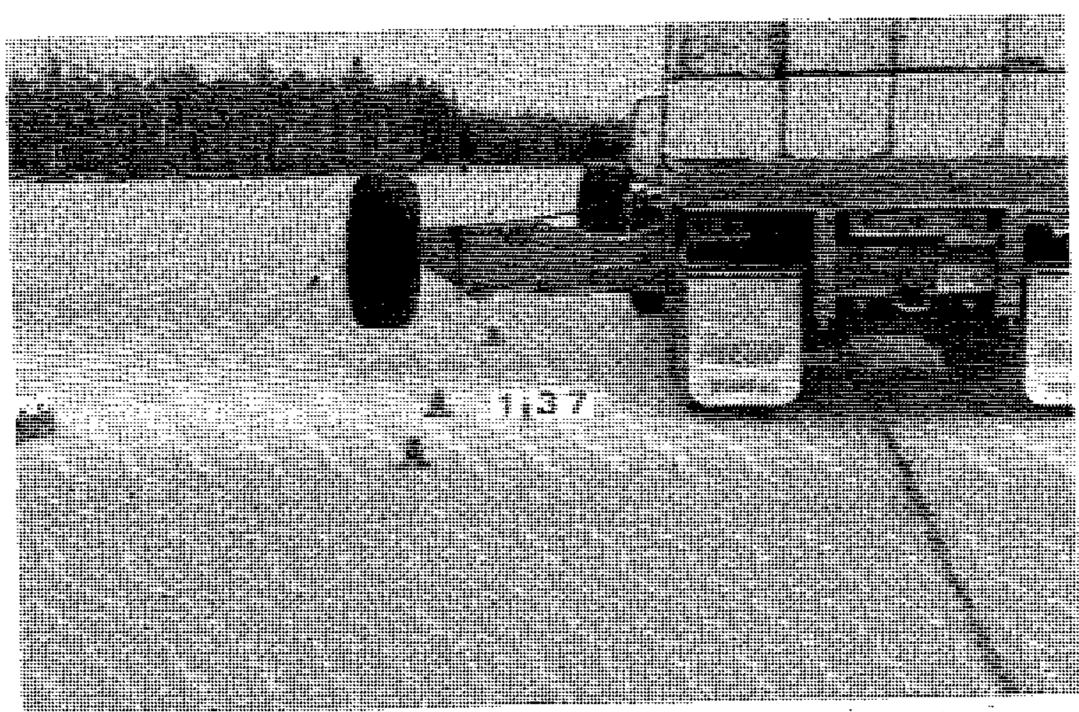


Figure 19/ C-Train Double, Clockwise Final Offtracking

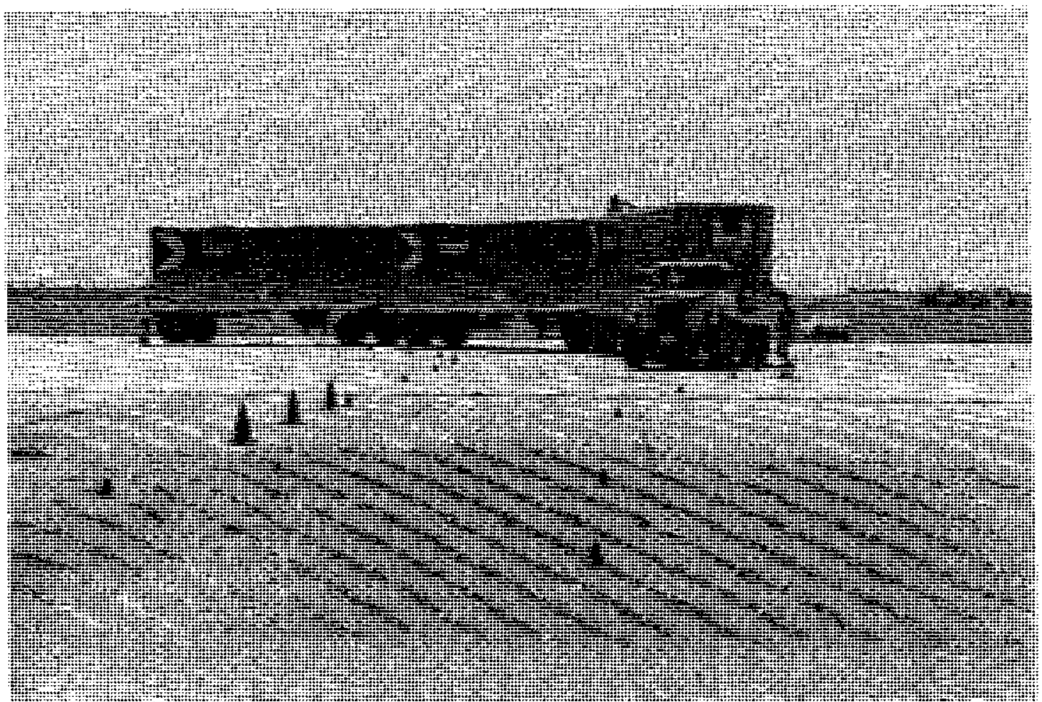


Figure 20/ C-Train Triple, Right-Hand Turn

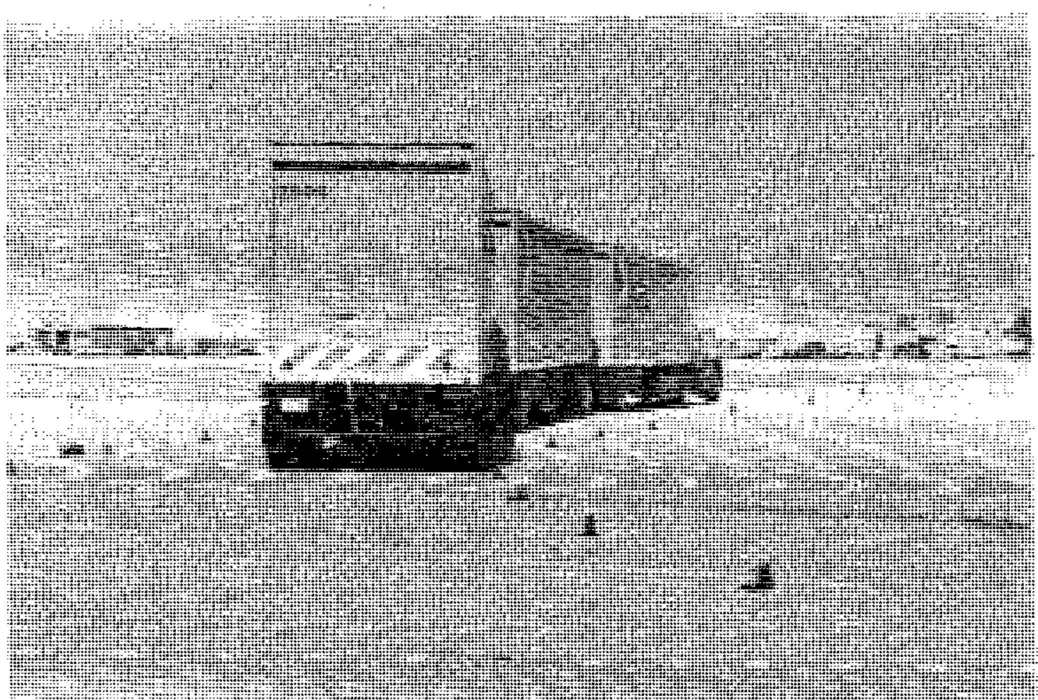


Figure 21/ C-Train Triple, Channelized Right Turn

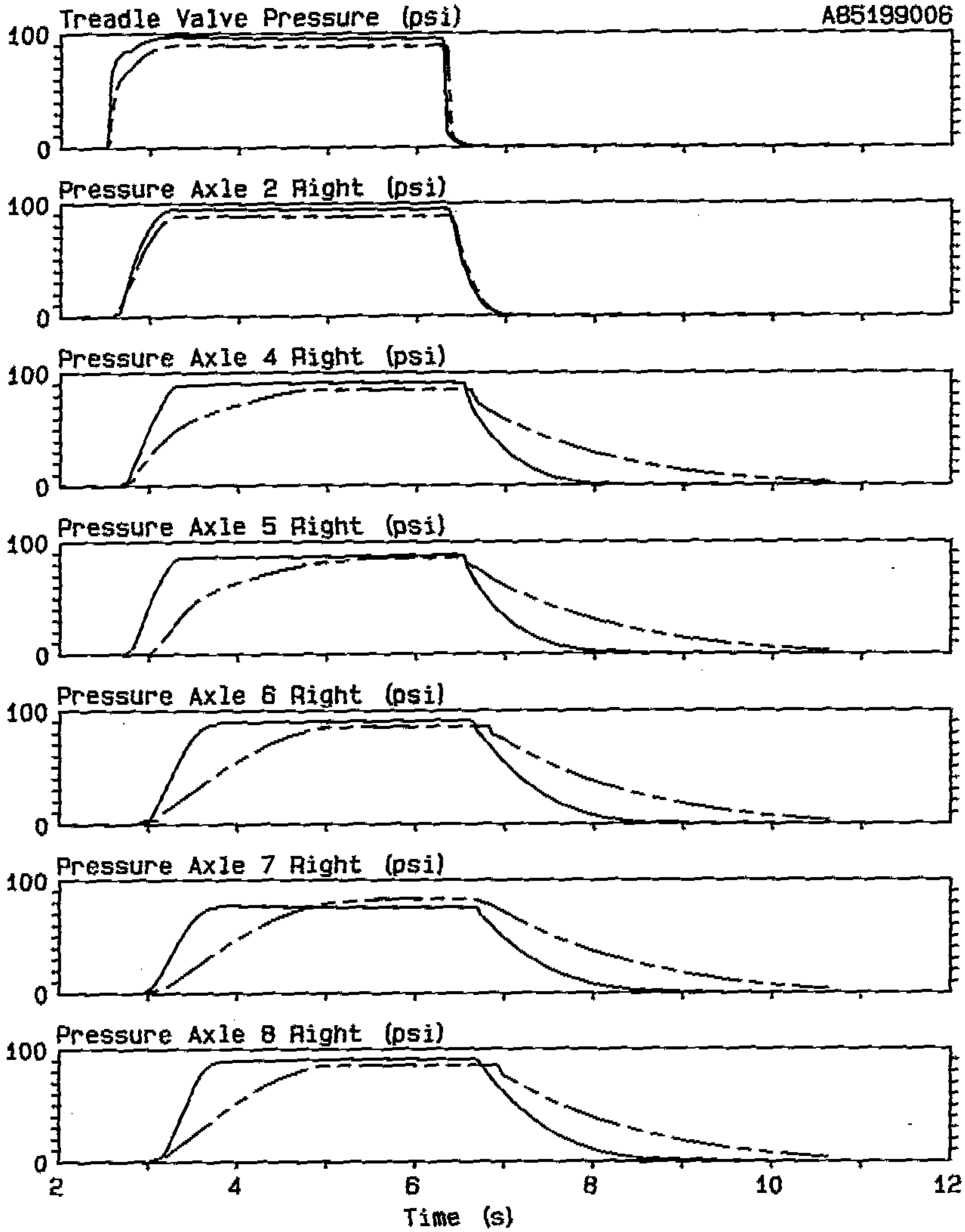


Figure 22/ A-Train and C-train Triples,
Air Brake Application and Release

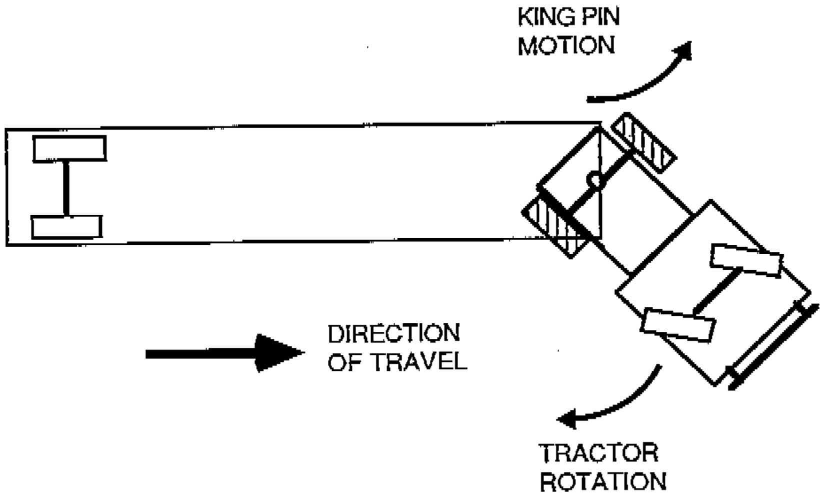


Figure 23/ Tractor Jackknife

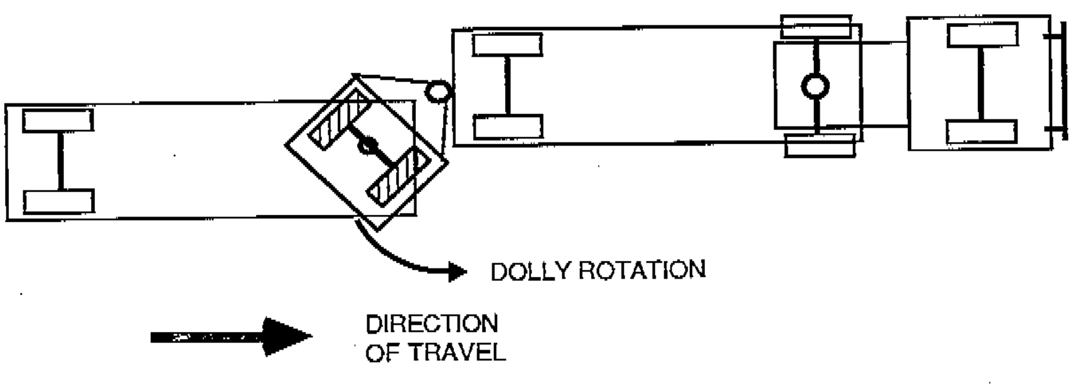


Figure 24/ A-Train Dolly Jackknife

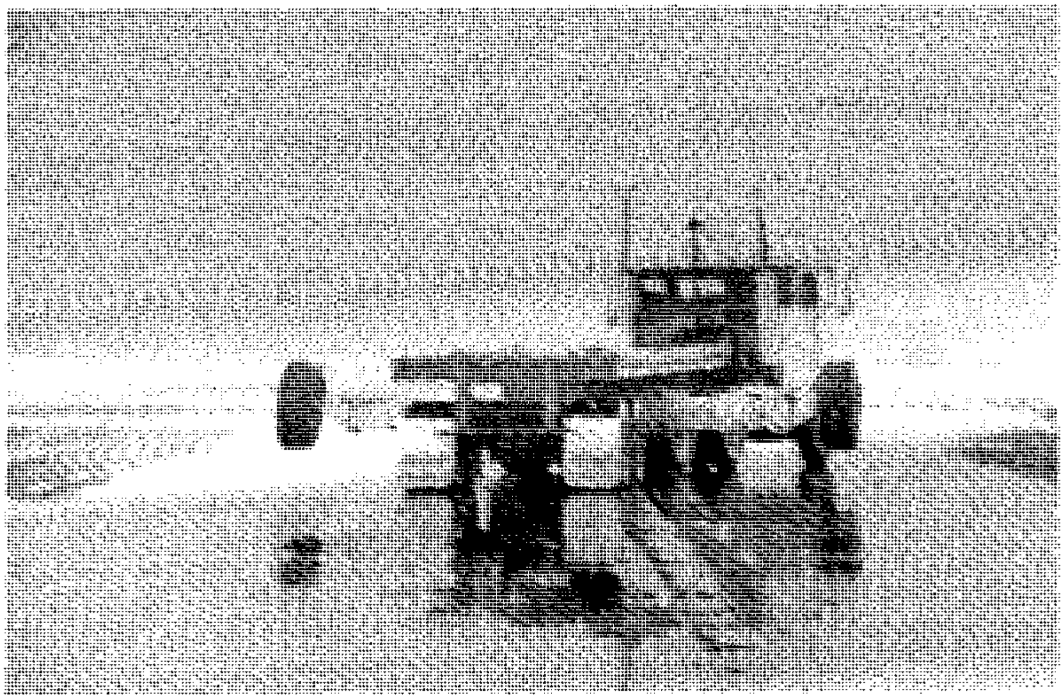


Figure 25/ 45 ft Semi, Straight-Line Braking

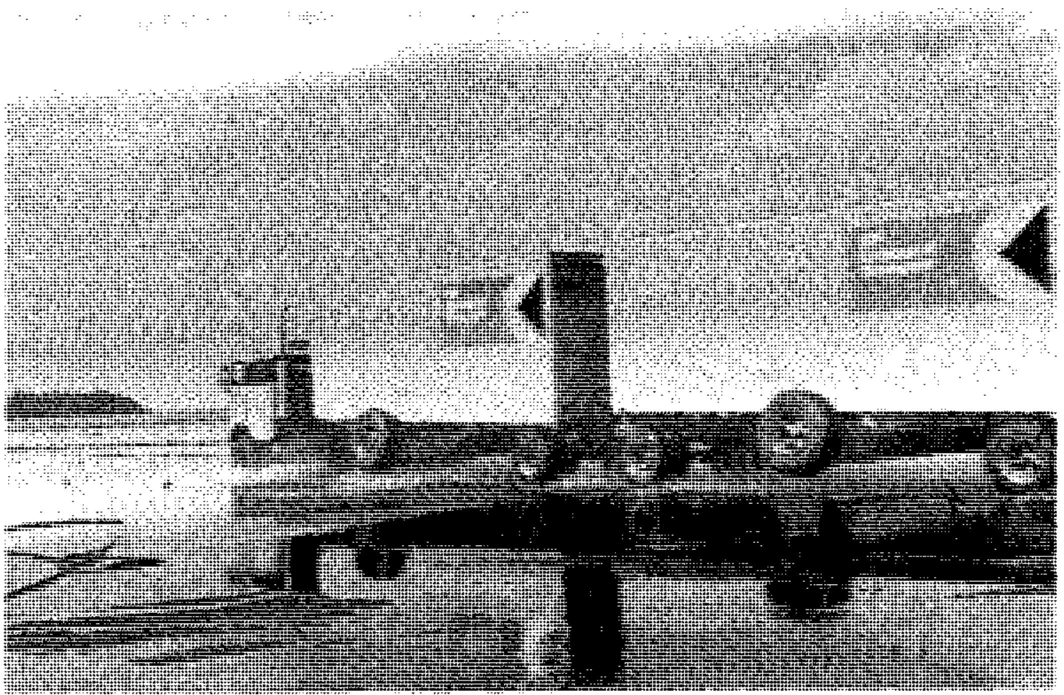


Figure 26/ A-Train Triple, Evasive Manoeuvre

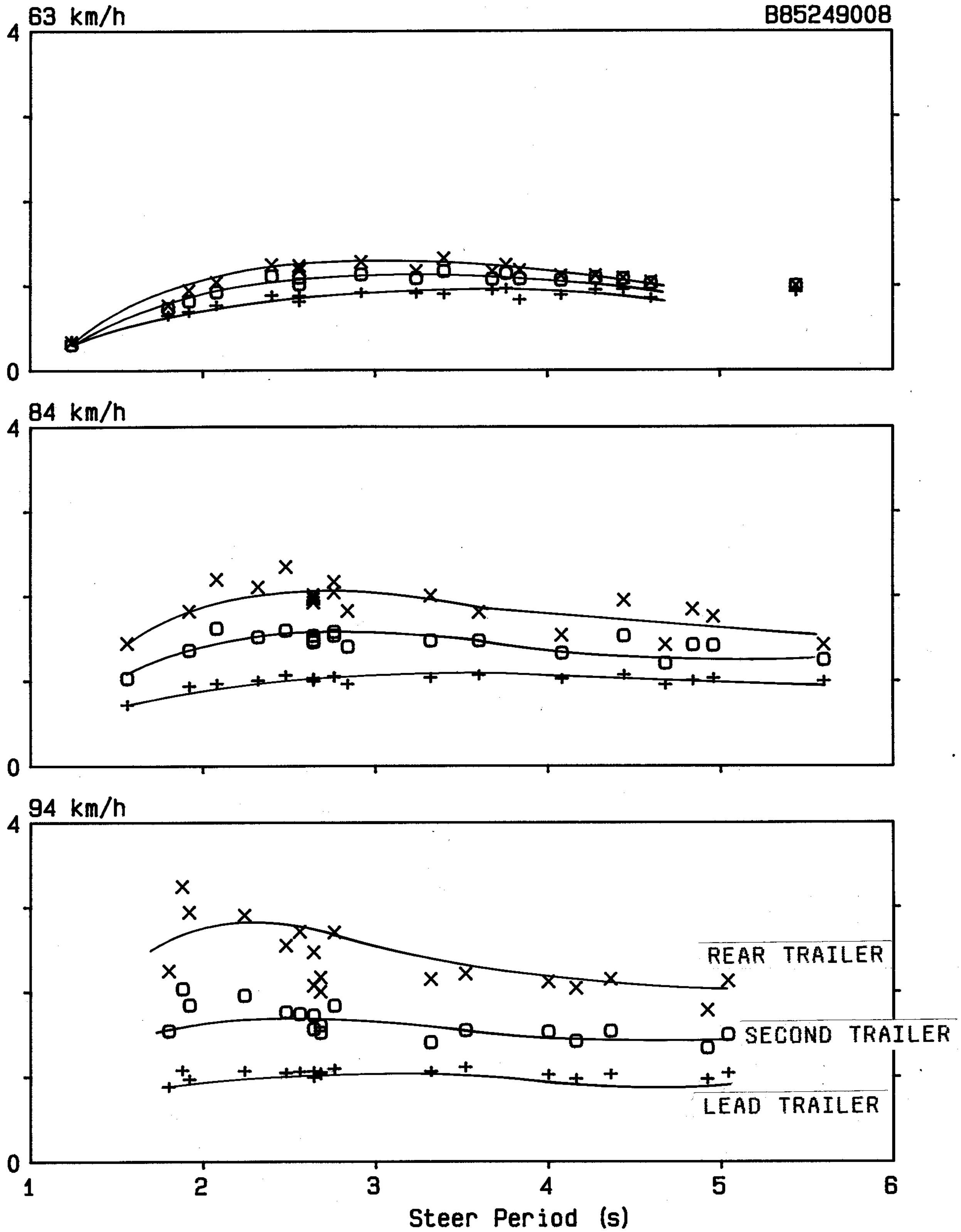


Figure 27/ A-Train Triple, Rearward Amplification of Lateral Acceleration

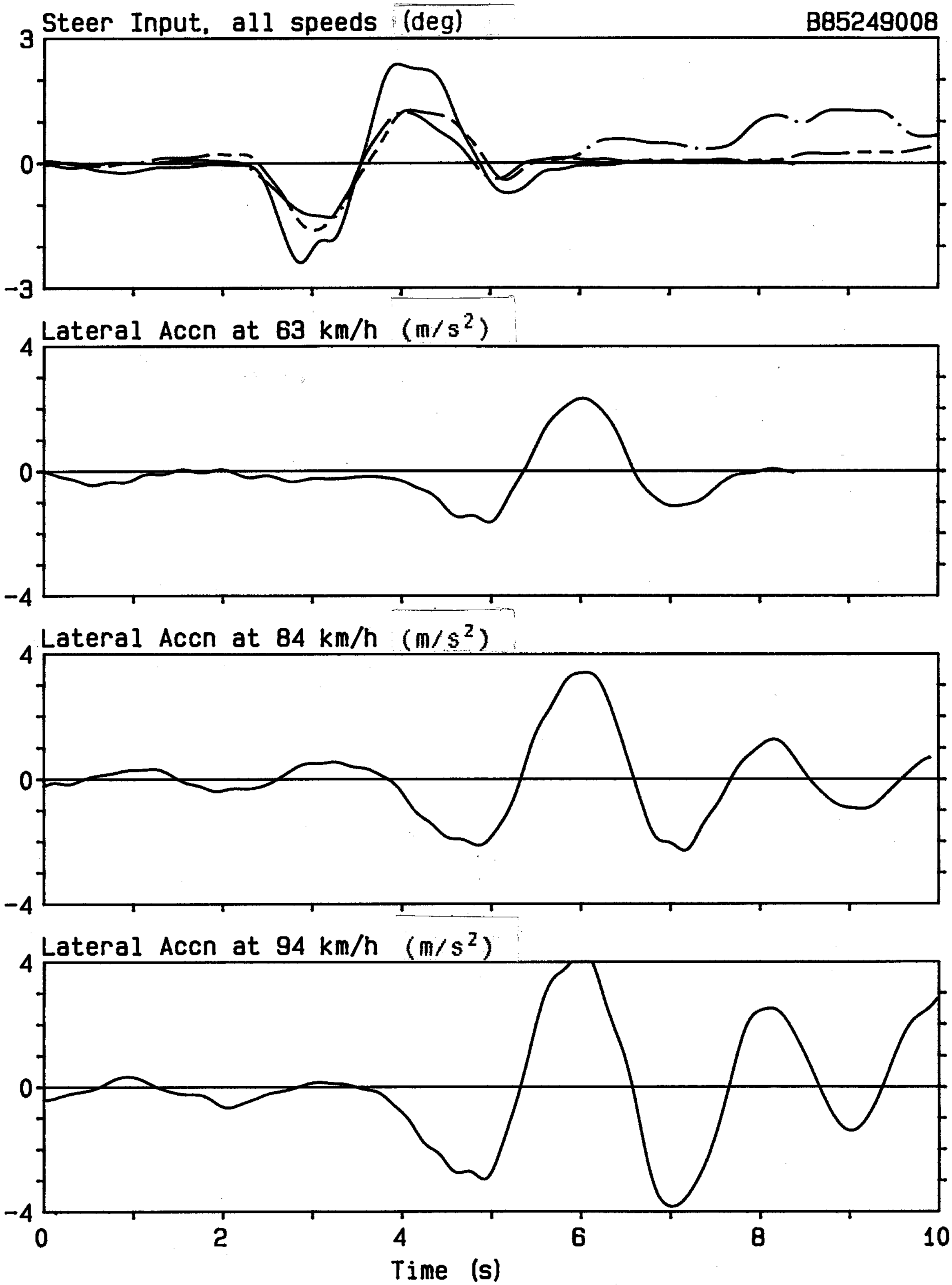


Figure 28/ A-Train Triple, Sinusoidal Steer, Rear Trailer Lateral Acceleration at Three Speeds

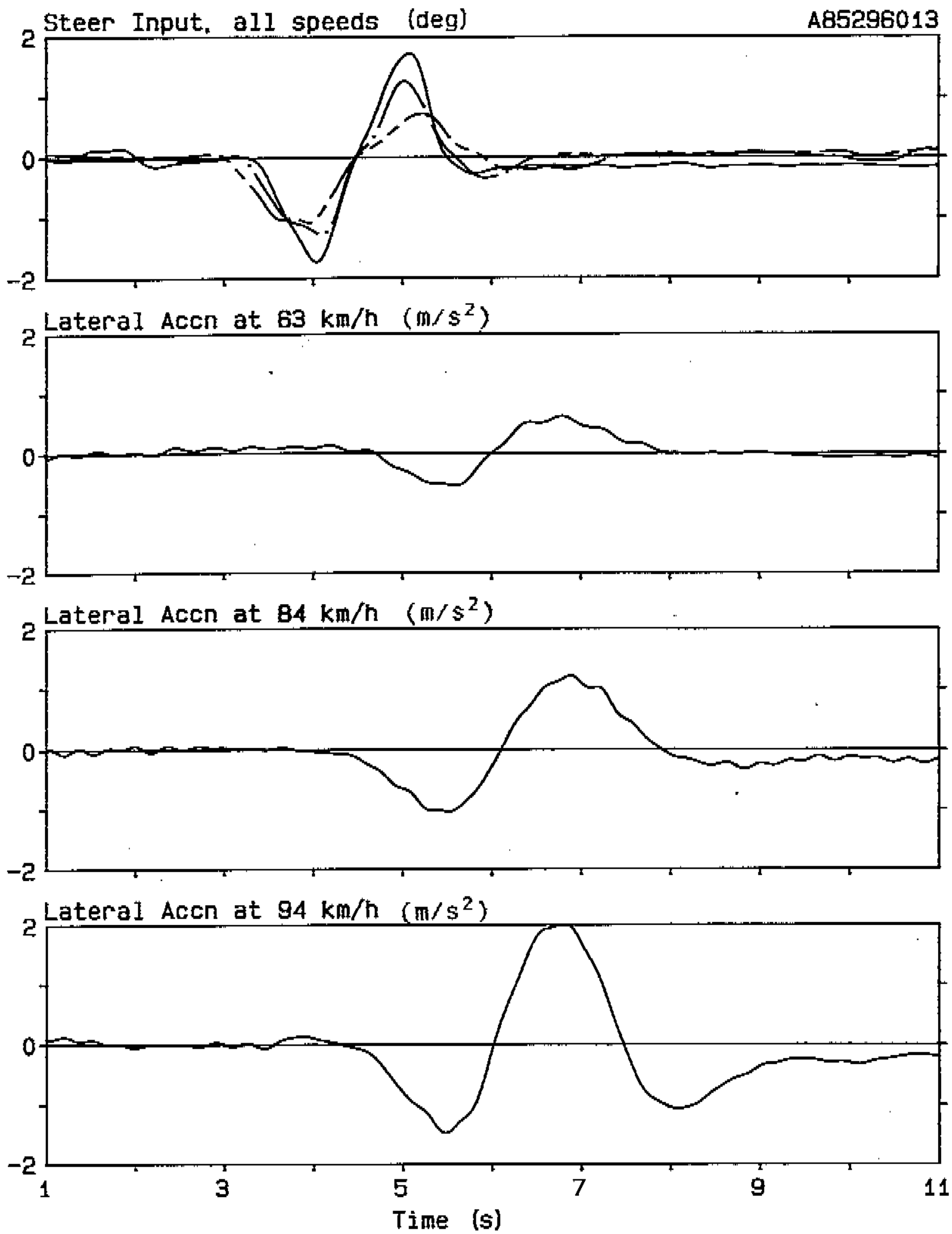


Figure 29/ C-Train Triple, Sinusoidal Steer, Rear Trailer Lateral Acceleration at Three Speeds

Figure 30/ B-Train Double, Lane Change

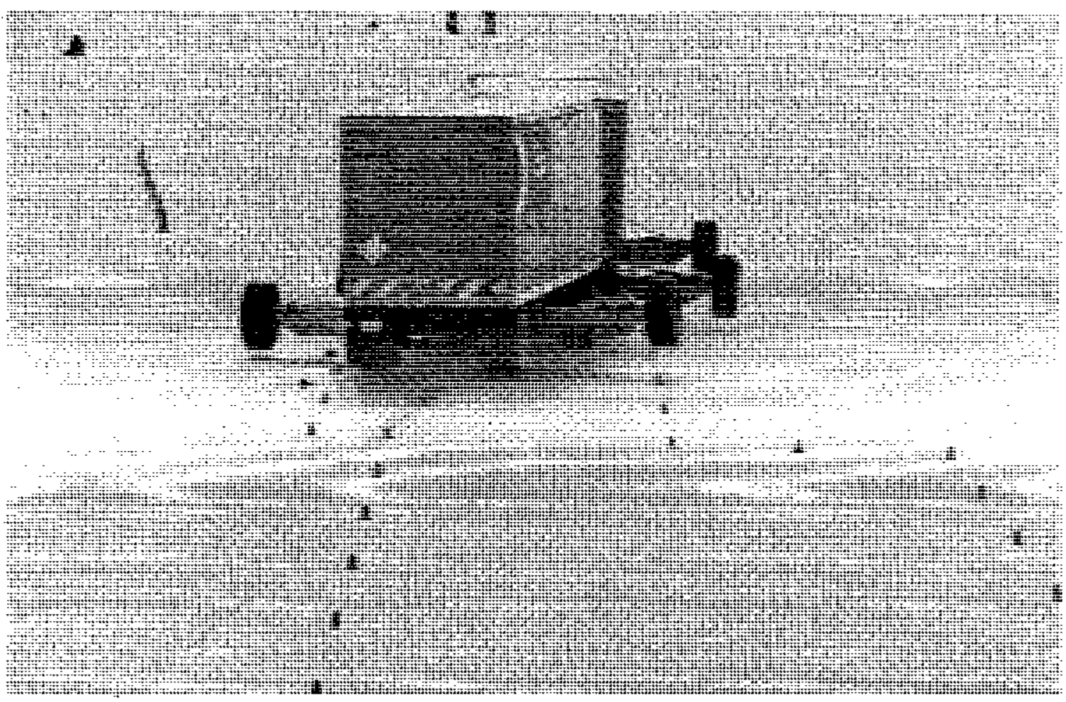


Figure 31/ A-Train Triple, Lane Change

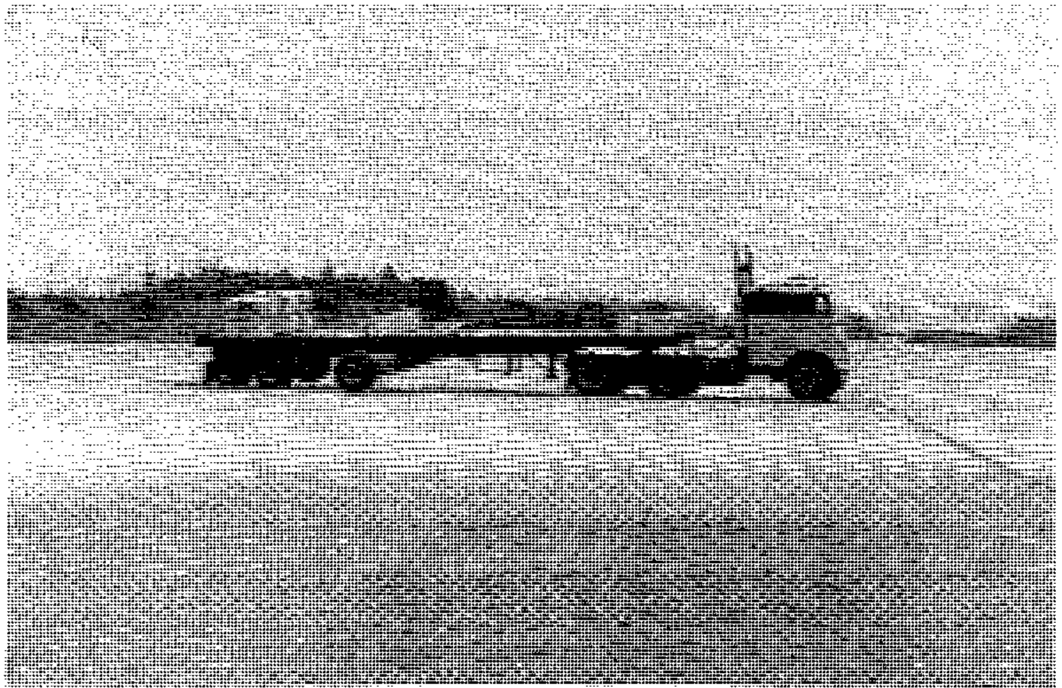


Figure 32/ 45 ft Semi, Steady Circular Turn

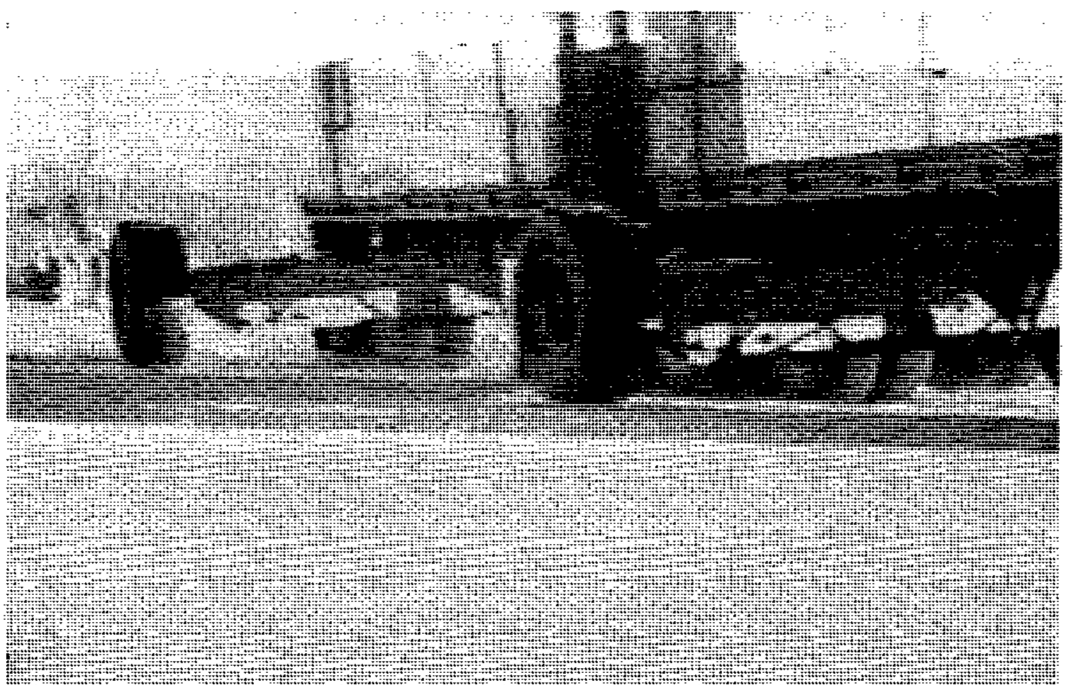


Figure 33/ B-Train Double, Steady Circular Turn

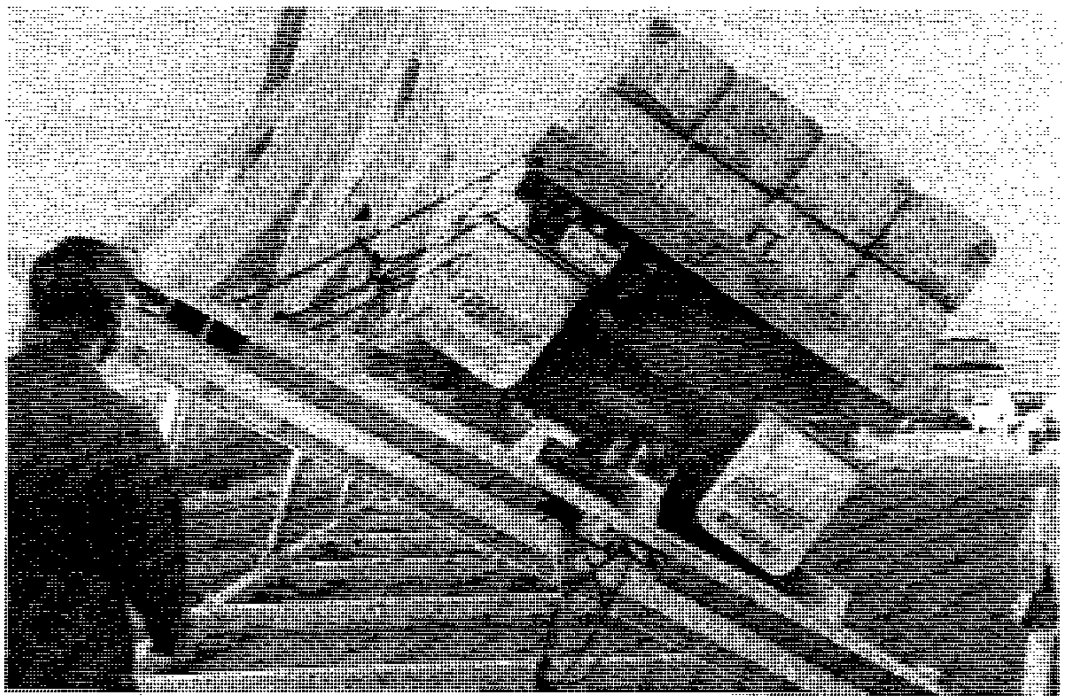


Figure 34/ A-Train Double, Tilt Test

CV-86-01

Procedures for Test of Baseline and Additional Vehicles

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ABSTRACT

A substantial program of full-scale heavy truck dynamic testing was undertaken in 1985 on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study by the Ontario Ministry of Transportation and Communications. Six baseline vehicle configurations and one four-axle semitrailer configured to provide three additional vehicle configurations were tested.

This report presents detailed information on vehicle preparation, test procedures, data processing, and other factors common to the test of the nine vehicle configurations. It supplements the individual vehicle test reports, which only discuss procedures which differ from the standard ones described here.

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This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson.

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1/ INTRODUCTION

The CCMTA/RTAC Vehicle Weights and Dimensions Study is examining the effects of weight and dimension parameters on heavy truck stability and control, and on pavement response. The objective 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, 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 defined as representative of each family and designated as the baseline vehicle configuration. Additional vehicles of interest were also defined. The Ontario Ministry of Transportation and Communications (MTC) was asked to test the six baseline vehicles and a four-axle semitrailer that could be configured to provide three additional vehicle configurations.

This report describes the test procedures employed in the tests of these vehicles. It presents those portions of the test program which were common to the test of all vehicles. It supplements the detailed test reports of each vehicle [2-10] and the summary report [11].

2/ TEST OBJECTIVES

Six baseline vehicle configurations, which are all in common use in some Canadian provinces, were defined. Each baseline vehicle served as a yardstick against which variations in weight, dimension, or equipment 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.

Several additional vehicle configurations were also defined, three of which were also subjected by MTC to exactly the same tests as the baseline vehicles. The objective of these tests was to highlight the characteristics of interest of these particular vehicles, again, to complement the computer simulation.

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.

3/ TEST VEHICLES

The set of vehicles to be tested was defined and provided to MTC. The baseline vehicle configurations are shown in Figure 1, and the additional vehicle configurations are shown in Figure 2. Detailed information on each vehicle may be found in its own test report [2-10]. The baseline vehicles are also described in a summary report [11].

4/ TEST SITES

4.1/ MTC Commercial Vehicle Test Facility (Centralia)

Empty vehicle, low-friction surface tests were conducted at the Ministry of Transportation and Communications (MTC) Commercial Vehicle Test Facility (Centralia). This test facility is located at Huron Industrial Park, Centralia, 45 km (28 mi) north of London, Ontario. The test track, shown in Figure 3, is a former airfield runway 1000 m long by 50 m wide (3281 by 164 ft). It has a test area, approximately 350 m (1148 ft) long, of smooth asphalt, with a smooth approach 150 m (492 ft) long. The test area includes a high-friction surface 150 m (492 ft) long with a dry skid number of about 96, and a low-friction surface 200 m (656 ft) long with a wet skid number of about 18 to 24. A sprinkler system is used for continuous wetting of this surface. There is also a curved entry, radius 86.7 m (284.4 ft), into the low-friction surface. The low-friction surface is abutted by smooth shoulders so that total loss of vehicle control would result in the vehicle sliding off the test area. There is also a low-friction lane on the approach, which can be used effectively to provide a split-friction surface. Vehicle speed through the high-friction test area is limited by the available approach length and tractor power to about 75 km/h. Speed through the low-friction test area is limited to about 60 km/h, to avoid hazard if the vehicle should spin after the safety cables become engaged as a result of loss of control.

The test facility also has about 2000 m^2 (21 529 ft^2) of work space for vehicle preparation and storage. It includes basic shop facilities, an electronics lab, office space, and a ground station for data acquisition and processing.

4.2/ Transport Canada Motor Vehicle Test Centre (Blainville)

Loaded-vehicle, high-friction surface tests were conducted at the Transport Canada Motor Vehicle Test Centre, located at Blainville, Quebec, 35 km (22 mi) north of Montreal. This facility was made available for the study by Transport Canada. The centre has a 6.5 km (4 mi) high-speed track, with high-speed entrance to and exit from the large vehicle dynamics area (VDA), as shown in Figure 4. The section of the VDA parallel to the high-speed track is about 400 m (1312 ft) long. The ASTM E274-77 dry pavement skid number of the VDA at 72 km/h and 30°C is about 90.

Vehicle tests conducted by the ministry were confined to the high-speed track and the VDA. In addition, tilt tests were conducted by others, using a tilt table installed at Blainville for the study [12].

5/ TEST PROGRAM

5.1/ Vehicle Preparation

Two tractors were used as power units for all combinations. A 1976 Freightliner 6x4 was used for all except two turning tests. A 1974 4x2 International Loadstar was used for these tests.

The MTC Freightliner shown in Figure 5 has been used in many previous test programs and was already fully instrumented for the requirements of these tests. It is 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 is rated at 8182 kg (18 000 lb), and the tandem drive axles use a Hendrickson RTE-440 walking beam suspension rated at 20 000 kg (44 000 lb). The wheelbase is 4.40 m (174 in), the tandem axle spread is 1.83 m (72 in), and the drive axle wheel track is 2.44 m (96 in). The fifth wheel is 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).

The 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. The tires were inflated to the manufacturer's recommended pressure of 689 kPa (100 psi) for the tire full rated load. This pressure was used for all tests. It represents the common practice of not reducing tire pressure when the truck runs empty. Tires were installed new and used continuously for tests with various combinations until about half the drive axle tire tread had been consumed. At this point, they were replaced with tires from the same production batch as the original tires for the balance of the test program.

The MTC International Loadstar shown in Figure 6 was used for two turning tests because it allowed the Freightliner to be available for other tests and vehicle preparation activities critical to the test schedule. This tractor is not typical at all of tractors which would haul the test trailers in interprovincial trucking. However, with a 3.81 m (150 in) wheelbase, and a fifth wheel 0.15 m (6 in) forward of the drive axle, its turning characteristics were regarded as sufficiently close to those of the Freightliner that the substitution was acceptable. Other specifications of this tractor are irrelevant to the test program and, therefore, are not presented.

The test trailers were equipped with the following:

- new tires
- outriggers
- safety cables
- instrument packages
- load

All trailers and converter dollies used Michelin XZA radial tires, load range H, size 11R22.5, from the same production batch. The tires were installed new and inflated to the manufacturer's recommended pressures of 689 kPa (100 psi) for the tire full rated load. Tires were run a variable distance before the test, ranging from zero for two airlift axles and three dolly axles to 500 km (350 mi) for vehicles whose first test was at Blainville. Once installed on a vehicle unit, tires were not changed. Thus, vehicle units used for more than one vehicle configuration experienced progressive tire wear as the tests proceeded. Most trailer tires showed little wear as a consequence of the tests, although some did experience severe wear in unusual patterns. However, no tire wore anywhere close to typical rejection limits.

Detachable beam-type underslung outriggers were specially designed, and three sets were fabricated for these tests. The outrigger consisted of a centre section which clamped to a trailer's frame rails and was bolted through the deck around the frame rails. Extension sections were pin jointed to the centre section. Each extension had a wheel fitted with a super single tire. Wheel height was adjustable to compensate for different ground clearances of trailer frame rails. The outrigger assembly is shown in Figures 7 and 8. The van-type trailers used in the triple combinations were basically monocoque construction and required an adapter to be mounted beneath the floor subframe, forward of the stub chassis, to accept and distribute outrigger loads. The outriggers were bolted to this adapter and secured by the triangulated tension chains, which reacted longitudinal load at outrigger touchdown, as seen in Figure 8. One of two pairs of conventional frame-type outriggers already available to MTC was used with the four-axle semitrailer that made up the additional vehicle configuration, as shown in Figure 9. Both sets of outriggers were set with a ground clearance of 0.25 to 0.30 m (10 to 12 in), which corresponds to a trailer roll angle of 6 to 7° at outrigger touchdown.

Some local strengthening of flatbed trailers was conducted so that the structure could resist touchdown loads without permanent deformation.

High-speed dynamic testing of combination vehicles on a low-friction surface carries the hazard of tractor or dolly jackknife, or trailer swing. To prevent damage from such loss of control, high-strength braided wire safety cables were installed between each consecutive pair of vehicle units to limit articulation angles to about 20°. The Freightliner had an auxiliary frame bolted to its frame rails for attachment of safety cables. Heavy-gauge steel clevis brackets were welded onto each trailer and dolly at appropriate locations to mount the articulation limiting cables. A typical safety cable installation is shown in Figure 10.

Each vehicle was tested nominally empty, which was without payload but equipped with instrumentation, outriggers, and safety cables. Each trailer, therefore, weighed about 1500 to 1800 kg (3300 to 4000 lb) more than it would on the highway.

Each vehicle was also tested at one nominal gross weight. This gross weight was achieved by loading trailers with concrete blocks, 53.3 x 70 x 121.9 cm (21 x 24 x 48 in) in size, weighing about 936 kg (2060 lb) each. Blocks were tightly secured with chains. It was specified in the study that the front axle load on all combinations not exceed 6000 kg (13 200 lb) and that all other axles be loaded to approximately 8000 kg (17 600 lb). Blocks were loaded in groups of one or two layers. Longitudinal and vertical location of the loaded trailer centre of gravity, and its roll and yaw moments of inertia, depended upon the trailer construction, number of axles, type of outrigger used, and load block locations.

Before testing, the vehicle was assembled in its test configuration, and the following additional measures were taken:

- The vehicle was checked for general mechanical fitness.
- Brake slack was checked and adjusted as necessary.
- Tire inflation pressure was set.
- Relevant vehicle dimensions were measured.
- The vehicle was weighed by axle, empty and loaded.
- Detailed measurements and an inventory of trailer structural numbers, fittings, and other components were made.
- Instrumentation was installed, as described in Section 5.2.
- Still photographs and video were taken of the vehicle as a whole, parts

thereof, and instrumentation installations.

5.2/ Instrumentation

The MTC Freightliner has been used in many previous test programs. It is equipped to measure the following driver inputs and vehicle responses:

- road wheel steer angle;
- speed;
- distance travelled;
- brake on/off;
- brake treadle valve pressure;
- brake chamber pressures;
- roll, pitch, and yaw angles;
- roll, pitch and yaw rates;
- longitudinal, lateral, and vertical accelerations measured from an inertial platform;
- lateral load at the fifth wheel;
- precise speed and position measurements, using an optical sensor;
- others, not required for this test program, such as steering wheel angle and rate, other wheel speeds, etc.

Integral to the instrumentation package was the Humphrey Model CF18-0907-1 directional gyroscope, shown in Figures 11 and 12. It contains three angular rate transducers to give the roll, pitch, and yaw angular rates; three directional gyroscopes that provide the roll, pitch, and yaw (or heading) angles; and a stabilized inertial platform on which accelerometers are mounted to measure the three linear accelerations. For these tests, only yaw rate, roll and yaw angles, and longitudinal and lateral accelerations were recorded. At the start of a test run, the inertial platform is "caged" or locked to its support frame. At some initial point, it is "uncaged" or released. The initial output from the package, therefore, represents the vehicle attitude as zero, and subsequent outputs through the run are all relative to this initial situation. All tests were conducted so that the vehicle was travelling initially at a steady speed in a straight line, to the greatest extent possible. The linear accelerations were essentially true values measured parallel to the vehicle position at the instant the gyroscope was uncaged. As the vehicle moved through a run, these outputs reflected any vehicle attitude changes due to the ground, such as changes in grade or crossfall and vertical curvature. Corrections may be necessary for this, as described in Section 5.5. The rate transducers have a resolution of 0.01°/s. The directional gyroscopes have a nominal resolution of 0.09° and an accuracy of 0.25°, which is the tolerance of the gyroscope alignment controller. The yaw gyroscope drifts steadily because of the rotation of the earth and is dependent upon latitude of the test site and vehicle heading. This was also corrected, as described in Section 5.5.

Road wheel steer angle was measured using a Spectrol model 139-0-0-502 continuous film rotary potentiometer with essentially infinitesimal resolution. It was mounted on the steering kingpin bushing of the left front wheel, to measure rotation of the spindle relative to the bushing. This measurement was used directly as the steer angle, without any correction for caster, camber, or Ackerman effect.

The brake light switch was used to provide brake on/off status. This was converted to a single bit and included with other vehicle status data in a digital word output by the data acquisition system, as described in Section 5.4.

Brake treadle valve pressure and pressure in the left brake chamber of the lead axle of the tractor drive tandem were measured using Celesco Model PLC-200G pressure transducers.

Vehicle speed was measured using an Airpax Model 087-304-0044 zero velocity magnetic pickup, which counted the passage of notches in the brake drum of the right front wheel. There were 60 milled notches in the drum. A tachometer signal conditioning card provided a continuously varying voltage proportional to notch passage rate. The cumulative notch passage count was also conditioned to provide a continuously varying voltage proportional to distance travelled. When the voltage reached full scale, it automatically reset to minus full scale. The output resulting from driving at a steady speed, therefore, was a continuous inverted N wave. Both these measurements were calibrated by marking the bottom of the right front tire with chalk, driving the vehicle forward slowly for exactly 10 wheel revolutions, and then measuring the distance travelled.

Lateral load at the tractor fifth wheel was measured using a fifth wheel specially modified by MTC, as shown in Figure 13. A long trunnion bar was obtained, and the fifth wheel mounts were modified to accept two cylindrical load cells which were specially fabricated and calibrated by the MTC Research Laboratory. The load cells were captured between the fifth wheel pillow blocks and the retainers by nuts which tensioned the trunnion bar, as shown in Figure 14. A compressive preload of about 22.3 kN (5000 lb) was put into each load cell. The load cells, therefore, gave an output proportional to trailer lateral load parallel to the fifth wheel trunnion bar. A load to the right would increase the left load cell output and correspondingly reduce the right load cell output. It was found that changes in vertical and longitudinal load, and perhaps roll moment, resulted in bending of the trunnion bar, which increased the output of each load cell. Net lateral load, therefore, was obtained from the mean difference of the individual load cell calibrated outputs.

The tractor was equipped to engage the instrumentation either by an automatic or a manual start that uncaged the gyroscope package, initialized the distance counter, commanded the data acquisition system through a calibration sequence, and finally returned it to data status. The automatic start was triggered by means of a downward facing optical sensor beneath the tractor, which responded to reflected light from the ground beneath. A highly reflective tape marker was placed on the ground a suitable distance ahead of the point where the test manoeuvre was to be made. This meant the data sequences for similar runs were alike, which simplified the development of computer data processing. Since the optical sensor would trigger on any reflective surface, it was normally inactive and was armed by the driver on the final approach just before the starting marker.

Each trailer was instrumented to measure the following basic responses:
- articulation angle
- lateral acceleration
- roll angle
- outrigger touchdown

Articulation angle of the lead trailer relative to the tractor was measured by means of the Celesco Model DV-301-150 pull-cord transducer shown in Figure 15. The transducer was fixed on the right-hand side of the tractor, and the pull cord was extended to clip on the left front corner of the trailer. Articulation of the trailer resulted in extension or retraction of the pull cord. The transducer provided a voltage output proportional to the pull-cord extension. Because trailer geometry varied, it was necessary to calibrate articulation angle against transducer output for each trailer. The procedure for this was as follows:

1/ Park the vehicle in a straight line on a level surface.
2/ Measure distances AE, ED, BE, and EC in Figure 16, with the trailer straight.
3/ Zero the transducer conditioned outputs.

4/ Record transducer positive and negative full-scale electronic calibrations.
5/ Measure distances BD and CD in Figure 16.
6/ Drive forward some distance, steering to the left, until transducer output is about 10% of full scale, then record transducer conditioned output and distances BD and CD.
7/ Repeat step 6 for additional increments of 10% of full scale until full scale is reached, then steer to the right until full scale to the right is reached, then return to a straight line.
8/ Compute articulation angles from the geometric measurements and obtain a nominal full-scale calibration for articulation angle from the slope of a least squares linear fit of articulation angle to transducer conditioned output.

Because articulation angles were limited to about 20° by the safety cables, all calibrations were linear within the resolution of the transducers and data acquisition system.

Articulation angle of other trailers relative to a towing unit was obtained by direct measurement, using a Spectrol model 140-0-0-502 small rotary potentiometer set inside a powerful permanent magnet. Because all towing units had fifth wheels without a continuous trunnion bar, there was space to mount the magnet directly onto the bottom of the trailer kingpin. A hole was drilled through the front flange of the fifth wheel, and a wire reference arm was put through the hole and fastened to the potentiometer rotor. An installation is shown in Figure 17. The potentiometer measured trailer articulation angle directly and, because of the wire arm location, was insensitive to longitudinal bumping of the trailer caused by free play of the kingpin in the fifth wheel jaws. Resolution of the potentiometer was 0.5°. The magnet used for this installation was an Eriez No. 277 with a clamping force of 44.5 N (160 oz) and a weight of only 57 g (2 oz). The magnet was powerful enough not only to remain attached to the greasy kingpin, but also to stay fixed in position, through some rather violent manoeuvres.

Lateral acceleration was measured with a Columbia Model SA-107 accelerometer mounted to the deck of the trailer. Unlike lateral acceleration of the tractor, which was measured from an inertial platform, this transducer was sensitive to roll of the trailer and measured a component of the gravitational acceleration due to roll. This was corrected, as described in Section 5.5.

Trailer roll angle was measured using a Humphrey Model VM02-0128-1 vertical gyroscope, the same model that was built into the gyroscope package in the tractor. The exception was the rear trailer of the triple combinations, where a Humphrey Model RT03-0502-1 rate transducer was installed, also the same model built into the tractor gyroscope package. Roll angle of this trailer was computed by integration of roll rate.

An outrigger touchdown indicator was set up by strain gauging the tabs to which the outrigger tension chains were attached, as shown in Figure 18. When an outrigger touched down, the change in chain tension resulted in a strain response offset. Left and right outriggers were rigged in a single channel so that right-side touchdown resulted in a positive response and left-side touchdown resulted in a negative response. However, these signals were noisy, tended to drift, and were ultimately not needed because the roll angle characteristic response gave a good indication of outrigger touchdown.

Additional Celesco model PLC-200G pressure transducers were installed in brake chambers of trailers and dollies for the brake tests, as shown in Figure 19. Generally, one transducer was installed for each axle of the trailer.

A single package containing the accelerometer and roll gyroscope, signal conditioning, multiplexer, and power supply contained the bulk of the instrumentation for each trailer. This package was mounted on the deck of the trailer midway between the kingpin and the centre of the trailer axles. It is shown in Figure 20, and its contents are shown in Figure 21.

Each A-dolly was instrumented to measure the hitch articulation angle by means of a Spectrol model 140 rotary potentiometer set inside a powerful permanent magnet, and a flexible reference arm, as shown in Figure 22. Each B-dolly was instrumented to measure its axle steer angle by means of a Spectrol model 139 rotary potentiometer, as shown in Figure 23. Each dolly also had an accelerometer installed to measure lateral acceleration at a point close to the trailer kingpin.

The data acquisition system described in Section 5.4 had a capacity of 42 channels, of which up to 36 were used. Fourteen channels were allocated to the tractor multiplex system for the entire test program. Ten channels were allocated to the multiplex system in the instrument box on the lead trailer, of which three were used for dynamic data; five, for pressure transducers used during brake tests; and two spares. Twelve channels were allocated to the multiplexer in the box on a second trailer, and for triples the third trailer transducers were wired into this box. The triples, therefore, used almost the full capacity of the multiplex system, and every other vehicle tested used a subset of the data channels, depending upon its configuration. The location and type of instruments and their allocation to the multiplex system are all presented in Table 1. Channels 1 to 17 and 20 to 24 were used for semi-trailers; channels 1 to 32 were used for doubles; and all 36 channels were used for triples.

5.3/ Detailed Test Procedures

The tests and demonstration conducted on all test vehicle configurations are broken down into four categories:

1/ Stationary
- Air brake system
- Tilt test

2/ Low-Speed Turns
- Steady-state offtracking
- Right-hand turn
- Channelized right turn

3/ Low-Friction Dynamic, Empty Vehicle
- Straight-line braking demonstration
- Evasive manoeuvre

4/ High-Friction Dynamic, Loaded Vehicle
- Sinusoidal steer
- Lane change
- Straight-line driving
- Steady circular turn

The following subsections present the rationale for each test and provide details of the procedure followed. The output expected from each test is presented in the corresponding subsection of Section 5.5, where details of the data processing are discussed.

For all driving tests where a sequence of runs at increasing speeds was required, speeds were selected that resulted from the driver using full

Table 1/ Instrumentation Installed

No	Measurement	Instrument	Full Scale
1	Tractor steer angle	Spectrol 139 potentiometer	25.02°
2	Tractor roll angle	Humphrey CF18-0907-1 gyroscope package	8.85°
3	Tractor lateral acceleration	Kistler 303B accelerometer	0.957 g
4	Tractor yaw rate	Humphrey RT03-0502-1 angular rate transducer	38.7°/s
5	Tractor longitudinal acceleration	Kistler 303B accelerometer	0.974 g
6	Tractor speed, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	104.8 km/h
7	Tractor distance, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	56.3 m/ramp
8	Tractor fifth wheel load, left-hand side	MTC load cell	9890 lb
9	Tractor fifth wheel load, right-hand side	MTC load cell	10290 lb
10	Tractor treadle valve pressure	Celesco PLC-200G	100 psi
11	Tractor brake pressure, axle 2 Left	Celesco PLC-200G	99.80 psi
12	Tractor lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
13	Tractor yaw angle	Humphrey CF18-0907-1 gyroscope package	17.73°
14	Trailer 1 articulation angle	Celesco pull cord DV-301-150	Varies
15	Trailer 1 lateral acceleration	Columbia SA-107 accelerometer	0.995 g
16	Trailer 1 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.90°
17	Trailer 1 outrigger touchdown	Strain gauge bridge	1.0 V
18	Dolly 1 hitch angle	Spectrol 139 potentiometer	25.0°
19	Dolly 1 lateral acceleration	Columbia SA-107 accelerometer	0.996 g
20	Brake pressure, axle 4 right	Celesco PLC-200G	104.96 psi
21	Brake pressure, axle 5 right	Celesco PLC-200G	101.06 psi
22	Brake pressure, axle 6 right	Celesco PLC-200G	102.07 psi
23	Brake pressure, axle 7 right	Celesco PLC-200G	101.93 psi
24	Brake pressure, axle 8 right	Celesco PLC-200G	106.79 psi
25	Spare		
26	Spare		
27	Trailer 1 articulation angle	Spectrol 140 potentiometer	22.8°
28	Trailer 2 lateral acceleration	Columbia SA-107 accelerometer	0.980 g
29	Trailer 2 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.91°
30	Trailer 2 outrigger touchdown	Strain gauge bridge	1.0 V
31	Dolly 2 hitch angle	Spectrol 139 potentiometer	25.0°
32	Dolly 2 lateral acceleration	Columbia SA-107 accelerometer	0.993 g
33	Trailer 3 articulation angle	Spectrol 140 potentiometer	22.7°
34	Trailer 3 lateral acceleration	Columbia SA-107 accelerometer	0.986 g
35	Trailer 3 roll rate	Humphrey RT03-0502-1 angular rate transducer	80.85°/s
36	Trailer 3 outrigger touchdown	Strain gauge bridge	1.0 V

throttle in the appropriate gear. The engine speed control then acted as a limiter to hold speed to the required value. This was beneficial, as manual speed control at the stability thresholds was difficult to maintain because of vehicle cab vibration, extraneous aerodynamic and inertial loading during an aggressive manoeuvre, and driver work load. The actual controlled speeds used in the various tests were 34, 40, 47, 55, 63, 72, 77, 80, 84, 89, and 94 km/h. The nominal speeds used by the driver were in miles per hour and differed somewhat from the actual values at the highest speed.

All tests except for the two right turns were conducted with outriggers and safety cables installed.

5.3.1/ Offtracking

The interaction of large trucks with highway geometrics was not specifically included in the study. It is, however, perhaps the most evident manifestation of increasing truck size to the motoring public in urban communities. Large trucks simply take more space and time to make turns than smaller trucks and, thus, appear to impede traffic. Three tests, therefore, were added to illustrate the space requirements needed for turns and to demonstrate the swept paths.

Steady-state offtracking is the most widely understood measure of the turning capability of large trucks. In normal driving, however, a steady-state offtracking situation would only likely be encountered in a 270° cloverleaf turn on a freeway ramp. In many cases these ramps are made up not of a principal circular arc with entry and exit spirals, but of several spirals and curves to accommodate the local space and terrain requirements. Trucks using these less regular ramps may not reach a true steady state. Nevertheless, steady-state offtracking remains a useful ranking of the space required to turn a large truck, though it may be somewhat misleading for some turns.

Steady-state offtracking was determined by driving the loaded vehicle on a high-friction surface at low speed, less than 5 km/h, in a circle of radius 29.87 m (98 ft). The turn was made with the truck on the inside of the circle with the tractor outer front wheel following the circumference. The vehicle traversed the circle until steady-state offtracking had been achieved and continued to about one full revolution. Measurements were then taken from the centre of the circle to each axle's innermost tire. The test was repeated in the opposite direction to determine if axle or chassis misalignment affected the results.

This test was conducted at Blainville, and the course is shown in Figure 24.

Instrumentation was used for the test, mainly to measure the lateral load at the tractor fifth wheel as the vehicle was driven through the manoeuvre. The axle spacings and loads on the trailers require the tractor to apply a lateral load to turn the combination through the manoeuvre from straight line to full curve. The lateral load measured was considered a measure of the trailer's resistance to turning. The load was measured by the tractor fifth wheel transducer.

The following procedure was used to conduct this test.

Vehicle Preparation

1/ All instrumentation operational.
2/ Vehicle loaded.

Test Area Preparation

1/ Set out cones to mark the 29.87 m radius circle and a tangential entry to the circle for each direction. Ensure there are suitable gaps for vehicle entry and exit. Mark the entry point with an extra cone.
2/ Park the cherry picker, with the bucket on the diameter which approximately bisects the entry tangents and is on the opposite side to the entries.

Test Procedure

1/ Approach the entry tangent at low speed with the vehicle straight; park with the tractor front axle on the tangent point and the wheels inside the circle.
2/ Command start tape.
3/ Wait 2 s, then uncage gyroscope.
4/ Wait 5 s, then proceed at low speed around the circle, with the tractor outer front wheel tracking the circle.
5/ Stop after at least a full circle has been completed, with the off-tracking of the last trailer maximally visible from the cherry picker.
6/ Wait 5 s, then cage the gyroscope.
7/ Stop the tape.
8/ Measure the distance from the centre of the circle to the inner wheel of each axle.

9/ Measure the distance from the rear axle to the circle.
10/ Videotape all runs from the cherry picker and other vantage points of interest.
11/ Take still photographs of the vehicle final position.

5.3.2/ Right-Hand Turn

The 90° right-hand turn is probably the most demanding turning manoeuvre for large trucks. In urban areas, or where there are low truck volumes, small curb radii are often found. When a long truck comes to such an intersection, where the truck is too large to make the turn with a simple steady steer input by the driver, there are two strategies available to create more space for the turn. Either the driver can move to the left of the entry lane to increase the radius or ahead and intrude into lanes beside the exit lane in the roadway into which the turn is being made. In either case, the driver is using the space of other vehicles, which increases the hazard of the turn. In the first case, it is possible that the driver of a small vehicle also intending to turn right could misunderstand the truck driver's intention in the initial move to the left and become trapped to the right of the truck as it started to turn to the right. This strategy is, therefore, considered undesirable. The second strategy also uses the space of other vehicles, but at least the presence and intention of the truck are clear throughout, and the truck driver would not normally enter that space if oncoming vehicles were too close.

Vehicle trajectory in a right-hand turn was evaluated using a 15 m (49 ft) curb radius, with entry and exit lane widths of 3.66 m (12 ft), as shown in Figure 25. This has been used in highway geometric design standards for many years for turns from a two-lane two-way road into a four-lane two-way road, where the vehicle may exit in the left-hand lane rather than the right- hand lane. The driver's task is to approach the turn in the entry lane and make the "best" turn possible to exit ultimately in the curb lane. The "best" turn is a turn that in the opinion of the driver and test director caused the rearmost axle right wheel to track parallel and as close to the circumferential curb as possible. The swept path of the tractor left front wheel, and rear trailer right rear wheel, were marked with cones on the rays shown in Figure 26. When the "best" turn was achieved, the positions of the marker cones were measured, and hence, the turn swept path was recorded.

This test was conducted at Centralia. The MTC International tractor was used as the power unit for all vehicles, and the trailers were empty. No instrumentation was used on this test.

The following procedure was used to conduct this test.

Vehicle Preparation
1/ Vehicle empty.

Test Area Preparation
1/ Survey the turn and measurement rays and mark them on the ground with spray paint.
2/ Set out the cones to mark the curb. Mark a start point at point 4 in Figure 25.
3/ Provide a marker cone near each measurement point.
4/ Park the cherry picker adjacent to the exit lane, with the bucket over the exit lane stripe.

Test Procedure
1/ Approach the test area with the vehicle straight; park with the front axle of the tractor at the start point.
2/ When all are ready, make a right-hand turn to exit ultimately in the exit lane. Do not move to the left out of the entry lane. Make the "best" turn possible without running over the "curb."
3/ Place a cone beside the left front wheel and the right rear wheel as each passes over a measurement ray.
4/ Videotape all runs from the cherry picker.
5/ Take still photographs.
6/ When the "best" turn has been achieved, measure the radii of inner and outer swept path cones from the centre of the curb circle.

5.3.3/ Channelized Right Turn

The overall course, with island geometry, is shown in Figure 26. This is a typical highway geometric design standard for use in urban areas, where property presents a problem and speeds are low. The taper lengths assume entry and exit roadway speed limits of 60 km/h. The turn might be superelevated and would have an advisory speed limit of 25 or 30 km/h. Vehicle trajectory in a channelized right-hand turn was evaluated using a 25 m (82 ft) curb radius with a channel width of 5.5 m (18 ft). Entry and exit lane widths were 3.66 m (12 ft), and deceleration and acceleration taper lengths were 75 and 50 m (246 and 164 ft), respectively.

This test was conducted at Centralia, with the MTC International used as the power unit for all vehicles and the test trailers empty. No instrumentation was used for this test.

The following procedure was used to conduct this test.

Vehicle Preparation

1/ Vehicle empty.

Test Area Preparation

1/ Survey the turn, island, and measurement rays; mark them on the ground with spray paint.
2/ Set out the cones to mark the curb, island, and exit lane. Mark a start point with an extra cone at point A of the course, shown in Figure 26.
3/ Provide a marker cone near each measurement point.
4/ Park the cherry picker with a view down the entrance channel towards the rear of the vehicle.

Test Procedure

1/ Approach the test area with the vehicle straight; park with the tractor front axle at the start point.
2/ When all are ready, drive at low speed so that the tractor left front wheel passes as close as possible to point B on the island bull nose. Follow the island curb as close as possible to point C in Figure 26, then proceed into the exit lane.
3/ Place a marker cone beside the innermost right rear wheel of the vehicle as it passes near each measurement ray.
4/ Videotape all runs from the cherry picker.
5/ Take still photographs.
6/ Measure the clearance from the curb to the measurement cones.

This procedure results in measurement of the transient offtracking of the vehicle during passage through the channel, with the tractor following the most favourable line. In practice, there would be a gutter, perhaps 0.30 m (1 ft) wide on the left-hand side, which the driver would not normally use, and the turn might well be made at a speed when the lateral acceleration would tend to reduce the offtracking. Of course, in a congested traffic situation the turn could also be taken at a very low speed.

5.3.4/ Air Brake System

Balanced braking of a combination vehicle requires that the brake systems of all vehicle units be compatible so that pneumatic and torque balances can be achieved at each axle. In addition, short brake application and release times provide a brake system responsive to the driver's needs and reduce stopping distance and fuel consumption. Pneumatic balance and brake timing are both determined by the details for the air brake system, valves, and plumbing. Torque balance is determined by the foundation brake characteristics and axle loads and is a much more complex subject. A comprehensive treatment of the braking characteristics of combination vehicles was beyond the scope of the study. The issues of air brake system compatibility, however, are much more straightforward and could be illustrated by two tests.

1/ The first test follows the style of SAE Standard J982a for timing of the air brake system of a single vehicle unit. The test was, however, applied to the entire vehicle as an operational combination. It uses a maximum rate brake application, with a regulated air supply at 689 kPa (100 psi). The time for the air pressure at each axle to reach 414 kPa (60 psi) is determined. The individual pressures at each axle are also found. Pressure differentials can cause differences in torque between axles, affecting the overall brake balance. Brake release times, which affect the drag on combination vehicles, were also determined. This test is very aggressive, as the high pressure gradients might, for instance, overcome "sticky" valves that would take a significant pressure differential to crack. This test represents the rare emergency brake situation where maximum performance is demanded.

2/ The second test was a service brake application, with treadle valve travel limited to provide about 118 kPa (20 psi) with a 689 kPa (100 psi) supply and a normal rate brake application. The timing and pressure differentials in this test illustrate how the air system behaves in normal use, the usual case.

The following procedure was used to conduct this test.

Vehicle Preparation

1/ Install a pressure transducer in the brake chamber or air hose of one axle of the group fed by each relay valve on each trailer and dolly.
2/ Supply tractor with shop air, regulated at 689 kPa (100 psi).

3/ Check brake strokes and adjust as necessary.

SAE J982a Test Procedure

1/ Select "steer period generator" (SPG) (described in Section 5.3.8) to 8 s.
2/ When all is ready, start tape, wait 2 s, then uncage gyroscope.
3/ Start SPG using the same hand as uncaged the gyroscope.
4/ When ready light sequence has been completed, apply maximum treadle valve, braking at maximum rate.
5/ When SPG completes one-half cycle, after 4 s, release treadle valve.
6/ When SPG completes the full cycle, cage the gyroscope.
7/ Stop the tape.
8/ Repeat three times.

Service Brake Application Test Procedure

1/ Install treadle valve limiting device and adjust such that maximum available travel corresponds to 118 kPa (20 psi) on the dashboard gauge.
2/ Select SPG to 8 s.
3/ When all is ready, start tape, wait 2 s, then uncage gyroscope.
4/ Start SPG using the same hand as uncaged the gyroscope.
5/ When ready light sequence has been completed, apply treadle valve, braking at a normal rate to the limit of available travel.
6/ When SPG completes one-half cycle, after 4 s, release treadle valve.
7/ When SPG completes the full cycle, cage the gyroscope.
8/ Stop the tape.
9/ Repeat three times.

5.3.5/ Straight-Line Braking Demonstration

The action of braking an empty combination vehicle to a halt on a low-friction surface may result in loss of vehicle control if the wheels are locked. The physical characteristics of current braking systems make it extremely difficult to conduct rigorous tests and obtain repeatable results that can be generalized to other vehicles. A series of straight-line stops was therefore conducted to demonstrate modes in which vehicles may become unstable.

In this demonstration the vehicle was driven at 47 km/h onto the wet low-friction test area, which had an approximate skid number of 20, and braked to a halt. A series of runs was conducted with increasing brake application pressure until all wheels of an axle group locked. The driver was allowed to steer as necessary to keep the tractor within the traffic lane. The speed was high enough that incipient unstable behaviour was always evident, but it was not so high as to be unnecessarily aggressive.

The primary results of this test were videotapes showing the vehicle's response to the braking input.

This test was conducted at Centralia. The following procedure was used.

Vehicle Preparation

1/ Deactivate tractor front axle brakes.
2/ Check brake strokes and adjust as necessary.
3/ Vehicle empty.
4/ Hook up treadle valve pressure limiter.

Test Area Preparation

1/ Wet the low-friction test area.
2/ Place a cone at a suitable point adjacent to a marked lane on the test area. This cone will mark the brake application point.
3/ Place a marker so that the gyroscope can be uncaged 90 m (295 ft) before the start cone.
4/ Park the cherry picker close to the approach and place the bucket as high as possible over the lane centreline.

Test Procedure

1/ Approach the test area at 47 km/h governed speed in a straight line.
2/ Start tape at least 2 s before start cone.
3/ Uncage gyroscope.
4/ Apply brakes with the treadle valve at the start cone, to the limit permitted.
5/ Do not steer unless a potentially hazardous situation is developing; then make a recovery.
6/ When the vehicle has come to a stop, keep brakes on, wait 2 s, then cage the gyroscope.
7/ Stop the tape.
8/ Videotape all runs from the cherry picker and other vantage points of interest.
9/ Take still photographs.
10/ Start with a brake pressure of 103 kPa (15 psi).
11/ For each run, increase brake pressure by 34 kPa (5 psi).
12/ Run once only if there is no lateral/directional instability. When

instability occurs, repeat the run to determine if the mode is consistent. Do not increase brake pressure after this. If the first unstable run is too violent, make the subsequent runs with a somewhat lower brake pressure. Do not increase brake pressure past the point where all axles are locking; if the vehicle remains in a straight line at this point, note behaviour.

5.3.6/ Evasive Manoeuvre

This test is representative of an obstacle avoidance manoeuvre on a two-lane, two-way highway, where the sudden appearance of an obstacle necessitates a fast lane change to the left, then return to the original lane to avoid oncoming traffic. The test course was laid out on a wet low-friction surface, using marker cones as shown in Figure 27. The vehicle was empty. The driver was instructed to approached the course at constant speed and manoeuvre the vehicle through the gates, 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 tractor jackknife, trailer swing, or dolly jackknife, or trailer response resulted a 1 m (3.3 ft) slide out of lane. Runs were repeated when responses were found to be inconsistent with the trend established by preceding runs, or when any cone was struck. When a run was made in which the vehicle response was unstable or undesirable, corroborating runs, varying by no more than 3 km/h, were conducted to bracket the stability boundary.

This test was conducted at Centralia. It was originally proposed as a lane-change manoeuvre, which is described in Section 5.3.8. However, this task did not sufficiently exercise most vehicles because the critical gate size for the most challenged vehicle, the 5-axle 48 ft (14.65 m) semi, had to be used. In the experience of ministry test staff, speeds in excess of 63 km/h were unduly hazardous for an empty vehicle equipped with safety cables on the wet low-friction surface. While the test area was provided with a high-friction shoulder, it was considered that the energy and momentum in total loss of control of a double or triple at any higher speed would be unnecessarily hazardous. Experience has shown that while the test driver is able to duplicate such manoeuvres consistently, the mode of loss of control may not be predictable, so speeds had to be limited for reasons of safety and preservation of equipment. A symmetrical gate arrangement was selected, and the gate size was the minimum that could be negotiated by the most critical vehicle at a speed below the 63 km/h safety limit.

The following procedure was used to conduct this test.

Vehicle Preparation

1/ Vehicle empty.

Test Area Preparation

1/ Set cones to mark an evasive manoeuvre, with gates of 22.5 m (73.8 ft) and 20 m (65.6 ft) in the left-hand lane.
2/ Set an automatic gyroscope to uncage at white marker 200 m (656 ft) before the gate.
3/ Position the cherry picker on the left side of the approach, with the bucket centred over the left-hand lane.
4/ Wet the low-friction test area.

Test Procedure

1/ Accelerate the vehicle to reach test speed with the vehicle straight at the gyroscope uncage marker.
2/ Start tape at least 2 s before the gyroscope uncage marker.
3/ Make manoeuvre through the marked gates, keeping all wheels of the vehicle inside the marked lanes as far as is possible. Exit straight along the marked exit lane.
4/ If a potentially hazardous situation develops, make a recovery.
5/ When the run has been completed, cage the gyroscope before turning to exit the test area.
6/ Stop the tape.
7/ Videotape all runs from the cherry picker and other vantage points of interest.
8/ Take still photographs.
9/ For the first run, use 47 km/h governed speed, then governed speeds until vehicle responses are considered potentially unstable or undesirable, then bracket.
10/ Make each run twice for consistency. When test limiting speed is approached, make any runs necessary to establish the stability characteristics and threshold. Do not exceed 63 km/h.

5.3.7/ 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, a vehicle trajectory similar to the lane change, described in Section

5.3.8. The lane change is constrained within a 3.66 m (12 ft) lane, whereas the sinusoidal steer results in a variable sidestep depending upon the speed and steer amplitude. The steer input was made to achieve a tractor lateral acceleration of about 0.15 g.

This steer input is a standard method by which lateral/directional response of the vehicle could be excited. The input was chosen to be large enough to get a reasonable response from the vehicle, but not so large that units of the most responsive vehicles would be sliding or rolling excessively. This steer input permitted the lateral acceleration of each trailer of a combination vehicle to be examined, relative to the tractor lateral acceleration. These acceleration ratios, properly known as rearward amplification of lateral acceleration, are an important inherent dynamic characteristic of combination vehicles. An acceleration ratio no greater than unity means the trailer has a lower acceleration than the tractor, so the driver may be considered aware of vehicle response as he is in a position to sense the greatest lateral acceleration in the vehicle. An acceleration ratio greater than unity means a trailer has a higher lateral acceleration than the tractor, and if the ratio and tractor lateral acceleration are high enough, the trailer may slide or roll over even though the driver feels the tractor is still fully under control.

A vehicle that has a higher rearward amplification than another results in a greater vehicle response per unit steer input. This means that it is more sensitive, or less stable, in its lateral/directional dynamic characteristics. This test, then, examines the inherent dynamic stability of the vehicle.

The test was run at speeds of 63, 84, and 94 km/h, which were the actual governed speeds in the gear that came closest to the target speeds of 60, 80, and 100 km/h. Steer periods of 4, 3.5, 3, 2.5, and 2 s were used. A true-tracking, sinusoidal input computer program for the Freightliner, using a 37.5:1 steer ratio, provided the necessary steer amplitudes to generate approximately 0.15 g lateral acceleration at the tractor for each speed and steer period tested. These amplitudes were provided to the driver by means of indicators on the steering wheel.

Since it was considered somewhat difficult for the driver to estimate and perform a steer input of specific period, an electronic cueing device was developed. The "steer period generator" (SPG) is shown in Figure 28 and consists of two modules. The first module contains the electronics and controls. The driver selected the desired steer period by means of a switch, in increments of 0.5 s. Immediately after the gyroscope was uncaged, the driver would start the SPG and follow the light sequence given by the display module. Staging lights came on at 1 s intervals to count down to the start of the steer. The horizontal, or "follow me," light cycle would come on in sequence from the centre to the left, go off in the reverse sequence, then come on in sequence from the centre to the right, and go off in the reverse sequence. One complete period for the horizontal cycle lights was the selected steer period. A second set of lights underneath the "follow me" lights was connected to the steering system and marked the regular position of the steering wheels. The driver merely needed synchronize steer with the "follow me" lights to achieve the correct steer period. This device worked well, allowing the driver to conduct the test in an orderly manner without the need for wasted runs to achieve a particular period by a series of trials. The device would also operate in a free-running, continuous mode. The driver sometimes used this mode, or the single-period mode, between two runs to get the "rhythm" of the next run.

This test was conducted at Blainville. The following procedure was used.

Vehicle Preparation
1/ Vehicle loaded.

Test Area Preparation
1/ Set cones to mark an approach to the test area.
2/ Set automatic gyroscope to uncage at white marker 200 m (656 ft) before the start of the manoeuvre.
3/ Park the cherry picker on the left side of the approach, with the bucket adjacent to the approach lane.

Test Procedure
1/ Mark steering wheel at the specified amplitude.
2/ Accelerate the vehicle to test speed, to reach test speed with the vehicle straight at the gyroscope uncage patch. Use governed speeds of 63, 84, and 94 km/h.
3/ Start tape at least 2 s before the gyroscope uncage patch.
4/ Start the SPG at a suitable point, about 4 to 5 s after gyroscope uncage.
5/ Make a sinusoidal steer to the left. The vehicle heading once the steer input has been completed is inconsequential, but the exit must

be straight and held long enough for vehicle responses to be completed before caging the gyroscope. Steer amplitudes should be kept such that the tractor lateral acceleration is in the range 0.1 to 0.2 g and the rear trailer is not sliding laterally.

6/ When the run has been completed, cage the gyroscope before turning to re-enter the high-speed track.
7/ Stop the tape.
8/ Videotape all runs from the cherry picker and other vantage point of interest, for typical runs.
9/ Take still colour photographs.

5.3.8/ Lane Change

The lane change on a standard highway requires a steer input by the driver that is 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 29. 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 gates 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 trailer swing, or trailer response resulted in a 1 m (3.3 ft) swing out of lane. The sinusoidal steer test described in Section 5.3.7 is a subcritical test, designed to display the dynamic characteristics of a vehicle. This test takes basically the same manoeuvre as the sinusoidal steer to determine the limits of stability of the vehicle and demonstrate the mode by which it becomes unstable. The cone layout imposes a limit on the driver and ensures repeatable results.

Runs were repeated when responses were found to be inconsistent with the trend established by preceding runs or when any cone was struck. When a run was made in which the response was unstable or undesirable, corroborating runs, varying by no more than 3 km/h, were conducted to bracket the stability boundary. The test was terminated if the vehicle reached 100 km/h, a typical maximum legal speed in provinces of Canada, and was still able to make the manoeuvre successfully.

This test was conducted at Blainville. The following procedure was used.

Vehicle Preparation

1/ Vehicle loaded.

Test Area Preparation

1/ Set cones to mark a lane change to the left, with a gate of 30 m (98 ft).
2/ Set the automatic gyroscope to uncage at the white marker 200 m (656 ft) before the gate.
3/ Position the cherry picker on the left side of the approach, with the bucket centred over the left-hand lane.

Test Procedure

1/ Accelerate the vehicle to reach test speed with the vehicle straight at the gyroscope uncage marker.
2/ Start tape at least 2 s before the gyroscope uncage marker.
3/ Make a lane change to the left through the gate, keeping all wheels of the vehicle inside the lanes as far as is possible. Exit straight along the marked exit lane.
4/ If a potentially hazardous situation is develops, abort the run.
5/ When the run has been completed, cage the gyroscope before turning to re-enter the high-speed track.
6/ Stop the tape.
7/ Videotape all runs from the cherry picker and other vantage points of interest.
8/ Take still colour photographs.
9/ For the first run, use 47 km/h, then governed speeds until vehicle responses are considered potentially unstable or undesirable, then as specified.
10/ Make each run twice for consistency, but when test limiting speed is approached, make any runs necessary to establish the stability characteristics and threshold.

5.3.9/ Normal Straight-Line Driving

The trailers of combination vehicles tend to sway a small amount in straight-line driving because of road roughness, aerodynamics, suspension characteristics, and the normal small steer corrections by the driver.

This sway is related to vehicle configuration in the same way as rearward amplification of lateral acceleration. Some jurisdictions may impose a 75 mm (3 in) sway amplitude limit on trailers. The limit, however, is non-specific because it is not related to the input to the vehicle. It is also difficult, if not impossible, to enforce because the sway cannot be measured; it can only be subjectively estimated.

This test was conducted at Blainville. The following procedure was used.

Vehicle Preparation
1/ Vehicle loaded.

Test Area Preparation
1/ Use a straight portion of the high-speed track.

Test Procedure
1/ Drive at a steady speed of 100 km/h.
2/ Start tape at least 2 s before gyroscope is uncaged.
3/ Uncage the gyroscope manually when the vehicle is travelling in a straight line down the track.
4/ Drive normally as if cruising in a lane on a highway.
5/ Cage the gyroscope before leaving the straight track.
6/ Shoot video from a chase car following the vehicle.
7/ Make at least two runs along the full length of the straight track section.

5.3.10/ Steady Circular Turn

A loaded vehicle can roll over in a steady circular turn if its speed is high enough. Such a situation typically occurs for vehicles with a high centre of gravity when driven at excessive speed on a freeway ramp. Dynamics are involved in such accidents, due to braking, steering, or both, as the driver attempts to negotiate the ramp. However, the essential mechanism involved is that of rollover in a steady circular turn, which is an important inherent stability characteristic of a vehicle. This test examined that characteristic.

Static rollover characteristics of all vehicles tested, except the triples, were examined in a parallel part of the study conducted by Centre de Recherche Industrielle du Quebec (CRIQ), using a tilt table built for this purpose. Vehicles were provided to CRIQ staff, loaded as for this test, but with outrigger outer sections removed so that the vehicle could fit on the tilt table. The vehicle was driven onto the table, with load cells located strategically beneath wheel groups on each side of the vehicle. The axles and trailer bed were suitably restrained, and tilt meters were attached. The table was then continuously tilted until enough axles on the high side of the vehicle had lifted for the vehicle to be deemed to have reached the rollover point. Results of the tilt tests have been presented separately by CRIQ [12].

The tilt test provides static roll characteristics of a vehicle. It may be presumed these would be related to the rollover characteristics arising from a steady circular turn.

The steady circular turn course was laid out using traffic cones on a dry high-friction surface, as shown in Figure 30. The circle had a radius of 50 m (164 ft) and was approached along a tangent leading to a 100 m (328 ft) long 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 tracked on the outside for 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. Sufficient runs were made to characterize the vehicle roll response as a function of 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 (6 to 8 in) at outrigger touchdown, which corresponds to about 6 to 7° of body roll. The outrigger clearance settings varied between vehicle units and vehicles, because of attachment and adjustment limitations. More important, however, were the differences in suspension and torsional stiffnesses between vehicles. The A-trains could clearly roll over the rear trailer. In others, outrigger touchdown may occur but the entire vehicle could still be short of rollover. Outrigger touchdown, therefore, simply denoted a point beyond which further testing was impractical. When wheel lift and outrigger touchdown occur for some vehicles, the vehicle speed often drops off significantly, and it becomes difficult for the driver to maintain the circular turn. Therefore, steady-state data for this condition cannot be obtained. There would not necessarily be any relationship between outrigger touchdown points for each vehicle. It was, therefore, considered more useful to map the vehicle characteristics as a function of speed rather than establishing an arbitrary outrigger touchdown point.

This test was conducted within the vehicle dynamics area at Blainville. The following procedure was used.

Vehicle Preparation

1/ Vehicle loaded.

Test Area Preparation

1/ Set cones to mark a circle of 50 m (164 ft) radius, with a suitable tangent and spiral entry.
2/ Set the automatic gyroscope uncage at the white marker a suitable distance on the tangent before the entry to the spiral.
3/ Park the cherry picker outside the circle about on a tangent from the point where the vehicle will roll over, with a view of the rear and outside of the vehicle.

Test Procedure

1/ Approach the test area along the entrance tangent at the specified speed, with the vehicle straight at the gyroscope uncage marker.
2/ Start tape at least 2 s before the gyroscope uncage marker.
3/ Proceed around the spiral and circle, at constant speed, with the left front wheel tracking the curve. Hold the circle for at least 90° or until outrigger touchdown occurs.
4/ If a potentially hazardous situation develops, make a suitable recovery.
5/ When the run has been completed, cage the gyroscope.
6/ Stop the tape.
7/ Videotape all runs from the cherry picker and other vantage points of interest.
8/ Take still colour photographs.
9/ For the first run use 35 km/h governed speed; then increase governed speeds incrementally according to vehicle response.
10/ Make each run twice for consistency. As the rollover speed is approached, runs necessary to establish the rollover threshold must be done.

5.4/ Data Capture

The data acquisition system consisted of a signal conditioning and pulse-amplitude modulated (PAM) multiplex system mounted in the sleeper portion of the MTC Freightliner, and others mounted in instrumentation boxes on the trailers. The systems were configured to provide the necessary transducer excitation and signal conditioning to permit multiplex transmission and recording of up to 40 individual signals. Electrical signals produced by the transducers were conditioned by individual plug-in-type adapter cards within the multiplex unit, as shown in Figure 31. A maximum input from each transducer was selected, and the conditioner parameters were adjusted to provide an output signal of 2.0 V for the chosen full-scale input. The conditioned output signals were transmitted as a PAM data stream from each multiplex system to a control unit in the tractor, which synchronized and merged the three PAM data streams. A 12-bit analog-to- digital converter in the control unit digitized the 36 data channels at a rate of 100 samples/s for each channel and produced a pulse-code modulated (PCM) data stream in a standard IRIG format. The control unit added two synchronization words containing a unique bit pattern, and two digital data words, to the 36 data words to produce a data frame of 40 twelve-bit words. One digital word was used to provide system and vehicle status, and the other was used for optical sensor status. The PCM data stream was broadcast by radio telemetry from the tractor to a ground station, using a radio frequency licensed to the ministry for use at both Centralia and Blainville.

The ground station was located in the MTC building at Centralia. The ground station equipment was mobilized in a former transit bus, which served as the ground station during tests at Blainville (Figures 32 and 33).

The ground station received the PCM data stream and recorded it as received on one track of a Honeywell 5600C instrumentation tape recorder. IRIG B time code generated by a Datum 9300 time clock was recorded on a second track of the recorder so that the location of a particular run could be found easily if data playback was required. This recording was for archival and backup purposes.

The PCM data stream was processed by the decommutator, which formatted it into a bit-parallel, word-serial, input stream for an Hewlett-Packard HP-1000 A700 computer in the ground station (Figure 34). The computer read each run in real time and created a raw data file on disk for subsequent processing. The project engineer at the computer graphics terminal had a quick-look display that provided an overview of system status functioning and data quality while the run was in progress.

Before each test session, an electronic calibration of the entire data acquisition system was conducted. Any necessary adjustments were identified and made, and a second calibration was recorded. At the beginning of each test run, the control unit on the tractor was made to step automatically through a calibration sequence, either by automatic command from the optical sensor or by manual command from the driver. This was recorded as part of the run data, to permit current system calibrations to be used for each run. The gyroscopes on board the vehicle were uncaged by a trigger signal from a reflective marker placed on the approach and sensed by an optical sensor.

Each run was recorded on colour videotape, from the vantage point of a cherry picker and other vantage points of interest, as shown in Figure 35. Each video sequence included the day and run numbers so that it was chronologically identifiable. The audio track of the video system was used to record ambient noise during testing, including incidental radio transmissions and comments.

Still colour photographs and colour slides of the vehicles, equipment, and activities were also taken. Manual notes and logs of all test conditions and observations were made. A log of all test runs was maintained within the computer.

5.5/ Data Processing

Data processing was conducted concurrent with testing. At the beginning of each day, certain data files and procedures were initialized within the HP-1000 computer system. Data from each run were captured in real time by the HP-1000, and the raw data were stored in a file on disk, as described previously. The raw data were reviewed by the project engineer on a graphics display, to determine whether all critical data channels were functioning correctly and whether the run appeared to meet the specified test conditions. The raw data file was then read, electronic calibrations were applied, each channel was converted to engineering units, and a calibrated data file was created. Quantities of interest were derived, and those critical to the test were displayed to the project engineer, who used them to radio recommendations for the next run to the test director on the track. After each test session, all raw data files; other files created in support of the data processing process, such as the run log file and a summary file of derived quantities; and all data input files which controlled the data processing were archived to a tape. The archived tape was indexed so that the processing of any particular run could be reconstructed.

Upon completion of the test program, all data processing procedures were exhaustively reviewed, and any necessary enhancements were implemented and validated. All supporting data files were also reviewed. Every run was carefully reviewed, and those runs that did not meet the particular test objective, or were otherwise so flawed that the data could not be processed, were discarded.

Data processing proceeded in four phases:
1/ raw data correction
2/ calibration
3/ treatment
4/ extraction of results

The first phase, raw data correction, simply corrected any data frames in which telemetry dropout occurred. These frames usually showed up as spikes on most data channels, as shown in Figure 36. Telemetry dropout occurred intermittently throughout the test program for no obvious reason. When it occurred, the decommutator was unable to find the 24-bit synchronization pattern in the PCM data stream and ceased transmission of data frames to the computer. This resulted in partial loss of the frame during which dropout occurred, total loss of an unknown number of complete frames, and capture of one or two scrambled frames while the computer data acquisition was regaining synchronization with the decommutator. Examination of the PCM data stream by oscilloscope showed that dropouts were usually momentary, so in most cases no more than one or two frames were actually lost. However, since the data acquisition procedure was taking its timing from the decommutator, not an independent source, the number of frames actually lost was never known. Runs were rejected in which there occurred frequent dropouts or dropouts during the steer input or vehicle response. It was only necessary to correct raw data when a dropout occurred in the approach to the manoeuvre or after vehicle response was complete. It was judged that loss of a few frames was not critical in these regions. The correction procedure for each dropout was simply a linear interpolation for each channel of all invalid frames between the last valid frame before the dropout and the first valid frame after the dropout.

Calibration proceeded in two phases. As previously mentioned, the on-board data acquisition system was commanded through an electronic calibration sequence at the beginning of data acquisition for each run. The calibration sequence consisted of approximately 0.5 s of each of negative full scale, zero, and positive full scale, as shown in Figure 37. The calibration was achieved by switching a precisely controlled voltage to all channels of the signal conditioners. A voltage calibration for each step of the calibration sequence was computed as the moving average value of lowest root mean square. If the root mean square exceeded 5% of full scale, the calibration was rejected. The calibrations usually differed from the nominal values by less than 1% of full scale. Any deviation of more than 2.5% was flagged as a potential error, requiring examination of the data for correctness and, perhaps, the instrument for function. Channels using strain gauge signal conditioner cards, where the data are superimposed upon the calibration and even a small drift from zero could result in a false error flag, were an exception. If nominal full scale is V volts, and the measured voltage is C volts, then a linear calibration of k units full scale must be applied to the actual data as V/C. This is done by modifying the value used for conversion to engineering units, the second phase of calibration. The actual details of this take account of both offsets and slopes for electronic and engineering units calibration and are a little more involved than the simplified explanation given here.

The term "treatment" is used for the sequence of operations whereby the calibrated data are processed so that specific quantities of interest for a particular test can be derived. Some of these operations are applied to the output of a particular instrument, while others may be used rather generally or various types of data. The following treatments were used in data processing:

1/ transformation of speeds of all instrumented wheels to the speed of the tractor right front wheel;
2/ transformation of the sawtooth wave distance measurement to actual distance;
3/ correction of trailer lateral accelerations for the gravitational effect of roll angle;
4/ integration of yaw and roll rates to yaw and roll angles, respectively;
5/ detrending of data;
6/ filtering of data.

The first four of these are straightforward; the other two need some explanation. Detrending removed trends in transducer responses. It was used in two ways. In most tests, the vehicle was assumed to be in a nominal zero condition initially, and the response of interest was relative to that condition. However, the actual measurements gave an initial mean value that was not zero. While these deviations were usually only a few percent of full scale, they could have a marked effect on results if not properly dealt with. The procedure used was to compute an average value for each nominally initially zero channel over a short period at the start of a run. This value was then subtracted from each data point for a channel, thus moving the initial average to zero. The second type of detrending was used for channels which should have returned to zero after a response to the input was complete but did not due to instrument drift during the run. Examples of these are the roll and yaw angles measured by the various gyroscopes. These channels were detrended by fitting a straight line by the least squares method to the nominally zero data segments at the beginning and end of the run, then subtracting this linear trend from the actual data. The detrending process is illustrated in Figure 38, for tractor yaw angle.

Filtering was used to remove unwanted frequency content from data. In most cases the responses of interest were related to the frequency content of the steer input, which was below 1 Hz. However, many channels had superimposed vibration responses of the vehicle, such as axle hop, vibration due to roadway irregularity, and a particular vibration apparently associated with the tractor drive axle tires. An optimal linear finite impulse response low-pass filter [13] was designed having a cutoff frequency of 1 Hz, a stop band 50 dB down at 4 Hz, and a 0.03 dB ripple in the passband. This filter had 53 weights and maximum deviations of 0.00441 and 0.00403 in the passband and stop band, respectively. This filter was applied to all data channels except wheel speed, distance, and brake chamber pressures.

The final phase of data processing was extraction of results. The method used depended entirely on the test being processed. Details of the methods are presented in the following sections. Some typical results extracted were speed, peak or average responses, response gains, and steer period. A summary file was created for each test, and the results for each run were stored in this file. At the completion of the test, the data in the summary file could be cross-plotted. For instance, rearward amplification gain for a series of steer period inputs could be plotted against the speed, or some peak response could be cross-plotted against speed or lateral acceleration. This provided an easy, semi-automatic way to view trends across all the runs of a particular test.

5.5.1/ Offtracking

The measurements recorded manually during the test were tabulated. Average values from the two turns were compared with a geometric estimate of steady-state offtracking made by the WHI formula [14].

5.5.2/ Right-Hand Turn

The measurements recorded manually during the test were tabulated and plotted. Intrusion of the vehicle into the exit lane was estimated from the plot.

5.5.3/ Channelized Right Turn

The measurements recorded manually during the test were tabulated and plotted.

5.5.4/ Air Brake System

The following procedure was used to derive the characteristics of the pneumatic system that affect balanced braking of a combination vehicle.

All brake pressure signals were detrended so that their initial average pressure was zero. Brake status was monitored using the brake light switch, the condition of which was stored as a single bit in a digital word provided by the PCM control unit in the tractor. The first frame which contained this bit was considered the start of brake application. The time for each brake chamber to reach 414 kPa (60 psi) from the start of brake application was computed. This was in accordance with the procedure of SAE J982a or US Standard FMVSS121. The final steady pressure before release was also computed. This final pressure did not always reach 689 kPa (100 psi) or even 655 kPa (95 psi). Release timing was therefore computed from the instant the treadle valve pressure began to decrease. The release time for each brake chamber was computed as the time for the pressure to reach 34 kPa (5 psi) from the instant of treadle valve release. This differs from the procedure of SAE J982a or FMVSS121, which require the vehicle pneumatic system to be charged to 689 kPa (100 psi) before release. However, those procedures apply to single vehicle units, and the procedure described here was considered adequate to provide insight into the pneumatic characteristics of the combination vehicle.

A typical time history from this test is shown in Figure 39.

Basically, the same procedure was used for the application and steady-state portion of the service brake application test, though in this case the timing was computed to 60% of the peak pressure arising during the test. Release characteristics were not considered during this test.

5.5.5/ Straight-Line Braking

While this demonstration was primarily qualitative, data were captured and processed to determine vehicle responses in straight-line braking.

All input channels were properly detrended, and all channels except the brake pressures were filtered.

The start of brake application was found as described previously and was used as the initiation of the manoeuvre. The initial average speed was found over the 1 s period before the instant of brake application. The end of the manoeuvre was defined either as the point where the vehicle's velocity became zero or the instant when the brakes were finally released if the driver drove out without coming to a complete stop. The stopping distance and time to stop (or deceleration distance and time, if it was not a complete stop), average deceleration, peak and average brake application pressures, peak steer angle, vehicle unit articulation angles, heading angles, and lateral accelerations were all computed over the period of the brake application.

5.5.6/ Evasive Manoeuvre

The following procedure was used to compute vehicle responses to an evasive manoeuvre and derive quantities of interest for summary of results of a series of runs.

All input channels were properly detrended and filtered.

The start of the steer input was found at the first point where the steer input exceeded a specified tolerance for five consecutive scans. The tolerance was chosen so that it was always greater than the small steer corrections made on approach, but was not so large that it approached the steer amplitude.

The initial speed was determined from the average speed for the 1 s of data immediately preceding the start of the steer input.

Peak values of steer input and specified responses were found from the start of the steer input to the end of the data, either end of record or end of a specified base segment. Specified responses were tractor yaw rate, lateral accelerations, articulation angles and vehicle unit heading angles, and all other channels of interest. Peak values were largest positive and least negative. The corresponding times at which these peaks occurred were also found. Care was taken to ensure that the data segment scanned included only the data of interest: for instance, if it included a sharp turn for vehicle recovery at the end of the run, this could result in misleading peak values in excess of those in the actual region of interest.

The three lateral acceleration response peaks due to the steer input and the two heading peaks and any overshoot were determined by a search procedure. The time at which the steer input first crossed zero was used as a time base. The tractor lateral acceleration was then searched from one-quarter the steer period before this time to one-half the steer period after its zero crossing. This was used as a new base, and the peak responses to each half-wave of the steer input were found by searching backward and forward from this for each trailer successively rearward.

5.5.7/ Sinusoidal Steer

The following procedure was used to compute vehicle responses to an evasive manoeuvre and derive quantities of interest for summary of results of a series of runs.

All input channels were properly detrended and filtered.

The start of the steer input was found at the first point where the steer input exceeded a specified tolerance for five consecutive scans. The tolerance was judiciously chosen so that it was always greater than the small steer corrections made on approach, but was not so large that it approached the steer amplitude.

The initial speed was determined from the average speed for the 1 s of data immediately preceding the start of the steer input.

The steer period was estimated by computing the steer angle autocorrelation for a specified number of lags, starting at the start point found. The autocorrelations were computed over the entire rest of the record. The autocorrelation of a sine wave is a cosine function of the same frequency. A single cycle sine wave results in a damped cosine. The autocorrelation crosses zero at a time which is one-quarter the period of the input sine wave. This point was found, and the period was assumed to be four times the lag which resulted in the autocorrelation crossing zero. This period was reduced by an empirical factor of 0.95, as this appeared to give a better fit to the measured data. A synthetic true sine wave of the period determined was created, centred to cross zero at the point the measured steer crossed zero. The amplitude of the synthetic steer was computed as

SUM(Y(I)*S(I))/SUM(S(I)*S(I)) for I = 1, N
where Y(I) is the measured steer input
S(I) is the synthetic steer

This gave a better overall fit than either using one of the measured peaks or an average of the two. The steer balance was computed as the integral of the measured steer angle over the period of the synthetic steer. This is close to zero for a well-balanced sinusoidal steer. The fit procedure just described worked reasonably for a well-balanced steer input but was not so good if the two half-waves were unbalanced in either amplitude or duration or if there was a third or subsequent small correction half-wave following the main steer input. Typical fitted sine waves are shown in Figure 40, for well-balanced and unbalanced sinusoidal steer inputs.

The tractor yaw rate response lag was computed as that lag time for which the cross-correlation of steer input and yaw rate was greatest. The correlation was the normalized cross-correlation for this lag.

Peak values of steer input and specified responses were found from the start of the steer input to the end of the data, either end of record or end of a specified base segment. Specified responses were tractor yaw rate, the gains found in lateral accelerations and roll angles, and all other channels of interest. Peak values were largest positive and least negative, and the correspoding times at which these peaks occurred were also found. Care was taken to ensure that the data segment scanned included only the data of interest: for instance, if it included a sharp turn for vehicle recovery at the end of the run, this could result in misleading peak values in excess of those in the actual region.

The two peaks in lateral acceleration and roll response, and the single heading response peak, were determined by a search procedure. This started from the tractor and proceeded rearward to the last trailer. The time at which the steer input crossed zero was used as a time base. The tractor lateral acceleration was then searched from one-quarter the steer period before this time to one-half the steer period after for its zero crossing. This was used as a new base, and the peak responses to each half-wave of the steer input were found by searching backward and forward from this for each trailer successively rearward. Lateral acceleration gains were then computed for all trailers. The gain was computed by dividing the peak-to-peak trailer response by the peak-to-peak response of the tractor, as shown in Figure 41. It gave the same result as the conventional method of dividing by the peak tractor response for the case of a well-balanced steer. This resulted in less data scatter for cases when the steer input was not well balanced, which was often the case for the small steer input required for responsive multi-trailer combinations.

Note that in cases of trailer swing or rollover, the rear trailer overshot the second half-wave and could have a third half-wave, which was sometimes of substantially greater amplitude than the two half-waves that are the forced response to the steer input. The overshoot half-wave was not recognized by this procedure but was identified by the peak response procedure previously described.

5.5.8/ Lane Change

The following procedure was used to compute vehicle responses to a lane-change manoeuvre and derive quantities of interest for summary of results over a series of runs.

This procedure was identical to that used to determine the start of the steer input, the initial speed, steer period, tractor yaw rate response, and peak responses and gains, described in Section 5.5.7. However, it was extended to select three response peaks, rather than the two of the sinusoidal steer. The first two peaks were the same for both manoeuvres because of the steer input required to make the lane change. At low speeds the vehicle was well damped and there was no third peak. However, as the limiting speed was approached there was a third peak, the overshoot caused by reduction in stability of the vehicle. A small overshoot may be seen in the trailer 2 lateral acceleration response at a time of about 7 s in Figure 41. Note that sometimes the driver completed the steer input, which was essentially sinusoidal, but overshot or deliberately corrected to exit straight along the marked lane. This additional steer, present to a small extent in the steer angle input of Figure 41, can be an influence in the overshoot. No distinction was made between the two possible causes of the response overshoot. In addition, the two response peaks of each vehicle unit's heading angle were found using the same technique. The basic tractor heading angle has a single peak, as shown in Figure 38, to which may be added an overshoot as the limit of stability is approached, particularly for trailers swinging out of lane.

5.5.9/ Normal Straight-Line Driving

Each run was detrended so that the steer articulation angles had an initial average value of zero. These data were also filtered. The sway at the rear of each trailer, relative to the tractor fifth wheel, was computed based on the articulation angles, kingpin-to-hitch distances, and kingpin-to-rear distances, for each trailer. The range and root-mean-square (RMS) steer input, and sway and lateral acceleration of each trailer, were computed for each run. Vehicles were then compared on the basis of the ratio of RMS sway to RMS steer input, in units of mm/°; the ratio of RMS lateral acceleration to RMS steer input, in g/°; and the sway range in mm. These simple ratios were used because much of the data were less than 1% of full scale, which is, in some cases, the level of resolution. A proper frequency domain analysis, therefore, did not appear warranted.

5.5.10/ Steady Circular Turn

The following procedure was used to compute vehicle responses to a steady circular turn and derive quantities of interest for summary results of a series of runs.

All input channels were properly detrended and filtered.

The start of the steer input was found at the first point where the steer input exceeded a specified tolerance for five consecutive scans. The tolerance was judiciously chosen so that it was always greater than the small steer corrections made on approach, but was not so large that it approached the steer amplitude.

The instantaneous radius of curvature was computed based on velocity and yaw rate or lateral acceleration. The high-speed offtracking was also computed, based on an assumed tractor attitude and the articulation angles.

The initial speed was determined from the average speed for the 1 s of data immediately preceding the start of the steer input.

Once the initial speed and start of steer input were known, it was possible to project forward to a region of steady-state response, because the length of the spiral course was known. It was easier to use a region fixed in space for each vehicle unit, rather than a fixed interval of time, because for the longest vehicles, the triples, the driver could have been starting recovery from the manoeuvre as the rear of the vehicle was reaching steady state. The steady-state segment, therefore, was defined as that location traversed by the tractor in the 4 s or as long as was available, after the tractor had been on the circular turn for 2 s. Note that there were complications with certain data. Some vehicles, particularly the B- and C-trains, tended to slow significantly in the circular turn due to tractive power demand. Further, when a rollover or trailer swing occurred, the driver commenced recovery, so for the most part, transient data existed for these most interesting cases.

Peak, mean, and RMS values of steer input and specified responses were found over the region of steady-state response. Specified responses were tractor yaw rate, lateral accelerations, roll angles, articulation angles, and corroborative data. Peak values, which were largest positive and least negative, and their corresponding times were recorded. Care was taken to ensure that the data segment scanned included only the data of interest: for instance, if the data included a sharp turn for vehicle recovery at the end of the run, it was noted and considered in the overall analysis.

6/ PERFORMANCE MEASURES

The vehicle configurations are evaluated using various performance measures. Some of the measures are addressed by simulation or analysis of various kinds, others by test, and some by both.

The following performance measures provide the basis of what will be considered from tests:

1/ steady-state roll characteristics, derived from circular turn manoeuvres for loaded vehicles;
2/ dynamic roll threshold, derived from lane-change manoeuvres for loaded vehicles;
3/ roll mode characteristics, from the manoeuvres of 1 and 2;
4/ rearward amplification of lateral acceleration, from sinusoidal steer and lane-change manoeuvres;
5/ lateral/directional stability (jackknife and trailer swing), derived from evasive manoeuvres with an empty vehicle on a low-friction surface;
6/ straight-line trailer sway for loaded vehicles;
7/ vehicle stability characteristics in straight-line emergency braking, empty on a low-friction surface;
8/ high-speed offtracking, derived from the steady circular turn;
9/ lateral loads at the tractor fifth wheel, derived from the steady circular turn and lane-change manoeuvres;
10/ yaw response gains and lag times;
11/ vehicle speed at lateral/directional and rollover stability thresholds;
12/ steady-state offtracking;
13/ swept paths in typical right-hand turns;
14/ air brake system application, release timing, and pneumatic balance.

These performance measures were computed from the measured data by the HP-1000 computer, as described previously. The values were stored in a file indexed by run, making it possible to display vehicle response characteristics against input parameters, for purposes of test management and data analysis.

7/ COMPUTER SIMULATION

The University of Michigan Transportation Research Institute (UMTRI) yaw/roll model [15] was installed on the HP-1000 computer used in the ground station for data capture and processing. The program was extended to simulate a triple trailer combination and was updated to include an improved B-dolly model developed by UMTRI, so that all vehicles tested could be simulated with the same program.

The properties of vehicle unit suspensions were available from parametric measurements made by UMTRI, as were tire properties [16]. The geometric properties of vehicles were measured, and mass properties were determined by a process of weighing and calculation. By this means, data sets were prepared that were representative of the vehicles as they were actually tested.

The program was also modified to read the steer input measured during a test run, and the initial conditions for some other model degrees of freedom, from the test data. It then integrated the equations of motion, computed responses of interest at the measurement locations on the test vehicle, and stored those responses in a data file having the same format as that containing the responses measured in the test. The test and simulation results could, then, be directly compared.

This test program consisted of standardized tests of nine vehicles of different configurations. It provided an opportunity to compare computer simulation with test data over a wide range of cases. The objective was to demonstrate that computer simulation could represent a vehicle's response in a specific manoeuvre and the trend in response characteristics over a range of manoeuvres. The program data were set up to be as representative as possible of the actual vehicle tested, using generic data where directly measured data were not available. This work was not a validation of the computer model.

Computer simulation was conducted for all vehicles for the following tests:
1/ sinusoidal steer
2/ lane change with loaded vehicle on high-friction surface
3/ steady circular turn

A detailed summary of this work is presented elsewhere [17].

8/ CONCLUSIONS

This report has presented procedural details for preparing and conducting tests and processing and analysing data, for testing baseline and additional vehicles for the CCMTA/RTAC Vehicle Weights and Dimensions Study. The report presents this information as a common reference for the detailed test reports for the particular vehicles.

9/ REFERENCES

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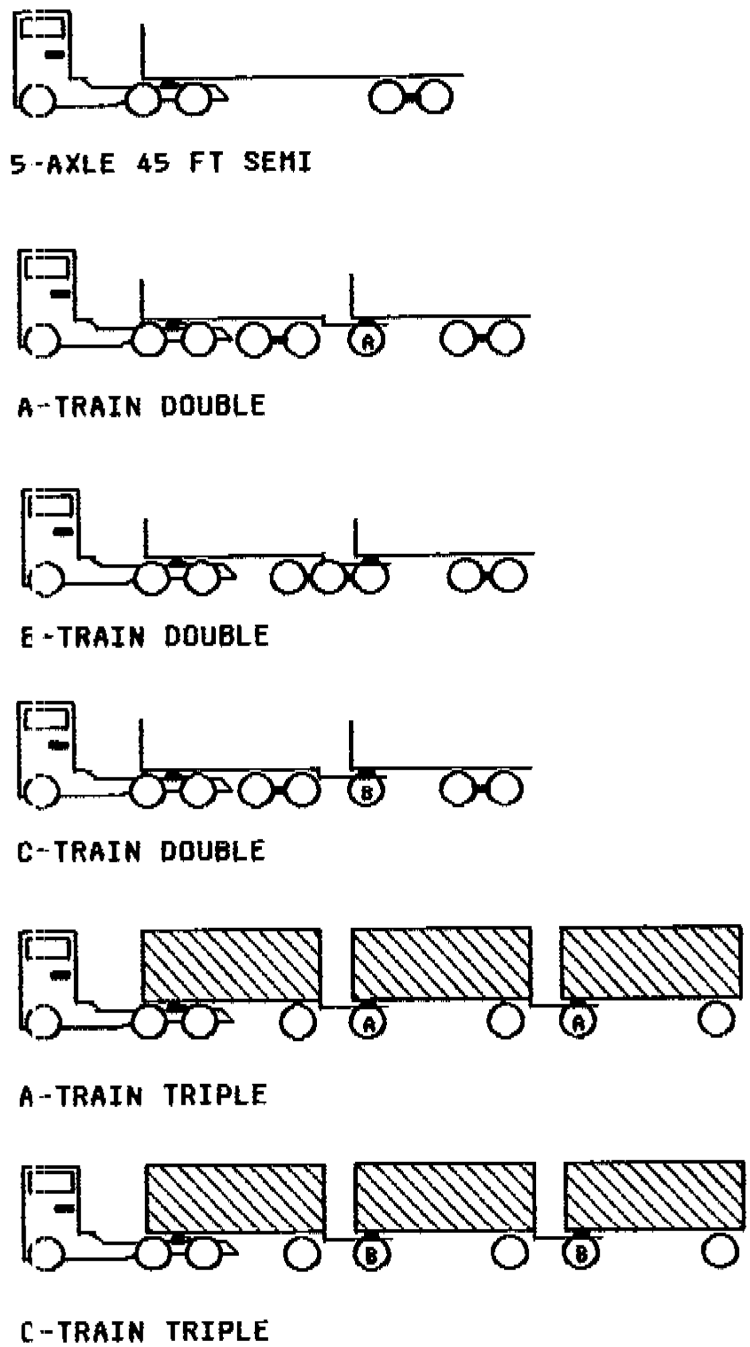
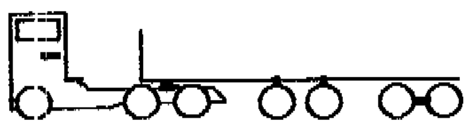


Figure 1/ Baseline Vehicle Configurations

5-AXLE 48 FT SEMI

6-AXLE 48 FT SEMI



7-AXLE 48 FT SEMI

Figure 2/ Additional Vehicle Configurations

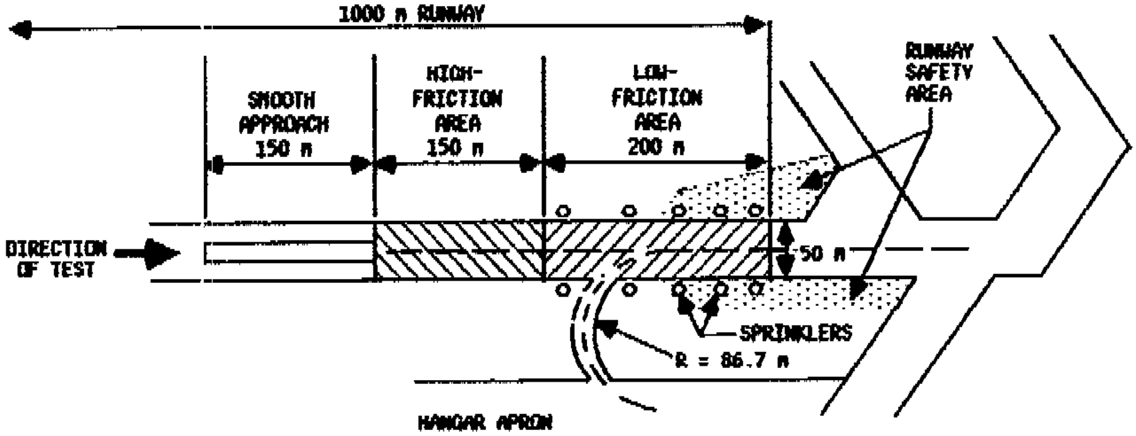


Figure 3/ MTC Commercial Vehicle Test Facility (Centralia)

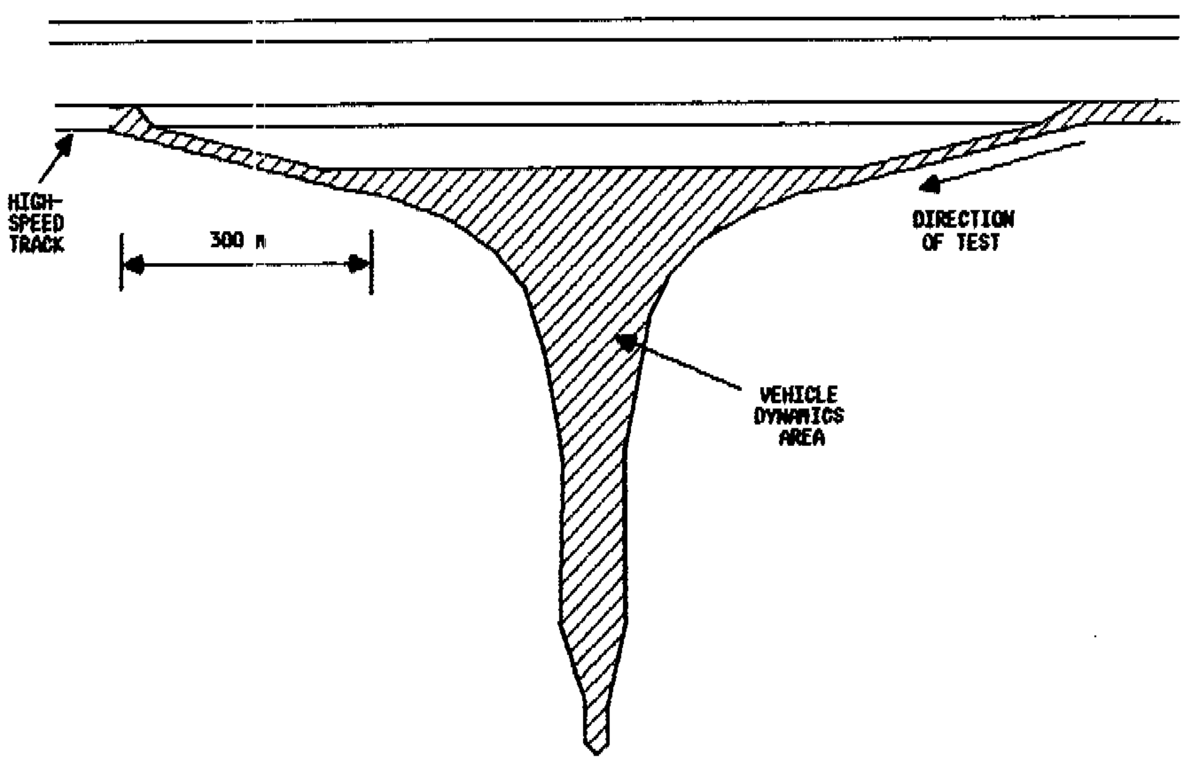


Figure 4/ Vehicle Dynamics Area, Transport Canada
Motor Vehicle Test Centre (Blainville)

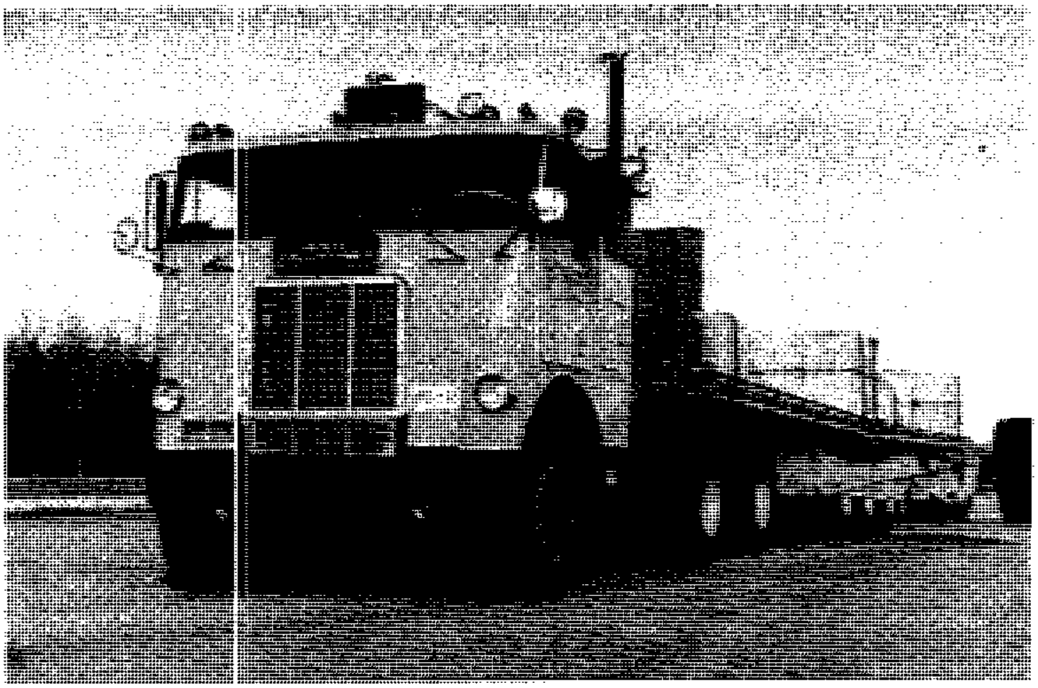


Figure 5/ MTC Freightliner

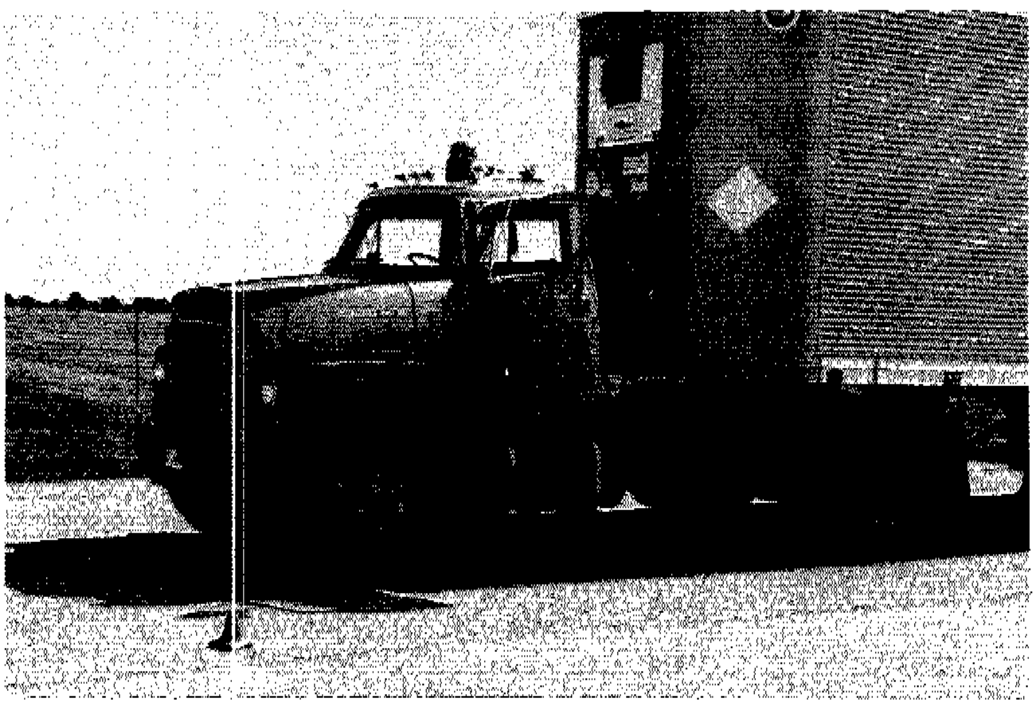


Figure 6/ MTC International

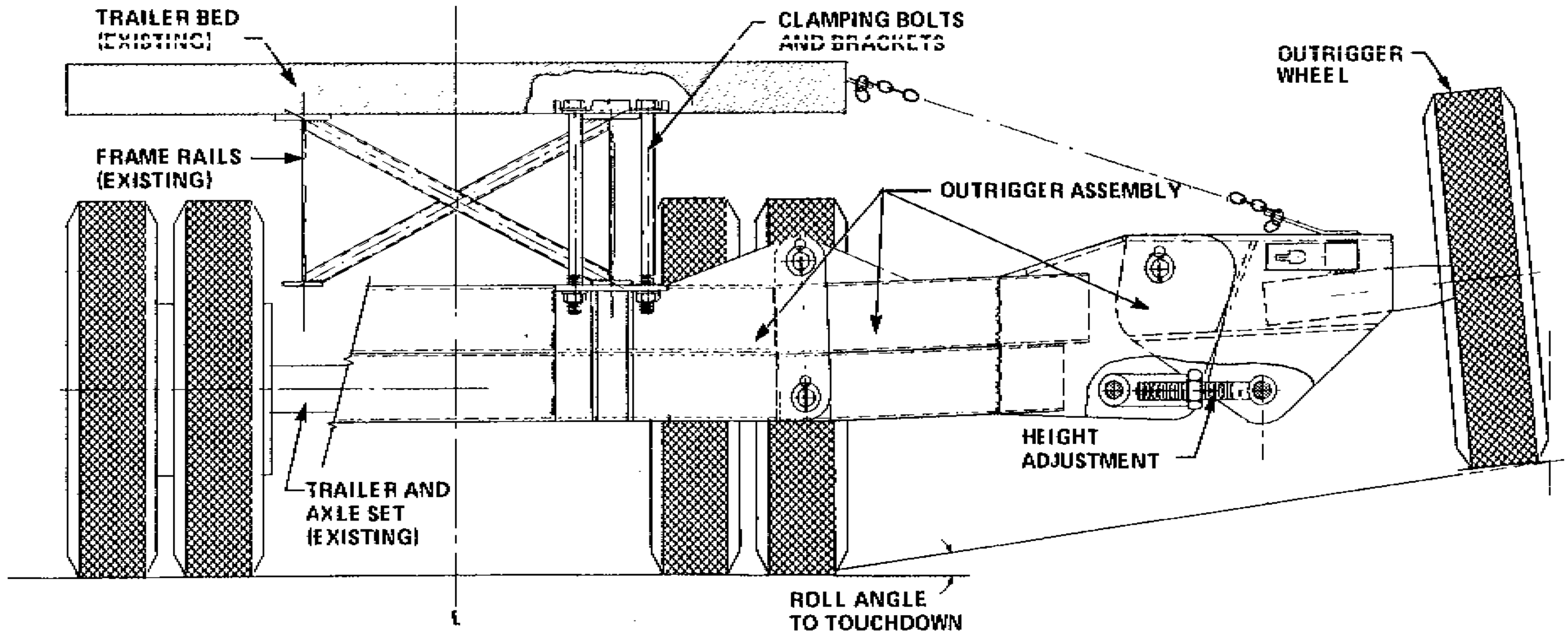


Figure 7/ Outrigger Assembly

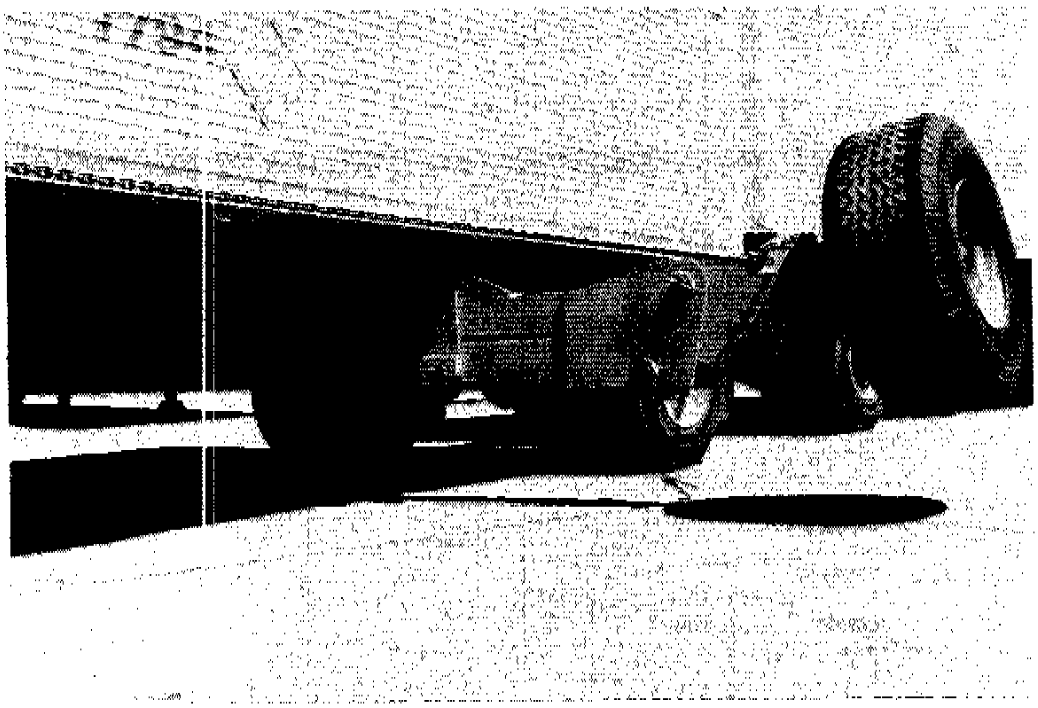


Figure 8/ Underslung Outrigger Installation

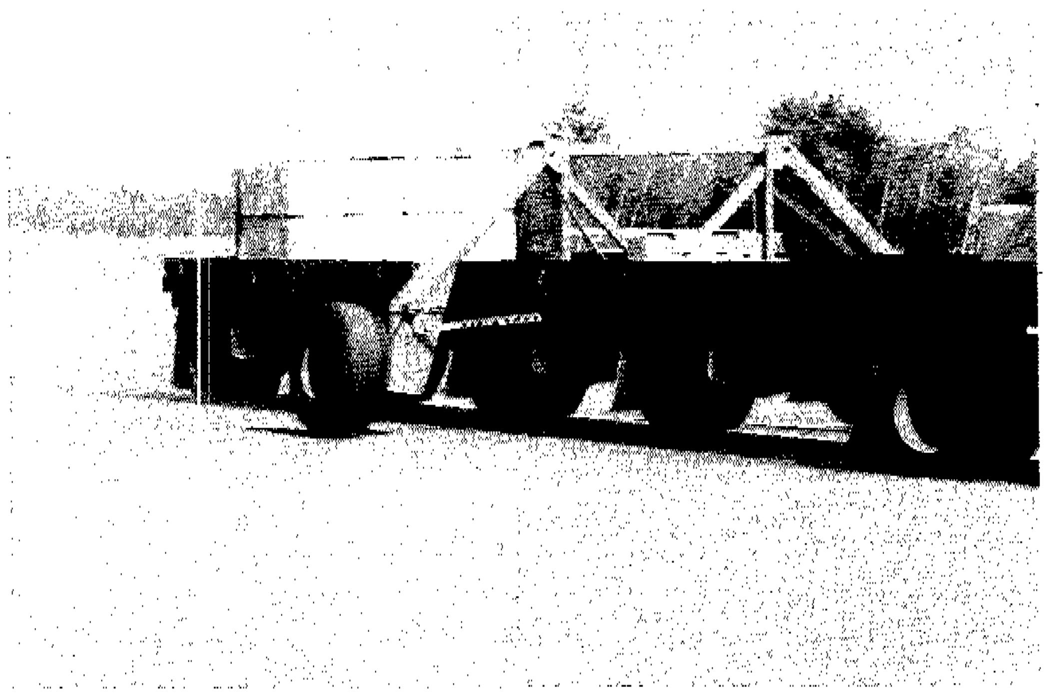


Figure 9/ Frame Outrigger Installation

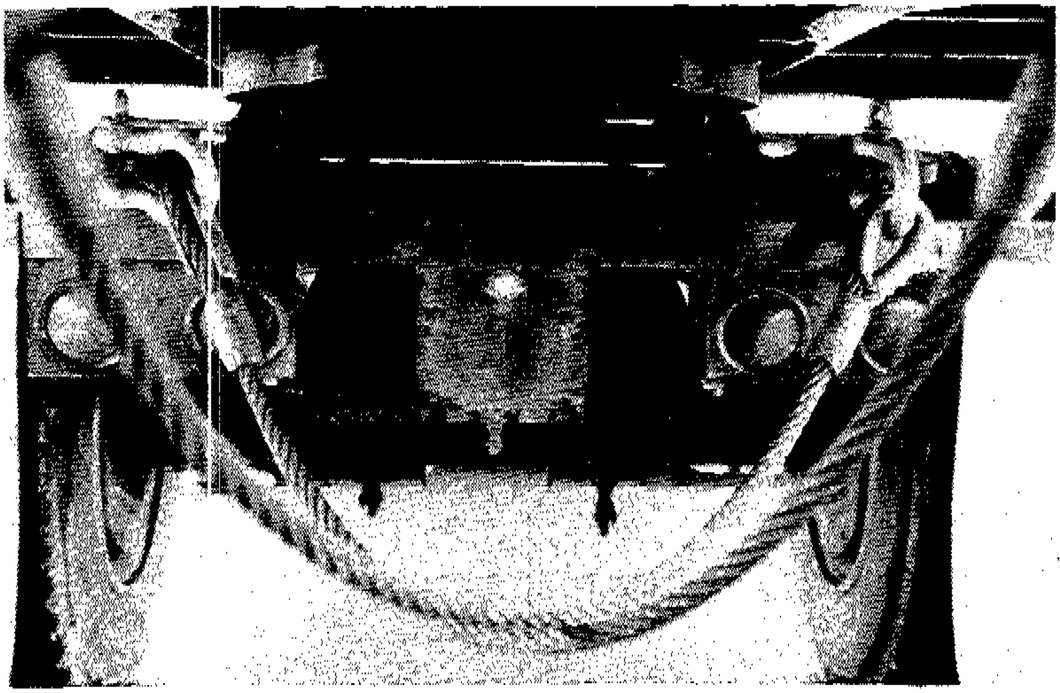


Figure 10/ Safety Cable Installation

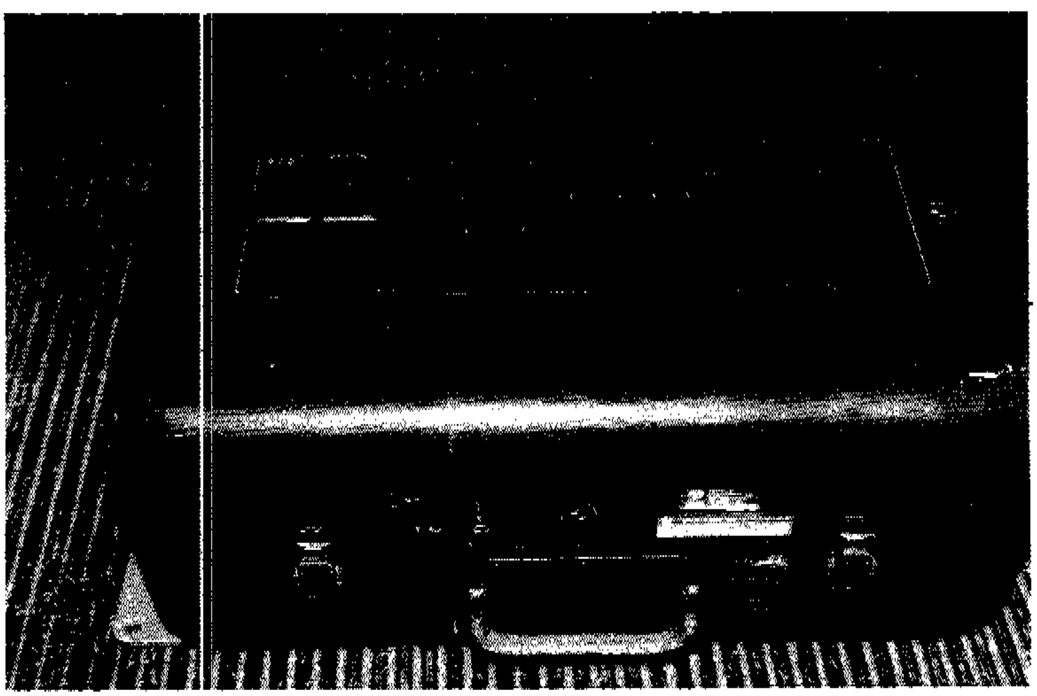


Figure 11/ Gyroscope Package

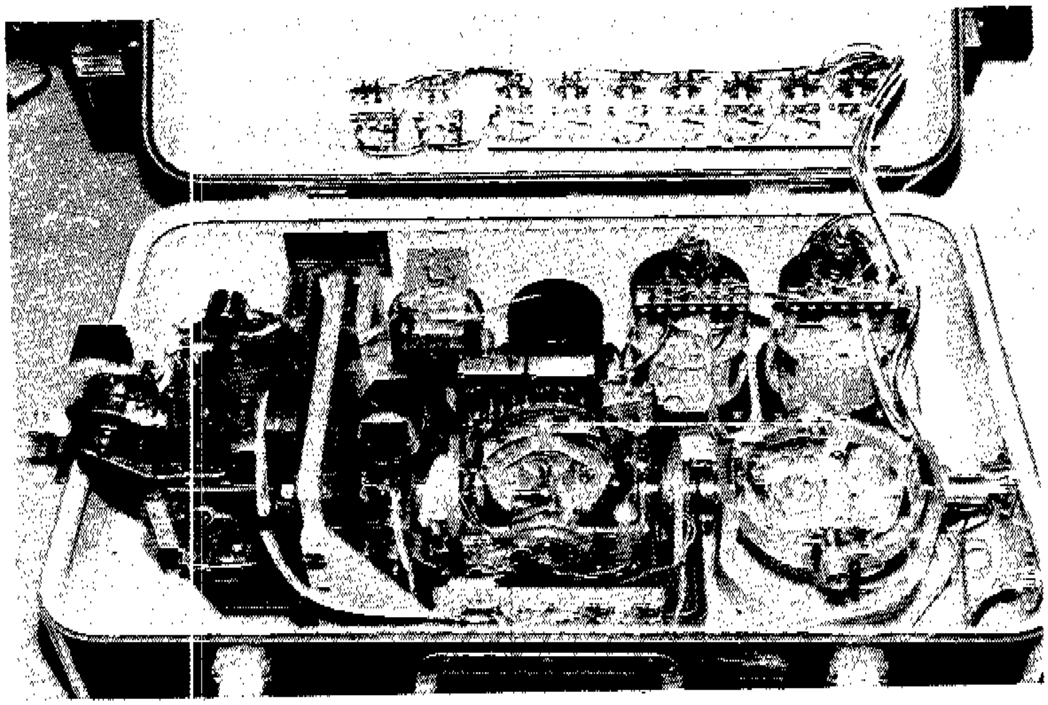
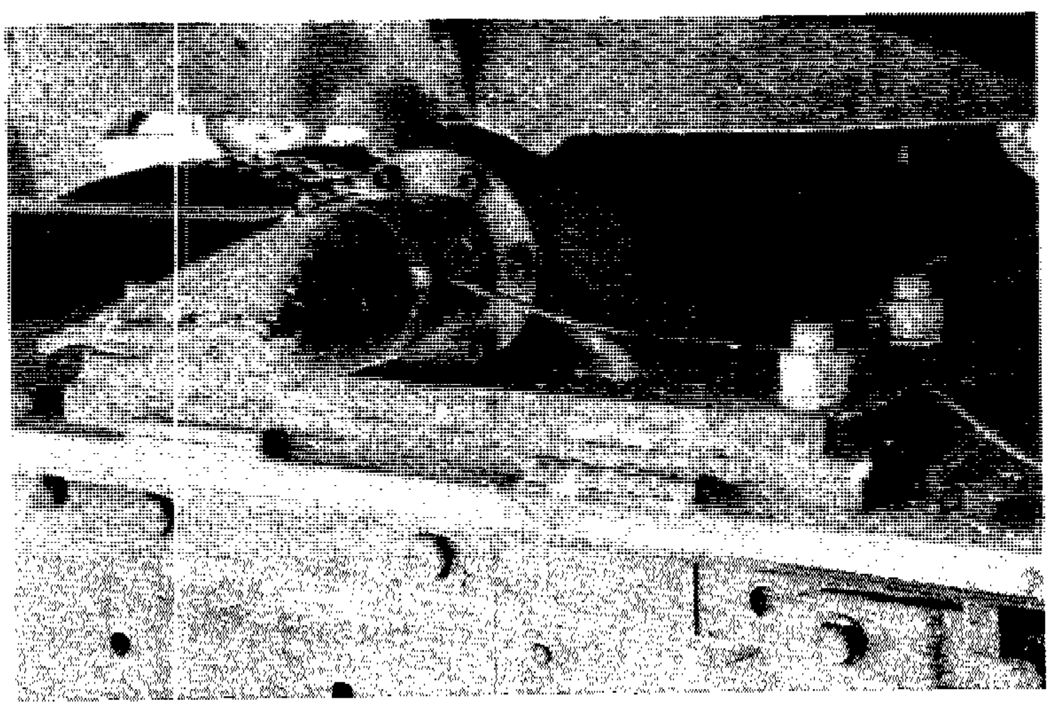


Figure 12/ Gyroscope Package



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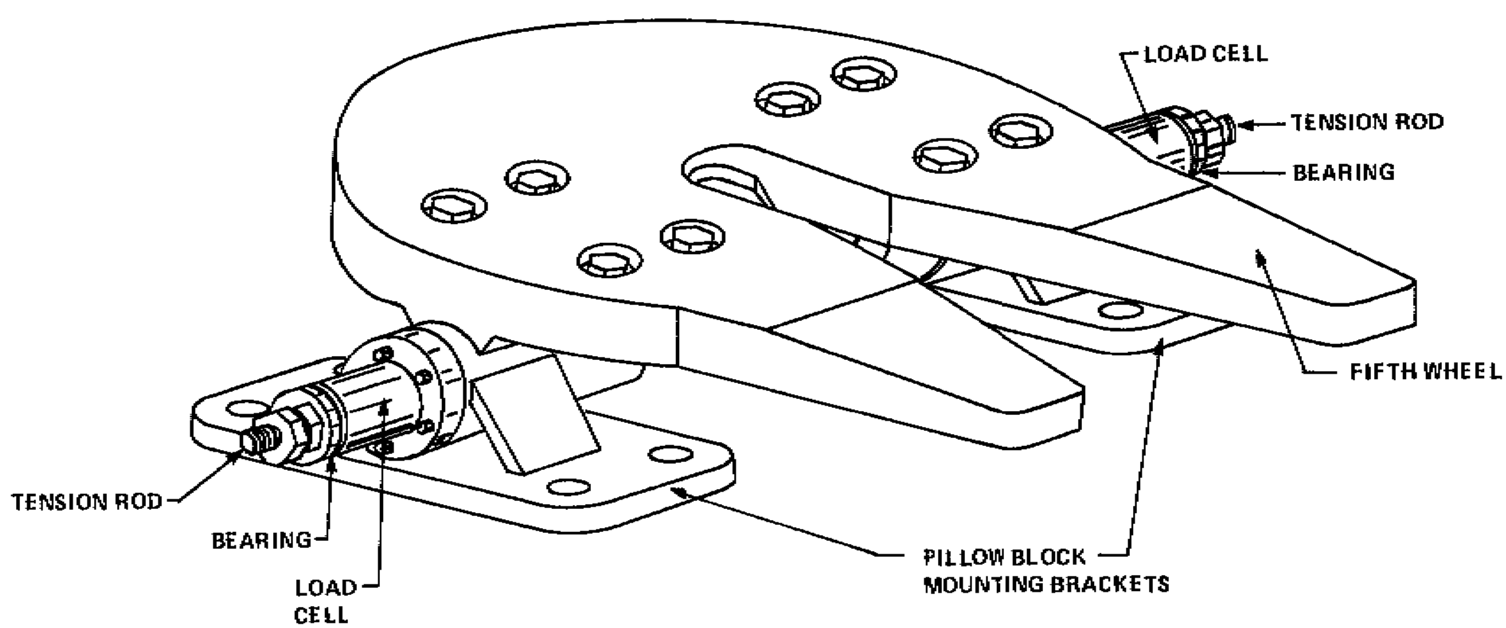

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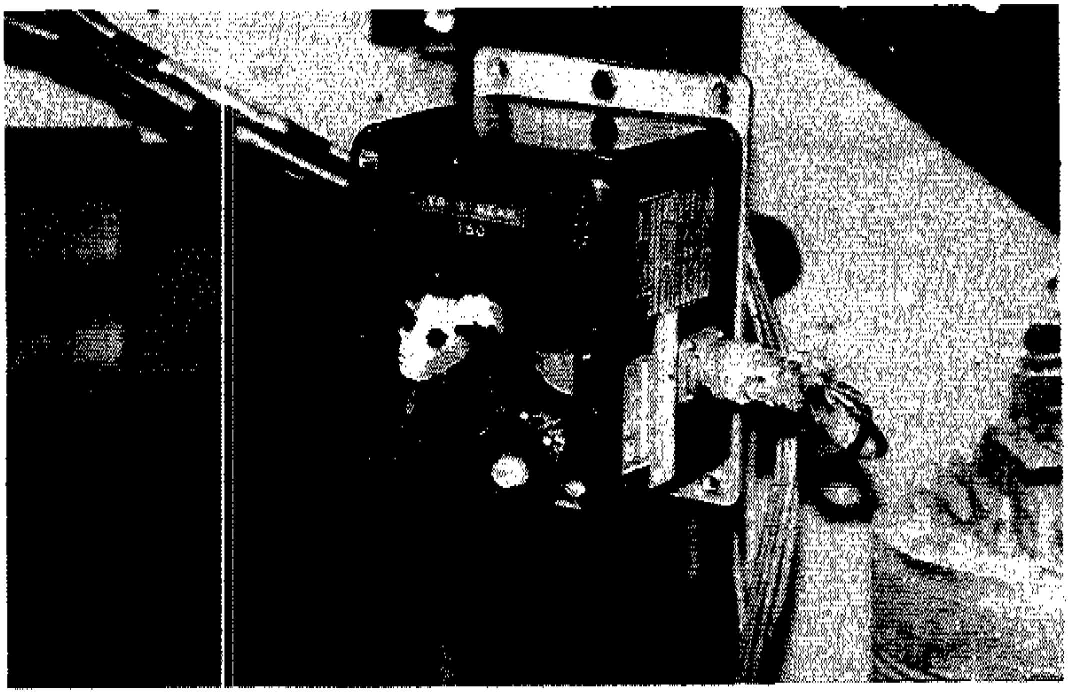

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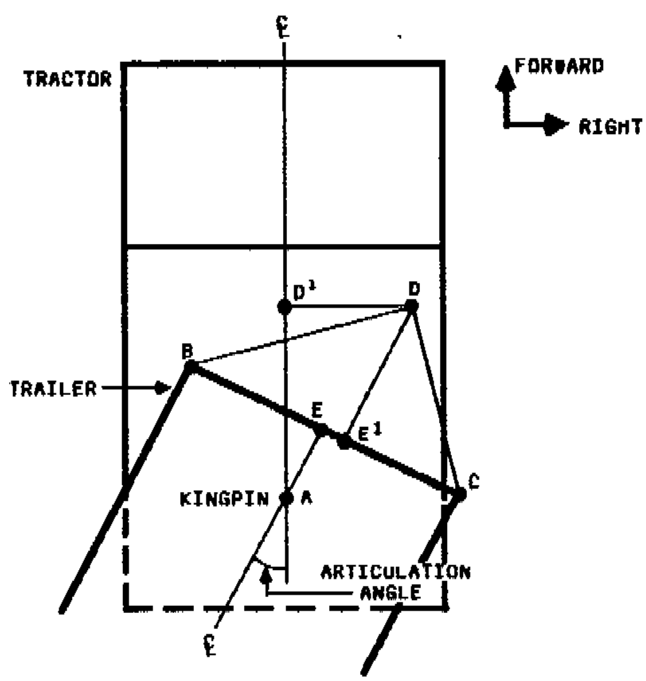

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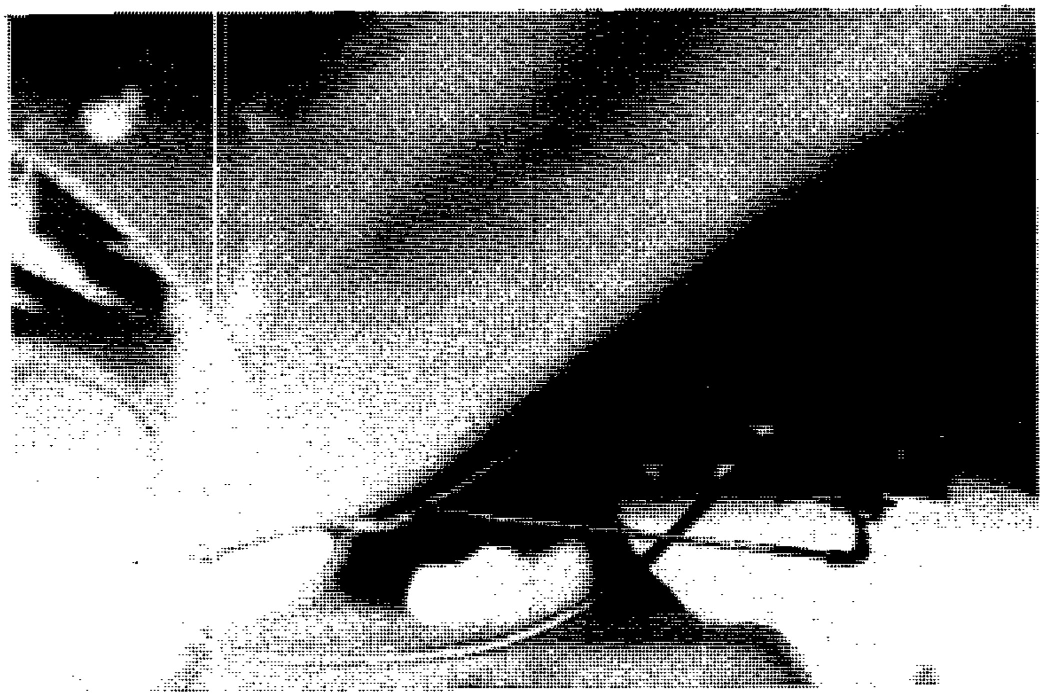

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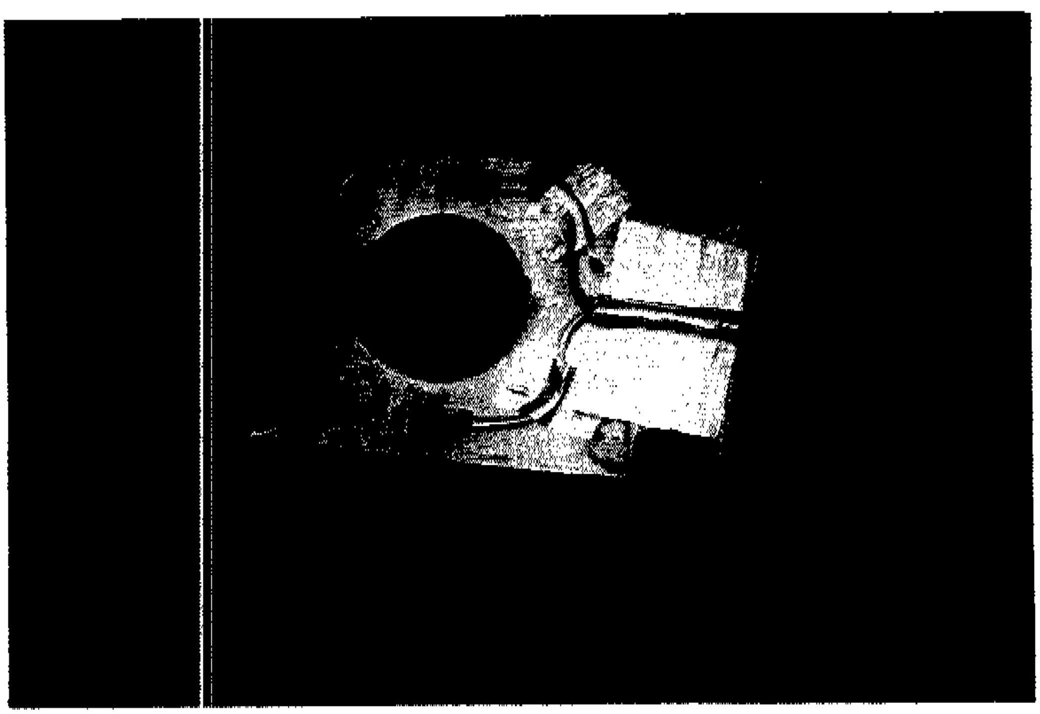

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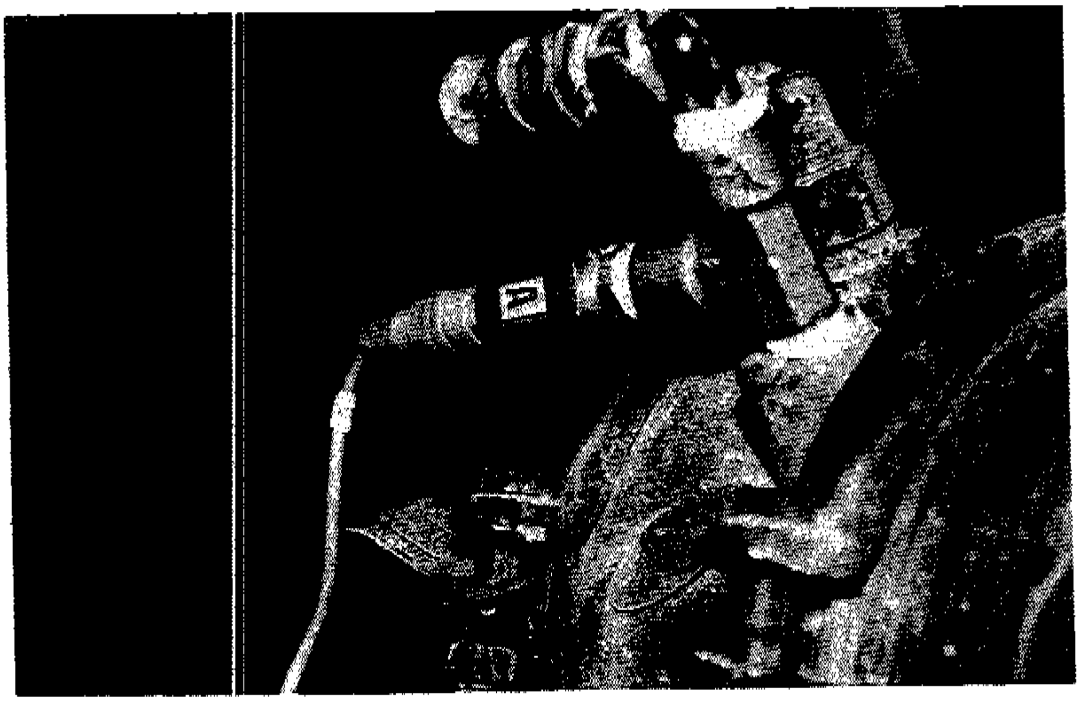

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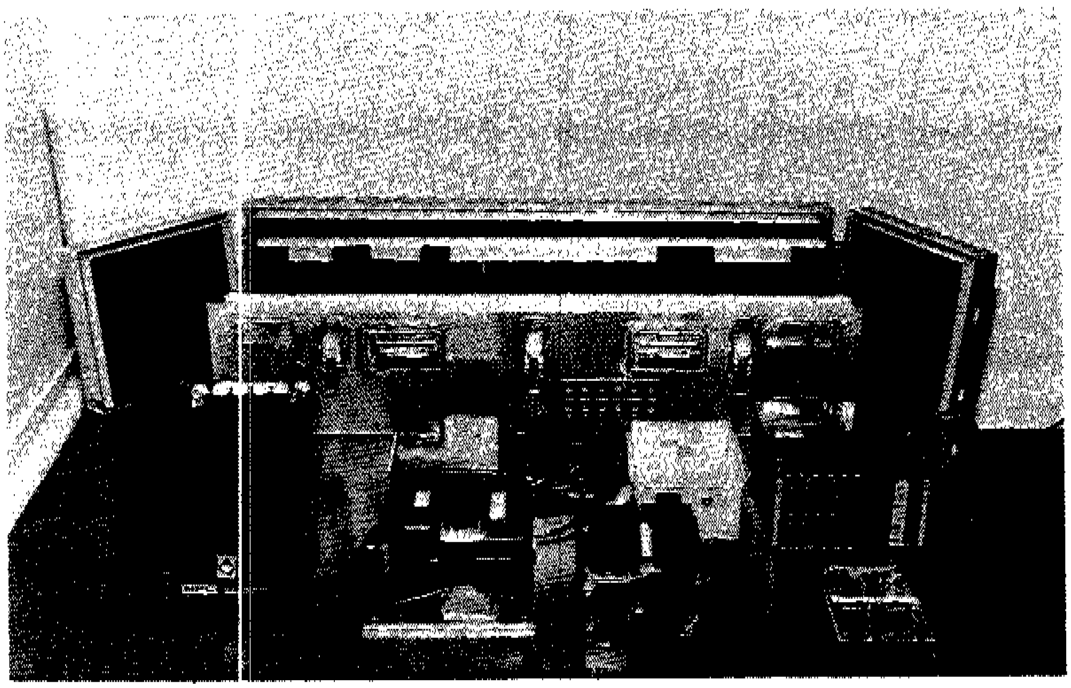

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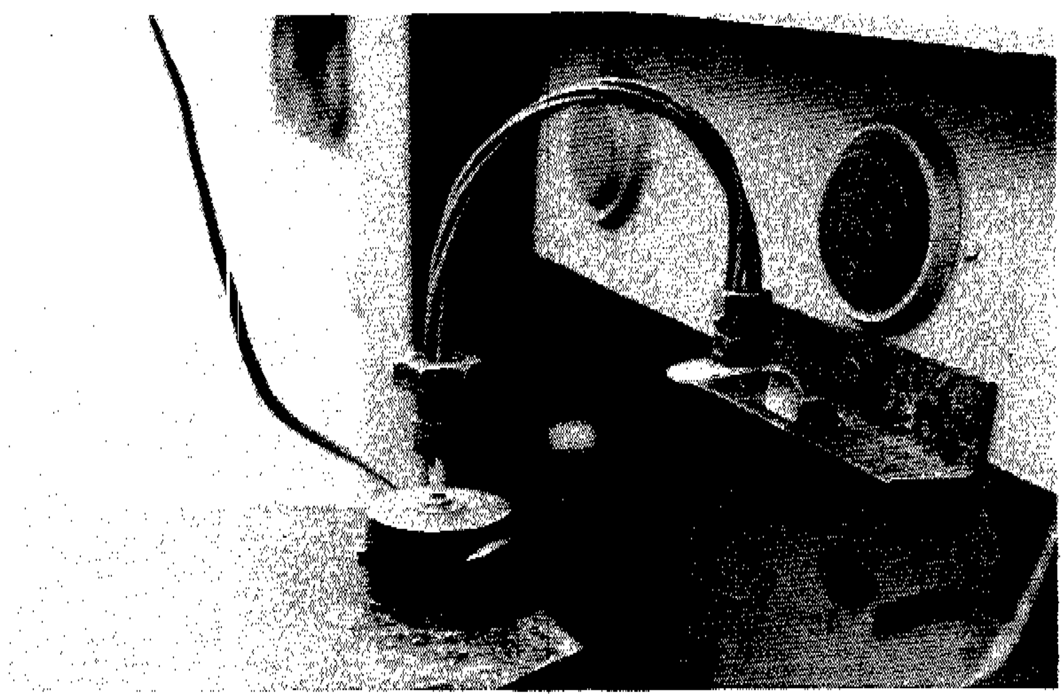

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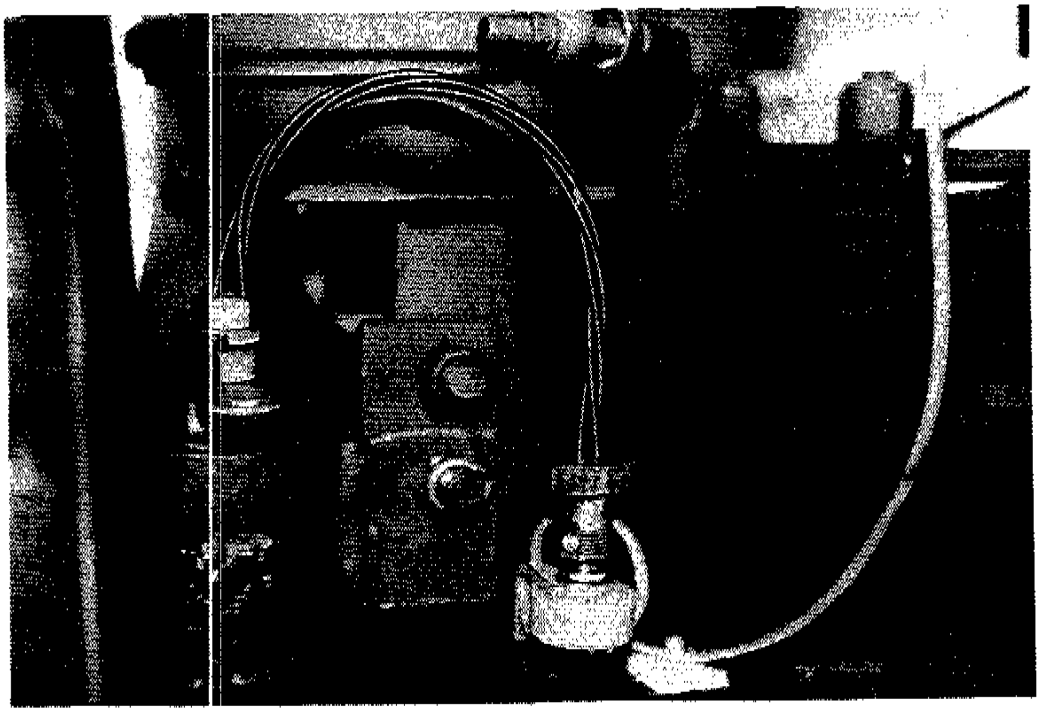

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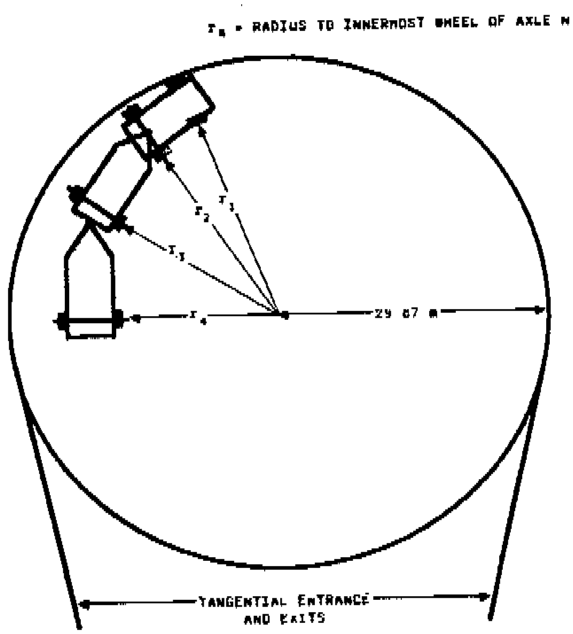

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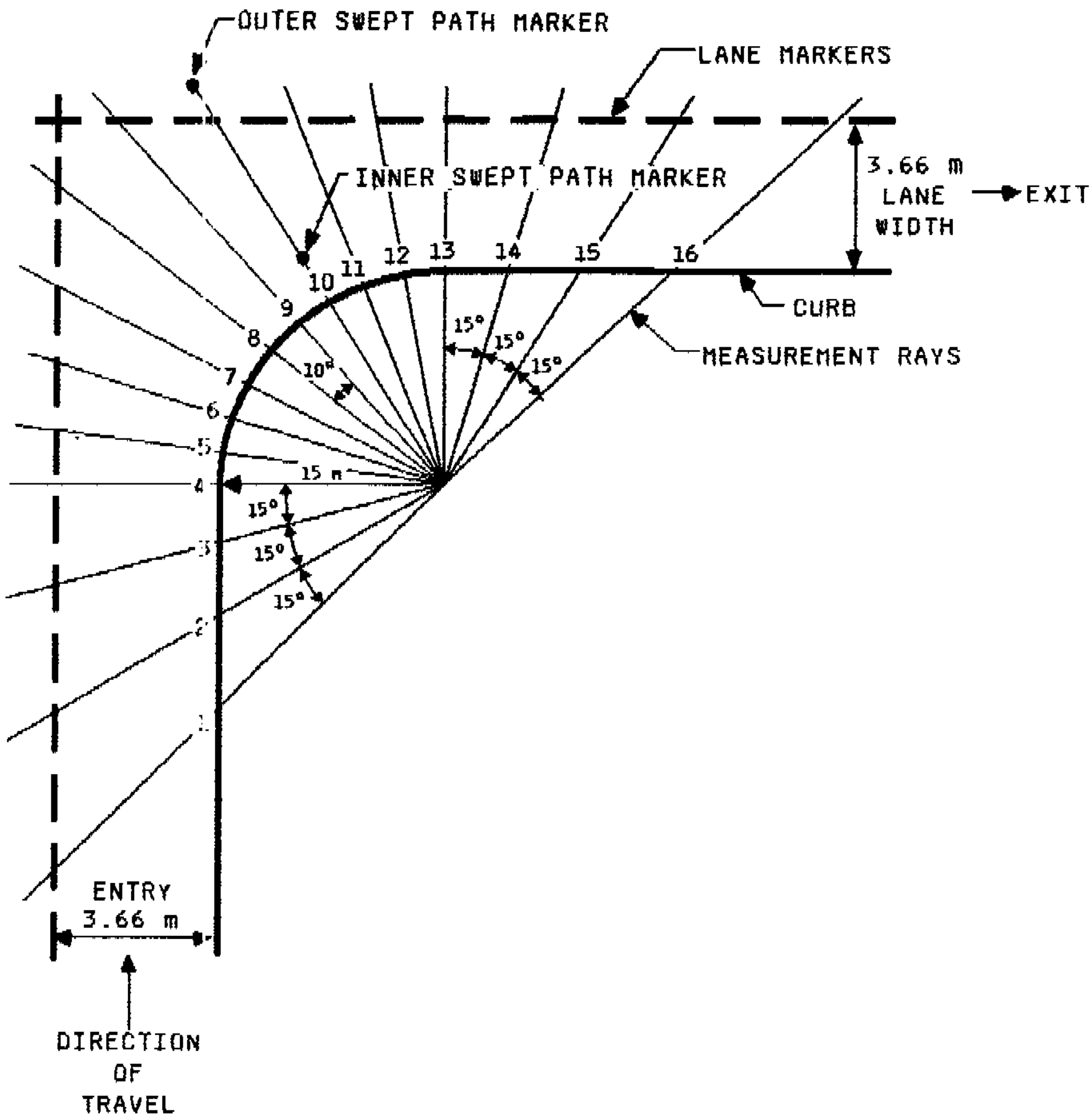

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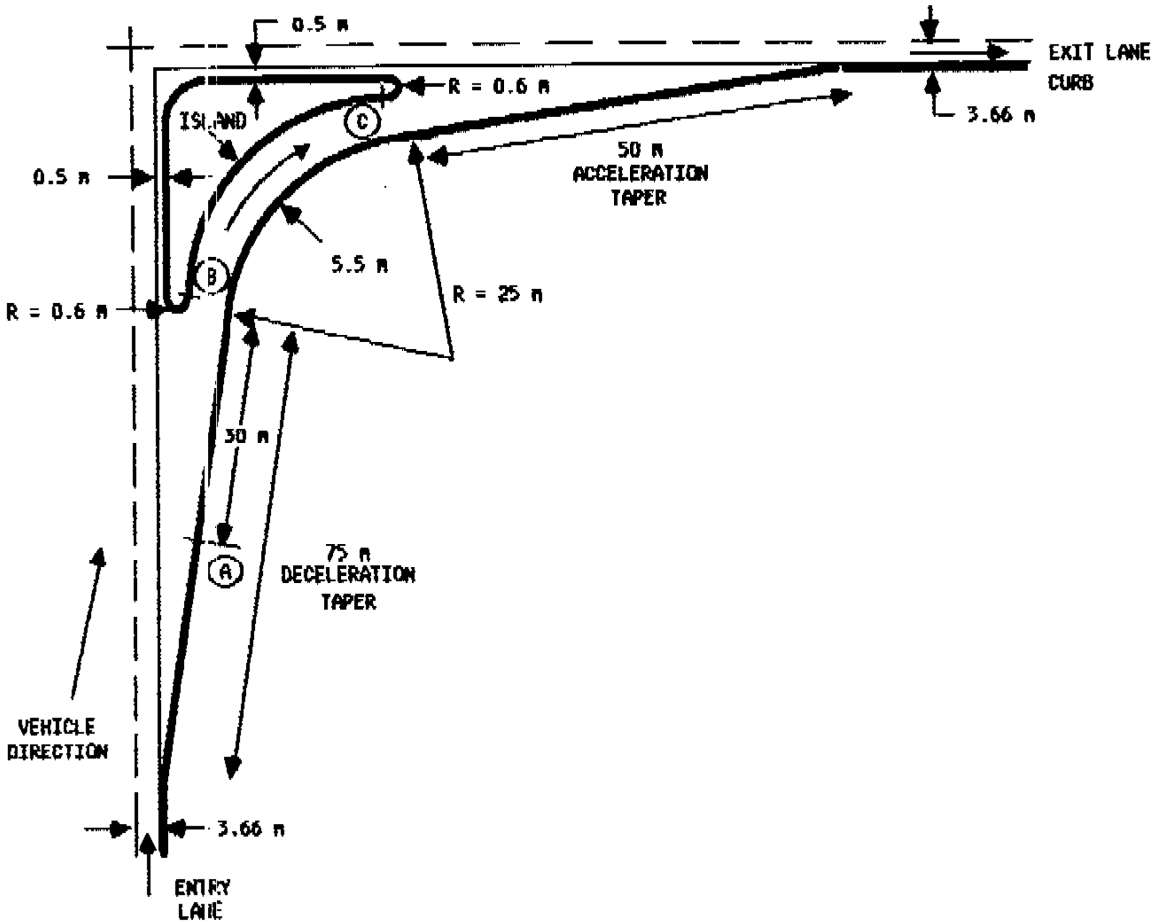

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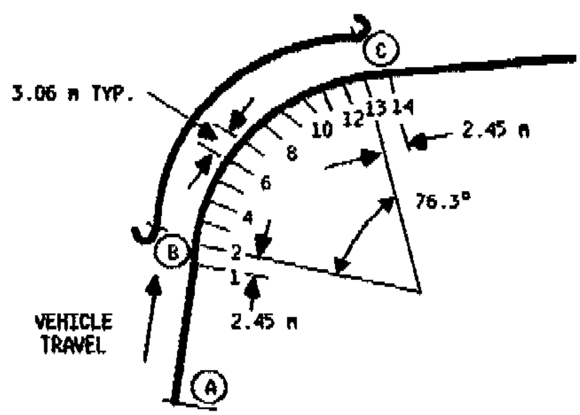

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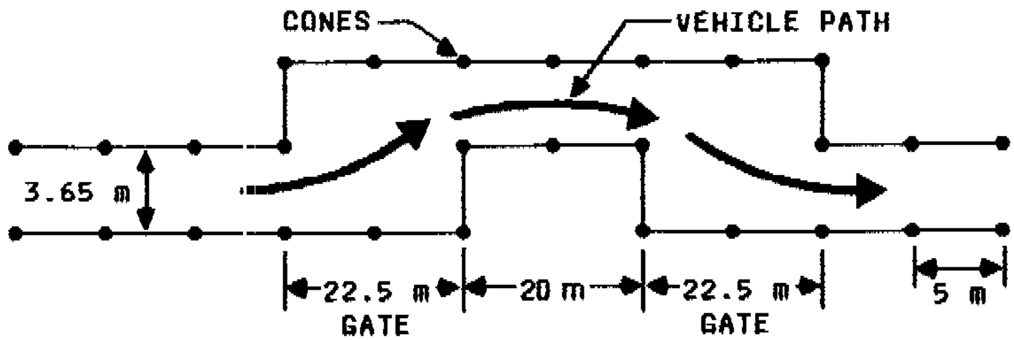

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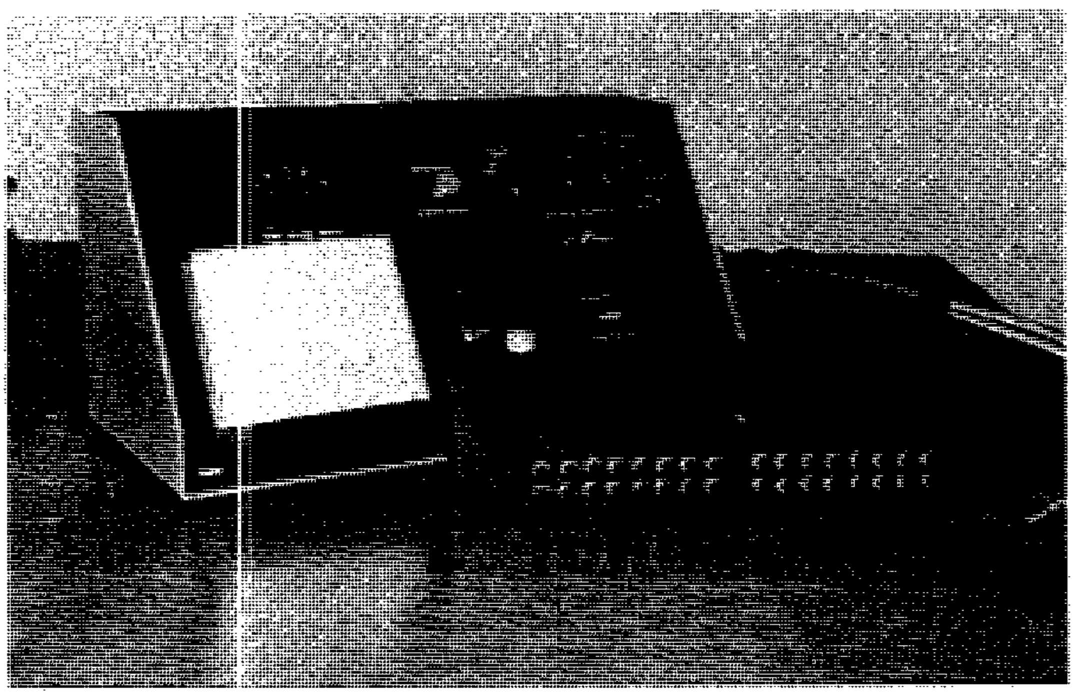

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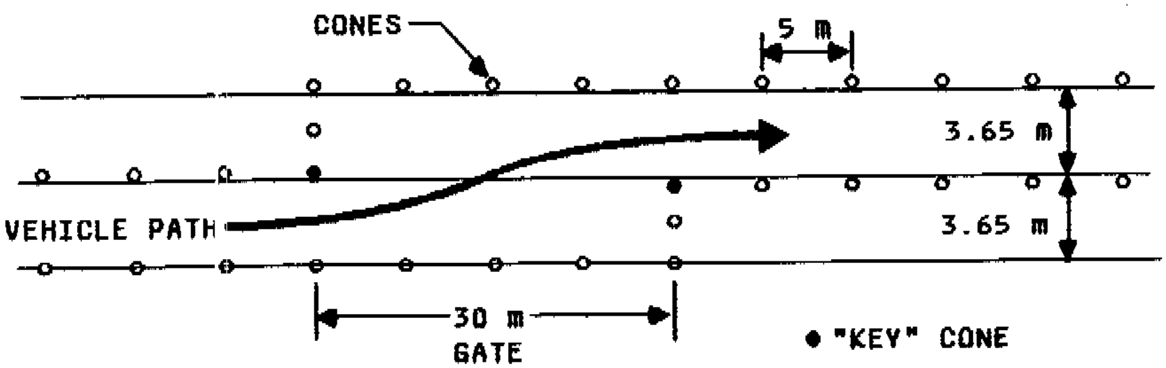

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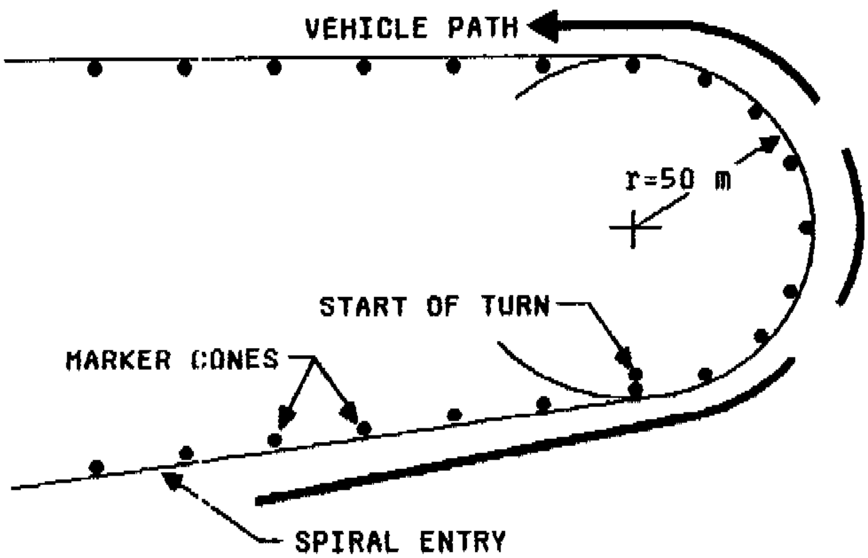

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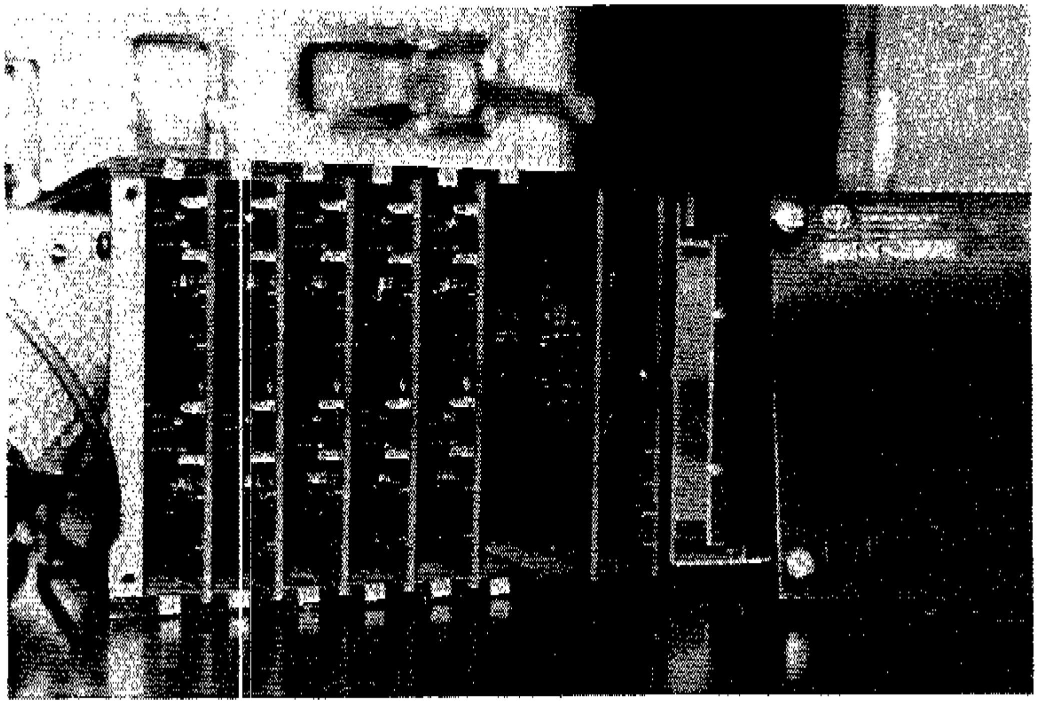

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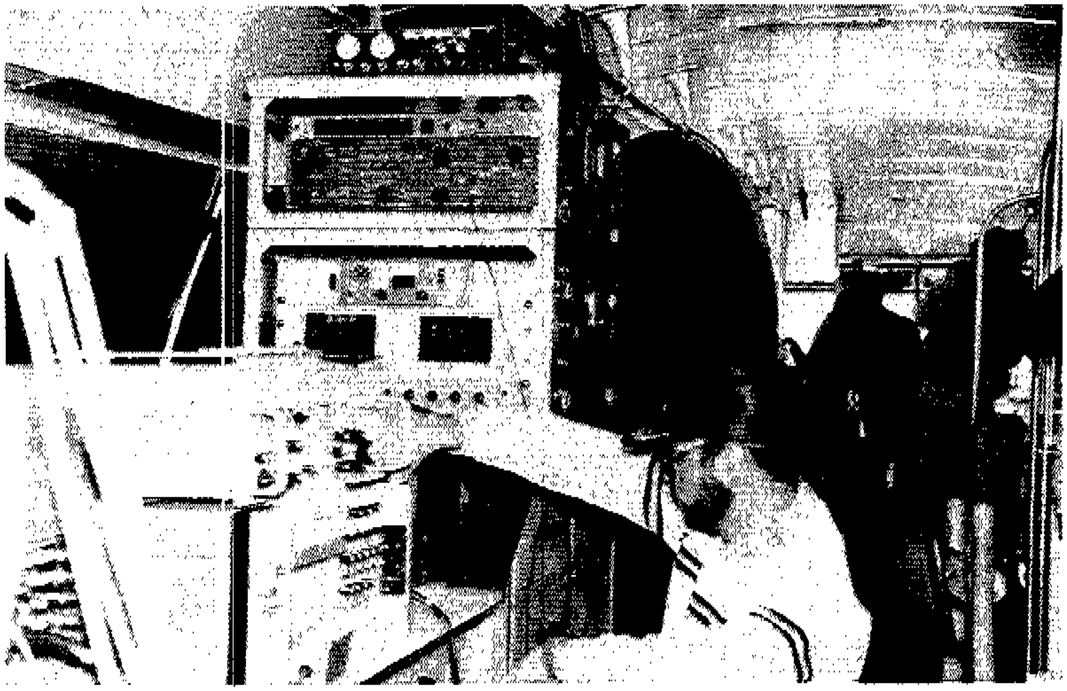

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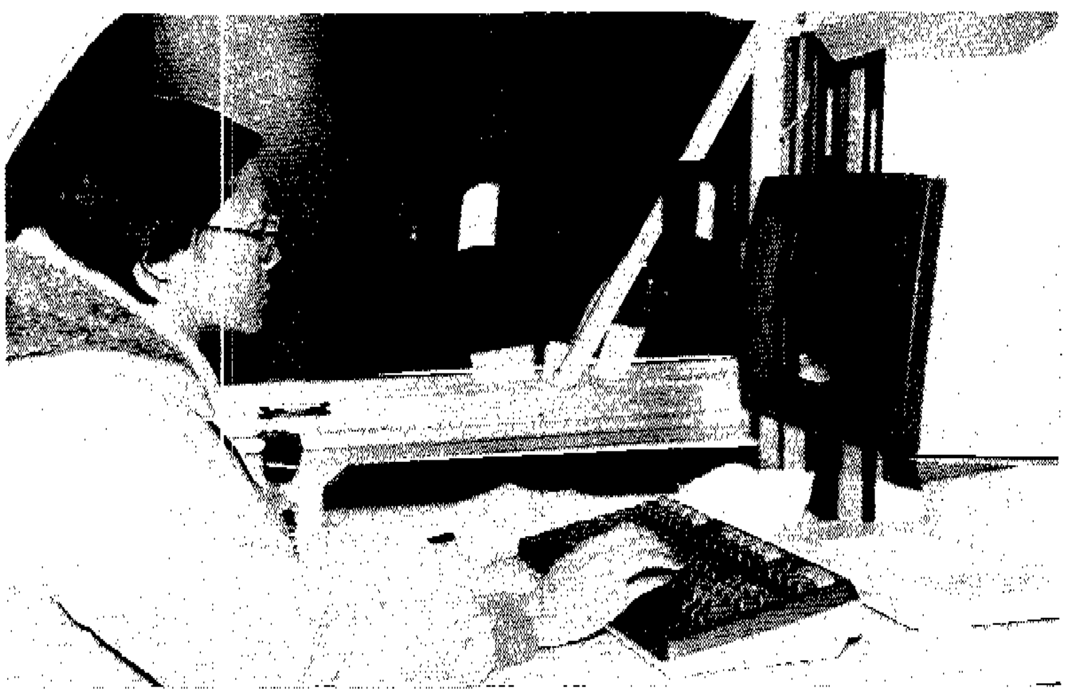

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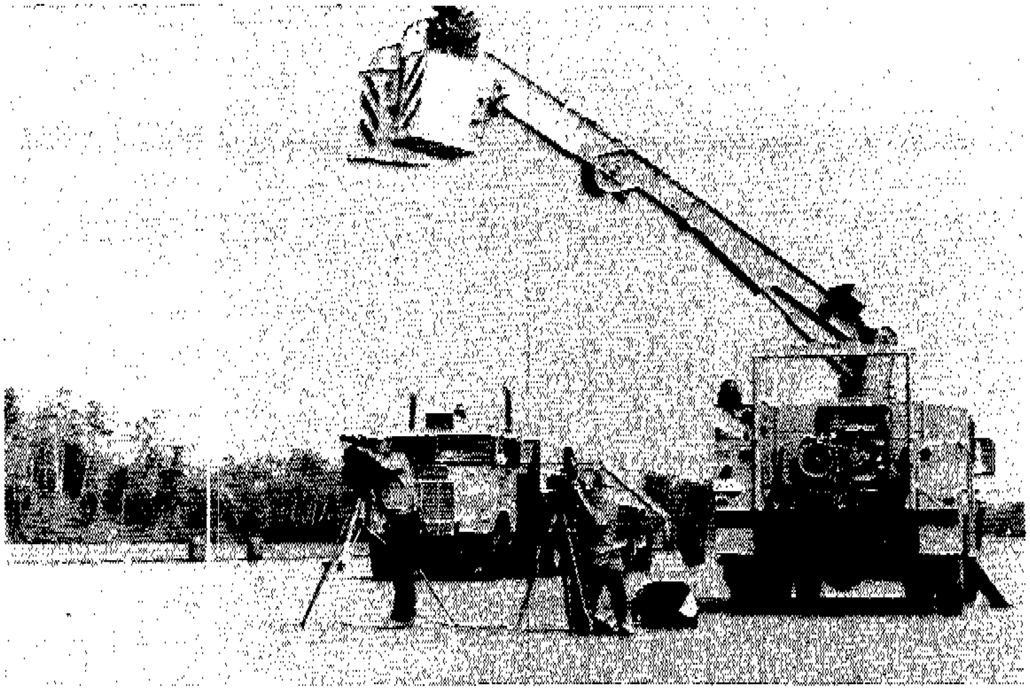

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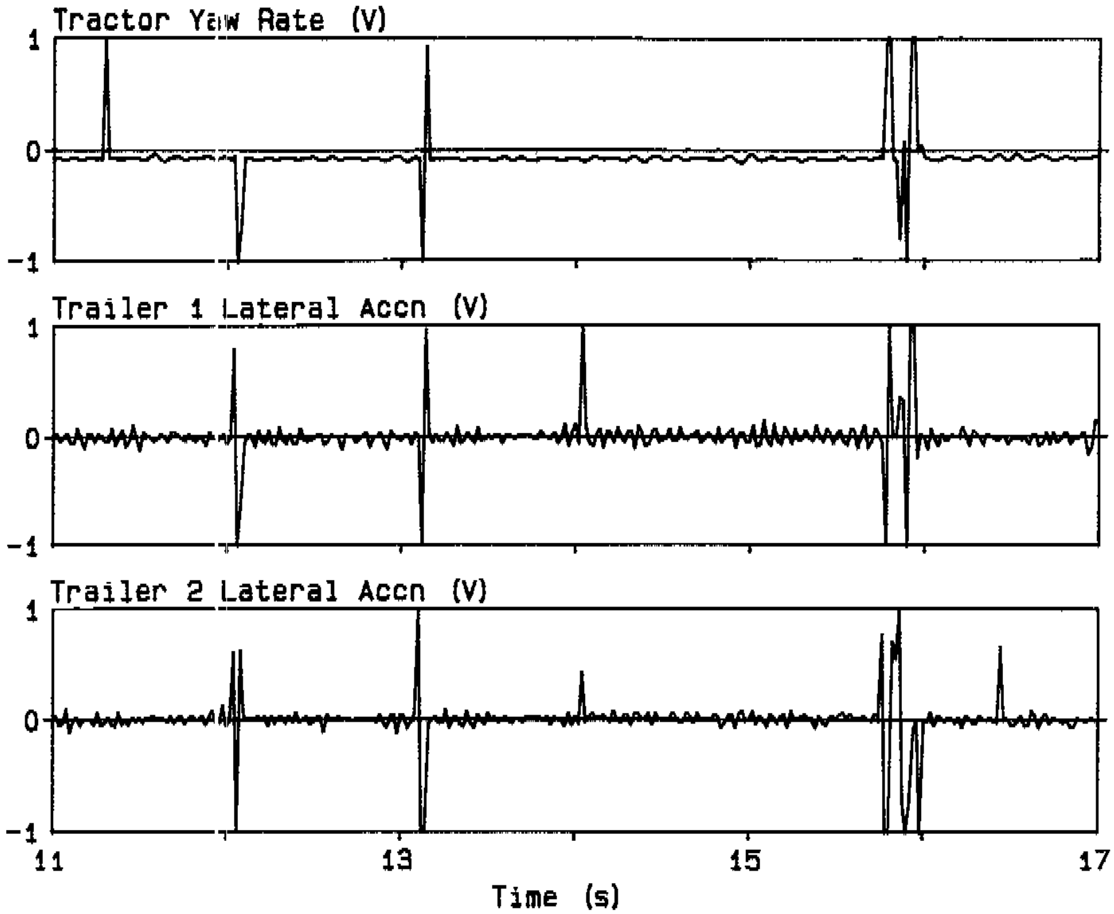

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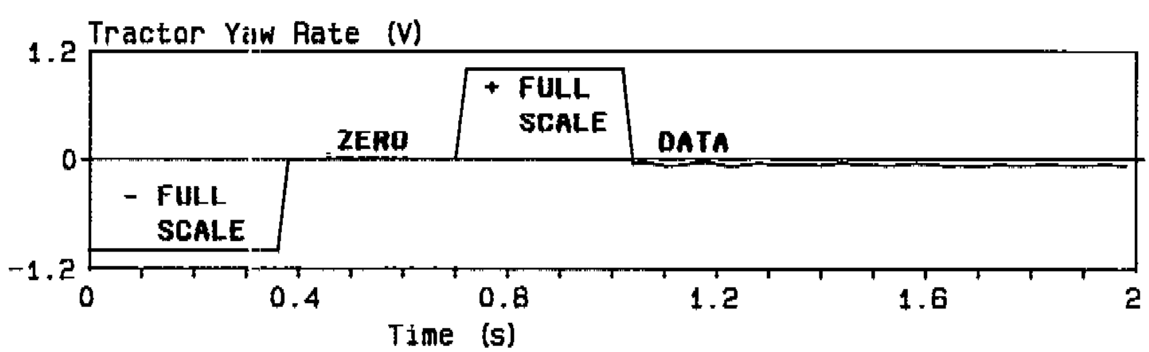

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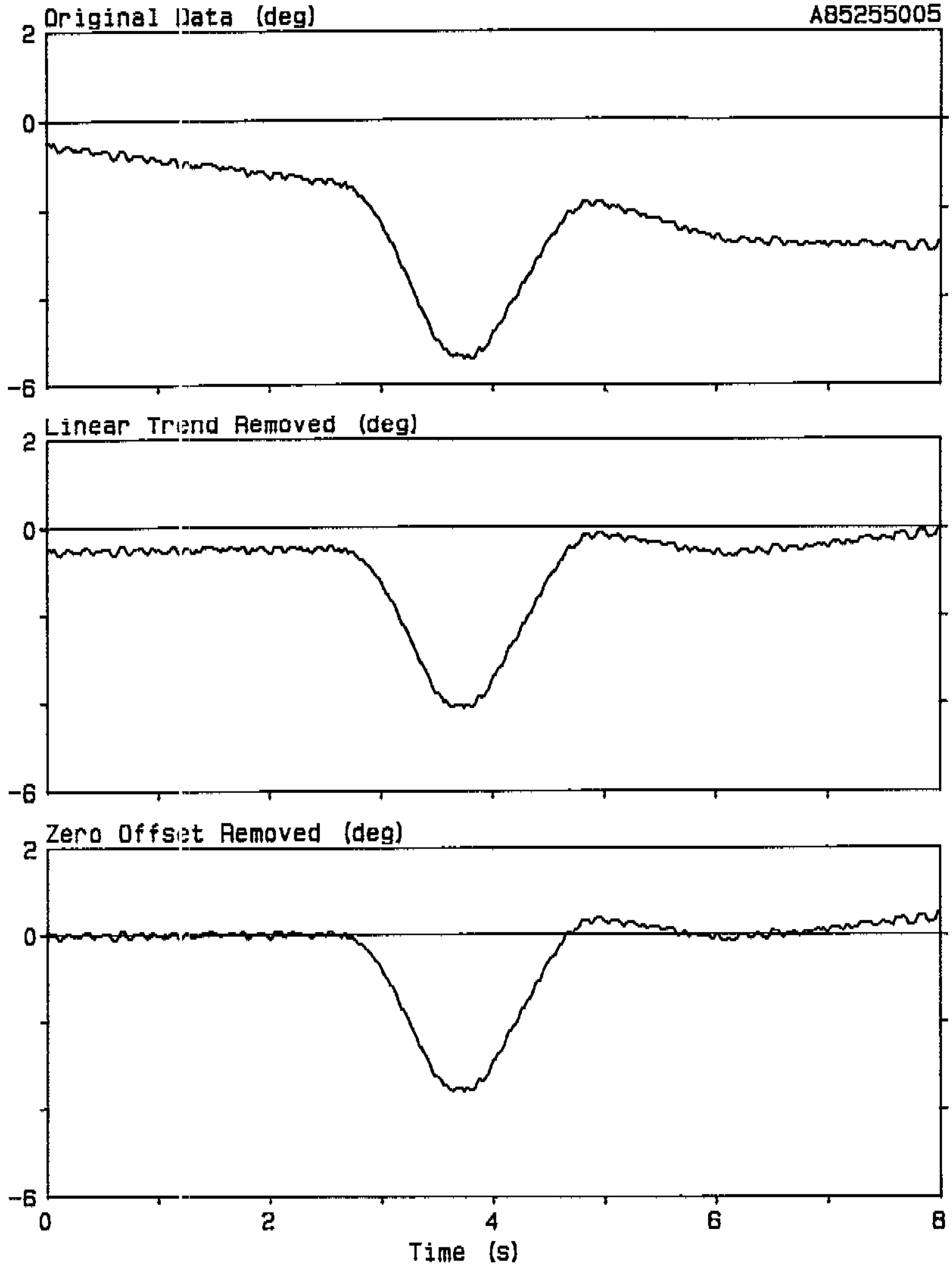

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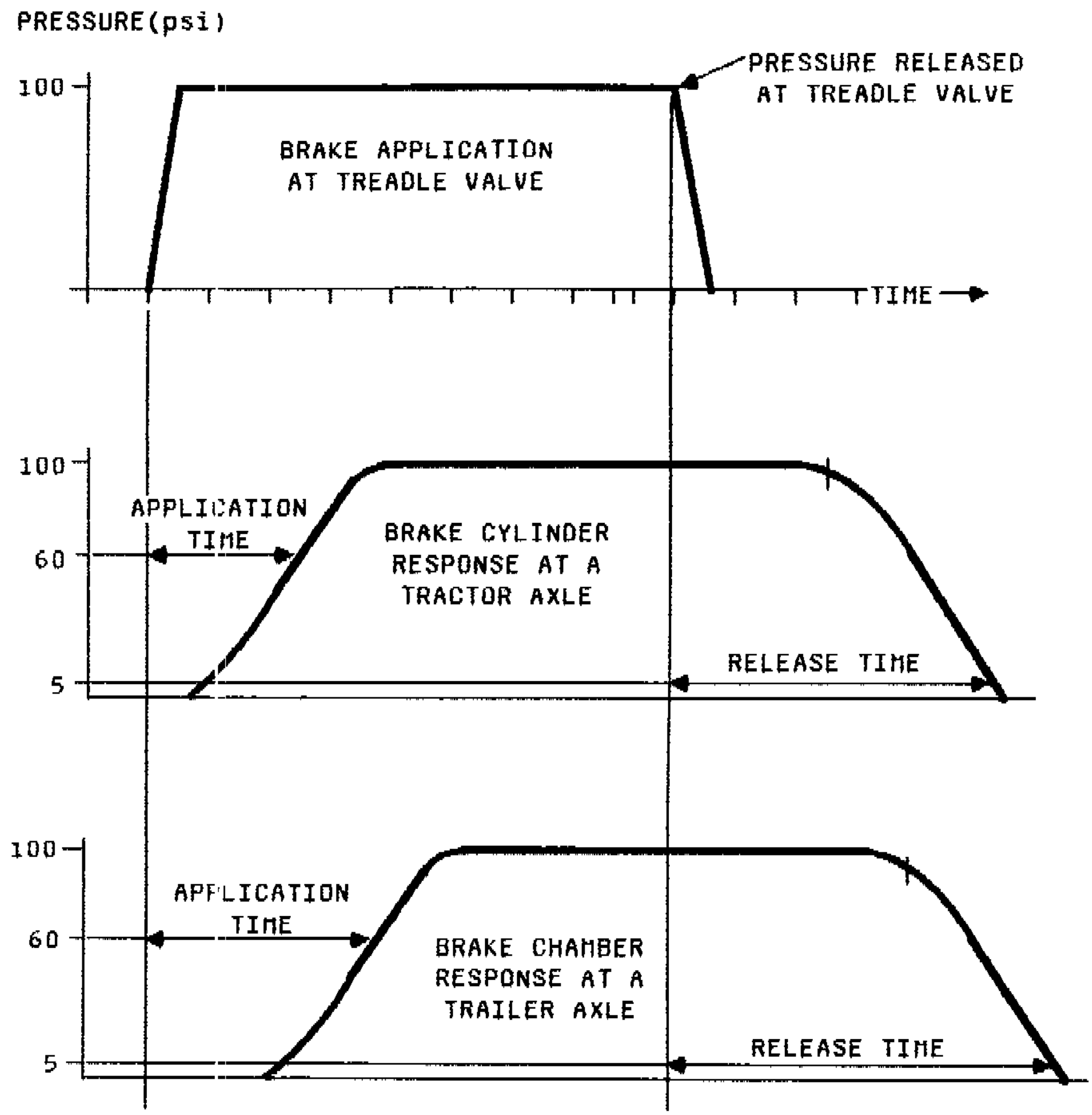

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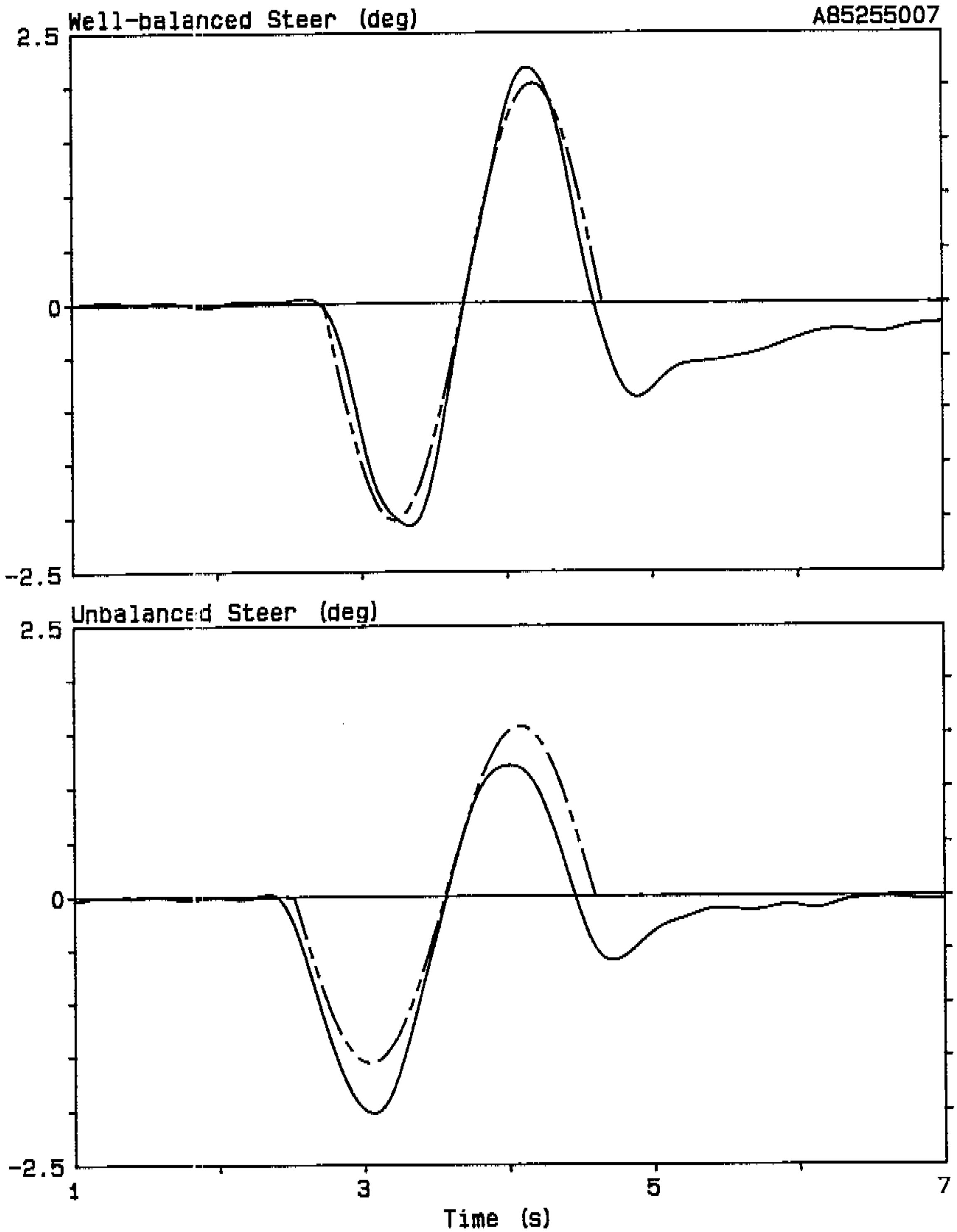

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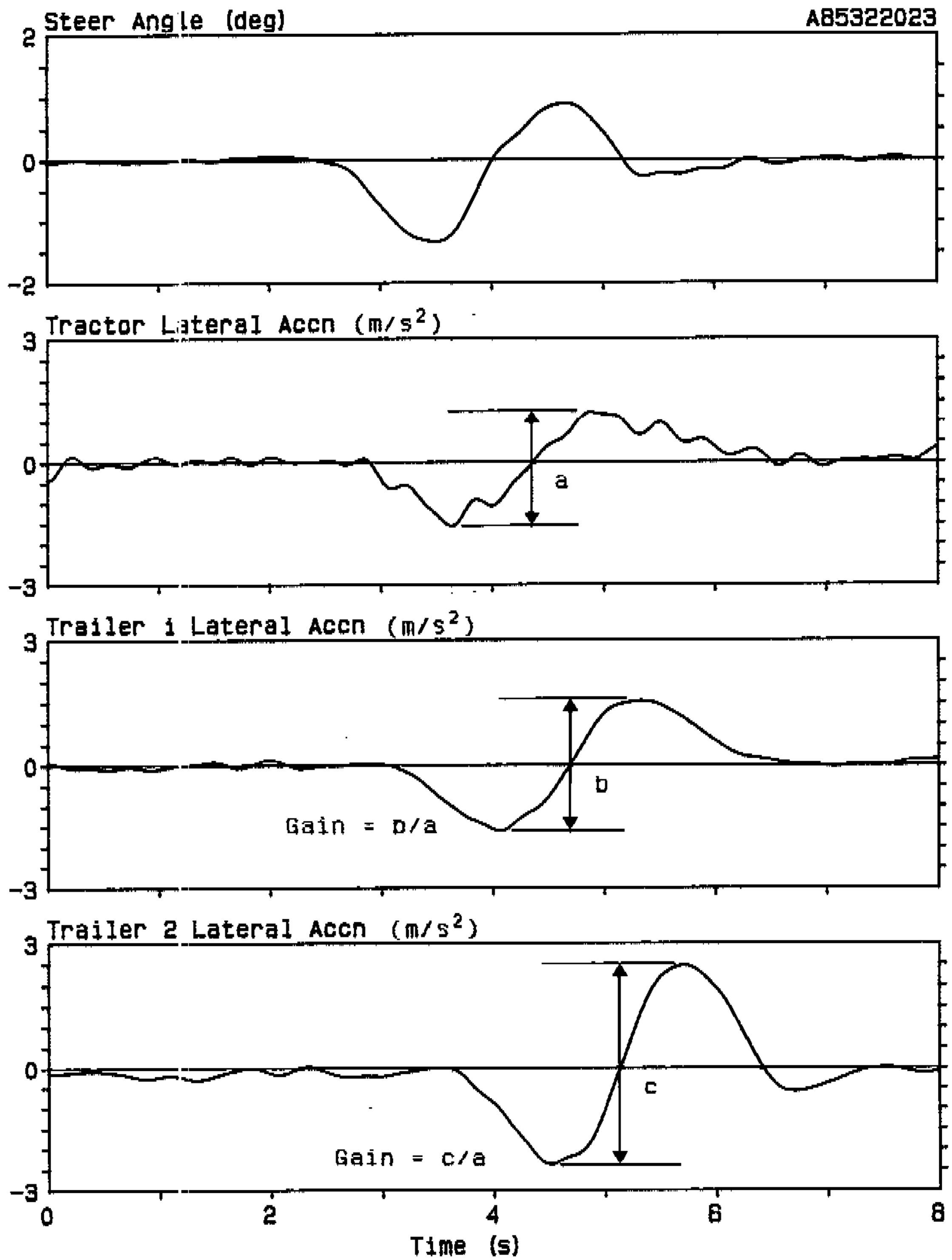

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CV-86-02

Demonstration of
Baseline Vehicle Performance: 45 ft Semi

J.R. Billing
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Ontario Ministry of Transportation
and Communications

ABSTRACT

A 45 ft (13.72 m) semitrailer combination was tested by the Ontario Ministry of Transportation and Communications (MTC) as part of the CCMTA/RTAC Vehicle Weight and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with the empty vehicle on a low-friction surface and the loaded vehicle on a high-friction surface.

This report presents detailed results of the tests and demonstrations.

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ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The trailer was provided by the Roads and Transportation Association of Canada (RTAC). Facilities of the Transport Canada Motor Vehicle Test Centre were made available to the Ministry of Transportation and Communications (MTC). Assistance with vehicle preparation, delivery, and refurbishment was arranged by Mr. Pearson in support of this work.

The work was principally undertaken by the staff of the Automotive Technology and Systems Office of the Transportation Technology and Energy Branch of MTC: N.R. Carlton; G.B. Giles; C.P. Lam, P.Eng.; W.R. Stephenson, P.Eng.; and M.E. Wolkowicz; and assigned students G. Goertzen, S. Jazic, and D.R. Sykes. Assistance was provided by staff of various other departments of the ministry and other organizations.

The efforts of all involved are hereby acknowledged with gratitude.

1/ INTRODUCTION

The effects of changes in truck weight and dimension parameters on combination vehicle stability and handling and on pavement response to axle group loading are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle portion of the study involved both computer simulation of vehicle dynamic manoeuvres and testing of vehicles and components. Combination vehicles were classified into six families, based on the number of trailers and methods of hitching. A representative of each family was designated as the baseline vehicle for that family. Additional vehicle configurations of interest were also defined. All baseline and additional vehicle configurations were tested to assemble a body of technical and visual data that described the stability and control characteristics of the vehicles with respect to certain performance measures.

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. This report presents the results of a test of a 45 ft (13.72 m) semitrailer combination baseline vehicle. It refers frequently to a report describing procedures and equipment common to tests of all nine vehicles undertaken by MTC [1]. Similar reports present details of the tests of the other eight vehicles [2-9], and a summary report presents the results of tests of all six baseline vehicles [10]. A computer simulation of vehicle responses to actual test inputs using estimated vehicle data has also been conducted [11].

2/ TEST VEHICLE DESCRIPTION

The test vehicle consisted of the MTC Freightliner [1] 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 1.83 m (72 in) or more tandem-axle spread, compared with the 1.37 m (54 in) of this trailer.

The equipment for these tests was provided by the Roads and Transportation Association of Canada (RTAC). No modifications were made to the trailer except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were affected.

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). The axle spacing was 1.37 m (54 in). Suspension was a four-spring leaf 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). The combination had an overall length of 17.17 m (58.30 ft).

The trailer was fitted with new Michelin XZA radial tires, in load range H and size 11R22.5. These tires were run a nominal distance of 600 km (370 mi) before any testing and were then, subsequently, used for all tests. Tire pressure was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load. This was used for all tests and represents the common operating practice of not reducing tire pressure when running empty.

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.

Table 1/ Axle Loads

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 empty weight exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. A target axle load of 8000 kg (17 600 lb) was set for all axles except for the steer axle. This was not closely attained. 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.

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.

3/ TEST PROGRAM

3.1/ Test Procedures

The test vehicle was prepared for testing in the following way:

1/ A mechanical inspection was carried out, and any necessary repairs or maintenance was done.
2/ Outrigger and safety cable attachments and load block retention sills were installed on the trailer.
3/ Outriggers were installed on the trailer.
4/ The boxes containing instrument packages, power supplies and signal conditioning, other instruments, and cabling were installed.
5/ New tires were installed, and pressures were set.
6/ Other fittings necessary for testing were installed.
7/ Concrete blocks were located on the trailer bed to achieve specified axle loads.
8/ Notes were made from a detailed physical inspection, including an inventory of components and measurement of dimensions.
9/ The MTC tractor was coupled to the trailer.
10/ The combination vehicle was weighed, empty and loaded.
11/ A functional test of the on-board electronics was conducted.
12/ Test runs were made to shake down the vehicle instrumentation and familiarize the test driver with the vehicle's handling characteristics.
13/ Articulation angle between the tractor and trailer was calibrated.
14/ Details of the vehicle and test equipment were recorded on photographs and videotape.

The following tests were performed:

- Offtracking
- Right-hand turn
- Channelized right turn
- Air brake system
- Straight-line braking, empty vehicle, low-friction surface
- Evasive manoeuvre, empty vehicle, low-friction surface
- Sinusoidal steer, loaded vehicle, high-friction surface
- Lane change, loaded vehicle, high-friction surface
- Normal straight-line driving
- Steady circular turn, loaded vehicle, high-friction surface

All tests followed standard procedures [1], except as noted.

3.2/ Instrumentation

The instrumentation shown in Table 2 was installed. Brake pressure transducers were only installed in the trailer for the air brake system test, but all other instrumentation was installed for all tests. Data were always captured from all instrumentation, but only those pertinent to a particular test were analysed.

Tractor instruments were selected from the instrumentation that is permanently installed on the tractor. Instruments for the trailer were mounted in a box placed on the trailer deck, which also contained power supplies and signal conditioning. Trailer lateral acceleration and roll angle were measured at a point midway between the kingpin and axle.

Full details of the instrumentation, signal conditioning, and data capture system are presented elsewhere [1].

3.3/ Data Capture and Data Processing

Data were digitized on board the vehicle and transmitted by telemetry as a pulse-code modulated (PCM) data stream to a ground station, where they were recorded on magnetic tape and captured in real time by an HP-1000 computer system. Test data for a run were processed immediately after the run, and results from a series of runs were subsequently analysed using the computer system [1].

Many test runs of all types were conducted for this vehicle. Not all these runs were used in the preparation of this report. In a number of instances, a run failed to meet a test condition.

Table 2/ Instrumentation Installed

No	Measurement	Instrument	Full Scale
1	Tractor steer angle	Spectrol 139 potentiometer	25.02°
2	Tractor roll angle	Humphrey CF18-0907-1 gyroscope package	8.85°
3	Tractor lateral acceleration	Kistler 303B accelerometer	0.957 g
4	Tractor yaw rate	Humphrey RT03-0502-1 angular rate transducer	38.7°/s
5	Tractor longitudinal acceleration	Kistler 303B accelerometer	0.974 g
6	Tractor speed, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	104.8 km/h
7	Tractor distance, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	56.3 m/ramp
8	Tractor fifth wheel load, left-hand side	MTC load cell	9890 lb
9	Tractor fifth wheel load right-hand side	MTC load cell	10 290 lb
10	Tractor treadle valve pressure	Celesco PLC-200G	100 psi
11	Tractor brake pressure, axle 2 Left	Celesco PLC-200G	99.80 psi
12	Tractor lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
13	Tractor yaw angle	Humphrey CF18-0907-1 gyroscope package	17.73°
14	Trailer 1 articulation angle	Celesco pull cord DV-301-150	18.361°
15	Trailer 1 lateral acceleration	Columbia SA-107 accelerometer	0.995 g
16	Trailer 1 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.90°
17	Trailer 1 outrigger touchdown	Strain gauge bridge	1.0 V
18	Brake pressure, axle 4 right	Celesco PLC-200G	104.96 psi
19	Brake pressure, axle 5 right	Celesco PLC-200G	101.06 psi

4/ RESULTS

4.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions, as shown in Figure 3. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [1].

The results are shown in Table 3. The measured data were averaged for the left and right turn and then compared to data generated by a simple offtracking formula [12]. The difference between actual and computed values, shown in the last column of Table 3, is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

The final offtracking for the clockwise turn is shown in Figure 4. After averaging for both directions and correcting for differences in axle track width, the offtracking of 2.65 m (8.69 ft), shown in Figure 4, became 2.82 m (9.25 ft).

Table 3/ Offtracking

Axle No.	Track Width (m)	Radius to Inner Wheel		Difference (m)	Average (m)	Calculated (m)	Difference %
		Right Turn (m)	Left Turn (m)				
1	2.31	27.62	27.70	0.08	27.66	27.56	-0.36
2	2.37	27.26	27.39	0.13	27.32	27.21	-0.40
3	2.37	27.22	27.36	0.14	27.29	27.21	-0.29
4	2.37	24.91	25.06	0.15	24 99	24.92	-0.28
5	2.37	24.88	25.03	0.15	24.96	24.92	-0.16

4.2/ Right-Hand Turn

A 90° right-hand turn is a very demanding manoeuvre for a large truck. The vehicle's swept path in a 90° right-hand turn of 15 m (49.2 ft) radius was measured, according to the standard test procedure [1]. This radius is typical in an urban area or where there is limited truck traffic. The swept path is shown in Figure 5.

The vehicle is shown in Figure 6 during the turn. The maximum excursion out of lane was 2.20 m (7.22 ft), just over half a lane width. It was out of the exit lane for a distance of 19.20 m (63.0 ft), as derived from Figure 5. This test was conducted at a creep speed and represents the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

4.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [1].

The vehicle is shown during the turn in Figure 7. The clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Figure 8 as a function of distance through the curve. The minimum clearance was only 0.89 m (35 in) in the 5.5 m (18 ft) wide roadway.

The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. The vehicle easily made it through the channel. The test was run at creep speed, the worst condition, as the effect of lateral acceleration is to reduce the geometric offtracking measured in this test.

4.4/ Air Brake System

The air brake system of the combination was evaluated according to standard test procedure [1].

The trailer air brake system was inspected. A schematic of the system is shown in Figure 9. All slack adjusters required manual adjustment. Stroke was adjusted to the minimum, about 32 mm (1.25 in) on each axle. The tractor was supplied with shop air, regulated at 689 kPa (100 psi). Pressure transducers were installed at both trailer axles.

The SAE J982a style test was performed for the full combination. The results of this test, presented in Table 4, are the average of several tests, each with a time resolution of 0.02 s. The application and release times of this test are typical of such equipment. A typical time history response of application and release is presented in Figure 10.

Table 4/ Air Brake Timing, SAE J982a Style Test

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.07	0.19	99.2
Axle 2	0.41	0.64	98.8
Axle 4	0.49	0.94	96.2
Axle 5	0.45	0.88	97.6

4.5/ Straight-Line Braking

It is difficult to conduct rigorous braking tests and achieve consistent results. A demonstration of modes of instability of the combination vehicle in straight-line braking was, therefore, conducted. A series of runs was made with the empty vehicle approaching the low-friction test area at 47 km/h and the driver braking using the treadle valve. Runs were made using various application pressures, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [1].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit.

The time history of a typical run that resulted in loss of control is shown in Figure 11. The initial average brake application of 311 kPa (45 psi) caused all brake wheels to lock, and the tractor jackknifed to the right. The driver reduced the brake pressure, as a consequence, and steered a little to the left, in controlled instinctive responses. The tractor, however, continued to rotate until the safety cables were engaged, as seen from the 15° limitation on articulation angle, and the vehicle rotated as a unit. The tractor heading reached the limit of the signal conditioning system. If the front axle brakes on the tractor had been used, it is likely that there would not have been a tractor jackknife. The vehicle final position is shown in Figure 12.

A summary of peak vehicle responses from the runs is shown in Figure 13 as a function of average treadle valve pressure over the entire stop.

The limit of surface adhesion of about 0.15 g was reached at about 159 kPa (23 psi), when most wheels were locking, but it was not until a significantly greater pressure that the vehicle actually became unstable. That point is seen in Figure 13 at about 221 kPa (32 psi) because of the averaging, although it was the much higher initial pressure that caused the instability.

4.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. Gates of 22.5 m (73.8 ft) were used for the lane change to the left and the return to the original lane, separated by 20 m (65.6 ft) in the left lane. The runs were made in accordance with the standard test procedure [1].

The vehicle combination was evaluated primarily in terms of the lateral acceleration and yaw responses of the vehicle units. These are shown in Figure 14. Each response is the peak-to-peak amplitude experienced by the vehicle in the manoeuvre. The lateral acceleration amplitude of tractor and trailer both increased to 5 to 5.5 m/s^2 near 56 km/h, where they tended to level off. It was evident from these data, driver reports, and observation that the tractor was close to the limits of adhesion, making it difficult to manoeuvre. The tractor and trailer heading angle remained uniform, indicating that although the driver had only partial steer control, he was able to maintain directional control. Run data indicated that the driver had to increase steer angle as speed increased, implying an increase in tractor understeer. Tractor control appeared to be the limiting factor for this vehicle in this manoeuvre.

The driver was able to make this manoeuvre up to 60 km/h. At 63 km/h he was unable to get the vehicle through the gate to return to the original lane, due to the limit on the tractor control and the length of the vehicle. While the objective of the manoeuvre was not achieved, the vehicle did not slide substantially. No higher speed was attempted. A typical run at 63 km/h is shown in Figure 15.

4.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for this combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 63, 84, and 94 km/h, with steer input periods between about 2 and 5 s.

The vehicle combination was evaluated in terms of lateral acceleration responses of the trailer. Rearward amplification of lateral acceleration is presented in Figure 16, as a function of tractor steer input period, for the three test speeds. This is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless [1].

It is evident from Figure 16 that rearward amplification remains relatively constant with respect to both speed and steer period. Its maximum value is about 1.05. Even at highway speed, the 45 ft (13.72 m) semi is a very stable vehicle, because of its low response to input.

Figure 17 shows the vehicle response from a typical run for a steer period of about 2 s at 94 km/h.

4.8/ Lane Change

The objective of this test was to evaluate vehicle stability characteristics in a dynamic manoeuvre. A series of runs was made where the driver made a lane-change manoeuvre, which is considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [1].

A gate of 30 m (98.4 ft) was used, to provide a vehicle speed of about 80 km/h, which is a typical speed limit and might permit some comparison of the results of this test with those described in the preceding sections. The vehicle is shown in this manoeuvre in Figure 18.

The results from all runs are summarized in Figure 19. The peak-to-peak lateral acceleration, roll, and yaw (or heading) angles all show an increase as the speed climbs. The lateral acceleration gains at 63, 84, and 94 km/h are consistent with those from the sinusoidal steer test. Lateral acceleration lag time shows some scatter at the higher speeds, indicating possible tractor slide within the lane, but is caused by the length of the vehicle and, in this case, is not considered to be a gauge of the driver's control of the vehicle. The yaw overshoot of the trailer clearly shows little or no rear trailer swing.

Figure 20 shows the steer input and vehicle response from a typical run at 94.8 km/h, the highest speed achieved. Both units were tracking close to each other with no sign of unstable behaviour or excessive roll.

4.9/ Normal Straight-Line Driving

The objective of this test was to attempt to evaluate lateral motion of the rear trailer of the combination, the phenomenon known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [1].

As previously mentioned, the vehicle was quite stable, and the slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in no perceptible trailer sway to the occupants of a chase vehicle. Root mean square (RMS) lateral acceleration of the rear trailer was 0.63 g/° of steer input.

4.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics, to determine the high-speed offtracking of the vehicle and to examine the side loads exerted on the tractor by the trailer. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The vehicle was evaluated primarily in terms of the roll response of the vehicle units. Average steady-state roll angle is presented in Figure 21 as a function of tractor lateral acceleration and is seen to increase with speed. At the limiting speed of 55 km/h, a peak lateral acceleration of 0.52 g, the trailer outrigger touched down rather gently, as shown in Figures 22 and 23. The trailer is clearly twisted in Figure 23, due to the distribution of the load. The tractor drive axles did not noticeably lift, so the vehicle was somewhat short of rollover. Average steady-state articulation angles decrease modestly with increase in lateral acceleration, as shown in Figure 21, and as a consequence, the offtracking decreases. The lateral force experienced by the tractor fifth wheel, expressed as a function of tractor lateral acceleration, shows a gradient of 50.8 kN/g (11 400 lb/g).

A tilt table test was conducted on this vehicle, as shown in Figure 24. It revealed 100% lateral load transfer on the high-side wheels at about 28.5°. The tangent of this roll angle should be equal to the lateral acceleration, in g, required to roll the vehicle in the steady circular turn. The tangent of the tilt table was 0.54, whereas the peak lateral acceleration of the trailer at outrigger touchdown was 0.61 g. The tilt test is treated in detail elsewhere [13].

5/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation.

Tests were conducted in various weather conditions. Tires wore progressively as the various tests were conducted. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailer were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal because of the underslung outriggers.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results, except for centre of gravity height. The typical 45 ft (13.72 m) semi is a van, which may, when loaded, have a trailer mass centre of gravity up to 1.20 m (4 ft) above the trailer floor, compared to the 0.17 m (7 in) for this vehicle. The effect of a raised centre of gravity would have been to reduce the vehicle's roll threshold from 0.54 g observed in the tilt test to, perhaps, 0.25 to 0.30 g [14]. This would have reduced the limiting speed in the steady circular turn and resulted in dynamic rollover in the lane change, as the vehicle lateral acceleration of both vehicle units reached 0.38 g in this manoeuvre. The results presented pertain to the particular vehicle tested, and results different in some respects might be obtained for another vehicle at another time.

The test driver felt that this vehicle tracked well and was easy to drive, as the trailer imposed modest forces on the tractor. However, its overall vehicle length meant that it required space to manoeuvre. The long wheelbase on this trailer made the evasive manoeuvre a difficult task, even though the vehicle had not reached its stability limit. It exhibited high stability in all dynamic manoeuvres.

6/ CONCLUSIONS

A 45 ft (13.72 m) semi was tested by the Ontario Ministry of Transportation and Communications, as part of the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with an empty vehicle on a low-friction surface and a loaded vehicle on high-friction surface.

The length of this vehicle contributed to the significant space required to make turns.

The air brake system was typical of such vehicles.

The lateral/directional stability of the vehicle was excellent, both empty on a low-friction surface and loaded on a high-friction surface. The roll stability was high because the centre of gravity of the trailer was very low. A higher centre of gravity would have reduced the roll threshold significantly.

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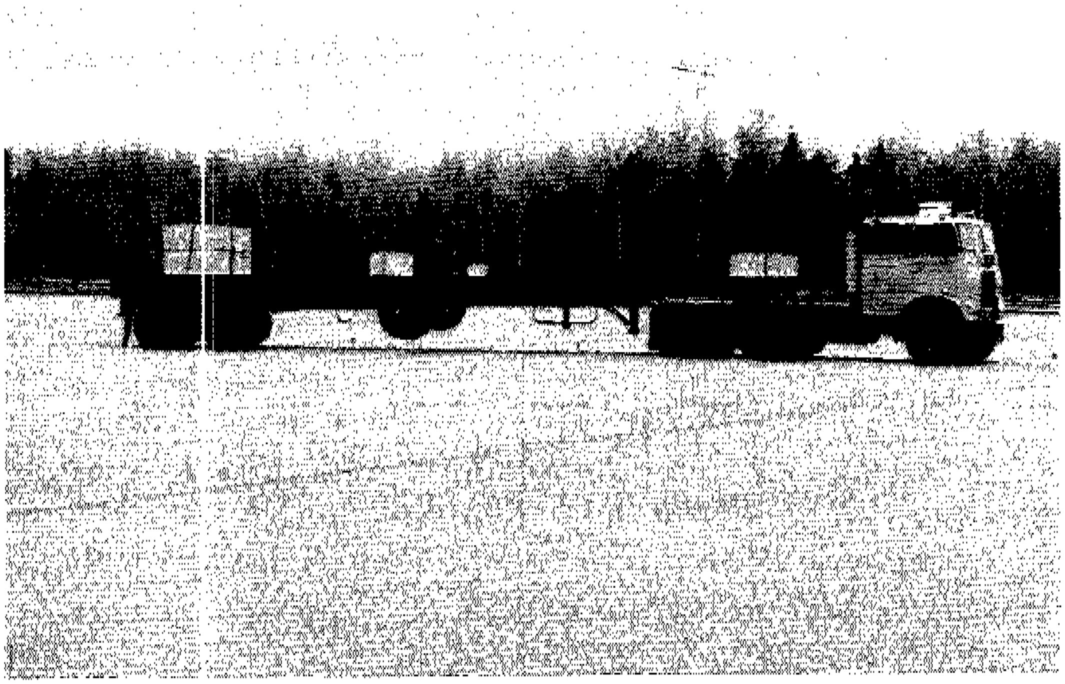


Figure 1/ View of Vehicle

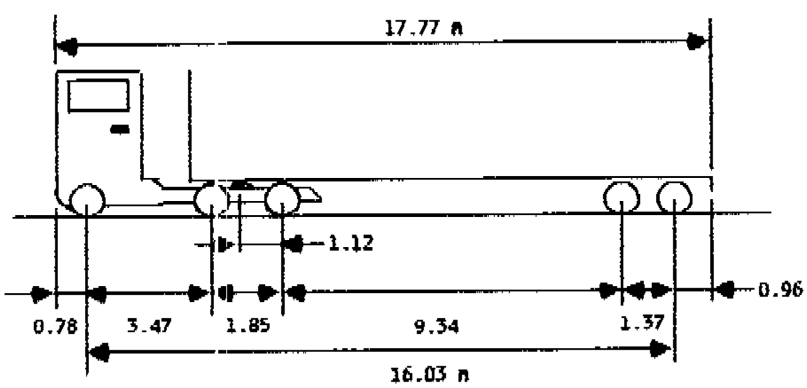


Figure 2/ Vehicle Dimensions

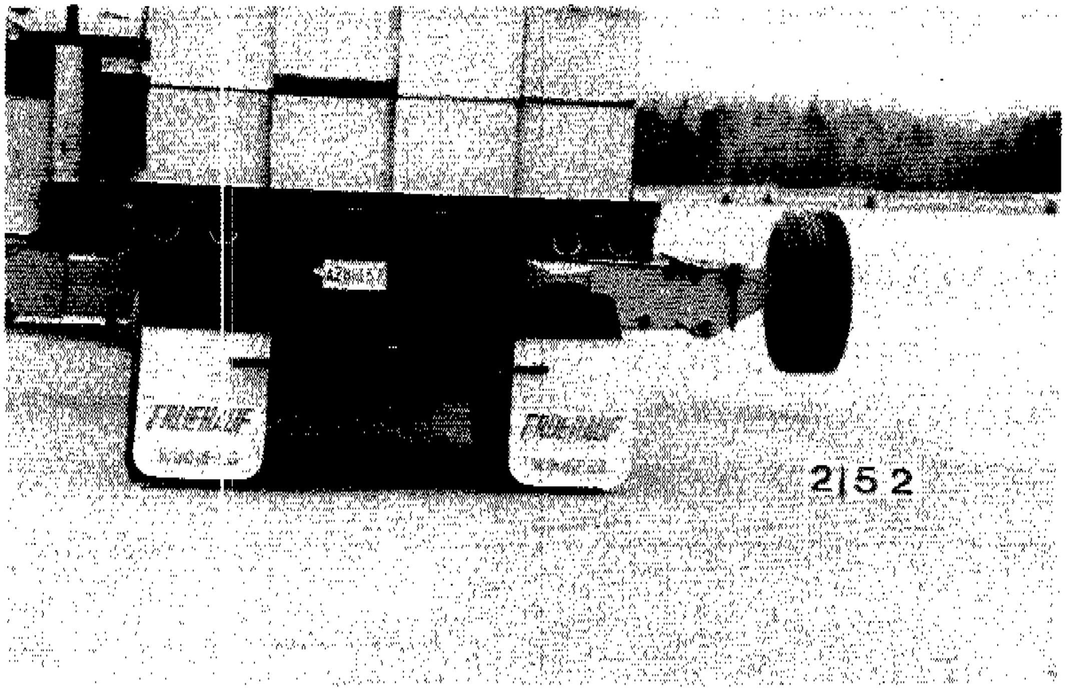


Figure 3/ Counter-Clockwise Offtracking

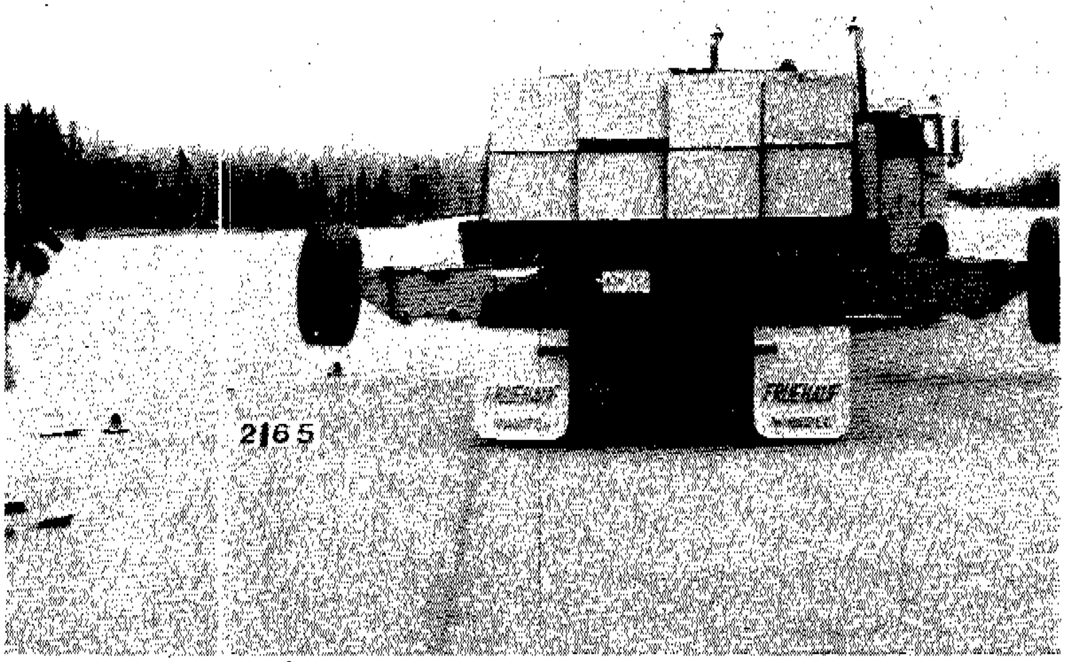
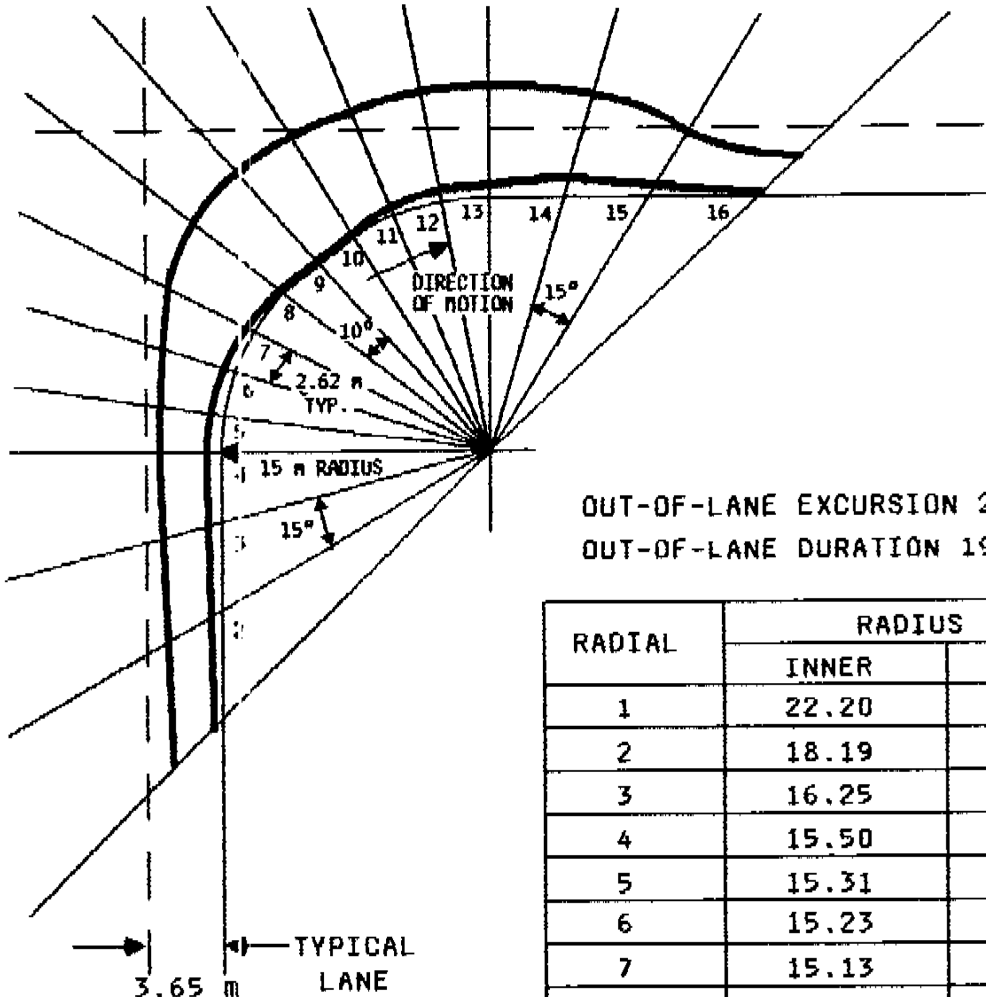


Figure 4/ Clockwise Final Offtracking



OUT-OF-LANE EXCURSION 2.2 m
OUT-OF-LANE DURATION 19.2 m

RADIAL	RADIUS (m)	
	INNER	OUTER
1	22.20	25.30
2	18.19	20.78
3	16.25	18.74
4	15.50	18.11
5	15.31	18.38
6	15.23	19.07
7	15.13	20.23
8	15.00	20.98
9	15.00	20.38
10	15.00	20.99
11	15.29	20.61
12	15.50	20.46
13	15.65	21.26
14	16.22	21.82
15	17.95	21.74
16	21.62	24.40

Figure 5/ Right-Hand Turn Swept Path

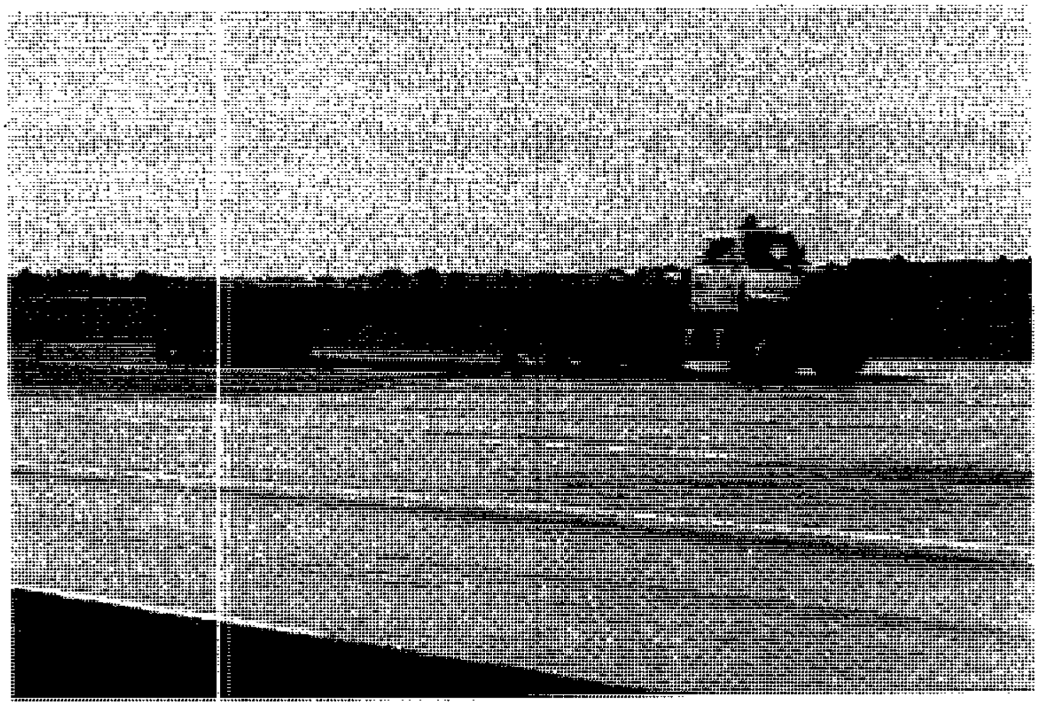


Figure 6/ Right-Hand Turn

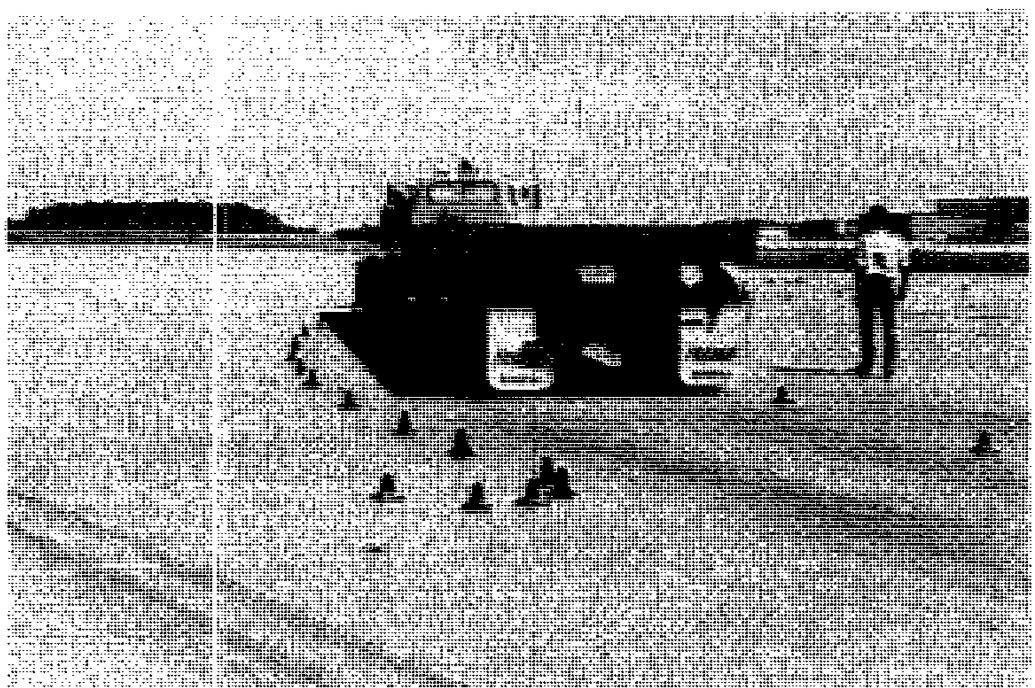
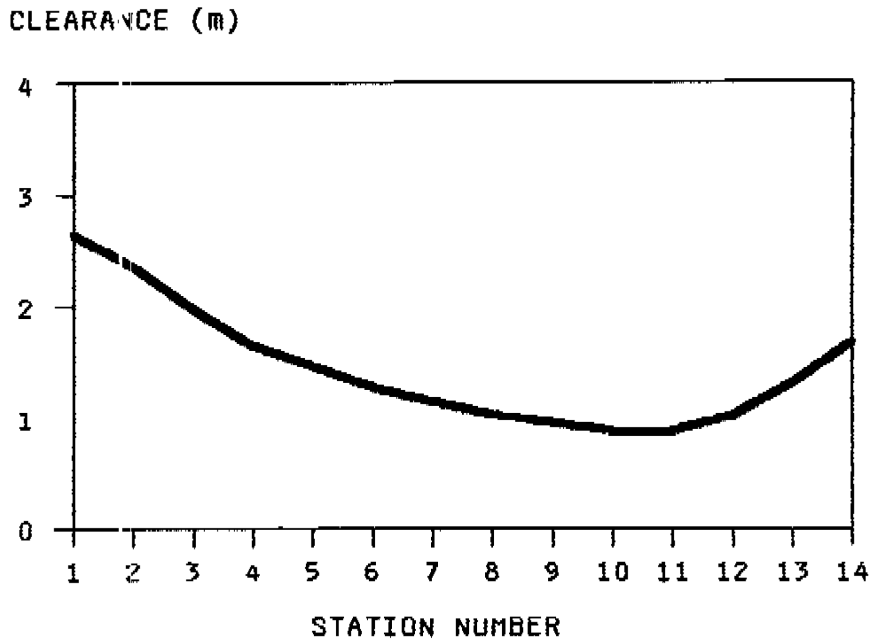


Figure 7/ Channelized Right Turn



STATION NUMBER	CLEARANCE (m)
1	2.64
2	2.37
3	1.97
4	1.66
5	1.45
6	1.27
7	1.15
8	1.04
9	0.97
10	0.90
11	0.89 *(LOW)
12	1.04
13	1.31
14	1.68

Figure 8/ Channelized Right Turn
Clearance from Inner Curb

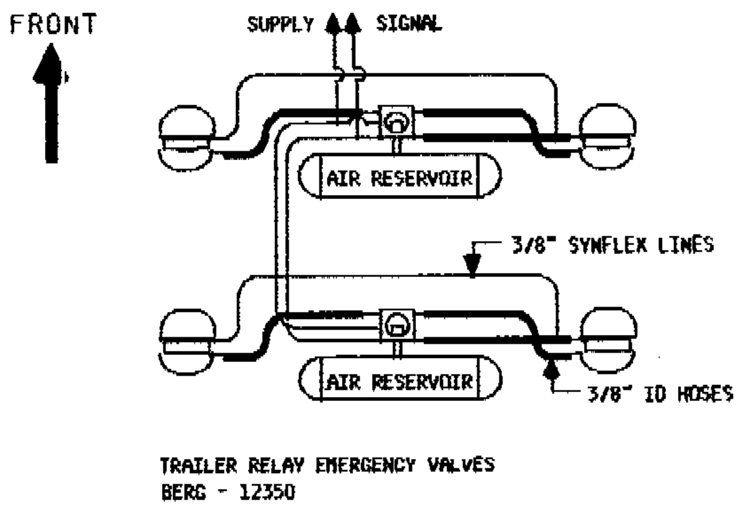


Figure 9/ Air Brake System Schematic

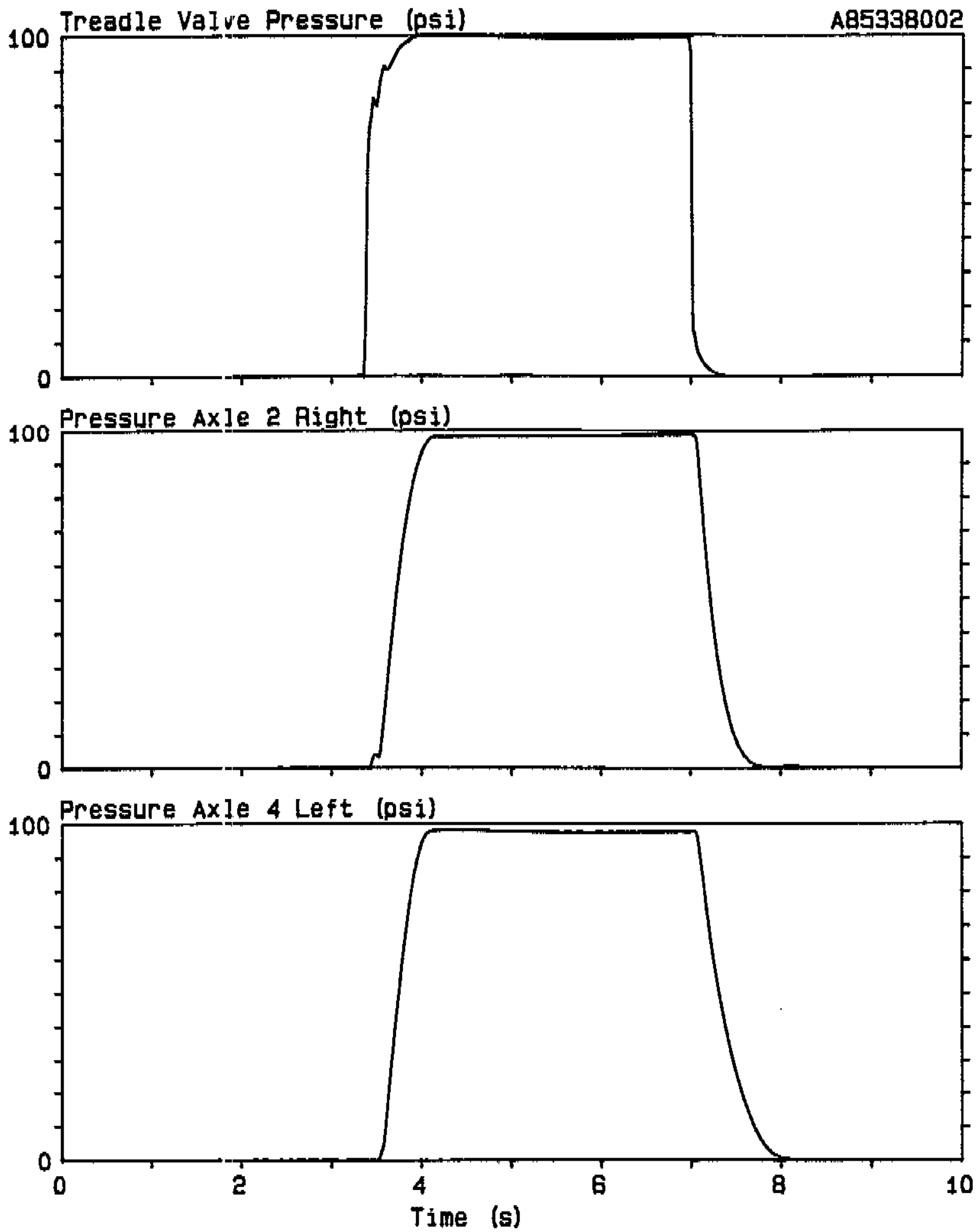


Figure 10/ Air Brake Application and Release

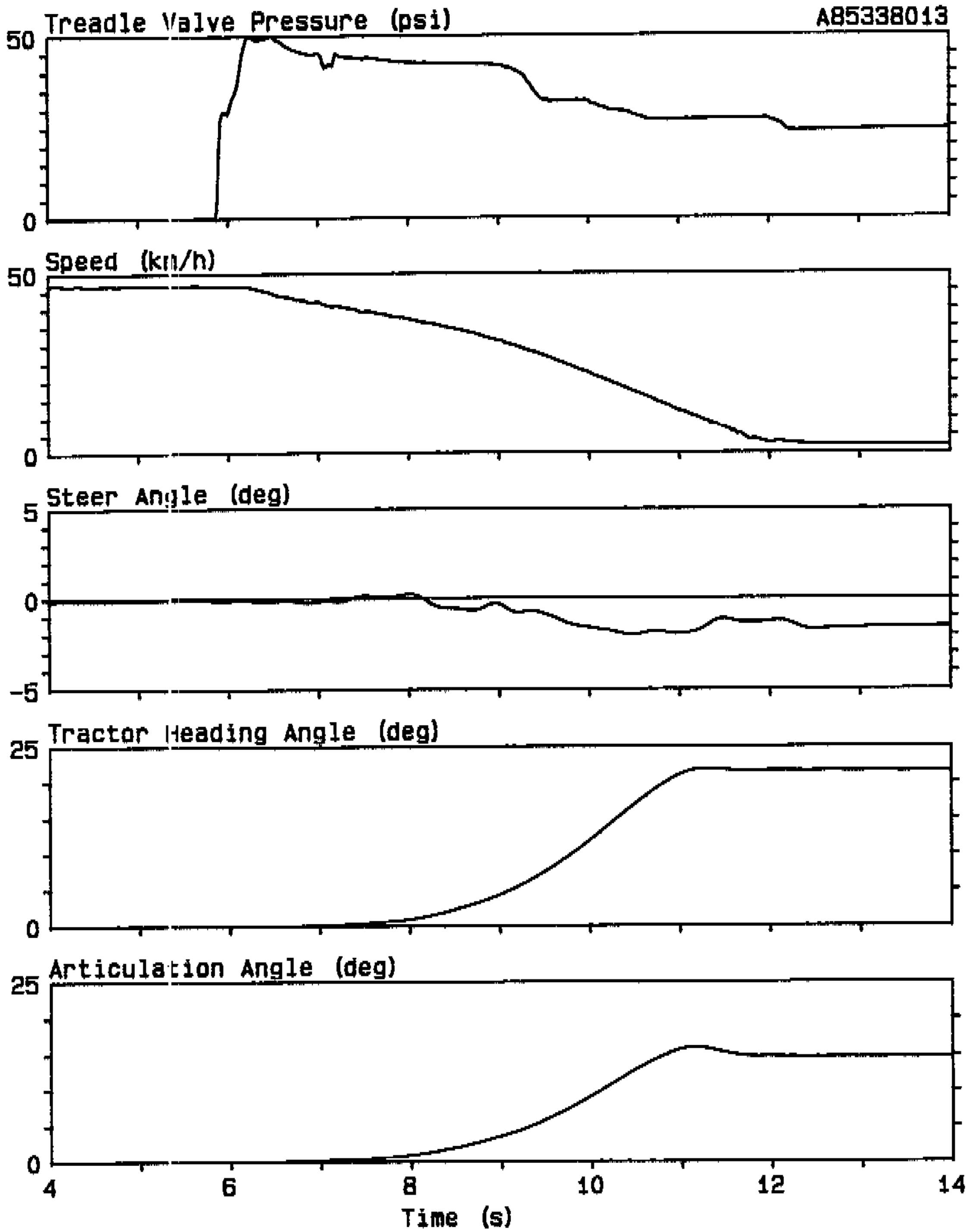


Figure 11/ Vehicle Response to Straight-Line Braking

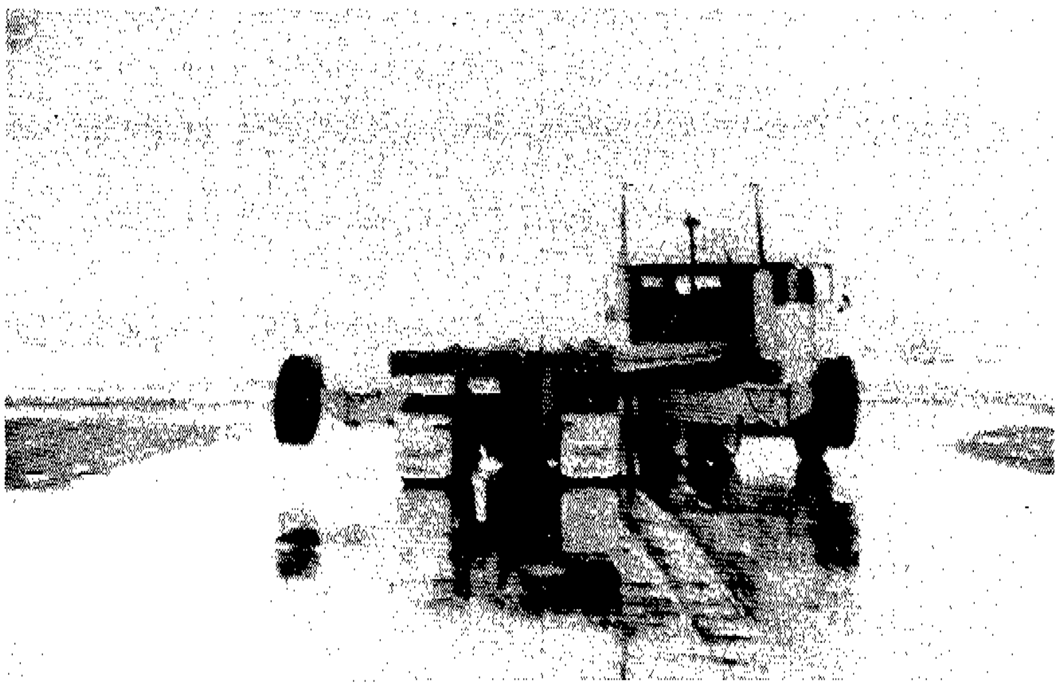


Figure 12/ Vehicle Final Position in
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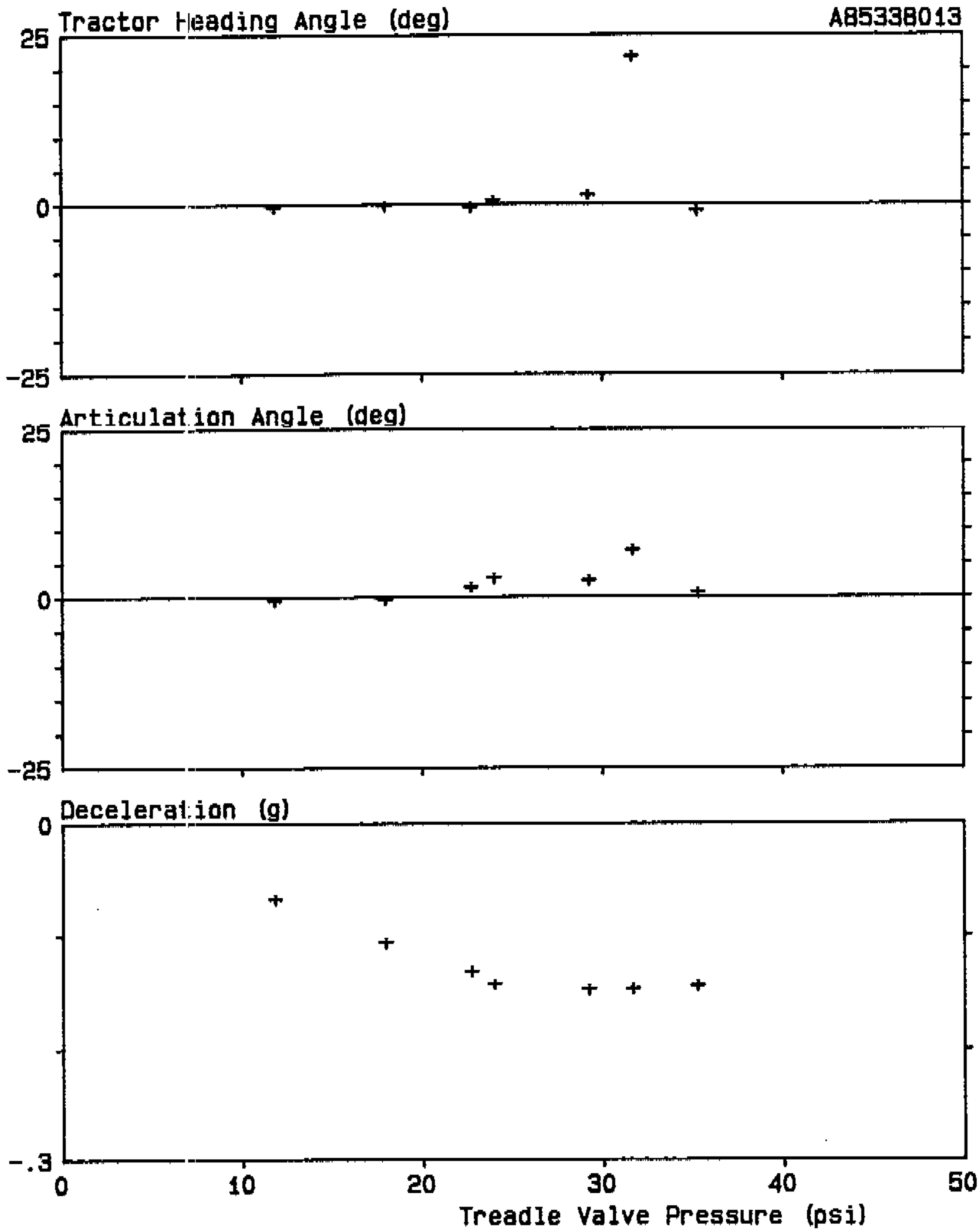
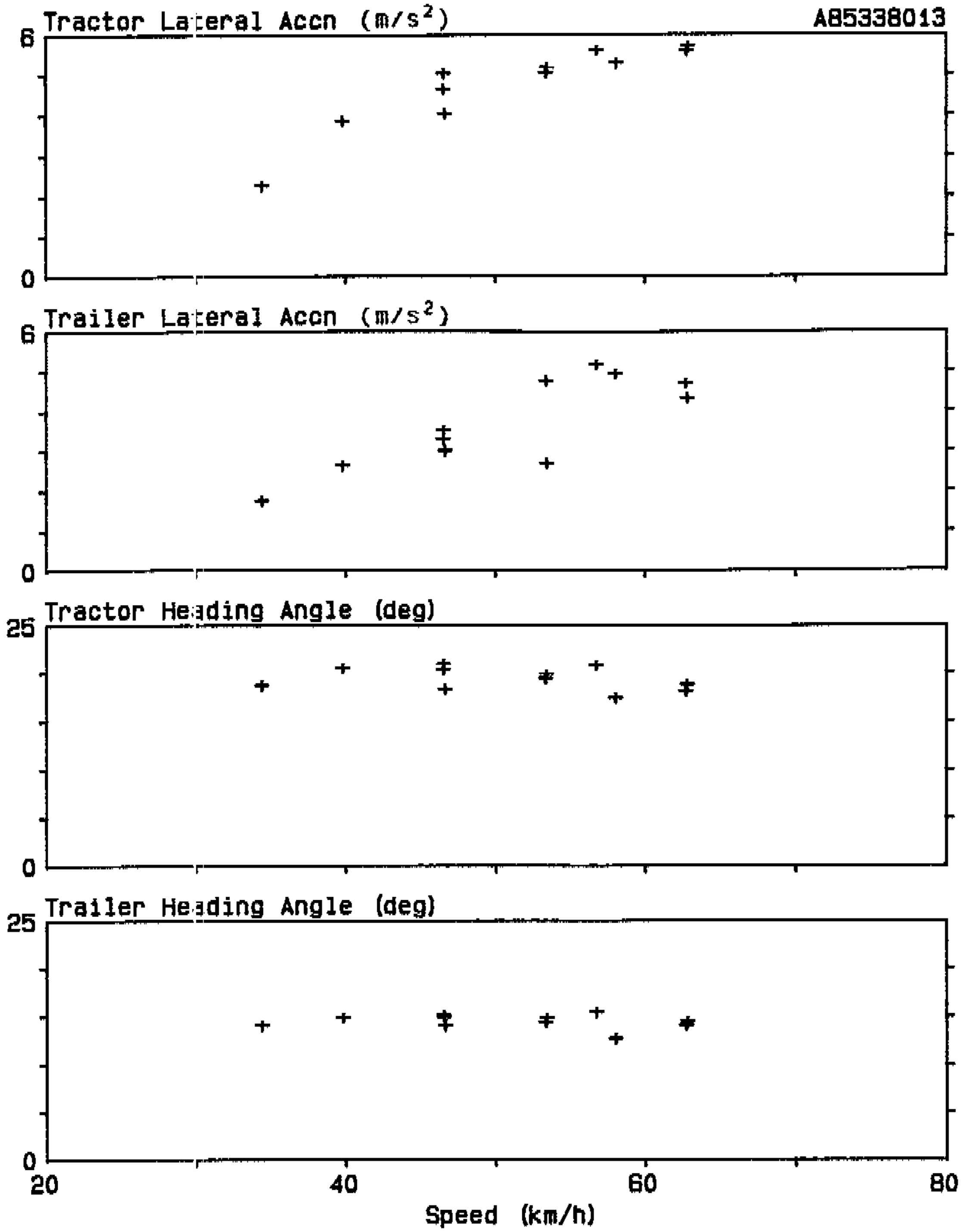


Figure 13/ Straight-Line Braking Responses vs
Treadle Valve Pressure



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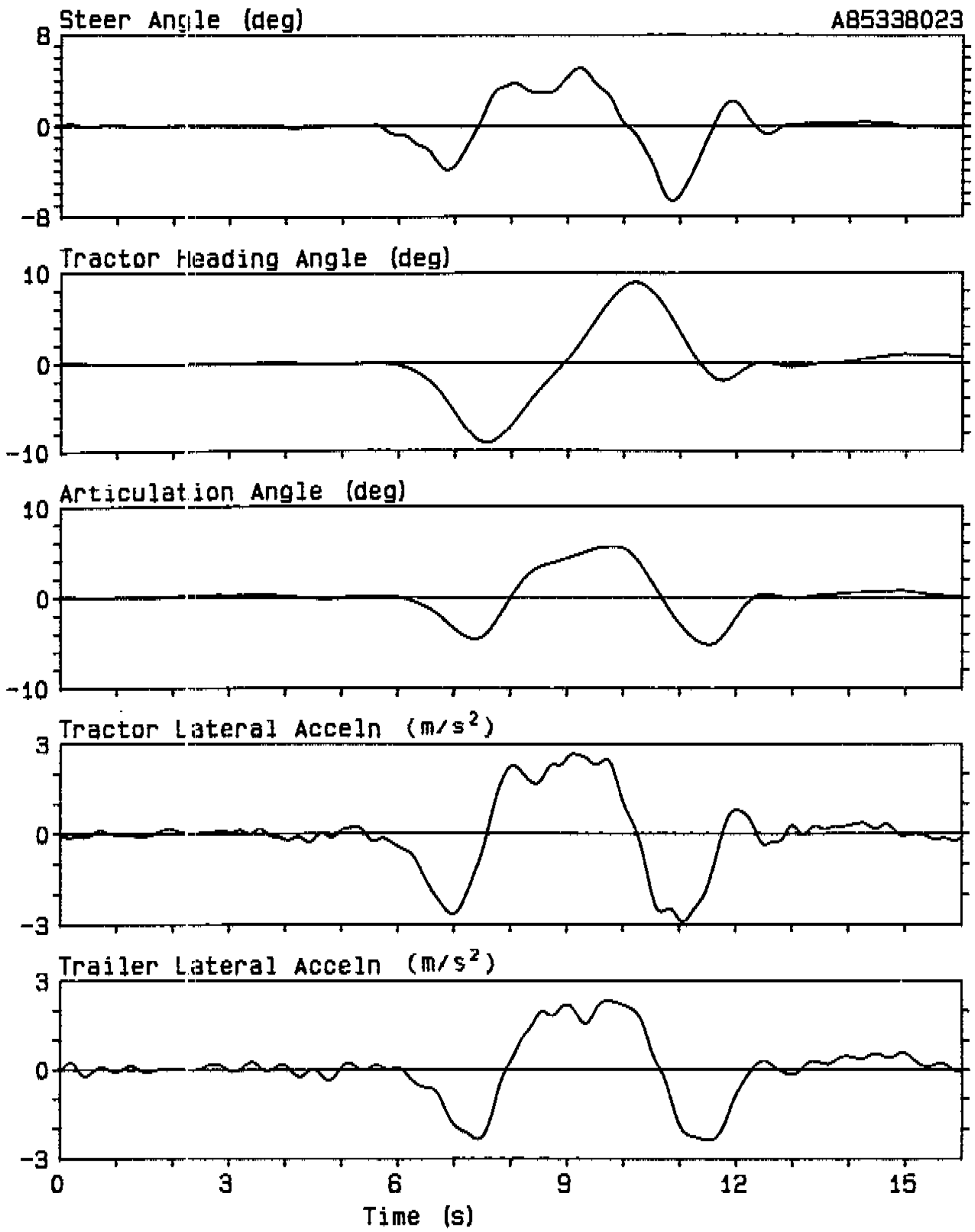


Figure 15/ Vehicle Response in Evasive Manoeuvre

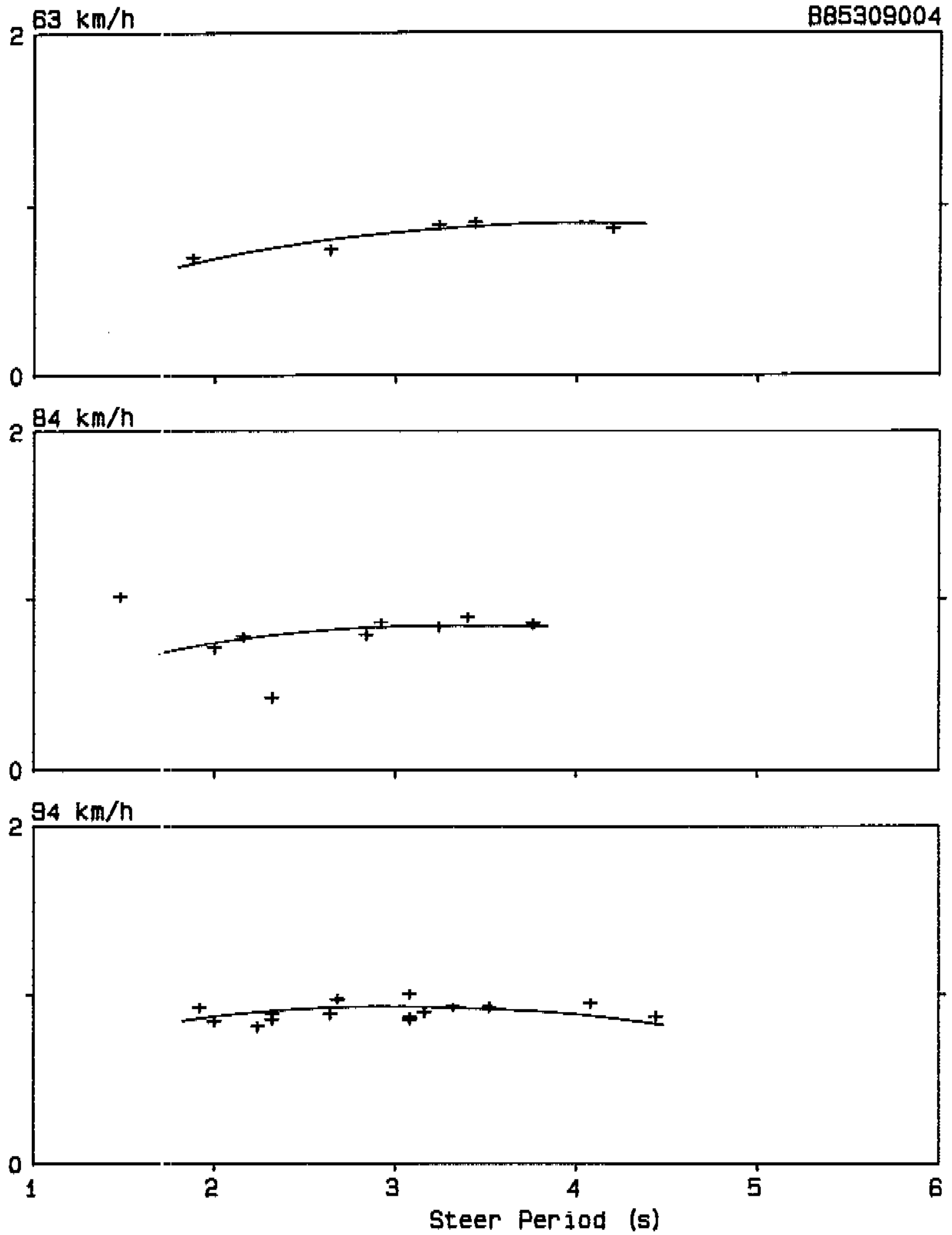


Figure 16/ Rearward Amplification of Lateral Acceleration

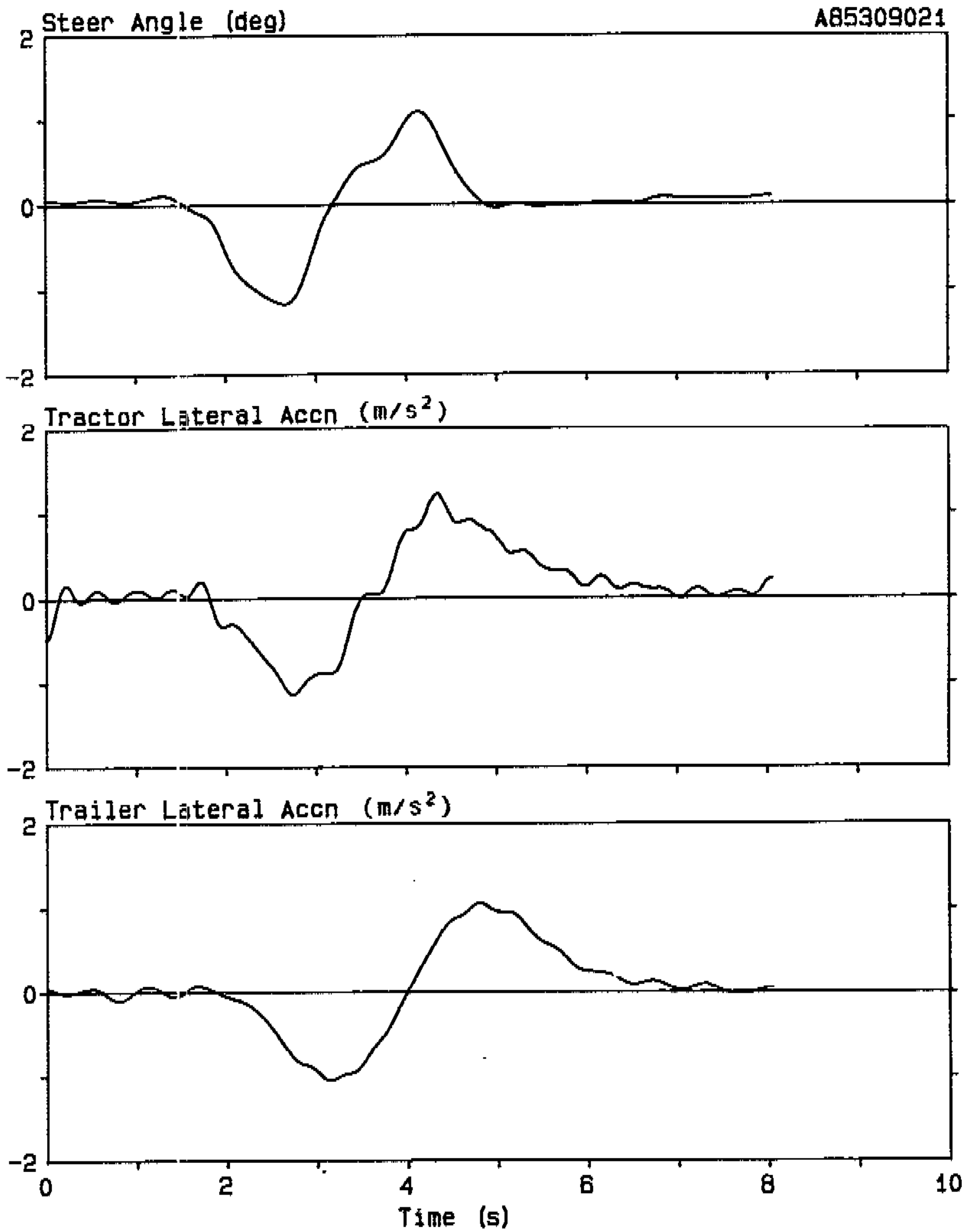


Figure 17/ Vehicle Response to Sinusoidal Steer at 94 km/h

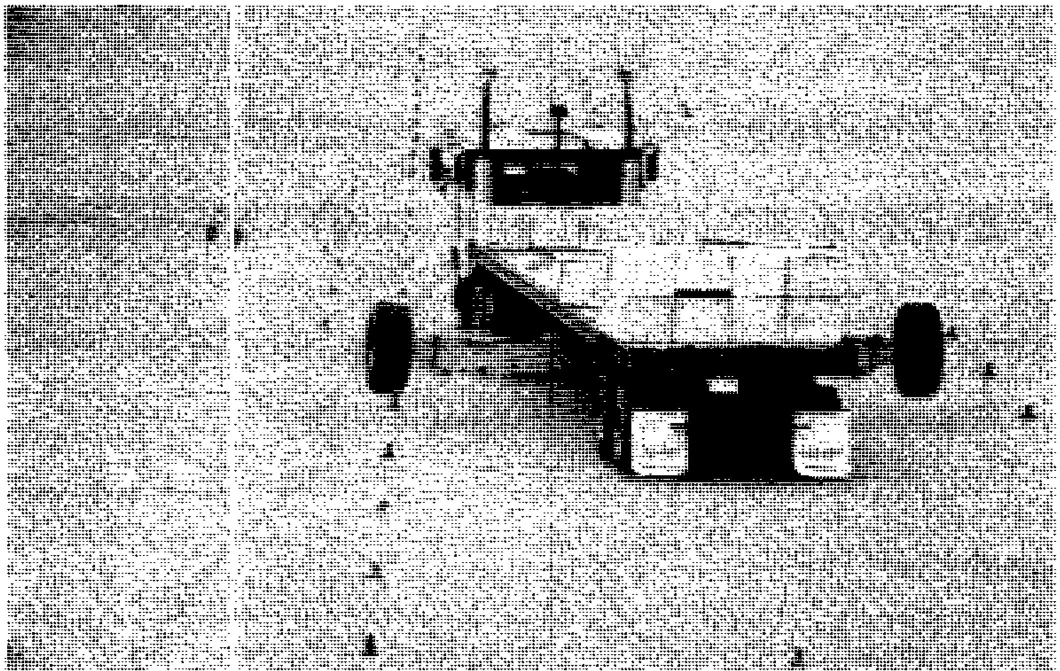
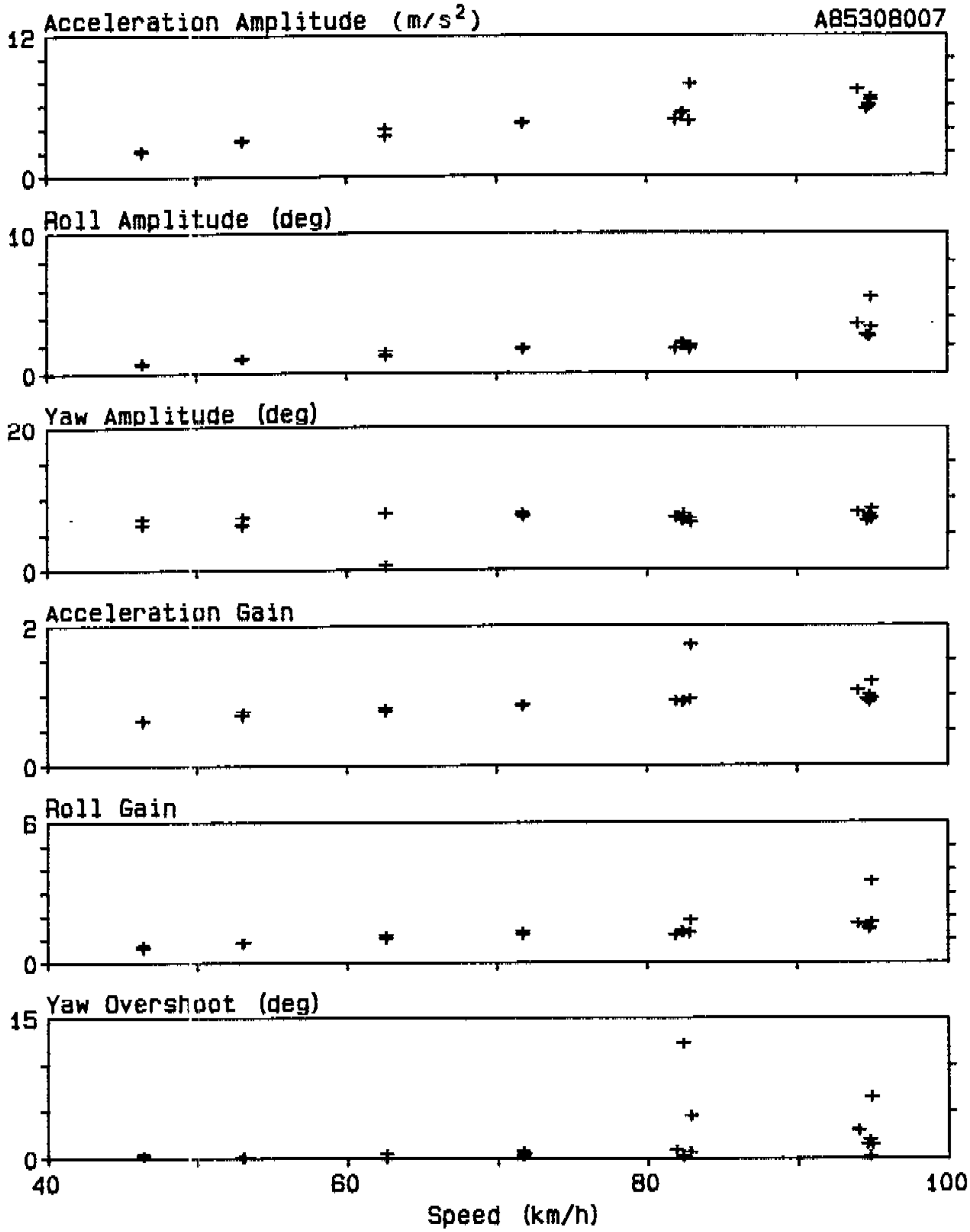


Figure 18/ Vehicle Making Lane Change



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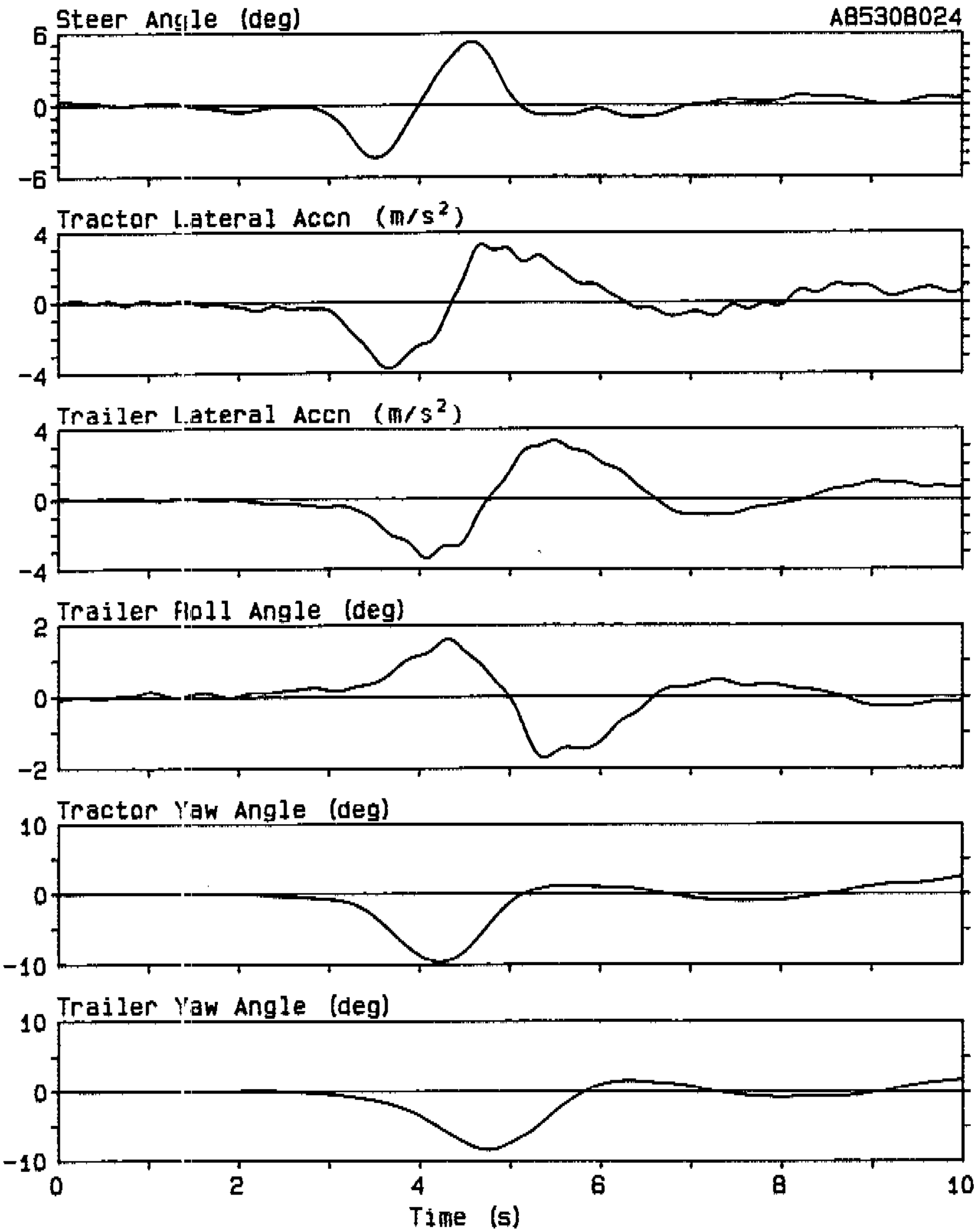
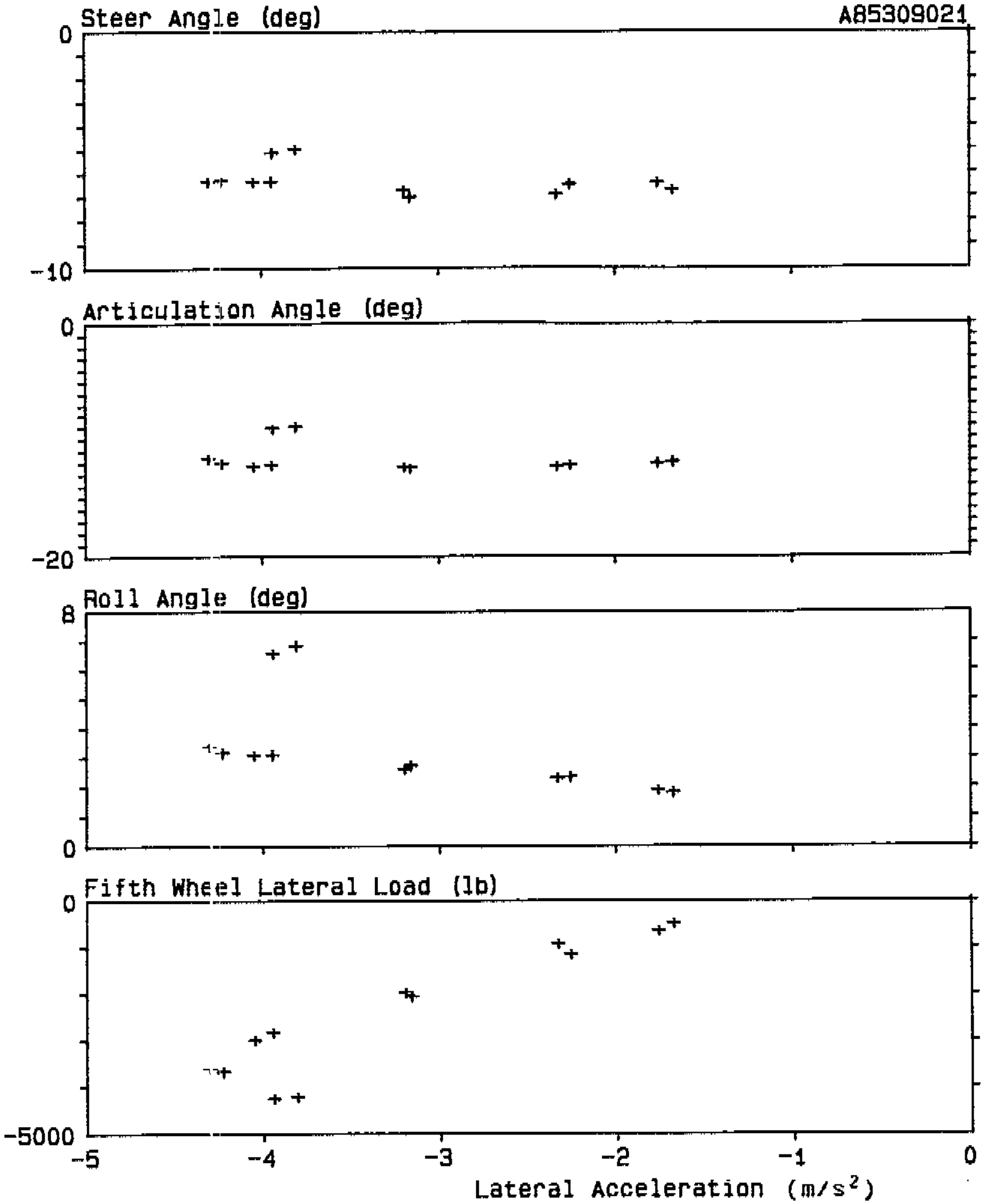


Figure 20/ Lane Change, Vehicle Responses at 94 km/h



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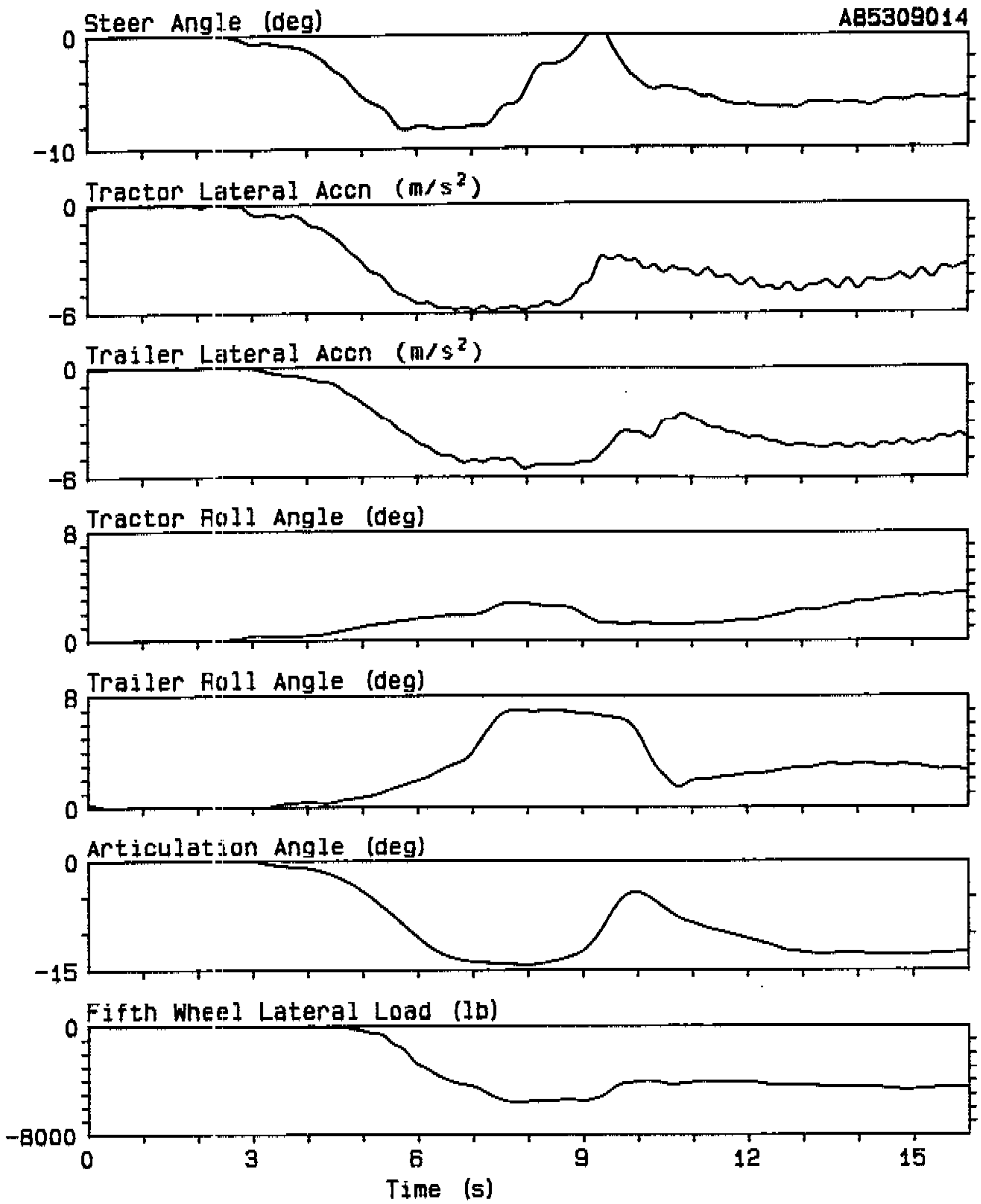

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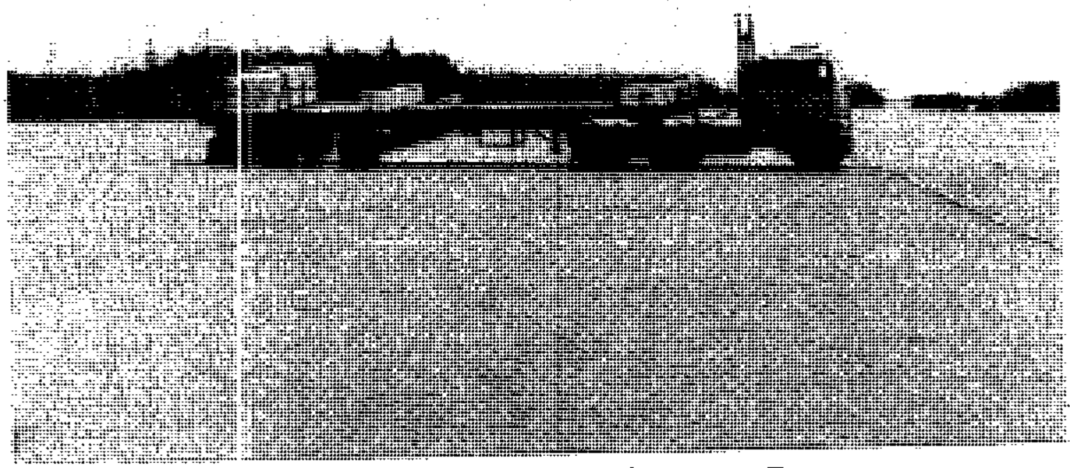

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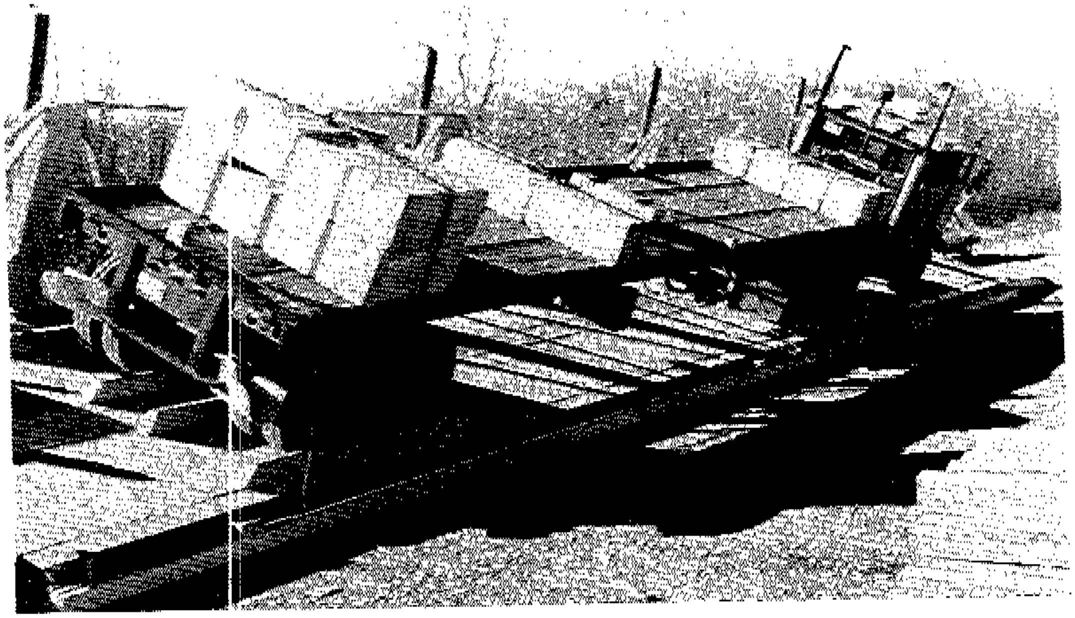

Figure 24/ Vehicle on Tilt Table

CV-86-03

Demonstration of Baseline Vehicle Performance: A-Train Double

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W. Mercer

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Ontario Ministry of Transportation
and Communications

ABSTRACT

An A-train double trailer combination was tested by the Ontario Ministry of Transportation and Communications (MTC) as part of the CCMTA/RTAC Vehicle Weight and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with the empty vehicle on a low-friction surface and the loaded vehicle on a high-friction surface.

This report presents detailed results of the tests and demonstrations.

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ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The trailers were provided by the Roads and Transportation Association of Canada (RTAC). Facilities of the Transport Canada Motor Vehicle Test Centre were made available to the Ministry of Transportation and Communications (MTC). Assistance with vehicle preparation, delivery, and refurbishment was arranged by Mr. Pearson in support of this work.

The work was principally undertaken by the staff of the Automotive Technology and Systems Office of the Transportation Technology and Energy, Branch of MTC: N.R. Carlton; G.B. Giles; C.P. Lam, P.Eng.; W.R. Stephenson, P. Eng.; and M.E. Wolkowicz; and assigned students G. Goertzen, S. Jazic, and D.R. Sykes. Assistance was provided by staff of various other departments of the ministry and other organizations.

The efforts of all involved are hereby acknowledged with gratitude.

1/ INTRODUCTION

The effects of changes in truck weight and dimension parameters on combination vehicle stability and handling and on pavement response to axle group loading are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle portion of the study involved both computer simulation of vehicle dynamic manoeuvres and testing of vehicles and components. Combination vehicles were classified into six families, based on the number of trailers and methods of hitching. A representative of each family was designated as the baseline vehicle for that family. Additional vehicle configurations of interest were also defined. All baseline and additional vehicle configurations were tested to assemble a body of technical and visual data that described the stability and control characteristics of the vehicles with respect to certain performance measures.

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. This report presents the results of a test of an A-train double trailer combination baseline vehicle. It refers frequently to a report describing procedures and equipment common to tests of all nine vehicles undertaken by MTC [1]. Similar reports present details of the tests of the other eight vehicles [2-9], and a summary report presents the results of tests of all six baseline vehicles [10]. A computer simulation of vehicle responses to actual test inputs using estimated vehicle data has also been conducted [11].

2/ TEST VEHICLE DESCRIPTION

The test vehicle consisted of the MTC Freightliner [1] 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 same combination was also tested concurrently as a C-train, using a B-type converter dolly [4].

The equipment for these tests was provided by the Roads and Transportation Association of Canada (RTAC). No modifications were made to the trailers or dolly except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were affected.

The trailers used were both manufactured by Fruehauf in Winnipeg and were model PB-F2-26-102-SF. Serial numbers were 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 leaf spring system with a torque rod. The A-dolly had a spring centre width of 0.98 m (38.5 in), and the track 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 trailers and dolly were fitted with new Michelin XZA radial tires, in load range H and size 11R22.5. These tires were run a nominal distance of 600 km (370 mi) before any testing and were then, subsequently, used for all tests. Tire pressure was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load. This was used for all tests and represents the common operating practice of not reducing tire pressure when running empty.

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 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 1.

Table 1/ Axle Loads

Axle No.	Empty (kg)	Empty (lb)	Loaded (kg)	Loaded (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 empty weight exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. A target axle load of 8000 kg (17 600 lb) was set for all axles except for the steer axle. This was not closely attained. 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.

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.

3/ TEST PROGRAM

3.1/ Test Procedures

The test vehicle was prepared for testing in the following way:

1/ A mechanical inspection was carried out, and any necessary repairs or maintenance was done.

2/ Outrigger and safety cable attachments and load block retention sills were installed on the trailers, and safety cable attachments were installed on the dolly.

3/ Outriggers were installed on the trailers.

4/ The boxes containing instrument packages, power supplies and signal conditioning, other instruments, and cabling were installed.

5/ New tires were installed, and pressures were set.

6/ Other fittings necessary for testing were installed.

7/ Concrete blocks were located on the trailer beds to achieve specified axle loads.

8/ Notes were made from detailed physical inspection, including an inventory of components and measurement of dimensions.

9/ The MTC tractor was coupled to the trailers.

10/ The combination vehicle was weighed, empty and loaded.

11/ A functional test of the on-board electronics was conducted.

12/ Test runs were made to shake down the vehicle instrumentation and familiarize the test driver with the vehicle's handling characteristics.

13/ Tires were run a nominal distance of 160 km (100 mi).

14/ Articulation angle between the tractor and lead trailer was calibrated.

15/ Details of the vehicle and test equipment were recorded on photographs and videotape.

The following tests were performed:

- Offtracking
- Right-hand turn
- Channelized right turn
- Air brake system
- Straight-line braking, empty vehicle, low-friction surface
- Evasive manoeuvre, empty vehicle, low-friction surface
- Sinusoidal steer, loaded vehicle, high-friction surface
- Lane change, loaded vehicle, high-friction surface
- Normal straight-line driving
- Steady circular turn, loaded vehicle, high-friction surface

All tests followed standard procedures [1], except as noted.

3.2/ Instrumentation

The instrumentation shown in Table 2 was installed. Brake pressure transducers were only installed in the trailers and dolly for the air brake system test, but all other instrumentation was installed for all tests. Data were always captured from all instrumentation, but only those pertinent to a particular test were analysed.

Tractor instruments were selected from the instrumentation that is permanently installed on the tractor. Instruments for the trailers were mounted in boxes placed on the trailer deck, which also contained power supplies and signal conditioning. Trailer lateral acceleration and roll angle were measured at a point midway between the kingpin and axle.

Full details of the instrumentation, signal conditioning, and data capture system are presented elsewhere [1].

3.3/ Data Capture and Data Processing

Data were digitized on board the vehicle and transmitted by telemetry as a pulse-code modulated (PCM) data stream to a ground station, where they were recorded on magnetic tape and captured in real time by an HP-1000 computer system. Test data for a run were processed immediately after the run, and results from a series of runs were subsequently analysed using the computer system [1].

Many test runs of all types were conducted for this vehicle. Not all these runs were used in the preparation of this report. In a number of instances, a run failed to meet a test condition.

Table 2/ Instrumentation Installed

No	Measurement	Instrument	Full Scale
1	Tractor steer angle	Spectrol 139 potentiometer	25.02°
2	Tractor roll angle	Humphrey CF18-0907-1 gyroscope package	8.85°
3	Tractor lateral acceleration	Kistler 303B accelerometer	0.957 g
4	Tractor yaw rate	Humphrey RT03-0502-1 angular rate transducer	38.7°/s
5	Tractor longitudinal acceleration	Kistler 303B accelerometer	0.974 g
6	Tractor speed, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	104.8 km/h
7	Tractor distance, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	56.3 m/ramp
8	Tractor fifth wheel load, left-hand side	MTC load cell	9890 lb
9	Tractor fifth wheel load right-hand side	MTC load cell	10290 lb
10	Tractor treadle valve pressure	Celesco PLC-200G	100 psi
11	Tractor brake pressure, axle 2 Left	Celesco PLC-200G	99.80 psi
12	Tractor lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
13	Tractor yaw angle	Humphrey CF18-0907-1 gyroscope package	17.73°
14	Trailer 1 articulation angle	Celesco pull cord DV-301-150	18.844°
15	Trailer 1 lateral acceleration	Columbia SA-107 accelerometer	0.995 g
16	Trailer 1 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.90°
17	Trailer 1 outrigger touchdown	Strain gauge bridge	1.0 V
18	Dolly 1 hitch angle	Spectrol 139 potentiometer	25.0°
19	Dolly 1 lateral acceleration	Columbia SA-107 accelerometer	0.996 g
20	Brake pressure, axle 4 right	Celesco PLC-200G	104.96 psi
21	Brake pressure, axle 5 right	Celesco PLC-200G	101.06 psi
22	Brake pressure, axle 6 right	Celesco PLC-200G	102.07 psi
23	Brake pressure, axle 7 right	Celesco PLC-200G	101.93 psi
24	Brake pressure, axle 8 right	Celesco PLC-200G	106.79 psi
25	Spare		
26	Spare		
27	Trailer 2 articulation angle	Spectrol 8409 potentiometer	26.511°
28	Trailer 2 lateral acceleration	Columbia SA-107 accelerometer	0.980 g
29	Trailer 2 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.91°
30	Trailer 2 outrigger touchdown	Strain gauge bridge	1.0 V

4/ RESULTS

4.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions, as shown in Figure 3. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [1].

This test was performed with a wet surface. The results are shown on Table 3. The measured data were averaged for the left and right turn and then compared to data generated by a simple offtracking formula [12]. The difference between actual and computed values, shown in the last column of Table 3, is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

The final offtracking for the counter-clockwise turn is shown in Figure 4. After averaging for both directions and correcting for differences in axle track width, it was found that the vehicle offtracked 1.45 m (4.76 ft).

Table 3/ Offtracking

Axle No.	Track Width	Radius to Inner Wheel: Right Turn (m)	Radius to Inner Wheel: Left Turn (m)	Difference (m)	Average (m)	Calculated (m)	Difference %
1	2.31	27.57	27.65	0.08	27.61	27.56	-0.18
2	2.37	27.22	27.35	0.13	27.29	27.21	-0.29
3	2.37	27.24	27.35	0.09	27.29	27.21	-0.29
4	2.37	26.63	26.77	0.14	26.70	26.64	-0.23
5	2.37	26.62	26.75	0.13	26.69	26.64	-0.19
6	2.37	26.58	26.69	0.12	26.64	26.59	-0.19
7	2.37	26.02	26.12	0.10	26.07	26.02	-0.19
8	2.37	26.01	26.08	0.07	26.05	26.02	-0.12

4.2/ Right-Hand Turn

A 90° right-hand turn is a very demanding manoeuvre for a large truck. The vehicle's swept path in a 90° right-hand turn of 15 m (49.2 ft)

radius was measured, according to the standard test procedure [1]. This radius is typical in an urban area or where there is limited truck traffic. The swept path is shown in Figure 5.

The vehicle is shown in Figure 6 during the turn. The maximum excursion out of lane was only 0.4 m (1.3 ft). It was out of the exit lane for a distance of 7.5 m (24.6 ft), as derived from Figure 5. This test was conducted at a creep speed and represents the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

4.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [1].

The vehicle is shown during the turn in Figure 7. The clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Figure 8 as a function of distance through the curve. The minimum clearance was 1.85 m (6.1 ft) in the 5.5 m (18 ft) wide roadway.

The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. The vehicle easily made it through the channel.

4.4/ Air Brake System

The air brake system of the combination was evaluated according to standard test procedure [1].

The trailer air brake system was inspected. A schematic of the system is shown in Figure 9. The dolly was not equipped with a booster relay valve to speed the signal. All slack adjusters required manual adjustment. Stroke was adjusted to the minimum, about 32 mm (1.25 in) on each axle. The tractor was supplied with shop air, regulated at 689 kPa (100 psi). Pressure transducers were installed at all trailer and dolly axles.

The SAE J982a style test was performed for the full double combination. The results of this test, presented in Table 4, are the average of several tests, each with a time resolution of 0.02 s. The application times of this test were typical of those obtained from tests on other double combinations [13]. The release times are considered very long, especially for the lead trailer. A typical time history response of application and release for the double is presented in Figure 10.

Table 4/ Air Brake Timing, SAE J982a Style Test

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.04	0.19	98.8
Axle 2	0.39	0.65	98.4
Axle 4	0.57	3.02	95.1
Axle 5	0.56	3.04	95.0
Axle 6	0.81	2.26	94.8
Axle 7	0.79	2.31	92.0
Axle 8	0.77	2.28	93.7

4.5/ Straight-Line Braking

It is difficult to conduct rigorous braking tests and achieve consistent results. A demonstration of modes of instability of the combination vehicle in straight-line braking was, therefore, conducted. A series of runs was made with the empty vehicle approaching the low-friction test area at 47 km/h and the driver braking using the treadle valve. Runs were made using various application pressures, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [1].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit. Yaw responses of all vehicle units are presented in Figure 4.5.1 as a function of brake application pressure.

The time history of a typical run that resulted in loss of control is shown in Figure 11. An average brake application of about 186 kPa (27 psi) over the entire stop caused all braked wheels, except axles 5 and 7 on the left-hand side, to lock. The tractor and trailer 1 remained straight, but the inertia of trailer 2 was sufficient to jackknife the dolly to the right. The tandem axle of trailer 2 remained more or less parallel to the tractor, but as a consequence of the dolly jackknife, trailer 2 headed to the right. While the entire vehicle actually remained within the lane, the dolly was unstable by jackknife, and this cannot be considered an acceptable stop.

A summary of peak vehicle responses from the runs is shown in Figure 12 as a function of average treadle valve over the entire stop. The limit of surface adhesion of about 0.15 g was reached by a brake application of 173 kPa (25 psi), when most braked wheels were locking. The dolly was clearly getting pushed in all stops. The vehicle, therefore, was sensitive to hard braking.

4.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. Gates of 22.5 m (73.8 ft) were used for the lane change to the left and the return to the original lane, separated by 20 m (65.6 ft) in the left lane. The runs were made in accordance with the standard test procedure [1].

The vehicle combination was evaluated primarily in terms of the lateral acceleration and yaw responses of the vehicle units. These are shown in Figure 13. Each response is the peak-to-peak amplitude experienced by the vehicle in the manoeuvre. The lateral acceleration amplitude of all vehicle units increased with speed up to approximately 63 km/h, at which point the tractor and trailer 1 tended to level off. The heading angle of the tractor and trailer 1 decreased, indicating minor in-lane sliding. The heading angles of the trailer 2 increased slightly with speed. Trailer 2 tended to swing on return to the original lane. The driver commented that the vehicle tended to "push" at higher speeds, and his steer pattern tended to change at higher speeds, indicating tractor understeer/oversteer at different points in the course. The driver was able to make this manoeuvre at 63 km/h, the maximum speed considered safe for such a manoeuvre at the test site. While the vehicle manoeuvred neatly through the second gate, the dolly appeared on the verge of jackknife, and this would have precipitated a severe and probably catastrophic trailer swing.

A typical run at 63 km/his shown in Figure 14.

4.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for this combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 63 and 94 km/h, with steer input periods between about 2 and 5 s. Weather conditions precluded runs at 84 km/h.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. Rearward amplification of lateral acceleration for the two trailers is presented in Figure 15, as a function of tractor steer input period for the two test speeds. Each gain is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless.

It is evident from Figure 15 that rearward amplification increases with speed, rearward by trailer, and is also somewhat sensitive to steer period, reaching its highest value for the rear trailer of about 1.80 at 94 km/h around 2 s. This result shows that, at highway speed, the A-train double is a highly responsive vehicle. The reason for this is that its inherent stability is rather low. Stability and response of mechanical systems have an inverse relationship: high stability means low response to input and vice versa.

Figure 16 shows the vehicle response from a typical run with a steer period of about 1.64 s at 94 km/h.

4.8/ Lane Change

The objective of this test was to evaluate vehicle stability characteristics in a dynamic manoeuvre. The test was not conducted for this vehicle because poor weather interfered with the test schedule. Exactly the same test was, however, conducted in an earlier test program with a similar vehicle [14]. A series of runs was made where the driver made a lane-change manoeuvre, which is considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [1].

A gate of 30 m (98.4 ft) was used, to provide a vehicle speed of about 80 km/h, which is a typical speed limit and might permit some comparison of the results of this test with those described in the preceding section.

From previous data it was found that lateral acceleration gain of the rear trailer increased from 1.2 at 75 km/h to 1.8 at 85 km/h, and roll gain increased from 3 at 74 km/h to 7 at about 75 to 80 km/h. The vehicle tended to slide as well as roll. Yaw overshoot of the rear trailerwas quite high at the ultimate speed of 83 km/h, when this trailer swung out of lane to the left and rolled violently, resulting in outrigger touchdown.

4.9/ Normal Straight-Line Driving

The objective of this test was to attempt to evaluate lateral motion of the rear trailer of the combination, the phenomenon known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [1].

As previously mentioned, the vehicle was highly responsive, so the slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in rear trailer sway that was perceptible to the occupants of a chase vehicle. Root mean square (RMS) lateral acceleration of the rear trailer was 1.74 g/° of RMS steer input.

4.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics to determine the high-speed offtracking of the vehicle and to examine the side loads exerted on the tractor by the trailers. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The results of this test are summarized in Figure 17 as average steady-state values. The vehicle combination was evaluated primarily in terms of the roll response of the vehicle units. At the limiting speed of 55 km/h, a lateral acceleration of 0.53 g, the trailer 2 rolled over and the dolly slid out from the circular trajectory, as shown in Figures 18 and 19. As Figure 17 shows, roll angles increased with speed. The values at the point of rollover are omitted because there was insufficient steady-state data to record a proper average. Average steady-state articulation angles decreased modestly with increase in lateral acceleration, and as a consequence, the offtracking decreased. The lateral force experienced by the tractor fifth wheel, presented as a function of tractor lateral acceleration, shows a gradient of about 49 kN/g (11 000 lb/g).

A tilt test was conducted on this vehicle as part of a separate test program [15]. The vehicle is shown in the tilt table in Figure 20. The high-side wheels of the rear trailer lifted at a tilt angle of 29.1° after all corrections were made, which corresponds to a lateral acceleration of 0.56 g. This is in quite good agreement with the rear trailer's lateral acceleration of 0.52 g at outrigger touchdown. A full discussion of the tilt test is presented elsewhere [15].

The trailer centre of gravity was about 1.75 m (70 in) from the ground. Van and tanker-type trailers can have centres of gravity up to about 2.5 m (100 in) from the ground, which would reduce the rollover threshold from 0.53 g in this test to about 0.30 g [16].

5/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation.

Tests were conducted in various weather conditions. Tires wore progressively as the various tests were conducted. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailers were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal, particularly for the loaded condition, because of the underslung outriggers.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results, except for centre of gravity height, which has been mentioned already where it may have affected the results. The results presented pertain to the particular vehicle tested, and results different in some respects might be obtained for another vehicle at another time.

This vehicle was considered an easy vehicle to drive by the test driver. The short trailer wheelbase made it easy to manoeuvre in both low-speed turns and dynamic tests, as the trailer imposed modest forces on the tractor. While the vehicle performed very well from the point of view of the driver to the point where loss of control occurred, at that point the consequences appear more severe than with the comparable B- or C-train. The driver can feel the approach to the stability threshold with these vehicles, whereas with the A-train, there is no feel for the rear trailer. This provides a definite difference in the test situation, where there is a steady approach to the stability threshold.

However, on the highway in an emergency accident avoidance situation, the driver has one chance to make the proper response. Many accidents are avoided by defensive driving. Others, unfortunately are unavoidable. Since loss-of-control-type accidents are relatively infrequent for heavy trucks, it may be questionable whether many, if any, are avoidable with a more stable vehicle configuration. In an A-train the driver emergency response may result in tractor or dolly jackknife on a low-friction surface, or rear trailer swing or rollover on a high-friction surface. Except for tractor jackknife, the driver would retain control of the tractor. However, with the B- or C-train, the rollover situation would result in rollover of the entire vehicle. This might be more hazardous to other road users than rear trailer rollover of the A-train, and, certainly, is more likely to cause serious or fatal injury to the driver. If it is accepted that there are very few true emergency situations when vehicle configuration might affect the outcome -- accident or no accident -- then there is little argument against the A-train. Indeed, as an easier vehicle to manoeuvre, and excepting trailer sway, it might be argued that it reduces hazard because of a lower driver workload.

In another area of safety, however, there are also few accidents that are clearly due to poor brakes, though it is well known that heavy truck brake standards and usage are much less than ideal. Yet it remains an article of faith with safety professionals that no effort should be spared to improve brake systems. Following similar logic, then, the B- or C-train should always be preferred to the A-train, not only because they have a margin of stability but, more particularly, the entire vehicle provides feedback to the driver. If the driver can feel some reduction in vehicle stability, particularly on a low-friction surface, then the responsible professional driver will drive more defensively, and potential accident situations will be avoided. However, doubles are typically driven by the more experienced drivers, so it may be questioned whether additional caution would be realistic. This topic has not been exhaustively researched, and further speculation is possible. For want of more information, however, there is no question at this time that the laws of physics should prevail, and the more stable vehicle configurations -- the B- and C-trains -- should be preferred to the A-train, to the greatest extent possible.

6/ CONCLUSIONS

An A-train double trailer combination was tested by the Ontario Ministry of Transportation and Communications, as part of the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with an empty vehicle on a low-friction surface and a loaded vehicle on high-friction surface.

The short trailers and articulation points of this vehicle clearly contributed to the modest space required to make turns.

The air brake system was typical of A-train doubles without a booster relay valve.

The vehicle was quite responsive, with a rearward amplification of lateral acceleration of about 1.80. The lateral/directional stability of the vehicle, therefore, was poor, both empty on a low-friction surface and loaded on a high-friction surface. Stability deteriorated at the highway speed limit of 100 km/h.

The A-train double configuration is considered undesirable because of its low stability at highway speeds. The C-train configuration is preferable from this point of view, as demonstrated in a parallel series of tests. However, the A-train is an easier vehicle to drive in some respects than the C-train.

The roll stability was relatively high because the centre of gravity of the trailer was very low. A higher centre of gravity would have significantly reduced the roll threshold.

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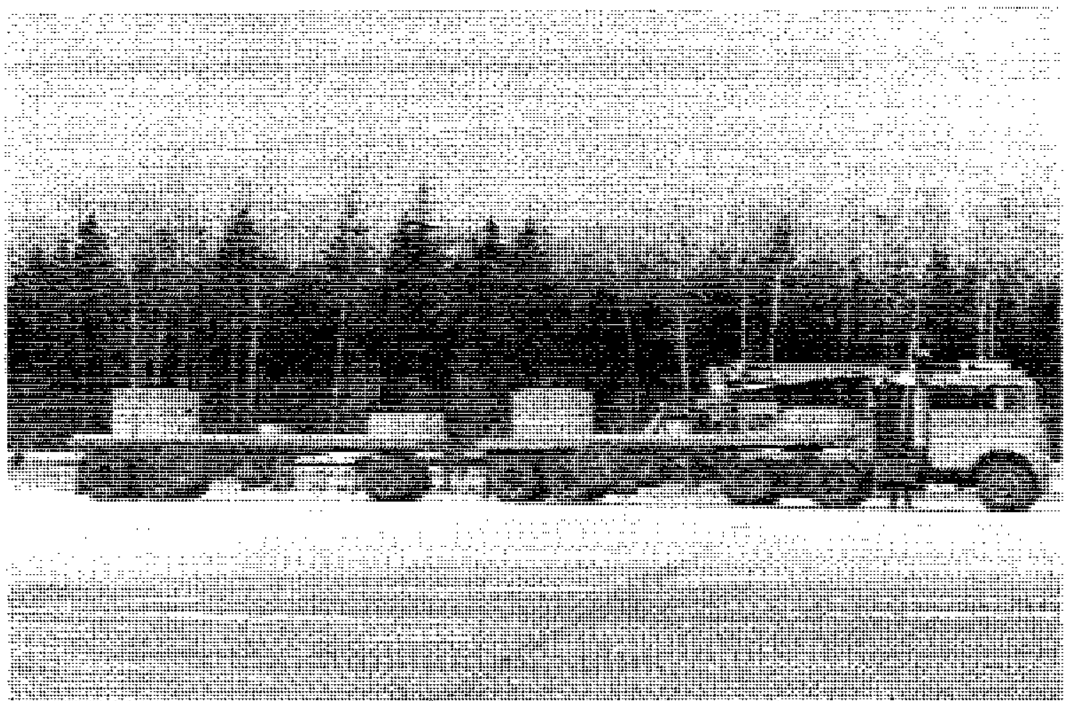


Figure 1/ View of Vehicle

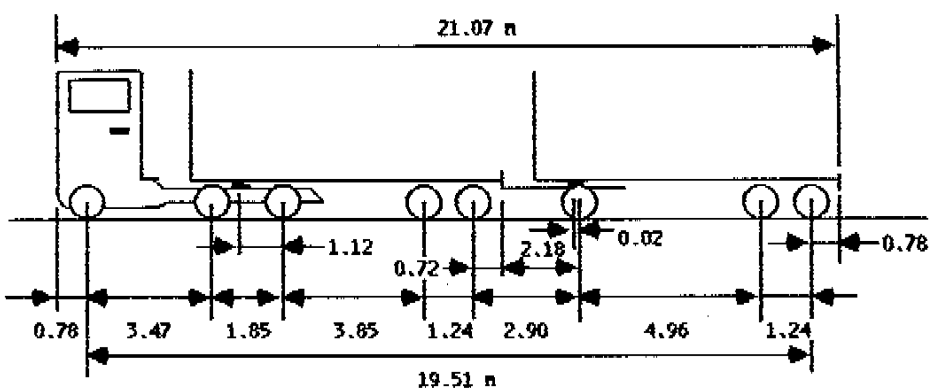


Figure 2/ Vehicle Dimensions

Figure 3/ Clockwise Offtracking

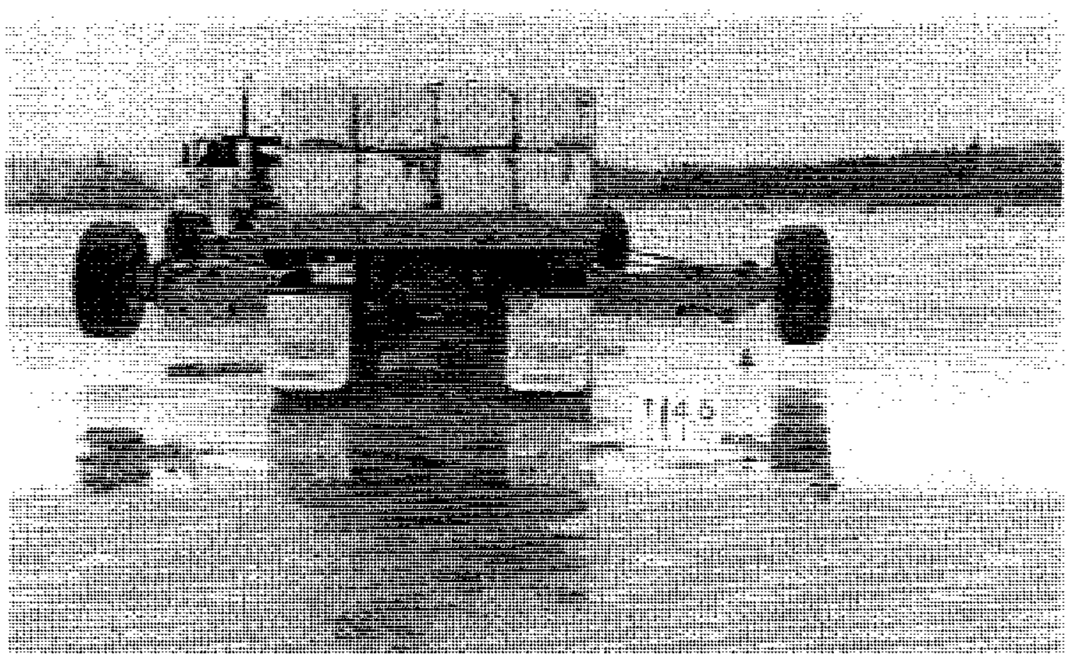
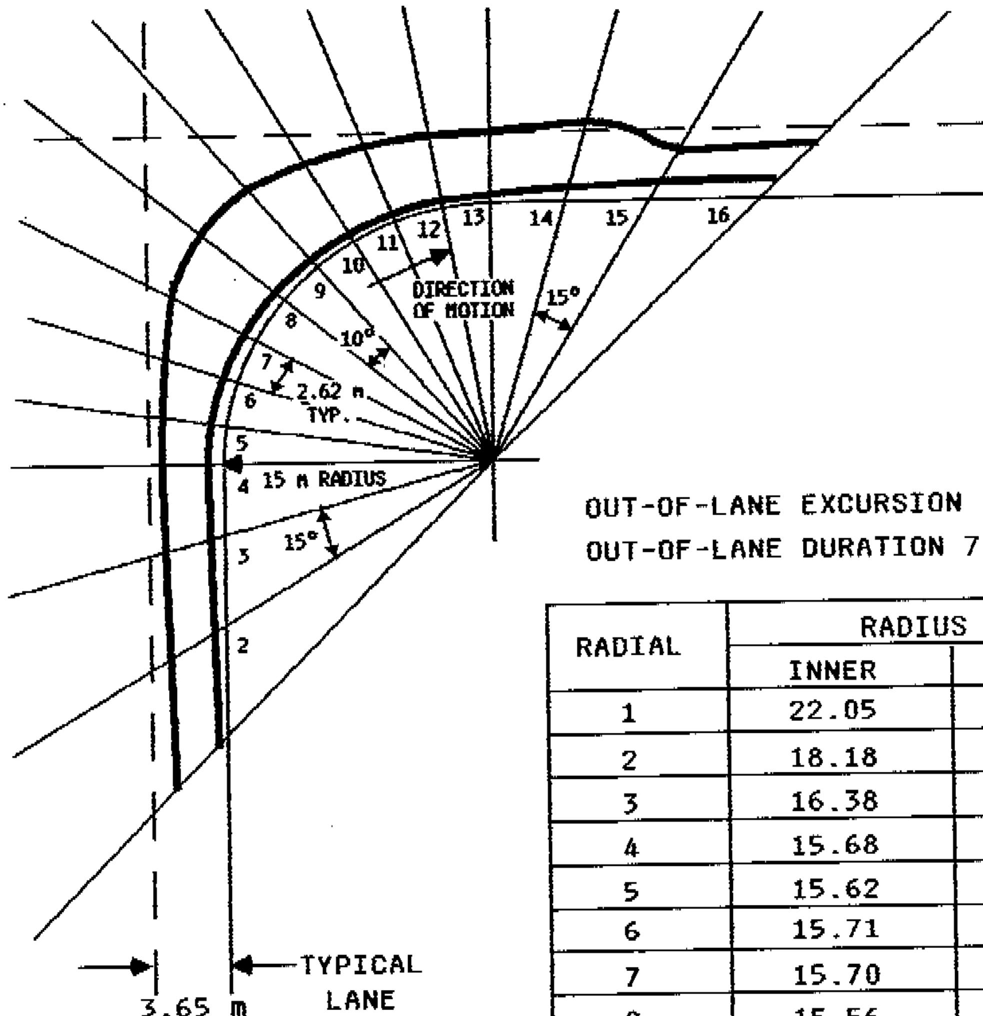


Figure 4/ Counter-Clockwise Final Offtracking



OUT-OF-LANE EXCURSION 0.4 m
OUT-OF-LANE DURATION 7.5 m

RADIAL	RADIUS (m)	
	INNER	OUTER
1	22.05	-
2	18.18	20.73
3	16.38	18.76
4	15.68	18.16
5	15.62	18.84
6	15.71	19.17
7	15.70	20.36
8	15.56	20.93
9	15.35	20.76
10	15.13	20.26
11	15.04	19.45
12	15.10	18.86
13	15.40	18.82
14	16.47	19.98
15	18.55	20.58
16	22.30	25.34

Figure 5/ Right-Hand Turn Swept Path

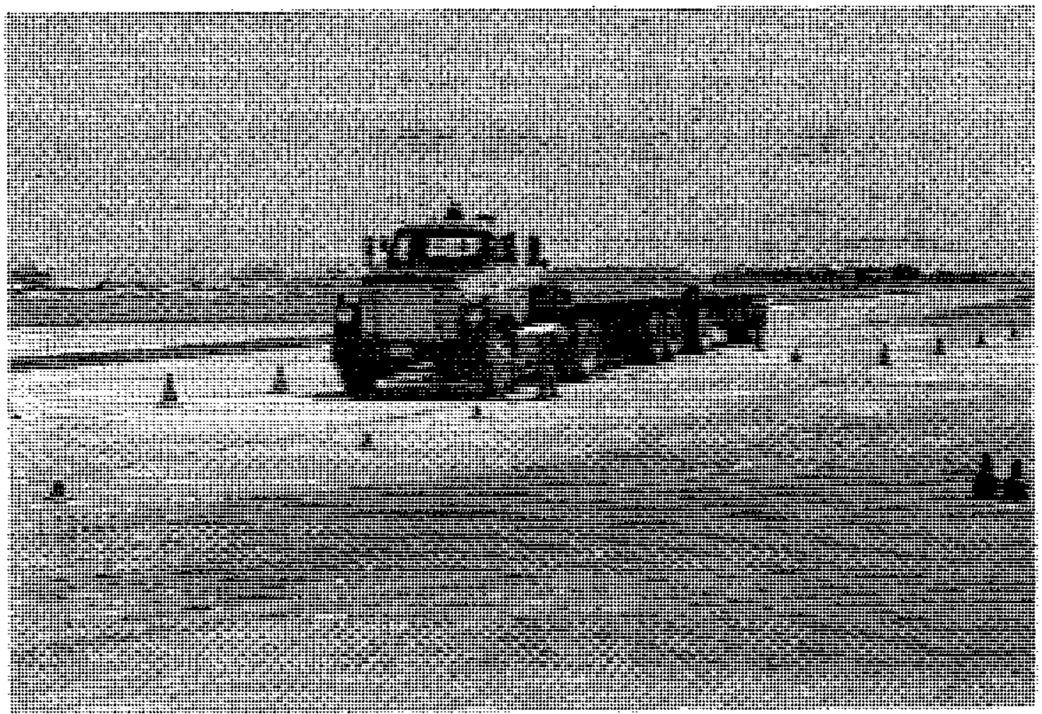
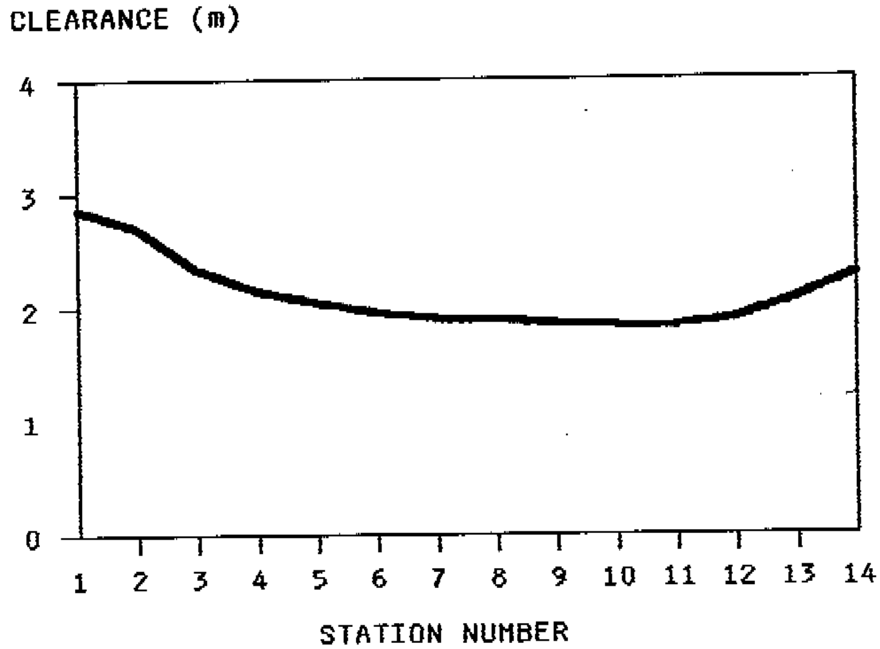


Figure 6/ Right-Hand Turn

Figure 7/ Channelized Right Turn



STATION NUMBER	CLEARANCE (m)
1	2.85
2	2.69
3	2.34
4	2.15
5	2.05
6	1.95
7	1.92
8	1.90
9	1.86
10	1.85 *(LOW)
11	1.85 *(LOW)
12	1.92
13	2.08
14	2.28

Figure 8/ Channelized Right Turn
Clearance from Inner Curb

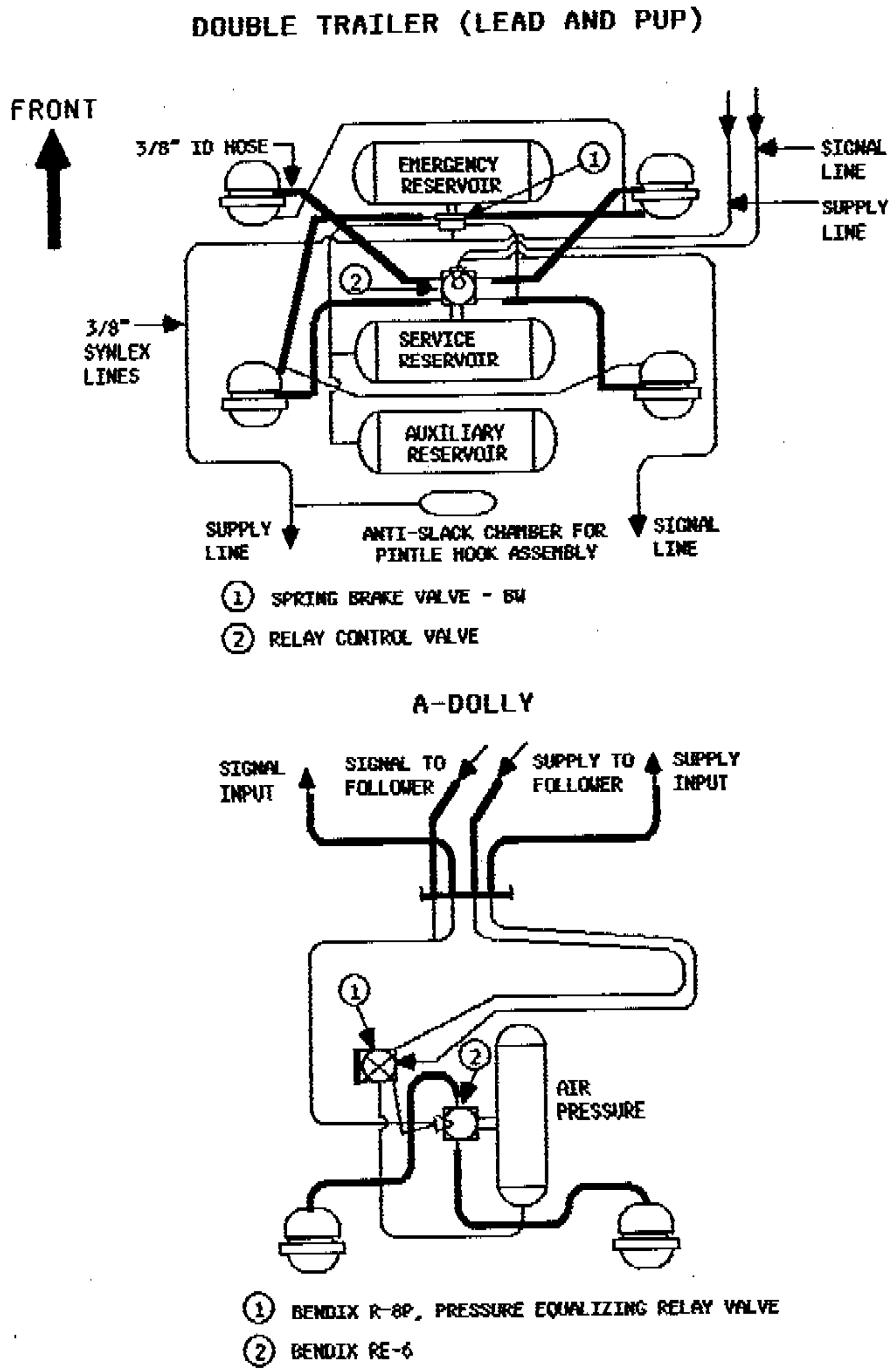


Figure 9/ Trailers and Dolly,
Air Brake System Schematic

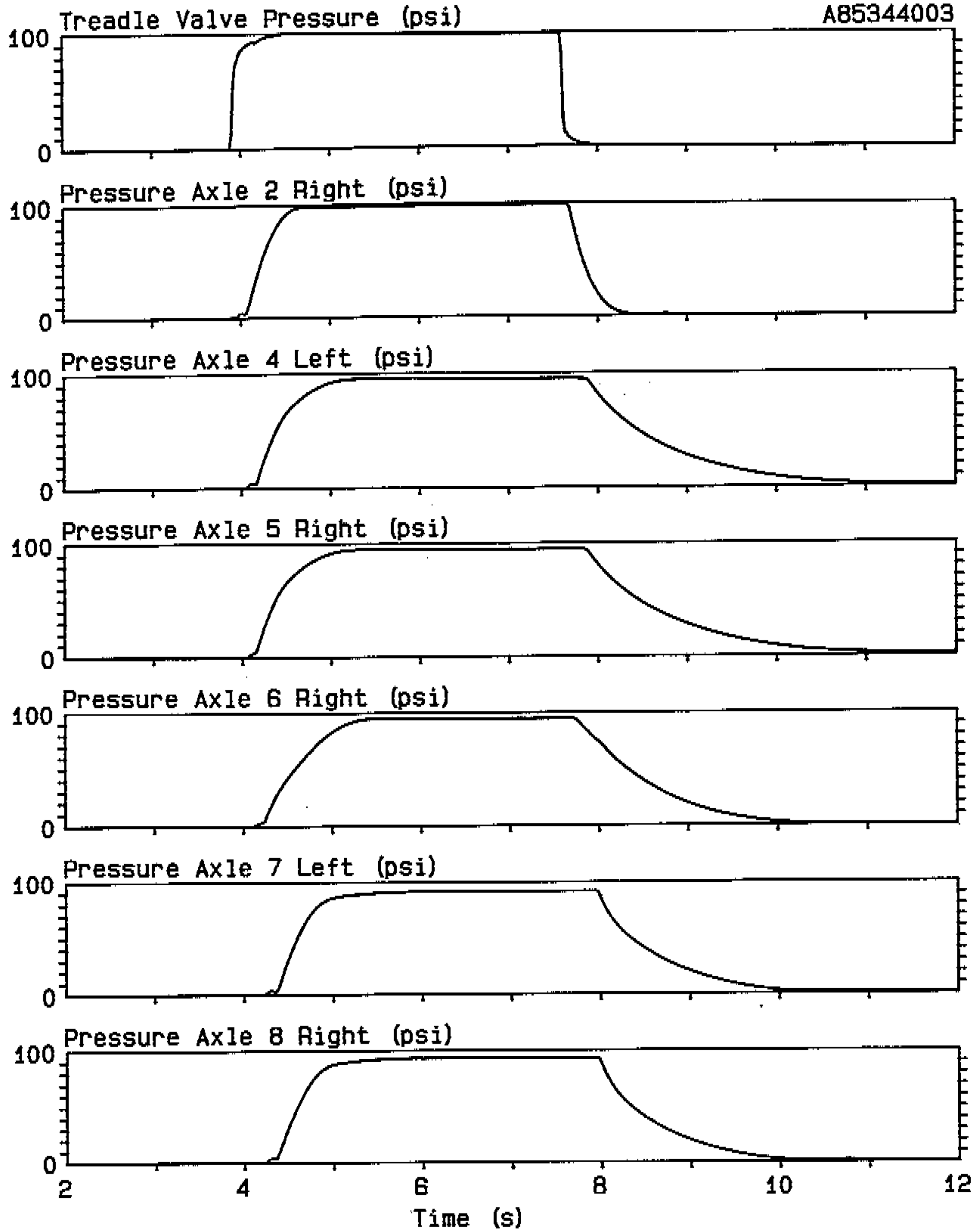


Figure 10/ Air Brake Application and Release

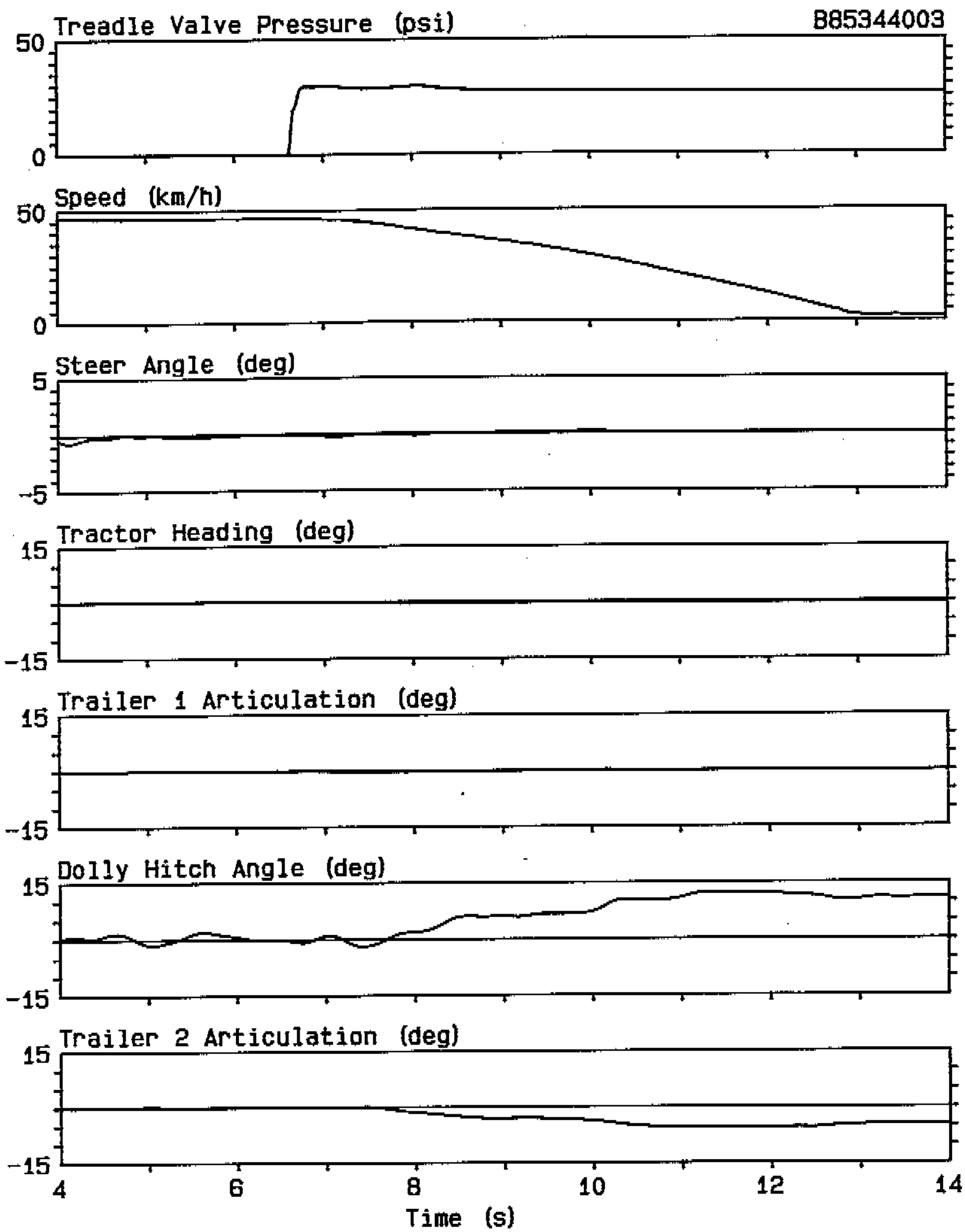


Figure 11/ Vehicle Response to Straight-Line Braking

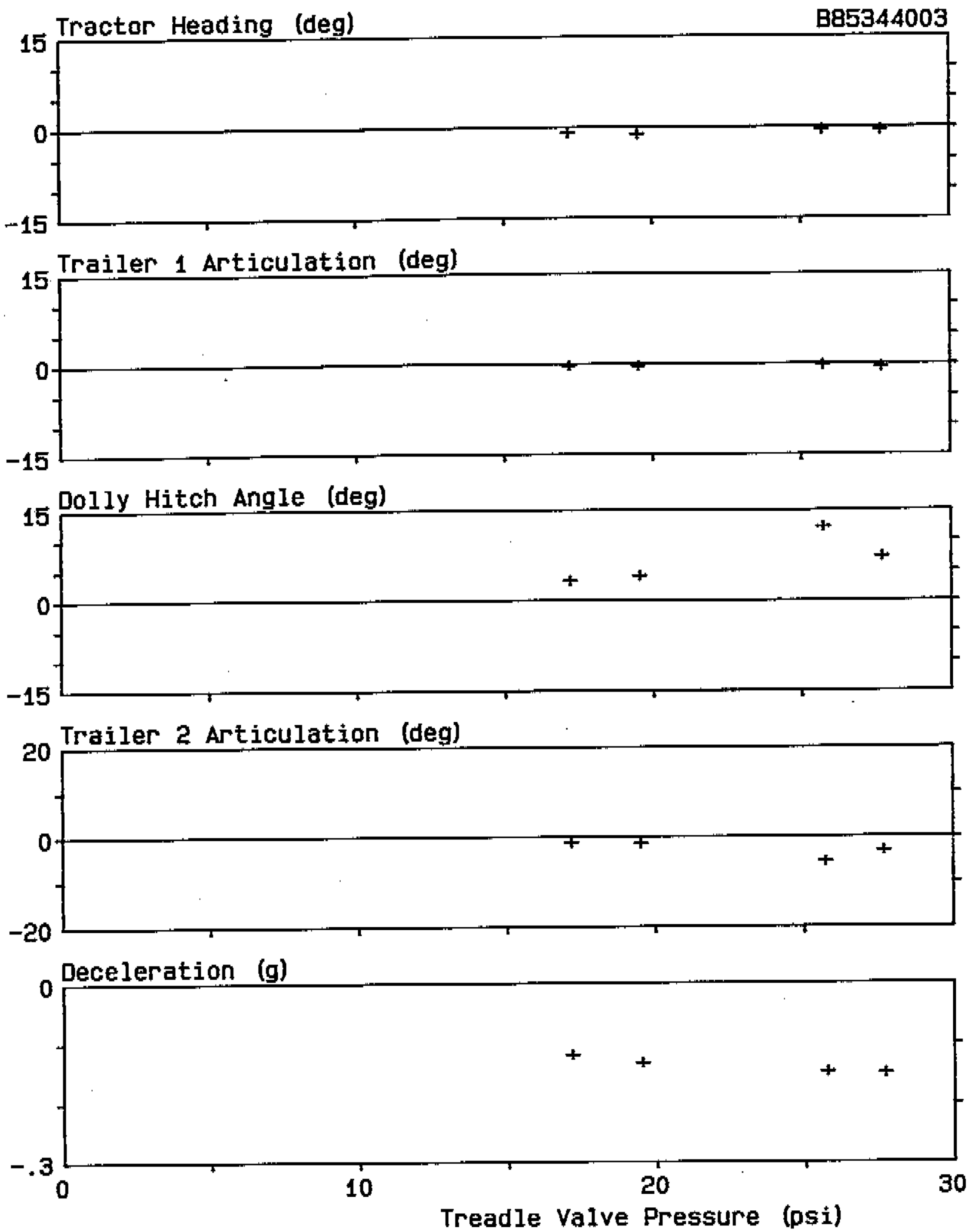


Figure 12/ Straight-Line Braking Responses vs
Treadle Valve Pressure

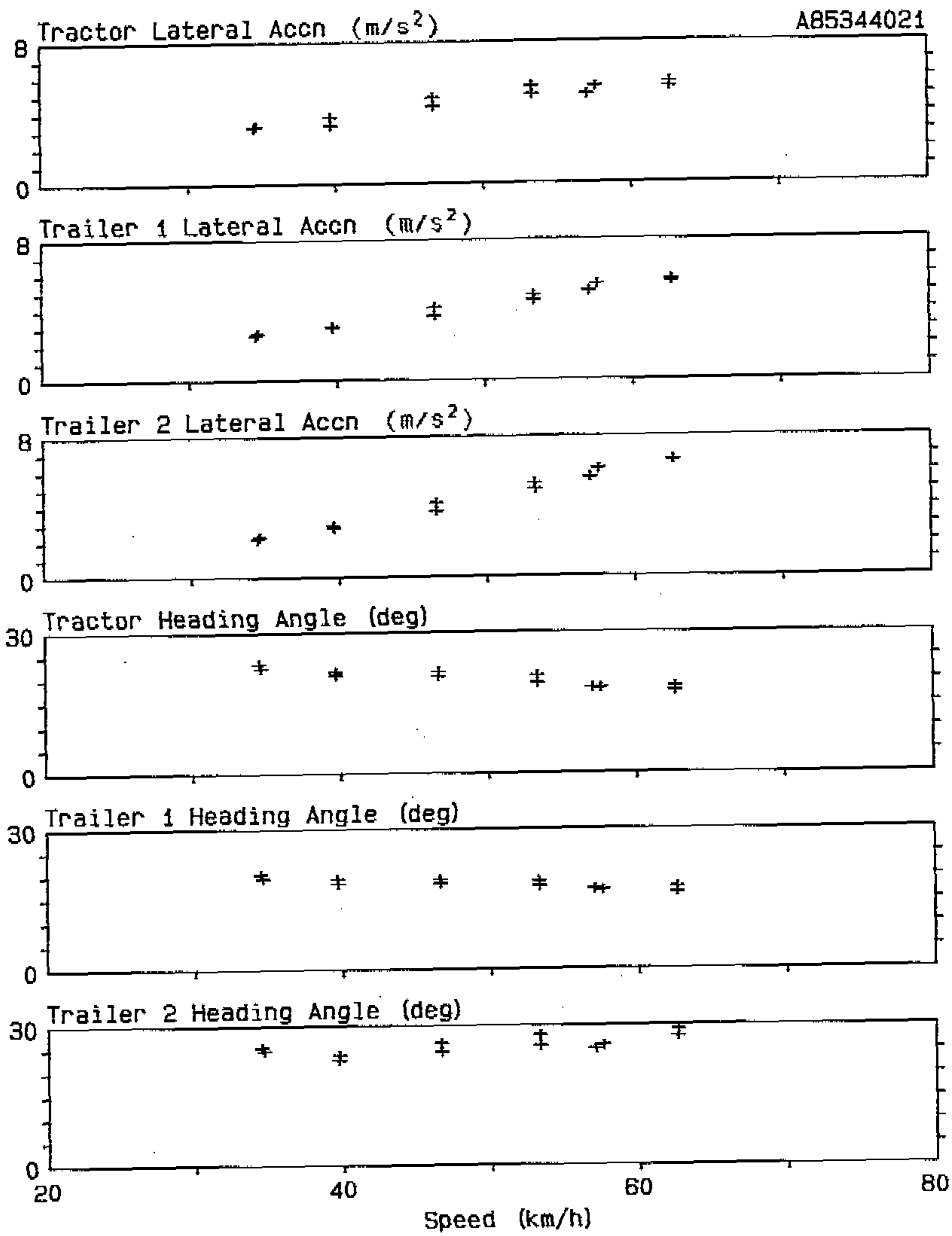


Figure 13/ Evasive Manoeuvre, Peak-to-Peak
Responses vs Speed

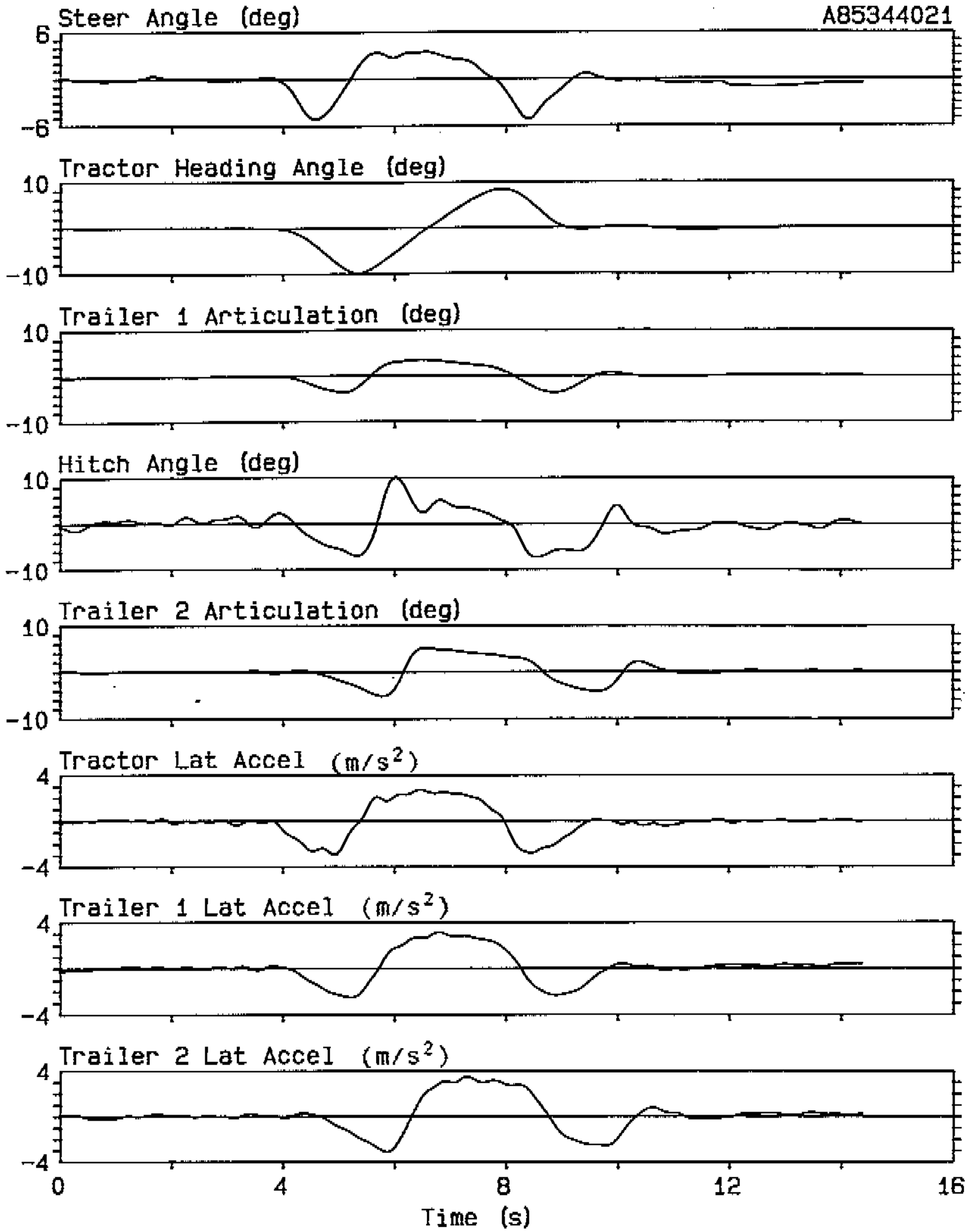


Figure 14/ Evasive Manoeuvre, Vehicle Response at 63 km/h

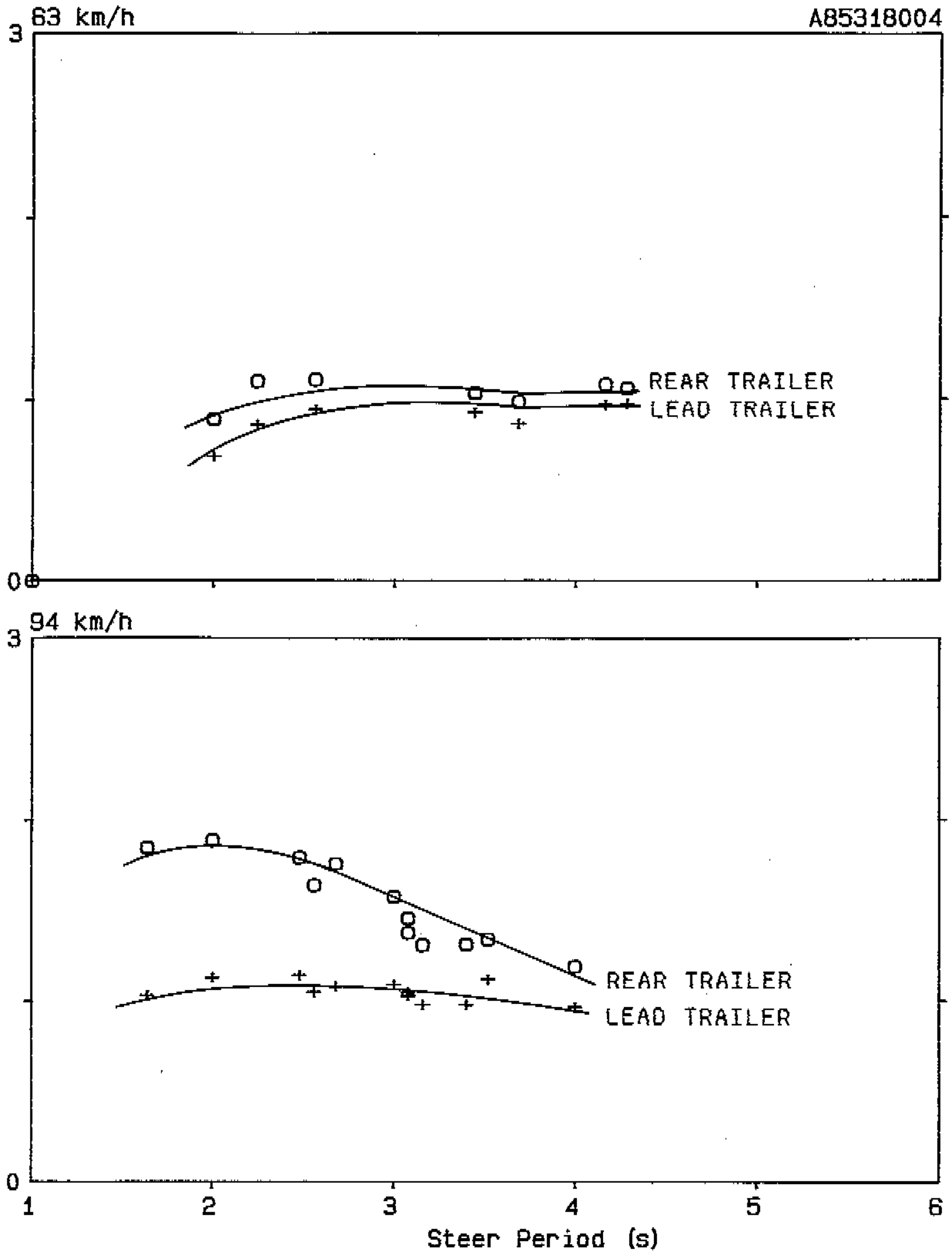


Figure 15/ Rearward Amplification of Lateral Acceleration

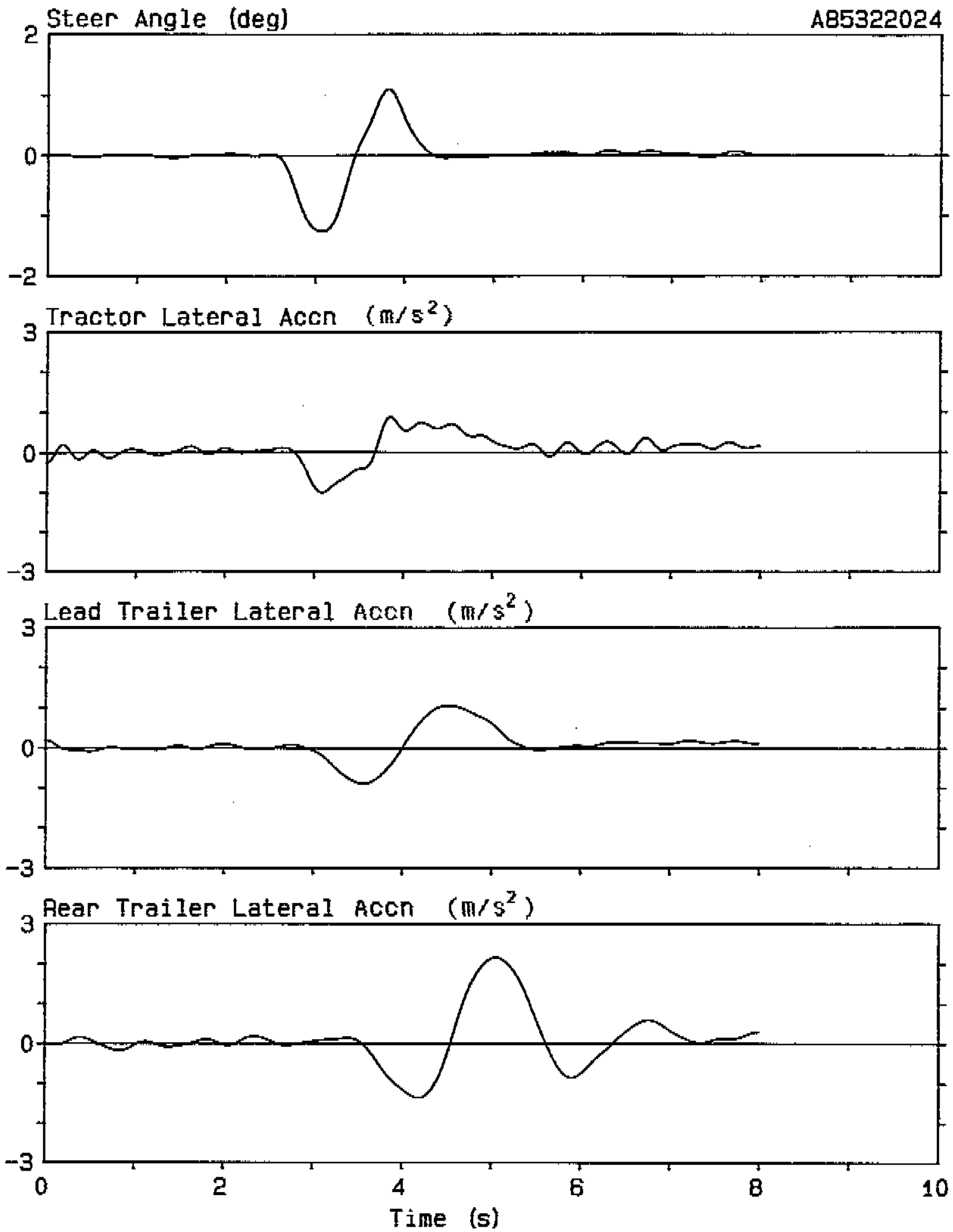


Figure 16/ Sinusoidal Steer, Vehicle Responses at 94 km/h

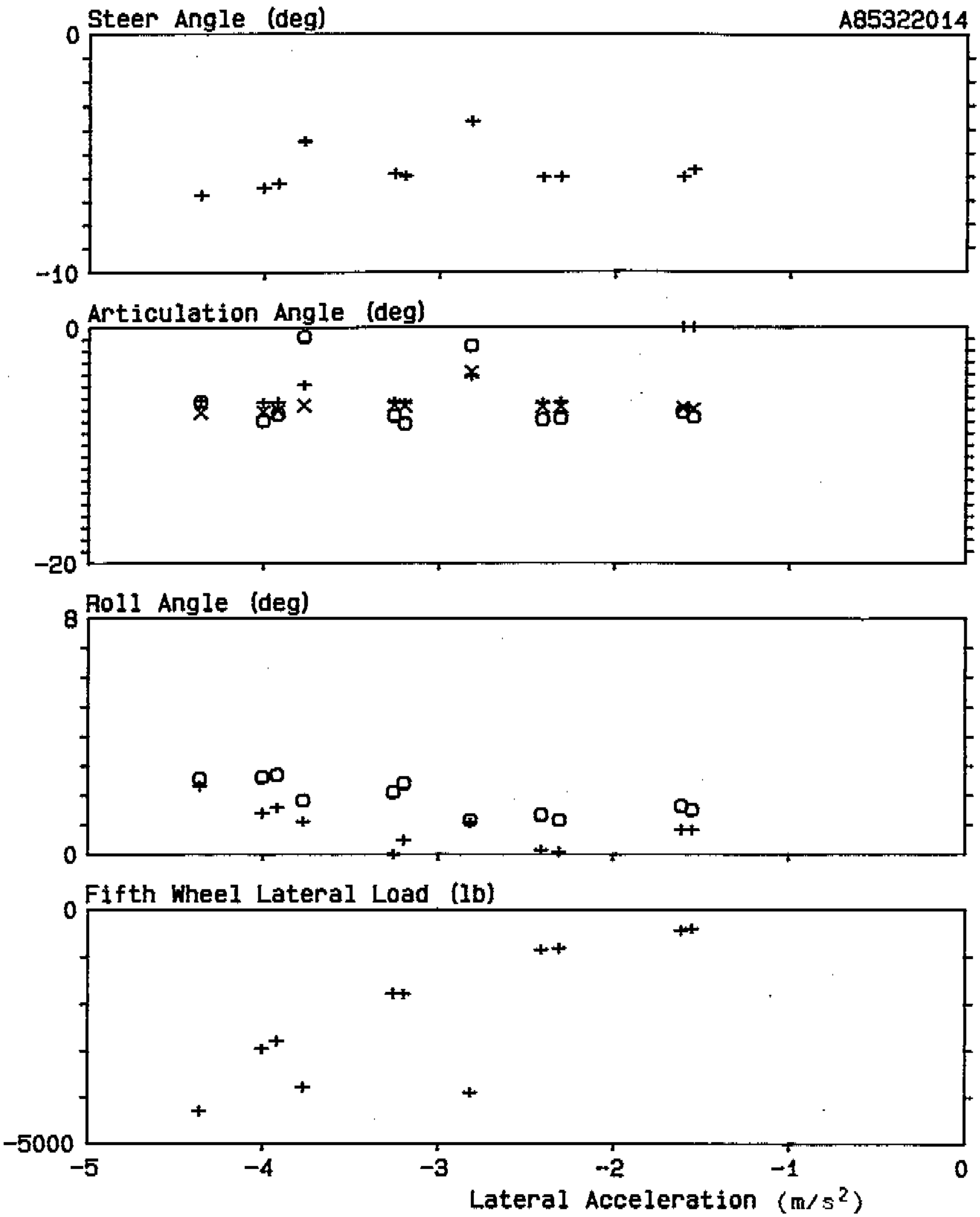


Figure 17/ Steady Circular Turn, Vehicle Responses vs
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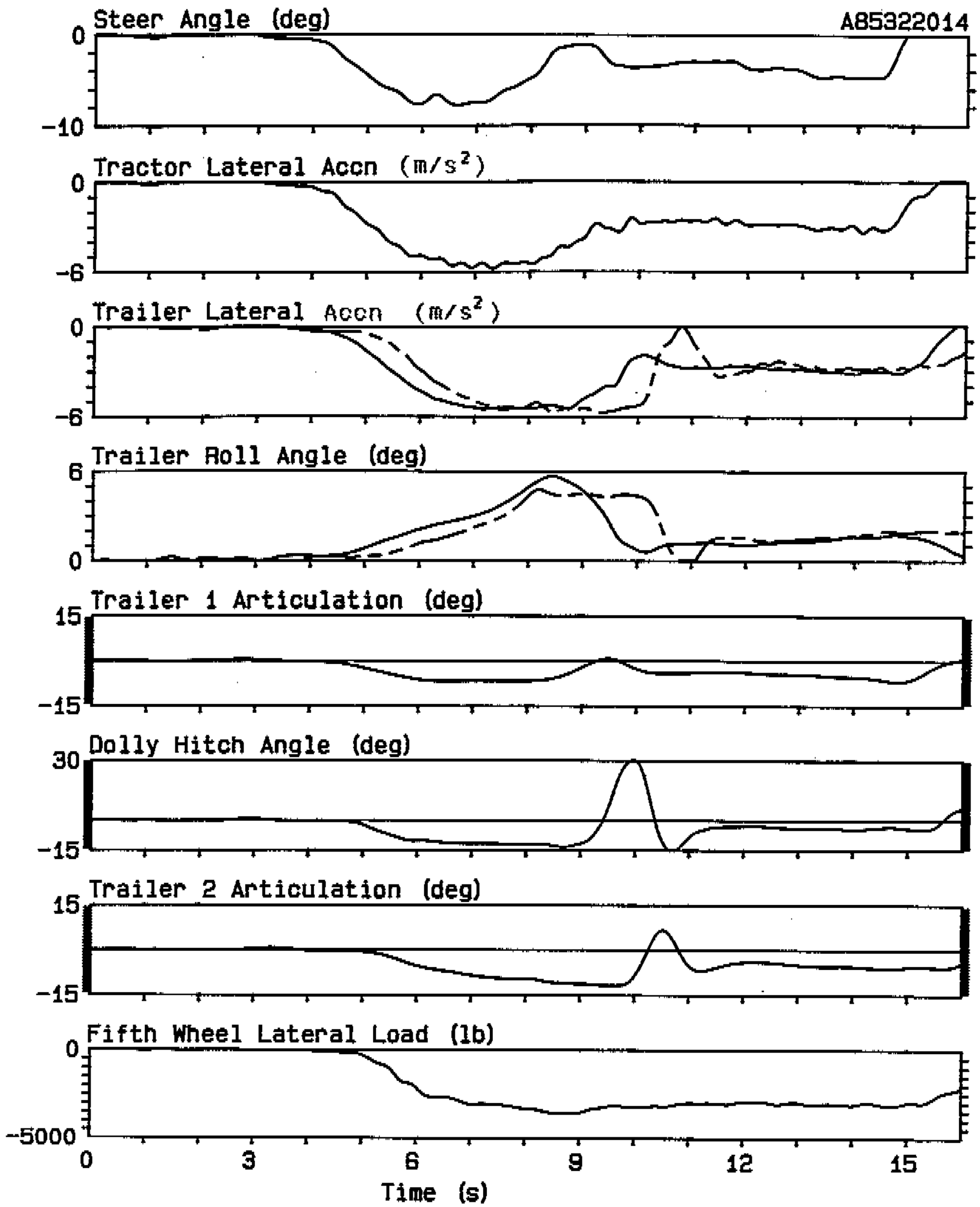

Figure 18/ Steady Circular Turn, Vehicle Responses at 62 km/h

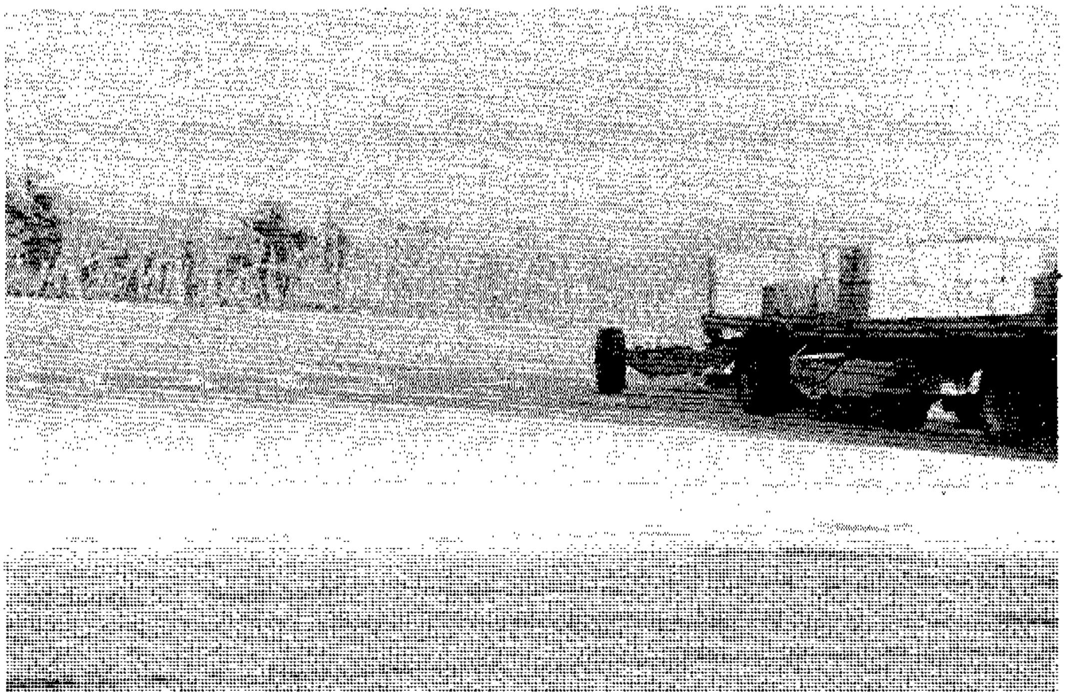

Figure 19/ Vehicle Making Steady Circular Turn

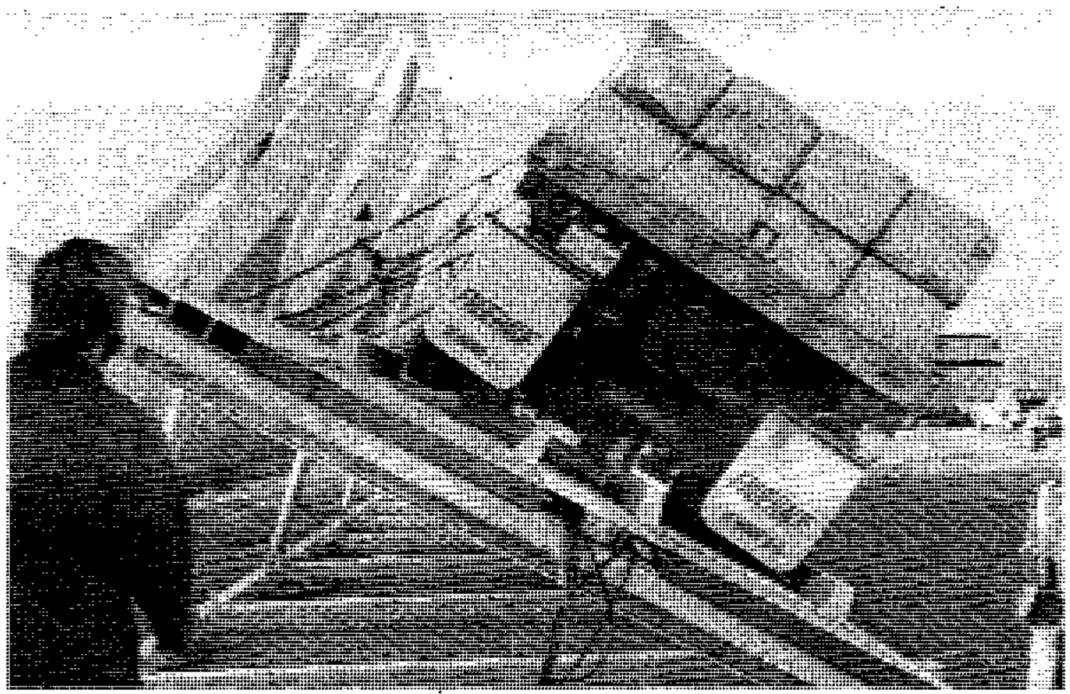

Figure 20/ Vehicle on Tilt Table

CV-86-04

Demonstration of Baseline Vehicle Performance: B-Train Double

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ABSTRACT

An B-train double trailer combination was tested by the Ontario Ministry of Transportation and Communications (MTC) as part of the CCMTA/RTAC Vehicle Weight and Dimensions Study. The vehicle was designated a base-line vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with the empty vehicle on a low-friction surface and the loaded vehicle on a high-friction surface.

This report presents detailed results of the tests and demonstrations.

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ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The trailers were obtained for the study from Transport Canada. Facilities of the Transport Canada Motor Vehicle Test Centre were made available to the Ministry of Transportation and Communications (MTC). Assistance with vehicle preparation, delivery, and refurbishment was arranged by Mr. Pearson in support of this work.

The work was principally undertaken by the staff of the Automotive Technology and Systems Office of the Transportation Technology and Energy Branch of MTC: N.R. Carlton; G.B. Giles; C.P. Lam, P.Eng.; W.R. Stephenson, P.Eng.; and M.E. Wolkowicz; and assigned students G. Goertzen, S. Jazic, and D.R. Sykes. Assistance was provided by staff of various other departments of the ministry and other organizations.

The efforts of all involved are hereby acknowledged with gratitude.

1/ INTRODUCTION

The effects of changes in truck weight and dimension parameters on combination vehicle stability and handling and on pavement response to axle group loading are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle portion of the study involved both computer simulation of vehicle dynamic manoeuvres and testing of vehicles and components. Combination vehicles were classified into six families, based on the number of trailers and methods of hitching. A representative of each family was designated as the baseline vehicle configuration for that family. Additional vehicle configurations of interest were also defined. All baseline and additional vehicle configurations were tested to assemble a body of technical and visual data that described the stability and control characteristics of the vehicles with respect to certain performance measures.

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. This report presents the results of a test of a B-train double trailer combination baseline vehicle. It refers frequently to a report describing procedures and equipment common to tests of all nine vehicles undertaken by MTC [1]. Similar reports present details of the tests of the other eight vehicles [2-9], and a summary report presents the results of tests of all six baseline vehicles [10]. A computer simulation of vehicle responses to actual test inputs using estimated vehicle data has also been conducted [11].

2/ TEST VEHICLE DESCRIPTION

The test vehicle consisted of the MTC Freightliner [1] and a B-train flatbed 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 equipment for these tests was obtained from Transport Canada for the study. No modifications were made to the trailers except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were affected [11].

The trailers were manufactured by Pullman Trailmobile Canada in February 1980 and bore the serial number 2.80.1110.1028.002. Both trailers had a nominal bed 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 was 2.44 m (96 in), and the axles were rated at 9616 kg (21 155 lb). The combination had an overall length of 22.1 m (72.5 ft).

The trailers and dollies were fitted with new Michelin XZA radial tires, [illegible] size 11R22.5. These tires were run a nominal dis-

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 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 1.

Table 1/ Axle Loads

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 empty weight exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. A target axle load of 8000 kg (17 600 lb) was set for all axles except for the steer axle. This was nearly attained, with the exception of the tractor drive axles and the last axle of the combination. Both trailers were loaded in the same fashion, consistent with normal practice. The legal gross weight of the vehicle tested is 56 600 kg (124 560 lb) in Quebec and 60 500 kg (133 100 lb) in Ontario, and would be about 52 000 kg (114 400 lb) where permitted in the prairie provinces.

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.

3/ TEST PROGRAM

3.1/ Test Procedures

The test vehicle was prepared for testing in the following way:

1/ A mechanical inspection was carried out, and any necessary repairs or maintenance was done.
2/ Outrigger attachments were installed on the trailers.
3/ Outriggers were installed on the trailers.
4/ The boxes containing instrument packages, power supplies and signal conditioning, other instruments, and cabling were installed.
5/ New tires were installed, and pressures were set.
6/ Other fittings necessary for testing were installed.
7/ Concrete blocks were located on the trailer beds to achieve specified axle loads.
8/ Notes were made from detailed physical inspection, including an inventory of components and measurement of dimensions.
9/ The MTC tractor was coupled to the trailers.
10/ The combination vehicle was weighed, empty and loaded.
11/ A functional test of the on-board electronics was conducted.
12/ Test runs were made to shake down the vehicle instrumentation and familiarize the test driver with the vehicle's handling characteristics.
13/ Tires were run a nominal distance of 600 km (370 mi).
14/ Articulation angle between the tractor and lead trailer was calibrated.
15/ Details of the vehicle and test equipment were recorded on photographs and videotape.

The following tests were performed:

- Offtracking
- Right-hand turn
- Channelized right turn
- Air brake system
- Straight-line braking, empty vehicle, low-friction surface
- Evasive manoeuvre, empty vehicle, low-friction surface
- Sinusoidal steer, loaded vehicle, high-friction surface
- Lane change, loaded vehicle, high-friction surface
- Normal straight-line driving
- Steady circular turn, loaded vehicle, high-friction surface

All tests followed standard procedures [1], except as noted.

3.2/ Instrumentation

The instrumentation shown in Table 2 was installed. Brake pressure transducers were only installed in the trailers for the air brake system test, but all other instrumentation was installed for all tests. Data were always captured from all instrumentation, but only those pertinent to a particular test were analysed.

Tractor instruments were selected from the instrumentation that is permanently installed on the tractor. Instruments for the two trailers were mounted in boxes placed on the trailer deck, which also contained power supplies and signal conditioning. Trailer lateral acceleration and roll angle were measured at a point midway between the kingpin and axle.

Full details of the instrumentation, signal conditioning, and data capture system are presented elsewhere [1].

3.3/ Data Capture and Data Processing

Data were digitized on board the vehicle and transmitted by telemetry as a pulse-code modulated (PCM) data stream to a ground station, where they were recorded on magnetic tape and captured in real time by an HP-1000 computer system. Test data for a run were processed immediately after the run, and results from a series of runs were subsequently analysed using the computer system [1].

Many test runs of all types were conducted for this vehicle. Not all these runs were used in the preparation of this report. In a number of instances, a run failed to meet a test condition.

Table 2/ Instrumentation Installed

No	Measurement	Instrument	Full Scale
1	Tractor steer angle	Spectrol 139 potentiometer	25.02°
2	Tractor roll angle	Humphrey CF18-0907-1 gyroscope package	8.85°
3	Tractor lateral acceleration	Kistler 303B accelerometer	0.957 g
4	Tractor yaw rate	Humphrey RT03-0502-1 angular rate transducer	38.7°/s
5	Tractor longitudinal acceleration	Kistler 303B accelerometer	0.974 g
6	Tractor speed, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	104.8 km/h
7	Tractor distance, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	56.3 m/ramp
8	Tractor fifth wheel load, left-hand side	MTC load cell	9890 lb
9	Tractor fifth wheel load right-hand side	MTC load cell	10290 lb
10	Tractor treadle valve pressure	Celesco PLC-200G	100 psi
11	Tractor brake pressure, axle 2 Left	Celesco PLC-200G	99.80 psi
12	Tractor lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
13	Tractor yaw angle	Humphrey CF18-0907-1 gyroscope package	17.73°
14	Trailer 1 articulation angle	Celesco pull cord DV-301-150	20.839°
15	Trailer 1 lateral acceleration	Columbia SA-107 accelerometer	0.995 g
16	Trailer 1 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.90°
17	Trailer 1 outrigger touchdown	Strain gauge bridge	1.0 V
18	Trailer 1 lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
19	Brake pressure, axle 4 right	Celesco PLC-200G	104.96 psi
20	Brake pressure, axle 5 right	Celesco PLC-200G	101.06 psi
21	Brake pressure, axle 6 right	Celesco PLC-200G	102.07 psi
22	Brake pressure, axle 7 right	Celesco PLC-200G	101.93 psi
23	Brake pressure, axle 8 right	Celesco PLC-200G	106.79 psi
24	Spare		
25	Spare		
26	Trailer 2 articulation angle	Spectrol 8409 potentiometer	22.8°
27	Trailer 2 lateral acceleration	Columbia SA-107 accelerometer	0.980 g
28	Trailer 2 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.91°
29	Trailer 2 outrigger touchdown	Strain gauge bridge	1.0 V

4/ RESULTS

4.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions, as shown in Figure 3. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [1].

The results are shown in Table 3. The measured data were averaged for the left and right turn and then compared to data generated by a simple offtracking formula [12]. The difference between actual and computed values, shown in the last column of Table 3, is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

The final offtracking for the counter-clockwise turn is shown in Figure 4. After averaging for both directions and correcting for differences in axle track width, the offtracking of 1.65 m (5.41 ft), shown in Figure 4, became 1.69 m (5.54 ft).

Table 3/ Offtracking

Axle No.	Track Width (m)	Radius to Inner Wheel		Difference (m)	Average (m)	Calculated (m)	Difference %
		Right Turn (m)	Left Turn (m)				
1	2.31	27.55	27.58	0.03	27.57	27.56	-0.04
2	2.37	27.26	27.32	0.06	27.29	27.21	-0.29
3	2.37	27.22	27.35	0.13	27.29	27.21	-0.29
4	2.37	26.41	26.55	0.14	26.48	26.07	-1.57
5	2.37	26.32	26.47	0.15	26.39	26.02	-1.42
6	2.37	26.34	26.45	0.11	26.40	26.07	-1.27
7	2.37	25.81	25.91	0.10	25.86	25.45	-1.61
8	2.37	25.76	25.86	0.10	25.81	25.45	-1.41

4.2/ Right-Hand Turn

A 90° right-hand turn is a very demanding manoeuvre for a large truck. The vehicle's swept path in a 90° right-hand turn of 15 m (49.2 ft)

radius was measured, according to the standard test procedure [1]. This radius is typical in an urban area or where there is limited truck traffic. The swept path is shown in Figure 5.

The vehicle is shown in Figure 6 during the turn, at a point close to its maximum excursion out of the exit lane. The maximum excursion out of lane was 0.90 m (2.95 ft). It was out of the exit lane for a distance of 18.00 m (59.0 ft), as derived from Figure 5. This test was conducted at a creep speed and represents the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

4.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [1].

The vehicle is shown during the turn in Figure 7. The clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Figure 8 as a function of distance through the curve. The minimum clearance was 1.55 m (5.1 ft) in the 5.5 m (18 ft) wide roadway.

The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. The vehicle easily made it through the channel.

4.4/ Air Brake System

The air brake system of the combination was evaluated according to standard test procedure [1].

The trailer air brake system was inspected. A schematic of the system is shown in Figure 9. The trailers were fitted with a Kelsey-Hayes antilock braking system, which was inactive for these tests. All slack adjusters required manual adjustment. Stroke was adjusted to the minimum, about 32 mm (1.25 in) on each axle. The tractor was supplied with shop air, regulated at 689 kPa (100 psi). Pressure transducers were installed at all trailer and dolly axles.

The SAE J982a style test was performed. The results of this test, presented in Table 4, are the average of several tests, each with a time resolution of 0.02 s. The application and release times this test compare favourably with those obtained from tests conducted on other double combinations [13]. The speed is due to the clean plumbing between the trailers, and the anti-lock system requirements. An additional 6 to 10 m (20 to 30 ft) of hose and various couplings on a converter dolly slow the A- or C-train brake timings significantly.

A typical time history response of application and release is presented in Figure 10.

Table 4/ Air Brake Timing, SAE J982a Style Test

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.04	0.12	84.4
Axle 2	0.40	0.54	87.6
Axle 4	0.56	1.46	84.1
Axle 5	0.62	1.50	83.5
Axle 8	0.68	1.56	84.3

4.5/ Straight-Line Braking

It is difficult to conduct rigorous braking tests and achieve consistent results. A demonstration of modes of instability of the combination vehicle in straight-line braking was, therefore, conducted. A series of runs was made with the empty vehicle approaching the low-friction test area at 47 km/h and the driver braking using the treadle valve. Runs were made using various application pressures, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [1].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit.

The time history of a typical run that resulted in loss of control is shown in Figure 11. The initial average brake application of about 276 kPa (40 psi) caused all braked wheels on the vehicle to lock. The tractor jackknifed to the right, but the driver steered to the left and was able to hold the tractor heading at about 10°. The two trailers remained under control, with the lead trailer heading to the right as the tractor moved out of the lane in that direction. If the front axle brakes on the tractor had been used, it is probable the tractor would not have jackknifed at this speed. The tractor and trailers were both fitted with anti-lock brakes. If these had been used, the wheels would not have locked until a low speed and, again, the vehicle would have remained under control.

A summary of peak vehicle responses from the runs is shown in Figure 12, as a function of average treadle valve pressure. The limit of surface adhesion of about 0.16 g was reached before 193 kPa (28 psi), but tractor jackknife did not occur until a significantly greater pressure was applied. Jackknifes occurred to both right and left, and in each case, the driver eased off the treadle valve during the stop, so the data points are plotted at a lower pressure than used initially.

4.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. Gates of 20.0 m (65.6 ft) were used for the lane change to the left and return to the original lane, separated by 20 m (65.6 ft) in the left lane. The runs were made in accordance with the standard test procedure [1].

The vehicle combination was evaluated primarily in terms of the lateral acceleration and yaw responses of the vehicle units. These are shown in Figure 13. Each response is the peak-to-peak amplitude experienced by the vehicle in the manoeuvre. The lateral acceleration of all vehicle units increased with speed up to 54 km/h. Trailer 2 had the highest rate of increase. The heading amplitude tended to decrease with speed for the tractor and trailer 1 and remained relatively constant for trailer 2. Data reveal that there was minor trailer 2 oscillation when the vehicle returned to the original lane. As the speed increased, increased steer at the tractor was necessary to negotiate the course. This indicated tractor understeer and is supported by the driver's comments that the vehicle tended to "push." At 54 km/h trailer 2 swung out of lane on the return to the original lane.

A typical run at this speed is shown in Figure 14.

4.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for this combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 63, 84, and 94 km/h, with steer input periods between about 2 and 5 s.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. Rearward amplification of lateral acceleration for the two trailers is presented in Figure 15, as a function of tractor steer input period for the three test speeds. Each gain is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless.

It is evident from Figure 15 that rearward amplification increases with speed, rearward by trailer, and is also somewhat sensitive to steer period, reaching the highest value of about 1.70 at about 2 s at 94 km/h. The results show that, at highway speed, the B-train double is a moderately responsive vehicle. The reason for this is that its inherent stability is high. Stability and response of mechanical systems have an inverse relationship: high stability means low response to input and vice versa.

Figure 16 shows the vehicle response from a typical run with a steer period of about 2 s at 94 km/h.

4.8/ Lane Change

The objective of this test was to evaluate vehicle stability characteristics in a dynamic manoeuvre. A series of runs was made where the driver made a fast lane change, which is considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [1].

A gate of 30 m (98.4 ft) was used, to provide a vehicle speed of about 80 km/h, which is a typical speed limit and might permit some comparison of the results of this test with that described in the preceding sections.

The results from all runs are summarized in Figure 17. The peak-to-peak lateral acceleration, roll, and yaw (or heading) angles all show an increase as the limiting speed of 85 km/h was reached, at which point trailer 2 rolled over to the left with outrigger touchdown, slid about 1 m (3.3 ft) into the adjacent lane, swung back to the right, and rolled with a second outrigger touchdown on the right. Figure 18 shows such a run. The response was rather violent, but the entire vehicle would not have rolled over. Lateral acceleration and roll gains are also shown in Figure 17. The lateral acceleration gains at 63 and 84 km/h were consistent with those from the sinusoidal steer test. Lateral acceleration lag time for trailer 1 tends to climb and stabilize, whereas for trailer 2 it tends to fall for the first response peak, due to the steer to the left. The rear trailer response lags 1.0 to 1.3 s behind the tractor. Therefore, once the driver initiates an input, the vehicle response will follow and there is little that the driver can do to modify it. This lag time is caused by the number of articulation points and length of the vehicle and is considered to reduce the driver's control of the entire vehicle. The yaw overshoot of the trailer clearly illustrates trailer 2 swing at the limiting speed and is partially as a result of roll states. In all cases, trailer 2 reacted more violently than trailer 1, except that trailer 1 overshot the most.

Figure 19 shows the steer input and vehicle response from a typical run at 85 km/h. The yaw histories show signs of oversteer, and the roll histories for trailers 1 and 2 show a roll response to the right after the vehicle has entered the exit lane, no doubt due to the preceding oversteer track.

4.9/ Normal Straight-Line Driving

The objective of this test was to attempt to evaluate lateral motion of the rear trailer of the combination, the phenomenon known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [1].

As previously mentioned, the vehicle was quite responsive, but the slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in rear trailer sway that was hardly perceptible to the occupants of a chase vehicle. Root mean square (RMS) lateral acceleration of the rear trailer was 1.49 g/° of RMS steer input.

4.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics to determine the high-speed offtracking of the vehicle and to examine the side loads exerted on the tractor by the trailers. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The results of this test are summarized in Figure 20. The vehicle combination was evaluated primarily in terms of the roll response of the vehicle units. At the limiting speed of 63 km/h, a lateral acceleration of 0.49 g, the outriggers of both trailers touched down, as shown in Figure 21 and 22. As Figure 20 shows, roll angles increased with speed and articulation angles decreased, and as a consequence, the offtracking decreased. The lateral force experienced by the tractor fifth wheel, presented as a function of tractor lateral acceleration, shows a gradient of 13.8 kN/g (3100 lb/g).

A tilt test was conducted on this vehicle as part of a separate test program [14]. The vehicle is shown on the tilt table in Figure 23. The high-side wheels of the rear trailer lifted at a tilt angle of 26.9°, after all corrections were made, which corresponds to a lateral acceleration of 0.51 g. This is in quite good agreement with the rear trailer's lateral acceleration of 0.49 g at outrigger touchdown. A full discussion of the tilt test is presented elsewhere [14].

5/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation.

Tests were conducted in various weather conditions. Tires wore progressively as the various tests were conducted. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailers were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal, particularly for the loaded condition, because of the underslung outriggers.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results. The results presented pertain to the particular vehicle tested, and results different in some respects might be obtained for another vehicle at another time.

This vehicle was considered an easy vehicle to drive by the test driver. The short trailer wheelbase made it easy to manoeuvre in low-speed turns, though high driver effort was required in these and dynamic tests, as the trailer imposed significant forces on the tractor. The vehicle was nearly as responsive as a similar A-train [5].

6/ CONCLUSIONS

A B-train double trailer combination was tested by the Ontario Ministry of Transportation and Communications, as part of the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with an empty vehicle on a low-friction surface and a loaded vehicle on high-friction surface.

The articulation of this vehicle clearly contributed to the small space required to make turns.

The air brake system was relatively fast and well balanced, largely because the B-train has no converter dolly and because the particular vehicle was equipped with anti-lock brakes.

The lateral/directional stability of the vehicle was moderate, both empty on a low-friction surface and loaded on a high-friction surface. Stability deteriorated at the highway speed limit of 100 km/h. The roll stability was high previously because of the low trailer centre of gravity height. A higher centre of gravity would significantly reduce the roll threshold.

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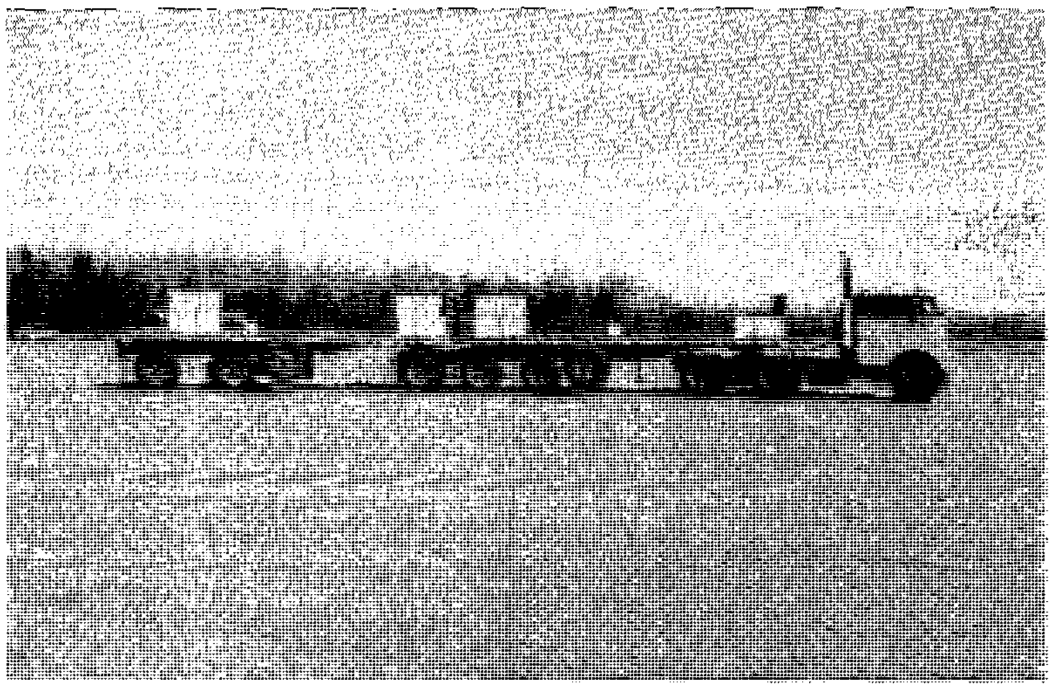


Figure 1/ View of Vehicle

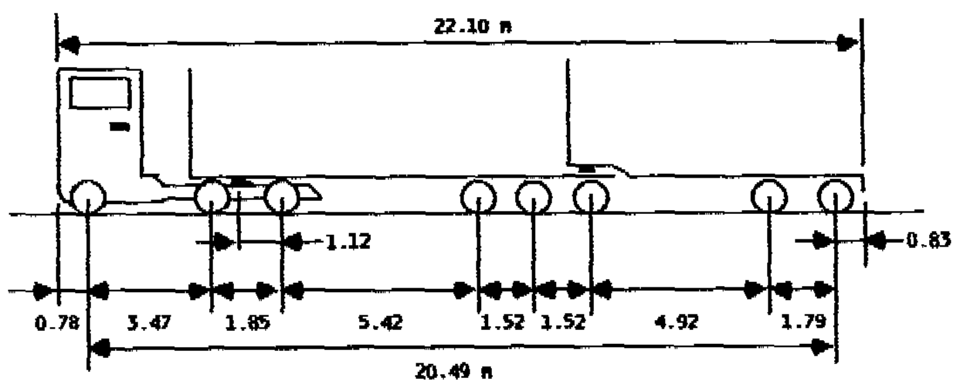


Figure 2/ Vehicle Dimensions

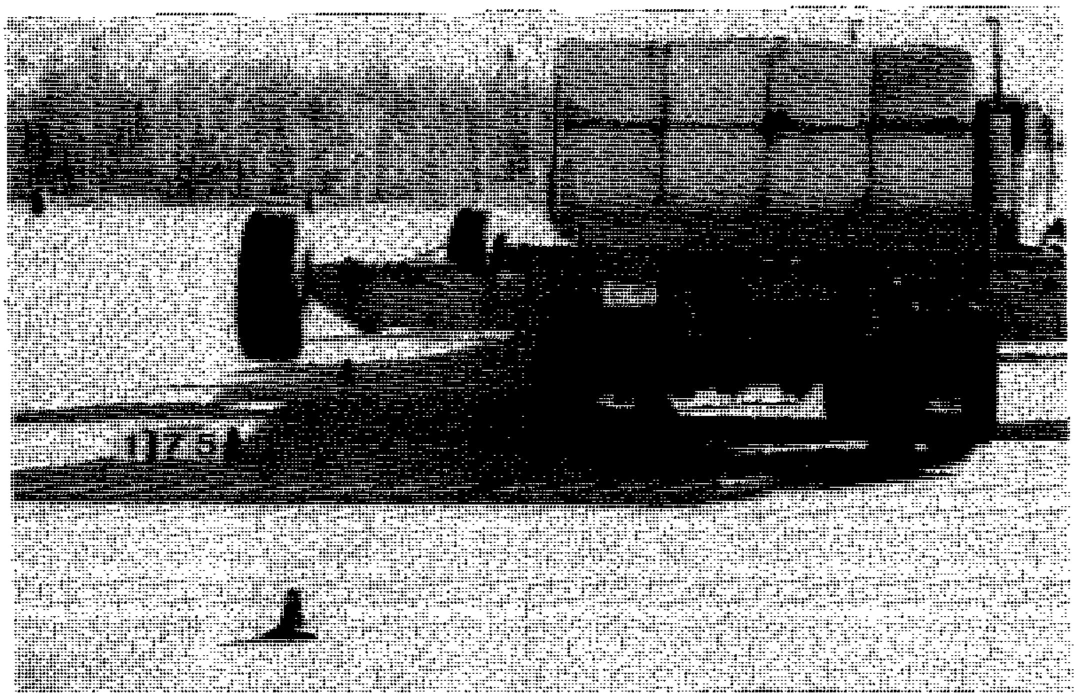


Figure 3/ Clockwise Offtracking

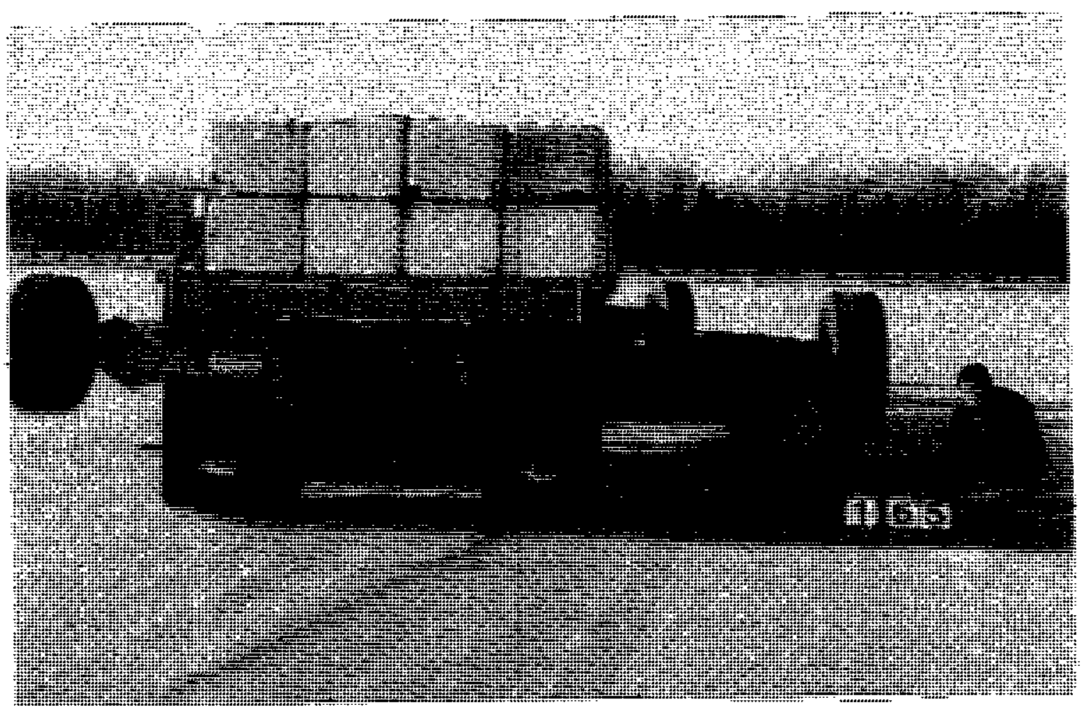
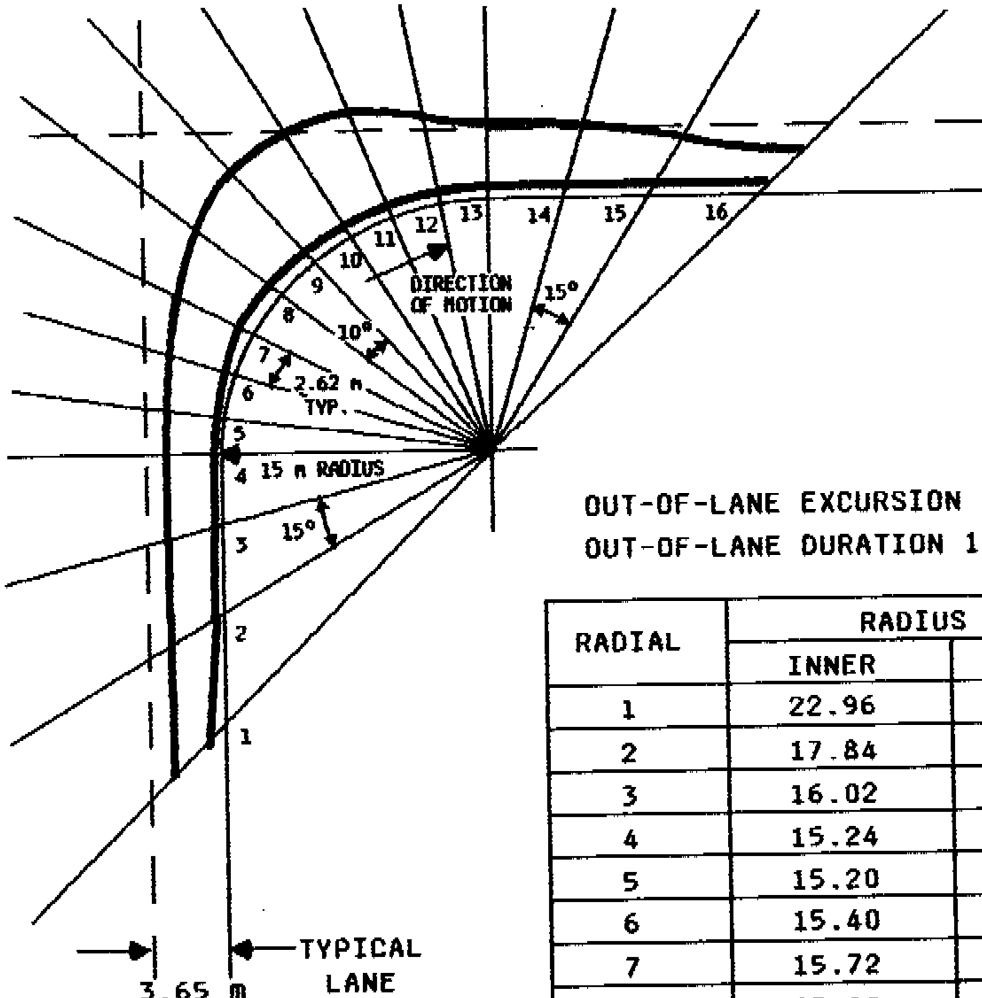


Figure 4/ Counter-Clockwise Final Offtracking



OUT-OF-LANE EXCURSION 0.9 m
OUT-OF-LANE DURATION 18 m

RADIAL	RADIUS (m)	
	INNER	OUTER
1	22.96	25.36
2	17.84	20.58
3	16.02	18.46
4	15.24	17.76
5	15.20	18.04
6	15.40	18.70
7	15.72	19.69
8	15.80	20.62
9	15.64	21.65
10	15.40	21.71
11	15.26	21.15
12	15.25	19.82
13	15.36	19.13
14	16.13	19.85
15	17.95	20.91
16	21.69	24.55

Figure 5/ Right-Hand Turn Swept Path

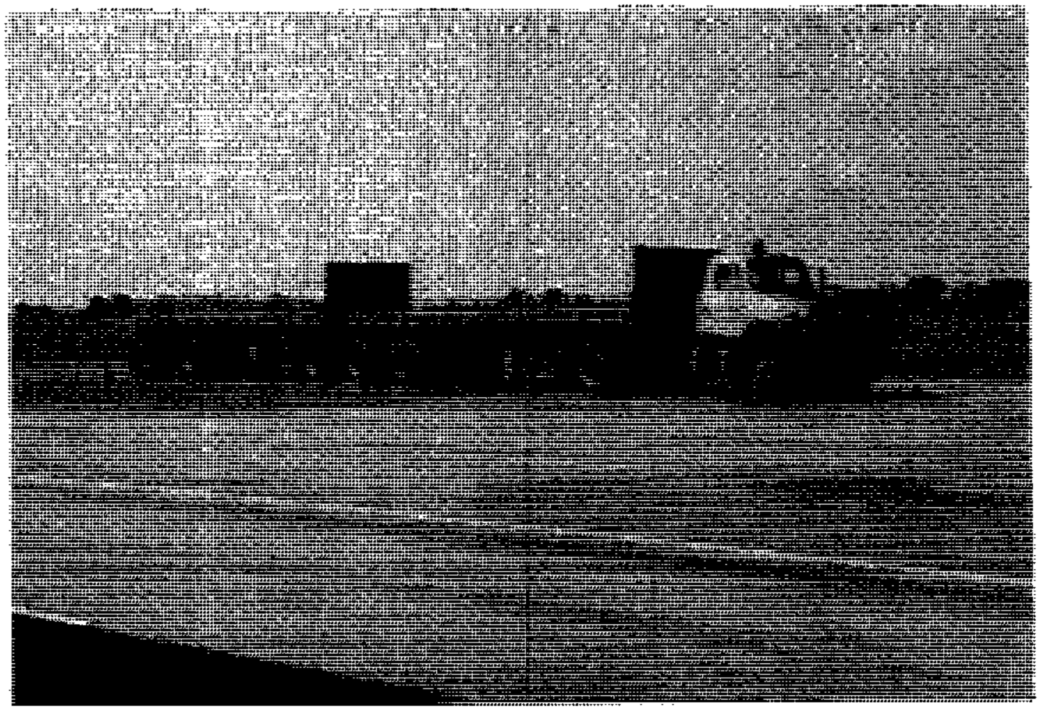
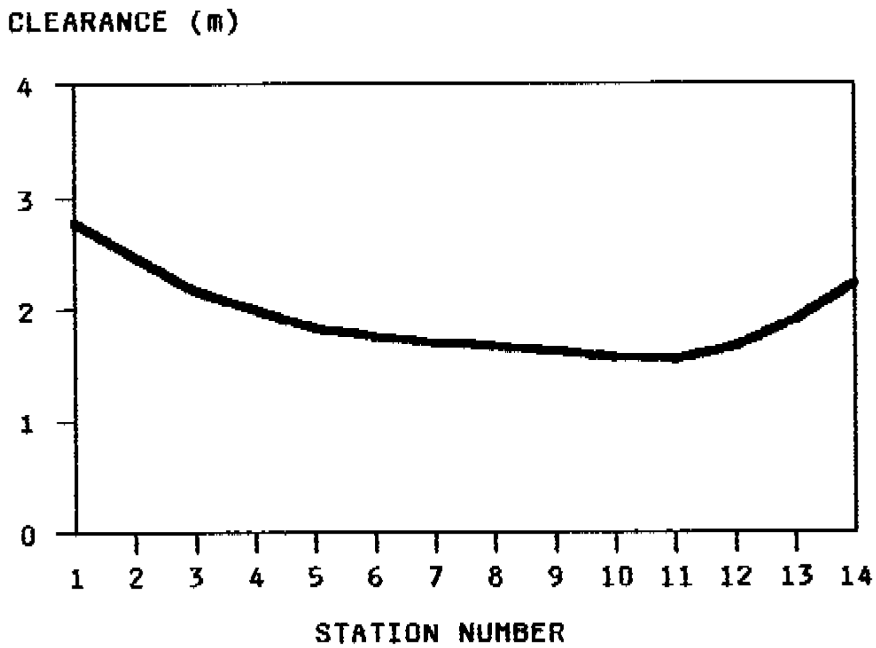


Figure 6/ Right-Hand Turn

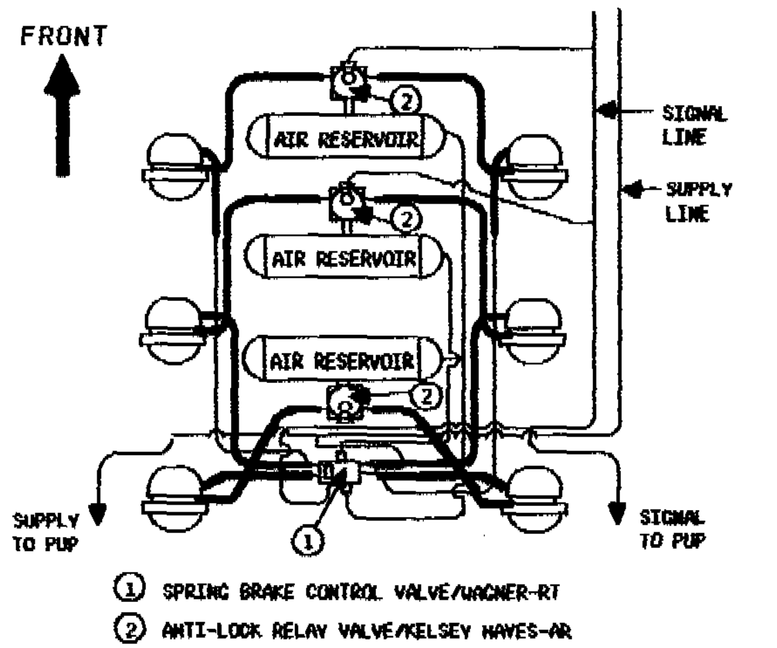
Figure 7/ Channelized Right Turn



STATION NUMBER	CLEARANCE (m)
1	2.79
2	2.48
3	2.18
4	2.00
5	1.85
6	1.76
7	1.69
8	1.68
9	1.62
10	1.57
11	1.55 *(LOW)
12	1.68
13	1.91
14	2.25

Figure 8/ Channelized Right Turn
Clearance from Inner Curb

FIRST TRAILER



SECOND TRAILER

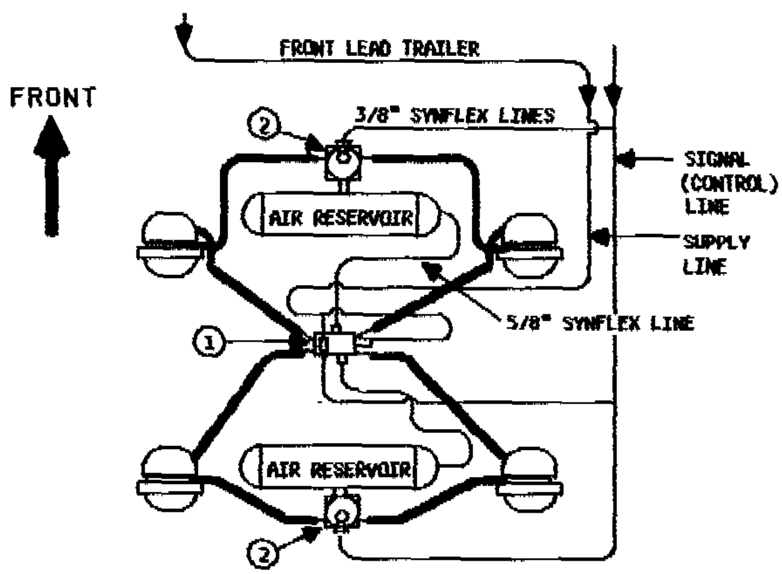


Figure 9/ Air Brake System Schematic

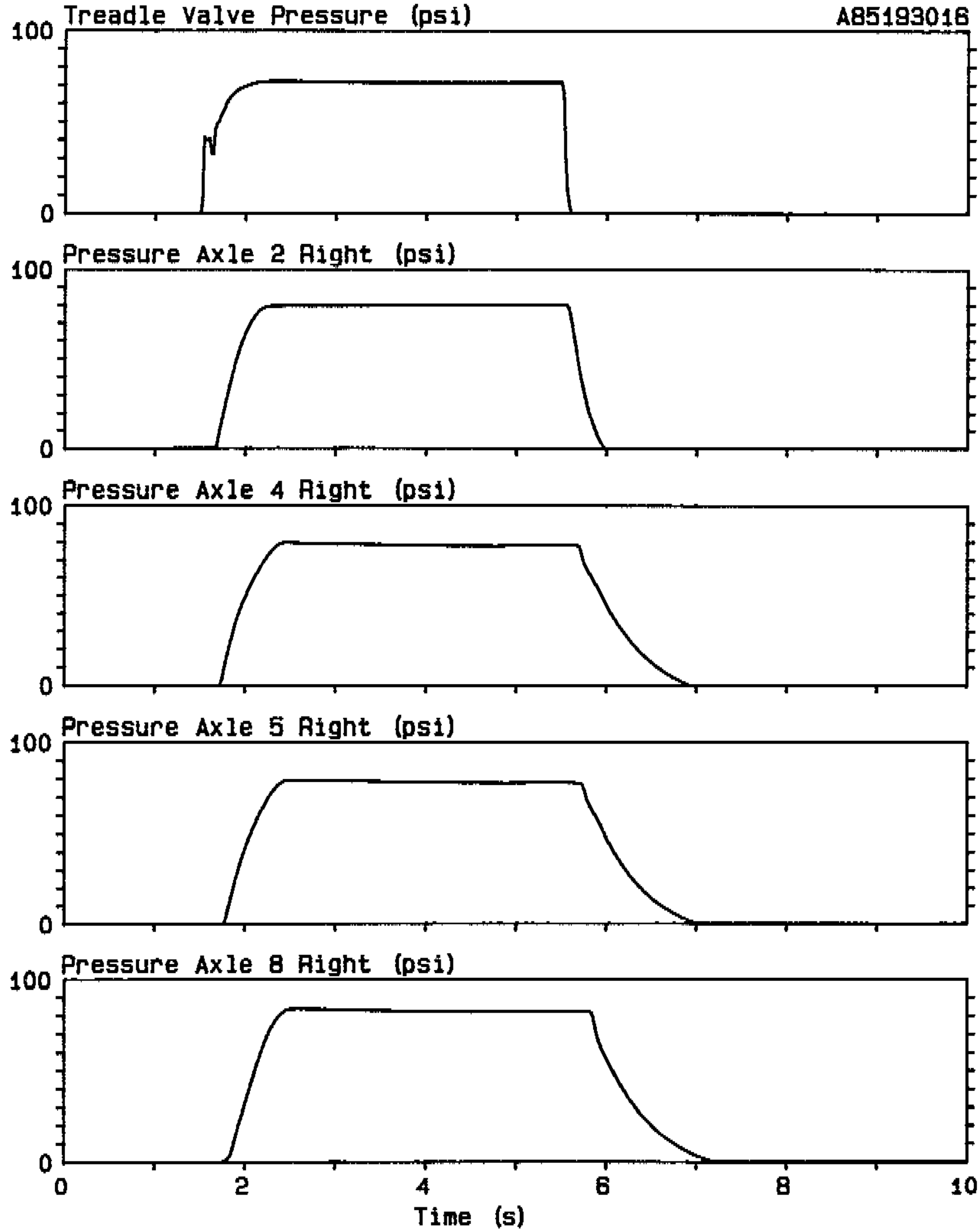


Figure 10/ Air Brake Application and Release

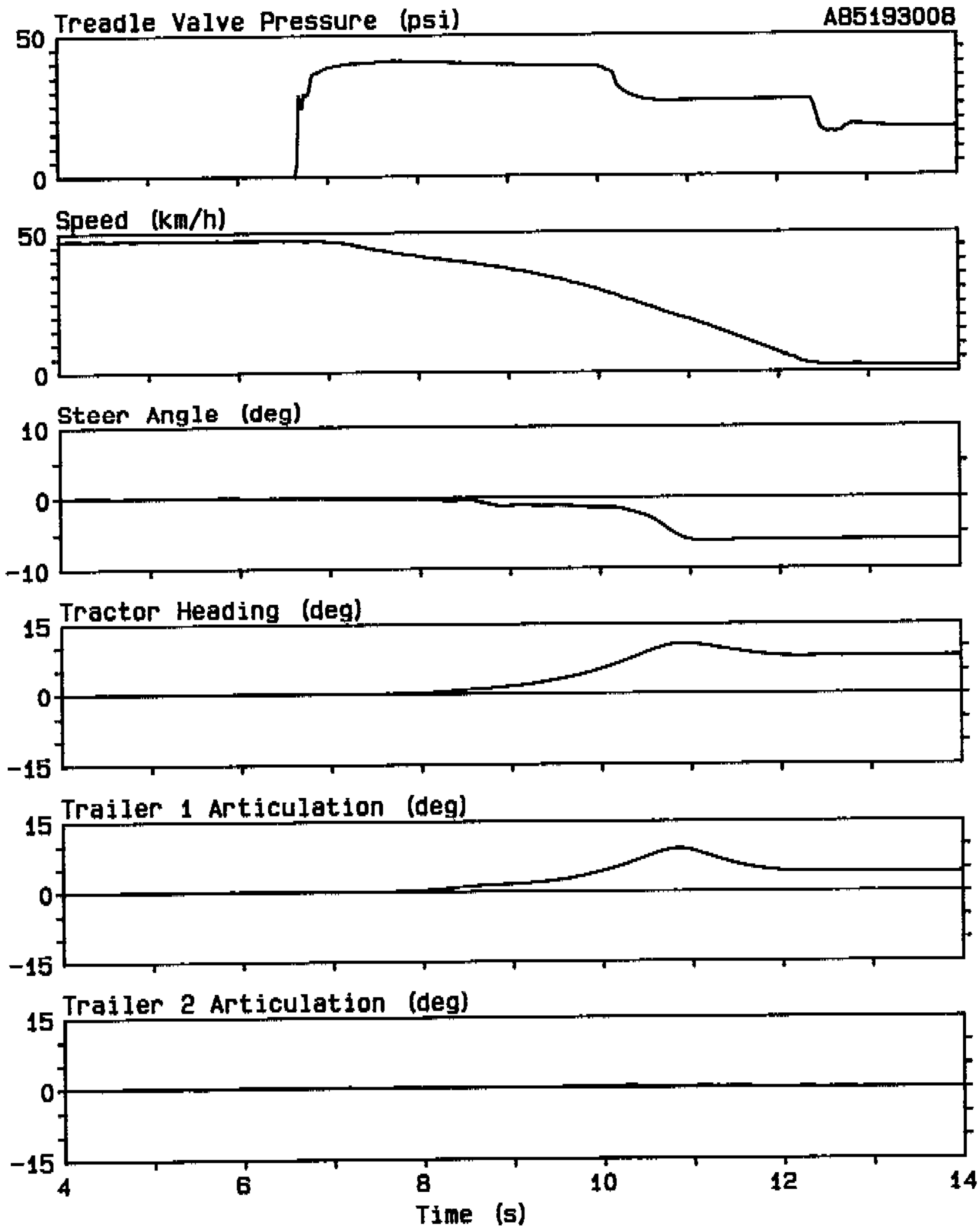


Figure 11/ Vehicle Response to Straight-Line Braking

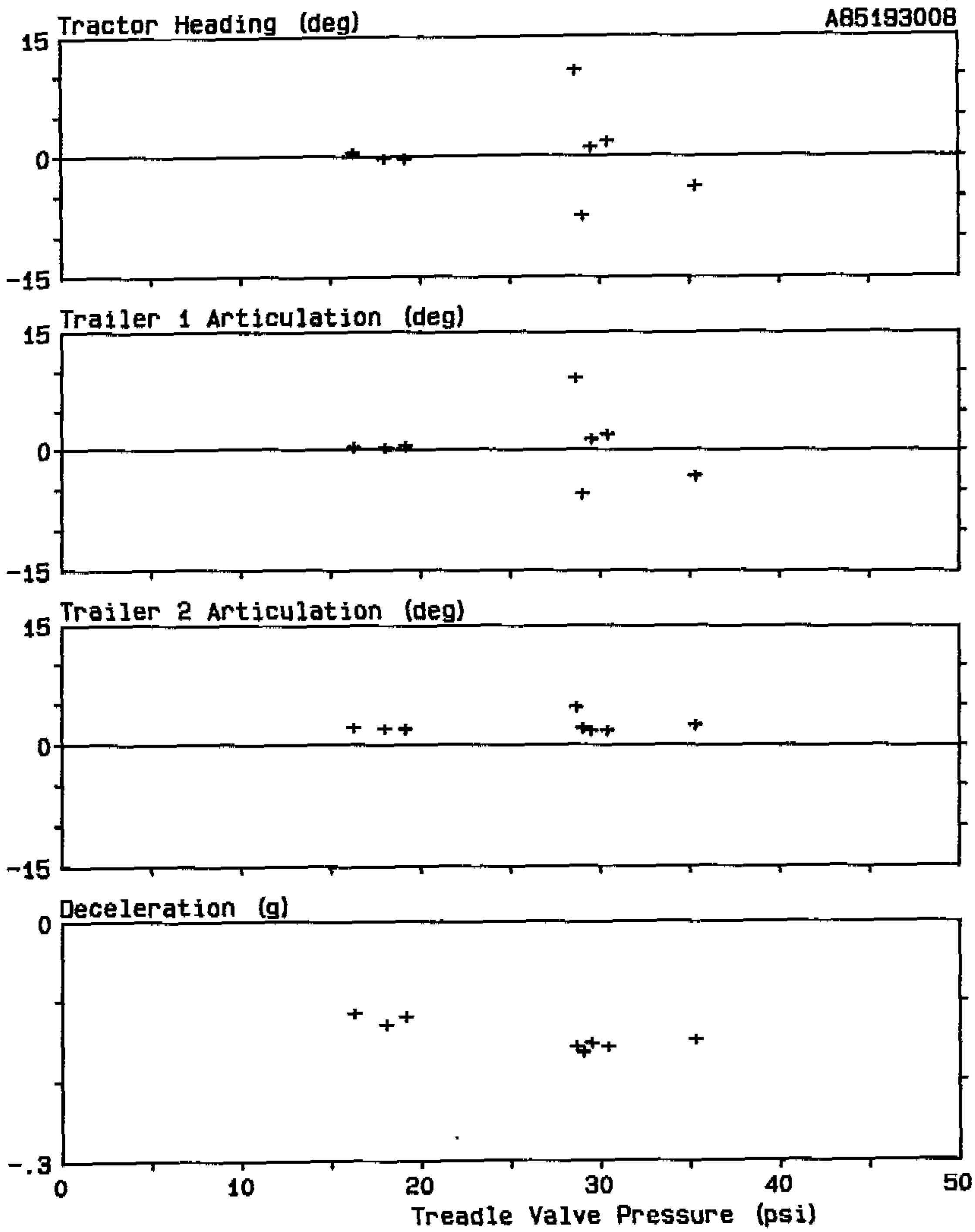


Figure 12/ Straight-Line Braking Responses vs
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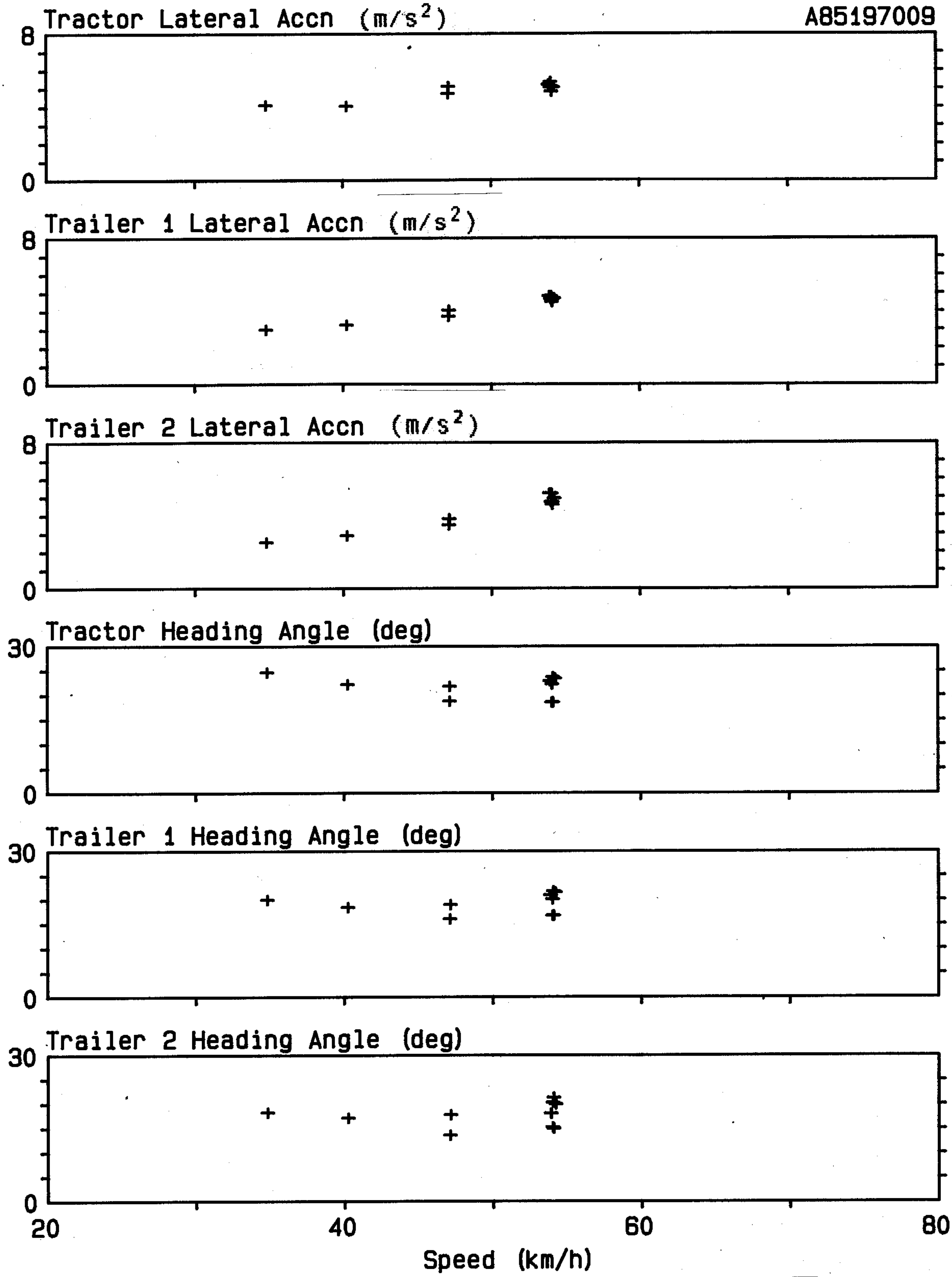


Figure 13/ Evasive Manoeuvre, Peak-to-Peak Responses vs Speed

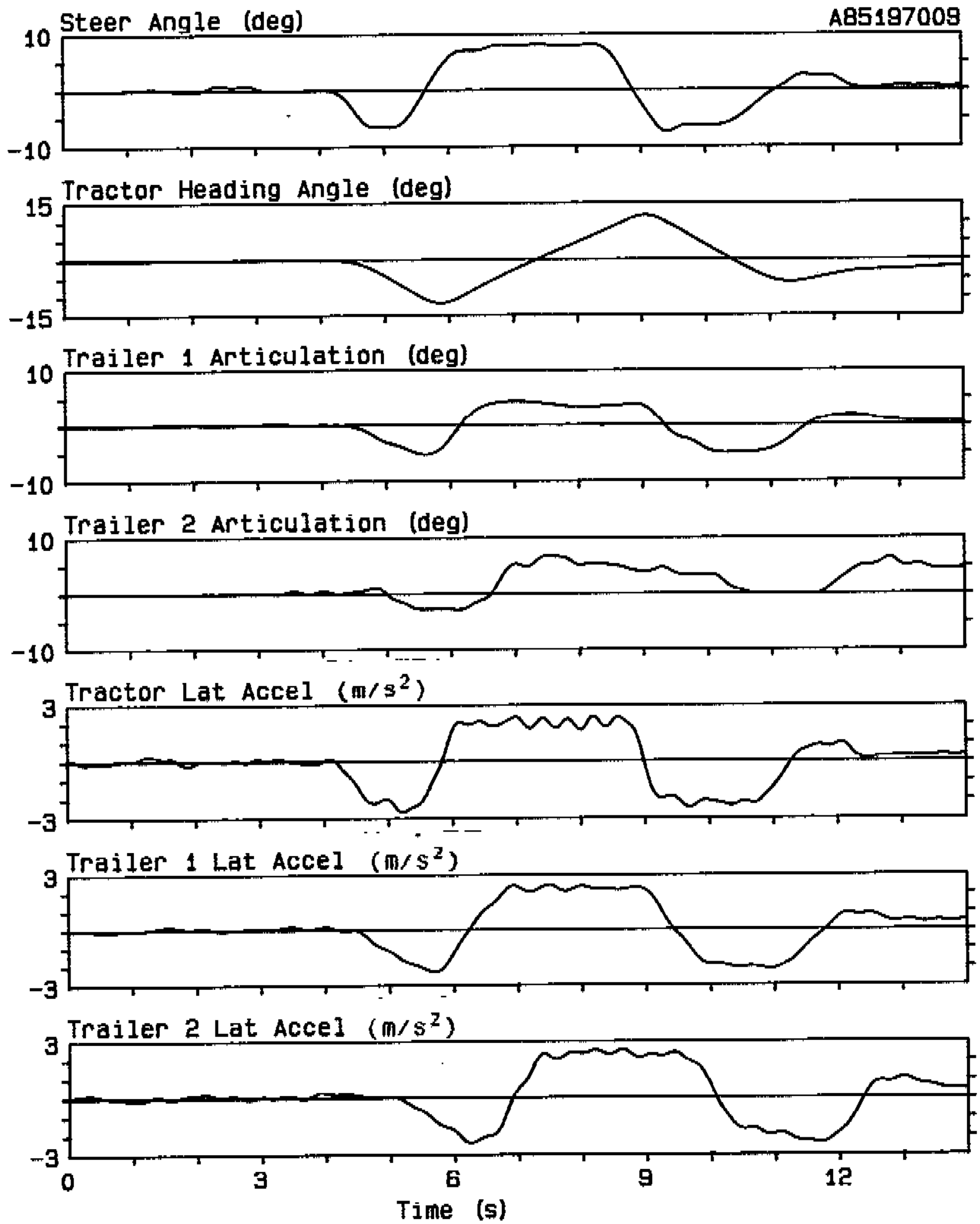


Figure 14/ Vehicle Response in Evasive Manoeuvre

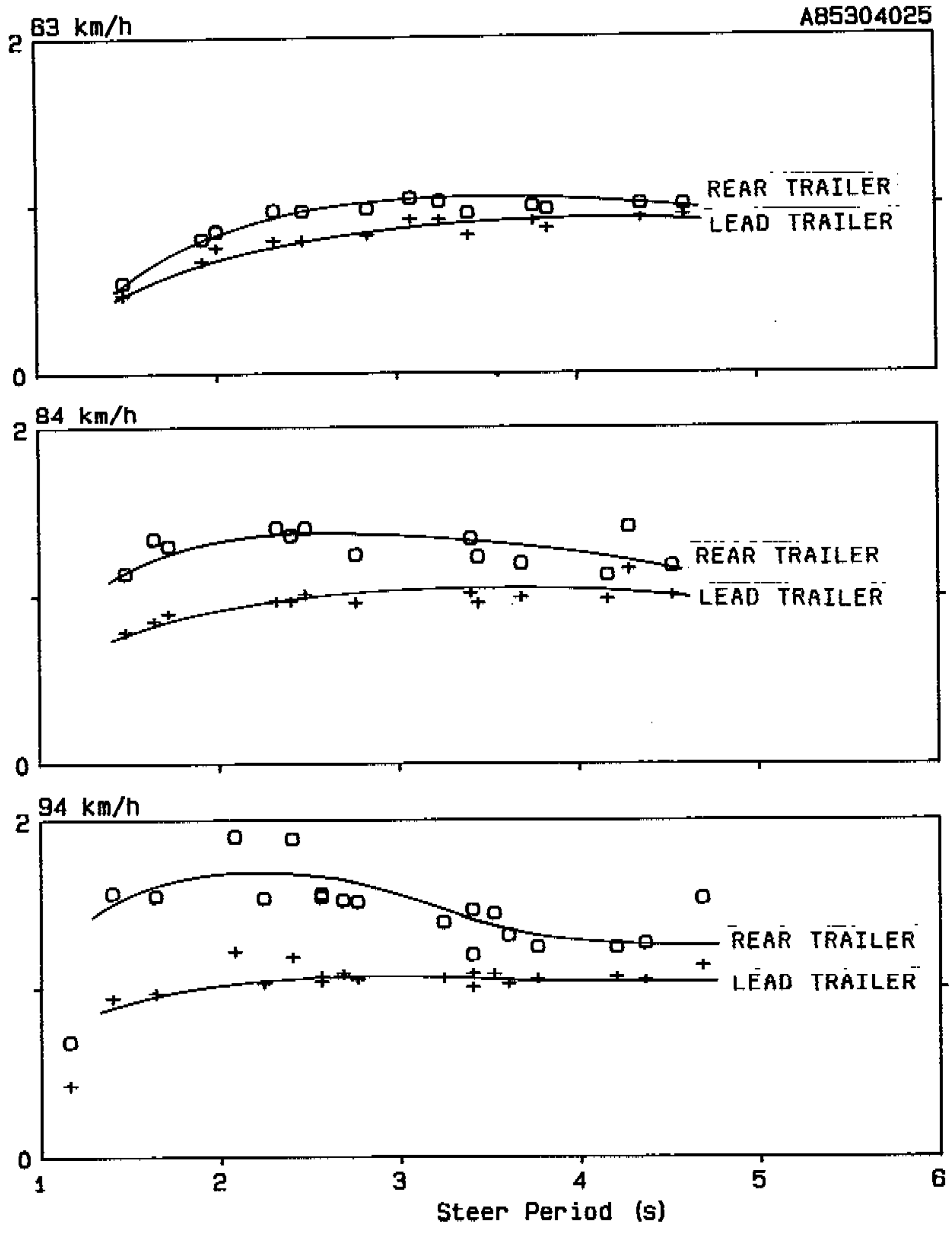
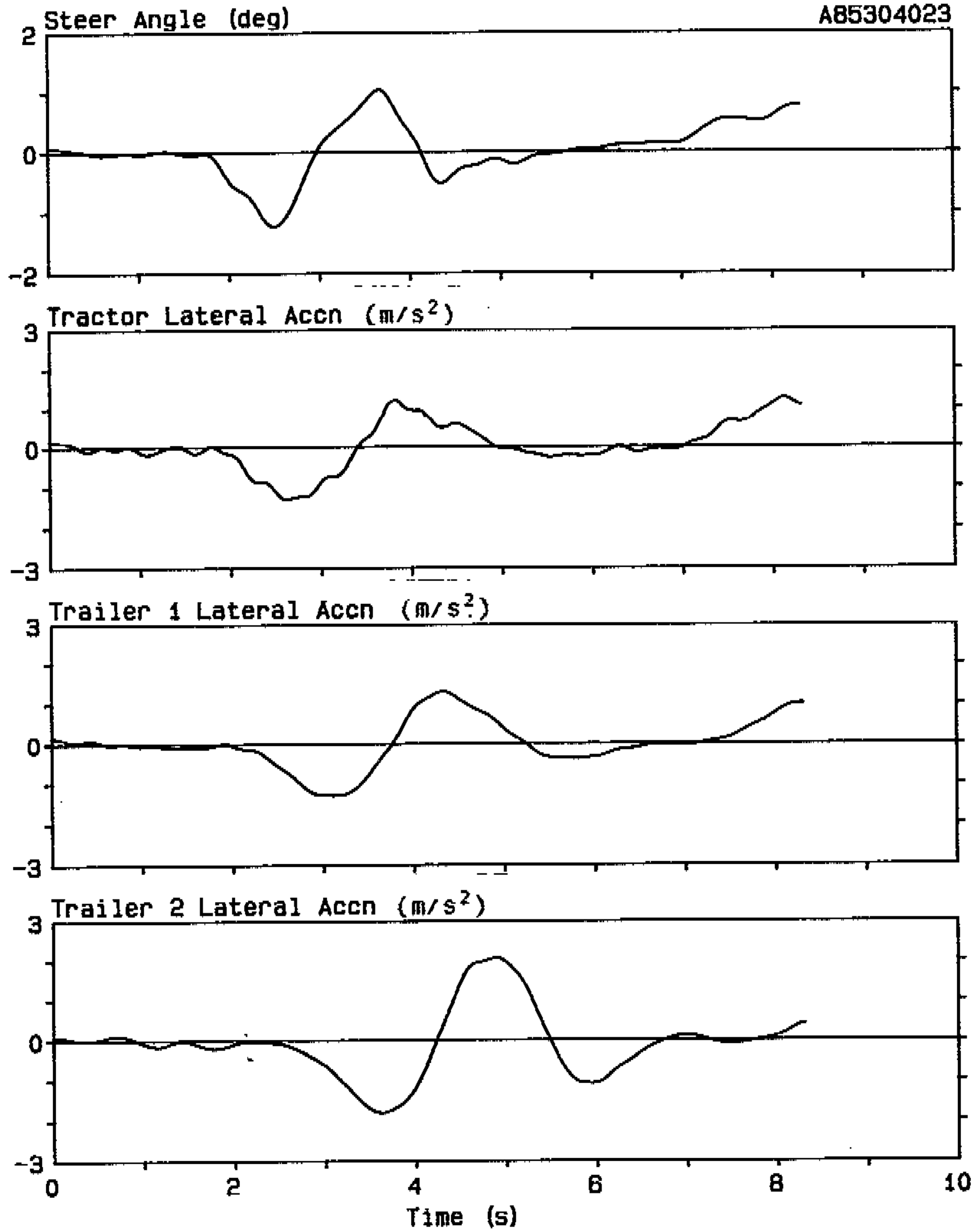


Figure 15/ Rearward Amplification of Lateral Acceleration



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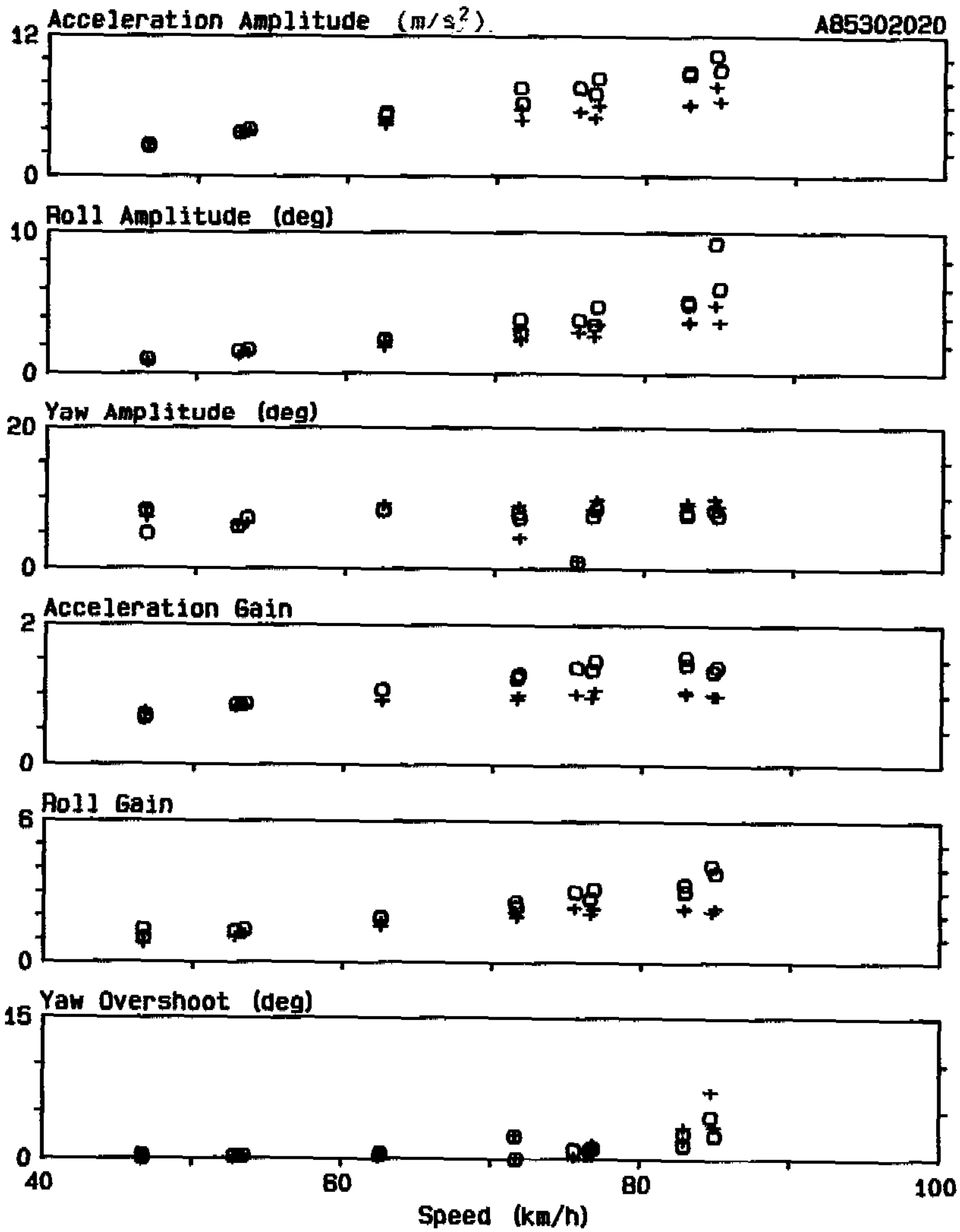

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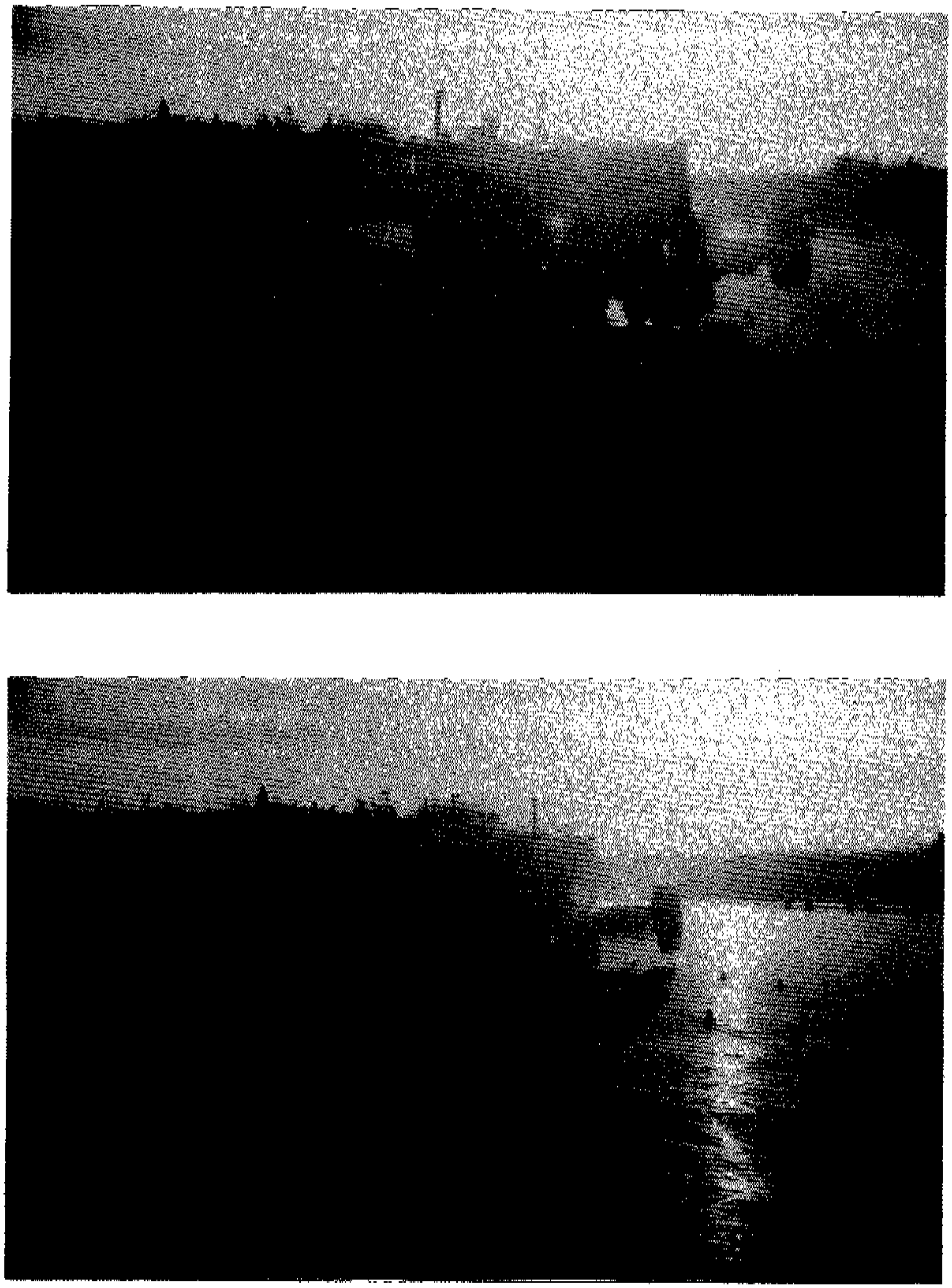


Figure 18/ Vehicle Making Lane Change

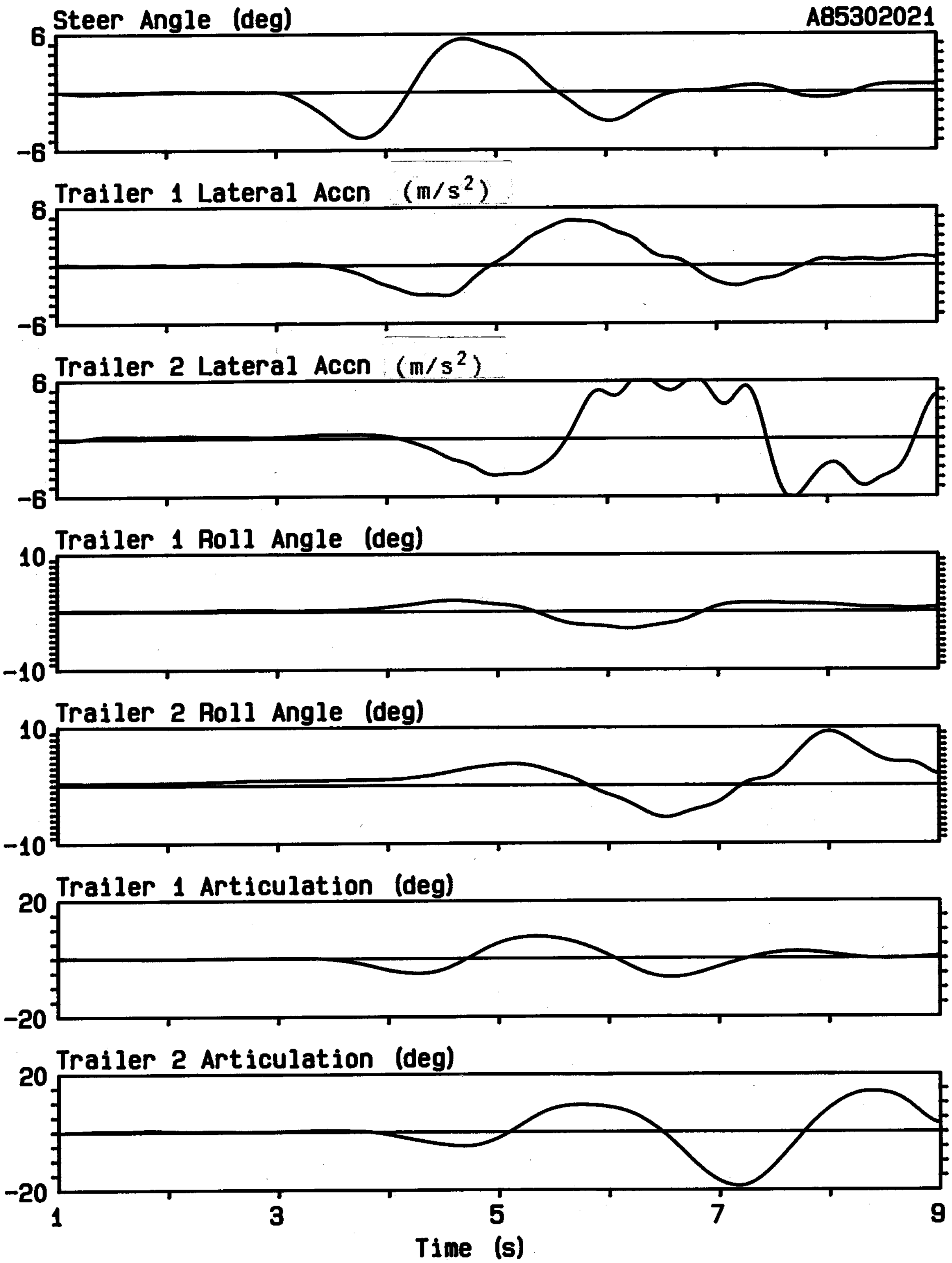


Figure 19/ Lane Change, Vehicle Responses at 85 km/h

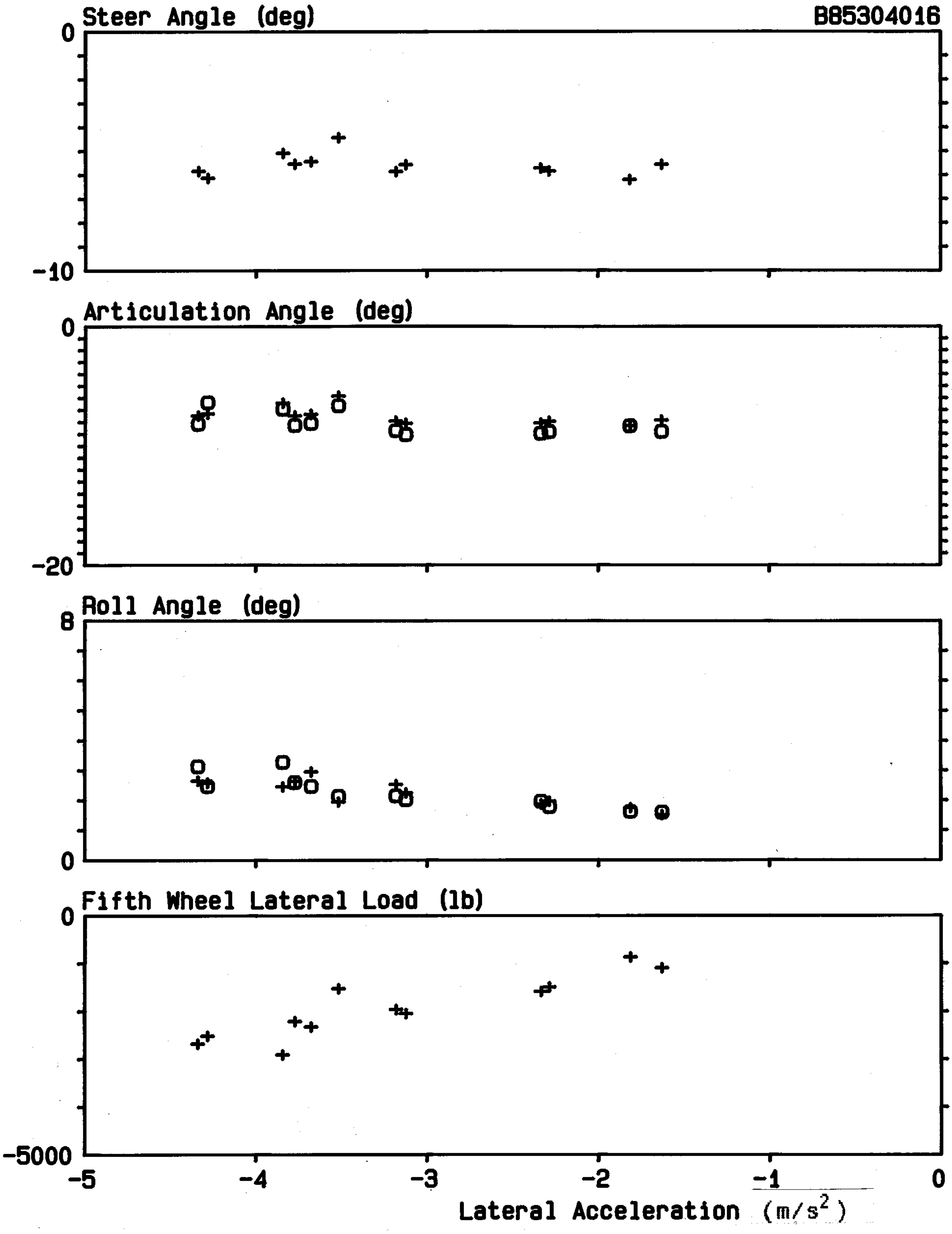
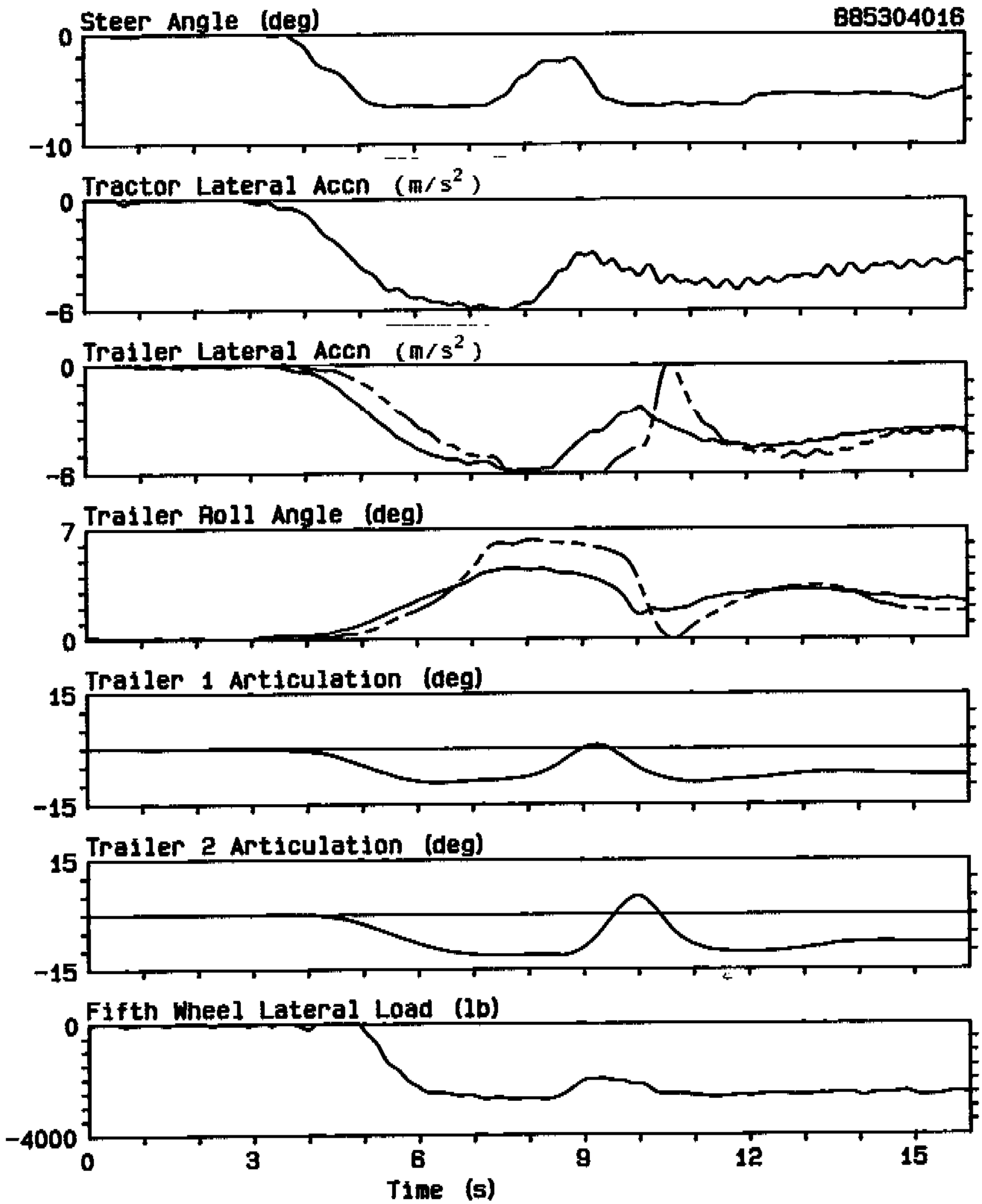


Figure 20/ Steady Circular Turn, Vehicle Responses vs Tractor Lateral Acceleration



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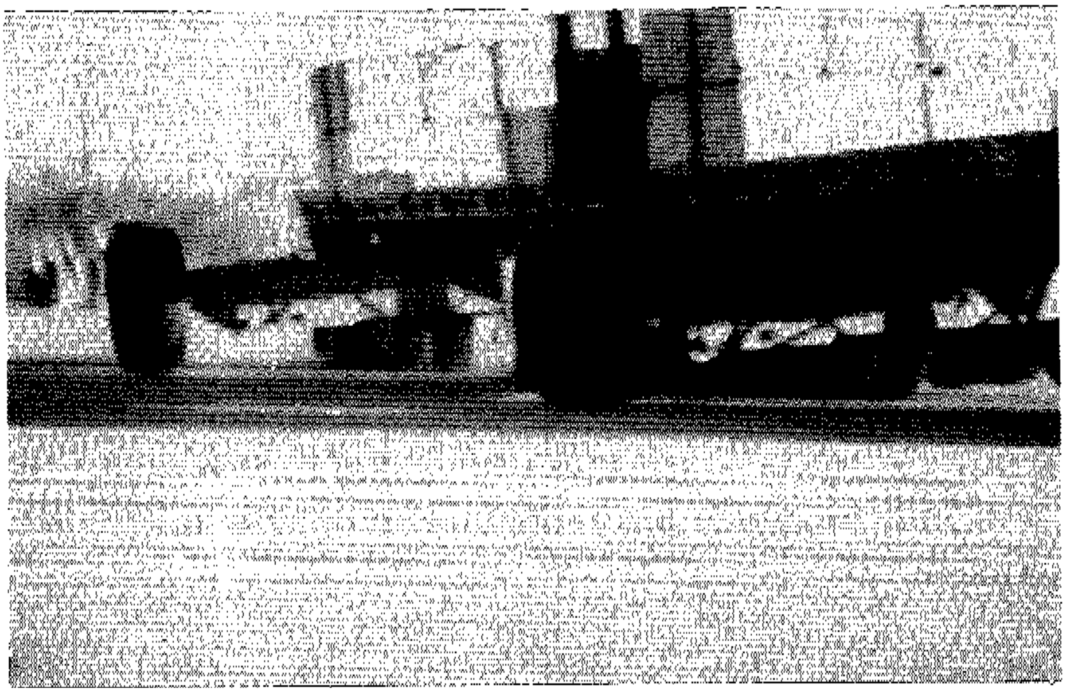

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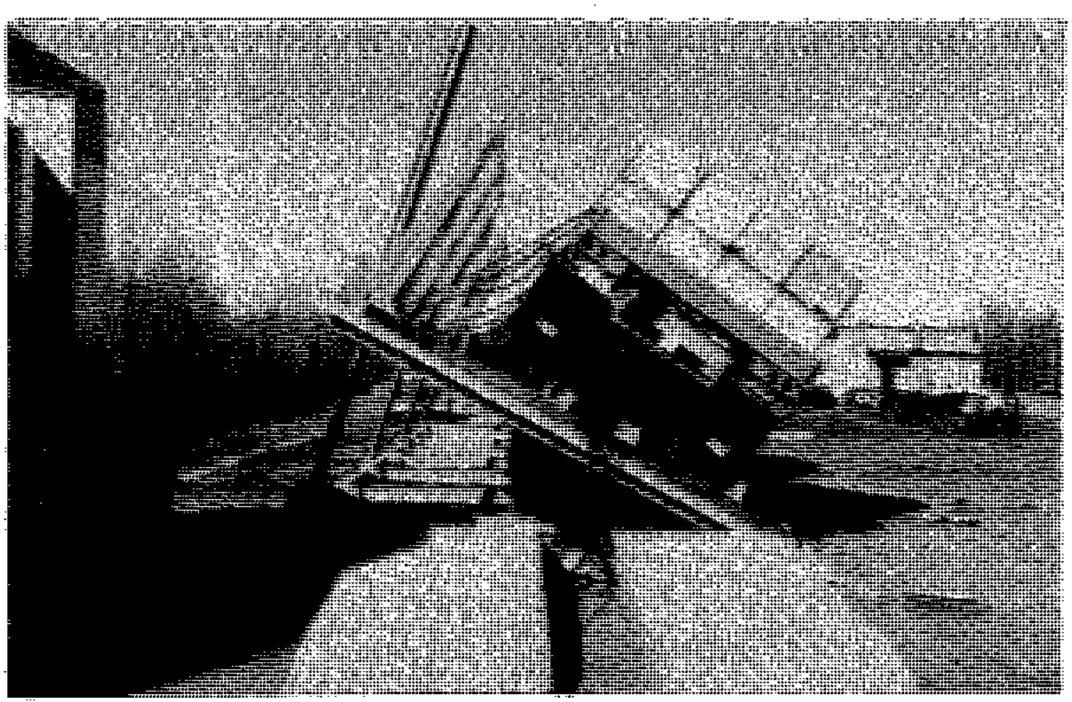

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CV-86-05

Demonstration of
Baseline Vehicle Performance: C-Train Double

J.R. Billing
W. Mercer

Commercial Vehicles Section
Ontario Ministry of Transportation
and Communications

ABSTRACT

A C-train double trailer combination was tested by the Ontario Ministry of Transportation and Communications (MTC) as part of the CCMTA/RTAC Vehicle Weight and Dimensions Study. The vehicle was designated a base-line vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with the empty vehicle on a low-friction surface and the loaded vehicle on a high-friction surface.

This report presents detailed results of the tests and demonstrations.

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ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The trailers were provided by the Roads and Transportation Association of Canada (RTAC). Facilities of the Transport Canada Motor Vehicle Test Centre were made available to the Ministry of Transportation and Communications (MTC). Assistance with vehicle preparation, delivery, and refurbishment was arranged by Mr. Pearson in support of this work.

The work was principally undertaken by the staff of the Automotive Technology and Systems Office of the Transportation Technology and Energy, Branch of MTC: N.R. Carlton; G.B. Giles; C.P. Lam, P.Eng.; W.R. Stephenson, P. Eng.; and M.E. Wolkowicz; and assigned students G. Goertzen, S. Jazic, and D.R. Sykes. Assistance was provided by staff of various other departments of the ministry and other organizations.

The efforts of all involved are hereby acknowledged with gratitude.

1/ INTRODUCTION

The effects of changes in truck weight and dimension parameters on combination vehicle stability and handling and on pavement response to axle group loading are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle portion of the study involved both computer simulation of vehicle dynamic manoeuvres and testing of vehicles and components. Combination vehicles were classified into six families, based on the number of trailers and methods of hitching. A representative of each family was designated as the baseline vehicle configuration for that family. Additional vehicle configurations of interest were also defined. All baseline and additional vehicle configurations were tested to assemble a body of technical and visual data that described the stability and control characteristics of the vehicles with respect to certain performance measures.

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. This report presents the results of a test of a C-train double trailer combination baseline vehicle. It refers frequently to a report describing procedures and equipment common to tests of all nine vehicles undertaken by MTC [1]. Similar reports present details of the tests of the other eight vehicles [2-9], and a summary report presents the results of tests of all six baseline vehicles [10]. A computer simulation of vehicle responses to actual test inputs using estimated vehicle data has also been conducted [11].

2/ TEST VEHICLE DESCRIPTION

The test vehicle consisted of the MTC Freightliner [1] and two tandem-axle flatbed semitrailers with a single-axle B-type converter dolly. The combination is typical of equipment used in all regions of Canada, except the Atlantic provinces, though the C-train configuration is much less common than the A-train. The same combination was also tested concurrently as an A-train, using an A-type converter dolly [3].

The equipment for these tests was provided by the Roads and Transportation Association of Canada (RTAC). No modifications were made to the trailers or dolly except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were affected.

The trailers used were both 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 2.59 m (102 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 dolly was made from the ASTL SSD frame, used in previous tests [12], and a Sauer model RLZ 10041 self-steering axle rated at 10 000 kg (22 000 lb) and placarded for a speed of 80 km/h. Suspension was a Reyco two-spring leaf system with a torque rod. The B-dolly had a spring centre width of 0.76 m (30 in), and the 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 trailers and dolly were fitted with new Michelin XZA radial tires, in load range H and size 11R22.5. These tires were run a nominal distance of 600 km (370 mi) before any testing and were then, subsequently, used for all tests. Tire pressure was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load. This was used for all tests and represents the common operating practice of not reducing tire pressure when running empty.

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 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 1.

Table 1/ Axle Loads

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 empty weight exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. A target axle load of 8000 kg (17 600 lb) was set for all axles except for the steer axle. This was not closely attained. 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.

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.

3/ TEST PROGRAM

3.1/ Test Procedures

The test vehicle was prepared for testing in the following way:

1/ A mechanical inspection was carried out, and any necessary repairs or maintenance was done.
2/ Outrigger and safety cable attachments were installed on the trailers, and safety cable attachments were installed on the dolly.
3/ Outriggers were installed on the trailers.
4/ The boxes containing instrument packages, power supplies and signal conditioning, other instruments, and cabling were installed.
5/ New tires were installed, and pressures were set.
6/ Other fittings necessary for testing were installed.
7/ Concrete blocks were located on the trailer beds to achieve specified axle loads.
8/ Notes were made from detailed physical inspection, including an inventory of components and measurement of dimensions.
9/ The MTC tractor was coupled to the trailers.
10/ The combination vehicle was weighed, empty and loaded.
11/ A functional test of the on-board electronics was conducted.
12/ Test runs were made to shake down the vehicle instrumentation and familiarize the test driver with the vehicle's handling characteristics.
13/ Tires were run a nominal distance of 600 km (370 mi).
14/ Articulation angle between the tractor and lead trailer was calibrated.
15/ Details of the vehicle and test equipment were recorded on photographs and videotape.

The following tests were performed:

- Offtracking
- Right-hand turn
- Channelized right turn
- Air brake system
- Straight-line braking, empty vehicle, low-friction surface
- Evasive manoeuvre, empty vehicle, low-friction surface
- Sinusoidal steer, loaded vehicle, high-friction surface
- Lane change, loaded vehicle, high-friction surface
- Normal straight-line driving
- Steady circular turn, loaded vehicle, high-friction surface

All tests followed standard procedures [1], except as noted.

3.2/ Instrumentation

The instrumentation shown in Table 2 was installed. Brake pressure transducers were only installed in the trailers and dollies for the air brake system test, but all other instrumentation was installed for all tests. Data were always captured from all instrumentation, but only those pertinent to a particular test were analysed.

Tractor instruments were selected from the instrumentation that is permanently installed on the tractor. Instruments for the two trailers were mounted in boxes placed on the trailer deck, which also contained power supplies and signal conditioning. Trailer lateral acceleration and roll angle were measured at a point midway between the kingpin and axle.

Full details of the instrumentation, signal conditioning, and data capture system are presented elsewhere [1].

3.3/ Data Capture and Data Processing

Data were digitized on board the vehicle and transmitted by telemetry as a pulse-code modulated (PCM) data stream to a ground station, where they were recorded on magnetic tape and captured in real time by an HP-1000 computer system. Test data for a run were processed immediately after the run, and results from a series of runs were subsequently analysed using the computer system [1].

Many test runs of all types were conducted for this vehicle. Not all these runs were used in the preparation of this report. In a number of instances, a run failed to meet a test condition.

Table 2/ Instrumentation Installed

No	Measurement	Instrument	Full Scale
1	Tractor steer angle	Spectrol 139 potentiometer	25.02°
2	Tractor roll angle	Humphrey CF18-0907-1 gyroscope package	8.85°
3	Tractor lateral acceleration	Kistler 303B accelerometer	0.957 g
4	Tractor yaw rate	Humphrey RT03-0502-1 angular rate transducer	38.7°/s
5	Tractor longitudinal acceleration	Kistler 303B accelerometer	0.974 g
6	Tractor speed, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	104.8 km/h
7	Tractor distance, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	56.3 m/ramp
8	Tractor fifth wheel load, left-hand side	MTC load cell	9890 lb
9	Tractor fifth wheel load right-hand side	MTC load cell	10290 lb
10	Tractor treadle valve pressure	Celesco PLC-200G	100 psi
11	Tractor brake pressure, axle 2 Left	Celesco PLC-200G	99.80 psi
12	Tractor lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
13	Tractor yaw angle	Humphrey CF18-0907-1 gyroscope package	17.73°
14	Trailer 1 articulation angle	Celesco pull cord DV-301-150	23.194°
15	Trailer 1 lateral acceleration	Columbia SA-107 accelerometer	0.995 g
16	Trailer 1 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.90°
17	Trailer 1 outrigger touchdown	Strain gauge bridge	1.0 V
18	Dolly 1 steer angle	Spectrol 139 potentiometer	25.0°
19	Dolly 1 lateral acceleration	Columbia SA-107 accelerometer	0.996 g
20	Brake pressure, axle 4 right	Celesco PLC-200G	104.96 psi
21	Brake pressure, axle 5 right	Celesco PLC-200G	101.06 psi
22	Brake pressure, axle 6 right	Celesco PLC-200G	102.07 psi
23	Brake pressure, axle 7 right	Celesco PLC-200G	101.93 psi
24	Brake pressure, axle 8 right	Celesco PLC-200G	106.79 psi
25	Spare		
26	Spare		
27	Trailer 2 articulation angle	Spectrol 8409 potentiometer	22.8°
28	Trailer 2 lateral acceleration	Columbia SA-107 accelerometer	0.980 g
29	Trailer 2 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.91°
30	Trailer 2 outrigger touchdown	Strain gauge bridge	1.0 V

4/ RESULTS

4.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions, as shown in Figure 3. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [1].

The results are shown in Table 3. The measured data were averaged for the left and right turn and then compared to data generated by a simple offtracking formula [13]. The difference between actual and computed values, shown in the last column of Table 3, is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

The final offtracking for the counter-clockwise turn is shown in Figure 4. After averaging for both directions and correcting for differences in axle track width, the offtracking of 1.35 m (4.34 ft), shown in Figure 4, became 1.31 m (4.29 ft).

Table 3/ Offtracking

Axle No.	Track Width	Radius to Inner Wheel: Right Turn (m)	Radius to Inner Wheel: Left Turn (m)	Difference (m)	Average (m)	Calculated (m)	Difference %
1	2.31	27.53	27.68	0.15	27.60	27.56	-0.14
2	2.37	27.24	27.30	0.06	27.27	27.21	-0.22
3	2.37	27.23	27.26	0.03	27.25	27.21	-0.15
4	2.37	26.63	26.65	0.01	26.64	26.64	0.00
5	2.37	26.60	26.61	0.01	26.61	26.64	+0.11
6	2.37	26.67	26.67	0.00	26.67	26.86	+0.71
7	2.37	26.20	26.23	0.03	26.22	26.29	+0.27
8	2.37	26.17	26.20	0.03	26.19	26.29	+0.38

4.2/ Right-Hand Turn

A 90° right-hand turn is a very demanding manoeuvre for a large truck. The vehicle's swept path in a 90° right-hand turn of 15 m (49.2 ft)

radius was measured, according to the standard test procedure [1]. This radius is typical in an urban area or where there is limited truck traffic. The swept path is shown in Figure 5.

The vehicle is shown in Figure 6 during the turn. The maximum excursion out of lane was 0.80 m (3.62 ft). It was out of the exit lane for a distance of 8.40 m (27.56 ft), as derived from Figure 5. This test was conducted at a creep speed and represents the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

4.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [1].

The vehicle is shown during the turn in Figure 7. The clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Figure 8 as a function of distance through the curve. The minimum clearance was 1.66 m (5.45 ft) in the 5.5 m (18 ft) wide roadway.

The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. The vehicle easily made it through the channel, with the left front wheel tracking right on the outer curb.

4.4/ Air Brake System

The air brake system of the combination was evaluated according to standard test procedure [1].

The trailer air brake system was inspected. A schematic of the system is shown in Figure 9. The dolly was not equipped with a booster relay valve to speed the signal. All slack adjusters required manual adjustment. Stroke was adjusted to the minimum, about 32 mm (1.25 in) on each axle. The tractor was supplied with shop air, regulated at 689 kPa (100 psi). Pressure transducers were installed at all trailer and dolly axles.

The SAE J982a style test was performed for the full double combination. The results of this test, presented in Table 4, are the average of several tests, each with a time resolution of 0.02 s. The application times of this test were typical of those obtained from tests conducted on other double combinations [14]. The release times are considered long. A typical time history response of application and release for the full double combination is presented in Figure 10.

Table 4/ Air Brake Timing, SAE J982a Style Test

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.03	0.18	98.3
Axle 2	0.43	0.64	97.5
Axle 4	0.54	1.65	93.3
Axle 5	0.53	1.59	95.5
Axle 6	0.85	1.96	94.2
Axle 7	0.83	2.39	94.0
Axle 8	0.83	2.43	94.2

4.5/ Straight-Line Braking

It is difficult to conduct rigorous braking tests and achieve consistent results. A demonstration of modes of instability of the combination vehicle in straight-line braking was, therefore, conducted. A series of runs was made with the empty vehicle approaching the low-friction test area at 47 km/h and the driver braking using the treadle valve. Runs were made using various application pressures, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [1].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit.

The time history of a typical run that resulted in loss of control is shown in Figure 11. The brake application of about 310 kPa (45 psi) caused all braked wheels to lock. The tractor was jackknifing to the left when the driver momentarily released the brakes and steered to the right. Trailer 2 swung to the left but then straightened up as the vehicle came to a stop. The driver managed to arrest the jackknife, but would not have been able to at the higher speed. If the tractor front axle brakes had been used, it is probable the tractor would not have jackknifed at this speed.

A summary of peak vehicle responses from the runs is shown in Figure 12, as a function of average treadle valve pressure. The limit of surface adhesion of about 0.15 g was reached at a brake pressure of about 173 kPa (25 psi), and the tractor started to jackknife at a brake pressure of about 290 kPa (42 psi).

4.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. Gates of 22.5 m (73.8 ft) were used for the lane change to the left and the return to the original lane, separated by 20 m (65.6 ft) in the left lane. The runs were made in accordance with the standard test procedure [1].

The vehicle combination was evaluated primarily in terms of the lateral acceleration and yaw responses of the vehicle units. These are shown in Figure 13. Each response is the peak-to-peak amplitude experienced by the vehicle in the manoeuvre. The lateral acceleration for all three vehicle units tended to increase with speed. The vehicle maintained stability up to approximately 63 km/h, at which point the tractor was unable to maintain, consistently, a trajectory through the course. No higher speed was attempted. Tractor steer input remained relatively uniform throughout the speeds tested, indicating some sliding but no serious instability. The driver noted slight "push" of the tractor and tire "howl." There was insufficient sideforce on the low-friction surface to cause any B-dolly steer. From that point of view, therefore, this vehicle was behaving as a B-train in this manoeuvre.

A typical run at 63 km/h is shown in Figure 14.

4.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for this combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 84 and 94 km/h, with steer input periods between about 2 and 5 s. Weather conditions precluded runs at 63 km/h.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. Rearward amplification of lateral acceleration for the two trailers is presented in Figure 15, as a function of tractor steer input period for the two test speeds. This is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless.

It is evident from Figure 15 that rearward amplification increases with speed, rearward by trailer, and is also somewhat sensitive to steer period reaching the highest value of about 1.50 around 2.5 s. The results, as seen in Figure 15, show that, at highway speed, the C-train double is not a very responsive vehicle. The reason for this is that its inherent stability is rather high. Stability and response of mechanical systems have an inverse relationship: high stability means low response to input and vice versa.

Figure 16 shows the response of a typical run for a steer period of about 2.5 s at 94 km/h.

4.8/ Lane Change

The objective of this test was to evaluate vehicle stability characteristics in a dynamic manoeuvre. A series of runs was made where the driver made a lane-change manoeuvre, which is considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [1].

A gate of 30 m (98.4 ft) was used, to provide a vehicle speed of about 80 km/h, which is a typical speed limit and might permit some comparison of the results of this test with those described in the preceding sections.

The results from all runs are summarized in Figure 17. The peak-to-peak lateral acceleration, roll, and yaw (or heading) angles all show an increase as the limiting speed of 94 km/h was reached, at which point the trailers slid to the left about 1 m (3.3 ft) into the adjacent lane. While the trailer did not roll over in this manoeuvre, it undoubtedly would have if its centre of gravity had been higher and, perhaps, at a somewhat lower speed than 95 km/h. The lateral acceleration gains are consistent with the rearward amplification and tend to increase at a moderate rate, as does the roll gain, the largest of each being the rearmost trailer. The yaw overshoot of the trailer clearly illustrates the rear trailer swing at the limiting speed. The vehicle generally tended to slide more than roll, although substantial roll was apparent.

Figure 18 is a time history of a run at 94 km/h, the steer input, and vehicle responses. As can be seen, the vehicle was active in overshoot of both trailers with large roll angles, because of the steer action of the B-dolly.

4.9/ Normal Straight-Line Driving

The objective of this test was to attempt to evaluate lateral motion of the rear trailer of the combination, the phenomenon known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [1].

As previously mentioned, the vehicle was not very responsive, and the slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in little rear trailer sway that was perceptible to the occupants of a chase vehicle. Root mean square (RMS) lateral acceleration of the rear trailer was 1.46 g/° of RMS steer input.

4.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics to determine the high-speed offtracking of the vehicle and examine the side loads exerted on the tractor by the trailers. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The results of this test are summarized in Figure 19. The vehicle combination was evaluated primarily in terms of the roll response of the vehicle units. Average steady-state roll angle is presented as a function of tractor lateral acceleration. At the limiting speed of 61 km/h, a lateral acceleration at 0.54 g, the steer of the B-dolly caused the outrigger of both trailers to touch down, as shown in Figure 20. As Figure 19 shows, roll angles increased with speed. Average steady-state articulation angles decrease modestly with increase in lateral acceleration, and as a consequence, the offtracking decreases. Offtracking was considerably further outward for this vehicle than for the comparable A-train [3]. The lateral force experienced by the tractor fifth wheel, presented as a function of tractor lateral acceleration, shows a gradient of 8.9 kN/g (2000 lb/g).

A tilt test was conducted on this vehicle as part of a separate test program [15]. The vehicle is shown on the tilt table in Figure 21. The high-side wheels of the vehicle lifted at a tilt angle of 28.0°, after all corrections were made, which corresponds to a lateral acceleration of 0.53 g. This is in quite a good agreement with the lateral acceleration of 0.54 g at outrigger touchdown. A full discussion of the tilt test is presented elsewhere [15].

5/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation.

Tests were conducted in various weather conditions. Tires wore progressively as the various tests were conducted. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailers were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal, because of the underslung outriggers.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results. The results presented pertain to the particular vehicle tested, and results different in some respects might be obtained for another vehicle at another time.

This vehicle was considered an easy vehicle to drive by the test driver. The short trailer wheelbase made it easy to manoeuvre in low-speed turns, though high driver effort was required in these and dynamic tests, as the trailer imposed significant forces on the tractor. The driver could feel the trailers pushing the tractor through a manoeuvre once it had started, because the B-dolly did not steer initially, if at all, on the low-friction surface. The vehicle was somewhat less responsive -- more stable -- than the comparable A-train [3]. The driver felt it handled quite well on the highway when returning to Centralia from Blainville in snow and icy road conditions.

6/ CONCLUSIONS

A C-train double trailer combination was tested by the Ontario Ministry of Transportation and Communications, as part of the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with an empty vehicle on a low-friction surface and a loaded vehicle on high-friction surface.

The short trailers and articulation points of this vehicle clearly contributed to the modest space required to make turns.

The air brake system was typical of doubles without a booster relay valve.

The lateral/directional stability of the vehicle was moderate, both empty on a low-friction surface and loaded on a high-friction surface. The roll stability was high, primarily because of the low trailer centre of gravity height. A higher centre of gravity would significantly reduce the roll threshold.

The C-train double configuration is preferable to the A-train double configuration because of its higher stability at highway speeds, as demonstrated in a parallel series of tests.

7/ REFERENCES

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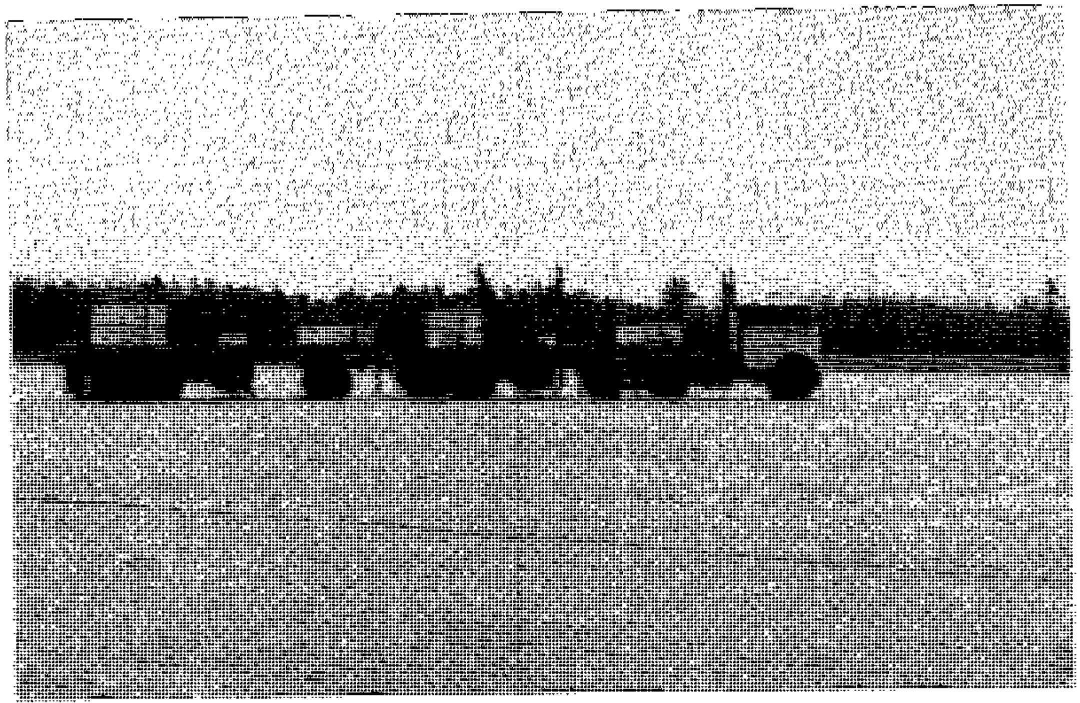


Figure 1/ View of Vehicle

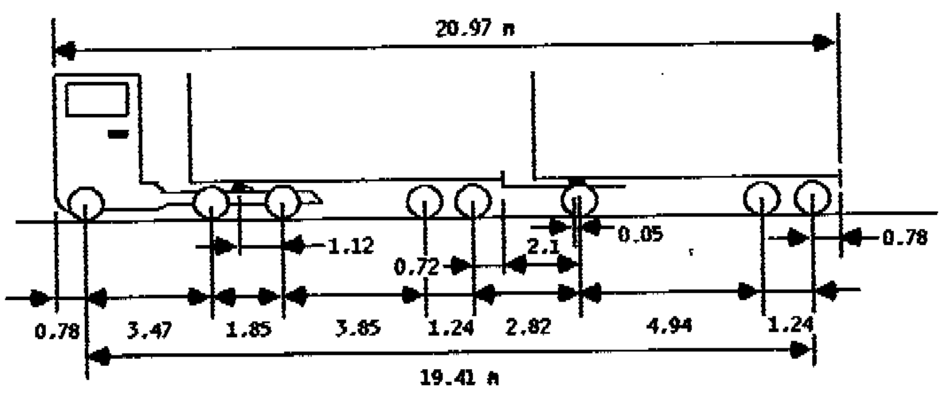


Figure 2/ Vehicle Dimensions

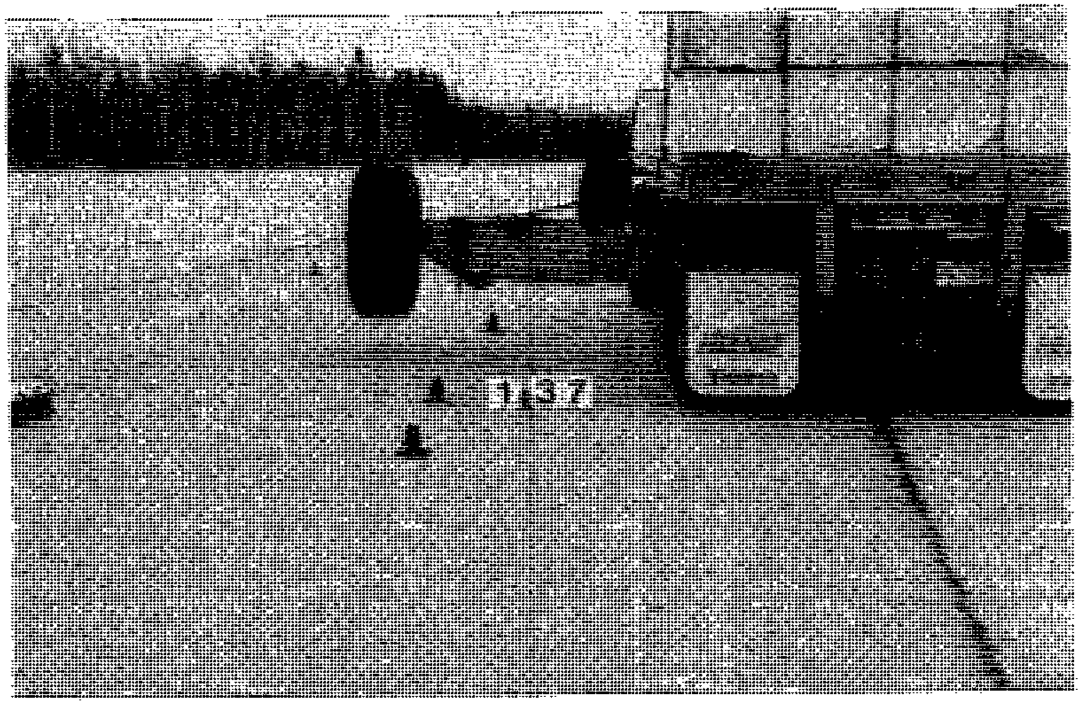


Figure 3/ Clockwise Offtracking

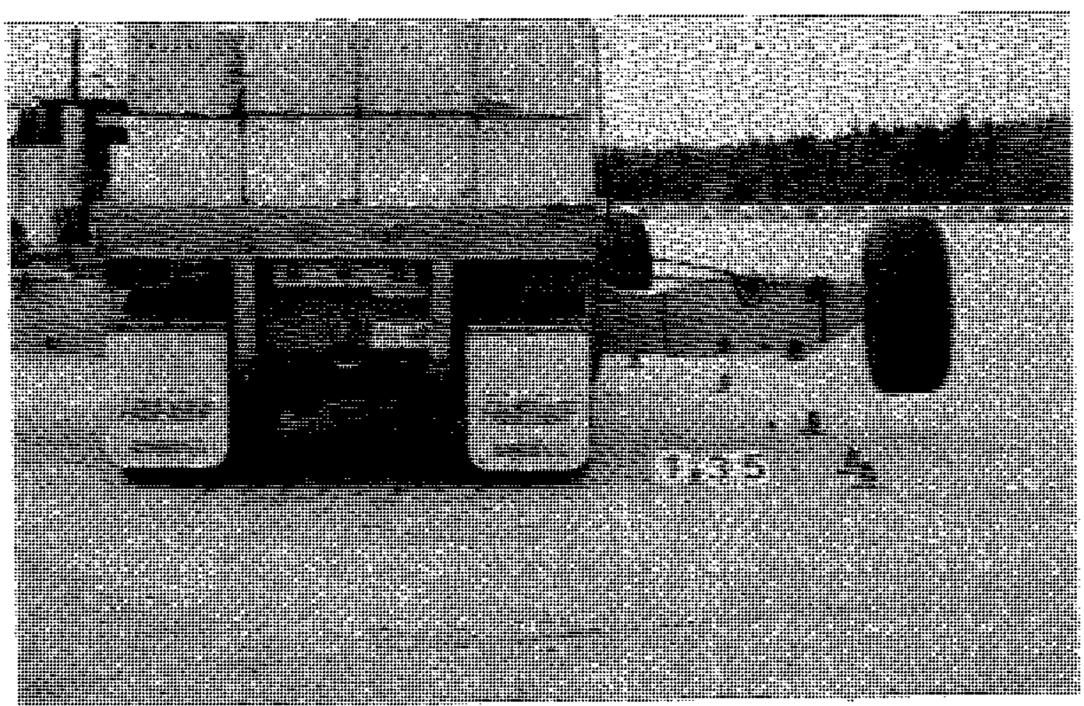
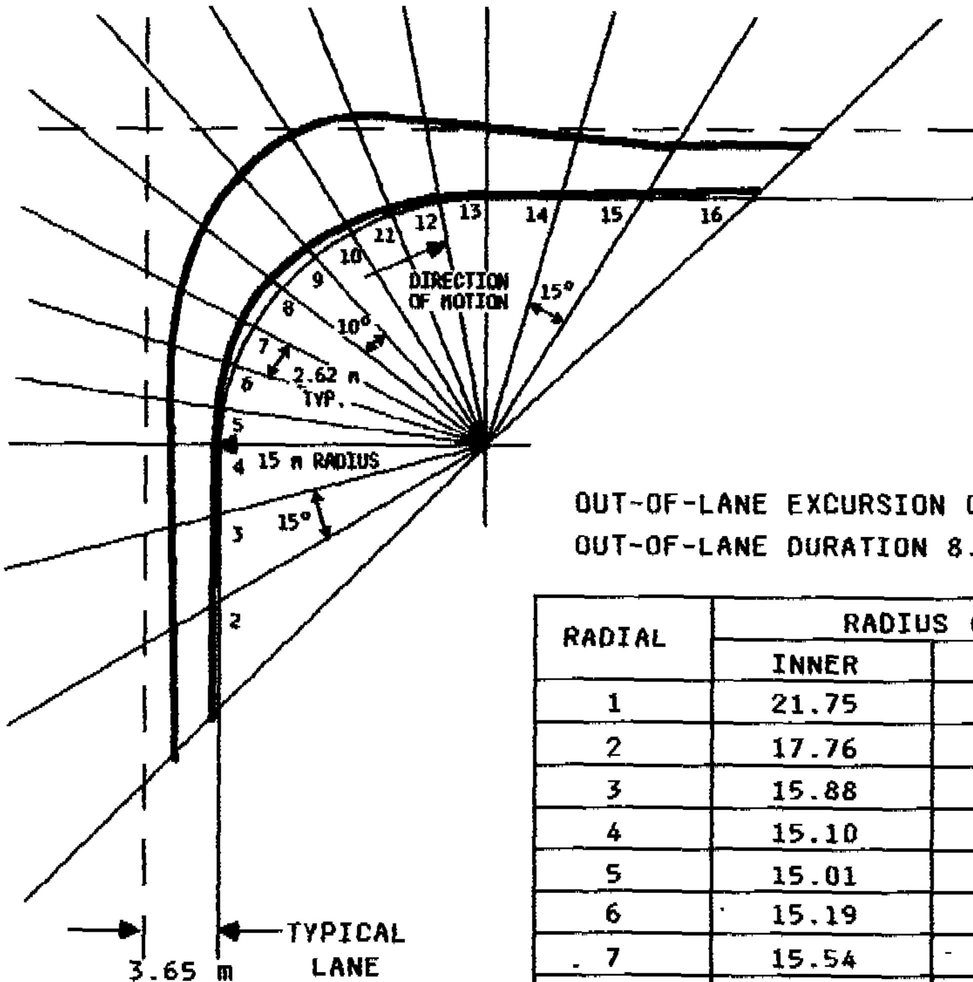


Figure 4/ Counter-Clockwise Final Offtracking



OUT-OF-LANE EXCURSION 0.8 m
OUT-OF-LANE DURATION 8.4 m

RADIAL	RADIUS (m)	
	INNER	OUTER
1	21.75	25.10
2	17.76	20.16
3	15.88	18.21
4	15.10	17.54
5	15.01	17.81
6	15.19	18.58
7	15.54	19.23
8	15.71	20.19
9	15.66	21.17
10	15.34	21.43
11	15.05	20.99
12	15.00	19.45
13	15.00	18.47
14	15.66	18.73
15	17.59	20.05
16	21.50	24.80

Figure 5/ Right-Hand Turn Swept Path

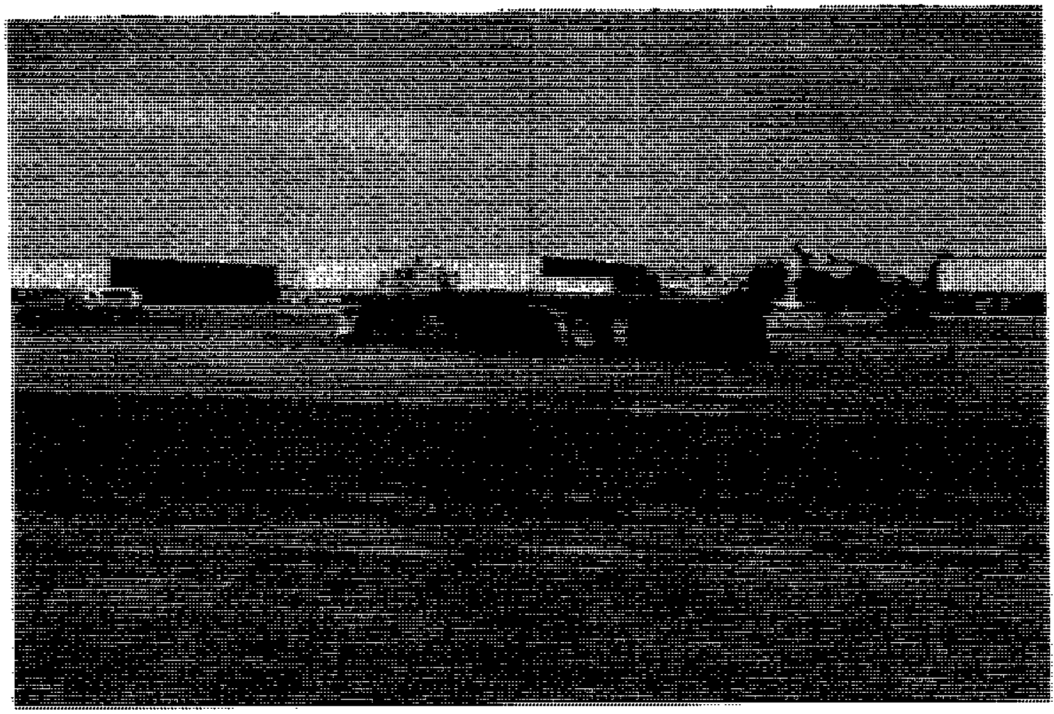


Figure 6/ Right-Hand Turn

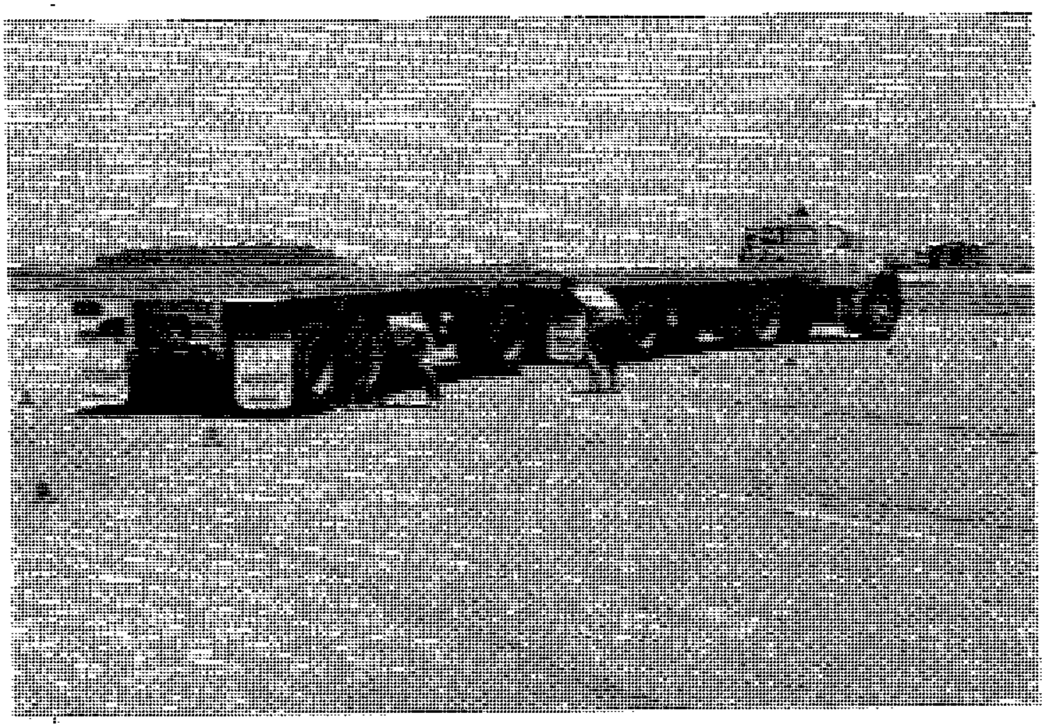
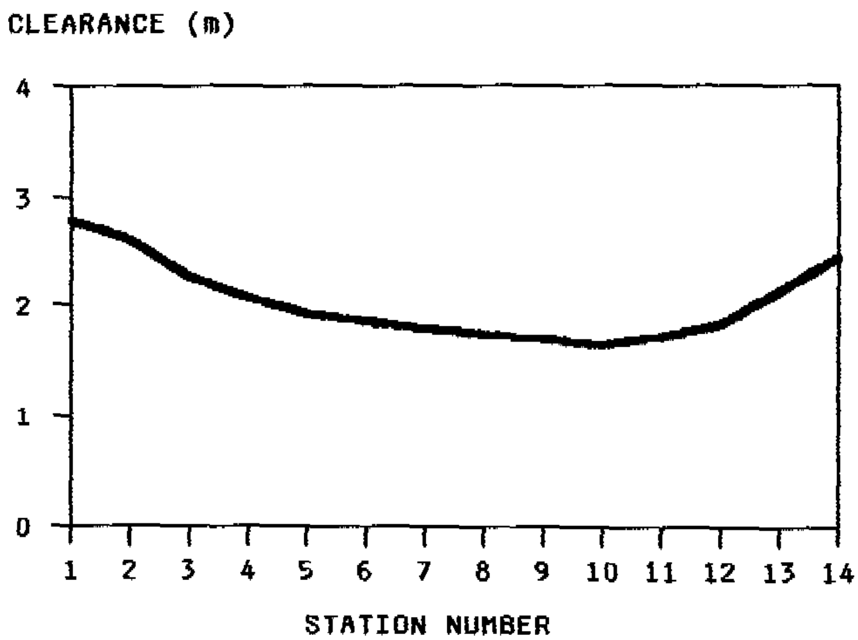


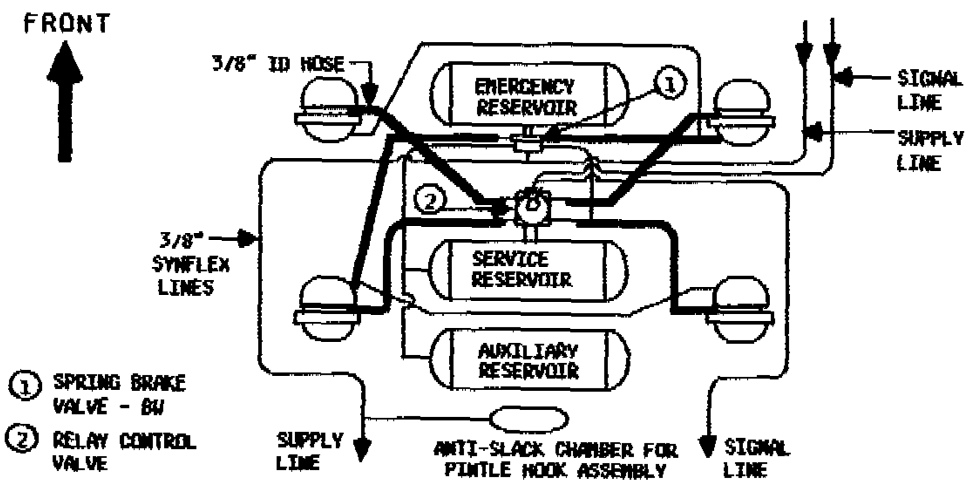
Figure 7/ Channelized Right Turn



STATION NUMBER	CLEARANCE (m)
1	2.78
2	2.62
3	2.26
4	2.08
5	1.94
6	1.86
7	1.79
8	1.75
9	1.69
10	1.66 *(LOW)
11	1.71
12	1.85
13	2.15
14	2.45

Figure 8/ Channelized Right Turn
Clearance from Inner Curb

DOUBLE TRAILER (LEAD AND PUP)



B-DOLLY

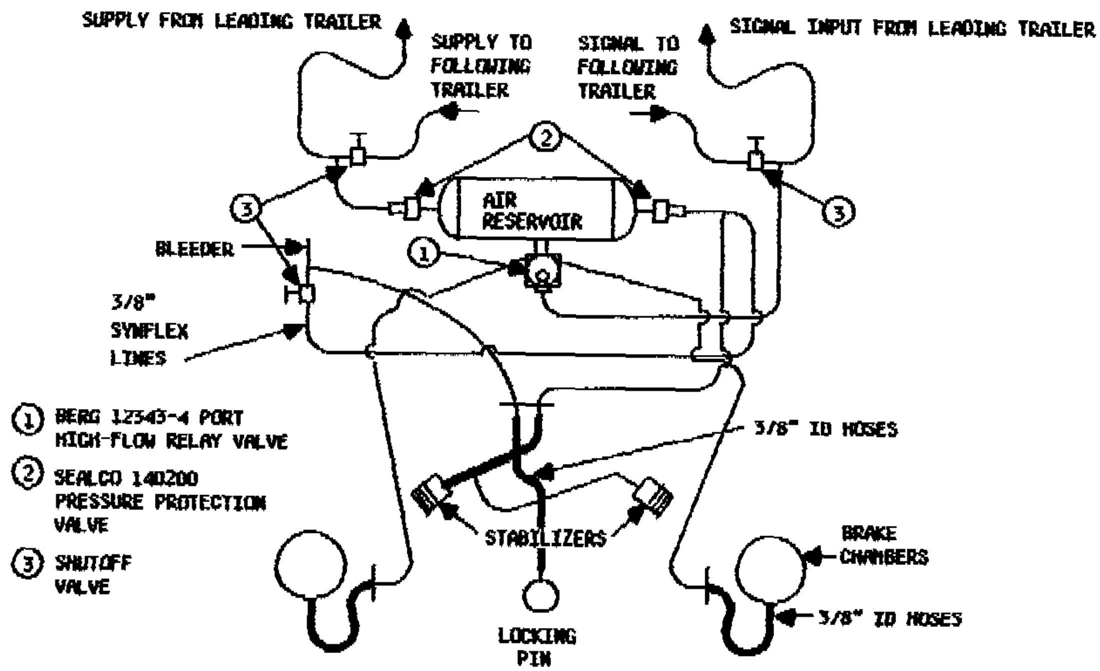


Figure 9/ Trailers and Dolly,
Air Brake System Schematic

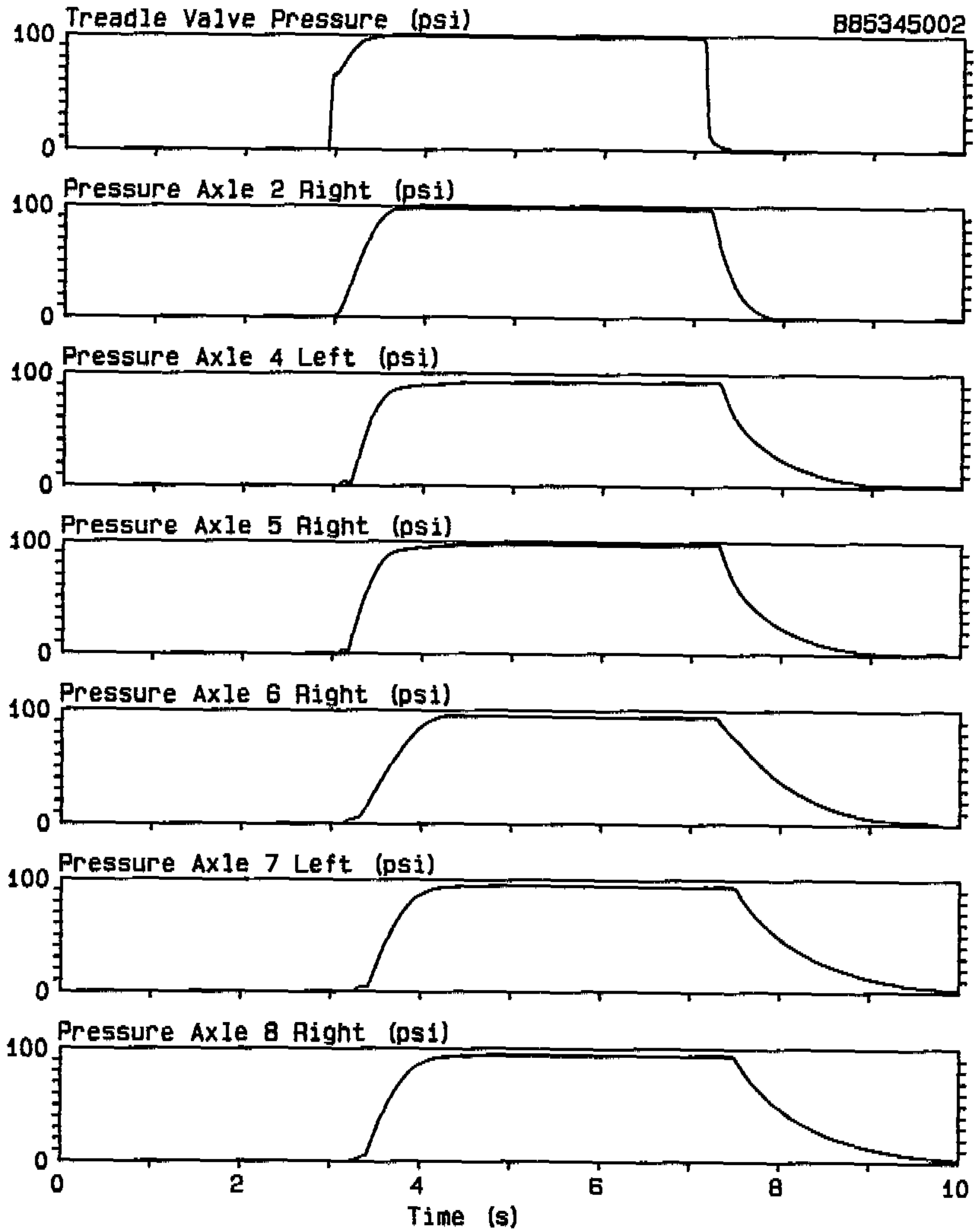


Figure 10/ Air Brake Application and Release

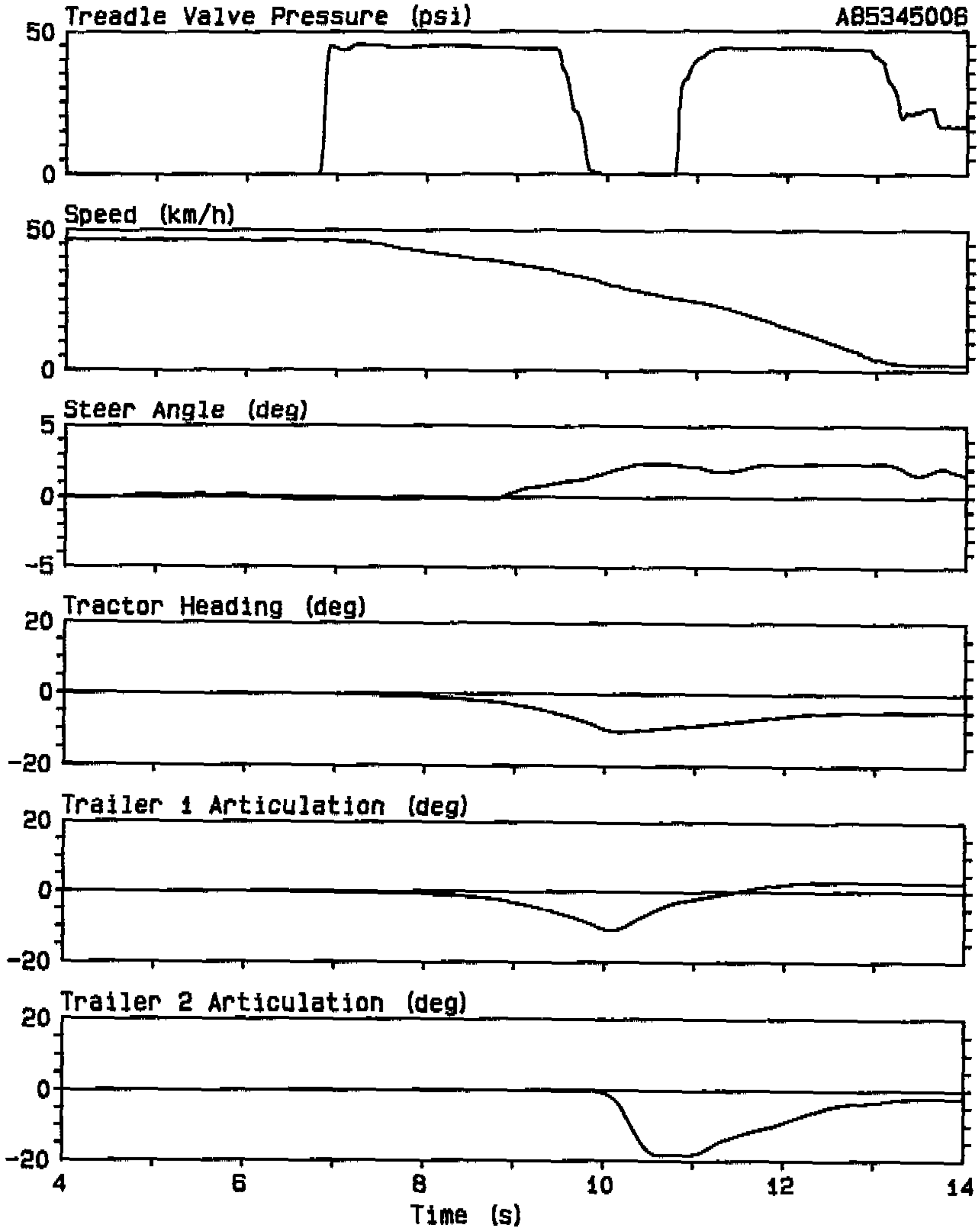


Figure 11/ Vehicle Response to Straight-Line Braking

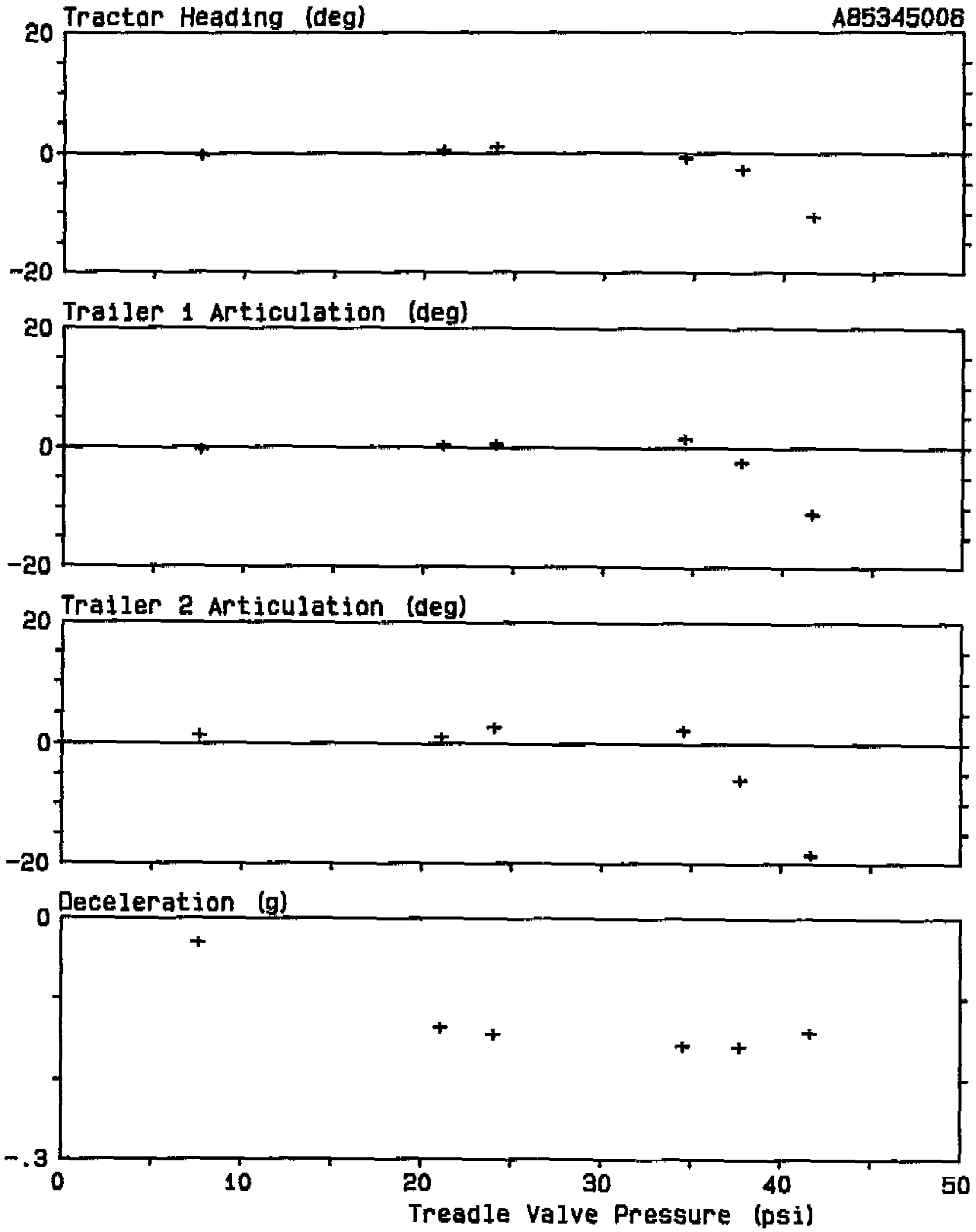


Figure 12/ Straight-Line Braking Responses vs
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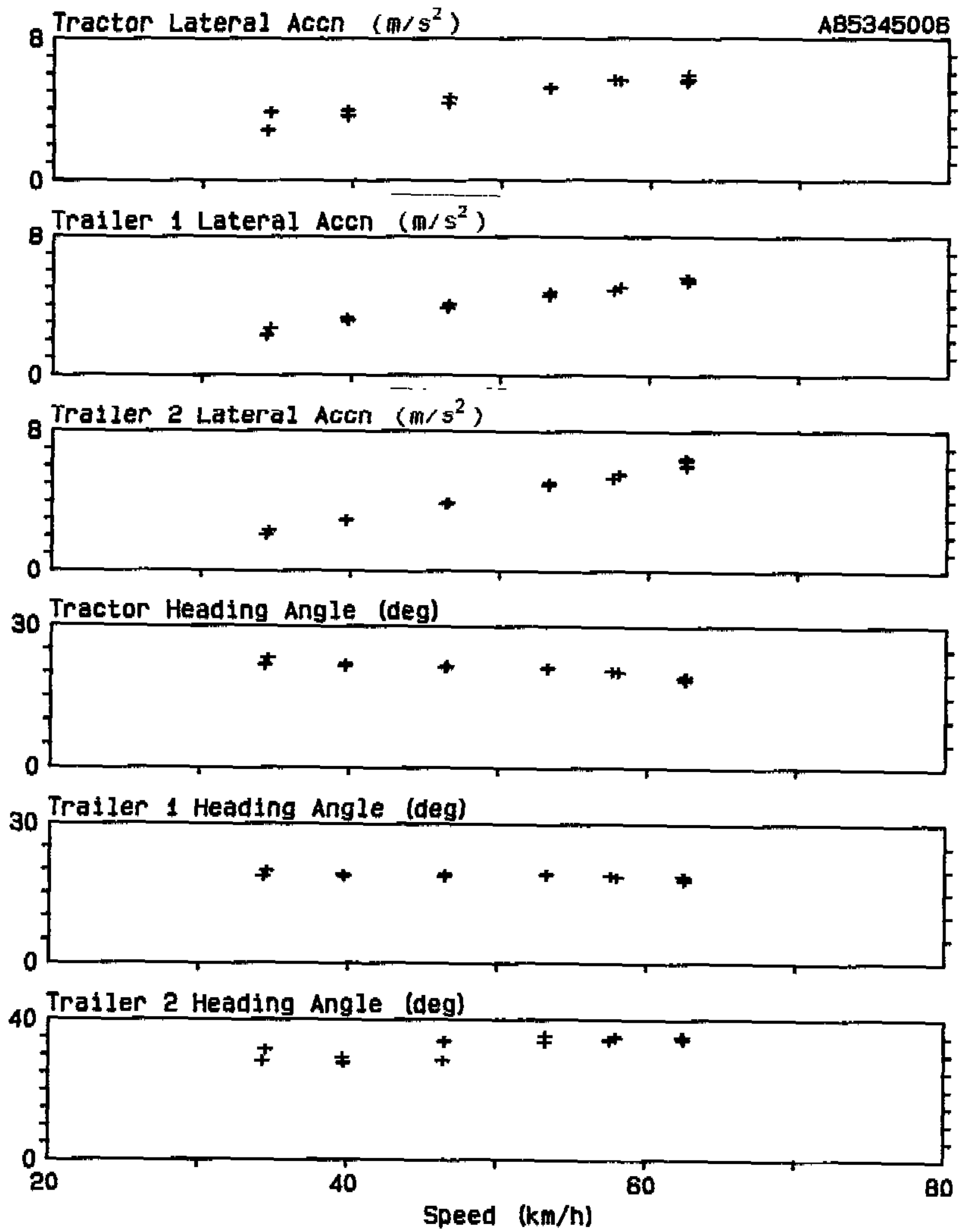

Figure 13/ Evasive Manoeuvre, Peak-to-Peak
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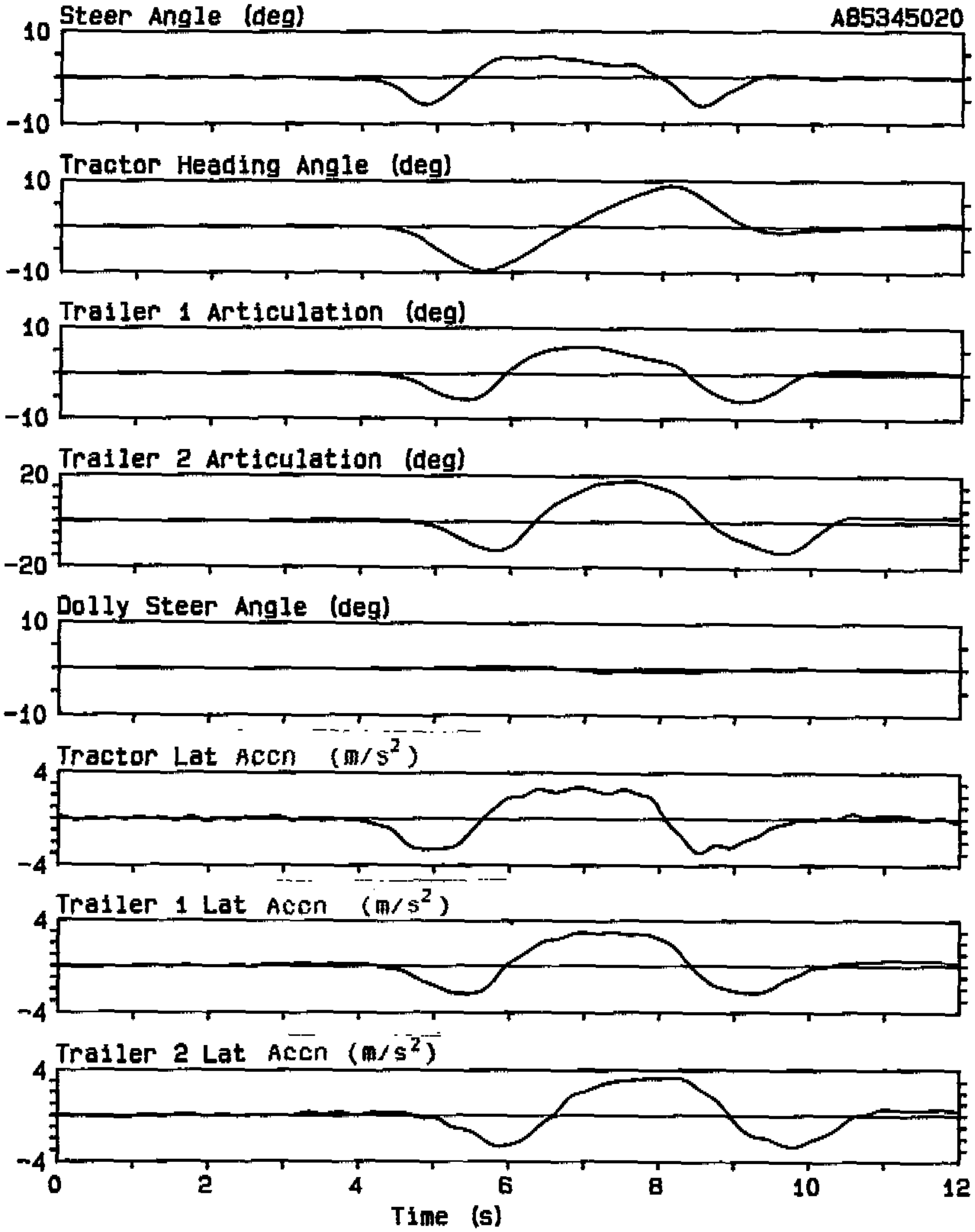

Figure 14/ Vehicle Response in Evasive Manoeuvre

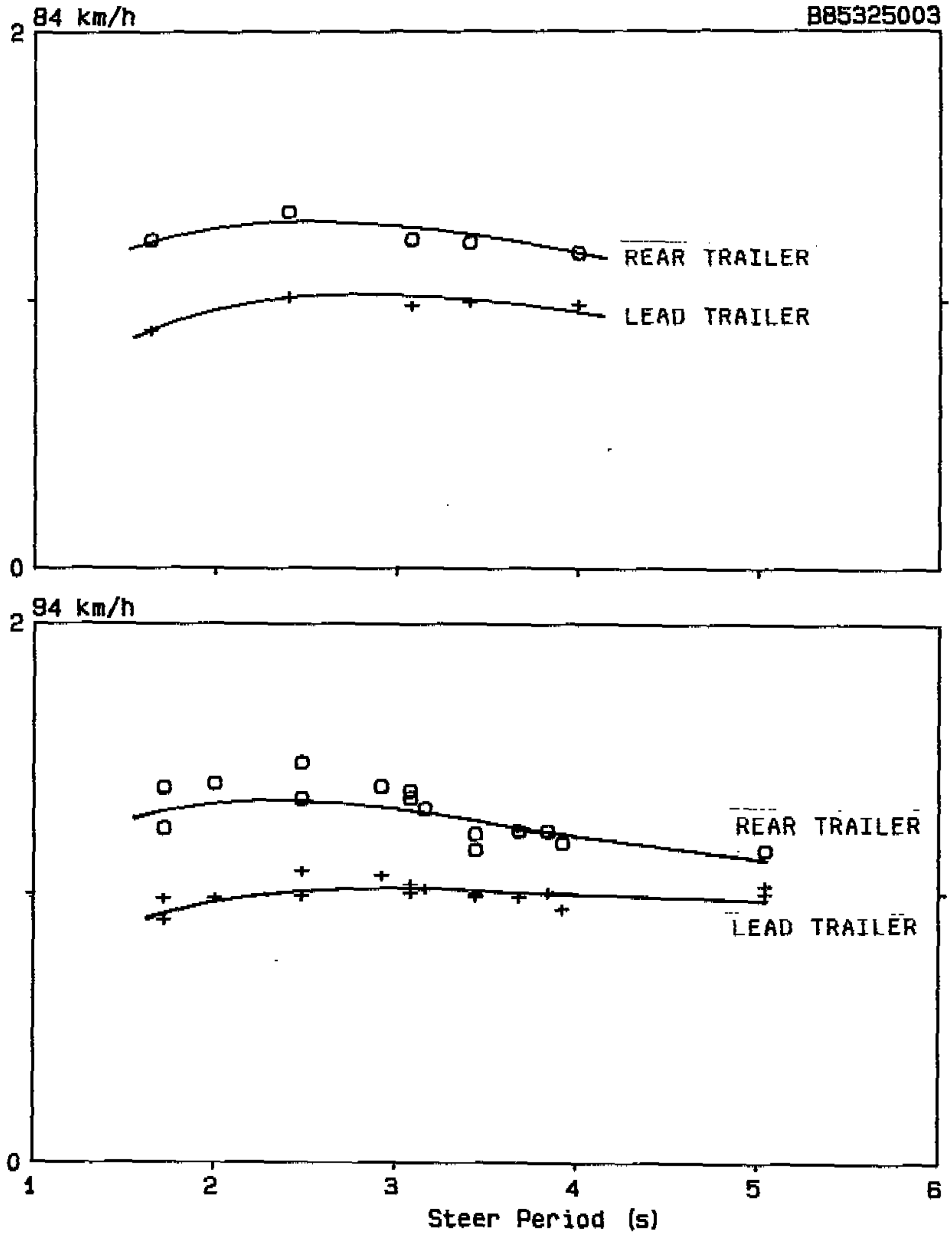

Figure 15/ Rearward Amplification of Lateral Acceleration

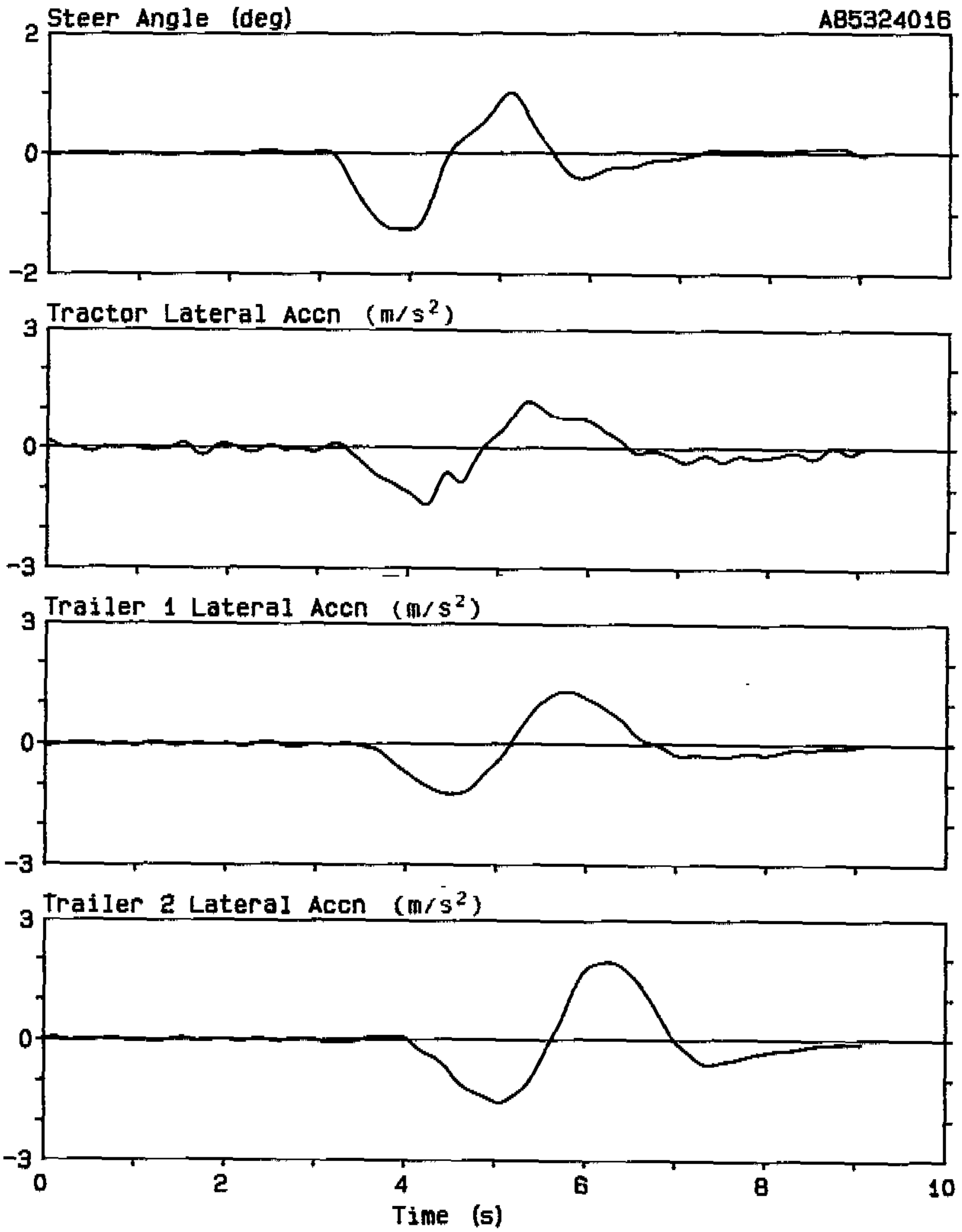

Figure 16/ Sinusoidal Steer, Vehicle Responses at 94 km/h

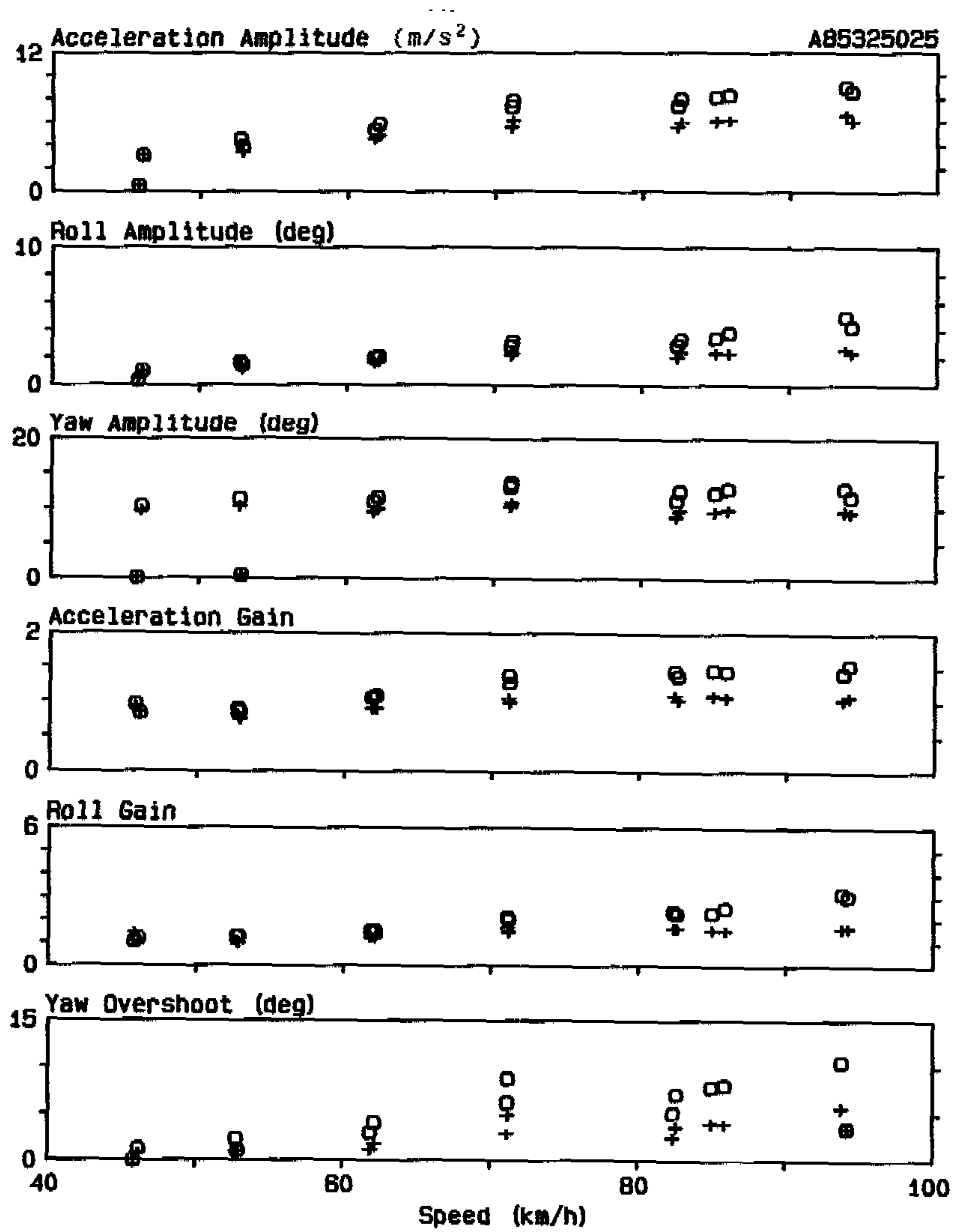

Figure 17/ Lane Change, Vehicle Responses vs Speed

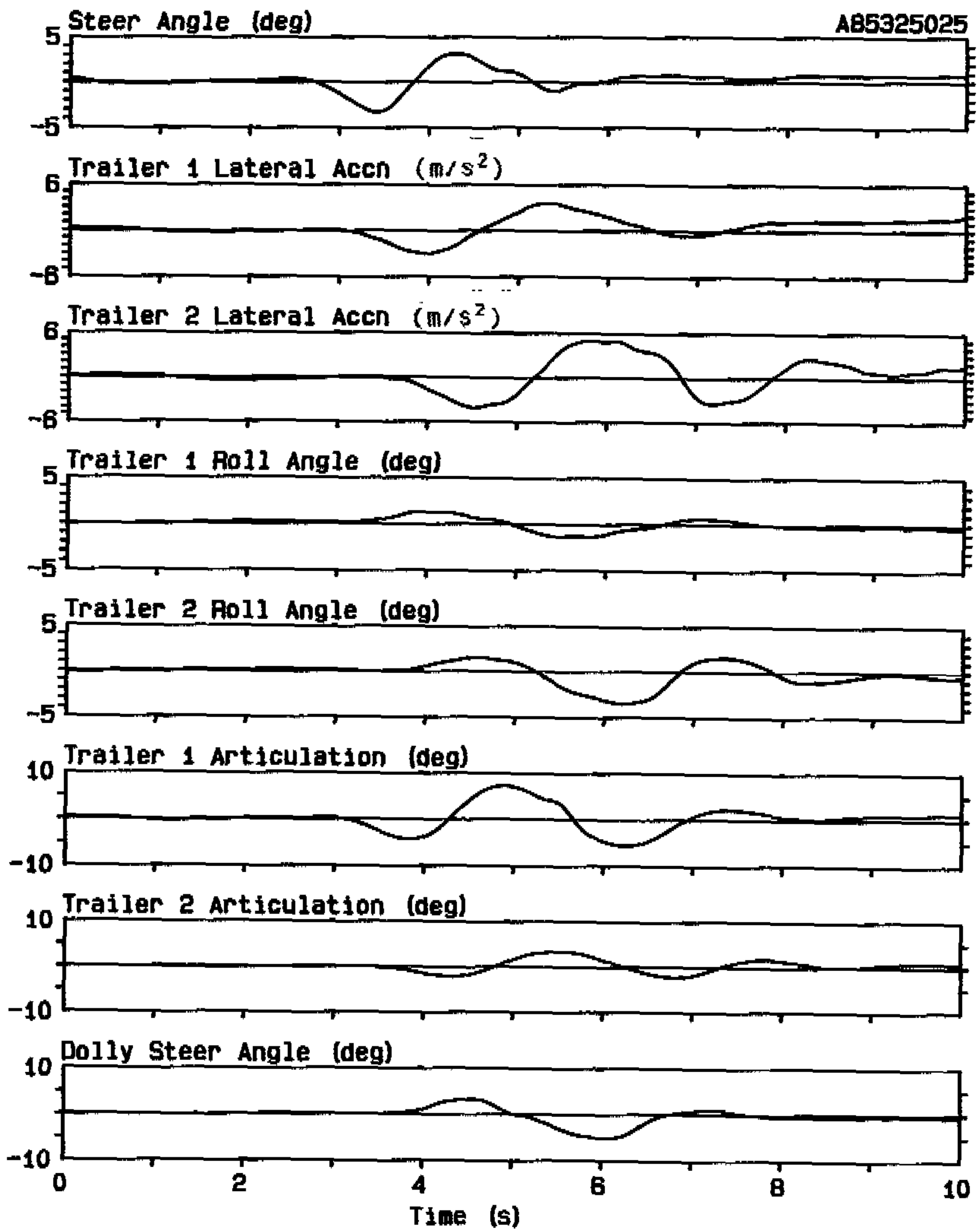

Figure 18/ Lane Change, Vehicle Responses at 95 km/h

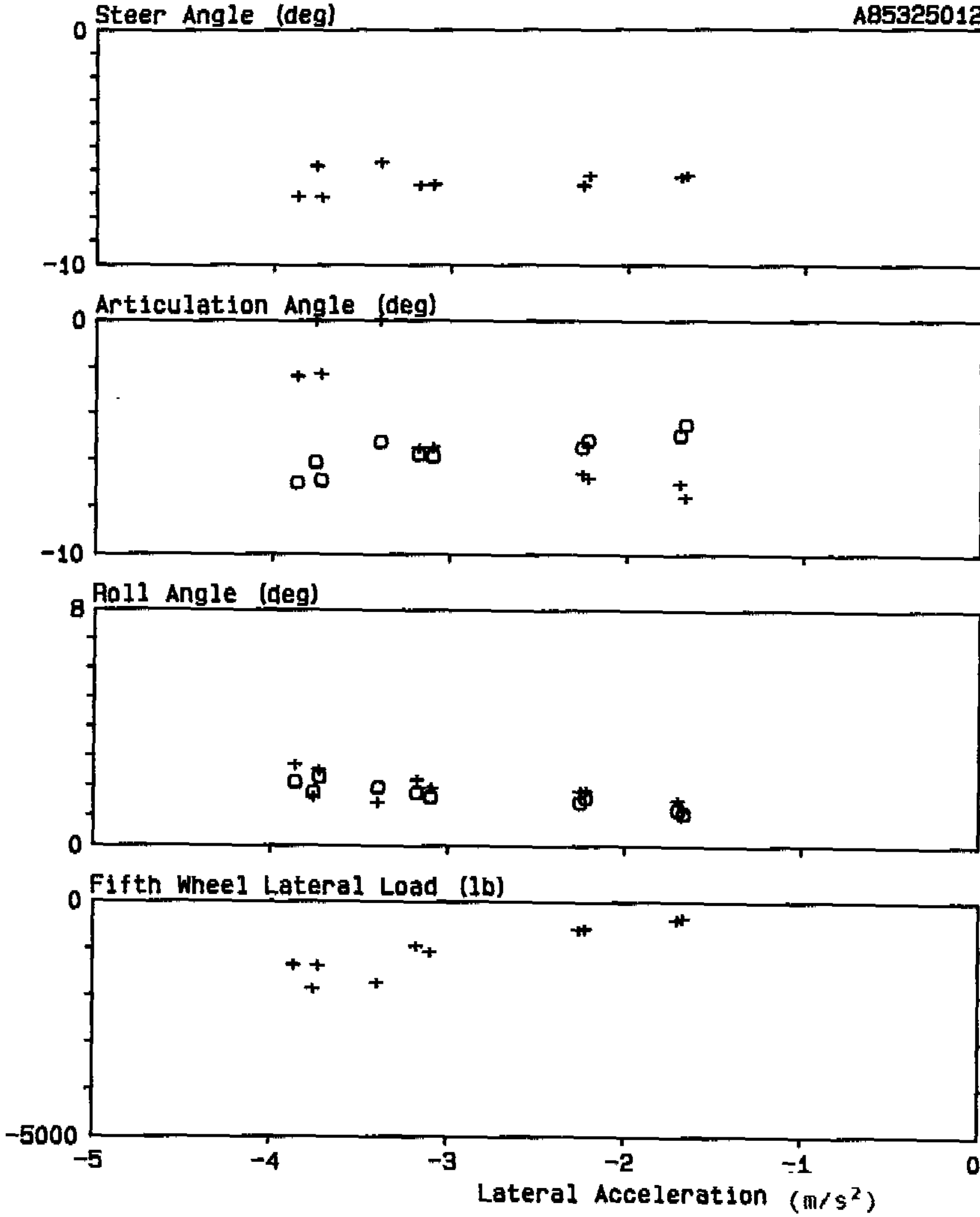

Figure 19/ Steady Circular Turn, Vehicle Responses vs Tractor Lateral Acceleration

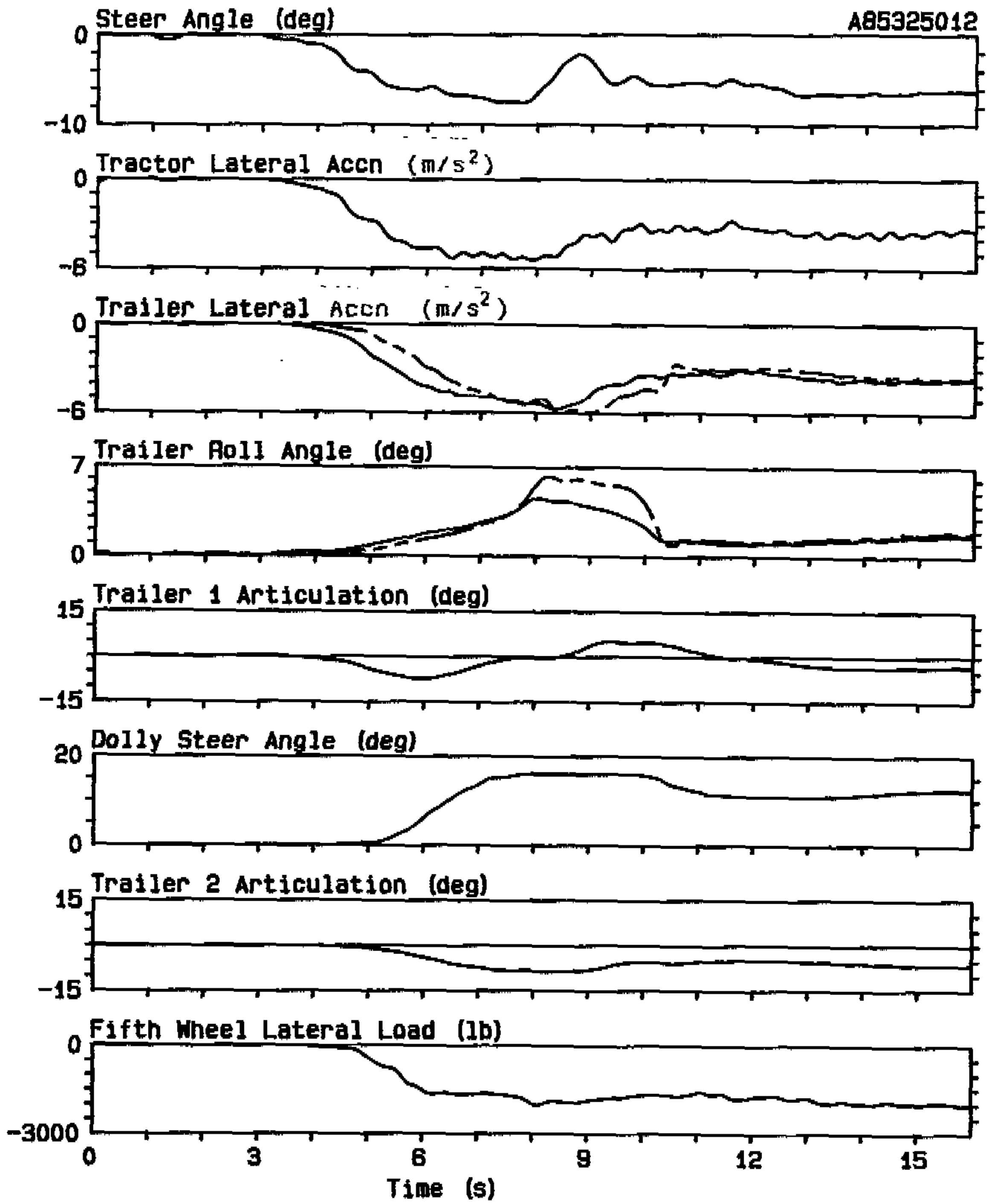

Figure 20/ Steady Circular Turn, Vehicle Responses at 61 km/h

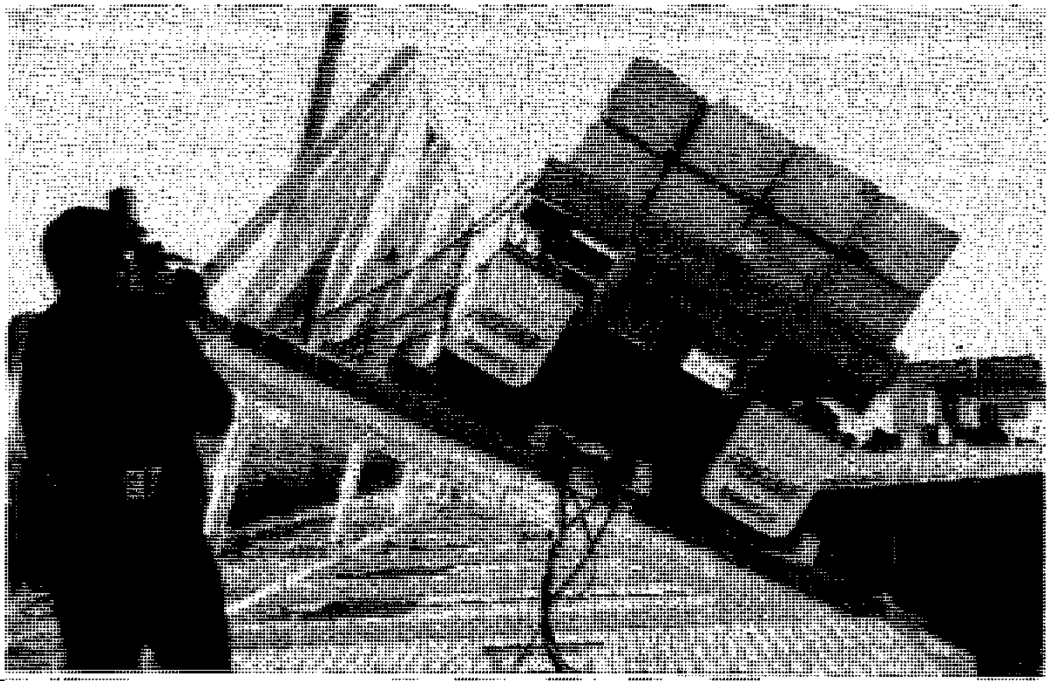

Figure 21/ Vehicle on Tilt Table

CV-86-06

Demonstration of Baseline Vehicle Performance: A-Train Triple

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and Communications

ABSTRACT

An A-train triple trailer combination was tested by the Ontario Ministry of Transportation and Communications (MTC) as part of the CCMTA/RTAC Vehicle Weight and Dimensions Study. The vehicle was designated a base-line vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with the empty vehicle on a low-friction surface and the loaded vehicle on a high-friction surface.

This report presents detailed results of the tests and demonstrations.

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ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The trailers were obtained by the study from CP Express and Transport. Facilities of the Transport Canada Motor Vehicle Test Centre were made available to the Ministry of Transportation and Communications (MTC). Assistance with vehicle preparation, delivery, and refurbishment was arranged by Mr. Pearson in support of this work.

The work was principally undertaken by the staff of the Automotive Technology and Systems Office of the Transportation Technology and Energy Branch of MTC: N.R. Carlton; G.B. Giles; C.P. Lam, P.Eng.; W.R. Stephenson, P.Eng.; and M.E. Wolkowicz; and assigned students G. Goertzen, S. Jazic, and D.R. Sykes. Assistance was provided by staff of various other departments of the ministry and other organizations.

The efforts of all involved are hereby acknowledged with gratitude.

1/ INTRODUCTION

The effects of changes in truck weight and dimension parameters on combination vehicle stability and handling and on pavement response to axle group loading are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle portion of the study involved both computer simulation of vehicle dynamic manoeuvres and testing of vehicles and components. Combination vehicles were classified into six families, based on the number of trailers and methods of hitching. A representative of each family was designated as the baseline vehicle configuration for that family. Additional vehicle configurations of interest were also defined. All baseline and additional vehicle configurations were tested to assemble a body of technical and visual data that described the stability and control characteristics of the vehicles with respect to certain performance measures.

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. This report presents the results of a test of an A-train triple trailer combination baseline vehicle. It refers frequently to a report describing procedures and equipment common to tests of all nine vehicles undertaken by MTC [1]. Similar reports present details of the tests of the other eight vehicles [2-9], and a summary report presents the results of tests of all six baseline vehicles [10]. A computer simulation of vehicle responses to actual test inputs using estimated vehicle data has also been conducted [11].

2/ TEST VEHICLE DESCRIPTION

The test vehicle consisted of the MTC Freightliner [1] 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 same combination was also tested concurrently as a C-train, using B-type converter dollies [6].

The equipment for these tests was obtained by the study from CP Express and Transport. No modifications were made to the trailers or dollies except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were affected. 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 trailers and dollies were fitted with new Michelin XZA radial tires, in load range H and size 11R22.5. These tires were run a nominal distance of 160 km (100 mi) before any testing and were then, subsequently, used for all tests. Tire pressure was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load. This was used for all tests and represents the common operating practice of not reducing tire pressure when running empty.

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 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 1.

Table 1/ Axle Loads

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 empty weight exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. The loaded weight is also 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. A target axle load of 8000 kg (17 600 lb) was set for all axles except for the steer axle. This was nearly attained, with the exception of the tractor drive axles, as 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.

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.

3/ TEST PROGRAM

3.1/ Test Procedures

The test vehicle was prepared for testing in the following way:

1/ A mechanical inspection was carried out, and any necessary repairs or maintenance was done.
2/ Outrigger and safety cable attachments and load block retention sills were installed on the trailers, and safety cable attachments were installed on the dollies.
3/ Outriggers were installed on the trailers.
4/ The boxes containing instrument packages, power supplies and signal conditioning, other instruments, and cabling were installed.
5/ New tires were installed, and pressures were set.
6/ Other fittings necessary for testing were installed.
7/ Concrete blocks were located on the trailer beds to achieve specified axle loads.
8/ Notes were made from detailed physical inspection, including an inventory of components and measurement of dimensions.
9/ The MTC tractor was coupled to the trailers.
10/ The combination vehicle was weighed, empty and loaded.
11/ A functional test of the on-board electronics was conducted.
12/ Test runs were made to shake down the vehicle instrumentation and familiarize the test driver with the vehicle's handling characteristics.
13/ Tires were run a nominal distance of 160 km (100 mi).
14/ Articulation angle between the tractor and lead trailer was calibrated.
15/ Details of the vehicle and test equipment were recorded on photographs and videotape.

The following tests were performed:

- Offtracking
- Right-hand turn
- Channelized right turn
- Air brake system
- Straight-line braking, empty vehicle, low-friction surface
- Evasive manoeuvre, empty vehicle, low-friction surface
- Sinusoidal steer, loaded vehicle, high-friction surface
- Lane change, loaded vehicle, high-friction surface
- Normal straight-line driving
- Steady circular turn, loaded vehicle, high-friction surface

All tests followed standard procedures [1], except as noted.

3.2/ Instrumentation

The instrumentation shown in Table 2 was installed. Brake pressure transducers were only installed in the trailers and dollies for the air brake system test, but all other instrumentation was installed for all tests. Data were always captured from all instrumentation, but only those pertinent to a particular test were analysed.

Tractor instruments were selected from the instrumentation that is permanently installed on the tractor. Instruments for the two front trailers were mounted in boxes placed inside the van on the trailer deck, which also contained power supplies and signal conditioning. Instruments for the rear trailer and dollies were wired into these boxes. Trailer lateral acceleration and roll angle were measured at a point midway between the kingpin and axle, which was very close to the trailer sprung mass centre of gravity.

Full details of the instrumentation, signal conditioning, and data capture system are presented elsewhere [1].

3.3/ Data Capture and Data Processing

Data were digitized on board the vehicle and transmitted by telemetry as a pulse-code modulated (PCM) data stream to a ground station, where they were recorded on magnetic tape and captured in real time by an HP-1000 computer system. Test data for a run were processed immediately after the run, and results from a series of runs were subsequently analysed using the computer system [1].

Many test runs of all types were conducted for this vehicle. Not all these runs were used in the preparation of this report. In a number of instances, a run failed to meet a test condition, or runs were made to evaluate the ability of the vehicle to make a particular manoeuvre.

Table 2/ Instrumentation Installed

No	Measurement	Instrument	Full Scale
1	Tractor steer angle	Spectrol 139 potentiometer	25.02°
2	Tractor roll angle	Humphrey CF18-0907-1 gyroscope package	8.85°
3	Tractor lateral acceleration	Kistler 303B accelerometer	0.957 g
4	Tractor yaw rate	Humphrey RT03-0502-1 angular rate transducer	38.7°/s
5	Tractor longitudinal acceleration	Kistler 303B accelerometer	0.974 g
6	Tractor speed, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	104.8 km/h
7	Tractor distance, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	56.3 m/ramp
8	Tractor fifth wheel load, left-hand side	MTC load cell	9890 lb
9	Tractor fifth wheel load right-hand side	MTC load cell	10 290 lb
10	Tractor treadle valve pressure	Celesco PLC-200G	100 psi
11	Tractor brake pressure, axle 2 Left	Celesco PLC-200G	99.80 psi
12	Tractor lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
13	Tractor yaw angle	Humphrey CF18-0907-1 gyroscope package	17.73°
14	Trailer 1 articulation angle	Celesco pull cord DV-301-150	23.194°
15	Trailer 1 lateral acceleration	Columbia SA-107 accelerometer	0.995 g
16	Trailer 1 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.90°
17	Trailer 1 outrigger touchdown	Strain gauge bridge	1.0 V
18	Dolly 1 hitch angle	Spectrol 139 potentiometer	25.0°
19	Dolly 1 lateral acceleration	Columbia SA-107 accelerometer	0.996 g
20	Brake pressure, axle 4 right	Celesco PLC-200G	104.96 psi
21	Brake pressure, axle 5 right	Celesco PLC-200G	101.06 psi
22	Brake pressure, axle 6 right	Celesco PLC-200G	102.07 psi
23	Brake pressure, axle 7 right	Celesco PLC-200G	101.93 psi
24	Brake pressure, axle 8 right	Celesco PLC-200G	106.79 psi
25	Spare		
26	Spare		
27	Trailer 2 articulation angle	Spectrol 8409 potentiometer	22.8°
28	Trailer 2 lateral acceleration	Columbia SA-107 accelerometer	0.980 g
29	Trailer 2 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.91°
30	Trailer 2 outrigger touchdown	Strain gauge bridge	1.0 V
31	Dolly 2 hitch angle	Spectrol 139 potentiometer	25.0°
32	Dolly 2 lateral acceleration	Columbia SA-107 accelerometer	0.993 g
33	Trailer 3 articulation angle	Spectrol 8409 potentiometer	22.7°
34	Trailer 3 lateral acceleration	Columbia SA-107 accelerometer	0.986 g
35	Trailer 3 roll rate	Humphrey RT03-0502-1 angular rate transducer	80.85°/s
36	Trailer 3 outrigger touchdown	Strain gauge bridge	1.0 V

4/ RESULTS

4.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions, as shown in Figure 3. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [1].

The results are shown in Table 3. The measured data were averaged for the left and right turn and then compared to data generated by a simple offtracking formula [12]. The difference between actual and computed values, shown in the last column of Table 3, is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

The final offtracking for the counter-clockwise turn is shown in Figure 4. After averaging for both directions and correcting for differences in axle track width, the offtracking of 2.68 m (8.79 ft), shown in Figure 4, became 2.77 m (9.09 ft).

Table 3/ Offtracking

Axle No.	Track Width (m)	Radius to Inner Wheel Right Turn (m)	Radius to Inner Wheel Left Turn (m)	Difference (m)	Average (m)	Calculated (m)	Difference %
1	2.31	27.45	27.47	0.02	27.46	27.56	+0.36
2	2.37	27.10	27.13	0.03	27.12	27.21	+0.33
3	2.37	27.07	27.08	0.01	27.07	27.21	+0.51
4	2.53	26.25	26.32	0.07	26.29	26.33	+0.15
5	2.53	26.20	26.27	0.07	26.24	26.27	+0.12
6	2.53	25.39	25.54	0.15	25.47	25.46	-0.04
7	2.53	25.31	25.49	0.18	25.40	25.39	-0.04
8	2.53	24.47	24.67	0.20	24.57	24.56	-0.04

4.2/ Right-Hand Turn

A 90° right-hand turn is a very demanding manoeuvre for a large truck. The vehicle's swept path in a 90° right-hand turn of 15 m (49.2 ft)

radius was measured, according to the standard test procedure [1]. This radius is typical in an urban area or where there is limited truck traffic. The swept path is shown in Figure 5.

The vehicle is shown in Figure 6 during the turn, at a point close to its maximum excursion out of the exit lane. The maximum excursion out of lane was 3.80 m (12.5 ft) or slightly over one lane width. It was out of the exit lane for a distance of 19.40 m (63.6 ft), as derived from Figure 5. This test was conducted at a creep speed and represents the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

4.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [1].

The vehicle is shown during the turn in Figure 7. The clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Figure 8 as a function of distance through the curve. The minimum clearance was only 0.51 m (20 in) in the 5.5 m (18 ft) wide roadway.

The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. The vehicle barely made it through the channel, with the left front wheel tracking right on the outer curb. In practice, a driver would allow some clearance on this side, if only to stay clear of catch basins. This would mean the rear axle would likely run over the inner curb. The test was run at creep speed, the worst condition, as the effect of lateral acceleration is to reduce the geometric offtracking measured in this test. However, in an urban area the truck driver cannot be guaranteed free-flowing traffic at such roadway geometry, so it is evident that this channelized right turn may limit access of such large combinations.

4.4/ Air Brake System

The air brake system of the combination was evaluated according to standard test procedure [1].

The trailer air brake system was inspected. A schematic of the system is shown in Figure 9. The dollies were equipped with a booster relay valve to speed the signal. All slack adjusters were automatic. Stroke was adjusted to the minimum, about 32 mm (1.25 in) on each axle. The tractor was supplied with shop air, regulated at 689 kPa (100 psi). Pressure transducers were installed at all trailer and dolly axles.

The SAE J982a style test was performed for the full triple combination; for the double, which resulted when air to the second dolly was shut off; and for the tractor-trailer when air to the first dolly was shut off. The results of these tests are presented in Tables 4, 5, and 6. A typical time history response of application and release for the full triple is presented in Figure 10. There appears to be something wrong with the two dolly valves, axles 5 and 7, as pressure did not rise fully. However, the timing of axles 7 and 8 on the rear trailer was very close. This is a desirable situation, because when a trailer axle is slower than its dolly axle, the inertia of the trailer pushes the dolly for a short time while the dolly axle is braking and the trailer axle is still rising to its steady pressure. This would provide a potential dolly jackknife situation in hard braking of an empty vehicle on a low-friction surface. The timing of axles 5 and 6 on the second trailer was not close.

Table 4/ Air Brake Timing, SAE J982a Style Test, Triple

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.07	0.18	95.6
Axle 2	0.37	0.58	95.0
Axle 4	0.54	1.42	92.6
Axle 5	0.57	1.50	88.9
Axle 6	0.85	1.92	93.1
Axle 7	0.95	1.95	77.0
Axle 8	0.97	2.05	92.4

Table 5/ Air Brake Timing, SAE J982a Style Test, Double

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.03	0.17	95.3
Axle 2	0.37	0.57	93.6
Axle 4	0.55	1.41	91.9
Axle 5	0.59	1.47	90.0
Axle 6	0.67	1.51	92.5

Table 6/ Air Brake Timing, SAE J982a Style Test, Semi

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.02	0.18	97.4
Axle 2	0.36	0.58	96.7
Axle 4	0.37	0.78	94.2

The results in these tables are the average of several tests in each case, each with a time resolution of 0.02 s.

The results when trailers were progressively added are interesting. As a semi (Table 6), application times for tractor and trailer were both 0.37 s, an ideal situation. When the second trailer was added (Table 5), the first trailer application time was prolonged to 0.55 s. When the rear trailer was added (Table 4), the second trailer application time was increased from 0.67 to 0.85 s. As each trailer was added, only the preceding trailer was affected, as the plumbing and valves prevented feedback to more than one trailer ahead. Similar results pertain for the release times.

The application times of the SAE J982a style test compare favourably with those obtained from a test conducted previously by MTC on another triple combination [13]. The release times are considered long, however, especially as it was shown that a quick-release valve operating with the booster relay valve could halve the release time [13]. The benefit to brake timing of the booster relay valves on the dollies is amply demonstrated when comparing timing results to triple combinations not so equipped [6,14].

4.5/ Straight-Line Braking

It is difficult to conduct rigorous braking tests and achieve consistent results. A demonstration of modes of instability of the combination vehicle in straight-line braking was, therefore, conducted. A series of runs was made with the empty vehicle approaching the low-friction test area at 47 km/h and the driver braking using the treadle valve. Runs were made using various application pressures, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [1].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit.

The time history of a typical run that resulted in loss of control is shown in Figure 11. The brake application of about 193 kPa (28 psi) caused the tractor to jackknife to the left. The driver released the brakes and steered out of the manoeuvre without coming to a complete stop. The remainder of the vehicle remained straight. He probably would not have been able to arrest the jackknife at a higher speed. If the tractor front axle brakes had been used, it is probable that the tractor would not have jackknifed at this speed.

A summary of peak vehicle responses from the runs is shown in Figure 12 as a function of average treadle valve pressure.

4.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. Gates of 22.5 m (73.8 ft) were used for the lane change to the left and the return to the original lane, separated by 20 m (65.6 ft) in the left lane. The runs were made in accordance with the standard test procedure [1].

The vehicle combination was evaluated primarily in terms of the lateral acceleration and yaw responses of the vehicle units. These are shown in Figure 13. Each response is the peak-to-peak amplitude experienced by the vehicle in the manoeuvre. The lateral acceleration of all units of the train increased to 54 to 57 km/h and then levelled off, indicating sliding. The tractor heading amplitude tended to decrease with speed, whereas the lead trailer's heading appeared to remain constant. These two components appeared to remain under control at all speeds. Trailers 2 and 3 showed an increase in heading angles, indicating slide while re-entering the original lane. At a speed of 54 km/h, the second dolly was jackknifing during the return to the original lane, which resulted in rear trailer swing. This was a consequence of the rearward amplification of lateral acceleration, discussed in Section 4.7 for the loaded vehicle. A typical run at 54 km/h is presented in Figure 14. The dolly jackknife is evident in the dolly 2 hitch angle trace, at a time of 10 s, and the trailer 3 articulation clearly shows the subsequent trailer swing.

The vehicle is shown in this manoeuvre in Figure 15.

4.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for this combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 63, 84, and 94 km/h, with steer input periods between about 2 and 5 s. The vehicle is shown in this manoeuvre in Figure 16.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. Lateral acceleration gains of the trailers are presented in Figure 17, as a function of tractor steer input period for the three test speeds. Each gain is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless.

It is evident from Figure 17 that rearward amplification increases with speed and rearward by trailer, for the two highest speeds. It is of interest, however, to see that there is little increase in lead trailer amplification with speed, which shows how little influence the other trailers have on this unit. Rearward amplification is also somewhat sensitive to steer period reaching the highest value at around 2 to 3 s.

The results show that, at highway speed, the A-train triple is a very responsive vehicle. The reason for this is that its inherent stability is rather low. Stability and response of mechanical systems have an inverse relationship: high stability means low response to input and vice versa.

Figure 18 shows the vehicles' responses from a typical run with a steer period of about 2.5 s at 94 km/h. This run illustrates well the increase, or amplification, rearward by trailer from the tractor. Notice, also, how the response of each trailer rearward lags behind the steer input at the tractor, nearly 2 s for the rear trailer. It can be seen that this trailer's peak response occurs some time after the driver completes the the steer input, and nothing the driver can do in the interim will affect the amplitude of the response. If the response is close to the limits of this trailer's stability, any action by the driver to try and effect recovery might only increase the response. This lag is caused by the number of articulation points and the length of the vehicle and is considered to affect adversely the driver's control of the vehicle.

Figure 19 shows rear trailer responses from typical runs with a steer period of about 2.5 s at each test speed. At 63 km/h the response is nearly deadbeat; at 84 km/h the rear trailer is clearly oscillating; and at 94 km/h the rear trailer is oscillating strongly. Those three time histories clearly depict the reduction in damping of the vehicle's lateral/directional response.

The responsiveness of this vehicle made this and other tests difficult to conduct:

1/ On approach, small steer corrections made by the driver were amplified rearward so that a desired steady period before the manoeuvre was rarely achieved. This made data detrending difficult [1] and may account for a certain amount of scatter in the data.

2/ The response to the manoeuvre itself continued to the point where the driver had to exit the test area; a complete response could not be obtained because the test area was simply not large enough.

3/ The steer inputs were very small, typically 25 to 35° of steering wheel angle, which is less than 1° steer at the front axle. This small steer resulted in a tractor lateral acceleration of about 0.1 to 0.15 g.

A rearward amplification of 3.0 did, on occasion, result in substantial trailer roll and sometimes trailer swing, even on the high-friction surface, as can be seen in Figure 16. However, tempering the steer input to avoid excessive rear trailer response resulted in such a small steer input that, while it was closely sinusoidal at the steering wheel, it was often rather poorly balanced at the front axle. The reason for this is probably backlash, compliance, and non-linearity within the steering system itself. A careful inspection and some tests of the steering system showed no evident defect or bias. The steering system had previously been inspected and aligned when the tires for the test program were installed. The front axle steer, however, is the actual input that causes vehicle response. Responses, therefore, were often not well balanced, which means that the steer input contained, perhaps, substantial other periodic content besides the intended steer period.

It is for this reason that the rearward amplifications were computed as the ratio of peak-to-peak trailer lateral acceleration response to peak-to-peak tractor lateral acceleration. This significantly reduced the scatter in the results and avoided the issue of whether the first, second, or highest input and response peaks should be used as the basis for these ratios. Nevertheless, because the input was often unbalanced and not a pure sine wave, it was likely that the response was somewhat attenuated compared to what would result from a pure sine wave. The data presented in Figure 17 are, therefore, considered optimistic, in the sense that they are probably lower than would arise from a perfect steering system or a computer simulation of the vehicle using a pure sine wave steer input.

Tests were only conducted to 94 km/h. It is our opinion that this vehicle would be even more responsive at a typical highway speed limit of 100 km/h. Actual speeds are often higher than this limit, and the vehicle would become yet more responsive if actual speeds did exceed 100 km/h. Despite the enviable safety record achieved by some special permit operations using A-train triples, this configuration cannot be recommended when the comparable C-train is so much less responsive [6]. The response characteristics of this vehicle were found to be much different from those of the comparable C-train, which was found to be much more stable [6].

4.8/ Lane Change

The objective of this test was to evaluate vehicle dynamic stability characteristics in a dynamic manoeuvre. A series of runs was made where the driver made a lane-change manoeuvre considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [1].

A gate of 30 m (98.4 ft) was used, to provide a vehicle speed of about 80 km/h, which is a typical speed limit and might permit some comparison of the results of this test with those described in the preceding sections

The results from all the runs are summarized in Figure 20. The peak-to-peak lateral acceleration, roll, and yaw (or heading) angles all showed an increase as the limiting speed of 74 km/h was reached, at which point the rear trailer was rolled rather violently to the left and slid about 1 m to the left into the adjacent lane. While the trailer did not roll over in this manoeuvre, it undoubtedly would have if its centre of gravity had been higher and, perhaps, at a somewhat lower speed than 74 km/h. The lateral acceleration gain was computed by the same method as rearward amplification and is consistent with the results obtained there by interpolation. The yaw overshoot of the trailer clearly illustrates the rear trailer swing at the limiting speed.

Figure 21 shows selected vehicle responses in a run at 75 km/h, where trailer swing was encountered. The swing is evident in the rear trailer yaw angle overshoot, around 8 s, and the trailer roll to the left, which reached 6°. The vehicle is shown in Figure 22 at about this point in that run. Note that the outrigger did not touch down.

4.9/ Normal Straight-Line Driving

The objective of this test was to attempt to evaluate lateral motion of the rear trailer of the combination, the phenomenon known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [1].

As previously mentioned, the vehicle was very responsive and even the slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in rear trailer sway that was strongly perceptible to the occupants of a chase vehicle. Root mean square (RMS) lateral acceleration of the rear trailer was 3.37 g/° of RMS steer input. RMS sway of the rear of the rear trailer relative to the tractor steer axle was 418 mm/° (16.5 in/°) of RMS steer input. This value is suspect because of the small articulation angles.

4.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics to determine the high-speed offtracking of the vehicle and to examine the side loads exerted on the tractor by the trailers. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The vehicle is shown in this manoeuvre in Figure 23. The results of this test are summarized in Figure 24. The vehicle combination was evaluated primarily in terms of the roll response of the vehicle units. Average steady-state roll angles, presented as a function of tractor lateral acceleration, increased with speed. However, the trailer centre of gravity was not high enough for the rollover point to be reached in this test. Rollover of the rear trailer would normally be expected with this vehicle, because the payload centre of gravity would usually be considerably higher than that of the vehicle as tested. Average steady-state articulation angles decreased modestly with increase in lateral acceleration, and as a consequence, the offtracking decreased. The lateral force experienced by the tractor fifth wheel, presented as a function of tractor lateral acceleration, shows a gradient of 33.4 kN/g (7500 lb/g).

At the limiting speed of 54 km/h, a peak lateral acceleration of 0.50 g, the rear trailer swung out and the driver departed from the circular trajectory, as shown in Figure 25.

5/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation.

Tests were conducted in various weather conditions. Tires wore progressively as the various tests were conducted. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailers were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal, particularly for the loaded condition, because of the underslung outriggers.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results, except for centre of gravity height, which has been mentioned already where it may have affected the results. The effect of raising the trailer centre of gravity to 1.20 m (48 in) above the trailer floor from 0.33 m (13 in) for this vehicle would be to reduce the vehicle's roll threshold to, perhaps, 0.30 g [15]. This would have reduced the limiting speed in the steady circular turn and resulted in dynamic rollover in the lane change. The results presented pertain to the particular vehicle tested, and results different in some respects might be obtained for another vehicle at another time.

This vehicle was considered an easy vehicle to drive by the test driver. The short trailer wheelbase and single axle made it easy to manoeuvre in both low-speed turns and dynamic tests, as the trailer imposed modest forces on the tractor. However, because it was so responsive it was very easy for the driver to create a trailer swing situation, and this would have been a rollover situation with a higher trailer centre of gravity. The driver had no feedback of second- or third-trailer response once a manoeuvre had started, because the A-dolly hitch does not transmit trailer roll moment forward. Once the driver had made an excessive input, there was nothing that could be done to alleviate trailer response, because rear trailer response lagged 1.5 to 2.0 s behind the steer input. The responsiveness of this vehicle in normal driving, particularly when empty, was a concern because rough roads excited considerable trailer sway. Even hauling two trailers to the test site on delivery was not a pleasant experience.

6/ CONCLUSIONS

An A-train triple trailer combination was tested by the Ontario Ministry of Transportation and Communications, as part of the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with an empty vehicle on a low-friction surface and a loaded vehicle on high-friction surface.

The length of this vehicle clearly contributed to the significant space required to make turns. Since such vehicles only operate by special permit, however, this may not be a major issue because the permit usually limits where the vehicle may go.

The air brake system was relatively fast and well balanced, largely because of the valves used. Booster relay valves on the dollies made a major contribution to this.

The lateral/directional stability of the vehicle was poor, both empty on a low-friction surface and loaded on a high-friction surface. Stability deteriorated quickly at the highway speed limit of 100 km/h. The vehicle was so responsive, with a rearward amplification of lateral acceleration of nearly 3, that it was easy to cause a trailer swing. The A-train triple configuration is considered undesirable because of its low stability at highway speeds. The C-train configuration is preferable from this point of view, as demonstrated in a parallel series of tests. The roll stability was high because the centre of gravity of the trailer was quite low. A higher centre of gravity would have reduced the roll threshold significantly.

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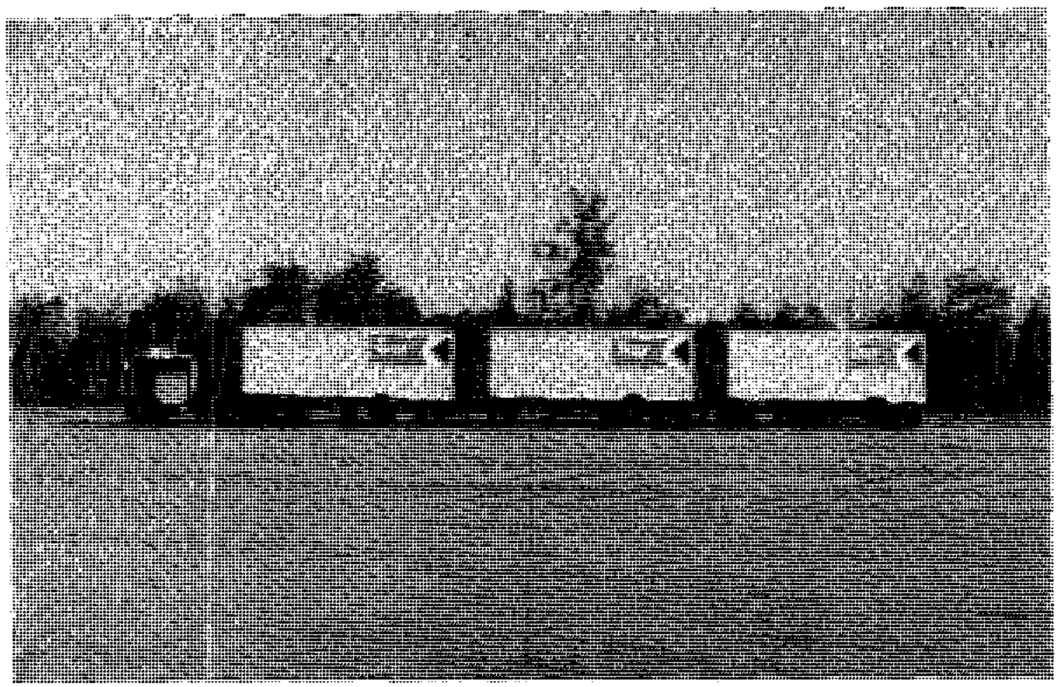


Figure 1/ View of Vehicle

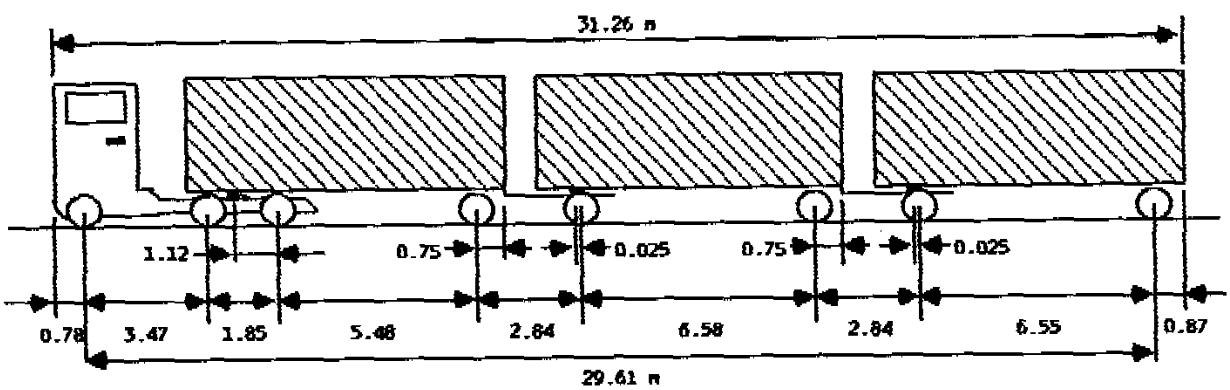


Figure 2/ Vehicle Dimensions

Figure 3/ Clockwise Offtracking

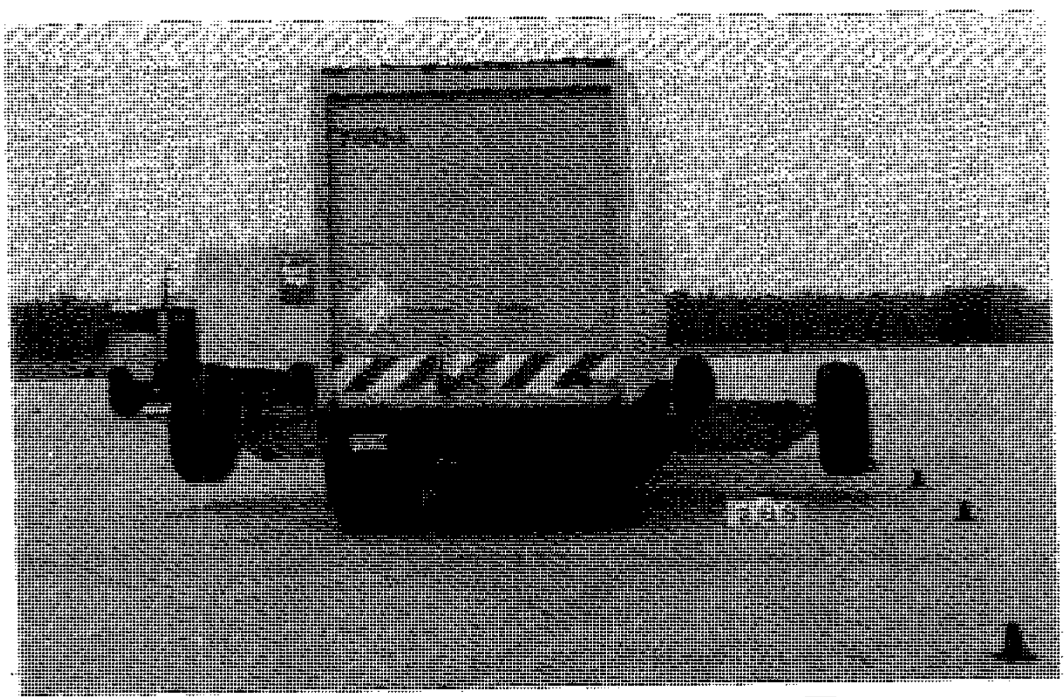
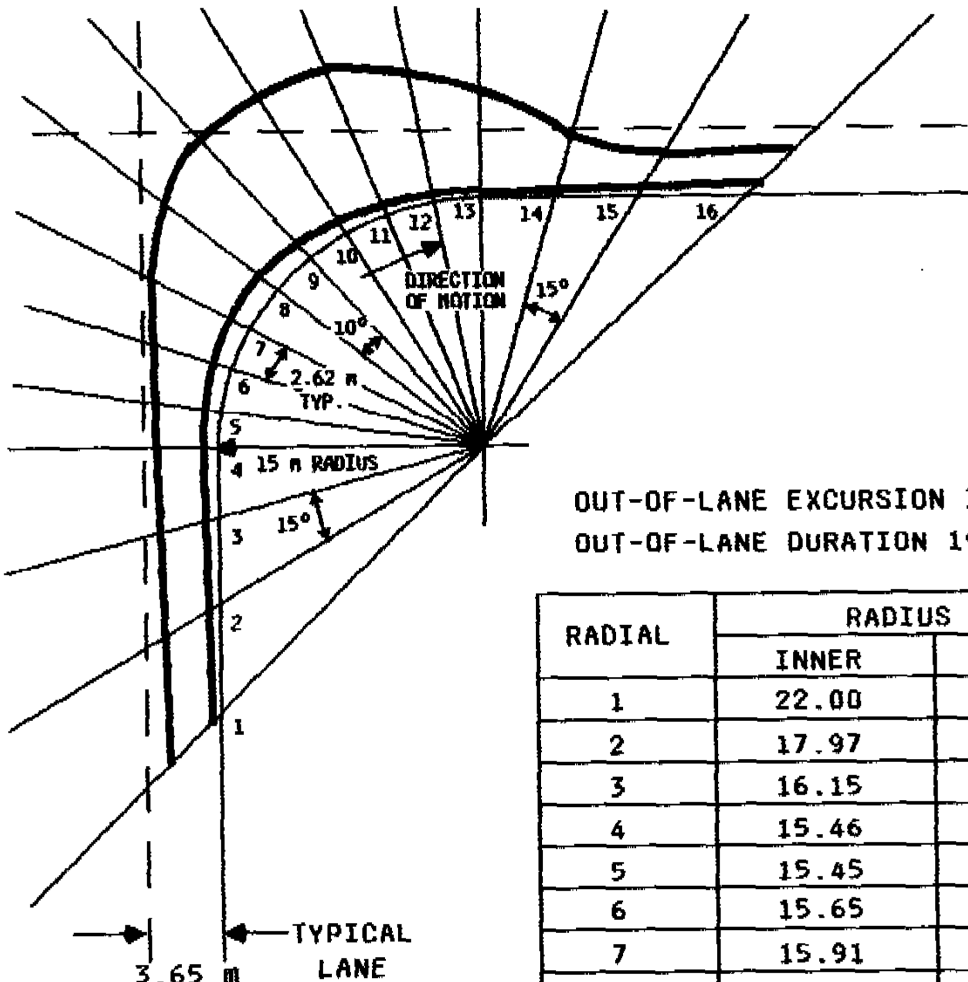


Figure 4/ Counter-Clockwise Final Offtracking



OUT-OF-LANE EXCURSION 3.8 m
OUT-OF-LANE DURATION 19.4 m

RADIAL	RADIUS (m)	
	INNER	OUTER
1	22.00	25.40
2	17.97	20.77
3	16.15	18.67
4	15.46	18.09
5	15.45	18.37
6	15.65	19.20
7	15.91	20.86
8	16.05	22.72
9	15.98	23.98
10	15.73	24.49
11	15.46	24.14
12	15.29	22.83
13	15.37	21.11
14	16.05	19.32
15	17.95	20.16
16	-	24.77

Figure 5/ Right-Hand Turn Swept Path

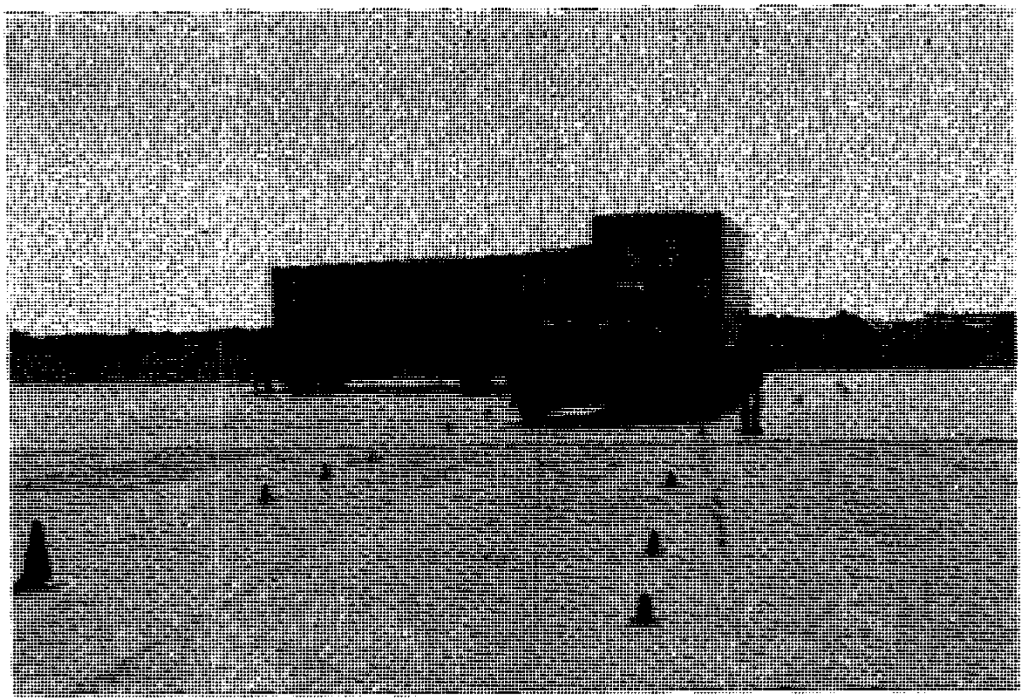


Figure 6/ Right-Hand Turn

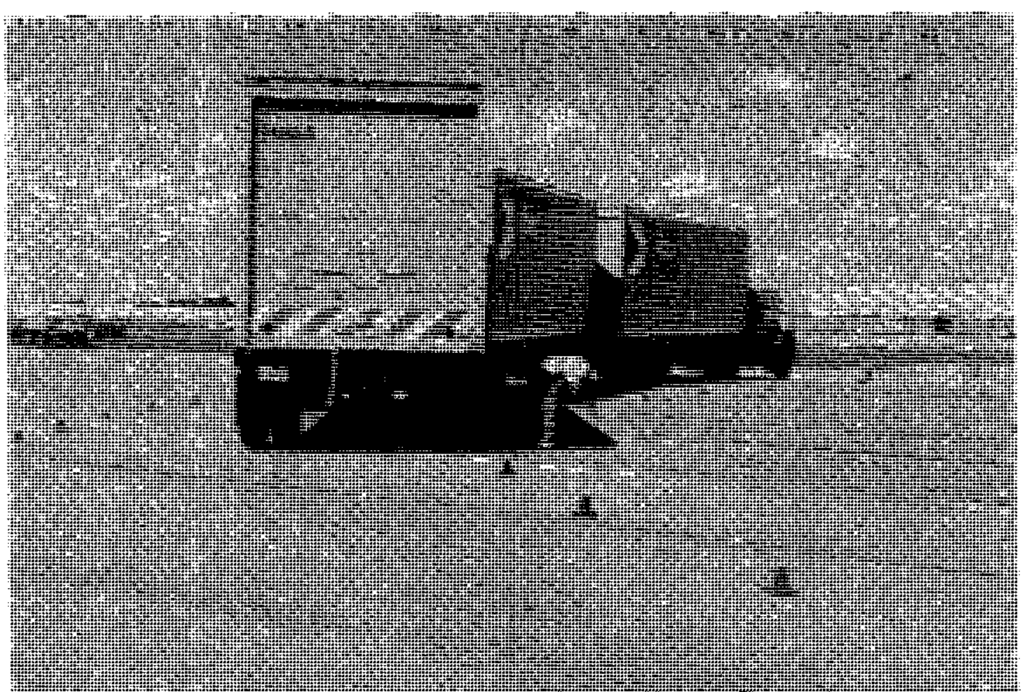
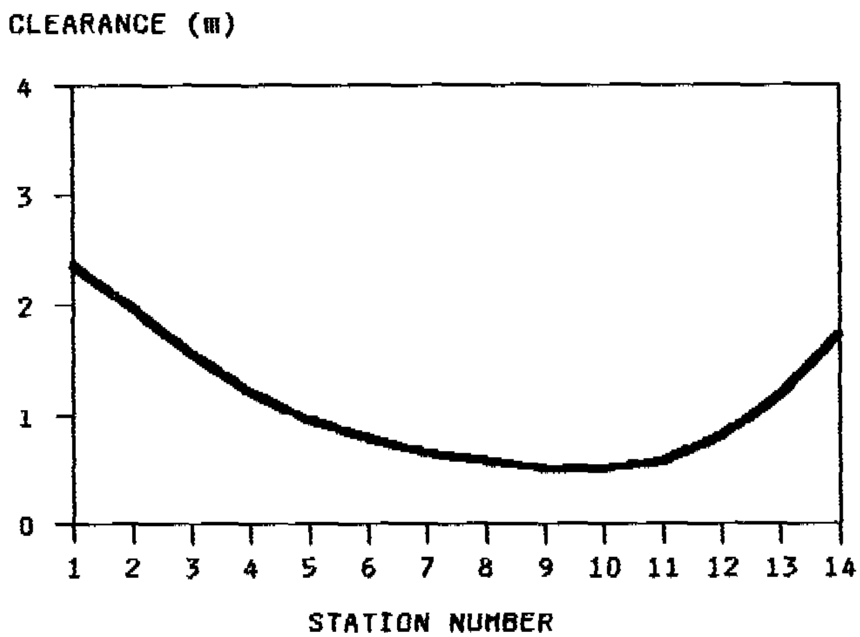


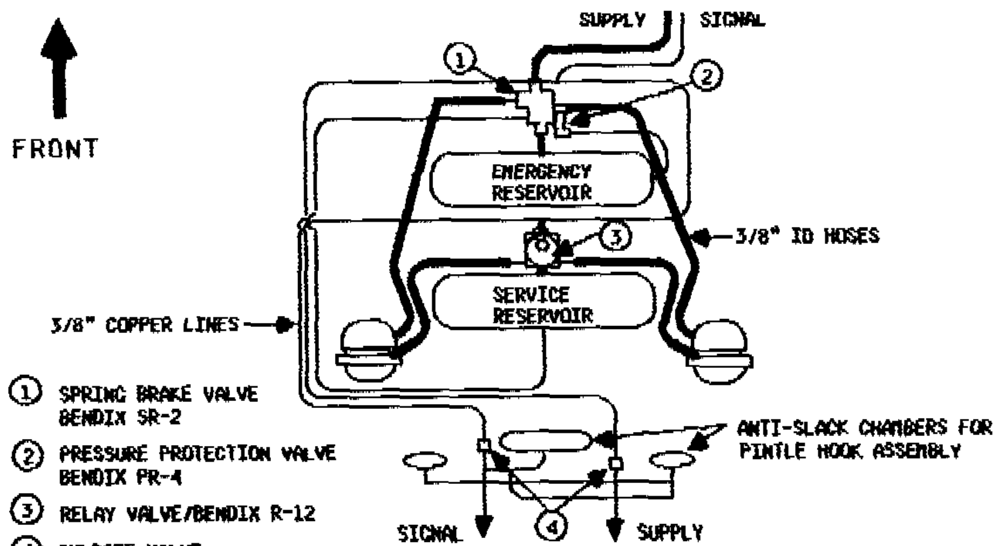
Figure 7/ Channelized Right Turn



STATION NUMBER	CLEARANCE (m)
1	2.36
2	1.98
3	1.58
4	1.21
5	0.97
6	0.80
7	0.65
8	0.57
9	0.51 *(LOW)
10	0.52
11	0.59
12	0.81
13	1.20
14	1.74

Figure 8/ Channelized Right Turn
Clearance from Inner Curb

28' TRAILER



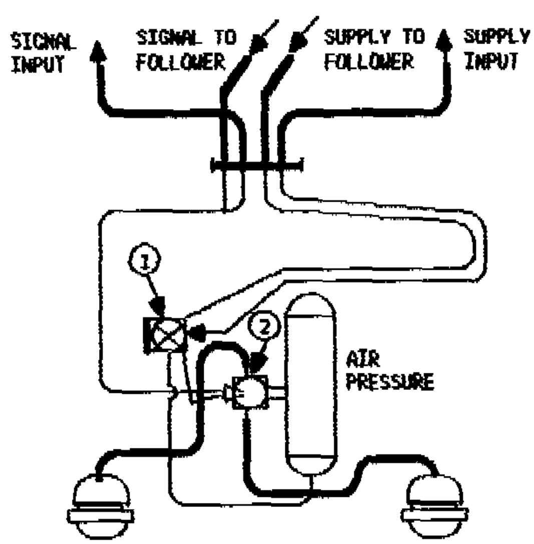
(1) SPRING BRAKE VALVE BENDIX SR-2

(2) PRESSURE PROTECTION VALVE BENDIX PR-4

(3) RELAY VALVE/BENDIX R-12

(4) SHUTOFF VALVE

A-DOLLY



(1) BENDIX R-8P, PRESSURE EQUALIZING RELAY VALVE

(2) BENDIX RE-6

Figure 9/ Trailer and Dolly
Air Brake System Schematic

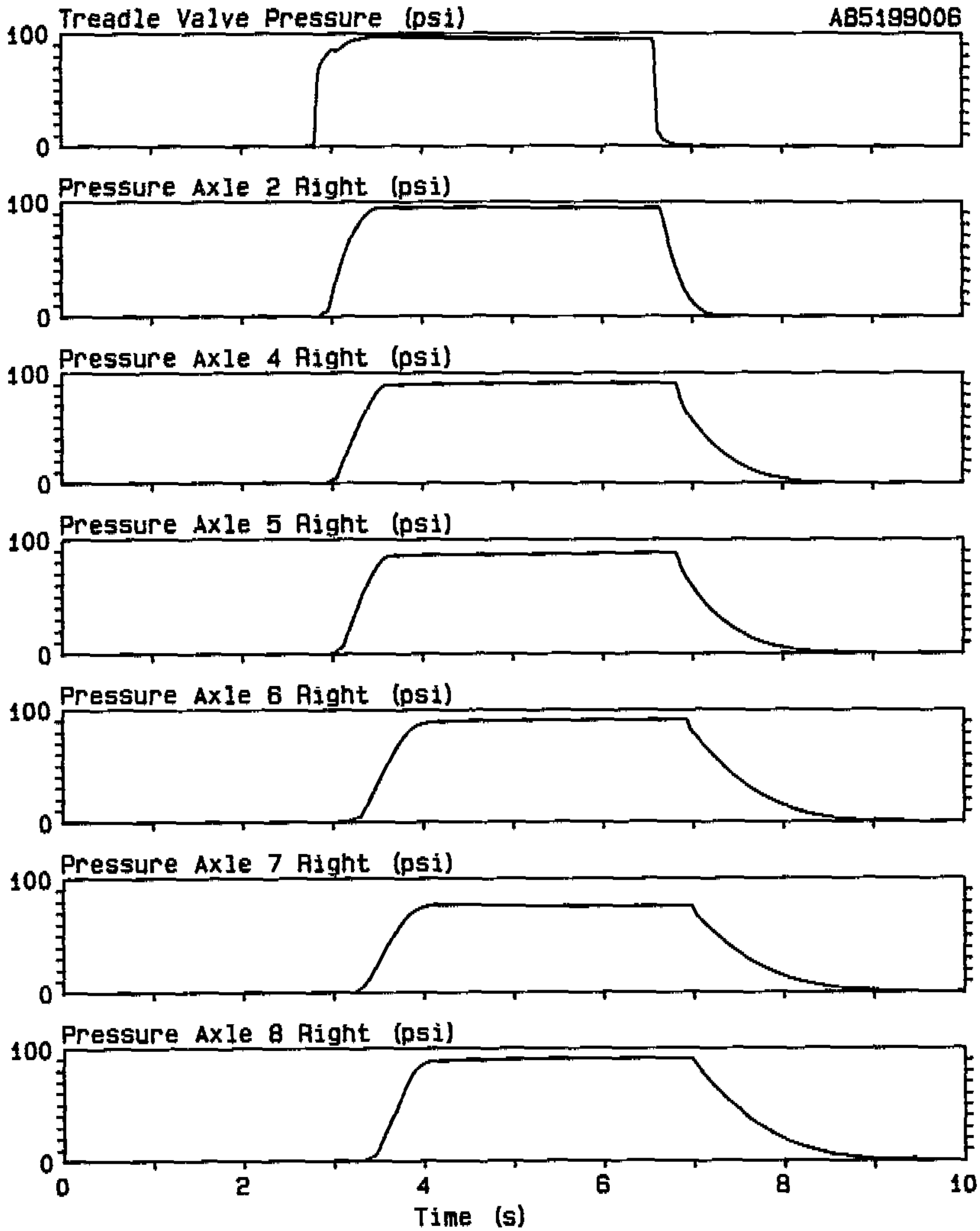


Figure 10/ Air Brake Application and Release

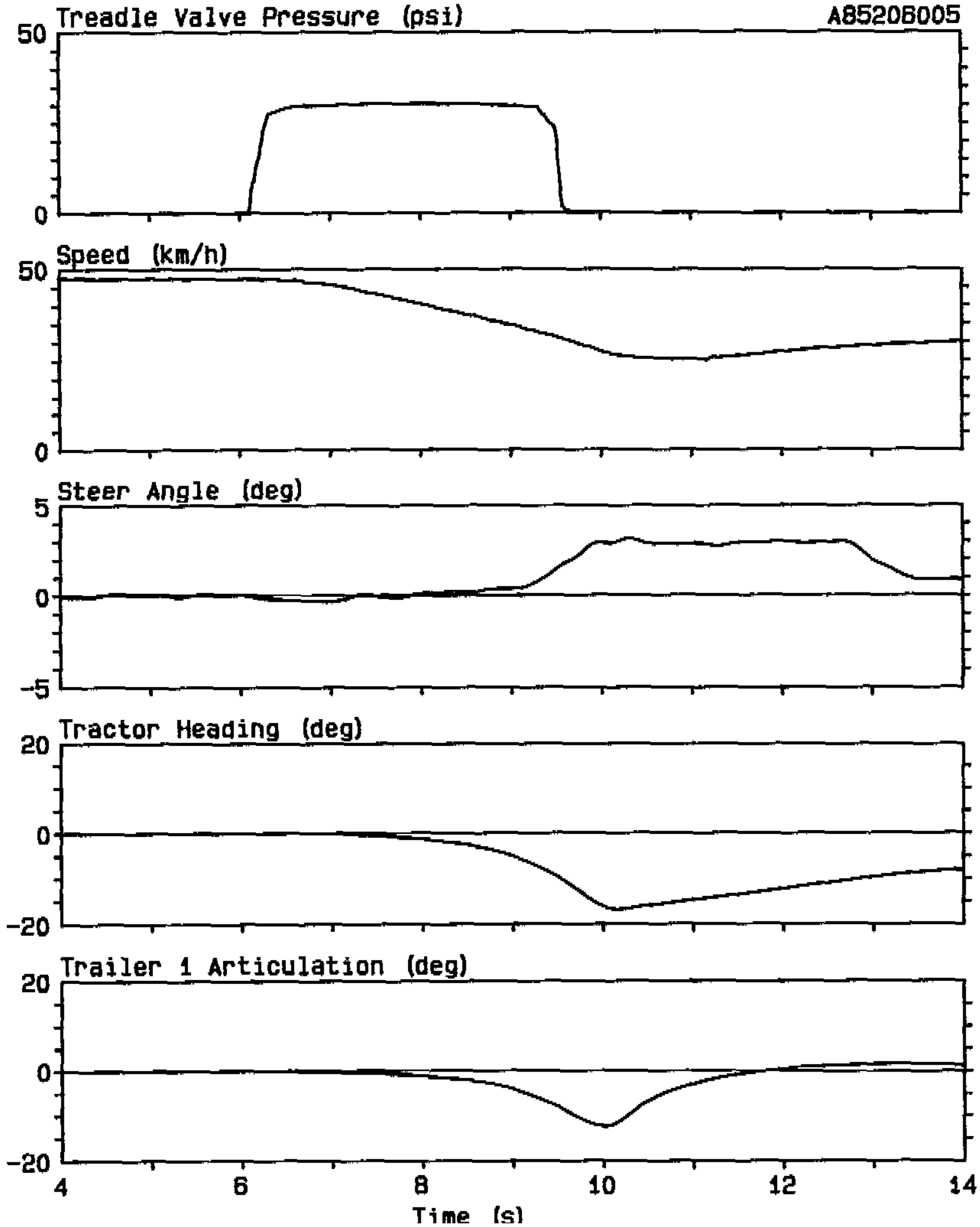


Figure 11/ Vehicle Response to Straight-Line Braking

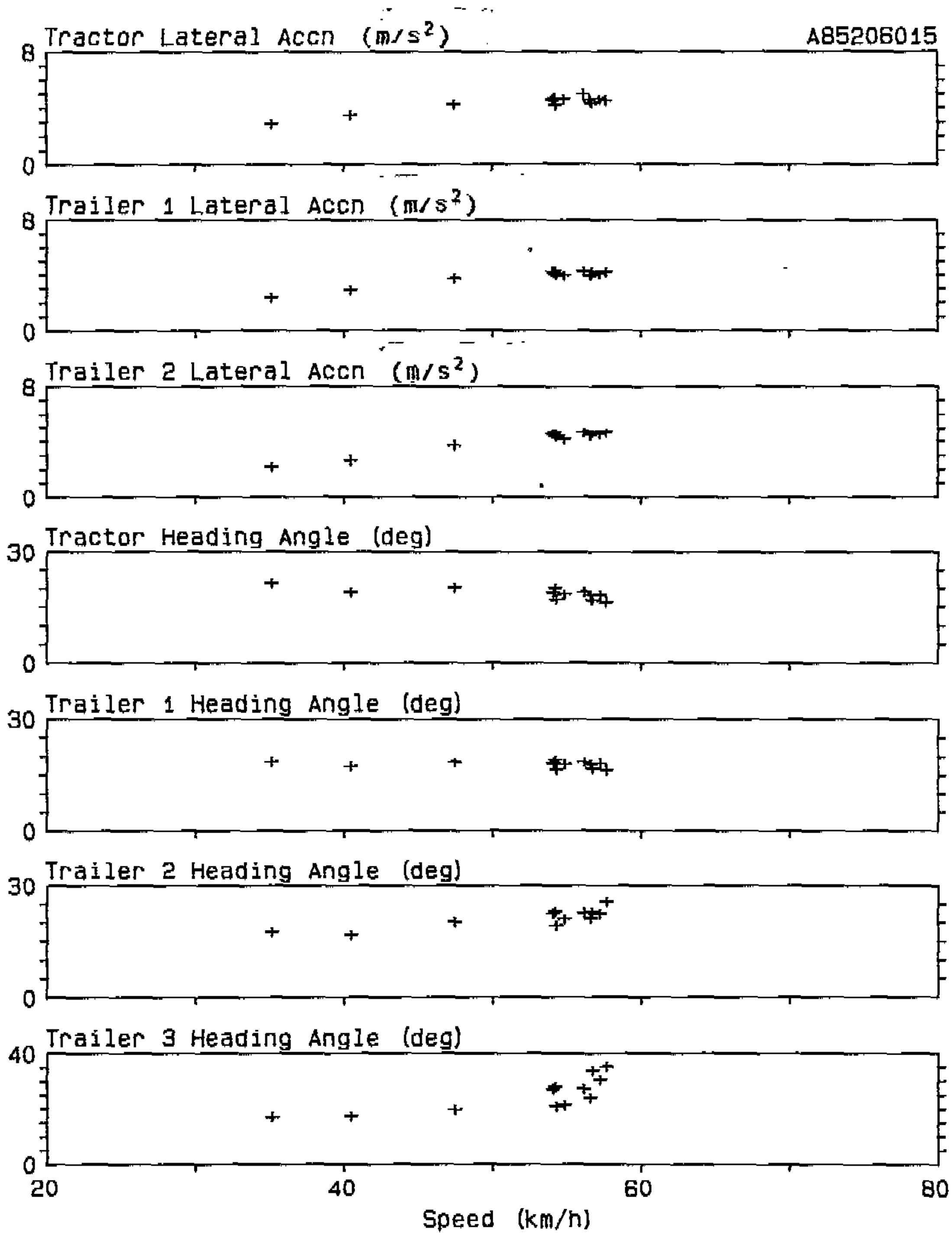


Figure 13/ Evasive Manoeuvre, Peak-to-Peak Responses vs Speed

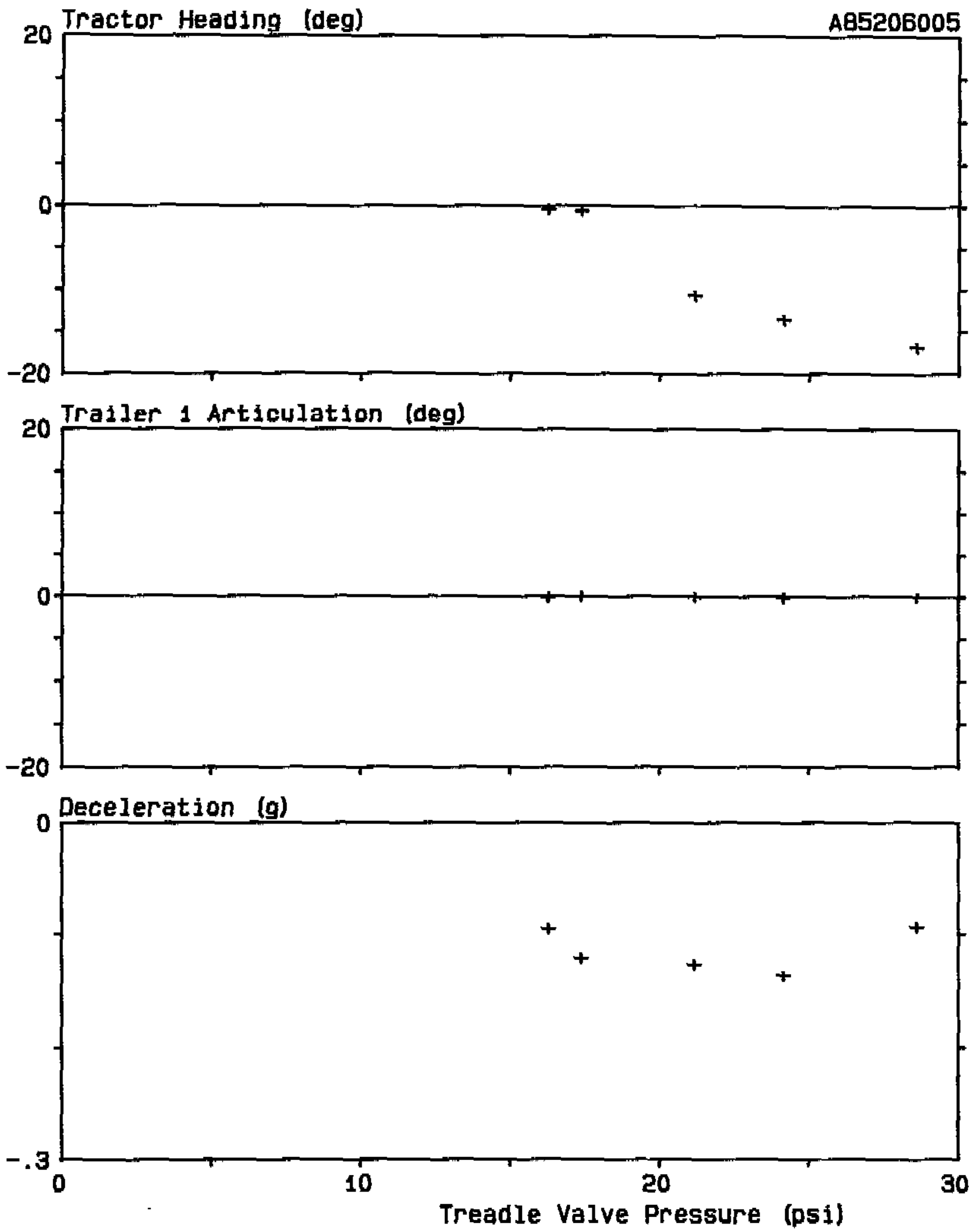


Figure 12/ Straight-Line Braking Responses vs
Treadle Valve Pressure

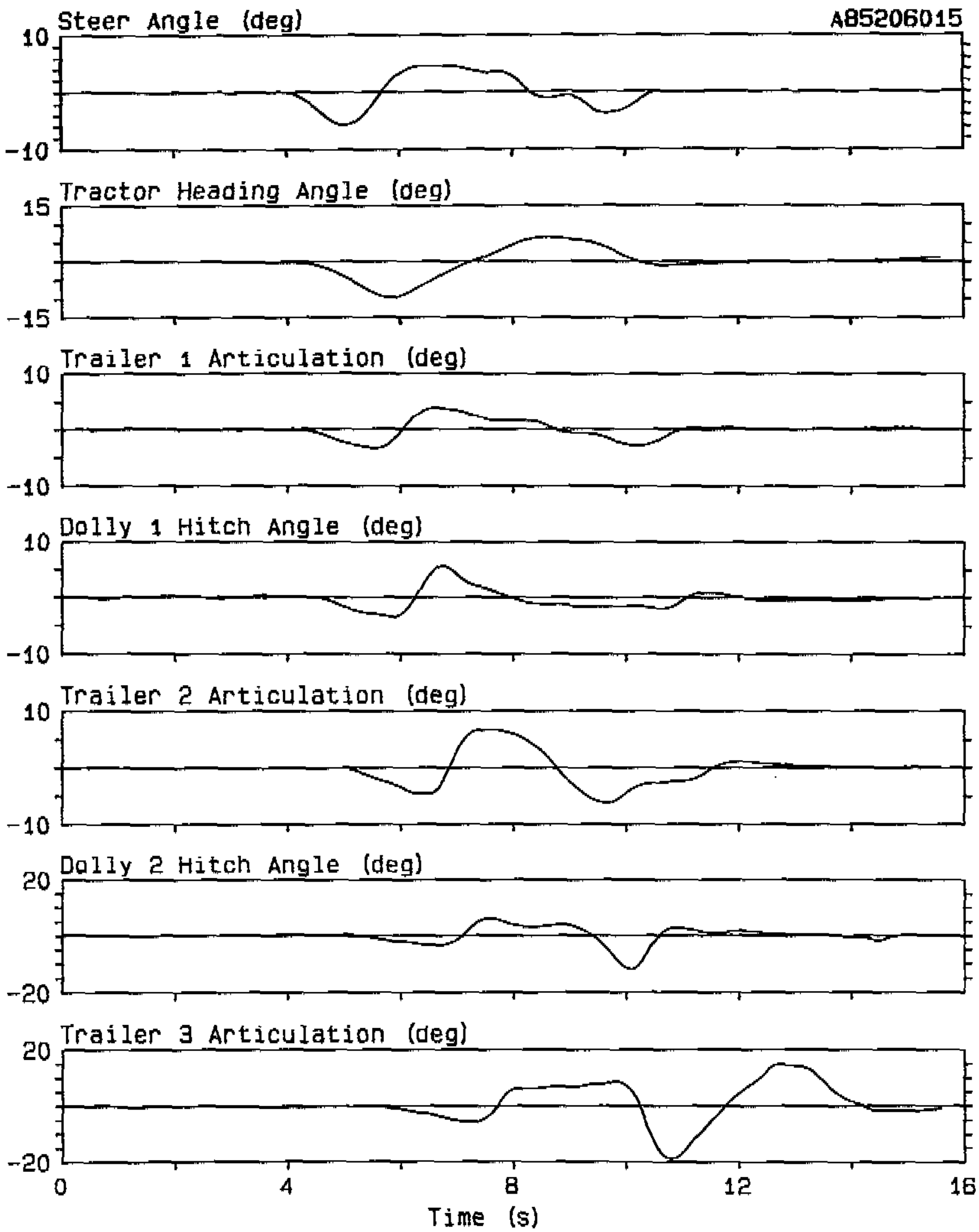


Figure 14/ Vehicle Response in Evasive Manoeuvre

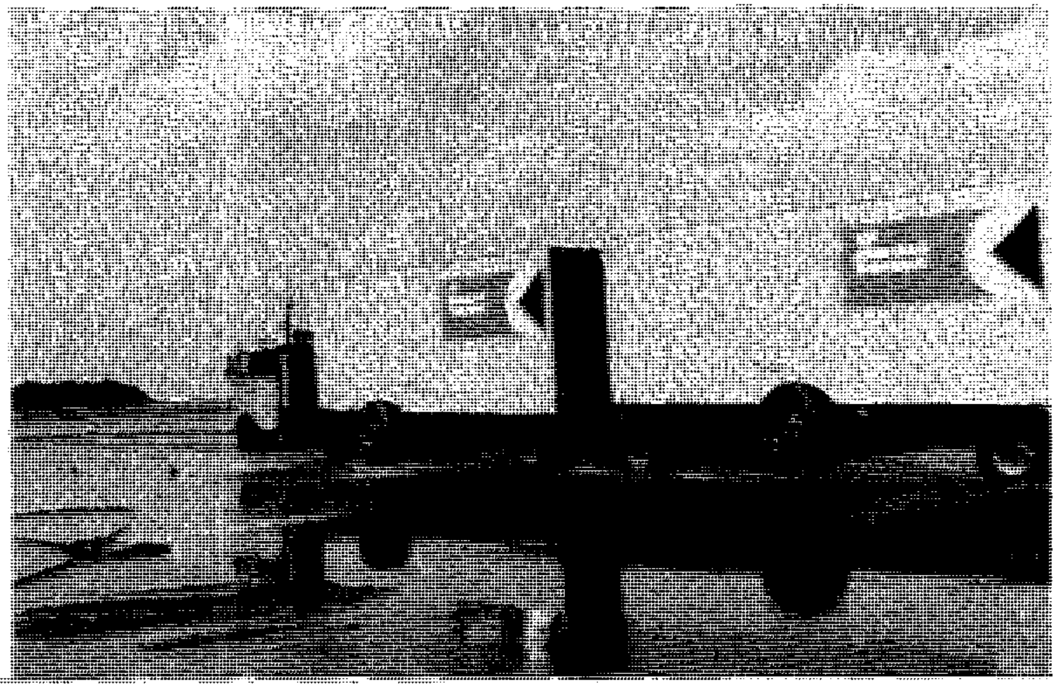


Figure 15/ Vehicle Making Evasive Manoeuvre

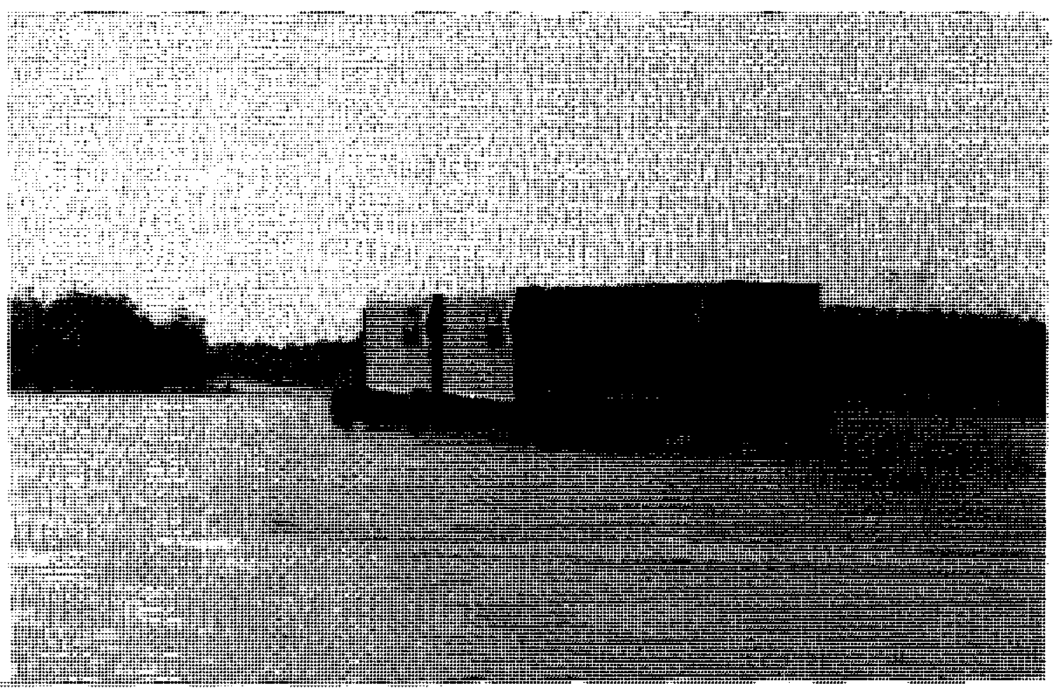


Figure 16/ Vehicle Making Sinusoidal Steer

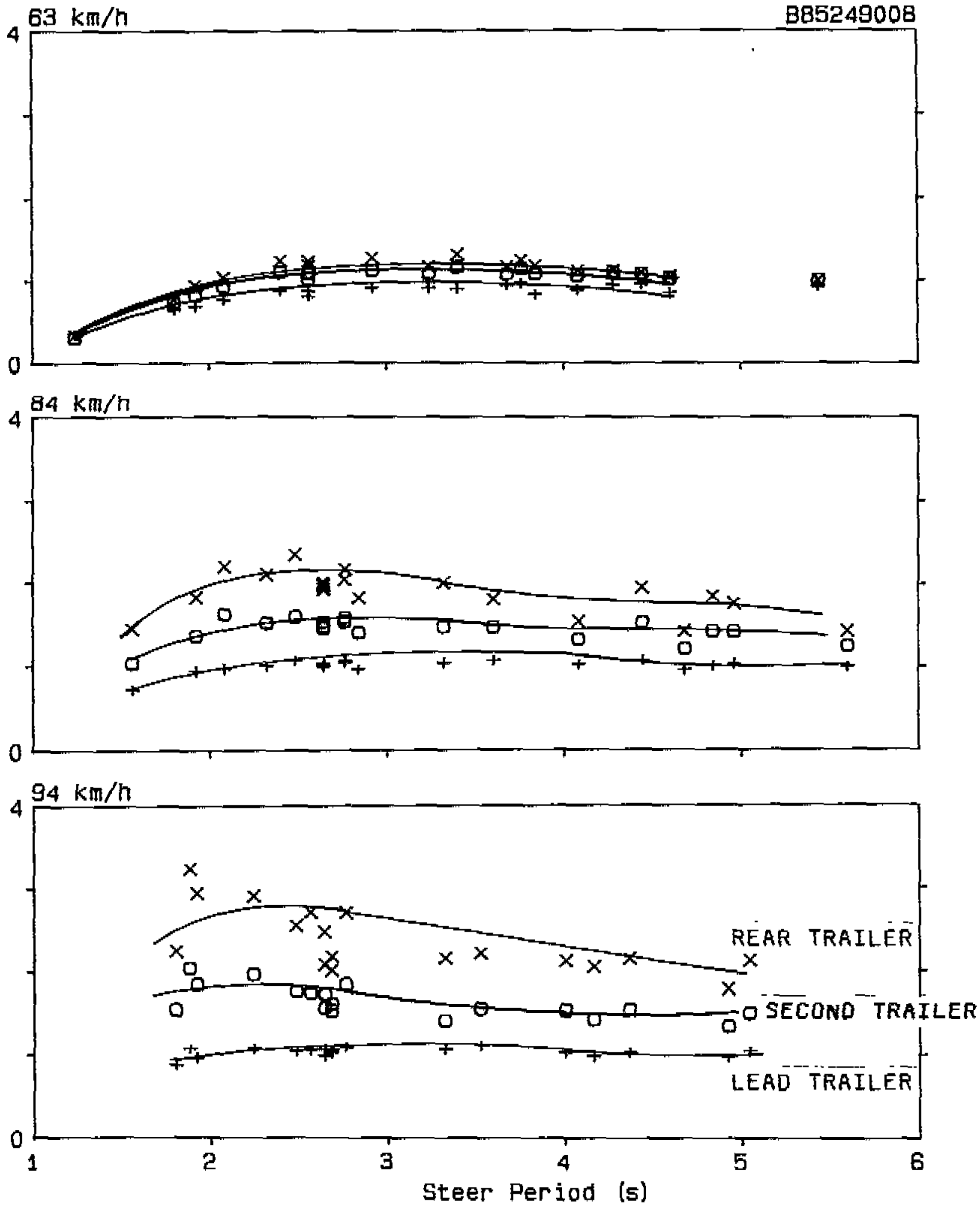
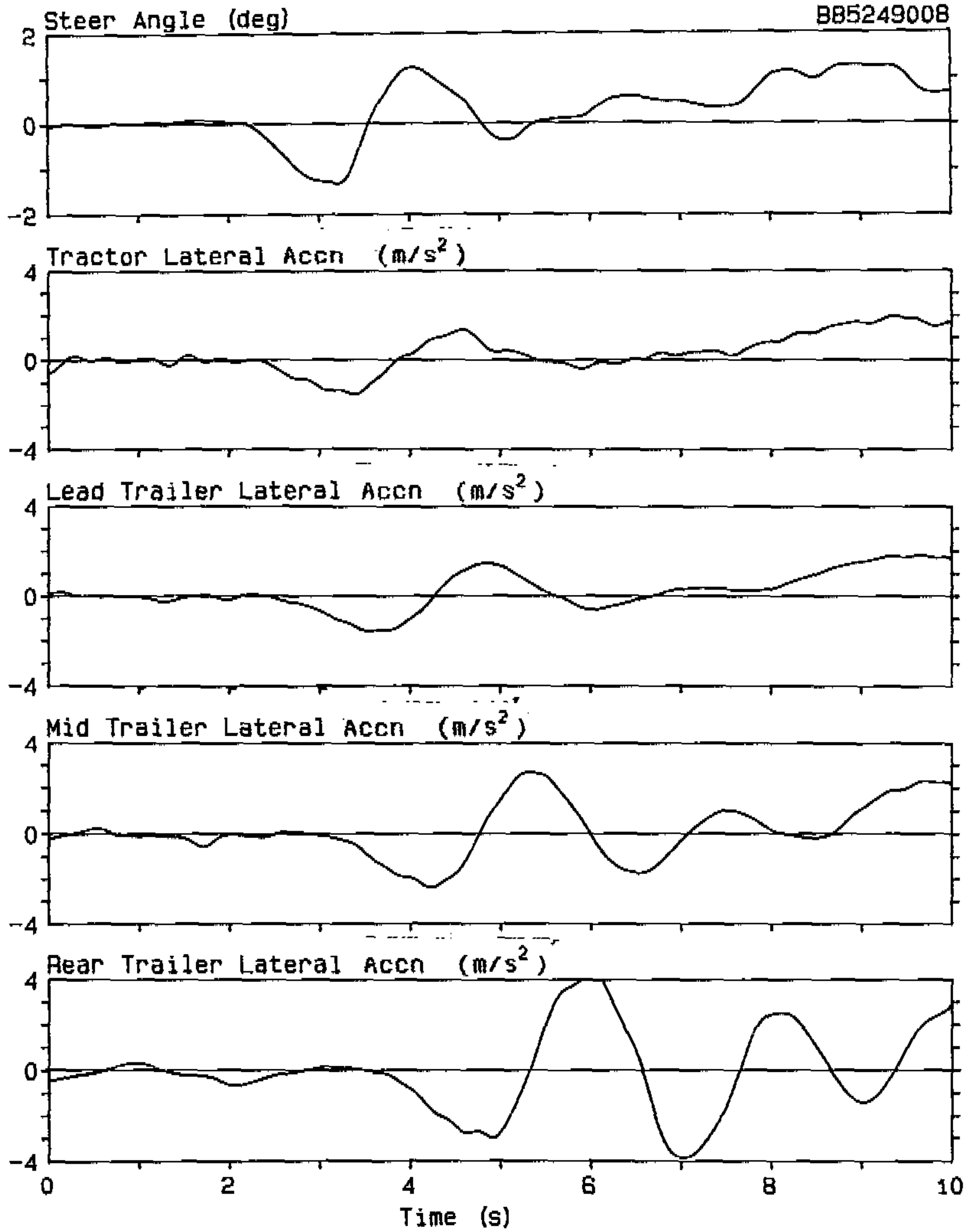


Figure 17/ Rearward Amplification of Lateral Acceleration



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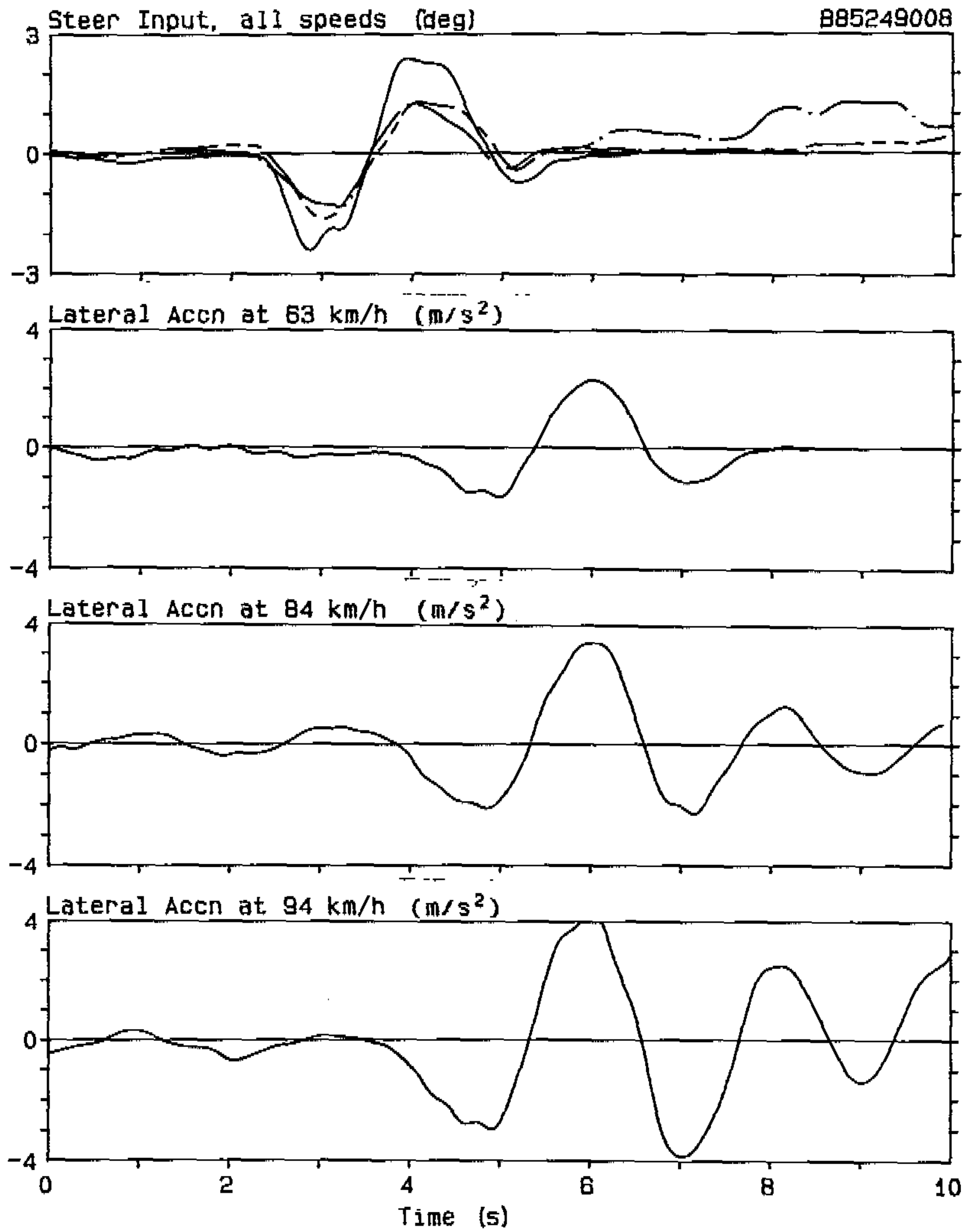

Figure 19/ Sinusoidal Steer, Rear Trailer Lateral Acceleration, Three Test Speeds

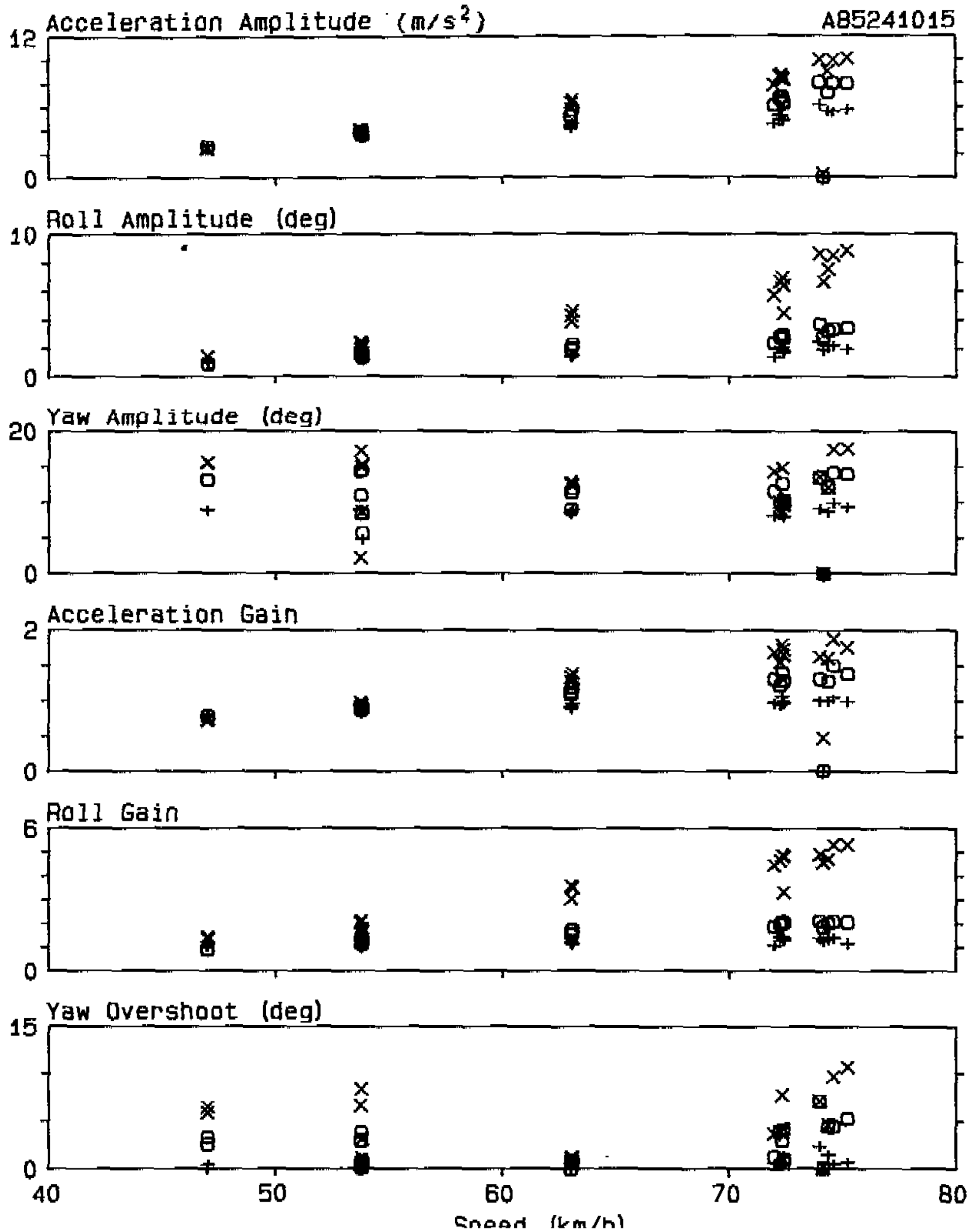

Figure 20/ Lane Change, Response Summary vs Speed

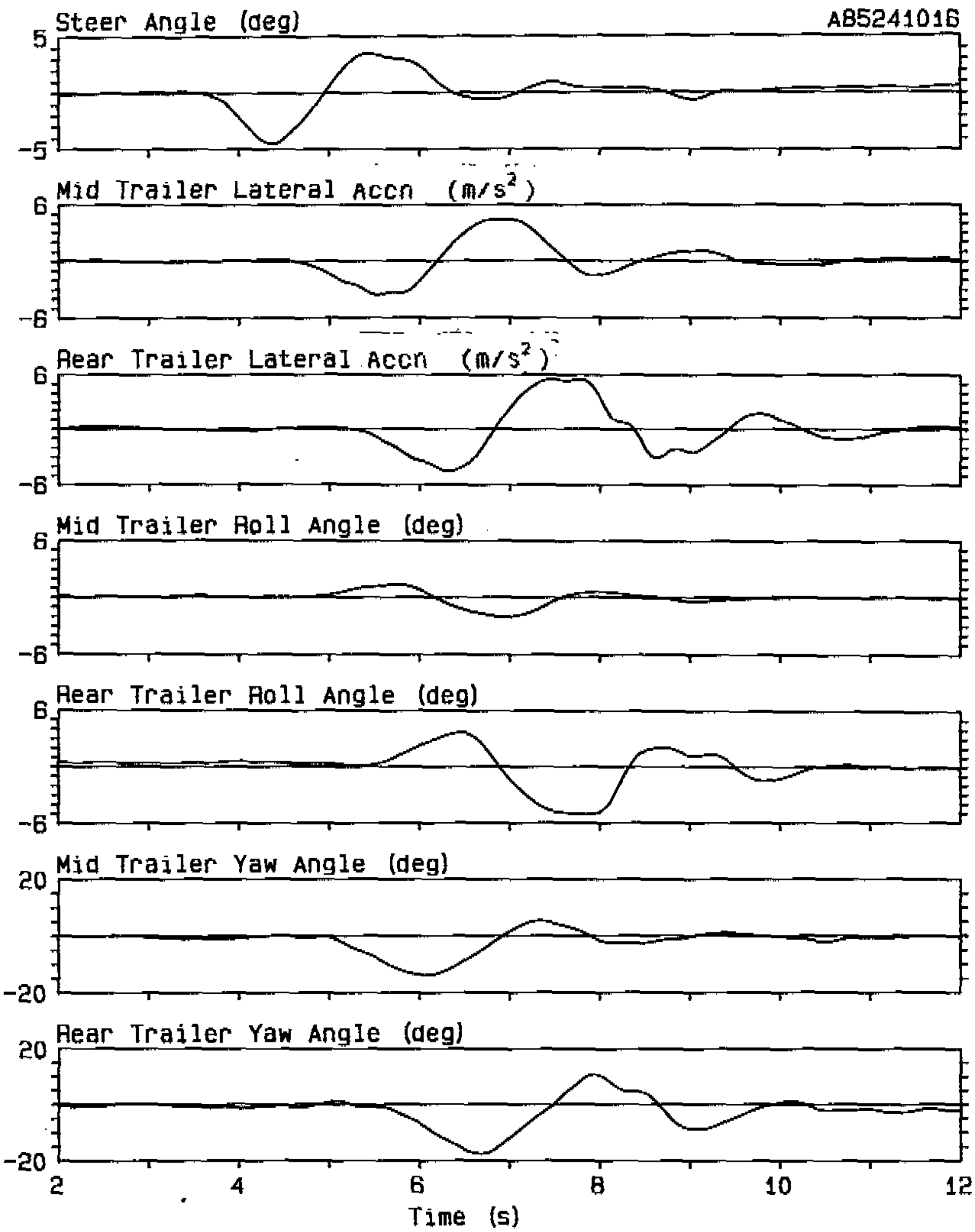

Figure 21/ Lane Change, Vehicle Responses at 75 km/h

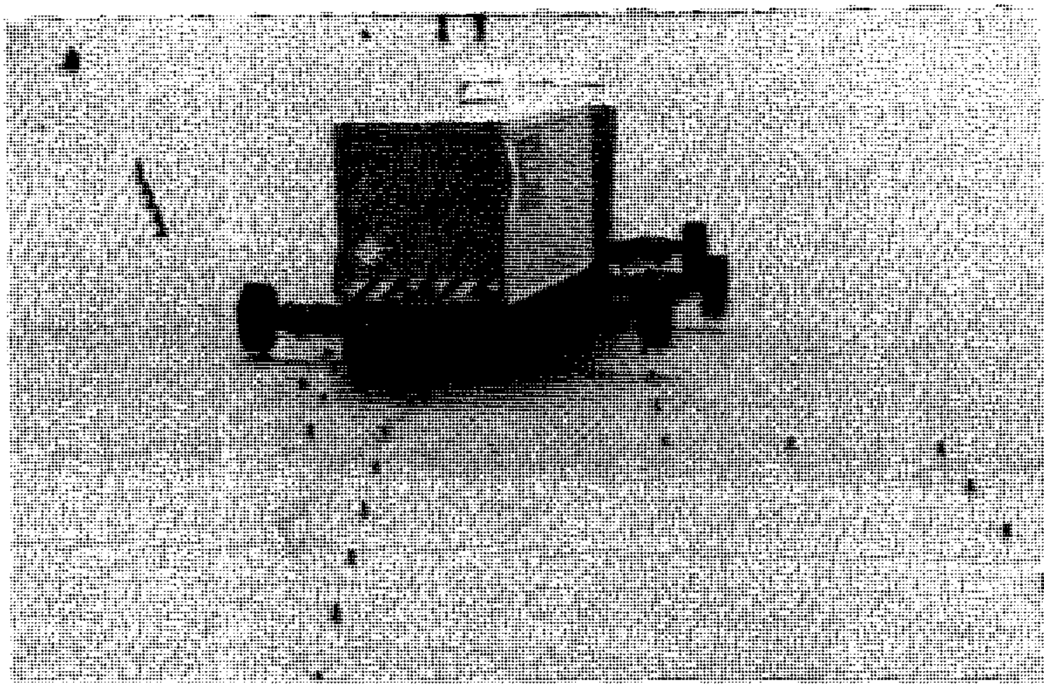

Figure 22/ Vehicle Making Lane Change

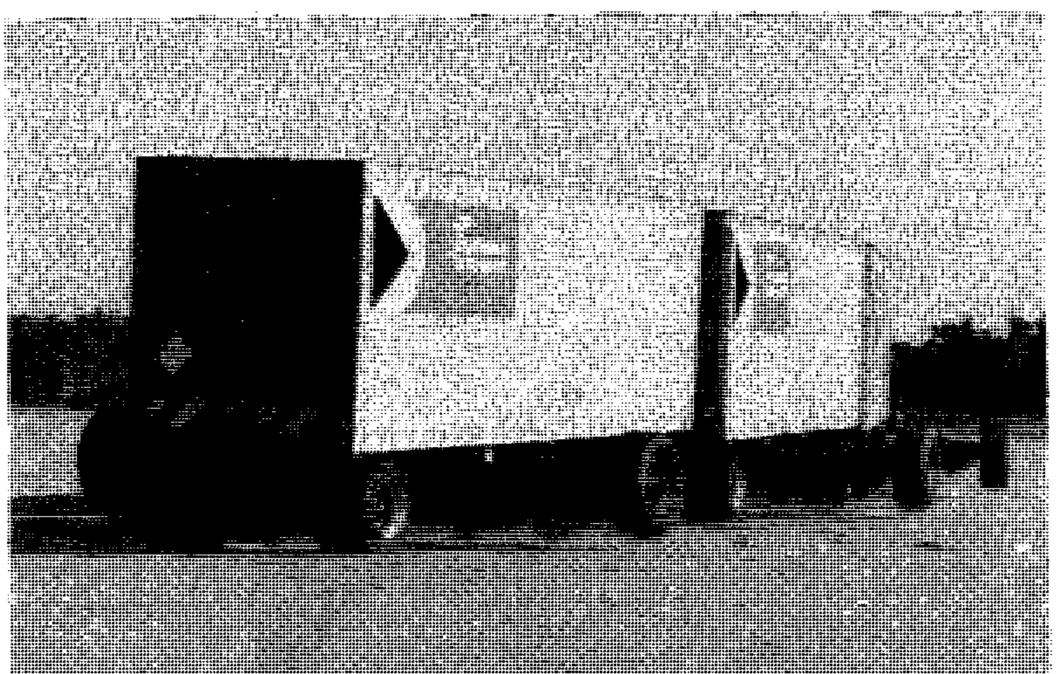

Figure 23/ Vehicle Making Steady Circular Turn

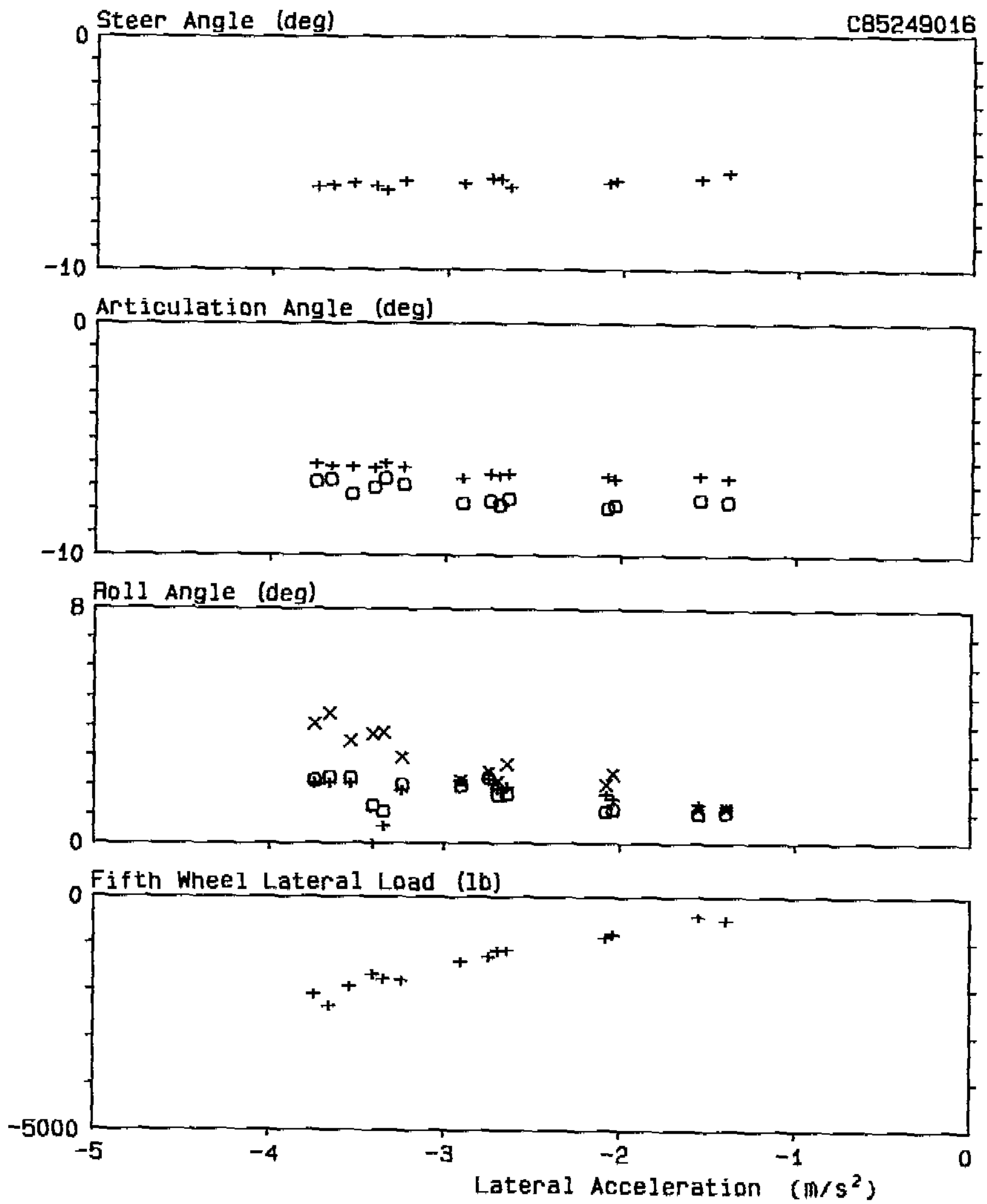

Figure 24/ Steady Circular Turn, Vehicle Responses vs Tractor Lateral Acceleration

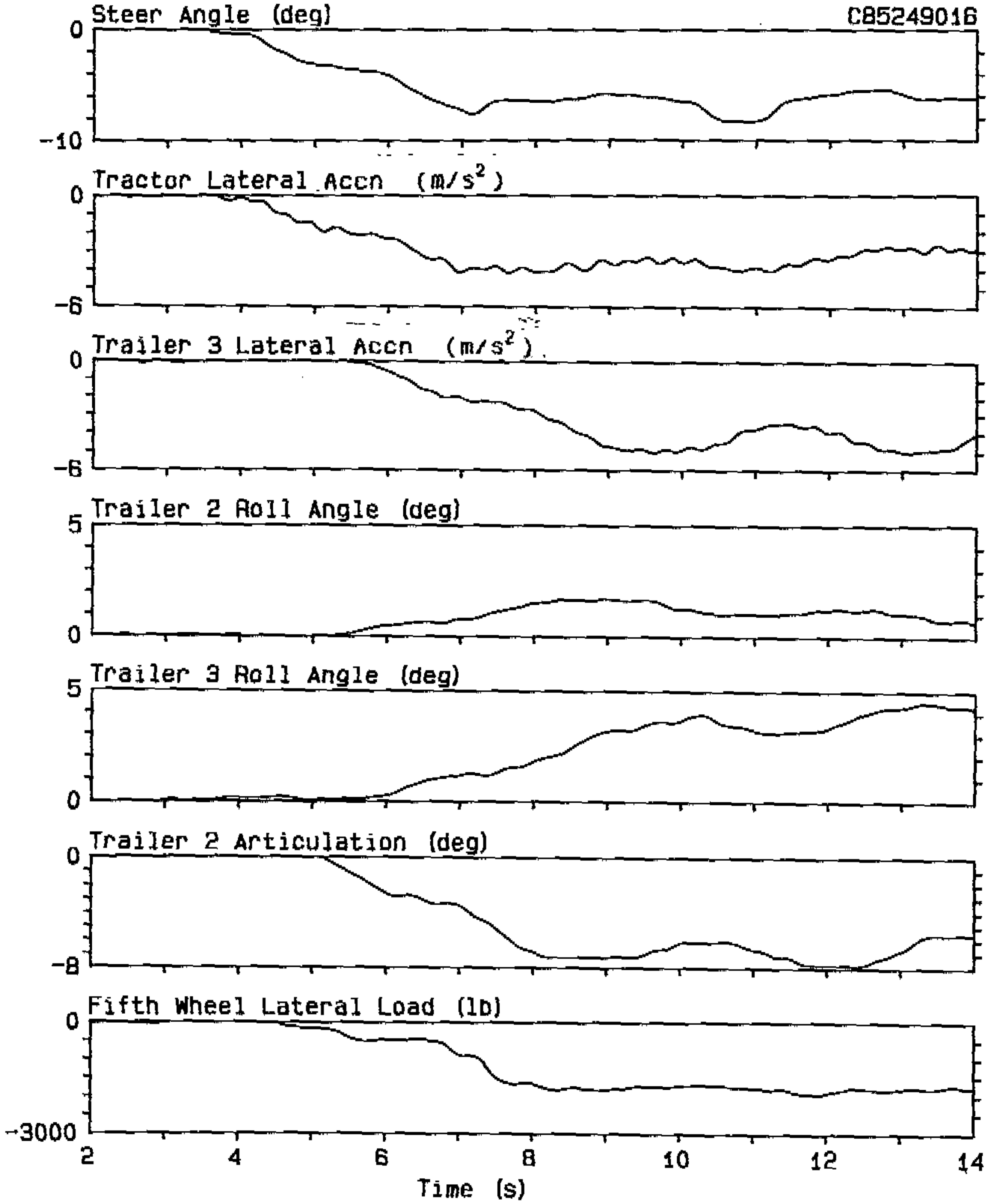

Figure 25/ Steady Circular Turn, Vehicle Responses at 54 km/h

CV-86-07

Demonstration of
Baseline Vehicle Performance: C-Train Triple

J.R. Billing
W. Mercer

Commercial Vehicles Section
Ontario Ministry of Transportation
and Communications

ABSTRACT

A C-train triple trailer combination was tested by the Ontario Ministry of Transportation and Communications (MTC) as part of the CCMTA/RTAC Vehicle Weight and Dimensions Study. The vehicle was designated a base-line vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with the empty vehicle on a low-friction surface and the loaded vehicle on a high-friction surface.

This report presents detailed results of the tests and demonstrations.

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ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The trailers were obtained by the study from CP Express and Transport. Facilities of the Transport Canada Motor Vehicle Test Centre were made available to the Ministry of Transportation and Communications (MTC). Assistance with vehicle preparation, delivery, and refurbishment was arranged by Mr. Pearson in support of this work.

The work was principally undertaken by the staff of the Automotive Technology and Systems Office of the Transportation Technology and Energy Branch of MTC: N.R. Carlton; G.B. Giles; C.P. Lam, P.Eng.; W.R. Stephenson, P.Eng.; and M.E. Wolkowicz; and assigned students G. Goertzen, S. Jazic, and D.R. Sykes. Assistance was provided by staff of various other departments of the ministry and other organizations.

The efforts of all involved are hereby acknowledged with gratitude.

1/ INTRODUCTION

The effects of changes in truck weight and dimension parameters on combination vehicle stability and handling and on pavement response to axle group loading are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle portion of the study involved both computer simulation of vehicle dynamic manoeuvres and testing of vehicles and components. Combination vehicles were classified into six families, based on the number of trailers and methods of hitching. A representative of each family was designated as the baseline vehicle configuration for that family. Additional vehicle configurations of interest were also defined. All baseline and additional vehicle configurations were tested to assemble a body of technical and visual data that described the stability and control characteristics of the vehicles with respect to certain performance measures.

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. This report presents the results of a test of a C-train triple trailer combination baseline vehicle. It refers frequently to a report describing procedures and equipment common to tests of all nine vehicles undertaken by MTC [1]. Similar reports present details of the tests of the other eight vehicles [2-9], and a summary report presents the results of tests of all six baseline vehicles [10]. A computer simulation of vehicle responses to actual test inputs using estimated vehicle data has also been conducted [11].

2/ TEST VEHICLE DESCRIPTION

The test vehicle consisted of the MTC Freightliner L1J 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 same combination was also tested concurrently as an A-train, using A-type converter dollies [6].

The equipment for these tests was obtained by the study from CP Express and Transport. No modifications were made to the trailers or dollies except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were affected. 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.

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 were made up from two ASTL SSD frames and a Sauer model RLZ 10041 self-steering axle rated at 10 000 kg (22 000 lb) and placarded for a speed of 80 km/h. The suspension was a two-spring leaf system with torque rods. The spring centre width was 0.76 m (30 in), and the track width was 2.44 m (96 in). The combination had an overall length of 31.14 m (102.17 ft).

The trailers and dollies were fitted with new Michelin XZA radial tires, in load range H and size 11R22.5. These tires were run a nominal distance of 160 km (100 mi) before any testing and were then, subsequently, used for all tests. Tire pressure was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load. This was used for all tests and represents the common operating practice of not reducing tire pressure when running empty.

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 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 1.

Table 1/ Axle Loads

	Empty		Loaded	
Axle No.	(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 empty weight exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. The loaded weight is also 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. A target axle load of 8000 kg (17 600 lb) was set for all axles except for the steer axle. This was nearly attained, with the exception of the tractor drive axles, as 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.

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.

3/ TEST PROGRAM

3.1/ Test Procedures

The test vehicle was prepared for testing in the following way:

1/ A mechanical inspection was carried out, and any necessary repairs or maintenance was done.
2/ Outrigger and safety cable attachments and load block retention sills were installed on the trailers, and safety cable attachments were installed on the dollies.
3/ Outriggers were installed on the trailers.
4/ The boxes containing instrument packages, power supplies and signal conditioning, other instruments, and cabling were installed.
5/ New tires were installed, and pressures were set.
6/ Other fittings necessary for testing were installed.
7/ Concrete blocks were located on the trailer beds to achieve specified axle loads.
8/ Notes were made from detailed physical inspection, including an inventory of components and measurement of dimensions.
9/ The MTC tractor was coupled to the trailers.
10/ The combination vehicle was weighed, empty and loaded.
11/ A functional test of the on-board electronics was conducted.
12/ Test runs were made to shake down the vehicle instrumentation and familiarize the test driver with the vehicle's handling characteristics.
13/ Tires were run a nominal distance of 160 km (100 mi).
14/ Articulation angle between the tractor and lead trailer was calibrated.
15/ Details of the vehicle and test equipment were recorded on photographs and videotape.

The following tests were performed:

- Offtracking
- Right-hand turn
- Channelized right turn
- Air brake system
- Straight-line braking, empty vehicle, low-friction surface
- Evasive manoeuvre, empty vehicle, low-friction surface
- Sinusoidal steer, loaded vehicle, high-friction surface
- Lane change, loaded vehicle, high-friction surface
- Normal straight-line driving
- Steady circular turn, loaded vehicle, high-friction surface

All tests followed standard procedures [1], except as noted.

3.2/ Instrumentation

The instrumentation shown in Table 2 was installed. Brake pressure transducers were only installed in the trailers and dollies for the air brake system test, but all other instrumentation was installed for all tests. Data were always captured from all instrumentation, but only those pertinent to a particular test were analysed.

Tractor instruments were selected from the instrumentation that is permanently installed on the tractor. Instruments for the two front trailers were mounted in boxes placed inside the van on the trailer deck, which also contained power supplies and signal conditioning. Instruments for the rear trailer and dollies were wired into these boxes. Trailer lateral acceleration and roll angle were measured at a point midway between the kingpin and axle, which was very close to the trailer sprung mass centre of gravity.

Full details of the instrumentation, signal conditioning, and data capture system are presented elsewhere [1].

3.3/ Data Capture and Data Processing

Data were digitized on board the vehicle and transmitted by telemetry as a pulse-code modulated (PCM) data stream to a ground station, where they were recorded on magnetic tape and captured in real time by an HP-1000 computer system. Test data for a run were processed immediately after the run, and results from a series of runs were subsequently analysed using the computer system [1].

Many test runs of all types were conducted for this vehicle. Not all these runs were used in the preparation of this report. In a number of instances, a run failed to meet a test condition.

Table 2/ Instrumentation Installed

No	Measurement	Instrument	Full Scale
1	Tractor steer angle	Spectrol 139 potentiometer	25.02°
2	Tractor roll angle	Humphrey CF18-0907-1 gyroscope package	8.85°
3	Tractor lateral acceleration	Kistler 303B accelerometer	0.957 g
4	Tractor yaw rate	Humphrey RT03-0502-1 angular rate transducer	38.7°/s
5	Tractor longitudinal acceleration	Kistler 303B accelerometer	0.974 g
6	Tractor speed, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	104.8 km/h
7	Tractor distance, axle 1 right	Airpax 087-304-0044 zero velocity magnetic pickup	56.3 m/ramp
8	Tractor fifth wheel load, left-hand side	MTC load cell	9890 lb
9	Tractor fifth wheel load right-hand side	MTC load cell	10 290 lb
10	Tractor treadle valve pressure	Celesco PLC-200G	100 psi
11	Tractor brake pressure, axle 2 Left	Celesco PLC-200G	99.80 psi
12	Tractor lateral acceleration at fifth wheel	Columbia SA-107 accelerometer	0.996 g
13	Tractor yaw angle	Humphrey CF18-0907-1 gyroscope package	17.73°
14	Trailer 1 articulation angle	Celesco pull cord DV-301-150	23.194°
15	Trailer 1 lateral acceleration	Columbia SA-107 accelerometer	0.995 g
16	Trailer 1 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.90°
17	Trailer 1 outrigger touchdown	Strain gauge bridge	1.0 V
18	Dolly 1 steer angle	Spectrol 139 potentiometer	25.0°
19	Dolly 1 lateral acceleration	Columbia SA-107 accelerometer	0.996 g
20	Brake pressure, axle 4 right	Celesco PLC-200G	104.96 psi
21	Brake pressure, axle 5 right	Celesco PLC-200G	101.06 psi
22	Brake pressure, axle 6 right	Celesco PLC-200G	102.07 psi
23	Brake pressure, axle 7 right	Celesco PLC-200G	101.93 psi
24	Brake pressure, axle 8 right	Celesco PLC-200G	106.79 psi
25	Spare		
26	Spare		
27	Trailer 2 articulation angle	Spectrol 8409 potentiometer	22.8°
28	Trailer 2 lateral acceleration	Columbia SA-107 accelerometer	0.980 g
29	Trailer 2 roll angle	Humphrey VM02-0128-1 vertical gyroscope	8.91°
30	Trailer 2 outrigger touchdown	Strain gauge bridge	1.0 V
31	Dolly 2 steer angle	Spectrol 139 potentiometer	25.0°
32	Dolly 2 lateral acceleration	Columbia SA-107 accelerometer	0.993 g
33	Trailer 3 articulation angle	Spectrol 8409 potentiometer	22.7°
34	Trailer 3 lateral acceleration	Columbia SA-107 accelerometer	0.986 g
35	Trailer 3 roll rate	Humphrey RT03-0502-1 angular rate transducer	80.85°/s
36	Trailer 3 outrigger touchdown	Strain gauge bridge	1.0 V

4/ RESULTS

4.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions, as shown in Figure 3. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [1].

The results are shown in Table 3. The measured data were averaged for the left and right turn and then compared to data generated by a simple offtracking formula [12]. The difference between actual and computed values, shown in the last column of Table 3, is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

The final offtracking for the counter-clockwise turn is shown in Figure 4. After averaging for both directions and correcting for differences in axle track width, the offtracking of 2.39 m (7.84 ft), shown in Figure 4, became 2.52 m (8.33 ft).

Table 3/ Offtracking

Axle No.	Track Width (m)	Radius to Inner Wheel Right Turn (m)	Radius to Inner Wheel Left Turn (m)	Difference (m)	Average (m)	Calculated (m)	Difference %
1	2.31	27.60	27.66	0.06	27.63	27.56	-0.25
2	2.37	27.26	27.31	0.05	27.29	27.21	-0.29
3	2.37	27.23	27.26	0.03	27.25	27.21	-0.15
4	2.53	26.29	26.35	0.06	26.32	26.33	+0.04
5	2.53	26.36	26.43	0.07	26.40	26.48	+0.30
6	2.53	25.50	25.58	0.08	25.54	25.66	+0.46
7	2.53	25.53	25.63	0.10	25.58	25.81	+0.89
8	2.53	24.75	24.86	0.11	24.80	24.98	+0.72

4.2/ Right-Hand Turn

A 90° right-hand turn is a very demanding manoeuvre for a large truck. The vehicle's swept path in a 90° right-hand turn of 15 m (49.2 ft)

radius was measured, according to the standard test procedure [1]. This radius is typical in an urban area or where there is limited truck traffic. The swept path is shown in Figure 5.

The vehicle is shown in Figure 6 during the turn, at a point close to its maximum excursion out of the exit lane. The maximum excursion out of lane was 3.70 m (12.14 ft) or slightly over one lane width. It was out of the exit lane for a distance of 22.0 m (72.18 ft), as derived from Figure 5. This test was conducted at a creep speed and represents the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

4.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [1].

The vehicle is shown during the turn in Figure 7. The clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Figure 8 as a function of distance through the curve. The minimum clearance was only 0.18 m (7 in) in the 5.5 m (18 ft) wide roadway.

The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. The vehicle barely made it through the channel, with the left front wheel tracking right on the outer curb. In practice, a driver would allow some clearance on this side, if only to stay clear of catch basins. This would mean the rear axle would likely run over the inner curb. The test was run at creep speed, the worst condition, as the effect of lateral acceleration is to reduce the geometric offtracking measured in this test. However, in an urban area the truck driver cannot be guaranteed free-flowing traffic at such roadway geometry, so it is evident that this channelized right turn may limit access of such large combinations.

4.4/ Air Brake System

The air brake system of the combination was evaluated according to standard test procedure [1].

The trailer air brake system was inspected. A schematic of the system is shown in Figure 9. The dollies were not equipped with a booster relay valve to speed transmission of the signal. All trailer slack adjusters were automatic, whereas those on the dollies required manual adjustment. Stroke was adjusted to the minimum, about 32 mm (1.25 in) on each axle. The tractor was supplied with shop air, regulated at 689 kPa (100 psi). Pressure transducers were installed at all trailer and dolly axles.

The SAE J982a style test was performed for the full triple combination; for the double, which resulted when air to the second dolly was shut off; and for the tractor-trailer when air to the first dolly was shut off. The results of these tests are presented in Tables 4, 5, and 6. A typical time history response of application and release for the full triple is presented in Figure 10. The timing of axle 7 is slower than axle 8 on the rear trailer. This is a desirable situation, because when a trailer axle is slower than its dolly axle, the inertia of the trailer pushes the dolly for a short time while the dolly axle is braking and the trailer axle is still rising to its steady pressure. This would provide a potential dolly jackknife situation in hard braking of an empty vehicle on a low-friction surface. The timing of axles 5 and 6 on the second trailer was not close.

Table 4/ Air Brake Timing, SAE J982a Style Test, Triple

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.11	0.16	88.6
Axle 2	0.39	0.56	88.2
Axle 4	0.96	3.68	85.3
Axle 5	1.25	3.78	85.9
Axle 6	1.52	3.98	86.4
Axle 7	1.70	4.00	83.9
Axle 8	1.57	4.08	85.9

Table 5/ Air Brake Timing, SAE J982a Style Test, Double

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.08	0.16	89.4
Axle 2	0.38	0.56	88.8
Axle 4	0.76	2.06	85.6
Axle 5	0.96	2.19	85.9
Axle 6	0.85	2.12	86.4

Table 6/ Air Brake Timing, SAE J982a Style Test, Semi

Location	Application Timing 0-60 psi (s)	Release Timing to 5 psi (s)	Final Pressure (psi)
Treadle	0.05	0.14	89.2
Axle 2	0.37	0.57	90.5
Axle 4	0.37	0.75	87.2

The results in these tables are the average of several tests in each case, each with a time resolution of 0.02 s. Figure 10 is a typical test used in these averages.

The results when trailers were progressively added are interesting. As a semi (Table 6), application times for tractor and trailer were both 0.37 s, an ideal situation. When the second trailer was added (Table 5), the first trailer application time was prolonged to 0.76 s. When the rear trailer was added (Table 4), the second trailer application time was increased from 0.85 to 1.52 s, and the first trailer application time, to 0.96 s.

The application times of the SAE J982a style test compare with those obtained from a test conducted previously by MTC on another triple combination [15]. The benefit to brake timing of booster relay valves on the dollies is amply demonstrated when comparing these timing results to triple combinations equipped with such valves [6,14]. The release times are considered excessive.

4.5/ Straight-Line Braking

It is difficult to conduct rigorous braking tests and achieve consistent results. A demonstration of modes of instability of the combination vehicle in straight-line braking was, therefore, conducted. A series of runs was made with the empty vehicle approaching the low-friction test area at 47 km/h and the driver braking using the treadle valve. Runs were made using various application pressures, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [1].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit.

The time history of a typical run that resulted in loss of control is shown in Figure 11. The brake application of about 221 kPa (32 psi) caused the tractor to jackknife to the left. The driver released the brakes, steered to the right, and drove out of the manoeuvre without coming to a full stop. He probably would not have been able to arrest the jackknife at a higher speed. If the tractor front axle brakes had been used, it is probable the tractor would not have jackknifed at this speed.

A summary of peak vehicle responses from the runs is shown in Figure 12 as a function of average treadle valve pressure.

4.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. Gates of 25 m (82 ft) were used for the lane change to the left and the return to the original lane, separated by 20 m (65.6 ft) in the left lane. This was necessary because the vehicle would not go through the standard. The runs were made in accordance with the standard test procedure [1].

The vehicle combination was evaluated primarily in terms of the lateral acceleration and yaw responses of the vehicle units. These are shown in Figure 13. Lateral acceleration amplitude for vehicle units increased as speed increased up to approximately 63 km/h. Tractor heading amplitude tended to decrease with speed, the first trailer remained relatively constant, and the second and third trailers increased slightly. The vehicle slid little, with the exception of the tractor. At the higher speeds the tractor tended to slide laterally on the return to the original lane. The steer input remained relatively constant throughout the speed range, indicating that the tractor's slide was possibly caused by lateral forces generated by the trailers. At 63 km/h there was severe second and third trailer swing as the driver recovered after returning to the original lane. There was insufficient sideforce on the low-friction surface to cause any B-dolly steer. From that point of view, therefore, this vehicle was behaving as a B-train in this manoeuvre.

A typical run at 63 km/h is shown in Figure 14.

4.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for this combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 63, 84, and 94 km/h, with steer input periods between about 2 and 5 s.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. Lateral acceleration gains of the three trailers are presented in Figure 15, as a function of tractor steer input period for the three test speeds. Each gain is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless.

It is evident from Figure 15 that rearward amplification increases moderately with speed, rearward by trailer, and is also sensitive to steer period reaching the highest value at around 2.5 s. The results, show that, at highway speed, the C-train triple is not a very responsive vehicle. The reason for this is that its inherent stability is high. Stability and response of mechanical systems have an inverse relationship: high stability means low response to input and vice versa.

Figure 16 shows the response of a typical run for a steer period of about 2.5 s at 94 km/h. Figure 17 shows typical rear trailer responses for the three test speeds. The response characteristics of this vehicle are much different than those of the comparable A-train, which was found to be much less stable [6].

4.8/ Lane Change

The objective of this test was to evaluate vehicle stability characteristics in a dynamic manoeuvre. A series of runs was made where the driver made a lane-change manoeuvre, which is considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [1].

A gate of 30 m (98.4 ft) was used, to provide a vehicle speed of about 80 km/h, which is a typical speed limit and might permit some comparison of the results of this test with those described in the preceding sections

The results from all runs are summarized in Figure 18. The peak-to-peak lateral acceleration, roll, and yaw (or heading) angles all show an increase as the limiting speed of 89 km/h was reached, at which point the trailers were sliding rather violently to the left into the adjacent lane. While there was no outrigger touchdown in this manoeuvre, there undoubtedly would have been if the centre of gravity of the trailers had been higher and, perhaps, at a somewhat lower speed than 84 km/h. Lateral acceleration and roll gains are reasonably consistent with the rearward amplifications at 63 and 84 km/h. The yaw overshoot of the trailer clearly illustrates the trailers swinging at the limiting speed.

Figure 19 shows the steer input and vehicle response for a test run at 89 km/h. As can be seen, roll and overshoot tend to occur at all trailers, whereas high left roll only is evident on trailer 3. Figure 20 shows this vehicle recovering from slide out of lane.

4.9/ Normal Straight-Line Driving

The objective of this test was to attempt to evaluate lateral motion of the rear trailer of the combination, otherwise known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [1].

As previously mentioned, the vehicle was not very responsive, and the slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in little rear trailer sway that was perceptible to the occupants of a chase vehicle. Root mean square (RMS) lateral acceleration of the rear trailer was 2.05 g/°of RMS steer input.

4.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics to determine the high-speed offtracking of the vehicle and examine the side loads exerted on the tractor by the trailers. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The vehicle is shown in this manoeuvre in Figure 21. The results of this test are summarized in Figure 22. The vehicle combination was evaluated primarily in terms of the roll response of the vehicle units. Average steady-state roll angles, presented as a function of tractor lateral acceleration, increased with speed. However, the trailer centre of gravity was not high enough for the rollover point to be reached in this test. Rollover would normally be expected with this vehicle, because the payload centre of gravity would usually be considerably higher than that of the vehicle as tested. Average steady-state articulation angles decrease modestly with increase in lateral acceleration, and as a consequence, the offtracking decreases. The lateral force experienced by the tractor fifth wheel, presented as a function of tractor lateral acceleration, shows a gradient of 23.4 kN/g (5250 lb/g).

At the limiting speed of 55 km/h, a lateral acceleration of 0.46 g, the rear trailer swung out and the driver departed from the circular trajectory, as shown in Figure 23.

5/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation.

Tests were conducted in various weather conditions. Tires wore progressively as the various tests were conducted. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailers were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal because of the underslung outriggers.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results, except for centre of gravity height, which has been mentioned already where it may have affected the results. The results presented pertain to the particular vehicle tested, and results different in some respects might be obtained for another vehicle at another time.

This vehicle was considered an easy vehicle to drive by the test driver. The short trailer wheelbase and single axle made it easy to manoeuvre in low-speed turns, though moderate driver effort was required in these and dynamic tests, as the trailers imposed significant forces on the tractor. The driver could feel the second and third trailers pushing the tractor through a manoeuvre once it had started, because the B-dolly did not steer initially, if at all, on the low-friction surface. The vehicle was much less responsive - more stable -- than the comparable A-train [6], which, in some respects, made it easier to drive because there was less trailer sway.

6/ CONCLUSIONS

A C-train triple trailer combination was tested by the Ontario Ministry of Transportation and Communications, as part of the CCMTA/RTAC Vehicle Weights and Dimensions Study. The vehicle was designated a baseline vehicle and the representative test vehicle for similar configurations.

The vehicle was subjected to turning, air brake system, lateral/directional and roll stability, and trailer sway tests. A demonstration of straight-line braking was also conducted. Tests were conducted with an empty vehicle on a low-friction surface and a loaded vehicle on high-friction surface.

The length of this vehicle clearly contributed to the significant space required to make turns. Since such vehicles only operate by special permit, however, this may not be a major issue because the permit usually limits where the vehicle may go.

The air brake system was slow, largely because booster relay valves were not used on the dollies.

The lateral/directional stability of the vehicle was good, both empty on a low-friction surface and loaded on a high-friction surface. The roll stability was good, primarily because of the low trailer centre of gravity height. A higher centre of gravity would significantly reduce the roll threshold.

The C-train triple is clearly preferable to the A-train triple because of its higher stability at highway speeds.

7/ REFERENCES

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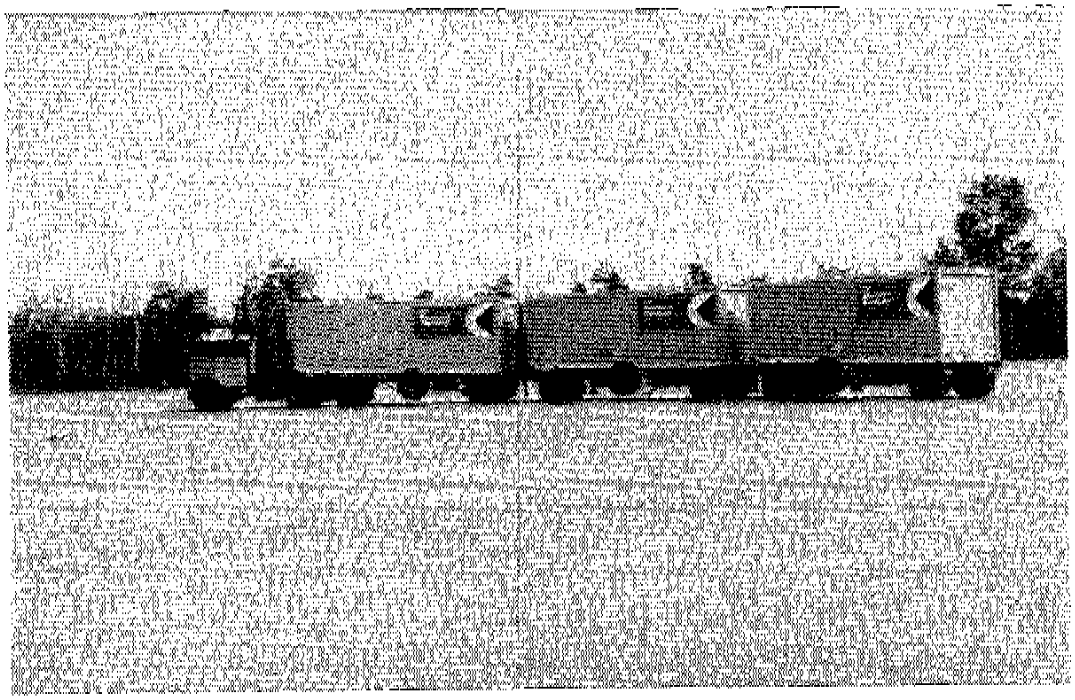


Figure 1/ View of Vehicle

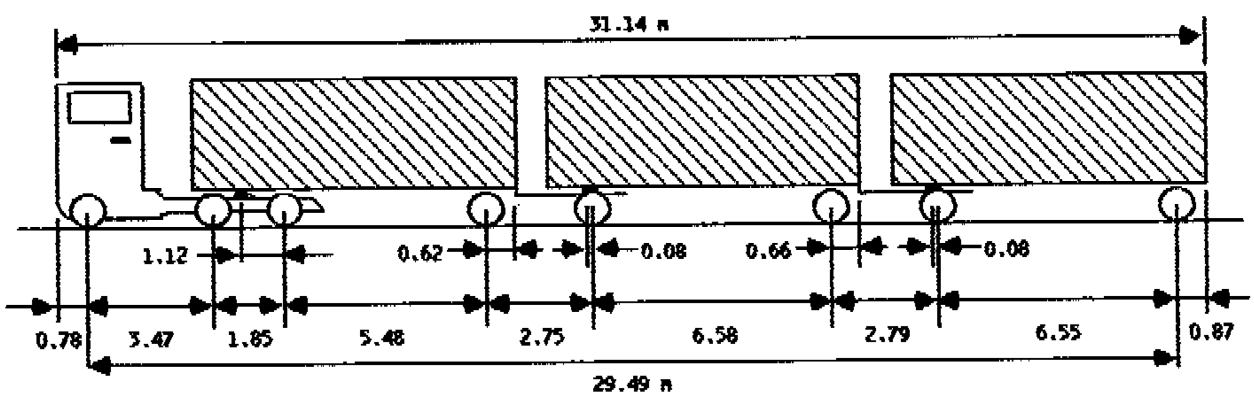


Figure 2/ Vehicle Dimensions

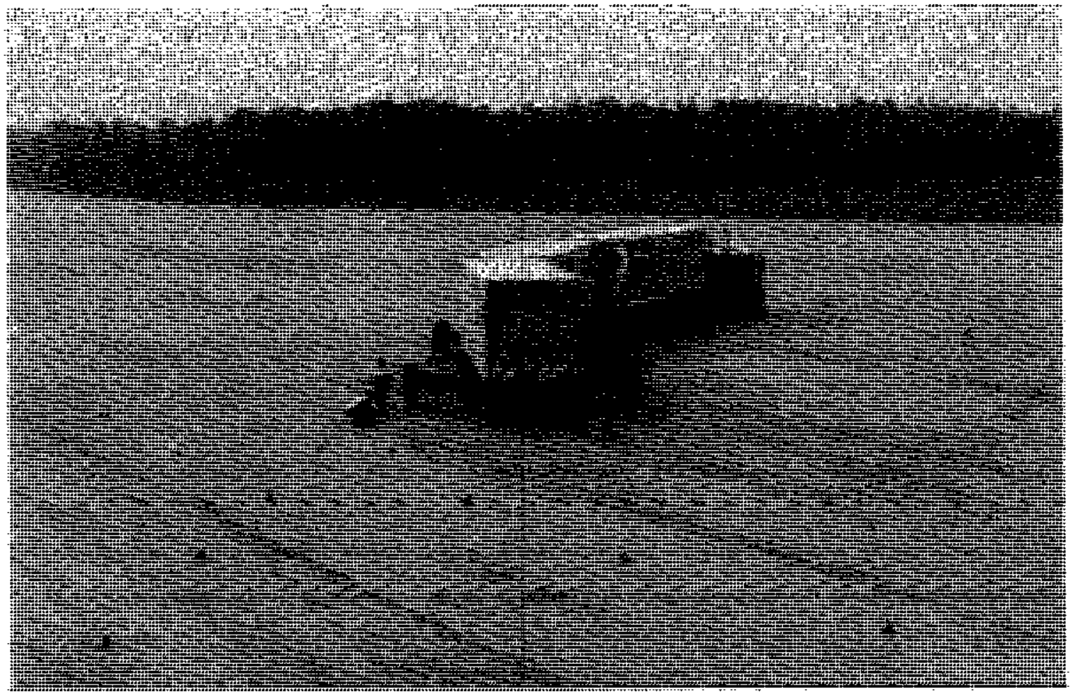


Figure 3/ Clockwise Offtracking

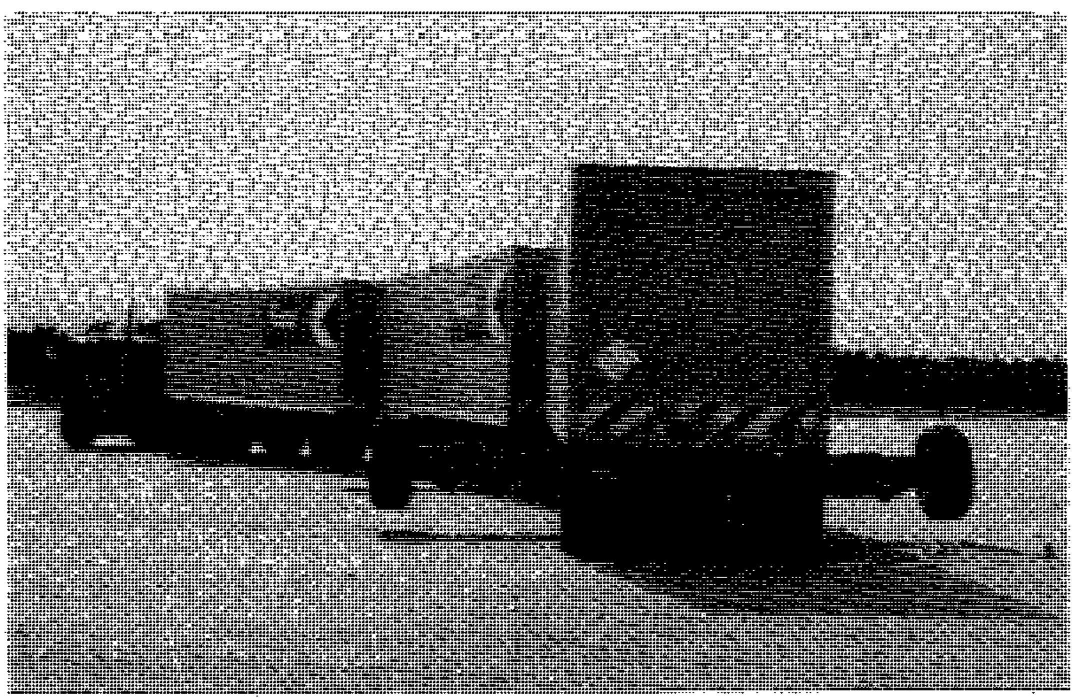
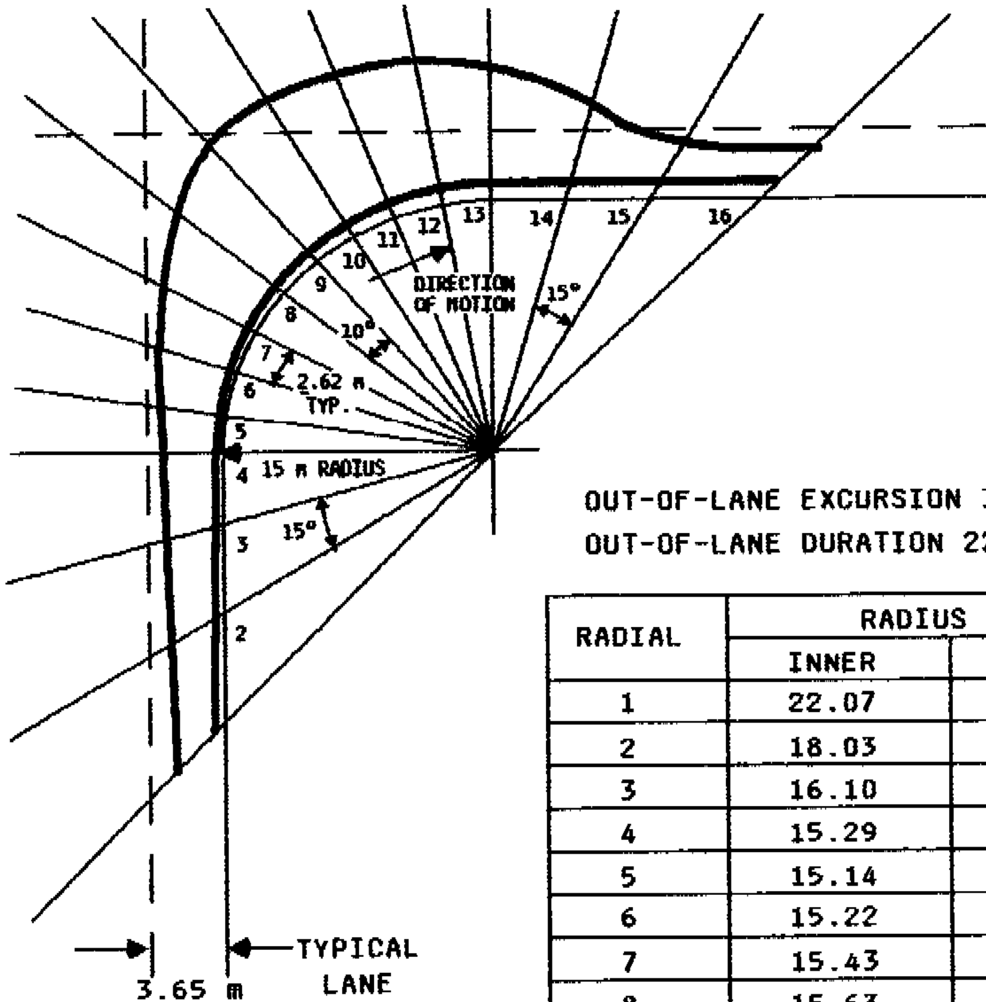


Figure 4/ Counter-Clockwise Final Offtracking



OUT-OF-LANE EXCURSION 3.7 m
OUT-OF-LANE DURATION 22 m

RADIAL	RADIUS (m)	
	INNER	OUTER
1	22.07	25.25
2	18.03	20.67
3	16.10	18.68
4	15.29	18.11
5	15.14	18.43
6	15.22	19.29
7	15.43	20.47
8	15.63	22.15
9	15.71	23.43
10	15.65	23.93
11	15.51	23.98
12	15.45	22.99
13	15.59	22.32
14	16.37	20.70
15	18.23	20.45
16		

Figure 5/ Right-Hand Turn Swept Path

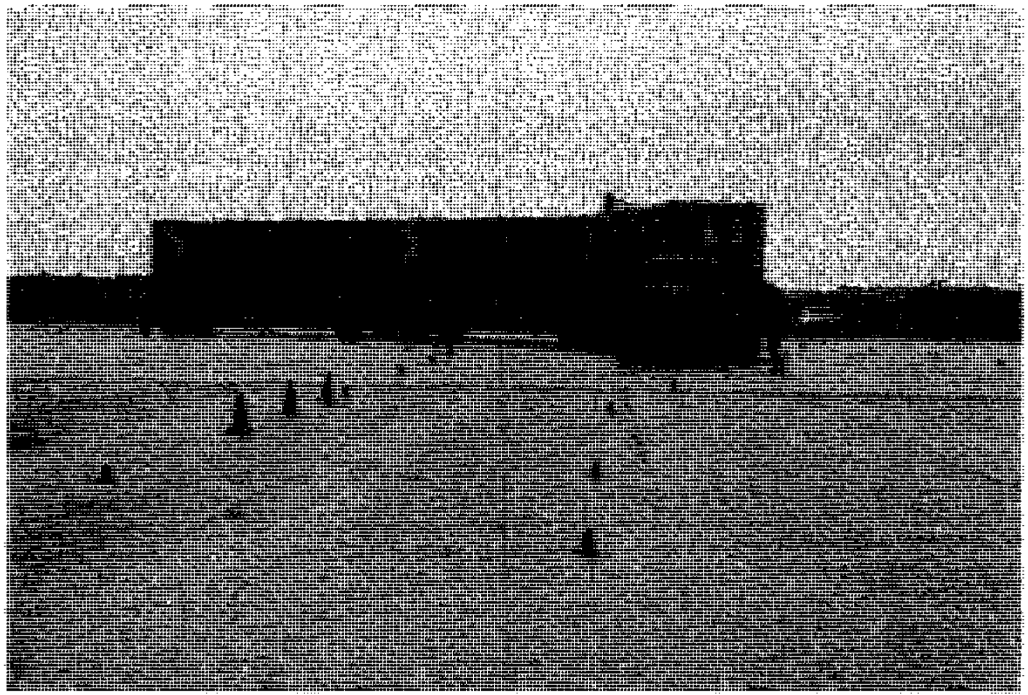


Figure 6/ Right-Hand Turn

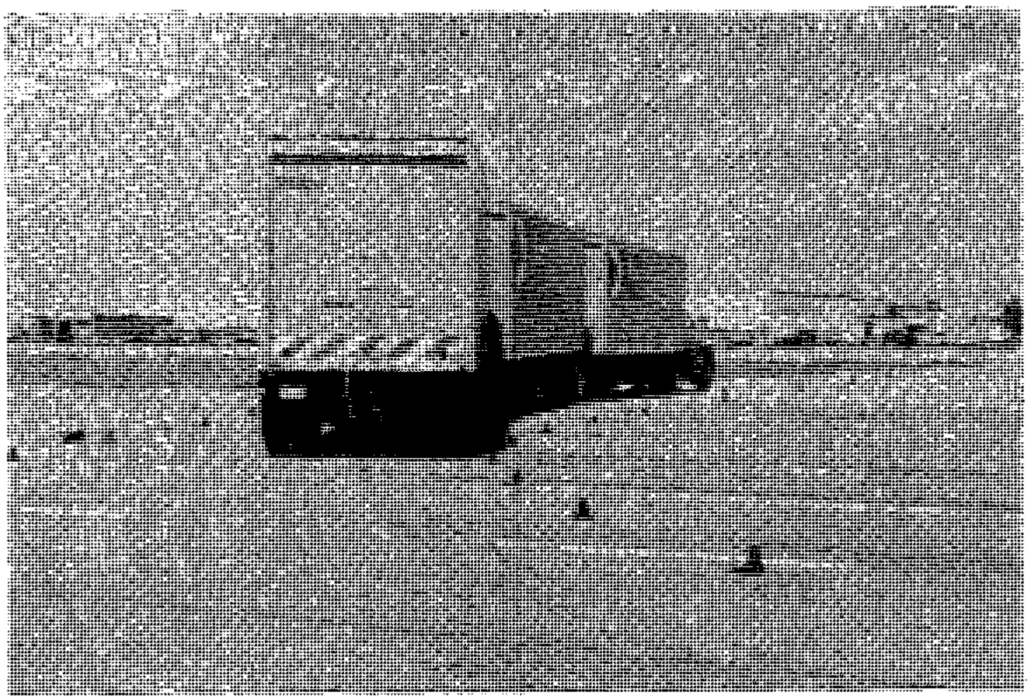
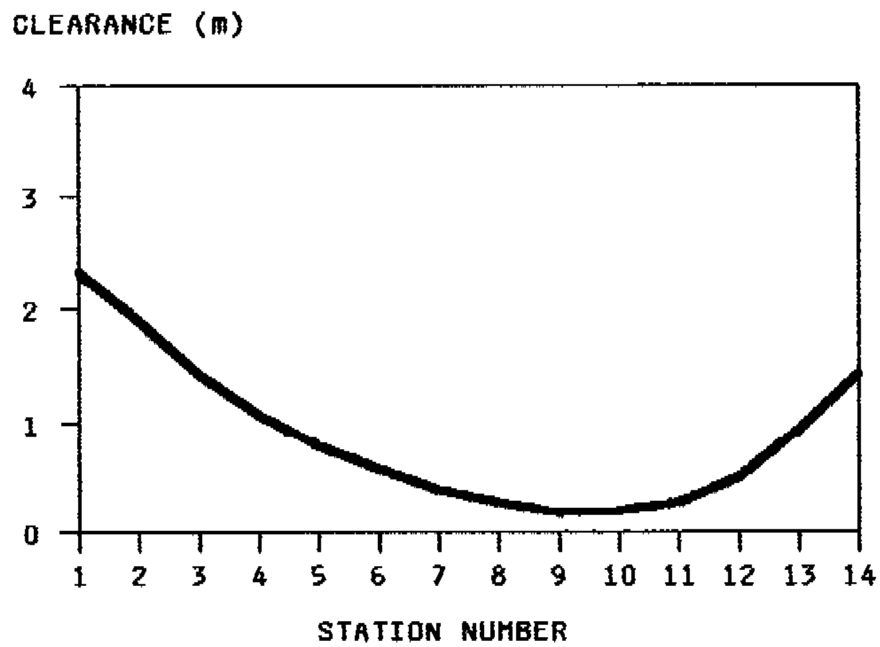


Figure 7/ Channelized Right Turn



STATION NUMBER	CLEARANCE (m)
1	2.34
2	1.92
3	1.44
4	1.07
5	0.79
6	0.58
7	0.39
8	0.27
9	0.18 *(LOW)
10	0.19
11	0.28
12	0.50
13	0.93
14	1.14

Figure 8/ Channelized Right Turn
Clearance from Inner Curb

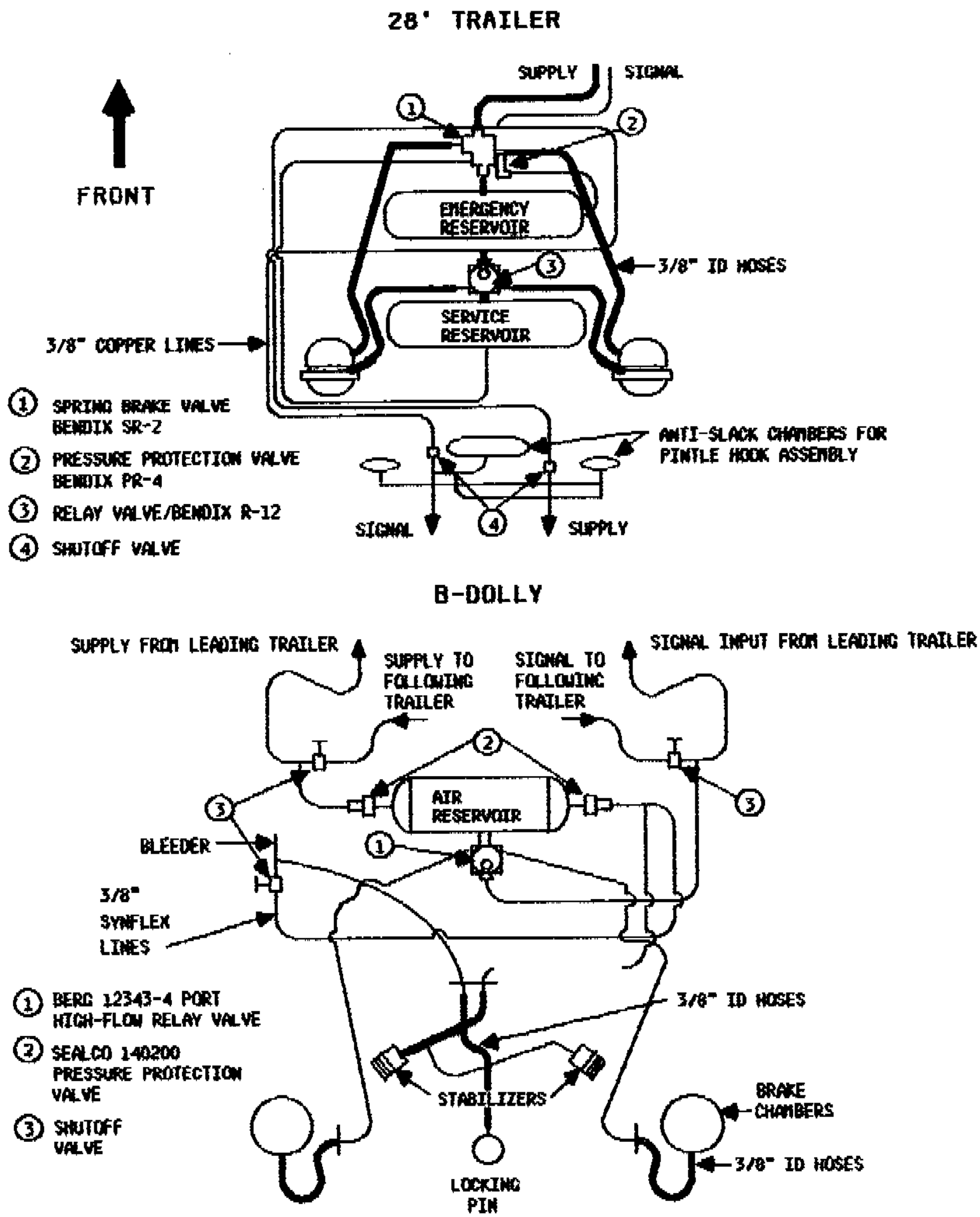


Figure 9/ Trailer and Dolly,
Air Brake System Schematic

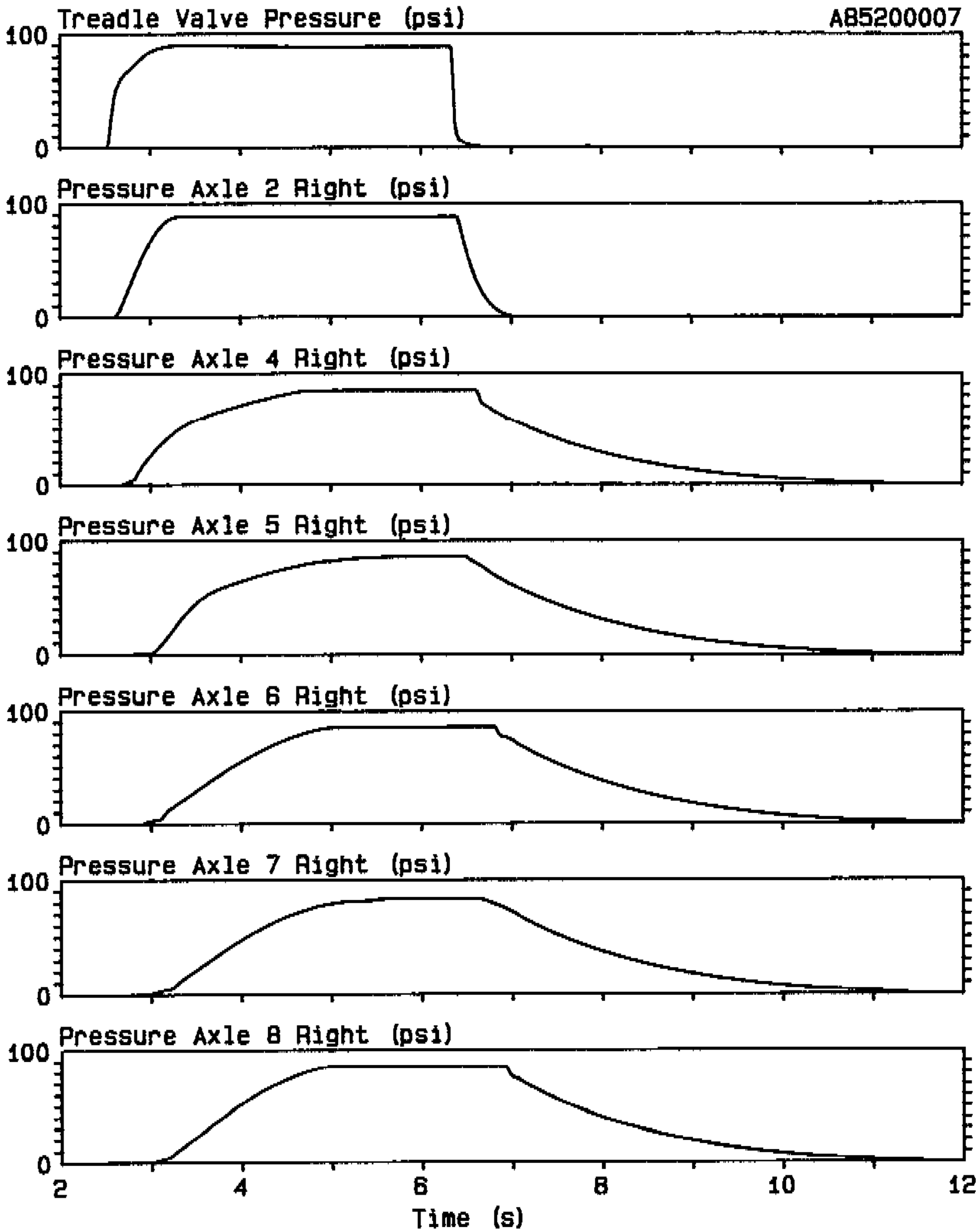


Figure 10/ Air Brake Application and Release

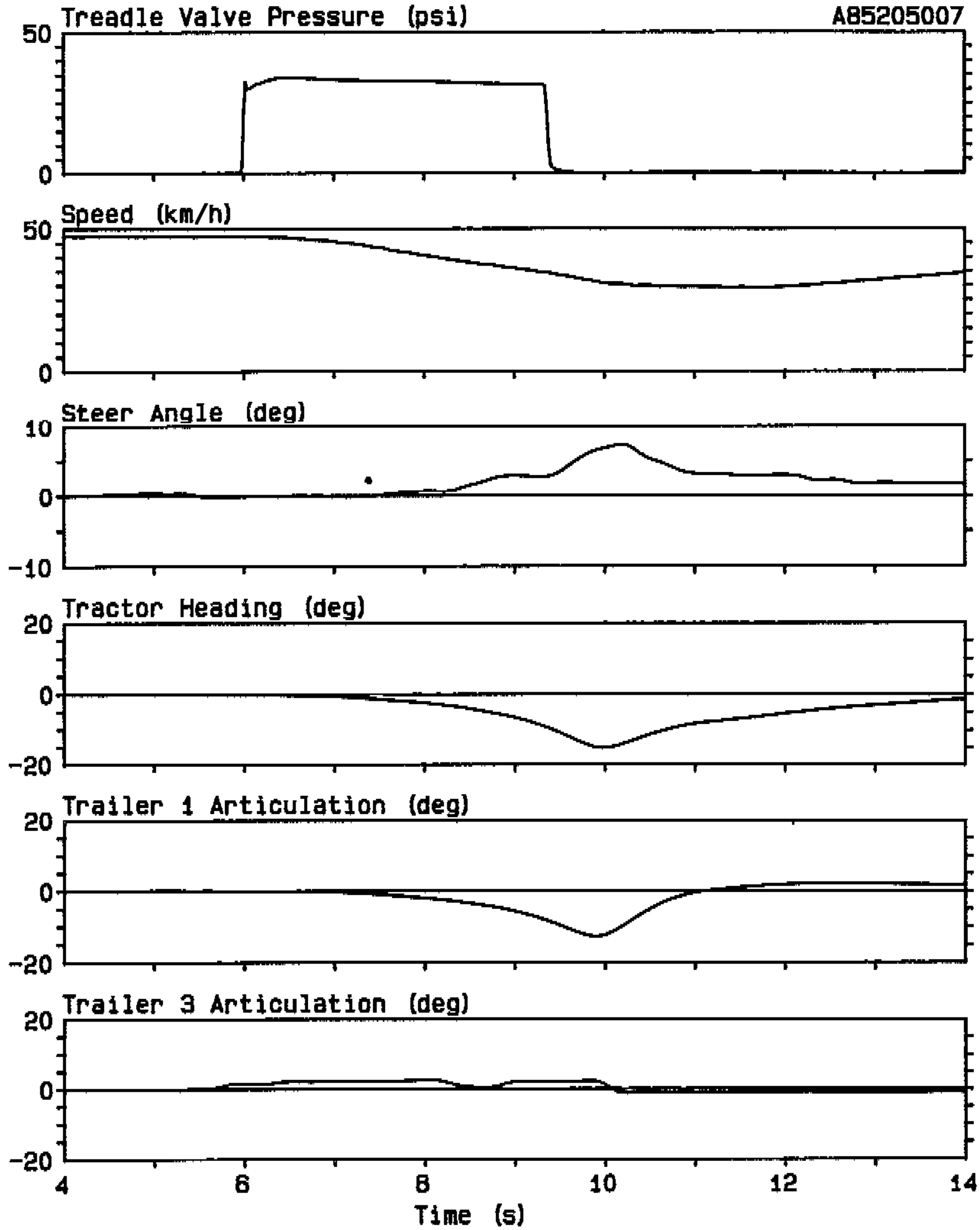


Figure 11/ Vehicle Response to Straight-Line Braking

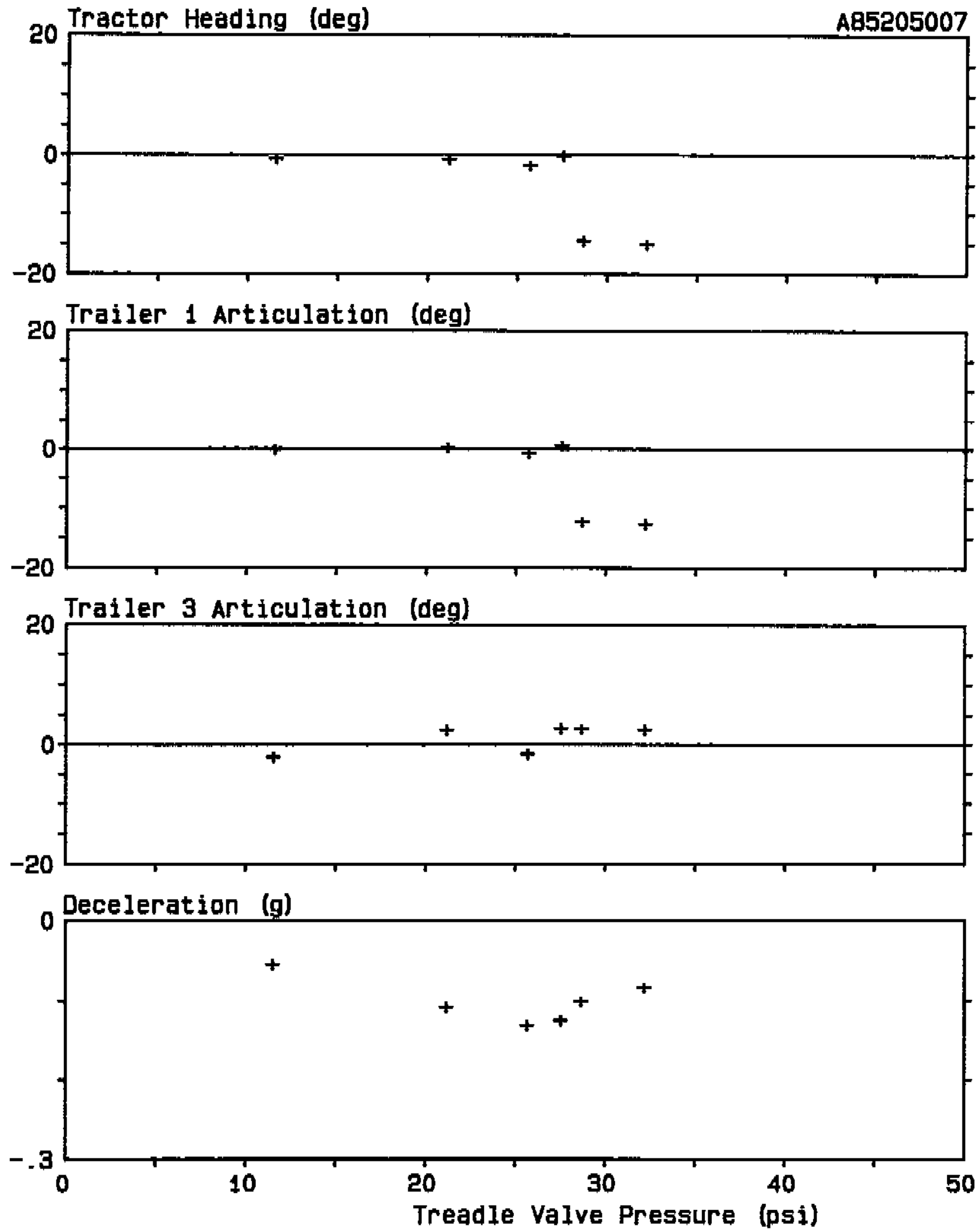


Figure 12/ Straight-Line Braking Responses vs
Treadle Valve Pressure

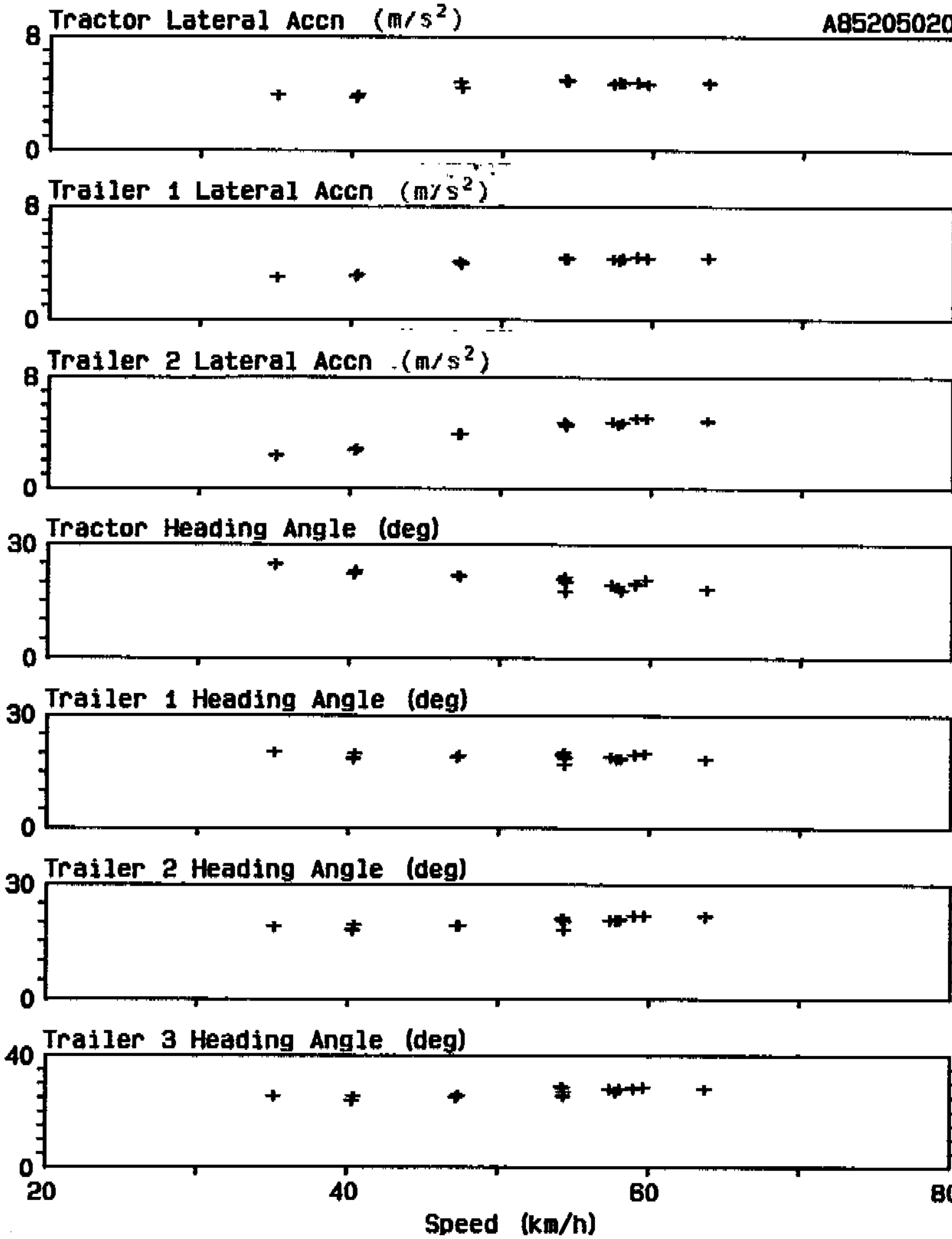


Figure 13/ Evasive Manoeuvre, Peak-to-Peak
Responses vs Speed

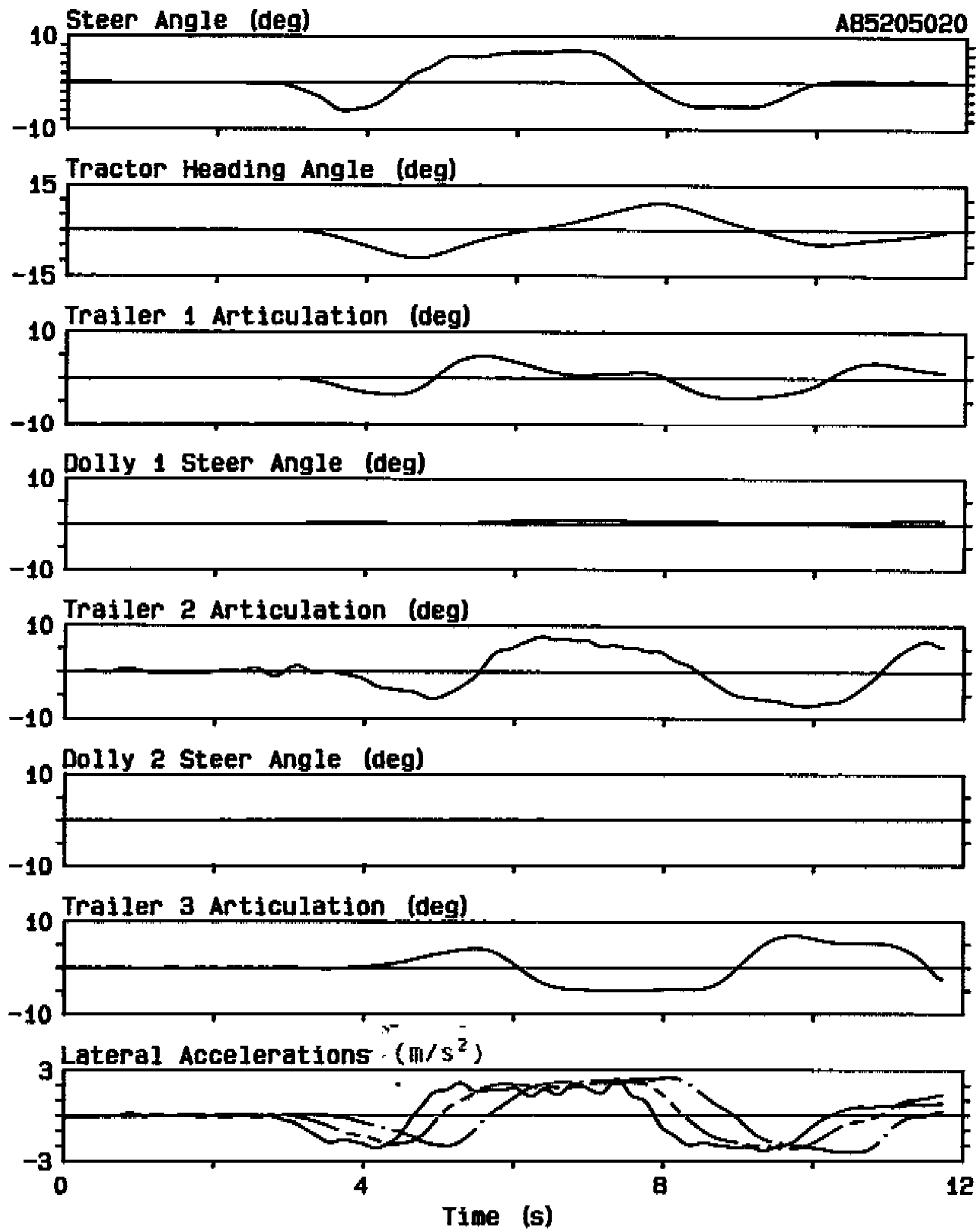


Figure 14/ Evasive Manoeuvre, Vehicle Responses at 63 km/h

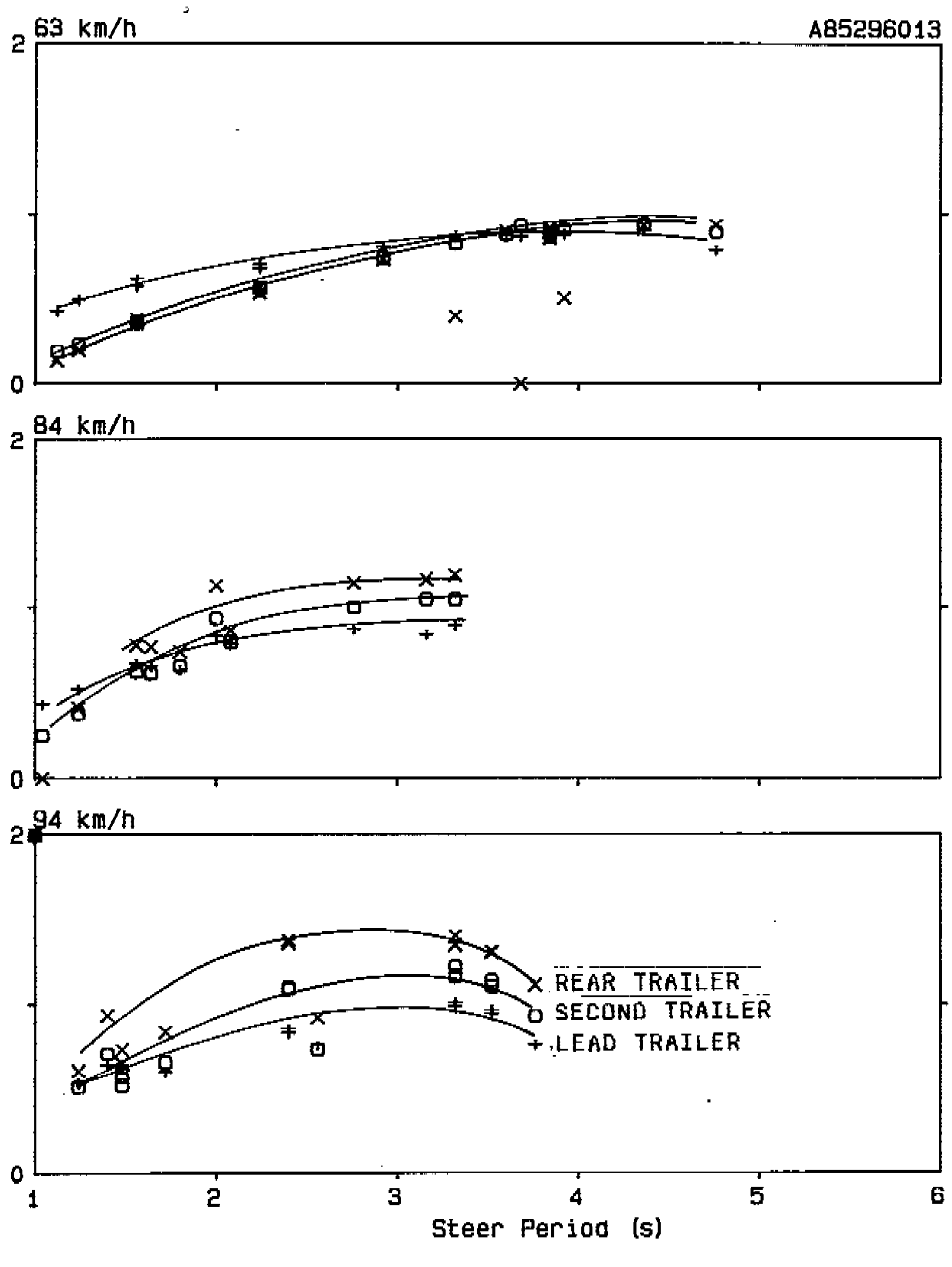


Figure 15/ Rearward Amplification vs Steer Period

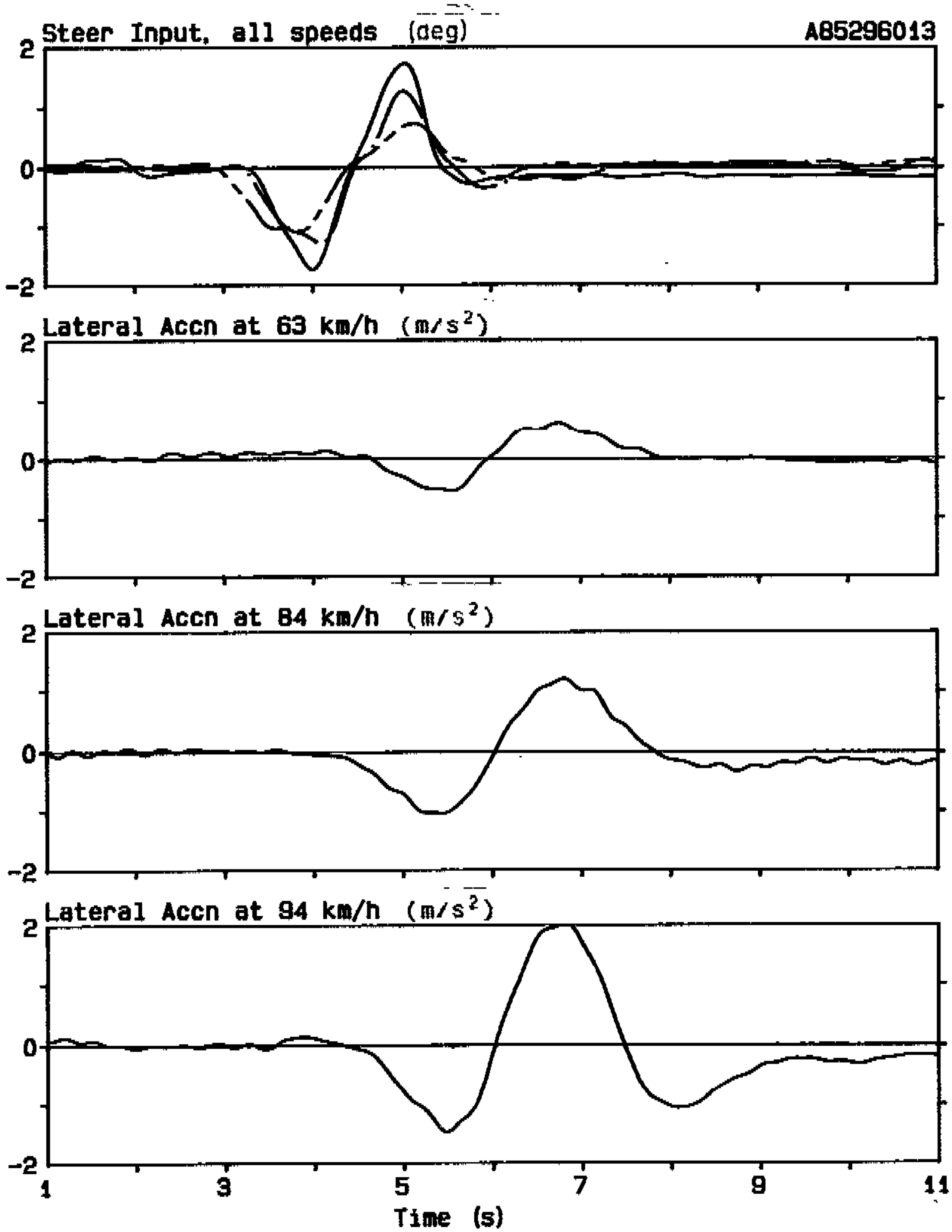


Figure 17/ Sinusoidal Steer, Rear Trailer Lateral Acceleration at Three Speeds

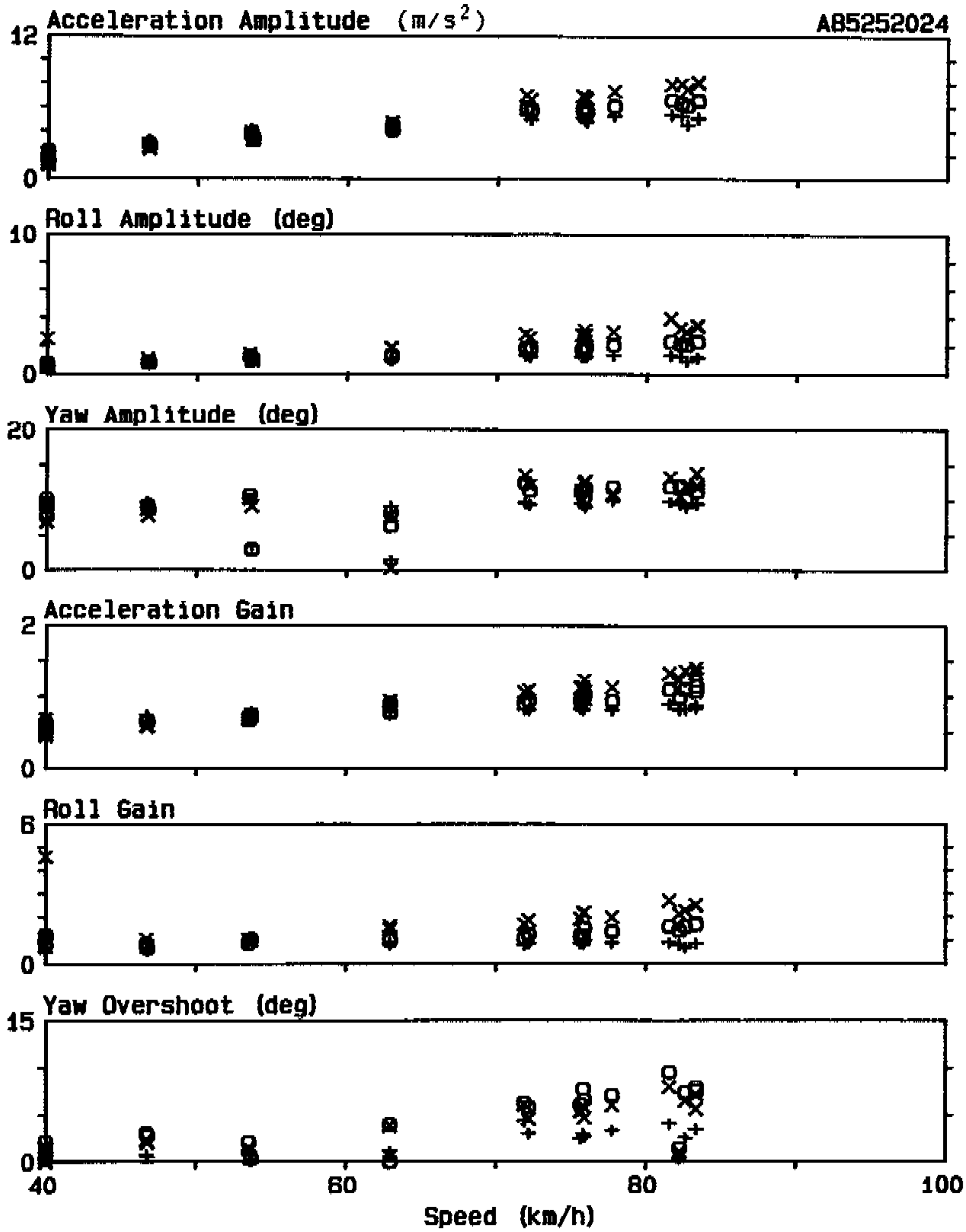


Figure 18/ Lane Change, Response Summary vs Speed

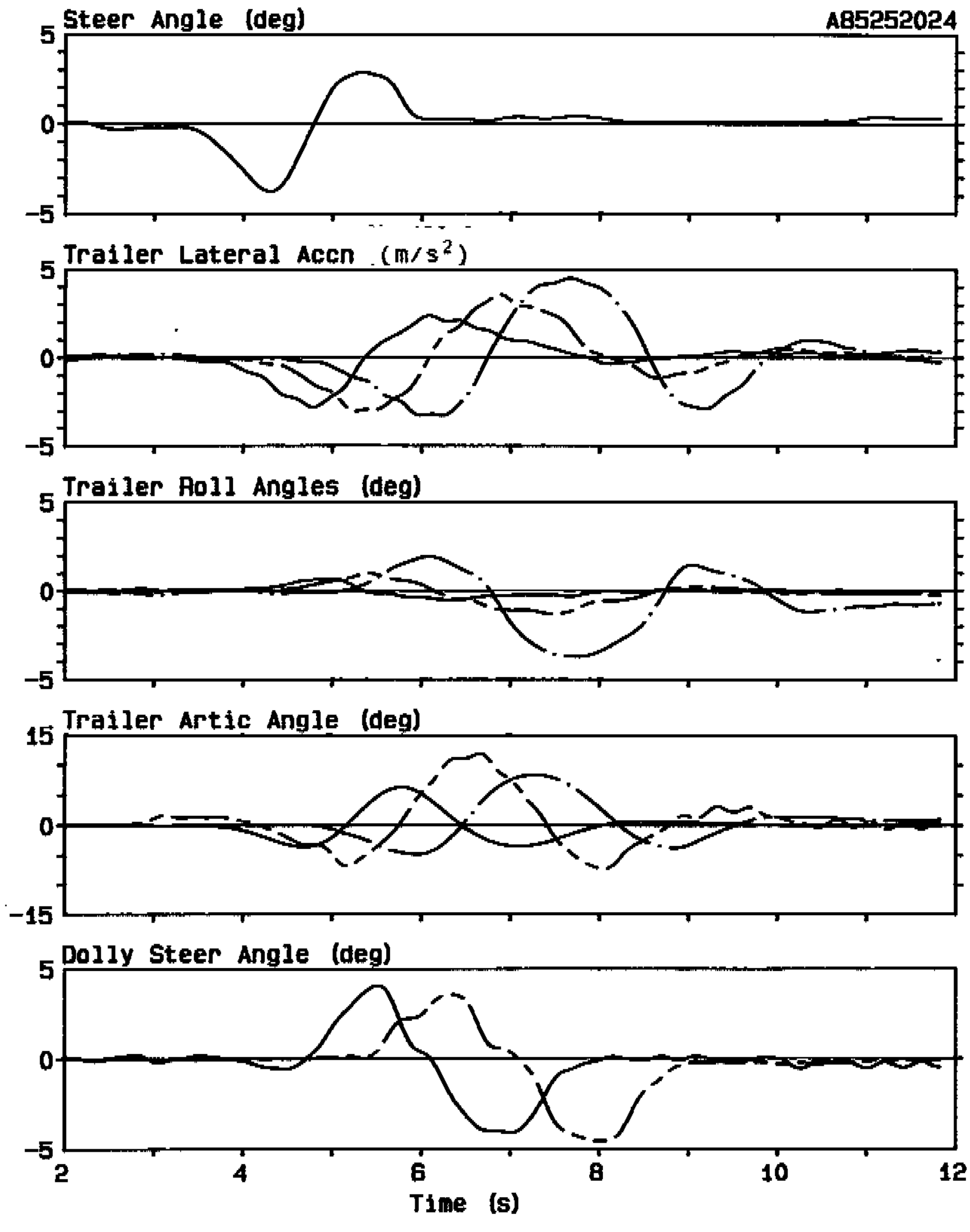


Figure 19/ Lane Change, Vehicle Responses at 83 km/h

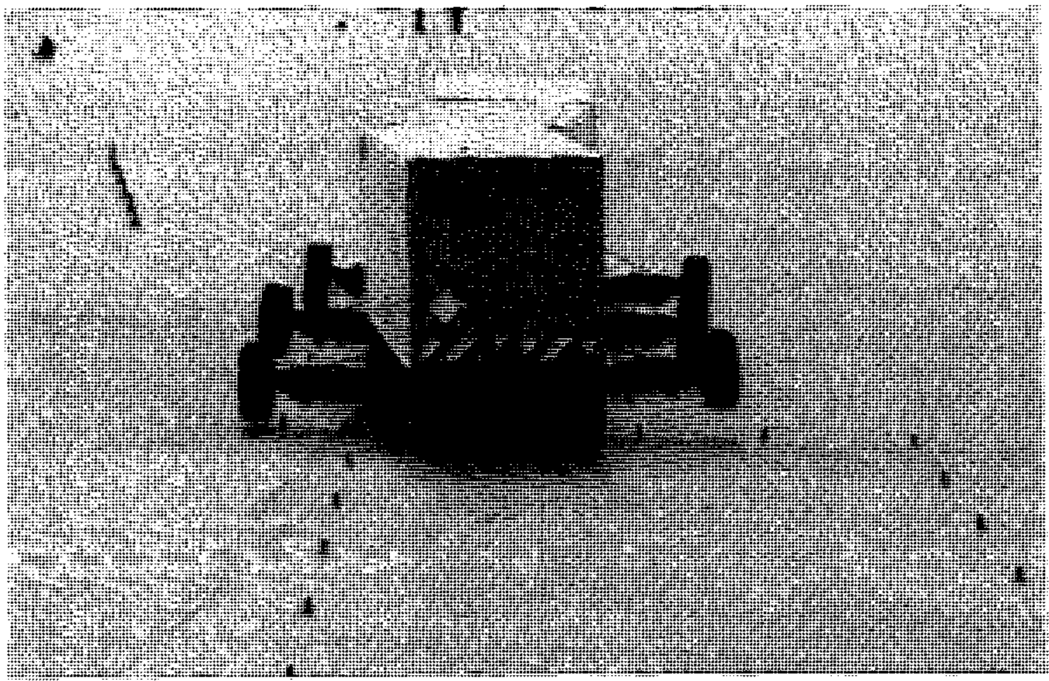


Figure 20/ Vehicle Making Lane Change

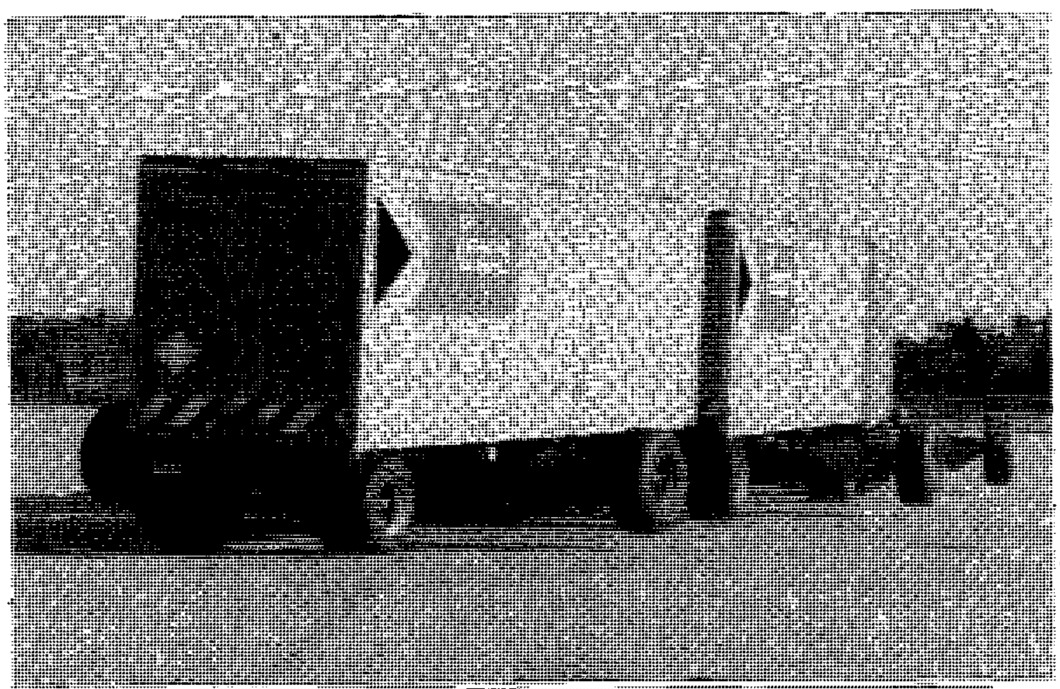


Figure 21/ Vehicle Making Steady Circular Turn

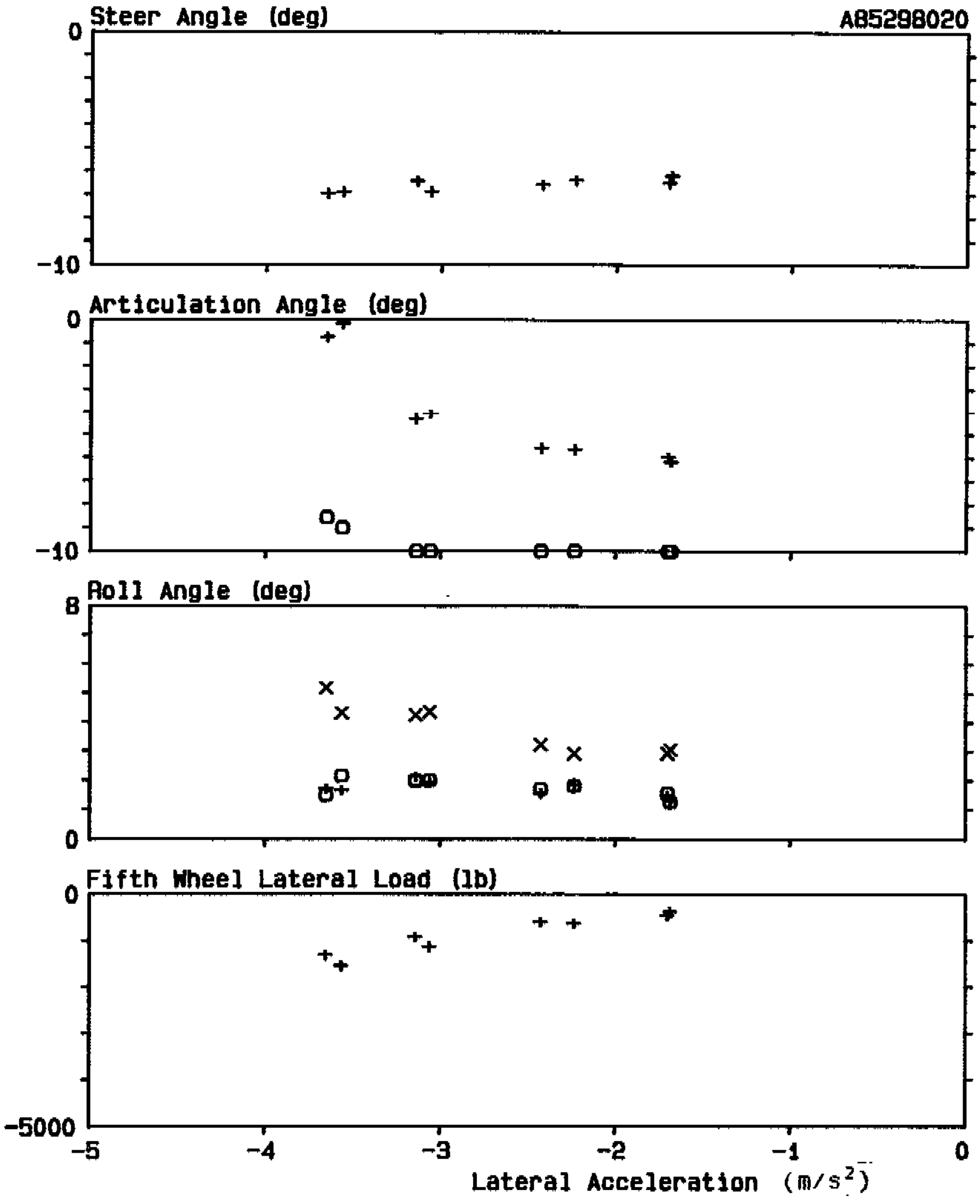


Figure 22/ Steady Circular Turn, Vehicle Responses vs Tractor Lateral Acceleration

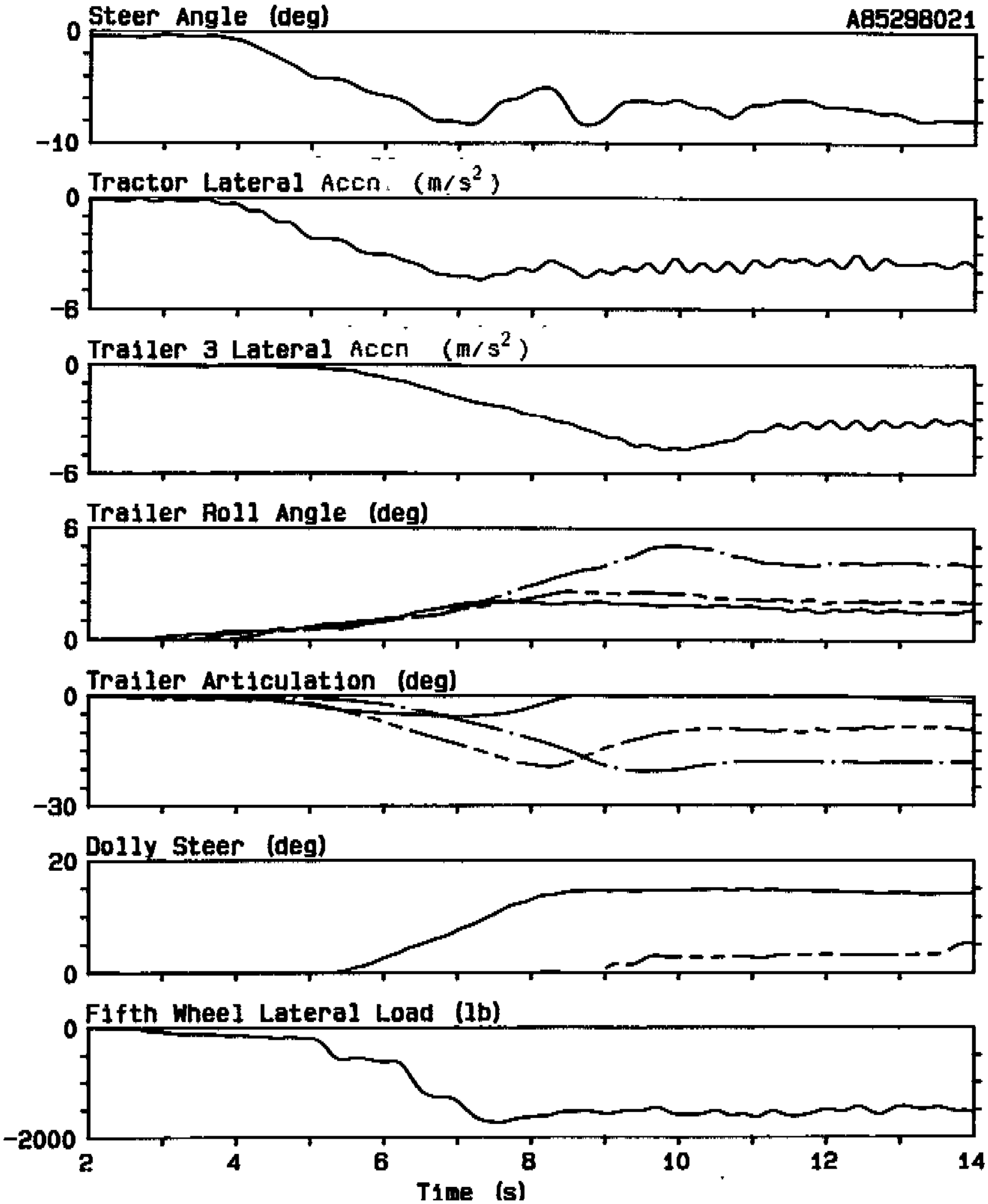


Figure 23/ Steady Circular Turn, Vehicle Responses at 53 km/h