# Heavy Truck Testing for the Canadian Vehicle Weights and Dimensions Study

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## ABSTRACT

Ontario Ministry of Transportation and Communications conducted three series of full-scale vehicle tests on behalf of the Canadian Vehicle Weights and Dimensions Study. The objective of the study is to develop a technical basis for greater uniformity in the regulations governing size and weight of heavy trucks, a responsibility of the 10 provinces of Canada.

The first series tested one example of each of the six baseline vehicle configurations identified by the study. These configurations were a 5-axle tractor-trailer; 8-axle A-, B- and C-train double trailer combinations; and A- and C-train triple trailer combinations. Tests of turning, braking and manoeuvering were conducted to the limits of stability for both empty vehicles on a low-friction surface and loaded vehicles on a high-friction surface. The same tests were conducted for each vehicle.

The second series consisted of the same tests as for the six baseline vehicles conducted on a single tractor-trailer that could be configured with 5, 6 or 7 axles.

The paper describes test equipment, and procedures and presents results and comparisons between vehicles of similar operational capability but different configuration.

The final series, an extension of earlier research, investigated the effects of drawbar length and hitch slack of the stability of a C-train double trailer combination, which uses the double drawbar converter dolly. The tests show that neither effect was significant for the vehicle and conditions tested, though, evidently, excessive hitch slack is undesirable and potentially destabilizing.


## 1. INTRODUCTION

Canada is a sovereign nation today because of the role transportation played in its development. Canada still depends upon its transportation system to move people for business and pleasure and goods from source to market. While the country developed around its waterways and railroad system, the truck now dominates goods movement for all but a few bulk commodities because of its flexibility and a well-developed and well-maintained highway network.

The division of power in Canada between the federal and provincial governments gives the provinces jurisdiction over highways and highway users – they fund construction and maintenance of highway facilities, regulate drivers, and regulate the vehicles that use the highways. The federal government retains jurisdiction over some matters which affect these areas. A natural consequence of 70 years of regulation by 10 provinces and two territories is that there are now 12 sets of regulations relating to truck weights and dimensions, among other things. The differences start with such fundamentals as definitions of terms and continue in diverse ways. There are, of course, many reasons for these differences. Regulations were adopted to accomplish some end directly or indirectly, perhaps to give advantage to some sector of industry or to curb the activity of another sector. As time passed and technology changed, some of these regulations influenced the development of trucks and trucking in ways which were not imagined at the time they were adopted.

Industry and the provinces recognized that differences in truck weight and dimension regulations were a hindrance to the smooth flow of interprovincial commerce and that they were a cost burden that a nation so dependent on transportation could ill afford. In 1972 the

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Canadian Conference of Motor Transport Administrators (CCMTA), which consists of the provincial officials responsible for highway transportation and safety, formed a joint committee on vehicle weights and dimensions with the Roads and Transportation Association of Canada (RTAC). A study of the effects of truck loads on the bridges on the principal highways used in interprovincial trucking was completed by 1979 (1). At this point, it was recognized that the liberal regulations of some of the provinces, particularly Ontario, had led to some vehicle configurations that were not entirely desirable from the viewpoint of vehicle stability and handling (2). Since industry naturally wanted the loads allowed by the most liberal province, other provinces had concerns about the results of changes to regulations without considering all factors. Stability was one such factor. A second factor was the effect of axle group loadings on pavement performance, as there were much more significant differences in highway construction standards between the provinces than there were in bridge design standards. A third factor, not considered at this stage but now more evident because of recent increases in both tractor and trailer lengths, is interaction between the truck and roadway geometrics -- the space required to turn and manoeuvre. A further study was defined to address these issues. It started in April 1984 and, with a budget of $2.83 million, was scheduled to provide the Council of Ministers Responsible for Highway Transportation with recommendations on uniformity on truck weights and dimensions by 1987.

The objective of this phase of the study is to compile technical information on the effects of truck weight, dimension, and configuration parameters on stability and control, and the effects of axle group loading on pavement response. The part of the study addressing pavement response is of no concern here. The stability and control of vehicles was addressed by means of a comprehensive computer simulation, conducted by the University of Michigan Transportation Research Institute (UMTRI). It was recognized, however, that the findings of a computer simulation might not be readily accepted by all and that there was a need for full-scale vehicle tests both to complement and to supplement the computer simulation. Three series of tests were defined.

The first series was known as the baseline vehicle tests. The truck population of Canada was surveyed (3), and six truck configuration families were defined, based on the number of trailers and the method of hitching. These were the tractor-semitrailer; A-, B-, and C-train doubles; and A- and C-train triples. The first four families contain all legal configurations and some extended-length configurations that operate under special permit in a number of provinces. The last two families only operate under special permit. Neither the straight truck nor the truck-trailer configurations were considered because they are insignificant in interprovincial trucking.

One representative of each family that was in common use in at least one region of the country was designated as the baseline vehicle for that family and was tested. The primary objective of these tests 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. A secondary objective was to conduct computer simulations using the measured test inputs and estimates of vehicle properties to demonstrate that computer simulation can represent vehicle responses for a wide range of vehicles and manoeuvres. These tests were conducted by the Ontario Ministry of Transportation and Communications (MTC) as part of its contribution to the study, to complement the comprehensive simulation conducted by UMTRI.

The study also defined additional vehicles of particular interest. MTC subjected a 4-axle 48 ft (14.65 m) semitrailer in three vehicle configurations with 5, 6, and 7 axles to the same tests as the six baseline vehicles. Other vehicles were also tested by UMTRI. The purpose of this second series of tests was to demonstrate the performance of these vehicles to supplement the simulation conducted by UMTRI.

The Weights and Dimensions Study makes a clear distinction between the six baseline vehicles and the three additional configurations of the 48 ft (14.65 m) semitrailer. The tests were considered to be quite separate parts of the study. However, as far as the test team was concerned, it was a single integrated program and all nine vehicles were subjected to the same tests. This paper also integrates these two groups of vehicles, to simplify the presentation.

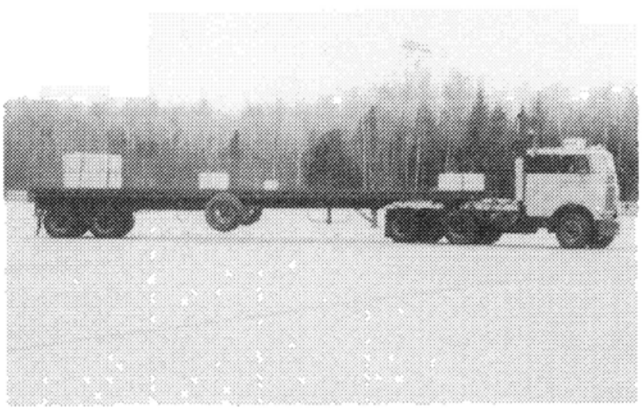
When the study was initiated, it was not clear that the B-dolly could be simulated properly. MTC, therefore, was requested to undertake a third series of tests, to investigate separately the effects of B-dolly hitch slack and drawbar length on C-train stability.

## 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) 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-train, 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 will always 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 low-density 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 the MTC Freightliner (4) and the trailer or trailer combination being tested. The 1976 Freightliner 6x4 seen in Figure 1, used for all except two turning tests, was a cab-over-engine type with integral sleeper. 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). The Freightliner front axle used Michelin XZA radial tires, load range G, size 11R-24.5, and the drive axles used Michelin XM+S4 radial tires, load range G, size 11R-24.5. 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) (3).



**45 ft semi**

**FIGURE 1**

A 1974 4x2 International Loadstar was used for two turning tests.

No modifications were made to any trailers except to attach test equipment.

The empty weight of the vehicles in test condition exceeded that which would normally be seen on the highway, because of the tractor and the weight of test equipment installed, particularly the outriggers. The study set a target load of 8000 kg (17 600 lb) for all axles in the loaded condition, except for the steer axle. Trailer widths and vehicle gross weights are presented in Table 1.

### 2.1 45 FT SEMI

The test vehicle, shown in Figure 1, 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 in the US. Semitrailers used in Central Canada now typically have a tandem-axle spread of 1.83 m (72 in) or more, compared with

**Table 1 – Trailer widths and gross weights**

| Vehicle | Width (m) | Truck width (m) | GCW empty (kg) | GCW loaded (kg) |
|---|---|---|---|---|
| 45 ft semi | 2.44 | 2.44 | 18 299 | 31 205 |
| A-double | 2.44 | 2.44 | 24 368 | 47 699 |
| B-double | 2.44 | 2.44 | 26 155 | 52 764 |
| C-double | 2.44 | 2.44 | 24 196 | 48 668 |
| A-triple | 2.59 | 2.59 | 33 087 | 55 942 |
| C-triple | 2.59 | 2.59 | 33 997 | 56 386 |
| 5-axle 48 ft semi | 2.59 | 2.44 | 22 595 | 34 409 |
| 6-axle 48 ft semi | 2.59 | 2.44 | 22 595 | 41 543 |
| 7-axle 48 ft semi | 2.59 | 2.44 | 22 595 | 49 878 |

the 1.37 m (54 in) of this trailer. The trailer had a four-spring leaf suspension. The combination had an overall length of 17.17 m (58.30 ft).

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 (5).

## 2.2 A-TRAIN DOUBLE

The test vehicle, shown in Figure 2, 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 for heavy haul in all regions of Canada, except the Atlantic provinces. The identical trailers had a nominal length of 7.93 m (26 ft) and a nominal width of 2.44 m (96 in), with two axles spaced 1.24 m (49 in) apart and suspended from a four-spring suspension. The A-dolly had a fifth-wheel-to-hitch distance of 2.14 m (7 ft). 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 (6).

## 2.3 B-TRAIN DOUBLE

The test vehicle, shown in Figure 3, 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.

Both trailers had a nominal length of 7.92 (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 six-spring suspension. It had a fifth wheel mounted above its rear axle. The tandem-axle rear trailer had an axle spacing of 1.79 m (70.5 in) and a four-spring suspension. The combination had an overall length of 22.1 m (72.5 ft) (7).

The legal gross weight of the vehicle tested is 56 600 kg (124 560 lb) in Quebec and 60 500 (133 100 lb) in Ontario. It would be about 52 000 kg (114 400 lb) where permitted in the Prairie provinces.

## 2.4 C-TRAIN DOUBLE

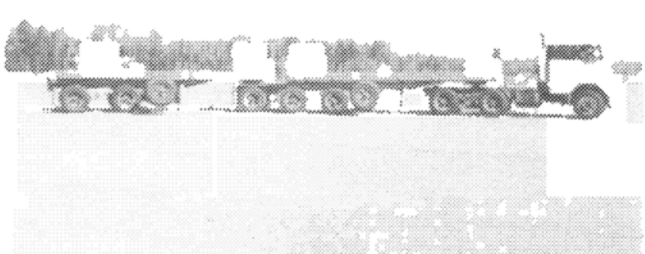
The test vehicle, shown in Figure 4, consisted of the MTC Freightliner and two tandem-axle flatbed semitrailers with a single-axle B-type converter dolly. The combination is otherwise identical to the A-train, as the trailers were the same but in the reverse order. The B-dolly was made up from an existing frame and a Sauer model RLZ10041 automotive steer-type self-steering axle rated at 10 000 kg (22 000 lb) and placarded for a speed of 80 km/h. 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 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 (8).

## 2.5 A-TRAIN TRIPLE

The test vehicle, shown in Figure 5, 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. 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

**A-train double**

**FIGURE 2**



**B-train double**

**FIGURE 3**

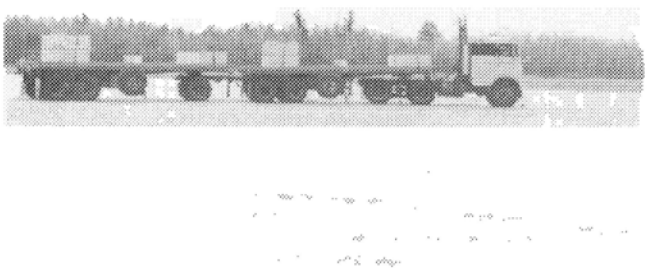
propane heater was installed at the front near the roof. The trailer suspension had a single tapered leaf spring and was rated at 9616 kg (21 155 lb). The spring spread was 1109 m (43 in), and the track width was 2.59 m (102 in). The trailers were equipped with an air-actuated no-slack pintle hook. The dollies had the same suspension as the trailers and a drawbar length of 2.13 m (84 in). The combination had an overall length of 31.08 m (102 ft).

The loaded weight is somewhat greater than that allowed by provinces where this combination runs under special permit. Typical loaded weights on the highway for such combinations are often much less than that allowed, by the nature of the cargo carried by the vehicle. All three trailers were loaded in the same fashion, consistent with normal practice (9).

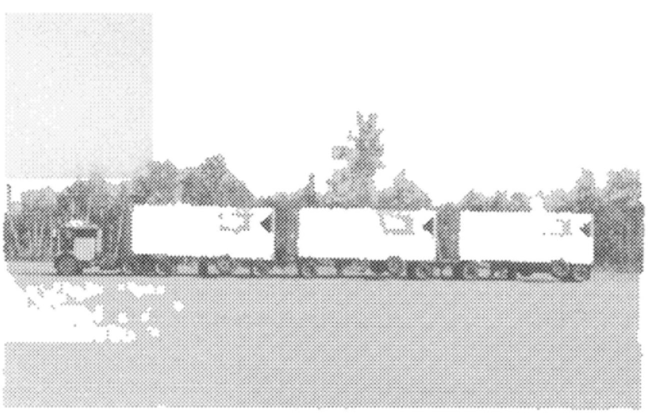
## 2.6 C-TRAIN TRIPLE

The test vehicle, shown in Figure 6, 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 Saskatchewan, where triple trailer combinations operate under special permit only in the C-train configuration.

The trailers were the same as those used for the A-train triple. The B-dolly of the C-train double, and another identical one, were used to couple the trailers (10).



**C-train double**
**FIGURE 4**

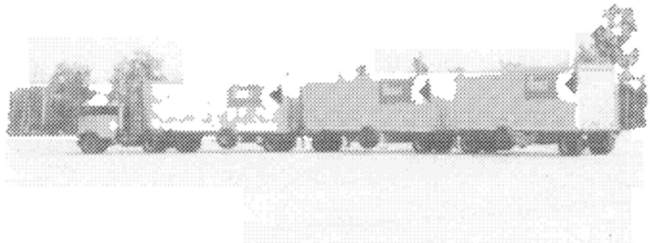


**A-train triple**
**FIGURE 5**

## 2.7 5-AXLE 48 FT SEMI

The test vehicle, shown in Figure 7, consisted of the MTC Freightliner and a 48 ft (14.63 m) tandem flatbed-type trailer. The combination is typical of equipment used in Central Canada, where additional weight can be carried on a widespread tandem axle. The flatbed semitrailer had two fixed axles and two non-steering airlift axles that were raised for these tests. The trailer had a nominal length of 14.63 m (48 ft) and a nominal width of 2.59 m (102 in). The trailer suspension comprised a Reyco four-spring leaf system with long equalizer arms on the fixed axles, which had a spacing of 2.77 m (109 in). The fixed tandem axle was placed to the rear of the trailer because in that position it can accrue a greater gross weight as a 4-axle trailer. However, current 48 ft (4.63 m) semitrailers often have their axles forward, at the same distance from the trailer kingpin as for a 45 ft (13.72 m) semitrailer, because under current regulations, no additional gross weight is gained for a rearward placement of the axles, and the turning performance is improved.

The empty weight exceeds that which would normally be seen on the highway because of the two lifted axles on the trailer. The legal gross weight for the vehicle tested varies between 36 500 and about 44 000 kg (80 300 to 96 800 lb), depending upon the province (11).



**C-train triple**
**FIGURE 6**

## 2.8 6-AXLE 48 FT SEMI

The test vehicle, shown in Figure 8, consisted of the MTC Freightliner and the same 48 ft (14.63 m) flatbed semitrailer just described. The combination is typical of equipment used in Central Canada, where trailers with a widespread tandem axle and an airlift belly axle are permitted additional weight. The trailer had a Neway air suspension system for the two airlift axles, with axle spacings of 2.74 and 2.77 m (108 and 109 in). The airlift axles had shock absorbers in parallel with the air springs.

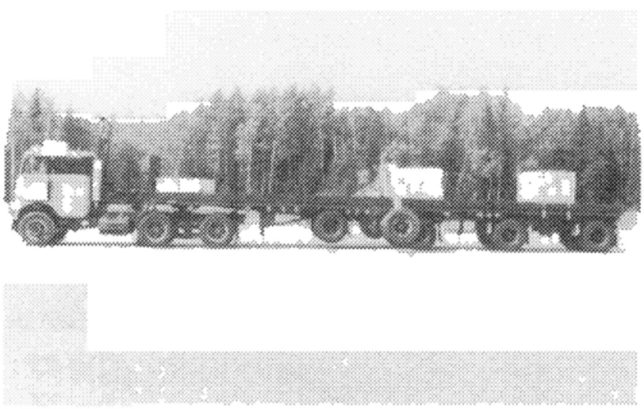
Airlift axle pressure was 159 kPa (23 psi) for the empty vehicle and 345 kPa (50 psi) loaded. The legal gross weight of the vehicle tested is about 50 000 kg (110 000 lb) in Ontario and Quebec and 47 700 kg (105 000 lb) in B.C., where the belly axle is required to be steerable (12).

## 2.9 7-AXLE 48 FT SEMI

The test vehicle, shown in Figure 9, consisted of the MTC Freightliner and the same 48 ft (14.63 m) semitrailer just described. The combination is typical of equipment used in Central Canada, where additional gross weight can be carried on a widespread tandem axle and belly axles. The trailer suspension comprised a four-spring leaf system with long equalizer arms on the fixed axles and a Neway air suspension system for the two airlift axles. The axle spacings were 2.74, 2.74, and 1.77 m (108, 108, and 109 in). Airlift axle pressure was 110 kPa (16 psi) on each axle for the empty vehicle and 345 kPa (50 psi) loaded. The legal gross weight for the vehicle tested is about 56 000 kg (123 000 lb) in Ontario (13).

**5-axle 48-ft semi**

**FIGURE 7**



**6-axle 48-ft semi**

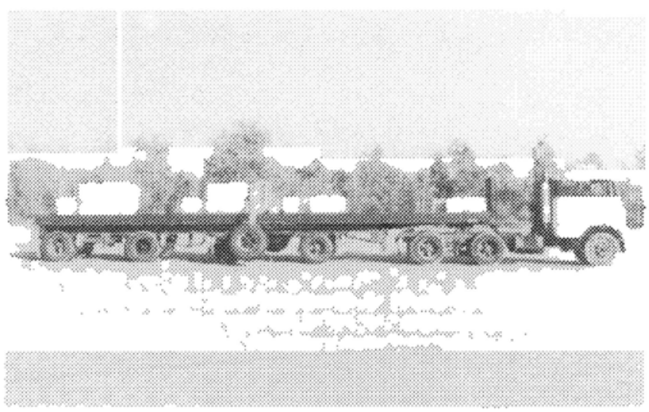
**FIGURE 8**

# 3. BASELINE AND ADDITIONAL VEHICLES 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), located at Huron Industrial Park, Centralia, 45 km (18 mi) north of London, Ontario. The test area includes a low-friction surface 200 m (656 ft) long with a sprinkler system. It has a wet skid number of about 18 to 24. The test facility also has about 2000 $m^2$ (21 529 $ft^2$) of work space, which was used for vehicle preparation and storage (4).

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 (4). In addition, tilt tests were conducted on the 45 ft (13.72 m) semi, the three doubles, and the three 48 ft (14.65 m) semitrailers by others, using a tilt table developed for the study (14).



**7-axle 48-ft semi**

**FIGURE 9**

## 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 11R-22.5. These tires were run a nominal distance before any testing. Tire pressure for all tests was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load on the tires. This 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 5. An existing frame-type outrigger was used for the 48 ft (14.65 m) semi, as shown in Figure 7.

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 the articulation angle 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 gross weight, achieved by loading it with concrete blocks weighing about 936 kg (2060 lb) each.

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.
- 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.
- Still photographs and video were taken of the instrumentation installations and of the vehicle as a whole and in parts.

Detailed descriptions of vehicle preparation are presented elsewhere (4).

## 3.3 INSTRUMENTATION

The MTC Freightliner has been used in many previous test programs. As a consequence, it was already equipped to measure the following driver inputs and vehicle responses:

- road wheel steer angle
- speed
- distance travelled
- brake on/off treadle valve and chamber pressures
- roll, pitch, yaw angles, and rates
- longitudinal, lateral, and vertical accelerations
- lateral load at the fifth wheel

The tractor was equipped to control the instrumentation. An automatic or a manual start uncaged the gyro package, initialized the distance counter, commanded the data acquisition system through a calibration sequence, and returned it to data status. The automatic start was triggered by a downward-facing optical sensor mounted beneath the tractor. It responded to a highly reflective patch of tape 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 similar, which simplified the development of computer data processing.

Each trailer was instrumented to measure the following basic responses:

- articulation angle
- lateral acceleration
- roll angle
- outrigger touchdown
- brake chamber pressures

The accelerometer and roll gyro, signal conditioning, multiplex unit, and power supply were installed in a package 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 presented elsewhere (4).

### 3.4 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. There they were digitized at a rate of 100 samples/s for each channel and transformed into a pulse-code modulated (PCM) data stream, which was broadcast by radio telemetry from the tractor to a ground station.

At the ground station, the PCM data stream was read in real time by a Hewlett-Packard HP-1000 A700 computer, creating a raw data file on disk for subsequent processing. The project engineer had a computer graphics terminal with a quick-look display that provided an overview of system status and data quality while the run was in progress. The data were converted to engineering units, quantities of interest were derived, and those critical to the test were displayed to the project engineer. The engineer then used them 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. 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 just before the initiation of the manoeuvre, from other vantage points of interest, or both. The audio track of the video system was used to record ambient noise during testing, including incidental radio transmissions. This was an invaluable complement to the engineering data, as it provided a permanent visual record of each run. The raw videotapes were edited into a video presentation to be used to supplement the paper reports.

A detailed description of data capture is presented elsewhere (4).

### 3.5 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 and processed concurrent with testing, as described previously. After each test session, the raw data files, and other files created in support of the data processing process, 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 and supporting data files were exhaustively reviewed, and necessary enhancements were implemented and validated. Every run was also carefully reviewed, and any that did not meet the particular test objective, or were otherwise flawed, were discarded.

Data processing proceeded in four phases:

1 raw data correction, which corrected any data frames in which telemetry dropout occurred;

2 calibration, which proceeded in two phases: first the electronic calibration sequence at the beginning of data acquisition for each run, then conversion to engineering units;

3 treatment, processing of the calibrated data so that specific quantities of interest for a particular test could be derived, such as correction of trailer lateral accelerations for the gravitational effect of roll angle, integration of angular rates, detrending, and filtering;

4 extraction of results, which depended upon the particular test.

Details of the methods are presented elsewhere (4).

## 3.6 THE TEST PROGRAM

The tests and demonstrations 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, outline the procedure followed, and summarize the results. Detailed procedures are presented elsewhere (4).

For all driving tests where a sequence of runs at increasing speeds was required, the driver used full throttle in the appropriate gear. The engine speed control then acted as a limiter to hold speed to the required value.

### 3.6.1 Offtracking

The interaction of large trucks with highway geometrics is, perhaps, the most evident manifestation of increasing truck size to the public, especially in urban communities. Large trucks take more space and time to make turns than smaller trucks and, therefore, appear to impede traffic.

Steady-state offtracking is the most widely understood measure of the turning capability of large trucks, though it rarely occurs in practice and may be misleading for ranking vehicles in some turns. It was determined by driving the loaded vehicle on a high-friction surface at low speed in a circle of radius 29.87 m (98 ft), with the tractor outer front wheel following the circle for one full revolution. Measurements were then taken from the centre of the circle to each axle's innermost tire. The test was conducted in both directions.

The results are shown in Table 2. The 45 ft (13.72 m) and 48 ft (14.65 m) semitrailers have large offtracking because of the length of the trailer and the rear placement of their bogies. The 6- and 7-axle 48 ft (14.65 m) vehicles have less offtracking than either 5-axle semi because the additional axles reduce the effective wheelbase of the trailer. 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 (15), and the same result pertains for the two triples. The differences within the three doubles and the two triples are attributable to the method of hitching and are not considered to be of great practical significance in their turning requirements.

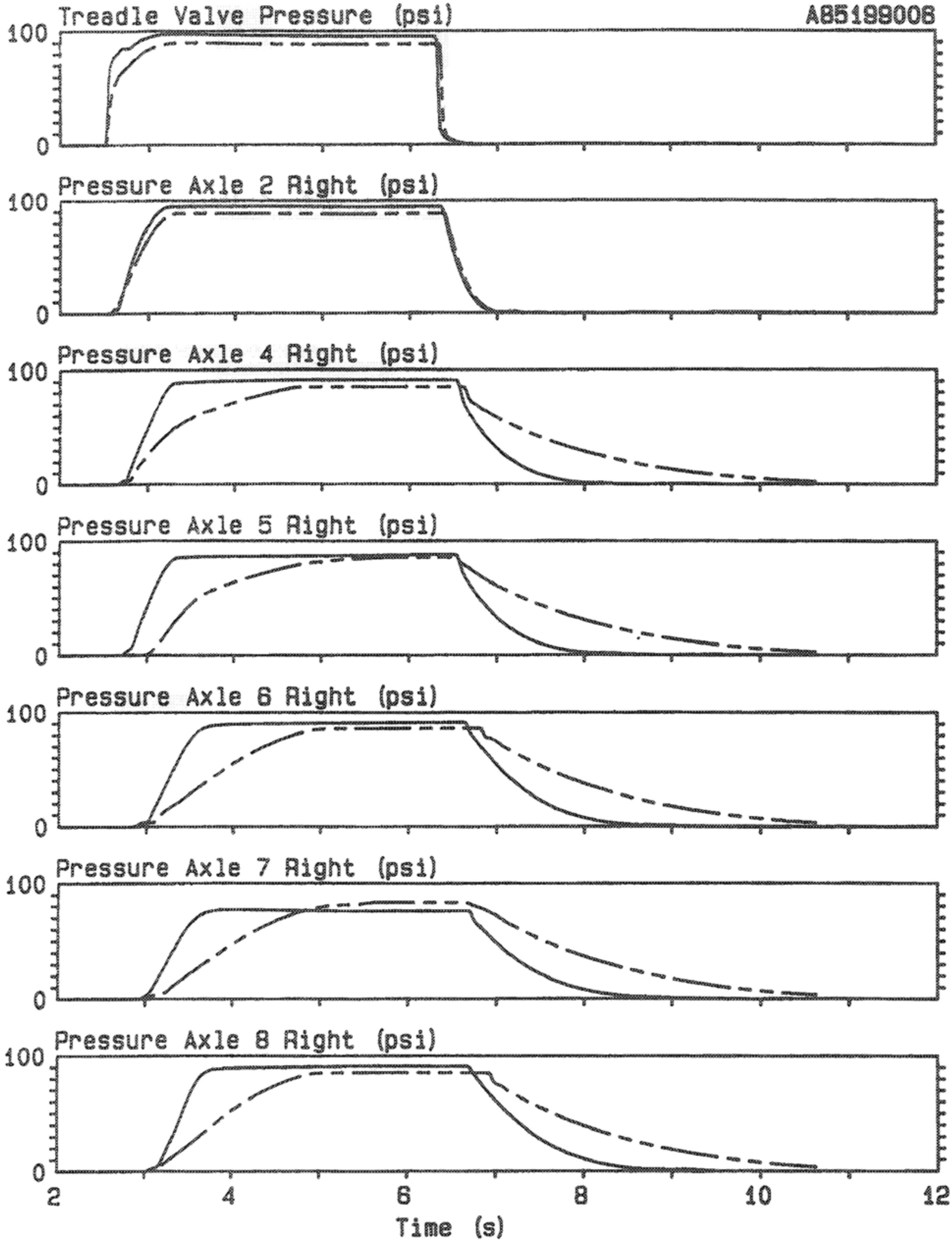
The measured data for all vehicles were compared to data generated by a simple offtracking formula (16). The difference was less than 0.5% for nearly all axles. Consequently, steady-state offtracking can be estimated very accurately by this formula.

### 3.6.2 Right-Hand Turn

The 90 right-hand turn is probably the most demanding manoeuvre for a large truck. In urban areas, or where there are low truck volumes, a

**Table 2 – 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-axle 48 ft semi | 2.82 |
| 6-axle 48 ft semi | 2.38 |
| 7-axle 48 ft semi | 2.13 |




**A-train and C-train triples, air brake application and release**

**FIGURE 10**

small curve radius may be used. When a long truck comes to an intersection and is too large for the driver to make the turn with a simple steady steer input, two ways to create more space for the turn are available: the driver can move to the left of the entry lane to increase the radius or ahead into lanes beside the lane into which is turning. In either case, the driver is using the space of other vehicles, increasing 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 when turning right. This strategy is, therefore, considered undesirable. The second strategy also uses the space of other vehicles. However, 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 (49.2 ft) curb radius, with entry and exit lane widths of 3.66 m (12 ft). This standard has been used 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 was to approach the turn in the entry land and make the "best" turn possible to exit ultimately in the right-hand exit lane. Definition of the "best turn was left to the judgement of the driver, who repeated turns until satisfied that no further improvement could be made. The swept path of the tractor left front wheel and the rear trailer right rear wheel were marked with traffic cones on the rays shown in Figure 10. When the "best" turn was achieved, the positions of the cones were measured, and hence, the turn swept path was recorded. The MTC International tractor was used as the power unit for all vehicles, and the trailers were empty.

**Table 3 – Right-hand turn**

| Vehicle | Maximum excursion out of lane (m) | Length of excursion (m) |
|---|---|---|
| 45-ft semi | 2.2 | 19.2 |
| A-double | 0.4 | 7.5 |
| B-double | 0.9 | 18.0 |
| C-double | 0.8 | 8.4 |
| A-triple | 3.8 | 19.4 |
| C-triple | 3.7 | 22.0 |
| 5-axle 48 ft semi | 2.0 | 26.0 |
| 6-axle 48 ft semi | 0.7 | 21.0 |
| 7-axle 48 ft semi | 0.8 | 20.4 |

The maximum excursion out of lane and the length of that excursion are presented in Table 3. The doubles and the 6- and 7-axle 48 ft (14.65 m) vehicles barely intruded into the lane adjacent to the exit lane, whereas the 45 ft and 5-axle 48 ft vehicles required more than half of it, and the triples required all of it and a little more. While this turn is very different than offtracking, the ranking of vehicles is similar for both. This test was conducted at a creep speed and represents about the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane, though the ranking should not change.

### 3.6.3 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). This is a typical highway geometric design standard for use in urban areas, where property presents a problem.

This test measured the transient offtracking of the vehicle passing through the channel, with the tractor following the island curb. The minimum clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Table 4. The doubles made it easily through the channel, but the semitrailers had less space, and the triples barely made it. The tractor's left front wheel tracked the curb, and a driver would normally leave some clearance on this side. Consequently, the triples would be very close to running over the inside curb.

### 3.6.4 Air Brake System

Balanced braking of a combination vehicle requires that the brake systems of all vehicle units be compatible so that pneumatic balance and torque balance can be achieved at each axle. Short brake application and release times provide a responsive brake system and reduce stopping distance and fuel consumption. Pneumatic

**Table 4 - 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-axle 48 ft semi | 0.73 |
| 6-axle 48 ft semi | 1.12 |
| 7-axle 48 ft semi | 1.47 |

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 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. The test used a maximum rate brake application with air supply regulated at 689 kPa (100 psi). At each axle, the pressures were found and the time for the air pressure to reach 413 Kpa (60 psi) was determined. 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 and represents the rare emergency brake situation where maximum performance is demanded.

The test was performed on the A- and C-train triples for the tractor-trailer when air to the first dolly was shut off; for the double, which resulted when air to the second dolly was shut off; and for the full triple combination. The results of these tests are presented in Tables 5, 6, and 7. A typical time history response of application and release for each triple is presented in Figure 10 – the A-train is the solid line and the C-train is the broken line.

**Table 5 – Air brake timing, semi of triples**

| | Application timing 0-60 psi (s) | | Release timing to 5 psi (s) | |
|---|---|---|---|---|
| **Location** | **A-train** | **C-train** | **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 6 – Air brake timing, double of triples**

| | Application timing 0-60 psi (s) | | release timing to 5 psi (s) | |
|---|---|---|---|---|
| **Location** | **A-train** | **C-train** | **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 |

Two interesting comparisons arise from these three tables. First, examine the effect of adding trailers progressively for the A-train. As a semi (Table 5), application times for tractor and trailer were both 0.37 s, an ideal situation. When the second trailer was added (Table 6), the first trailer application time was prolonged to 0.55 s. When the rear trailer was added (Table 7), 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 more than one trailer ahead. Similar results pertain for the release times.

The A-train dollies both had booster relay valves to speed the signal to the following trailers. The C-train was not so equipped. Table 5 shows that application times for the A- and C-trains are the same within test errors, as they were, in fact, 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 speed both application and release times, it inhibits the third trailer slowing the first, as happens for the C-train.

Notice in Table 7 that for both vehicles axle 5 on the first dolly is faster than axle 6 on the second trailer. This means that as the brakes are applied, the inertia of the last two trailers bears momentarily on the first dolly as it starts to brake but before the brakes on the last two trailers become effective. In an aggressive braking situation with an empty vehicle on a low-friction surface, this provides potential for a dolly jackknife. However, the timing of the corresponding axles 7 and 8 on the rear trailer is very close for the is even reversed for the C-train, with the dolly axle reaching full braking after the

**Table 7 – Air brake timing, triples**

| | Application timing 0-60 psi (s) | | Release timing to 5 psi (s) | |
|---|---|---|---|---|
| **Location** | **A-train** | **B-train** | **A-train** | **B-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 |

trailer axle. This latter situation is considered desirable if it can be achieved without an excessive brake application time, which was certainly 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 designed as a combination as was the A-train. The desirable rear trailer brake timing was a result, simply, of hasty assembly of the second B-dolly from less than ideal parts. Note that 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 (17), no such work is known for dolly jackknife on doubles or triples.

The application times are comparable with those obtained from tests conducted previously by MTC on other triple combinations (18, 19). 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 (19). Not only can a faster or more responsive braking system be created at little, if any, cost difference to an "ordinary" system, but fuel can be saved by reducing the need to accelerate against momentarily dragging brakes. Indeed, an elementary calculation can show 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 times for the other seven vehicles were typical of other tests on similar combinations (17, 19). The times 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, so the plumbing was cleaner, and it was equipped with an anti-lock braking system which requires faster components.

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.

This test illustrated that air brake system performance depends upon the number of vehicle units – trailers and dollies. It also showed 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 – low pressure differentials between axles – is part of obtaining proper distribution of braking to all axles of the combination.

### 3.6.5 Straight-Line Braking Demonstration

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 where the empty vehicle approached the low-friction test area at 47 km/h and 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 (4).

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 8.

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 semitrailers and the B- and C-train doubles required considerably harder braking before they became unstable.

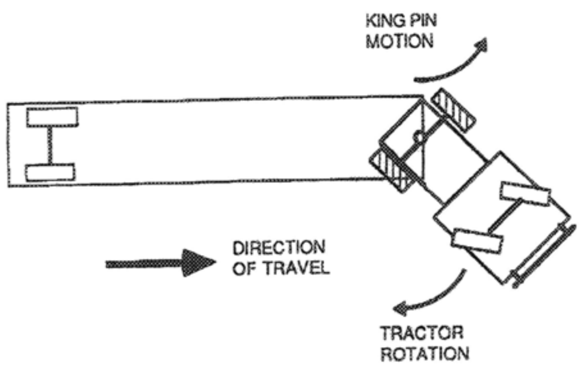
The tractor of the 45 ft (13.72 m) semi jackknifed to the right as illustrated in Figure 11. The dolly of the A-train double jackknifed to the right, as illustrated in Figure 12. While the whole vehicle remained within the lane during this stop, the dolly actually was unstable. If either speed or brake 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

**Table 8 - Straight-line braking demonstration**

| 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 |
| 5-axle 48 ft semi | 35 | Tractor jackknife |
| 6-axle 48 ft semi | 43 | Tractor jackknife |
| 7-axle 48 ft semi | 35 | Tractor jackknife |

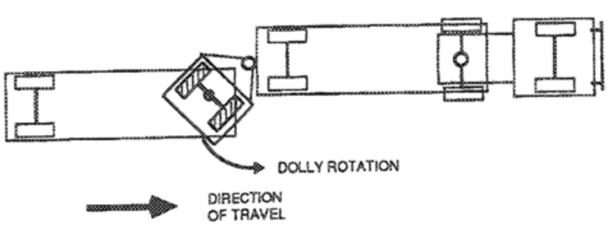
lead trailer, and presuming the hitch did not fail the trailer would then have swung around and started the whole vehicle spinning when it reached the safety cable limits. The speed and brake application pressure were selected so that the mode of instability was just demonstrated, and this violent and hazardous consequence was avoided. The B- and C-train doubles, both triples, and the three 48 ft (14.65 m) semitrailers 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 demonstration was conducted without front axle brakes on the tractor. 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 if the driver kept them straight. The vehicle would simply slide to a stop, not necessarily entirely under control of the driver, but at least 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 on the A-train double combinations.




**Tractor jackknife**

**FIGURE 11**



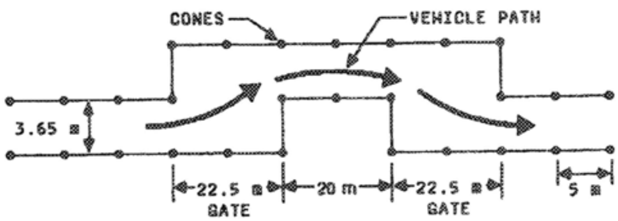

**A-train dolly jackknife**

**FIGURE 12**

### 3.6.6 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 (4). For most vehicles, the test used gates of 22.5 m (73.8 ft) 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, as shown in Figure 13. 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 9.

The evasive manoeuvre is complex and subtle. The frequency content of the steer input, therefore, changes with speed and is more complex than the basically sinusoidal steer required by the lane




**Evasive manoeuvre course**

**FIGURE 13**

**Table 9 - Instability in the evasive manouvre**

| 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 through return to original lane |
| A-triple | 22.5 | 58 | Dolly jackknife and rear trailer swing |
| C-triple | 25.0 | 63 | Tractor pushed through return to original lane, and rear trailer swing |
| 5-axle 48 ft semi | 22.5 | 60 | Reached limit of tractor control |
| 6-axle 48 ft semi | 22.5 | 58 | Reached limit of tractor control |
| 7-axle 48 ft semi | 22.5 | 57 | Reached limit of tractor control |

change. Because of the complexity of the manoeuvre, it is a little 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 somewhat higher speed, where the steer input can be made more smoothly.

The speed at which this manoeuvre can be made may be slightly misleading as a ranking of the stability characteristics of the vehicle. Rather, attention should be given to the mode of instability, summarized in Table 9. 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 with the best radius that the driver could achieve, the trailer was too long to go through the gate and return to the original lane. The three 48 ft (14.63 m) semitrailers behaved similarly, although the limiting speed was reduced as axles were added because the trailer became progressively more difficult to turn. With both the A-train double and A-train triple the driver had excellent control of the tractor in this manoeuvre, as the short trailer exerts little force on the tractor. The A-train double just made the manoeuvre at 63 km/h, but the dolly slid through the gate to return to the original lane and was on the verge of a dolly jackknife. Rear trailer swing and total loss of control would have resulted. In contrast, there was greater lateral acceleration at the rear trailer of the A-train triple due to rearward amplification. The second dolly jackknifed in the return to the original lane, and the rear trailer swung out of lane to the right. The B-train double experienced 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 through the original lane as it returned through the second gate. The tractor was at the limits of control, but the trailers remained stable. 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 (14). The tractor of the C-train triple was also pushed 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.

### 3.6.7 Sinusoidal Steer

In this manoeuvre, the driver, with a loaded vehicle, approached an open high-friction test area at constant speed and executed a sinusoidal steer input at the steering wheel. This created a sinusoidal lateral acceleration input at the tractor, which resulted in a variable sidestep to the left, depending upon the speed, steer period, and steer amplitude.

This steer input is a standard method by which lateral/directional response of the vehicle could be excited. The input was chosen to provide a tractor lateral acceleration of about 0.15 g,l which was 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 dynamic characteristic of combination vehicles. An acceleration ratio no greater than unity means the trailer has a lower acceleration than the tractor, so basically the driver may be considered in control 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, so basically the driver may be considered in control 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 ration 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.

The test was run at speeds of 63, 84, and 94 km/h, with steer periods between 2 and 5 s. The steer amplitudes were provided to the driver by means of indicators on the steering wheel, and an electronic device was developed that provided a light sequence for the driver to follow to achieve the correct steer period.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. The maximum rearward amplification of each vehicle for the three test speeds is presented in Table 10. 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 (4). The maximum value was estimated by scribing a line by French curve through the gains obtained from runs on the various steer periods at each speed. This procedure was not exact, but is considered adequate to illustrate the major differences between vehicles.

It is evident from Table 10 that rearward amplification increases with speed. It also increases rearward by trailer, and is somewhat sensitive to steer period, as seen in Figure 13 for the A-train triple. The results, as seen in Figure 14 and Table 10, show that, at highway speed, the A-train triple is a very responsive vehicle. This is because its inherent stability is rather low. Stability and response of mechanical systems have an inverse relationship. Figure 15 shows the rear trailer response of a typical fun for 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. These three time histories clearly depict the reduction in damping of the vehicle's lateral/directional response as speed is increased. Figure 16 shows the three comparable conditions for the C-train triple.

Tests were only conducted to 94 km/h. It was apparent that the stability of the A-train triple was decreasing with increase in speed. This vehicle would be even less stable at a typical highway speed limit of 100 km/h. Actual speeds are often higher than this limit, and the vehicle would become yet less stable if actual speeds did exceed 100 km/h. These data, and the visual observation of the vehicles, 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.

**Table 10 – Rearward amplification of lateral acceleration at the last trailer**

| Vehicle | 63 km/h | 84 km/h | 94 km/h |
|---|---|---|---|
| 45 ft semi | 0.85 | 1.00 | 1.05 |
| A-double | 1.10 | - | 1.85 |
| B-double | 1.05 | 1.30 | 1.80 |
| C-double | - | 1.30 | 1.50 |
| A-triple | 1.50 | 2.60 | 3.30 |
| C-triple | 1.15 | 1.30 | 1.70 |
| 5-axle 48 ft semi | 0.85 | 0.92 | 0.96 |
| 6-axle 48 ft semi | - | - | 0.92 |
| 7-axle 48 ft semi | 0.81 | 1.00 | 1.05 |

The results presented in Table 10 are reasonably consistent with other test and simulation findings (20), though those results were obtained for somewhat different vehicles and loadings.

### 3.6.8 Lane Change

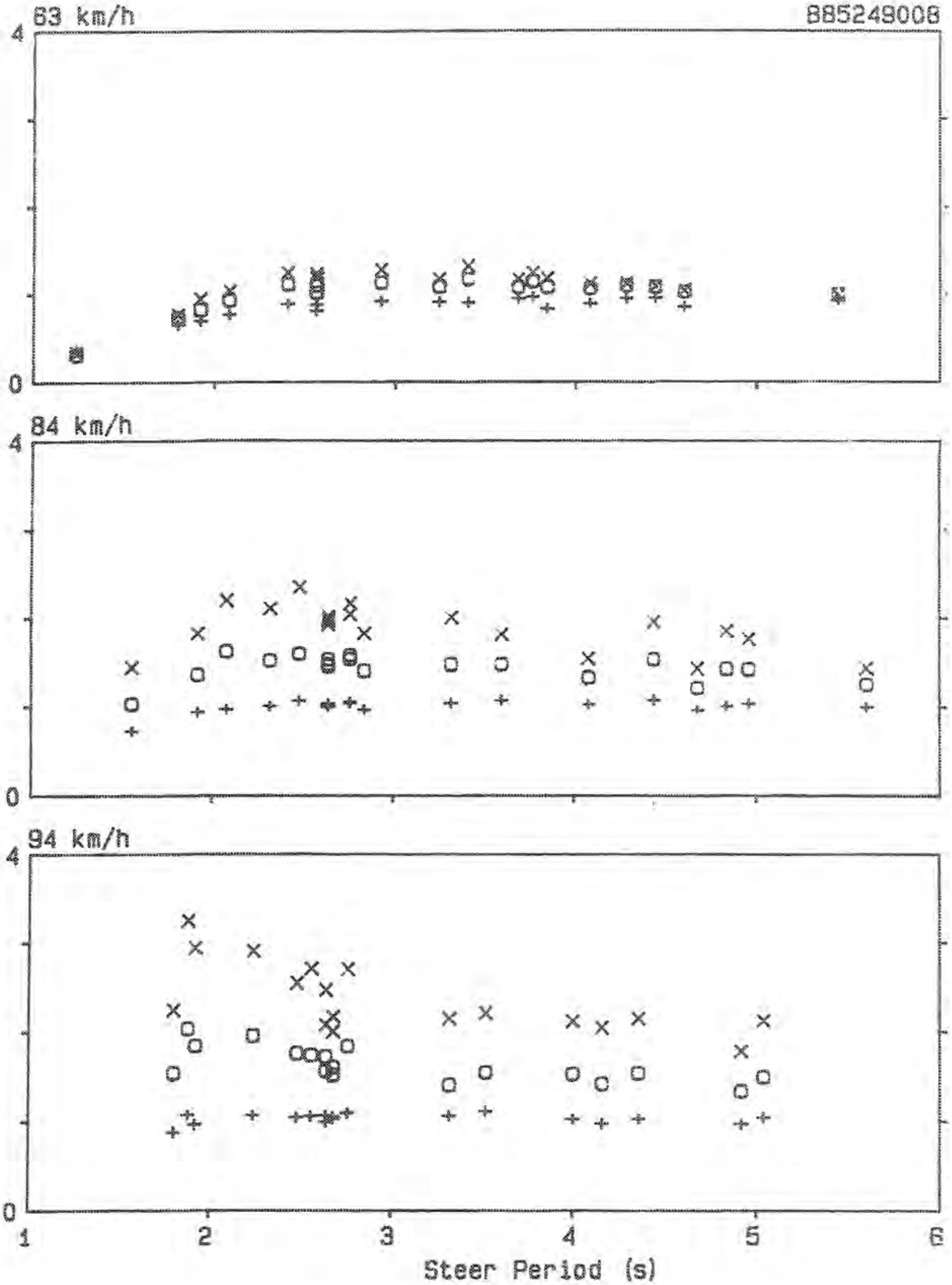
The lane change on a standard highway requires a steer input by the driver that is similar to the sinusoidal steer. This test is representative of an obstacle avoidance manoeuvre on a multilane highway, where the sudden appearance of an obstacle necessitates a fast lane change to the left.

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 gate while maintaining speed, 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 by rollover or an unacceptable trailer swing out of lane, defined here as in excess of 1 m, or the limiting speed of 94 km/h was reached. The sinusoidal steer test described in Section 3.6.7 is a sub-critical test, designed to display the dynamic characteristics of a vehicle. This test uses 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 simply imposes a task on the driver and ensures repeatable results. The results are summarized in Table 11.

The 45 ft (13.72 m) semi and the three 48 ft (14.63) semi-trailers were able to negotiate the course at

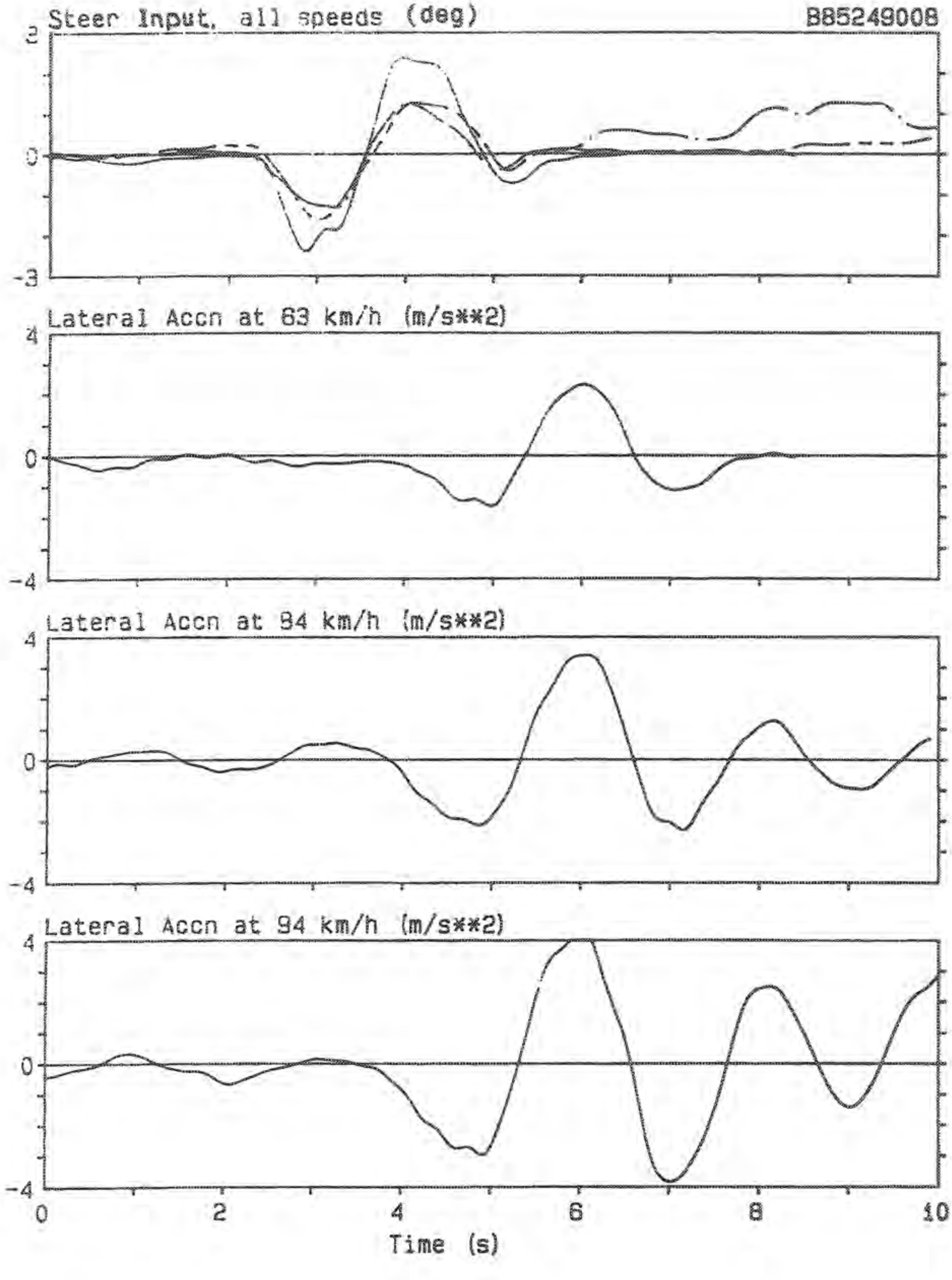
**Table 11 – Instability in the lane-change manoeuvre**

| 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 |
| 5-axle 48 ft semi | >95 | None |
| 6-axle 48 ft semi | >95 | None |
| 7-axle 48 ft semi | >95 | None |



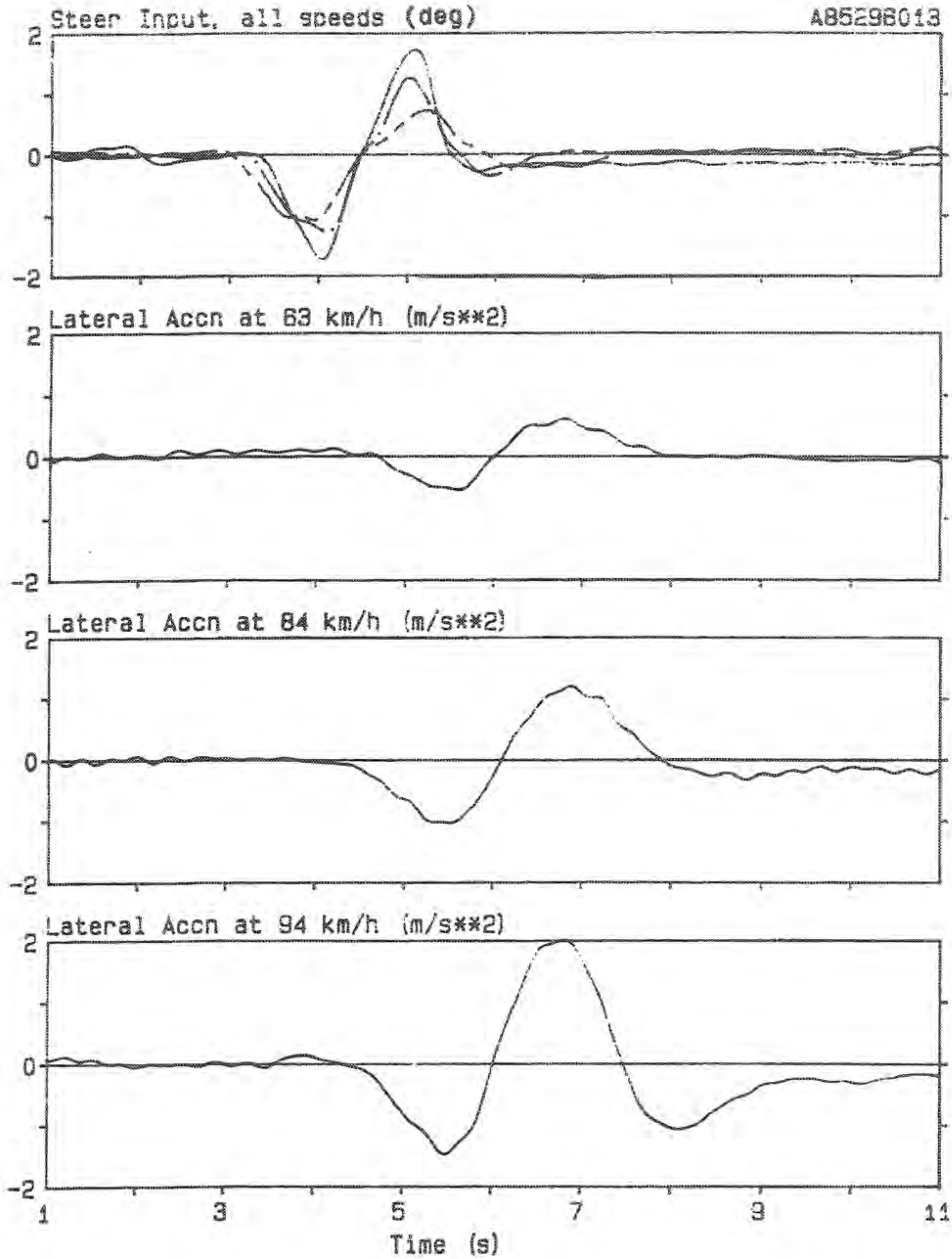

**A-train triple, rearward amplification of lateral acceleration**

**FIGURE 14**




**A-train triple, sinusoidal steer, rear trailer lateral acceleration at three speeds**

**FIGURE 15**

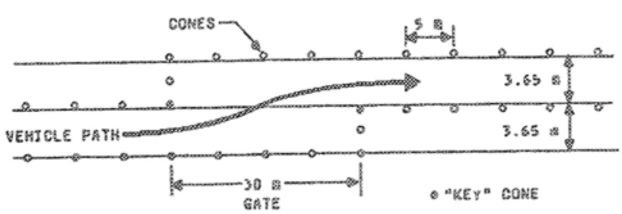



**C-train triple, sinusoidal steer, rear trailer lateral acceleration at three speeds**
**FIGURE 16**

the maximum test speed of 95 km/h and were, clearly, the most stable vehicles. As the limiting speed was approached, it was evident that the 6- and 7-axle 48 ft vehicles were exhibiting progressively more trailer swing.

While this test was not conducted for the A-train double, the same test was conducted for a very similar vehicle in a previous test program, which resulted in slide and violent rollover of the rear trailer (15). The rear trailer of the B-train double swung rather violently, and its outrigger touched down on both sides. The vehicle would not have rolled over, but the response was certainly undesirable. When the C-train double reached a sufficiently high speed in the manoeuvre, the B-dolly steered out. This transferred lateral load from the rear trailer to the lead trailer tandem axles. These became overloaded, so the lead trailer slid left towards the edge of the lane, and rear trailer simply tracked behind. The response of this vehicle was rather mild, certainly not as violent as that of 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 18. No outrigger touchdown occurred, because the centre of gravity was low and the wheel track width was 2.59 m (102 in), whereas for the other vehicles it was 2.44 (96 in). Nevertheless, if the trailer centre of gravity had been at a more typical height, the rear trailer would undoubtedly have rolled over violently, as it did for the A-train double. While rollover was the "expected" mode of instability in such manoeuvres for this vehicle, this test shows that another mode of instability is possible. The C-train triple was relatively mild in its response compared to the A-train. The mechanism was the same as described earlier for 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. However, 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.




**Lane-change manoeuvre course**

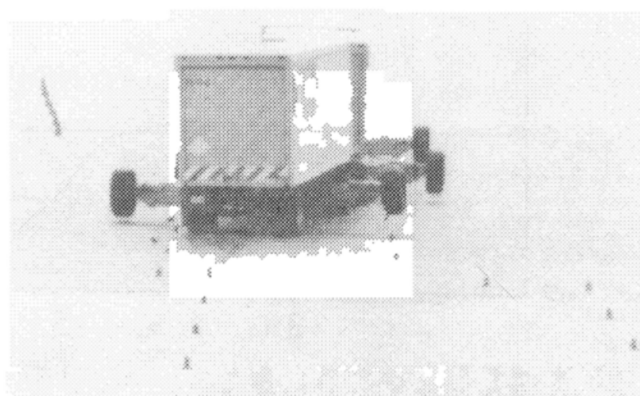
**FIGURE 17**

The sinusoidal steer test ranked the six vehicles in terms of stability: the higher the rearward amplification, the lower the stability. When the rearward amplification of Table 10 are compared with the limit speeds of Table 11, 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.

### 3.6.9 Normal Straight-Line Driving

The trailers of combination vehicles, when driven normally in a straight line, tend to sway a small amount due to road roughness and the small steer corrections by the driver. This sway is related to vehicle configuration and speed 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.

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. The results were questionable and are not presented. There is no doubt, however, that there was no perceptible sway to observers in a chase vehicle for the semitrailers. For the doubles and the C-train triple, some other reference, such as a



**A-train triple, lane change**

**FIGURE 18**

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 highly visible, with a distinct component of about 2 s period and 0.05 g lateral acceleration at the rear trailer.

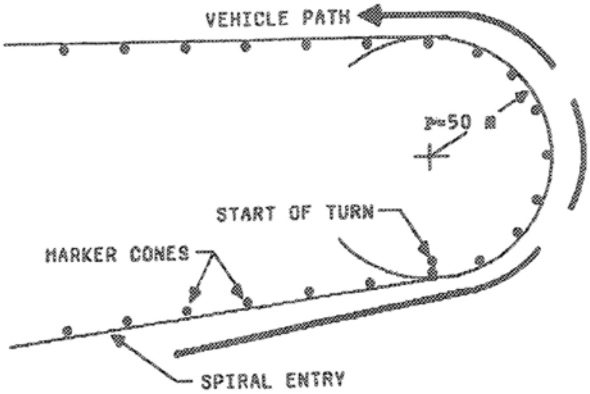
**3.6.10 Steady Circular Turn**

A loaded vehicle can roll over in a steady 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. There are often dynamics 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 stability characteristic of a vehicle. This test examined that characteristic.

The steady circular turn course was laid out using traffic cones on a dry high-friction surface, as shown in Figure 19. 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 smoothly, and followed on the outside for as long as possible. A sequence of runs was conducted at increasing speed 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 map out the vehicle roll response as a function of speed.

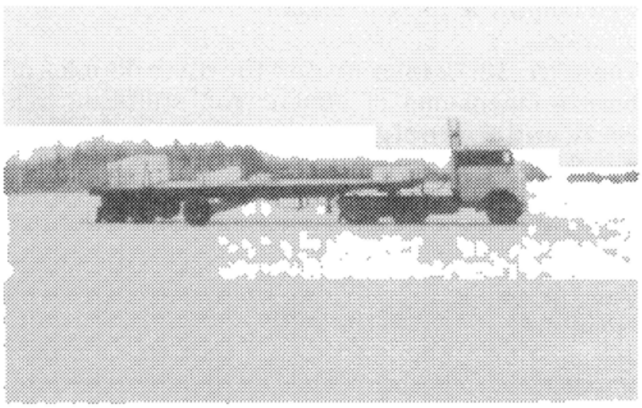
The outriggers were set such that the vehicle wheels on the inside of the turn would lift by 0.15 to 0.20 m (6 to 8 in) at outrigger touchdown, which corresponds to about 6 of body roll. The A-trains could clearly roll over the rear trailer, whereas for the other vehicles, outrigger touchdown might occur, but the entire vehicle could still be somewhat short of the point of rollover. Outrigger touchdown, therefore, simply denoted a point beyond which further testing was impractical. There would not necessarily by any relationship between these points for each vehicle.

The 45 ft (13.72 m) semi experienced a smooth outrigger touchdown at 0.52 g, as shown in Figure 20. The trailer was twisting due to the load distribution, and the entire vehicle may 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 rather violent response, unlike the smooth rollover of a similar A-train in an earlier test (15). The B- and C-train doubles both had so much 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



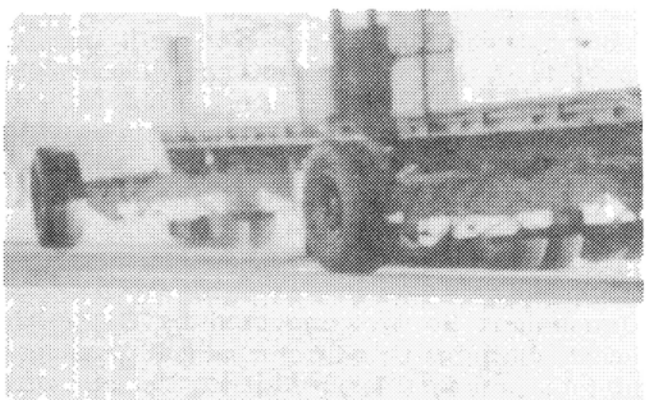

**Steady circular turn course**

**FIGURE 19**



**45 ft semi, steady circular turn**

**FIGURE 20**



**B-train double, steady circular turn**

**FIGURE 21**

B-train and 0.54 g for the C-train. Whether these vehicles would actually have rolled over is questionable. All wheels except those of the tractor clearly lifted for the B-train (Figure 21). For both A- and C-train triples the low trailer centre of gravity previously mentioned and the 2.59 m (102 in) 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, and the driver steered out from the circle, at 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 undoubtedly 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 already seen for the lane change. The outriggers of the 5- and 6-axle 48 ft (14.63 m) semitrailers touched down at lateral acceleration of 0.52 and 0.53 g, respectively, and the trailers than swung out. There was so much drag on the 7-axle 48 ft (14.63 m) semi that the driver could only reach 0.39 g, well below the roll threshold.

The 45 ft (13.72 m) semi and the three doubles all have suspensions of similar roll stiffness, axle loads, and centre of gravity heights. It is, therefore, hardly surprising that they have similar roll characteristics. In a manoeuvre at the limits of stability in an A-train, the driver has little, if any, feel for the rear trailer's state, and the trailer can rollover 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 rollover, may have an opportunity to stabilize the vehicle. 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, the driver might respond to the vehicle and be better able to avoid the marginal situation. From this point of view, the B- or C-train double is preferred to the A-train.

Static rollover characteristics of all vehicles tested, except for the triples, which were too long, were examined in a parallel part of the Weights and Dimensions Study, conducted by Centre de Recherche Industrielle du Quebec (CRIQ), using a tilt table built for this purpose (14). Vehicles were provided to CRIQ staff, loaded as for these tests, except that outrigger outer sections were removed to get the vehicle onto the tilt table. The vehicle was driven onto the table, 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 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. 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 since the dolly hitch offers no roll restraint. For all other 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 vehicle units of these combinations. A typical rollover condition is shown in Figure 22, with the A-train double. The angles at which rollover occurred in the tilt test are compared with the peak lateral acceleration at which outrigger touchdown occurred in the steady circular turn in Table 12.

The agreement here seems quite good, but the data are sparse, based on a single test in each case. It is interesting that, except for the C-train double, all lateral accelerations in the steady circular turn are slightly less than those from the tilt test. This supports the observer's opinion that some of these vehicles might not have rolled over despite the outrigger touchdown.

The closeness of the tilt test results for the 45 ft (13.72 m) semi and the three doubles 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

**A-train double, tilt test**
**FIGURE 22**

in a truck. The 1.75 m (70 in) centre of gravity height of Table 12 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 about 0.3 g, a substantial decrease (20). 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.

## 3.7 COMPUTER SIMULATION

The University of Michigan Transportation Research Institute (UMTRI) yaw/roll program (21) 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. Therefore, 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 program was modified to read the steer input measured during a test run, and the initial conditions for some model degrees of freedom. 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 so that the test and simulation results could be compared.

The test program consisted of standardized tests of non vehicles of different configuration. 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 the same generic data (22) for suspension and tire characteristics as UMTRI used for its simulation study. This work was not a validation of the computer model.

Computer simulation was conducted for all vehicles in the loaded condition for sinusoidal steer, lane-change, and steady circulation turn tests on a high-friction surface.

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 and 7-axle 48 ft (14.63) semi to match the lane-change test results as well as the other seven 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 same tire modification was found essential for all nine vehicles if the simulation was to match the test results in the steady circular turn.

This work showed that the computer simulation could produce a reasonable agreement with test results for a range of vehicle configurations and conditions, both for individual runs as a trend over a number of runs, 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. In many instances, differences between simulation and test results identified difficulties with measurements rather than the simulation.

A detailed summary of this work is presented elsewhere (23,24).

**Table 12 - Comparison of roll thresholds, tilt test and steady circular turn**

| Vehicle | Tilt angle (deg) | Tangent of tilt angle | Lateral acceleration 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 |
| 5-axle 48 ft semi | 31.0 | 0.60 | 0.52 | |
| 6-axle 48 ft semi | 29.3 | 0.56 | 0.53 | |
| 7-axle 48 ft semi | 29.1 | 0.56 | -- | |

## 3.8 DISCUSSION

Tests were conducted with the equipment 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 and ended in mid-December. 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. The B-train and A- and C-train triples were tested in similar warm conditions, whereas the 45 ft (13.72 m)d 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. Tires were installed new 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. The three 48 ft (14.63 m) semitrailers were tested in sequence. When the tires were used for the second series of tests, they could still be described as "nearly new" and were without evident unusual wear patterns, except for the right rear axle tires of the 48 ft (14.63 m) vehicles, which got badly scalloped on their outer edge.

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 45 ft (13.72 m) semi was considered an easy vehicle to drive by the test driver. It tracked well, manoeuvred well, and was very stable. It took more space to turn than the three doubles, due to the trailer length. The A-train double was also an easy vehicle to drive, particularly in the evasive manoeuvre on the low-friction surface. The trailers had little influence on vehicle handling in this case, whereas the trailers of both B- and C-train doubles were pushing the tractor 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. 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 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 in manoeuvres. With regard to the C-trains, the driver felt that the Sauer axle was preferable to the axle tested previously (15) 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. The 5-axle 48 ft (14.63 m) semi was similar to the 45 ft (13.72 m) semi. The 7-axle vehicle drove well in a straight line, but took a lot of effort to turn, and the tractor was particularly sensitive in the wet. The 6-axle vehicle was intermediate between the other two.

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 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 driver had no feel for second trailer response which is available with the other two configurations. However, from previous experience (15), 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.

# 4. C-TRAIN HITCH SLACK AND DRAWBAR LENGTH TESTS

## 4.1 INTRODUCTION

A study of C-train stability was conducted in 1982 by MTC, the National Research Council of Canada (NRC), and UMTRI (25). That study consisted principally of tests conducted by MTC (15), with component parameter measurements and computer simulation by UMTRI. It was found that a C-train using an automotive steer-type dolly had some desirable stability characteristics relative to the comparable A-train.

A serious accident occurred to a C-train, where it was thought that excessive slack at the B-dolly hitch contributed to loss of lateral/directional stability of the vehicle (26). The A-train dolly is free to rotate in yaw about the hitch of its towing trailer. The double drawbars of the B-dolly, in principle, prevent this yaw rotation. However, to assist in vehicle manoeuvrability the B-dolly is provided with a self-steering axle. A- and C-trains, therefore, have the same number of dynamic degrees of freedom, with A-dolly yaw replaced by B-dolly axle steer for the C-train. If there is slack at the B-dolly hitches, the dolly and the entire vehicle accrue two more degrees of freedom. The first is dolly longitudinal motion, and the second is dolly yaw. The amplitudes of these degrees of freedom are limited by the amount of slack. Now compare a C-train with hitch slack to an A-train. For small amplitude motions, both dollies are free to yaw. The C-train now has two additional degress of freedom, dolly longitudinal motion, and axle steer. Depending upon the properties of the components, it could be less stable than the A-train in some respects because of these extra degrees of freedom. Stability would depend on speed, and it was expected that there would exist some critical speed at each hitch slack at which the vehicle would become unstable. A lateral motion would develop that would increase in amplitude until limited by non-linear vehicle characteristics or structural failure occurred. As the critical speed was approached, the vehicle would exhibit lateral motions having low damping. It was considered desirable by the study that the effect of hitch slack on C-train stability be investigated.

In practice, vehicles are configured for a specific mission, and the regulations of some provinces permit greater gross weight to be carried if the drawbar of the dolly of a doubles combination is longer. Drawbar length can clearly affect C-train stability, particularly for the empty vehicle on a low-friction surface. Since this was not covered in the earlier tests, the study considered it desirable that the effect of drawbar length on C-train stability be investigated.

Neither of these topics were readily amenable to computer simulation, because of the complexity of the model and the non-linear effects of slack and self-steering axle Coulomb friction. They were therefore investigated by full-scale vehicle tests, using the same vehicle as was used in the previous tests (15).

## 4.2 TEST VEHICLE

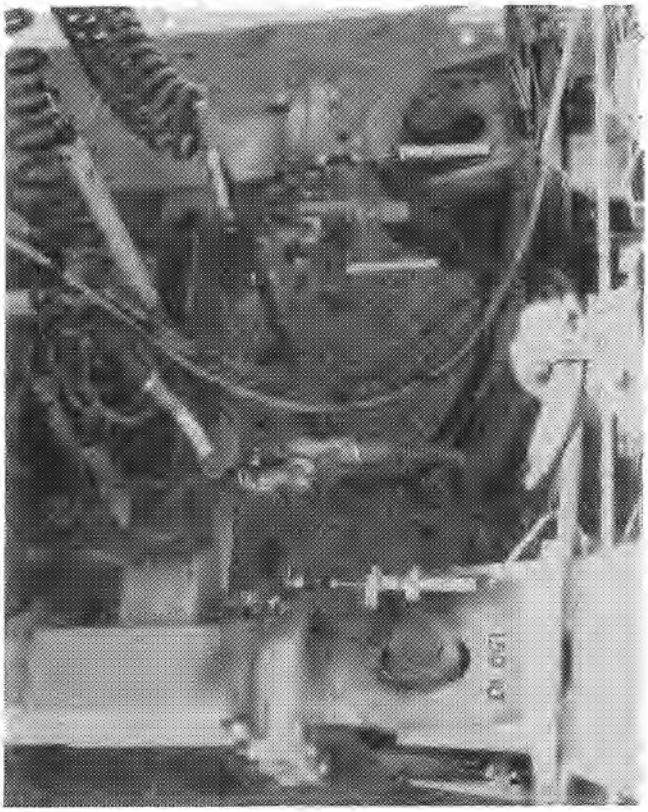
The test vehicle consisted of the MTC Freightliner, the trailers of the MTC doubles combination, and a B-dolly fabricated specially for these tests. The B-dolly had a frame with two bolt-on drawbar extensions, which permitted drawbar lengths of 1.65, 2.13, and 3.05 m (5, 7, and 10 ft). The dolly used the same BPW self-steering axle that was used on the ASTL B-dolly of the earlier tests (15). The test vehicle was also the same, except that it was fitted with Michelin XZA radial tires rather than the Firestone Transport 1 bias ply tires of the earlier tests. Two hitches shown in Figure 23 were specially fabricated by NRC for these tests, with longitudinal slack adjustable from 0 to 50 mm (0 to 2 in) in increments of 6 mm (0.25 in) (27).

## 4.3 TEST PROGRAM

The test program was divided into two parts, one for hitch slack and the other for drawbar length.

It was expected that with slack at the dolly hitch there would be a low-damped oscillation of the vehicle as a critical speed was approached. The vehicle response could only be evaluated properly if a standard input was used to excite the vehicle. A 414 kPa (60 psi) brake pulse of 2 s duration applied to the right-hand wheel of the B-dolly was chosen as the excitation. This caused the wheel to steer to the right as it momentarily locked, and produced a lateral/directional response of the dolly and rear trailer. Runs were made on a high-friction surface at a series of speeds between 33 and 72 km/h at slack up to 50 mm (2 in).

The effect of drawbar length on vehicle stability was evaluated by three tests. First, the loads at the tractor fifth wheel were examined as a function of speed. Various runs through a fixed curve representative of a portion of a freeway ramp were conducted for each drawbar length. These loads were expected to be related to vehicle stability. This was investigated by an evasive manoeuvre conducted on a low-friction surface. A series of runs was made at increasing speeds until the driver was unable to maintain control of the entire vehicle through the manoeuvre. Finally, the effect of braking was introduced by making stops using both symmetric and asymmetric dolly braking in a curve on a low-friction surface.



**Hitch slack measurement**

**FIGURE 23**

The test procedures and data processing were generally similar to those described above for the baseline vehicles.

## 4.4 HITCH SLACK TEST RESULTS

When the test was initiated, it was expected that increasing slack and vehicle speed would result in the emergence of a low-damped lateral/directional oscillation of the vehicle. It was for this reason that the brake on the right-hand wheel of the B-dolly was pulsed as a method of excitation, as at low levels of damping, only a small input is necessary to cause considerable vehicle response. However, with slack up to 50 mm (2 in), no such oscillation arose to a speed of 72 km/h, the highest possible at the test area. The brake pulse momentarily locked the wheel and caused the axle to steer to the right. This caused the dolly to yaw to the right-hand hitch moving forward to the full extent of the slack. The rear trailer responded simply by moving to the right, and the vehicle progressed with the rear trailer offset a small amount to the right. When the brake released, the B-dolly axle self-steering mechanism centred itself, and the vehicle returned to normal.

Variations in the amplitude and duration of the brake pulse had no effect on the vehicle response. The brake pulse was applied during the normal method of running, which was at full throttle, in a specified gear when the engine governor provided a controlled speed and the vehicle was fully stretched out. Runs were made when the brake was pulsed with the clutch depressed and the vehicle slowly decelerating against the various resistances, when the B-dolly tended to float within its hitch slack. Runs were also made when the brake was pulsed with the rear trailer brakes disabled and the lead trailer brakes lightly applied by means of the hand valve, when the B-dolly and rear trailer bunched up on the lead trailer. Runs were made with the same variations with the vehicle following a spiral trajectory. Finally, runs were made without pulsing the brake but with a small sinusoidal steer input. None of these inputs resulted in any significant response of the vehicle that had the appearance of low-damped oscillation; indeed, in all cases, the response was well damped.

This test had various limitations relative to the particular conditions of the accident that identified the issue. Stability is strongly affected by speed, details of the vehicle, and other factors. The maximum speed achieved was substantially below that at which trucks travel on the highway. The high on-centre stiffness and high Coulomb friction in the automotive steer mechanism of the axle are both very beneficial to stability, and a different result might have ensued if a turntable-type B-dolly, which has much less friction, had been used. Indeed, if nothing else, this test confirmed the desirable properties of the BPW axle that were so apparent in the earlier tests (15). The null result should certainly not be construed as a finding that any amount of slack at the hitch is acceptable. Since slack adds degrees of freedom to the dynamic system that is the truck, and this is inherently destabilizing, any slack at all is undesirable. Some slack, perhaps 6 mm (0.25 in) is inevitable from the need to couple the dolly to the trailer, and the effects of wear. Even this should always be controlled by an air-actuated no-slack type pintle hook. Any more slack, whether by design, wear, or due to compliance of hitch components, is considered unacceptable.

### 4.5 DRAWBAR LENGTH TEST RESULTS

Increase in drawbar length from 1.52 to 3.05 m (5 to 10 ft) had little effect in reducing the stability of the empty vehicle on a low-friction surface. While some weight regulations may tend to encourage longer drawbars, there are severe structural problems caused by twist of the dolly frame as the vehicle drives across an uneven surface. This is expected to mitigate any tendency towards longer drawbars. There was little change as far as the driver was concerned. The differences between the extremes of the drawbar length were much less than the difference between the A-train and a C-train. Because the driver can feel the action of the trailers with this configuration, he will become familiar with the handling of the particular vehicle he is driving. A professional driver should drive according to both the road conditions and the characteristics of his vehicle. Drawbar length is, therefore, not considered a major consideration in stability and control of the C-train. A short drawbar is preferred both for vehicle stability and dolly structural design.

This investigation also included some C-train responses to braking. It was not possible to generate consistent results in this test, which simply served to demonstrate that steering of the axle of the B-dolly appeared to have no effect on vehicle stability when braking with locked wheels on high-, low-, and split-friction surfaces.

## 5. 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.

Static roll stability is essentially independent of vehicle configuration where vehicles have the same suspension, axle load, and centre of gravity height.

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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