

**Vehicle Weights and Dimensions Study**

**Volume 6**

**Hitch Slack and Drawbar Length Effects on  
C Train Stability and Handling**

Copyright 1986 by:

Canroad Transportation  
Research Corporation  
1765 St. Laurent Blvd.  
Ottawa, Canada K1G 3V4

ISBN: 0-919098-83-5

# RTAC REPORT DOCUMENTATION FORM

Project No.	Report No.	Report Date	IRRD No.
		July 25, 1986	
Project Manager			
J.R. Pearson			
Title and Subtitle			
Volume 6 -- Hitch Slack and Drawbar Length Effects on C Train Stability and Handling			
Author(s)		Corporate Affiliation(s)	
J.R. Billing		Head, Commercial Vehicles Section Ontario Ministry of Transportation and Communications Downsview, Canada M3M 1J8	
Sponsoring/Funding Agency and Address		Performing Agency Name and Address	
Canroad Transportation Research Corporation 1765 St. Laurent Blvd. Ottawa, Canada K1G 3V4		<b>Roads and Transportation Association of Canada</b> 1765 St. Laurent Blvd. Ottawa, Canada K1G 3V4	
Abstract			Keywords
<p>Three series of tests of a C-train were conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study.</p> <p>The first series investigated the effect of hitch slack on vehicle stability. No instability occurred with slack up to 50 mm at speed up to 72 km/h. Slack should, nevertheless, be maintained at a minimum.</p> <p>The second series investigated the effect of drawbar length on vehicle stability. Minimal effect was found but should not be a concern, because structural limitations will dictate the drawbar length.</p> <p>The final series was intended for validation of computer simulation, but the desired test conditions could not be achieved. It did demonstrate that B-dolly steer did not appear to be a serious problem when braking.</p>			<p>C-train B-dolly stability braking vehicle testing</p>
No. of Pages	No. of Figures	Language	
29		English	
Supplementary Information			

## DISCLAIMER

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

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

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

## PREFACE

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

The Ontario Ministry of Transportation and Communications was responsible for carrying out a program of testing to examine the influence of drawbar length and hitch slack on C Train configuration stability. The cooperation of the following agencies and companies is gratefully acknowledged for their assistance in the conduct of this program:

National Research Council of Canada  
Westank Willock

Funding to conduct the research was provided to Canroad Transportation Research Corporation by:

Alberta Transportation  
British Columbia Ministry of Transportation and Highways  
Manitoba Highways and Transportation  
New Brunswick Department of Transportation  
Newfoundland Department of Transportation  
Nova Scotia Department of Transportation  
Ontario Ministry of Transportation and Communications  
Prince Edward Island Transportation and Public Works  
Ministère des Transports du Québec  
Saskatchewan Highways and Transportation  
Transport Canada  
Motor Vehicle Manufacturers Association  
Canadian Trucking Association  
Truck Trailer Manufacturers Association  
Private Motor Truck Council

John Pearson, P.Eng.  
Project Manager  
Vehicle Weights and Dimensions Study

**VEHICLE WEIGHTS AND DIMENSIONS STUDY  
TECHNICAL STEERING COMMITTEE**

Project Manager      John R. Pearson, Senior Programs Manager, Roads and  
Transportation Association of Canada

Chairman              M.F. Clark, Associate Deputy Minister (Engineering),  
Saskatchewan Highways and Transportation

Members

Dr. J.B.L. Robinson, Director of Technical Programs, Roads and Transportation  
Association of Canada

M. Brenkmann, Director, Research Program Development, Transport Canada

M.W. Hartin, Manager, Vehicle Standards Office, Ontario Ministry of  
Transportation and Communications

R.J. Lewis, Special Consultant, Canadian Trucking Association

M. Ouellette, Manager, Engineering, Mack Canada Inc.

R. Saddington, National Technical Advisor, Esso Petroleum Canada

W.A. Phang, Head, Pavement Research Division, Ontario Ministry of  
Transportation and Communications

G. Tessier, Direction de la recherche, Ministère des Transports du Québec

E. Welbourne, Head, Vehicle Systems, Transport Canada

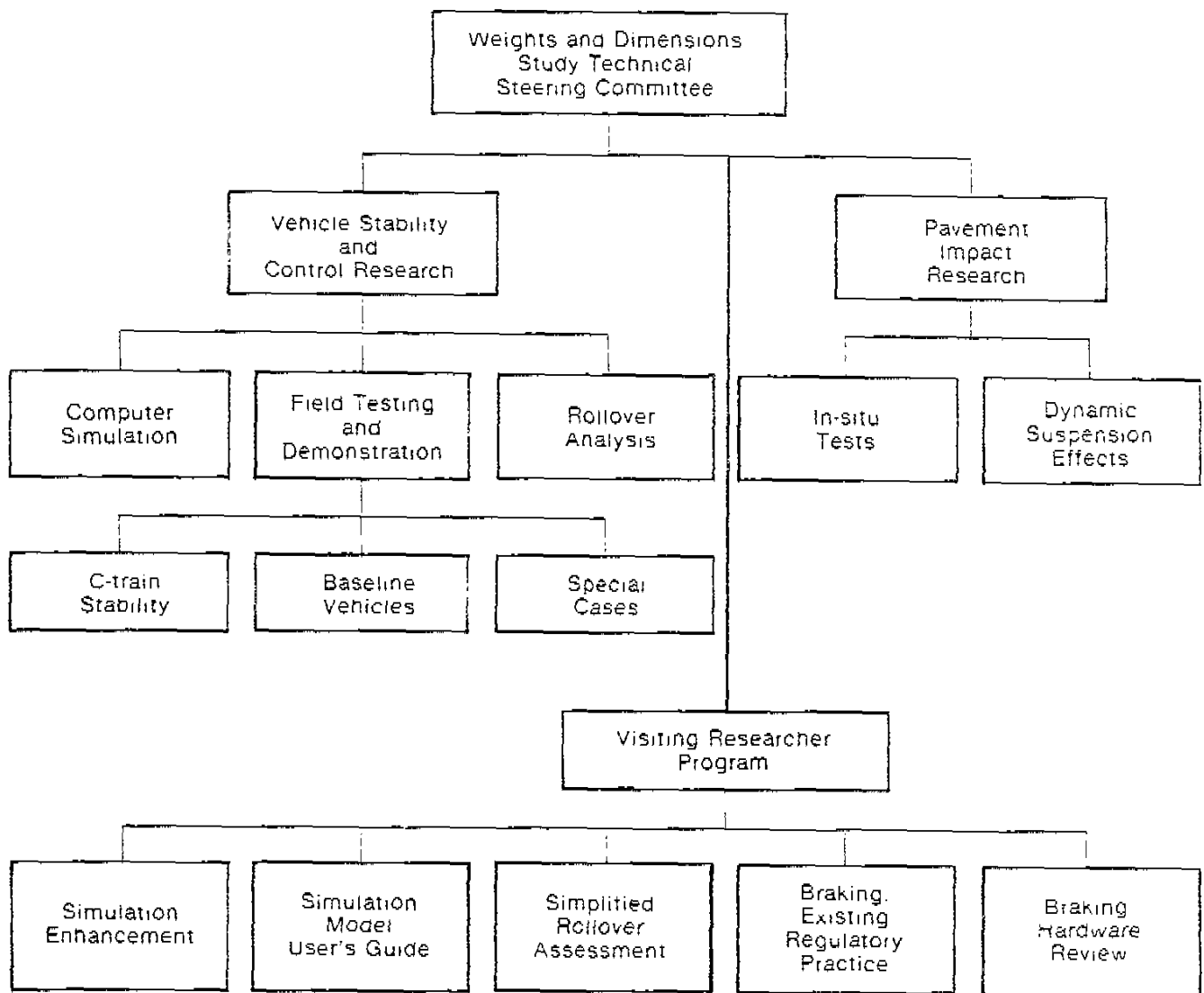
R. Zink, Chief Engineer, North Dakota State Highway Department (representing  
AASHTO)

D.J. Kulash, Assistant Director, Special Projects, Transportation Research  
Board



# HEAVY VEHICLE WEIGHTS AND DIMENSIONS STUDY

## TECHNICAL WORK ELEMENTS OVERVIEW



CV-86-13

Volume 6

**Hitch Slack and Drawbar Length Effects on C Train Stability  
and Handling**

J.R. Billing  
W. Mercer

Commercial Vehicles Section  
Ontario Ministry of Transportation  
and Communications



## ABSTRACT

Three series of tests of a C-train were conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study.

The first series investigated the effect of hitch slack on vehicle stability. No instability occurred with slack up to 50 mm at speeds up to 72 km/h. Slack should, nevertheless, be maintained at a minimum.

The second series investigated the effect of drawbar length on vehicle stability. Minimal effect was found but should not be a concern, because structural limitations will dictate the drawbar length.

The final series was intended for validation of computer simulation, but the desired test conditions could not be achieved. It did demonstrate that B-dolly steer did not appear to be a serious problem when braking.

## TABLE OF CONTENTS

	PAGE
1/ INTRODUCTION . . . . .	1
2/ TEST DEFINITION . . . . .	3
2.1/ Test Vehicle Configuration . . . . .	3
2.2/ Hitch Slack Investigation. . . . .	4
2.3/ Drawbar Length Investigation . . . . .	5
2.4/ Simulation Validation. . . . .	6
3/ TEST EQUIPMENT AND PROCEDURES . . . . .	9
3.1/ Test Site. . . . .	9
3.2/ Instrumentation. . . . .	9
3.3/ Data Capture . . . . .	10
4.4/ Data Processing and Analysis . . . . .	11
4/ RESULTS . . . . .	12
4.1/ Hitch Slack Investigation. . . . .	12
4.2/ Drawbar Length Investigation . . . . .	13
4.3/ Simulation Validation. . . . .	15
5/ CONCLUSIONS . . . . .	17
6/ REFERENCES . . . . .	19

## LIST OF FIGURES

	PAGE
1/ Articulation of A- and C-Train Doubles. . . . .	20
2/ Limited Articulation of a B-Dolly Due to Hitch Slack. . . . .	21
3/ Test Vehicle. . . . .	22
4/ Test Vehicle Dimensions . . . . .	22
5/ Hitch Slack Device. . . . .	23
6/ B-Dolly, Short Drawbar. . . . .	23
7/ B-Dolly, Medium Drawbar . . . . .	24
8/ B-Dolly, Long Drawbar . . . . .	24
9/ Evasive Manoeuvre Course. . . . .	25
10/ UMTRI Mobile Dynamometer. . . . .	26
11/ MTC Commercial Vehicle Test Facility (Centralia). . . . .	26
12/ Load-Measuring Fifth Wheel on Mounting Plate. . . . .	27
13/ Load-Measuring Fifth Wheel Assembly . . . . .	27
14/ Hitch Slack Measurement . . . . .	28
15/ Response to Brake Applications, Axle 6 Right, Wet High-Friction Surface . . . . .	28
16/ Vehicle Making Evasive Manoeuvre on Low-Friction Surface . . . . .	29

## ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The dolly frame was provided by the Roads and Transportation Association of Canada (RTAC), and the hitch slack devices were provided by the Railway Laboratory of the National Research Council.

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

These reports were produced by T. Burt, L. Hobbs, B. McAdam, A. Marshall, and B. Mitchell of Technical Publications.

The efforts of all involved are hereby acknowledged with gratitude.

## 1/ INTRODUCTION

The CCMTA/RTAC Vehicle Weights and Dimension Study is a program of research intended to obtain a uniform understanding of the stability and control characteristics of heavy truck combinations and the effects of these vehicles on pavement responses. The goal of the study is to achieve uniformity in the application of vehicle weight and dimension regulations across Canada.

Within the vehicle stability portion of the study, the primary objective was to determine the nature and magnitude of the likely stability and control problems which could be expected from truck configurations meeting various weight and dimension constraints. This portion of the study was based primarily on computer simulation, which permits ranges of vehicle configurations and conditions to be easily examined. It was also supported by full-scale vehicle tests, to demonstrate significant performance characteristics of particular vehicles and investigate conditions not easily simulated.

The B-converter dolly, or double-drawbar dolly, has been identified as a means to improve the dynamic characteristics of double and triple trailer combinations [1,2]. It achieves this by means of the double hitch, which prevents dolly articulation relative to its towing trailer. This means a C-train double has only two points of articulation, whereas a conventional A-train double has three, as shown in Figure 1. A C-train triple has three points of articulation, and the A-train triple has five. While elimination of hitch articulation with the B-dolly results in much improved high-speed dynamic characteristics, it also results in high loads on the dolly axle and hitch, unless the axle is provided with self-steering. A previous study identified the desirable characteristics for self-steering and hitching of B-converter dollies [1], based largely on field testing of a particular dolly [3]. The US Federal Highway Administration (FHWA) currently has a study under way to refine these desirable characteristics.

The B-dolly concept is based on elimination of the hitch articulation, which necessitates a self-steering axle. If some hitch articulation should develop, because of wear or by design at the hitch, then the C-train would have the same hitch articulation as the A-train, though, presumably, it would be limited to a small amplitude, as shown in Figure 2. It would also still have the self-steer capability of the B-dolly axle. Such a vehicle could potentially have very poor dynamic

stability characteristics because self-excited oscillation might occur. A serious accident attributed to free play of the hitch has, indeed, occurred [4]. Therefore, for this study, the effect of B-dolly hitch slack on vehicle dynamic stability was investigated.

The weight and dimension regulations of various provinces are generally drafted so that the greatest gross combination weight (GCW) occurs when the overall vehicle length and axle group spacings are greatest. This encourages long converter dolly drawbars, to the length possible within the desired load-bed length. Previous tests showed that when an empty or loaded C-train was driven on a smooth high-friction surface, relatively modest steer was sufficient to break out the B-dolly centre detent, having the relatively high centring force and steer friction that gives desirable high-speed characteristics [3]. The same test also showed, though, that the high centring force would lead to tractor jackknife rather than trailer swing when the C-train was driven empty in high-speed lane-change manoeuvres on a low-friction surface. Indeed, a spectacular loss-of-control incident from a jackknife resulted in premature termination of a portion of the investigation [3]. Therefore, for this study, the effect of B-dolly drawbar length on vehicle stability and control was investigated. Emphasis was on empty vehicle behaviour on a low-friction surface, since a good understanding of the loaded C-train high-speed dynamic characteristics was obtained in the previous study [1,3].

The Weights and Dimensions Study was based primarily on computer simulations conducted by the University of Michigan Transportation Research Institute (UMTRI). A significant segment of the study addresses the C-train, which is a vehicle configuration not represented in the computer simulations developed by UMTRI. UMTRI, therefore, modified their programs to represent the B-dolly and, hence, the C-train. The modifications were validated by simulation of actual tests conducted on a known vehicle. One of the concerns identified, but not addressed in the previous study, was C-train response due to differential longitudinal forces at each wheel of a B-dolly steer axle [1]. UMTRI conducted the validation exercise, using the comprehensive handling and braking model (phase IV model). The tests were conducted using a C-train with characteristics representative of typical highway carriers used in Canada [5]. The MTC test vehicle was, in key respects, similar to the vehicle specified by UMTRI, though different in others not critical to the tests conducted. The necessary validation of C-train braking and dynamic characteristics was conducted consecutively with the tests described previously.

## 2/ TEST DEFINITION

### 2.1/ Test Vehicle Configuration

The MTC test vehicle was used for all tests. The tractor was a 1975 three-axle Freightliner cab-over-engine type with integral sleeper and two drive axles. The two-axle King trailers and converter dolly were specially built to MTC specifications for research and testing. The trailers were equipped with outriggers and safety cables to permit testing to the limits of stability, without hazard to the vehicle or its driver. The outriggers were set so that trailer body roll at outrigger touchdown was about 6 to 7°. Safety cables between each vehicle unit limited articulation angles in jackknife or trailer swing to about 20° to prevent damage to the vehicle from uncontrolled articulation. The trailers can be loaded to any desired gross weight and centre of gravity by standard concrete blocks weighing about 6.9 kN (2000 lb) each.

The C-train test vehicle configuration is shown in Figure 3, and its dimensions are given in Figure 4. The nominal length of each trailer was about 7.3 m (24 ft), but the trombone-type lead trailer may extend to lengths of 8.5 and 9.75 m (28 and 32 ft). All tests were conducted using the lead trailer at its shortest. Extension of this trailer caused little difference in vehicle rollover responses on a dry surface. The overall length of this combination was 20.8 m (68.2 ft), with a B-dolly drawbar length of 2.19 m (7 ft) [3].

The C-train characteristics are greatly affected by the air pressure applied to the self-steering axle centring mechanism. The manufacturer's recommended values of 241 and 483 kPa (35 and 70 psi) were used as the nominal values for empty and loaded vehicles, respectively. In addition, the limiting condition of 0 kPa, which locks the steering, and 124 kPa (18 psi), which is close to free casting, were used.

The Michelin XZA rib-type radial ply tire was used for tractor steer, trailer, and dolly axles, and the Michelin XM+S4 lug-type radial ply tire was used for tractor drive axles. Tire size 11R24.5 was used on the tractor and 11R22.5 on trailers and dolly. All new tires were run a distance of 160 km (100 mi) to provide nominal wear conditions. All tires were inflated to the manufacturers recommended pressure for maximum load, 690 kPa (100 psi).

The hitch slack device, shown in Figure 5, was provided by the study as

part of the B-dolly drawbar modification. It has slack in the longitudinal direction only, in increments of 6 mm (0.25 in) over a range of 0 to 50 mm (0 to 2 in).

The dolly braking system was modified to allow application of a specified pressure to either brake chamber by means of a switch in the tractor. The switch activated a cycle timer, which activated a solenoid valve on a second reservoir added to the dolly, which was fed by a pressure regulation valve so that the brake chamber pressure could be limited to the specified pressure. This reservoir fed the dolly relay valve, through a limiting valve, to give a slow pressure rise. Shutoff valves were installed on both output ports so that neither, either, or both of the dolly brakes could be applied. The nominal brake pulse selected was 414 kPa (60 psi) and 2 s duration on the right dolly wheel only. This caused that wheel to lock momentarily and steer to the right.

To test the effect of B-dolly drawbar length, a new frame with an extendable drawbar was made for the B-dolly that had previously been tested [3]. The original drawbar length gave a tow-eye-to-fifth-wheel distance of 2.19 m (7 ft). The new frame had a nominal tow-eye-to-fifth-wheel distance of 1.52 m (5 ft), and two extension frames were made, which extended this distance to 2.19 m (7 ft) and 3.05 m (10 ft). A fourth length, using both extensions together to give a distance of 3.66 m (12 ft), was not run. The three drawbar lengths are shown in Figures 6, 7, and 8.

## 2.2./ Hitch Slack Investigation

As speed was increased with slack in the dolly hitch, it was expected that the vehicle would become less stable. At the critical speed, the vehicle would be neutrally stable, and at any higher speed, it would be inherently unstable. Any input whatever at this point would result in a rapidly increasing lateral/directional response of the vehicle. This might be limited by a non-linear characteristic of the vehicle, or if the response was sufficiently violent, there could be structural failure. As the critical speed was approached, a low-damped oscillation of vehicle response was expected.

The effect of hitch slack was investigated using the B-dolly at its short drawbar length of 1.52 m (5 ft), with an empty vehicle on a high-friction surface. Several values of hitch slack were used, and the B-dolly steer axle steer pressure was set at 241 kPa (35 psi), the manufacturer's



recommended value for no load. A standard excitation of the vehicle was executed, and the magnitude of the response was recorded as the vehicle approached the critical speed. Responses such as rear trailer lateral acceleration, articulation, or path were used for evaluation, all normalized by an input. The vehicle was excited by a pulse input on the independent hand-valve actuation of the B-dolly brakes, with the vehicle travelling in a straight line and one output port of the dolly relay valve closed. This applied the brake on one wheel of the B-dolly, which resulted in steering of the axle and a transient response of the dolly and trailers. Vehicle stability was then evaluated by comparing the magnitude of this response with the magnitude of the brake pulse.

Speed was increased in small increments, up to a maximum of about 72 km/h, which was the highest possible speed through the high-friction test area. Testing was to be terminated when it became evident that the critical speed was very close or when 72 km/h was reached.

### 2.3/ Drawbar Length Investigation

The effect of dolly drawbar length for the three lengths given in Section 2.1 was evaluated, with the B-dolly steer axle pressure at the manufacturer's recommended value and locked steer. This evaluation was conducted with an empty vehicle, because the dolly centring force is expected to have the greatest effect at this condition.

The effect of dolly drawbar length on lateral force at the tractor fifth wheel was evaluated by driving the vehicle through a fixed curve representative of a freeway ramp at various speeds, up to a lateral acceleration of about 0.20 g, on a high-friction surface. Plots of lateral force at the tractor fifth wheel against such measures as distance travelled or tractor lateral acceleration gave a comparison of the effects of dolly drawbar length.

The effects of drawbar length on vehicle stability were further investigated by means of a series of evasive manoeuvres, as shown in Figure 9. These were conducted on a low-friction surface for the three drawbar lengths, with dolly steer pressure set according to the manufacturer's recommendation. The gate size was such that the vehicle configuration with the lowest sideforce at the tractor was just able to make the lane change at 40 km/h. Runs were made at steady speed and repeated as necessary to ensure consistent results.

The speeds of runs were increased until two speeds were found to bracket the stability boundary of the vehicle. At the lower speed, the vehicle was able to accomplish the manoeuvre consistently, and at the upper speed the driver always lost control.

The effect of braking on vehicle stability was examined by driving the empty test vehicle onto the wet low-friction surface through the 86.7 m (284.5 ft) radius curve. The vehicle was driven at about 40 km/h, which corresponds to a lateral acceleration of about 0.15 g, and the service brakes were applied. The effects of B-dolly drawbar length were then evaluated by performing the same manoeuvre but with the brakes on one side of the B-dolly axle deactivated.

#### 2.4/ Simulation Validation

This series of tests examined the interaction of differential B-dolly braking on C-train response and vehicle response to a rapid obstacle-avoidance-type manoeuvre.

The B-dolly brake torque characteristics were determined by making vehicle runs at 50 km/h on the split-friction surface, using the dolly brakes alone by means of the switch described in Section 2.1. Brakes were applied in pressure increments of 15 kPa (2 psi) in successive runs until the pressure level required to exceed the peak traction capability of the tires on each surface was bracketed. This was achieved by finding the highest pressure at which wheel lockup did not occur and the lowest pressure at which it always occurred, with at least three occurrences in each group. This procedure was repeated for the high-friction side of the split-friction surface. The peak longitudinal traction performance of the B-dolly tires on the test surfaces was then determined using the UMTRI mobile dynamometer shown in Figure 10. The calibrated load cell in this device permitted the B-dolly brake characteristics to be determined.

In the second step, a known steering moment was applied to the B-dolly, using key brake pressure levels determined in the previous test. This results in a steer response of the B-dolly axle and response of the rest of the vehicle. The simulation objective was then to match this response. The tests were conducted at 60 km/h, with the vehicle straddling the junction between the low- and high-friction surfaces. Runs were made at several pressure levels, such that neither wheel locked, the low-friction side wheel locked, and finally, both wheels locked. Runs

were also made with brakes active on only one side, to the point where wheel lock occurred.

In the third step, full vehicle braking was applied by the treadle valve, with simultaneous application of the B-dolly brakes by means of the switch. This test was conducted at 60 km/h on the split-friction surface, and sufficient B-dolly braking was applied to lock the low-friction wheel while the high-friction wheel remained rolling. The test was first conducted at a vehicle deceleration of about 0.1 g and then repeated with a deceleration of about 0.2 g. This test was primarily of an investigative nature.

The fourth step required that the B-dolly brakes be re-plumbed to be activated by the treadle valve. The test was conducted at 60 km/h on the split-friction surface, and a series of runs was made at increasing brake inputs until a condition was found at which the B-dolly wheel on the low-friction surface became locked and on the high-friction surface remained rolling. This condition was considered to give a representation of the hazard faced by the C-train braking on a non-homogeneous surface.

For the final step, the test vehicle approached the low-friction surface on the curved entry of radius 86.7 m (284.5 ft), at a speed of about 47 km/h, which corresponds to a lateral acceleration of about 0.2 g. When on the low-friction test area, the throttle was released and the B-dolly brakes were applied alone, using the switch and regulated pressure. A series of runs was made at increasing regulated pressures until a pressure level was bracketed, at which the lightly loaded wheel locked and the heavily loaded wheel remained rolling. A further series of runs was made using the treadle valve to achieve vehicle decelerations of 0.2, 0.3, and 0.4 g, while simultaneously using the switch to the regulated pressure just determined to cause only the lightly loaded side of the B-dolly axle to lock. Another series was made using treadle valve application of all brakes, at decelerations up to the point where the lightly loaded B-dolly wheel locked. This last series was intended to give a representation of the actual hazard faced by a C-train braking on a wet and slippery curve. All these braking tests were conducted with load on the front of the lead trailer and on the front and rear of the rear trailer. This unusual condition was designed to promote lock of the lead trailer's wheels.

The rapid obstacle-avoidance-type manoeuvres were conducted on the dry high-friction surface at a speed of 71 km/h. The vehicle was empty

except for blocks loaded at the rear of the rear trailer. This unusual configuration was selected to promote large vehicle responses, in lieu of those which occur at highway speeds of 90 to 120 km/h, which were un-reachable at the test facility. The driver released the throttle, depressed the clutch, and applied a steer input representing a single-cycle sine wave form. This steer input was applied at periods of about 5, 4, 3, and 2 s, with amplitude scaled to achieve a peak lateral acceleration at the tractor of about 0.2 g.

### 3/ TEST EQUIPMENT AND PROCEDURES

#### 3.1/ Test Site

Field tests were conducted at the MTC Commercial Vehicle Test Facility (Centralia). This is located at Huron Industrial Park, Centralia, 45 km (28 mi) north of London, Ontario. The test track, shown in Figure 11, is a former airfield runway 1000 m long by 50 m wide (3281 by 164 ft). It has a test area approximately 350 m long (1148 ft) of smooth asphalt, with a smooth approach 150 m long (492 ft). The test area includes a high-friction surface 150 m long (492 ft) with a dry skid number of about 96, and a low-friction surface 200 m (656 ft) long with a wet skid number of about 18 to 24. A sprinkler system is used for continuous wetting of this surface. There is also a curved entry of radius 86.7 m (284.4 ft) into the low-friction surface. The low-friction surface is abutted by smooth shoulders so that total loss of vehicle control would result in the vehicle sliding off the test area. There is also a low-friction lane on the smooth approach, which is used to provide a split-friction surface. Vehicle speed through the high-friction test area is limited by the available approach length to about 75 km/h with a loaded combination. Speed through the low-friction test area is limited to 63 km/h, to avoid the hazard of the vehicle spinning out of control after the safety cables are engaged.

The test facility also has about 2000 m<sup>2</sup> (21 529 ft<sup>2</sup>) of work space for vehicle preparation and storage. It includes basic shop facilities, an electronics lab, office space, and the ground station for data acquisition and processing, which is described in Section 3.2.

#### 3.2/ Instrumentation

The MTC test vehicle has been extensively instrumented to provide a range of dynamic variables and has been used for a number of test programs. For any new test, it is merely a matter of selecting the variables of interest, adding the new ones special to that test, and allocating the variables to channels of the data acquisition system. For these tests, sufficient on-board instrumentation was present to describe driver input and vehicle responses [6].

Lateral load at the tractor fifth wheel was measured using a fifth wheel specially modified by MTC, as shown in Figure 12. A long trunnion bar was obtained, and the fifth wheel mounts were modified to accept two

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

The B-dolly hitch slack was measured at each hitch, using a linear variable displacement transformer (LVDT), as shown in Figure 14. B-dolly steer angle was measured on both sides, using a Spectrol model 139 rotary potentiometer attached to each kingpin.

Wheel speeds at axles used in braking tests were measured using a flexible cable from the wheel to a rotary continuous potentiometer mounted on the vehicle. Brake chamber pressures were measured using Celesco model 2006 pressure transducers installed in the brake lines adjacent to the brake chambers.

### 3.3/ Data Capture

The data acquisition system on board the vehicle provided the necessary transducer excitation and signal conditioning for 36 individual signals. Each conditioned signal was digitized at a rate of 100 scans/s, and a digital pulse-code modulated (PCM) data stream was produced with appropriate synchronization words. The PCM data stream was broadcast by telemetry from the tractor to a ground station.

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

The PCM data stream was processed by a decommutator, which formatted it into a 16-bit parallel input stream for a Hewlett-Packard HP-1000 A700 computer, in the ground station. The computer read each run in real

time and created a raw data file on disk for subsequent processing.

This system is described in more detail elsewhere [6].

Each run was also recorded on colour videotape, generally from the vantage point of a cherry picker. Other sequences of the test program, and of the test devices, were also videotaped. Still photographs and slides of the test devices and testing were taken, as were notes of all test conditions.

### 3.4/ Data Processing and Analysis

Data processing was conducted concurrent with testing. At the beginning of each day, certain data files and procedures were initialized within the HP-1000 computer system. Data from each run were captured in real time and previewed by the test engineer on a graphics display to determine whether all critical data channels were functioning correctly and the run appeared to meet the general requirements. Portions of the run were selected for analysis, the details of which would vary depending upon the particular type of run. The raw data file was read, any corrections necessary were made, calibrations were applied to bring each channel to engineering units, and other quantities of interest were derived. The quantities critical to the test were displayed to the test engineer and used to make recommendations regarding the next run, which were transmitted by radio to the test director on the track. At the end of each test session, all data files created were archived to tape. The archive tape was indexed and complete, so that the processing of any particular run could be reconstructed at a later date.

The time history results of particular test runs, and cross-plots of typical desired quantities over a series of test runs, were used as the basic input to analysis of the various tests and the test program as a whole for the report.

Further details of this process are presented elsewhere [6].

#### 4/ RESULTS

##### 4.1/ Hitch Slack Investigation

When the test was initiated, it was expected that increasing slack and vehicle speed would result in emergence of a low-damped lateral/directional oscillation of the vehicle. For this reason, the brake on the right-hand wheel of the B-dolly was pulsed as a method of excitation, because only a small input is necessary to cause considerable vehicle response at low levels of damping. However, with slack up to 50 mm (2 in), no such oscillation arose up 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, with the left-hand hitch remaining at full extension and the right-hand hitch moving forward to the full extent of the slack. The rear trailer responded by moving to the right, and the vehicle progressed with the rear trailer offset a small amount to the right. When the brake was released, the B-dolly axle self-steering mechanism centred itself, and the vehicle returned to normal. The time history of typical runs is shown in Figure 15.

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 extended. These runs were made with the brake pulsed and the clutch depressed, resulting in the vehicle slowly decelerating against the various resistances and the B-dolly floating within its hitch slack. Runs were also made with the brake pulsed, the rear trailer brakes disabled, and the lead trailer brakes lightly applied by means of the hand valve, resulting in the B-dolly and rear trailer bunching 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 vehicle response that had the appearance of a low-damped oscillation; in all cases, the response was rather 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. 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, which were so apparent in the earlier tests [3].

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 this dynamic system and is inherently destabilizing, any slack is undesirable. Some slack, perhaps 6 mm (0.25 in), is inevitable from the need to couple the dolly to the trailer and because of 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.

#### 4.2/ Drawbar Length Investigation

The effect of drawbar length was investigated by three tests, as described previously.

The loads at the fifth wheel were measured during a spiral curve entry with the empty vehicle on a high-friction surface. The change in drawbar length was expected to affect the force required to turn the lead trailer, which would require a greater steer effort by the driver during a dynamic manoeuvre, to meet the increased side friction demand [7]. An increase in steer effort was considered to result in an earlier loss of control, as the limit of side friction was reached. No clear patterns emerged from these tests, in part because of developmental problems with the load-measuring fifth wheel.

The evasive manoeuvre was conducted with the empty vehicle, using gates of 20 m (65.6 ft) with 20 m in the left lane. A typical run is illustrated in Figure 16. This test was originally proposed as a lane change, but preliminary test runs showed that the vehicle could reach the safe limit speed for this type of test at the test area for any gate size the vehicle was able to get through. The evasive manoeuvre is much more complex than the lane change. The vehicle was evaluated in terms of various responses, with the dolly steer pressure set at 241 kPa (35 psi) to permit dolly steer. With the dolly steer locked, the vehicle became somewhat representative of a B-train. The limit speed, in kilometres/hour, at which the vehicle became unstable is presented in Table 1.

Table 1/ Instability in Evasive Manoeuvre

Drawbar	Dolly Steering	Dolly Locked
Short	57	52
Medium	58	57
Long	55	52

In all cases, the mode of instability was rear trailer swing during the return to the original lane. When the dolly was not locked, it did steer a small amount, 2 or 3°, during the manoeuvre. The driver felt that the dolly behaved much more consistently than in the previous tests [3], when the steer would break out inconsistently and, hence, unexpectedly, affecting driver performance of the manoeuvre. The driver also felt that the surface was less slippery than in the previous tests, though those tests were performed with different tires. For each drawbar length, there is a small reduction, as seen in Table 1, in the speed at which the vehicle could make the manoeuvre between the steering and locked cases, as would be expected. The results for the short drawbar, however, appear somewhat anomalous. The single physical difference between the three series of tests was air temperature, which was about 15°C for the short- and medium-drawbar tests, and 25-30° for the long- drawbar tests. The difference, therefore, is not readily accountable.

The principal conclusion from these tests is that the C-train, the case with the dolly steering, appears more stable than the B-train, represented by the dolly steer locked case, because of a reduced side friction demand. If the C-train dolly steer did not break out, the vehicle behaved as a B-train, so it can be concluded that the C-train is no less stable than a B-train. Since there are some B-trains with very large centre-axle group spreads or with a third single axle on one or other of the trailers, the C-train, even with a long drawbar, is probably no less stable than some of these B-trains. There may be some B-trains with small axle spreads that would be more stable than this C-train. Beyond that, it also appears that the effect of drawbar length on vehicle stability and control is relatively small. The principal benefit of the B- or C-train is that the driver has some feel for the rear trailer, feel which is not available with the A-train. There is a substantial difference in the stability characteristics of A- and C-trains [3]. The differences to the driver between the C-trains, due to drawbar length, are much less than due to the difference between A- and C-trains. There are

also a number of semitrailers, such as the 3-axle trailer with a wide-spread tandem and an airlift belly axle or any trailer of four or more axles, which have very much higher side friction demands than any C-train. Since drivers are readily able to adapt their driving techniques to the differences between the C-train and other configurations, the subtle differences caused by drawbar length should not cause much difficulty.

The final test was braking in a turn. The driver braked to a stop from 40 km/h, with a deceleration of about 0.18 g, which required a brake application hard enough to lock some wheels. The test was performed with the B-dolly both locked and steering and with brakes on the left side only, right side only, and both sides of the B-dolly. Wheels locked erratically in the various runs, and any steering of the B-dolly did not seem to have any significant effect on the vehicle response. It was possible to provoke a tractor jackknife with a harder brake application or trailer swing if a higher speed was used, but these instabilities are essentially independent of vehicle configuration. It was concluded that any band of operating conditions where the B-dolly steering or drawbar length would potentially cause a difference in vehicle response for the C-train is so small that it may reasonably be ignored.

Drawbar length, therefore, is not considered a significant factor in C-train stability and control, but it is a very significant structural concern. Previous tests [3] showed that it was possible to develop very high loads at the hitch, loads close to yielding the dolly frame in as simple a manoeuvre as driving the vehicle over a curb. Structural considerations, therefore, should be governing and should curb any tendency, not just to long drawbars but to large spreads between the last axle of the lead trailer and the dolly axle, driven by loading considerations. The drawbar should be as short as possible to minimize this spread, but overall, this is not a serious concern as there are many vehicles on the highway with a much greater side friction demand than any C-train [7].

#### 4.3/ Simulation Validation

These tests were performed with the B-dolly in the short drawbar configuration with a hitch-to-fifth-wheel distance of 1.52 m (5 ft).

All the braking tests were inconclusive, since brake applications, brake torque, and tire-road traction are all essentially uncontrolled variables. While individual test points could be reasonably closely

replicated, as shown in Figure 15, the result in terms of wheel lock was random, especially for the braking in a turn. A discussion with the UMTRI staff indicated that there were corresponding difficulties with the computer simulation. They found that instability only resulted in some unusual conditions that would not be expected in normal use of such a vehicle. The tests, then, demonstrated that the effect of B-dolly steering on stability is negligible, at least at speeds that were feasible and safe for the test area, up to 63 km/h, in the situations examined.

For most stops in straight-line braking, the vehicle remained essentially straight and in-lane. The exceptions were on the low-friction surface, when a tractor jackknife and a trailer swing were encountered. The former would certainly be expected, because front axle brakes were not used on the tractor. This mode is independent of any B-dolly action. The trailer swing was an isolated occurrence that may or may not have been due to the action of B-dolly steer. The reason for the general lack of serpentine responses appears to be that on the low-friction surface, there is insufficient sideforce generated by the B-dolly to push the lead trailer laterally. On a split-friction surface with the high-friction B-dolly wheel braked or on a high-friction surface, the sideforce of the rear trailer's axles is sufficient to stabilize the vehicle.

For stops in a turn, there was a tendency for the vehicle to understeer out of the turn, which leads to tractor jackknife or trailer swing. There did not appear to be any tendency for the B-dolly steer to push the lead trailer laterally, which would be accentuated by the inertia of the rear trailer pushing at an articulation on the dolly.

It is concluded, therefore, that the stability characteristics of the C-train while braking are similar to those of the B-train. It must also be recalled that this test was conducted with an unusual load distribution on the vehicle, which was designed to increase the likelihood of an unstable response. It is likely that there would have been further instabilities if it had been possible to conduct tests at highway speeds. There appeared to be no reason to believe, however, that these would be any less catastrophic with this C-train than they would with any A- or B-train.

Sinusoidal steer tests were conducted at a speed of 71 km/h, with the vehicle loaded in the atypical manner used for the braking tests. The rearward amplification of lateral acceleration for the rear trailer was about 1.20 for a steer period of 2 s and 1.35 for a steer period of 3 s.

## 5/ CONCLUSIONS

Three series of tests have been conducted on a C-train double trailer combination on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study.

The first series investigated the effect of hitch slack on vehicle stability. Tests were conducted with slack from 0 to 50 mm (2 in), at speeds up to 72 km/h. There was no significant reduction in the stability of the vehicle. The B-dolly used was of the automotive steer type. A turntable steer type, which has much less internal friction, may have produced a different result. If a higher speed could have been attained in the test area, instability possibly could have occurred at some slack. Presence of slack tends to be destabilizing, and hence, minimal slack associated with coupling and wear is considered tolerable. The finding of this test does not imply that any slack is either desirable or acceptable. Slack is potentially hazardous, particularly for low-stability combinations such as a triple using turntable-steer B-dollies or a double with a rearward-biased load on the rear trailer. No-slack pintle hooks or any other coupling that ensures no slack should be used.

The second series investigated the effect of drawbar length on vehicle stability. Increase in drawbar length from 1.52 to 3.05 m (5 to 10 ft) had little effect in reducing the inherent stability of the empty vehicle on a low-friction surface. While some weight regulations may tend to encourage longer drawbars, severe structural problems caused by twist of the dolly frame as the vehicle drives across an uneven surface are encountered. It is hoped that this will mitigate any tendency towards longer drawbars. There was little change from the driver's perspective. The handling differences between the extremes of drawbar length were much less than the differences between the C-train and an A-train or some semitrailers having three or more axles. Because the driver can feel the response 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 from this point of view and dolly structural design.

The third test series was primarily concerned with C-train response to braking, for purposes of validation of computer simulations. It was not

possible to generate consistent results in this test. The test served to demonstrate that steering of the B-dolly axle appeared to have little effect on vehicle stability when locked wheel braking was applied on high-, low-, and split-friction surfaces.

- 19 -

## 6/ REFERENCES

- [1] Woodrooffe, J.H.F., and Billing, J.R., "Characteristics of Truck Combinations with the Double Drawbar Dolly," RTAC, Ottawa, 1983.
- [2] Ervin, R.D., Nisonger, R.L., MacAdam, C.C., and Fancher, P.S., "Influence of Size and Weight Variables on the Stability and Control Properties of Heavy Trucks, Volume 1," University of Michigan, Transportation Research Institute, Report UMTRI-83-10/1, March 1983.
- [3] Billing, J.R., Mercer, W., Lam C.P., Wolkowicz M.E., Stephenson, W.R., and Woodrooffe, J.H.F., "Tests of a B-Train Converter Dolly," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report TVS-CV-82-111, May 1983.
- [4] Woodrooffe, J.H.F., "Accident Investigation Report," National Research Council, Division of Mechanical Engineering, Report TR-RW-1, June 1984.
- [5] Ervin, R.D., "RTAC Study on Weights and Dimensions, Reports on Task 1", University of Michigan Transportation Research Institute, August 1984
- [6] Billing, J.R., Mercer, W., and Stephenson, W.R., "Procedures for Test of Baseline and Additional Vehicles," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-01, June 1986.
- [7] Ervin, R.D., and Guy, Y., "The Influence of Weights and Dimensions on the Stability and Control of Heavy Duty Trucks in Canada," Vehicle Weights and Dimensions Study Final Technical Report, Volume 2, Roads and Transportation Association of Canada, Ottawa, July 1986.

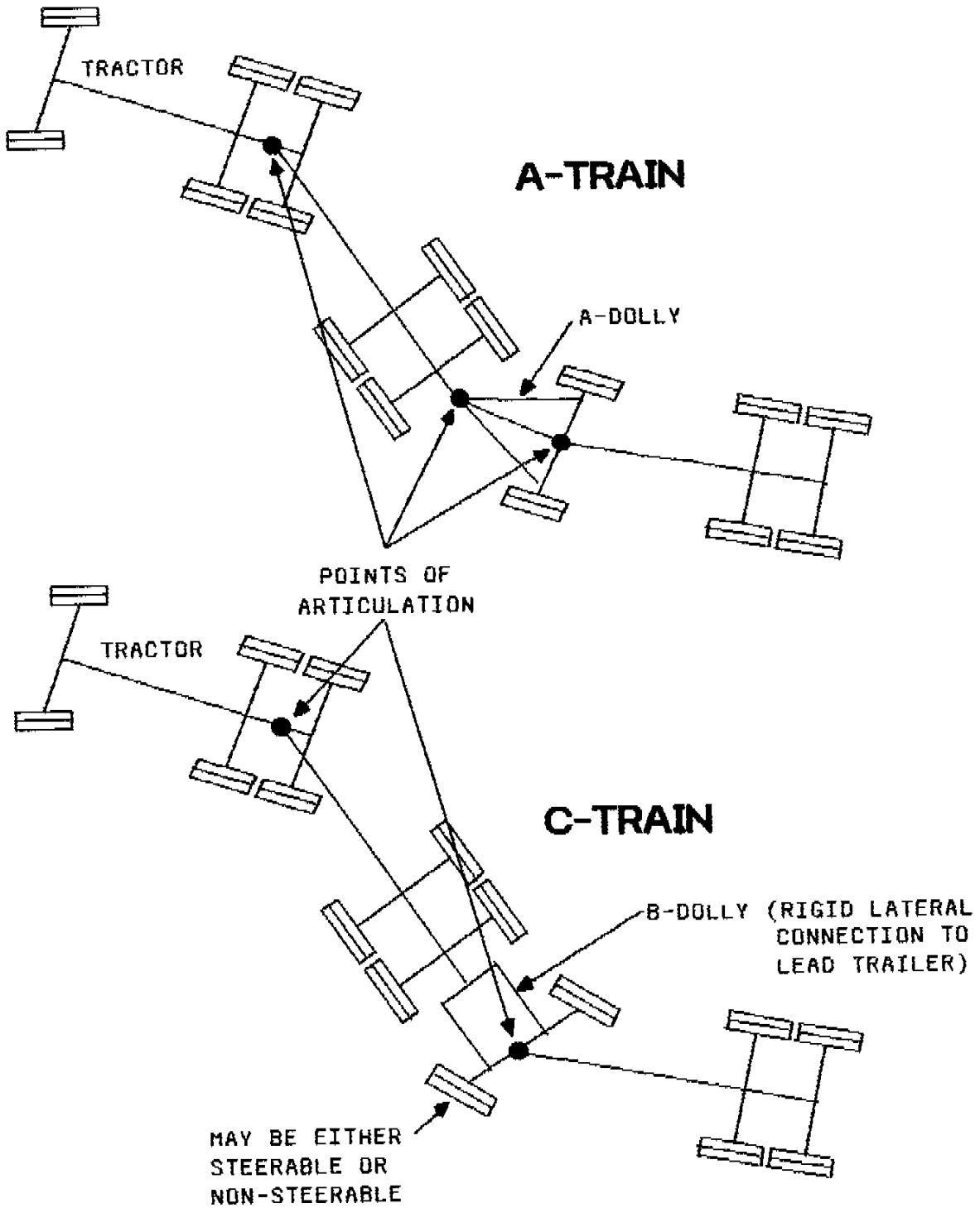


Figure 1/ Articulation of A- and C-Train Doubles



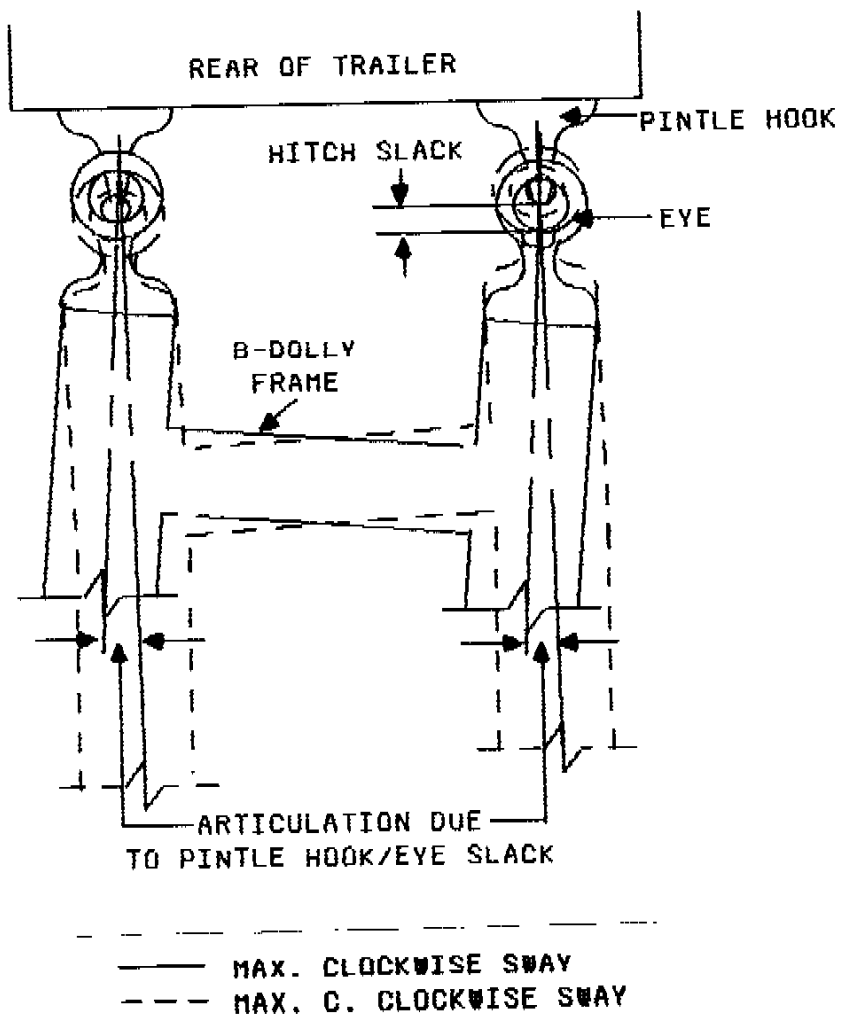


Figure 2/ Limited Articulation of a B-Dolly Due to Hitch Slack

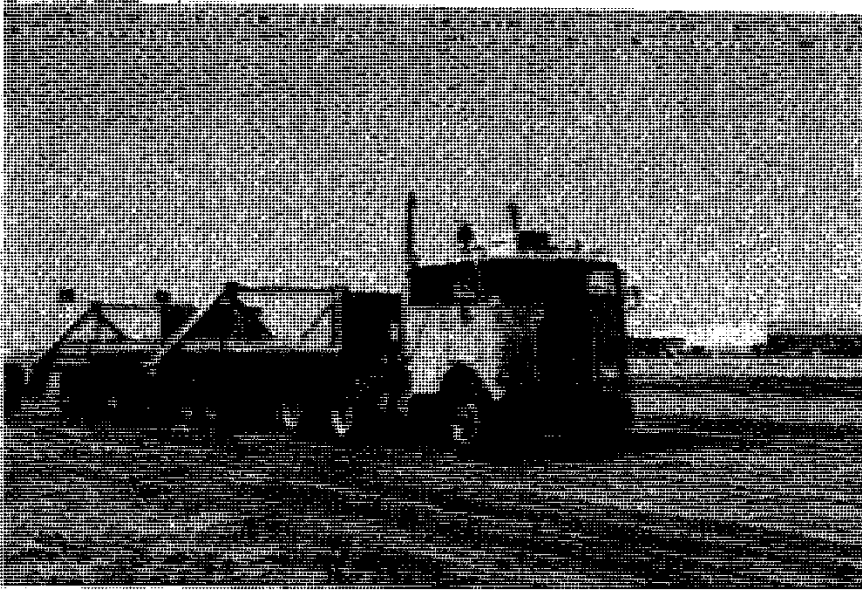


Figure 3/ Test Vehicle

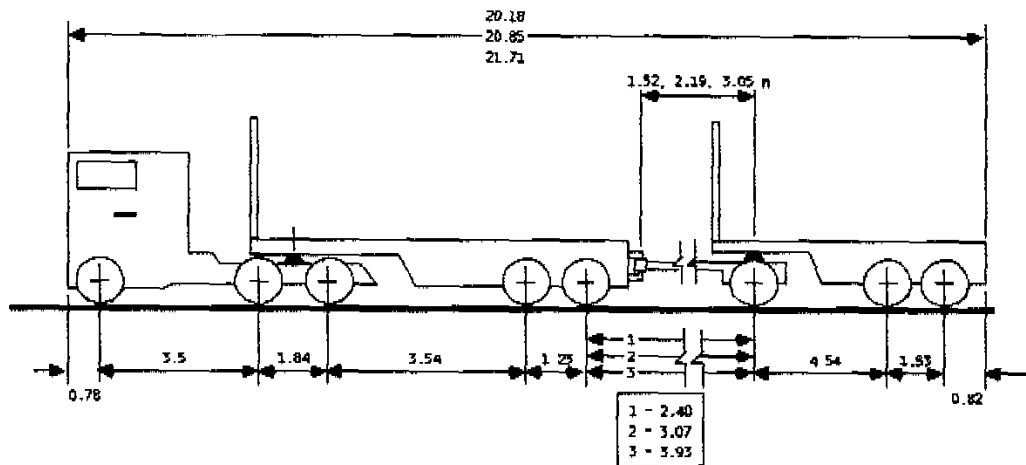


Figure 4/ Test Vehicle Dimensions

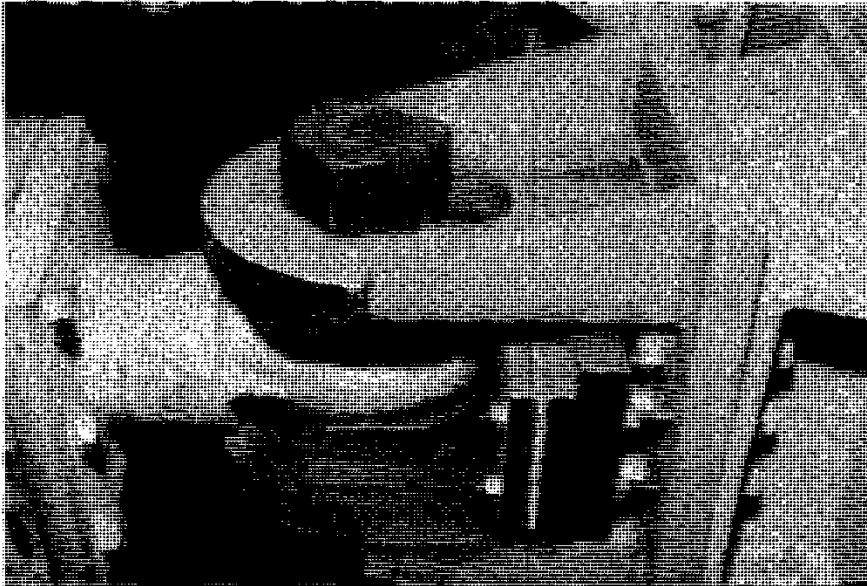


Figure 5/ Hitch Slack Device

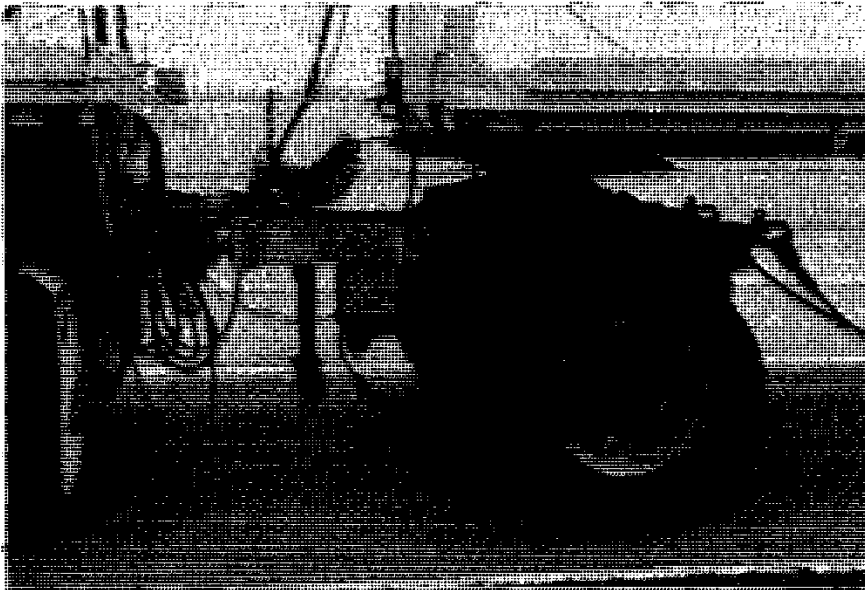


Figure 6/ B-Dolly, Short Drawbar

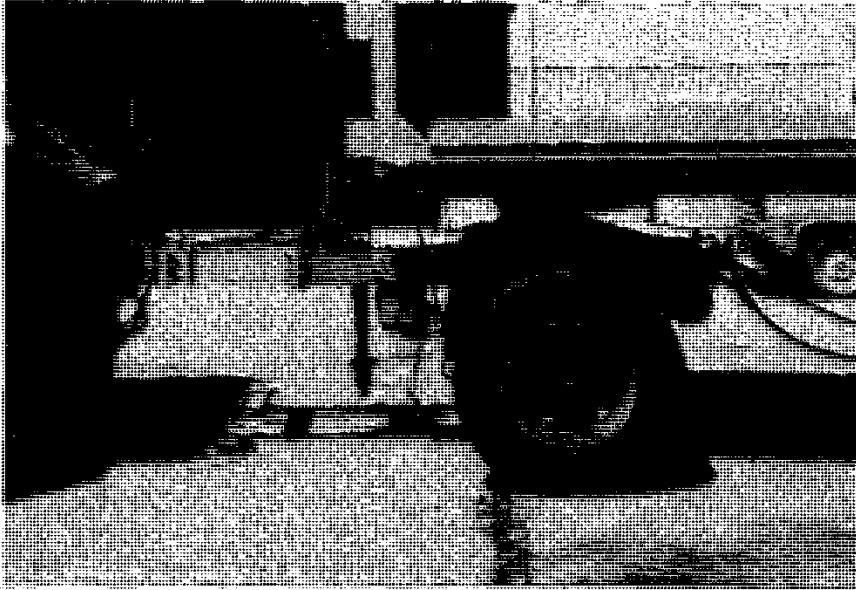


Figure 7/ 8-Dolly, Medium Drawbar

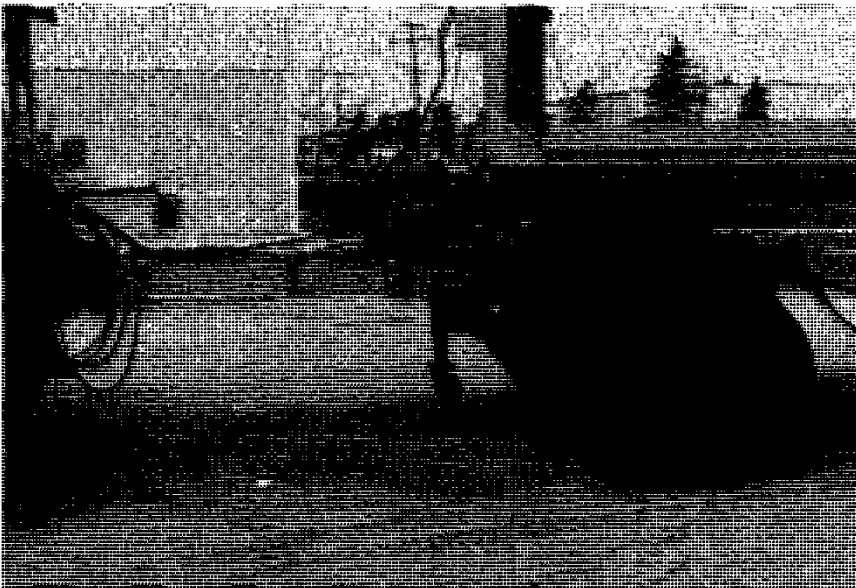


Figure 8/ 8-Dolly, Long Drawbar

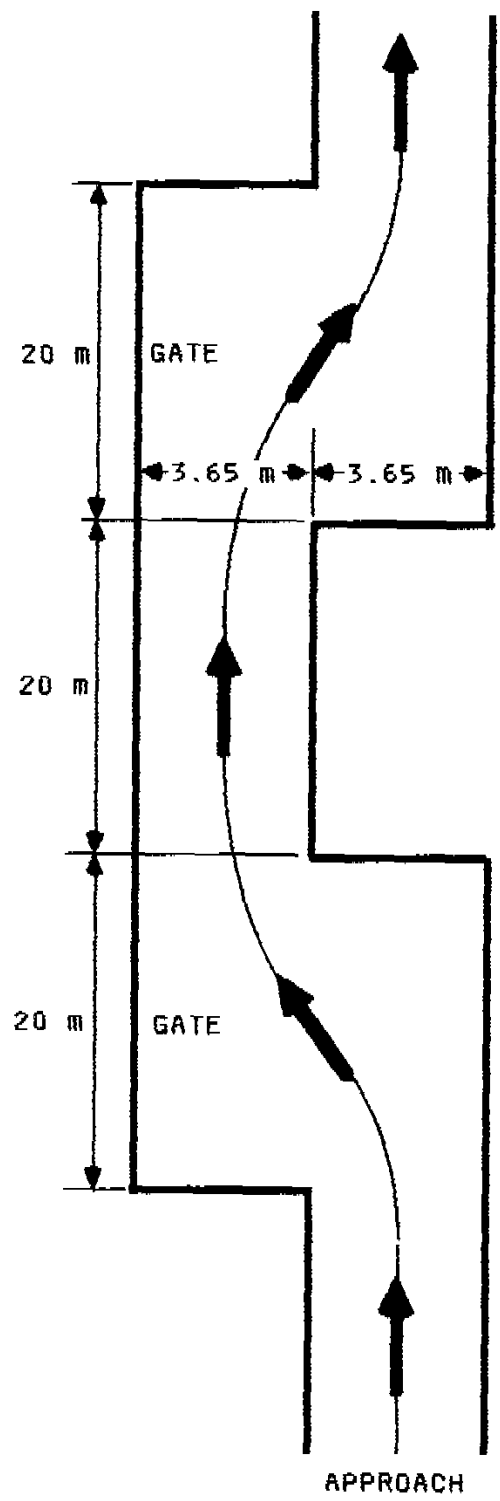


Figure 9/ Evasive Manoeuvre Course



Figure 10/ UMTRI Mobile Dynamometer

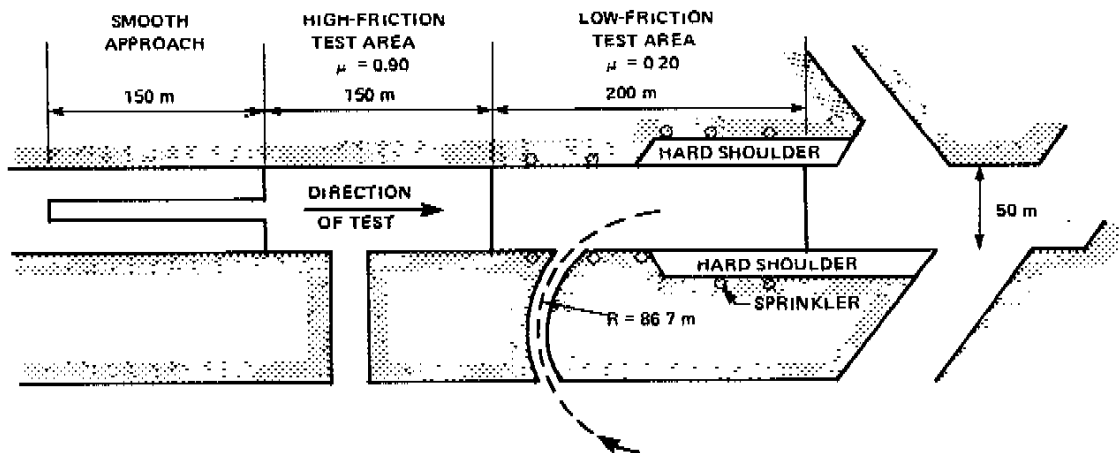


Figure 11/ MTC Commercial Vehicle Test Facility (Centralia)

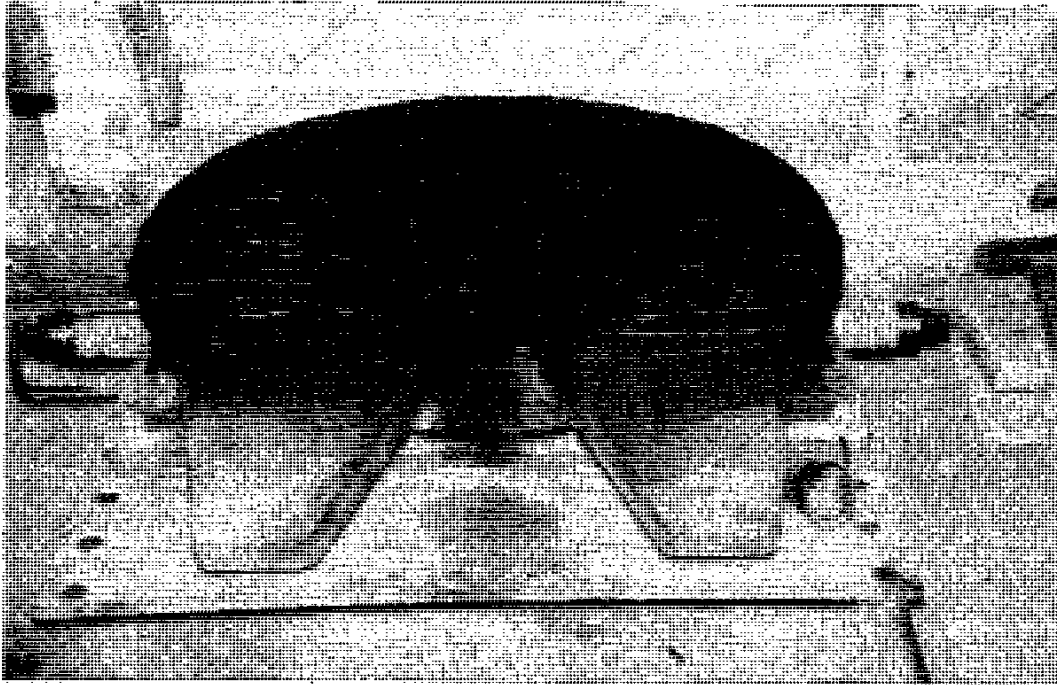


Figure 12/ Load-Measuring Fifth Wheel on Mounting Plate

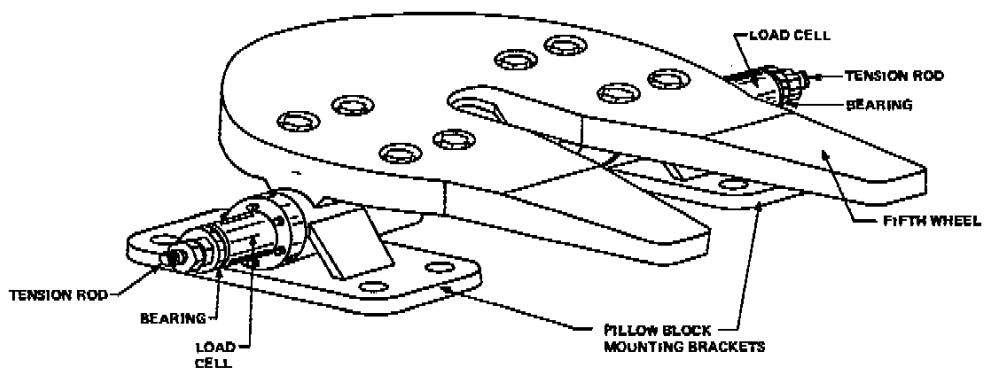


Figure 13/ Load-Measuring Fifth Wheel Assembly

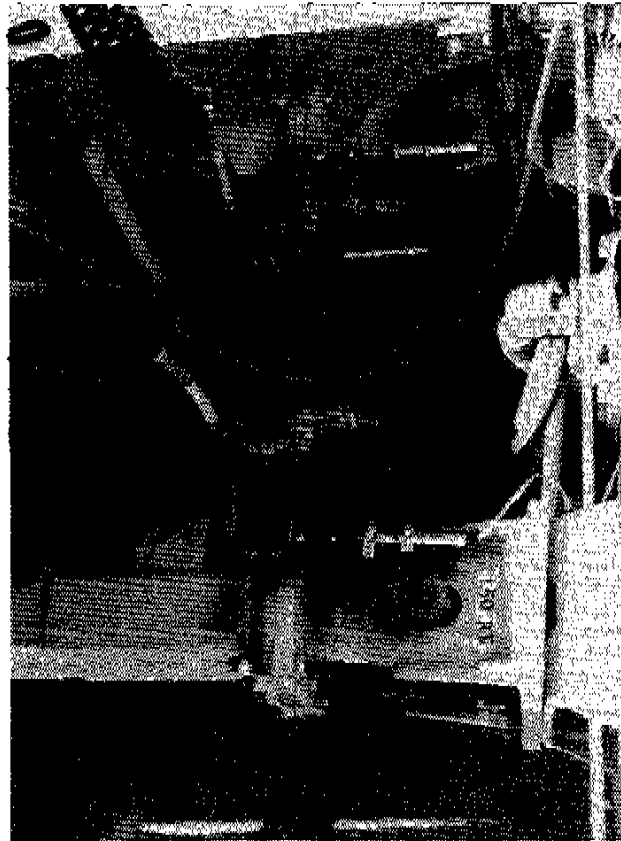


Figure 14/ Hitch Slack Measurement

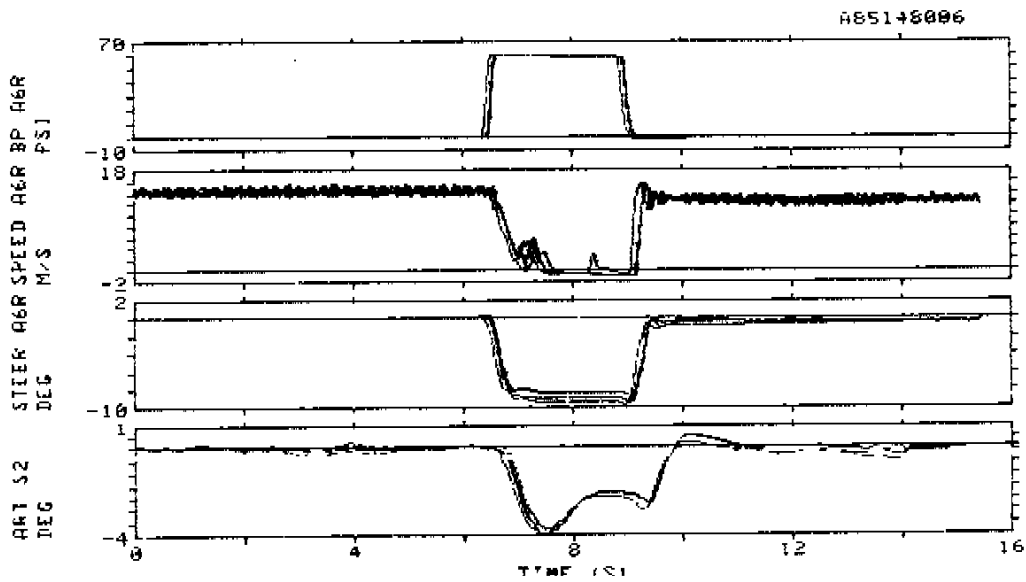
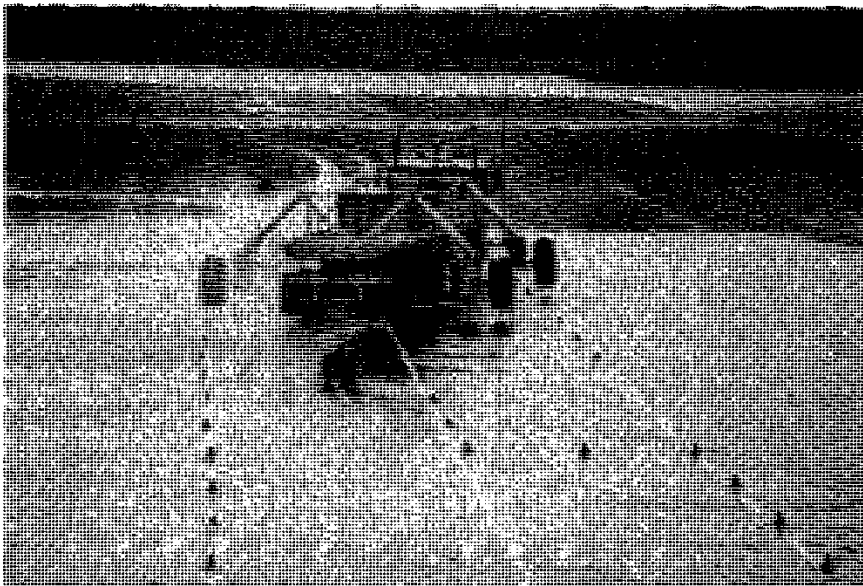
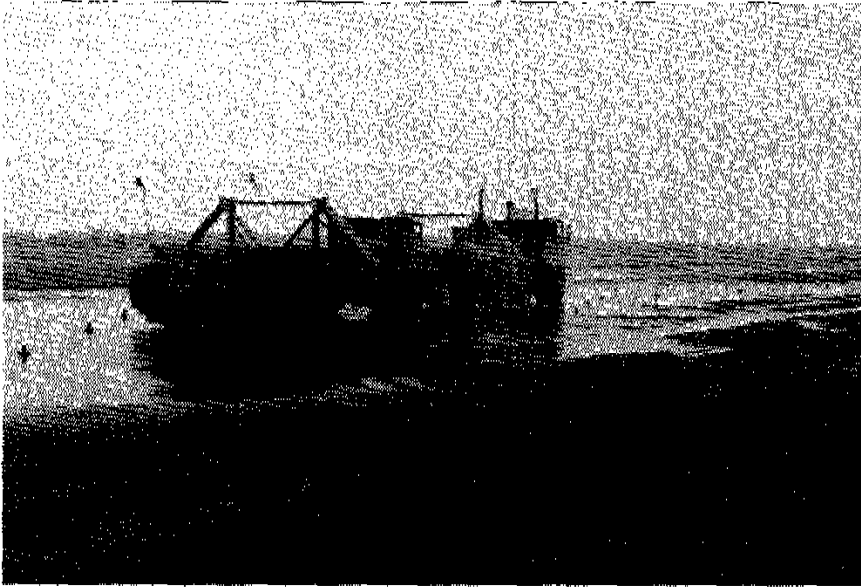


Figure 15/ Response to Brake Applications,  
Axle 6 Right, Wet High-Friction Surface





**Figure 16/ Vehicle Making Evasive Manoeuvre on  
Low-Friction Surface**