CV-86-13

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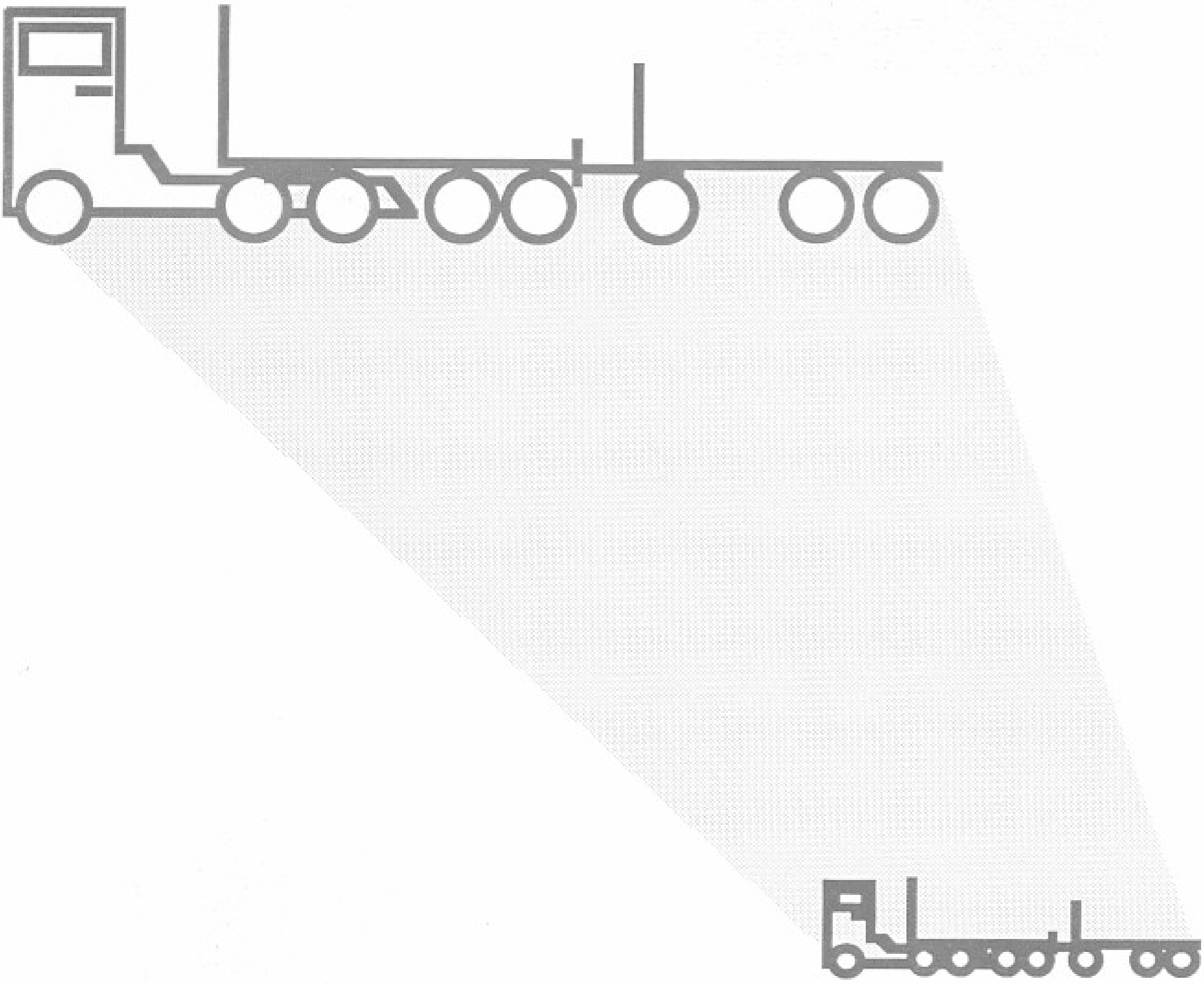
Hitch Slack and Drawbar Length Effects on C-Train Stability and Handling



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Prepared for:
CCMTA/RTAC Vehicle Weights and Dimensions Study

Published by:
Automotive Technology and Systems Office
Transportation Technology and Energy Branch
Ontario Ministry of Transportation and Communications
Hon. Ed Fulton, Minister
D.G. Hobbs, Deputy Minister

For additional copies, write:
The Editor, Technical Publications
Ontario Ministry of Transportation and Communications
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8

June 1986

Technical Report Documentation Page

MTC Report Number	ISBN Number:	Other Document Number:	Date:
CV-86-13			June 1986

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Published by:
Automotive Technology and Systems Office,
Transportation Technology and Energy Branch, MTC

Client Group:
CCMTA/RTAC Vehicle Weights and Dimensions Study

Participating Agencies:

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The second series investigated the effect of drawbar length on vehicle stability. A small effect was found, but this should not be a concern, as structural consideration will often keep the drawbar length down.

The final series was intended for validation of computer simulation, but the desired test conditions could not be achieved. Nevertheless, the tests demonstrated that B-dolly steer should not be a serious problem when braking.

Key Words: C-train, B-dolly, stability, braking, vehicle testing.

Comments:

Distribution: by request

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ACKNOWLEDGEMENTS

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

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 rather 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 test 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 hitch 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 is, 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. This tractor double trailer combination was heavily instrumented for test purposes. The tractor was a 1975 three-axle Freightliner cab-over-engine type with integral sleeper, with 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 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 manufacturers 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 castering, 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 valve 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 the magnitude of this response compared 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. 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 manufacturers 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 then 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 of runs was then 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 usual 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 unreachable 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 should total loss of vehicle control 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^2 (21 529 ft^2) 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. It has been used for a number of test programs, and 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, 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 200G 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 reads each run in real time and creates 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 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 stretched out. Runs were made with the brake pulsed and the clutch depressed, when the vehicle slowly decelerated against the various resistances, and the B-dolly floated 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 response of the vehicle that had the appearance of a low-damped oscillation; indeed, 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, 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, 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 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 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 expectation from this test was that the change in drawbar length would affect the force required to turn the lead trailer, which would require a greater steer effort by the driver during a dynamic manoeuvre. An increase in steer effort was considered to result in an earlier loss of control. No clear patterns emerged from these tests, in part because of developmental problems with the load-measuring fifth wheel.

The evasive manoeuvre was conducted using gates of 20 m (65.6 ft) with 20 m in the left lane. A typical run is shown in Figure 15. 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, which affected the performance of the manoeuvre by the driver. 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. If the C-train dolly steer did not break out, that vehicle acts as a B-train, so it is fair to say 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. Since drivers are readily able to adapt their driving techniques to this difference, there is no reason that the subtle differences caused by drawbar length should cause any 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 sufficiently hard brake application 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 apparently have any significant effect on the vehicle response. It was found possible to provoke a tractor jackknife with a harder brake application or trailer swing if a higher speed was used, but these modes of instability 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.

The conclusion from these tests really is that drawbar length is not a significant factor in C-train stability and control. However, it is a very significant structural concern. The previous tests [3] showed that it was possible to develop very high loads at the hitch. Indeed, these loads were 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 there should not be any tendency to long drawbars. It is clearly desirable that the drawbar should be as short as possible. However, overall, drawbar length is not considered a serious concern.

4.3/ Simulation Validation

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

All the braking tests were inconclusive, for the usual reason that brake applications, brake torque, and tire-road traction are all essentially uncontrolled variables. Therefore, it proved very difficult to set up the desired test conditions. While individual test points could be reasonably closely replicated, as shown in Figure 15, the result in terms of wheel lock was rather 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 rather unusual conditions that would not be expected in any normal use of such a vehicle. The tests, then, served as a demonstration 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.

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 encounterd. The former would certainly be expected, because front axle brakes were not used on the tractor, and 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 interesting responses must be that on the low-friction surface, there is insufficient sideforce generated by the B-dolly to push the lead trailer laterally, and 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 plough 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 from these tests, therefore, that the stability characteristics of the C-train while braking are essentially 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 is 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.

A few 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 about 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 apparent significant reduction in the stability of the vehicle through these tests. The B-dolly used was of automotive steer type, and a turntable steer type, which has much less internal friction, might have produced a different result. If a higher speed had been possible at the test area, instability might have occurred at some slack. Presence of slack is certainly destabilizing, and the minimum slack consistent with coupling and wear is considered appropriate. No slack-type pintle hooks should be used. The null finding of this test does not imply that any slack is either desirable or acceptable. Any 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.

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 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 drawbar length were much less than the difference between an 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 from this point of view and dolly structural design.

The third 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, 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.

6/ REFERENCES

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[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.

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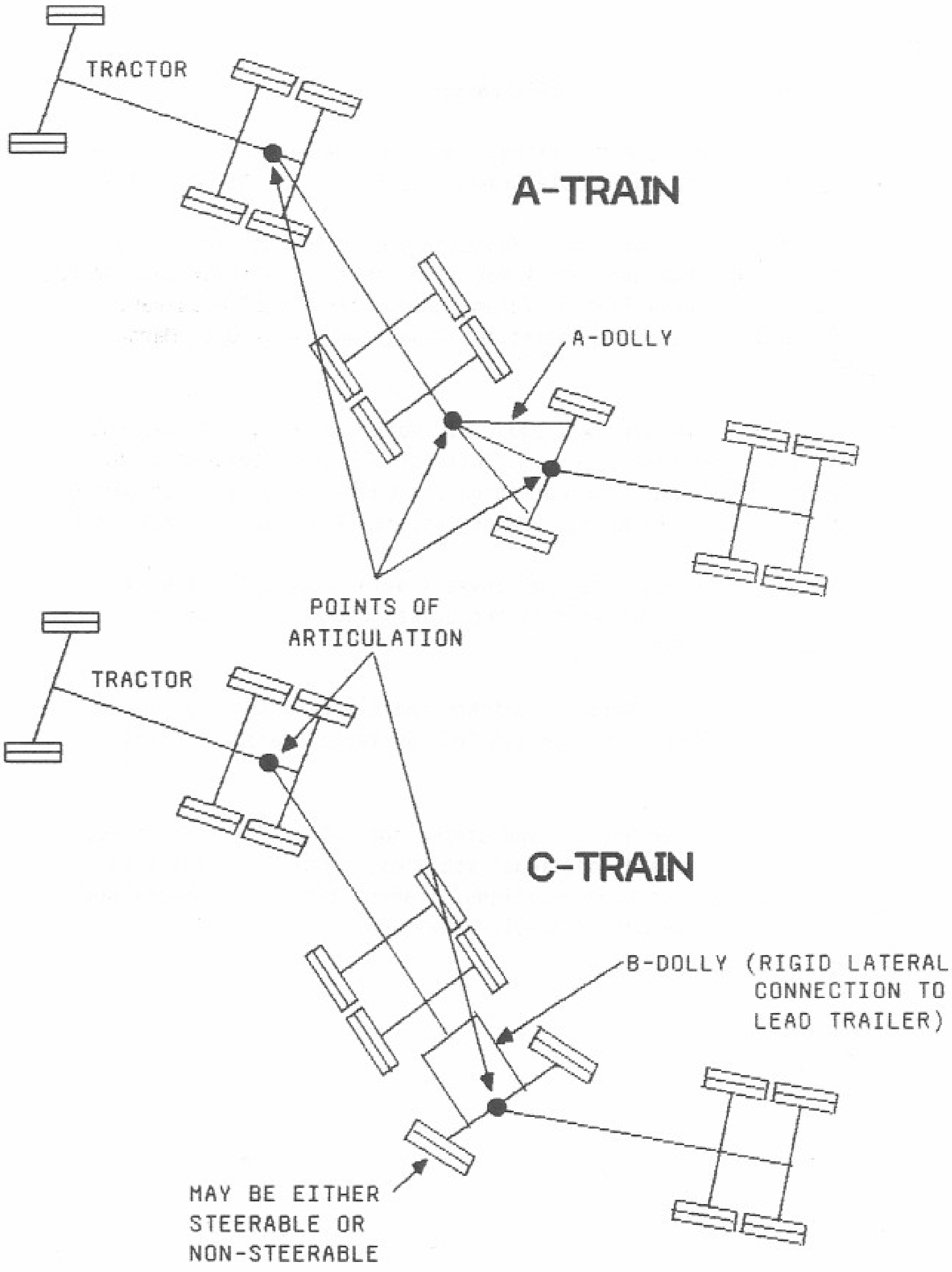

Figure 1/ Articulation of A- and C-Train Doubles

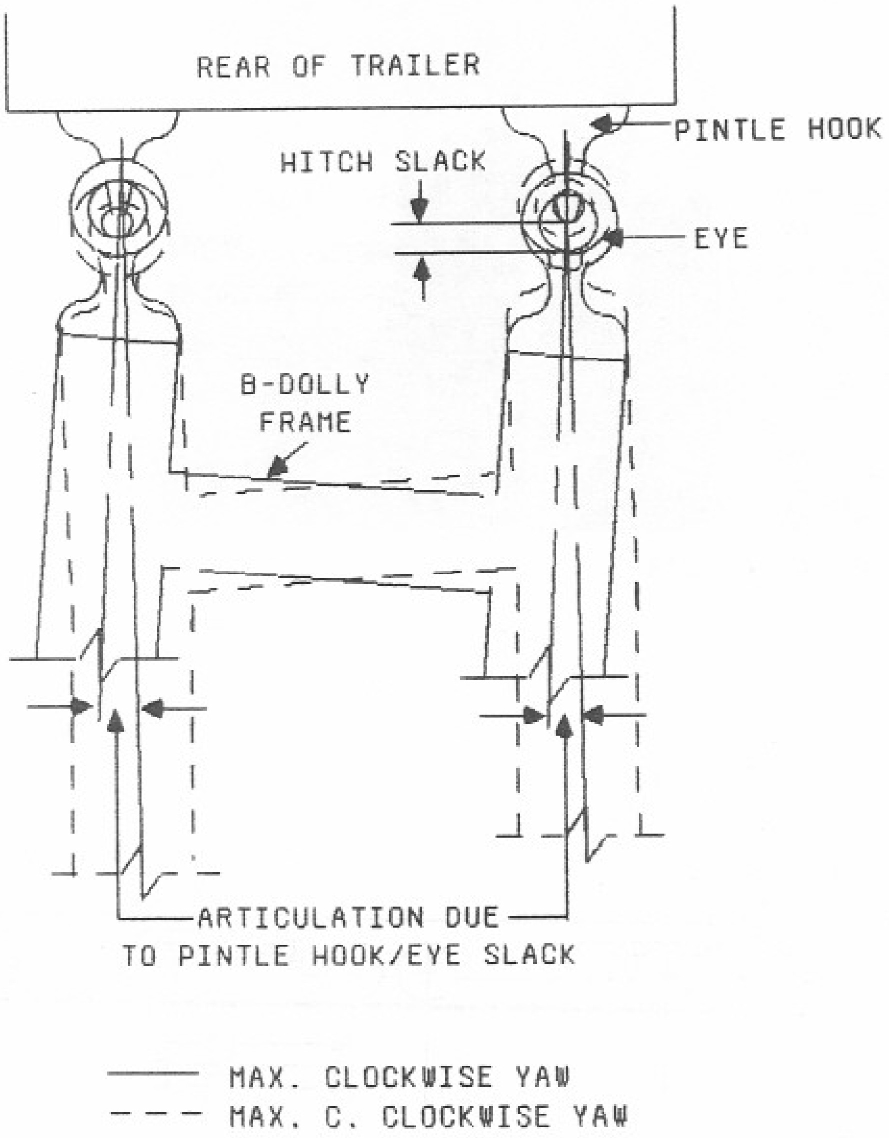

Figure 2/ Limited Articulation of a B-Dolly
Due to Hitch Slack

Figure 3/ Test Vehicle

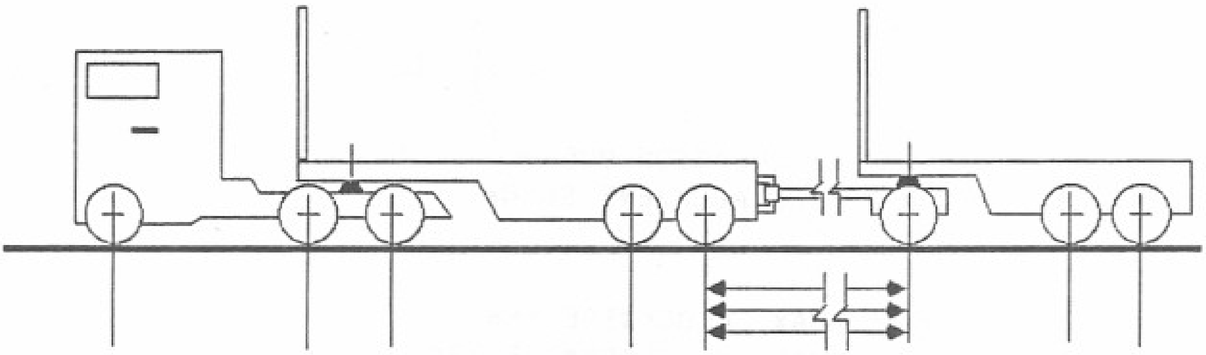

Figure 4/ Test Vehicle Dimensions

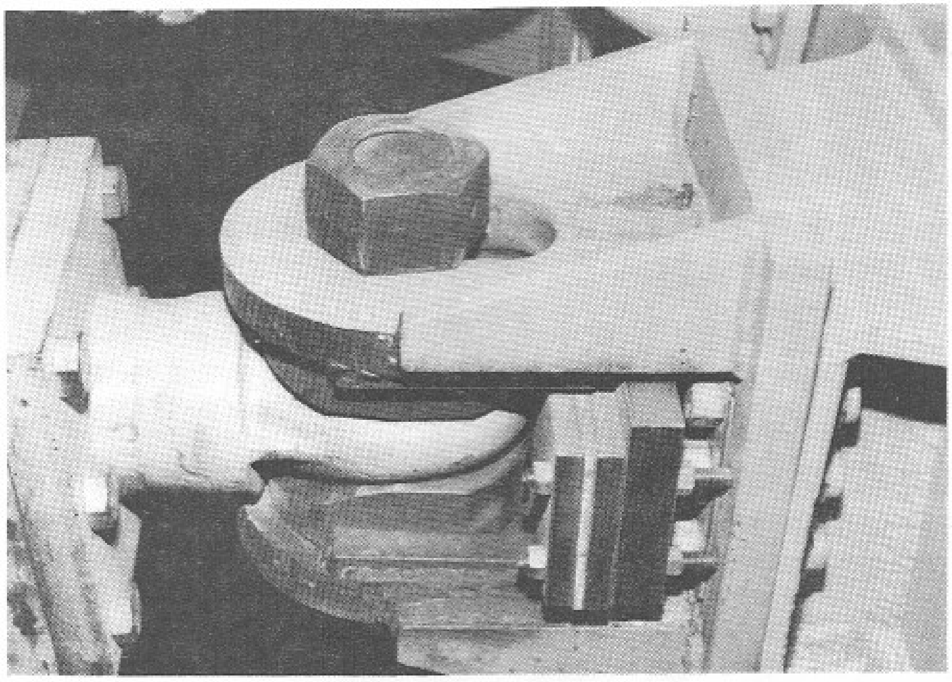

Figure 5/ Hitch Slack Device

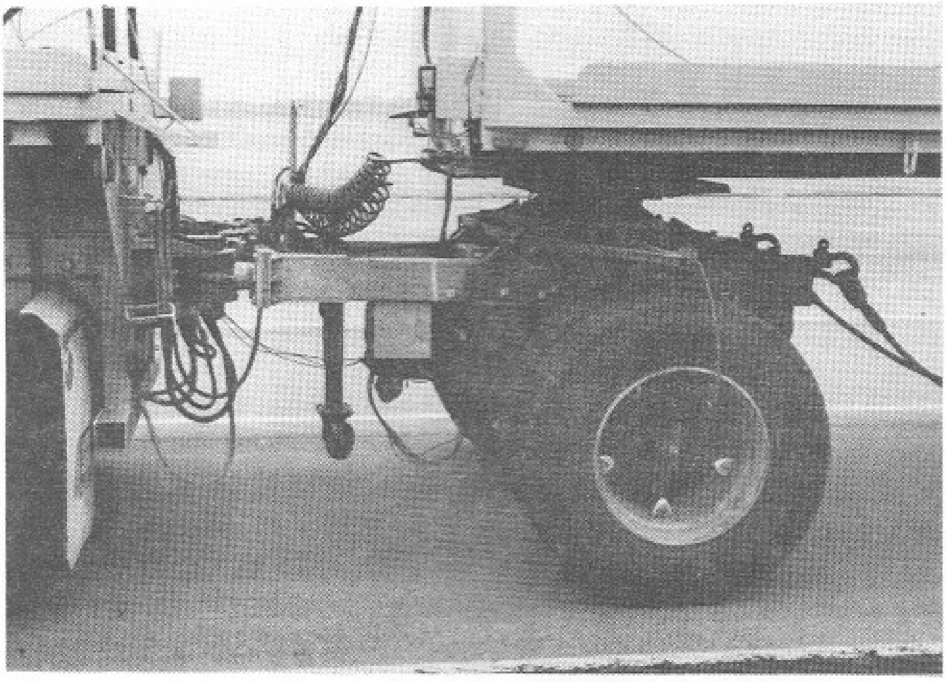

Figure 6/ B-Dolly, Short Drawbar

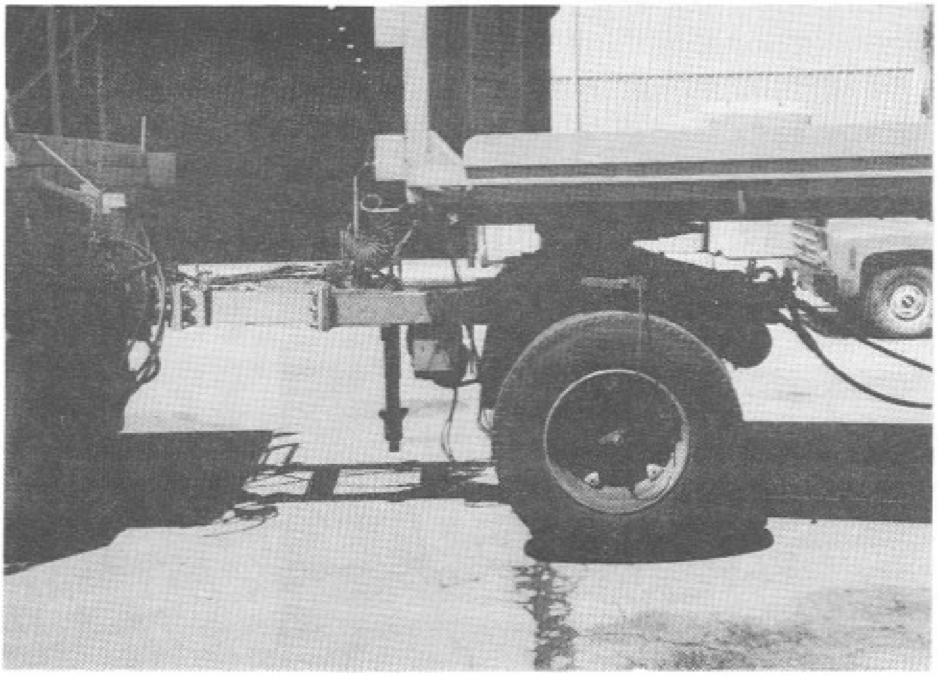

Figure 7/ B-Dolly, Medium Drawbar

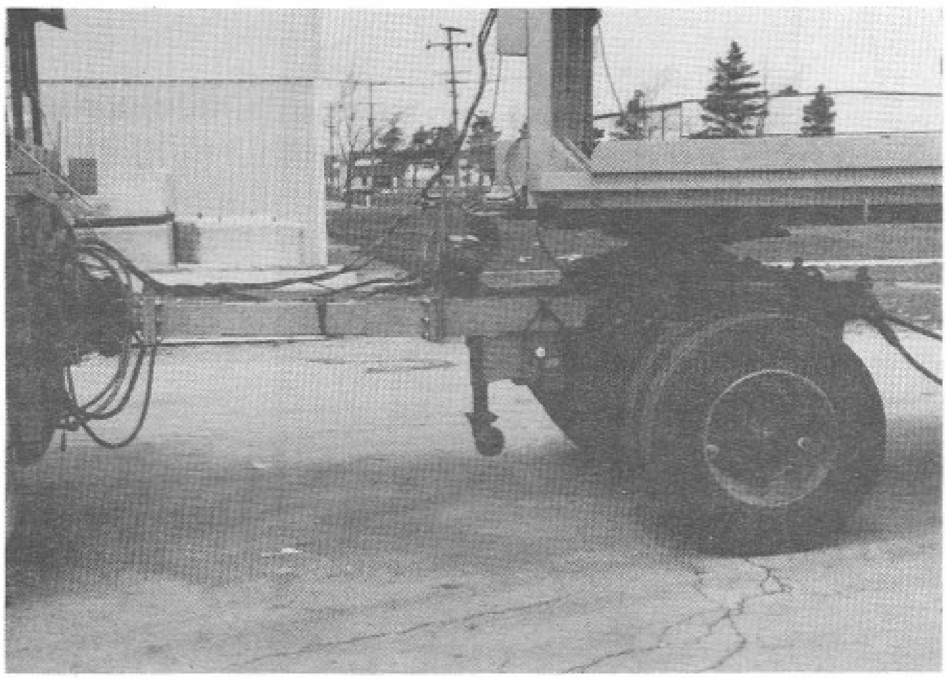

Figure 8/ B-Dolly, Long Drawbar

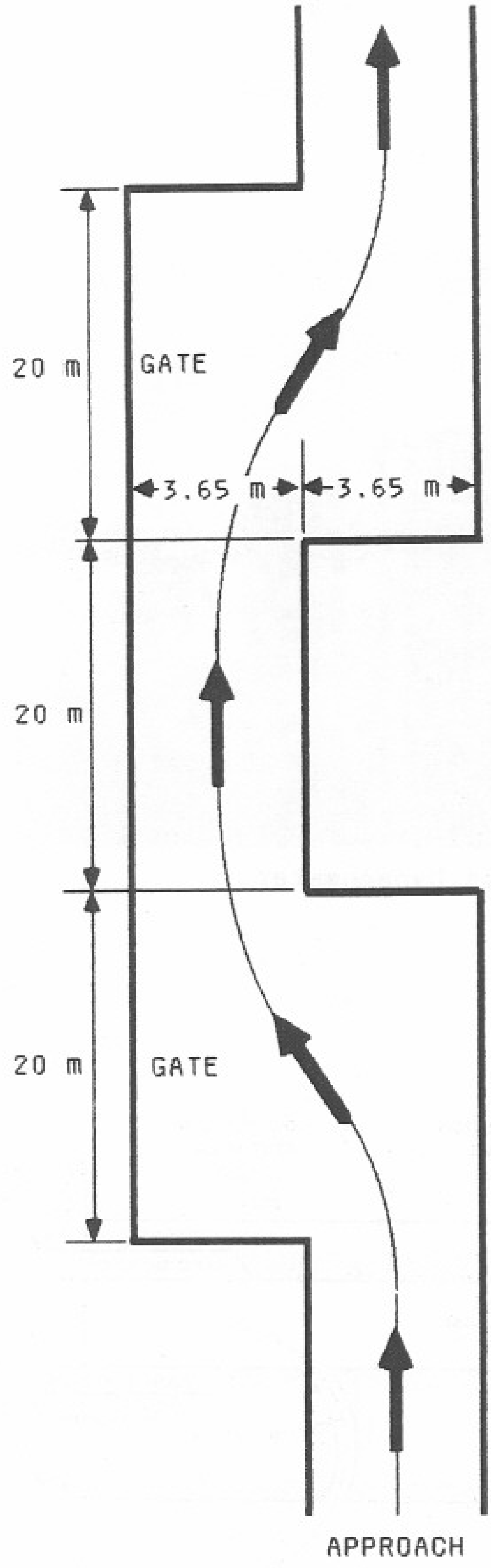

Figure 9/ Evasive Manoeuvre Course

Figure 10/ UMTRI Mobile Dynamometer

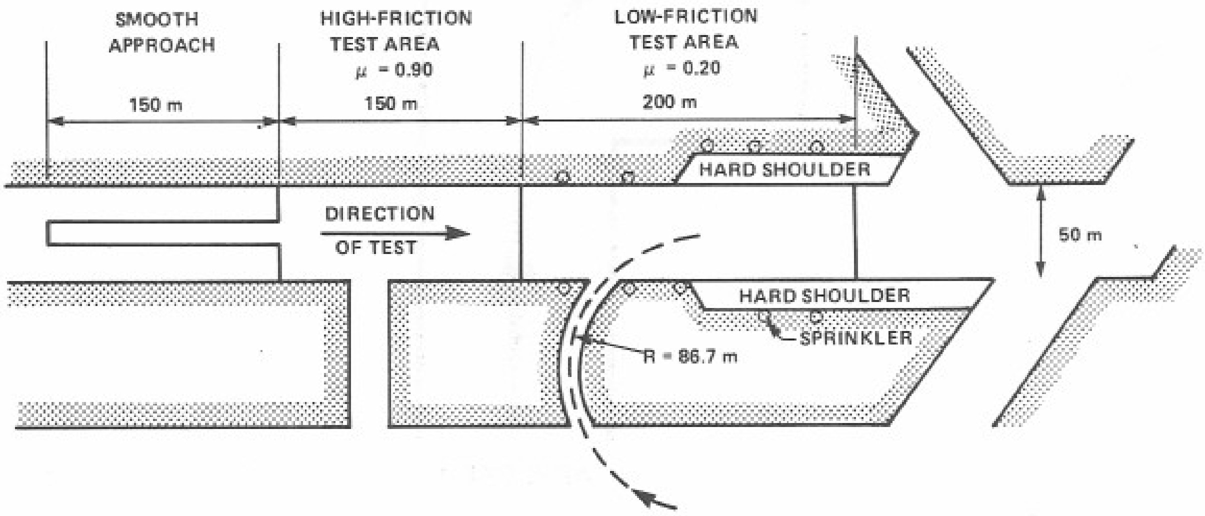

Figure 11/ MTC Commercial Vehicle Test Facility (Centralia)

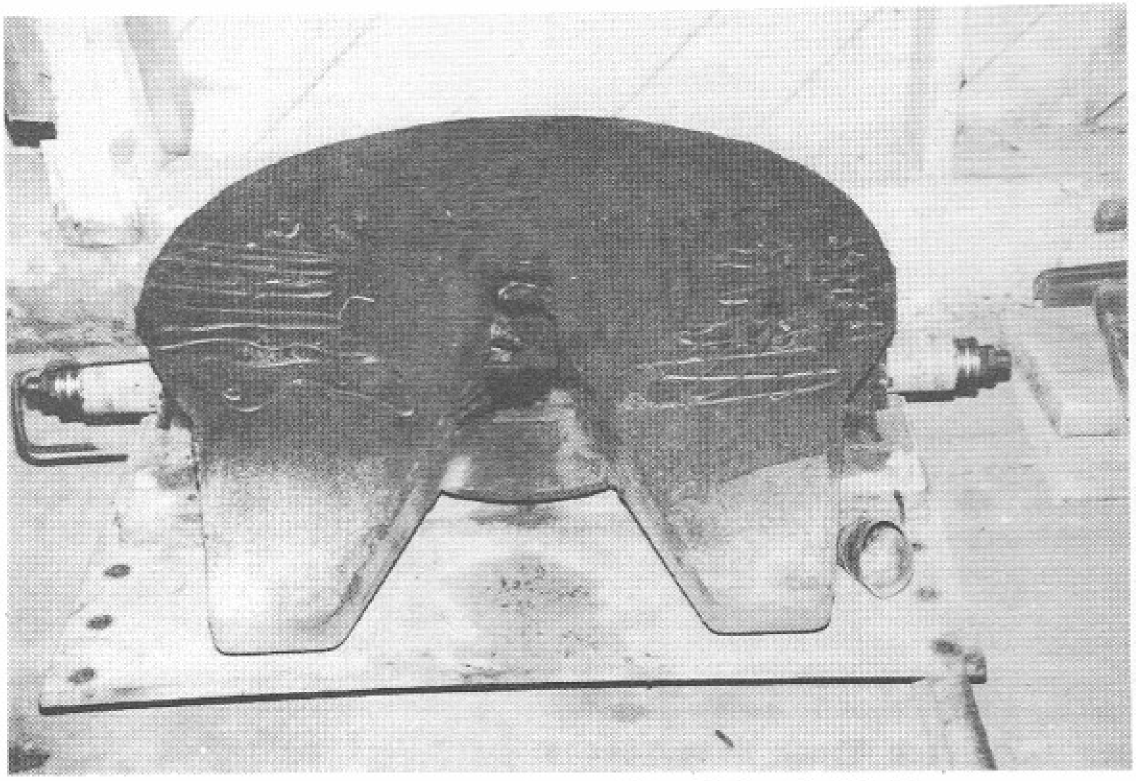

Figure 12/ Load-Measuring Fifth Wheel Installation

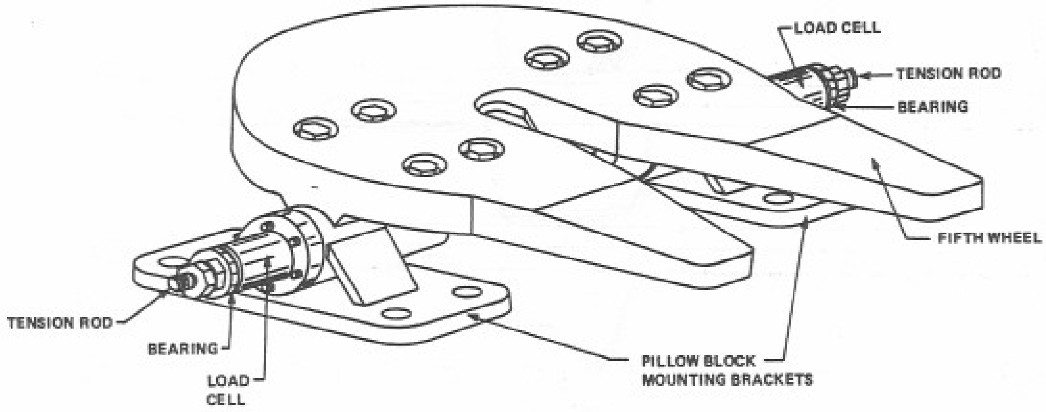

Figure 13/ Load-Measuring Fifth Wheel Assembly

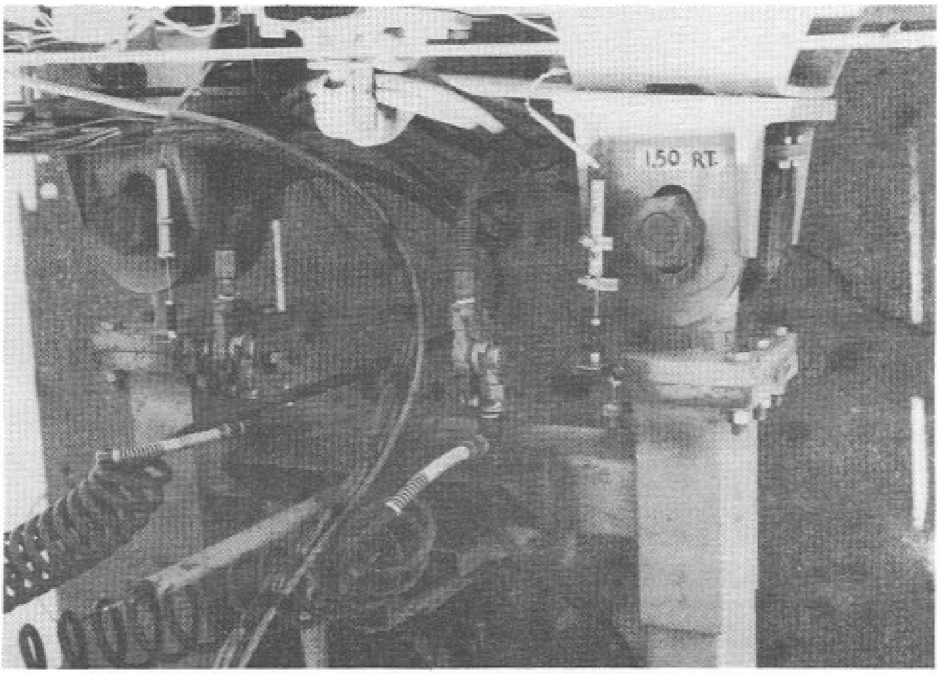

Figure 14/ Hitch Slack Measurement

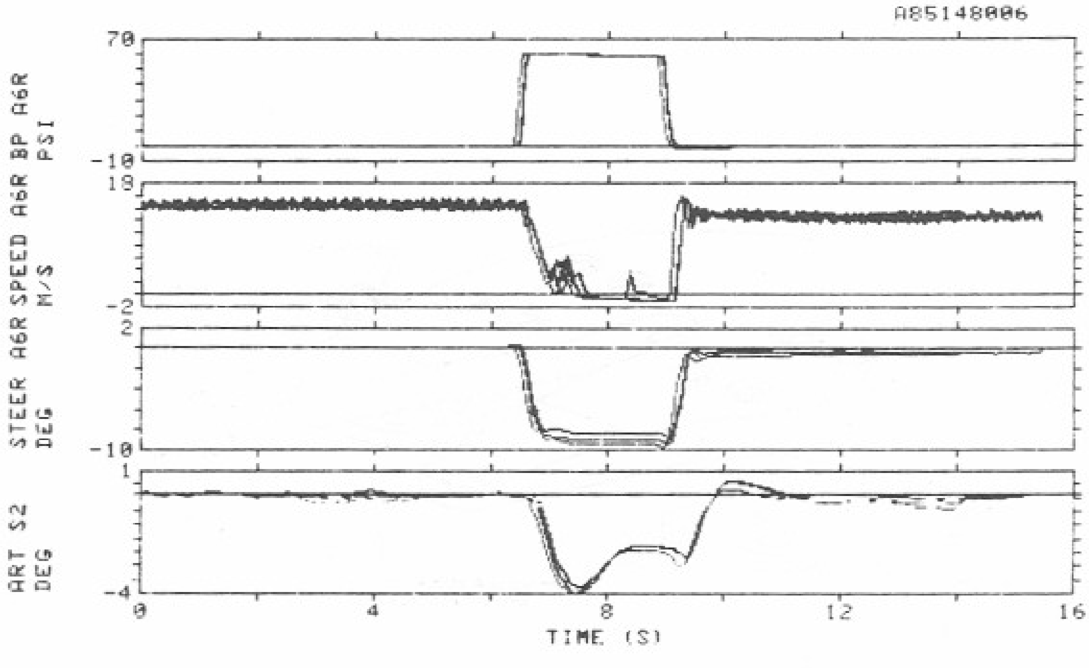

Figure 15/ Response to Brake Applications,
Axle 6 Right, Wet High-Friction Surface

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