DEVELOPMENT OF DESIGN AND OPERATIONAL GUIDELINES FOR THE C-CONVERTER DOLLY

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SESSION 2 – VEHICLE PERFORMANCE 1

Chairman: Bob Ervin, University of Michigan
Transportation Research Institute

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ABSTRACT

The C-converter dolly or double drawbar dolly is a unique and innovative device used to enhance the handling and stability performance of commercial road trains. Since its introduction in 1980, the device has slowly gained acceptance and has been found to be effective in improving the general performance of road trains. Research and accident investigations have found that the performance of vehicles using C-dollies is highly dependent on the design of the C-dolly and the vehicle layout. This design dependent performance variation was found to be sufficiently broad to warrant the development of standards for the C-dolly and the C-train.

This paper describes the research study that was conducted in support of this regulatory effort and presents, in general form, design and operational guidelines for the C-converter dolly and C-train.

1.0 Introduction

The double drawbar dolly (C-dolly) is an innovative device used for coupling two trailers together in a manner that may be beneficial to vehicle stability performance. It takes the form of an extension of the lead trailer's frame on which the trailing trailer is coupled through a fifth wheel. The dolly is supported by a caster steering axle which is required to reduce high stress levels in the equipment due to tire scuffing forces associated with low speed turns. The C-dolly is an improvement over the common A-dolly as it eliminates one articulation point, couples the two trailers in roll and improves low speed off-tracking.

Previous studies (1,2,3,4) have shown that a vehicle combination, coupled together with a C-dolly (forming a C-train) has improved yaw and roll performance characteristics when compared with the common A-train (Figure 1). These studies also list a caution that the self-steering axle and the C-dolly hitches require specific characteristics to benefit vehicle handling.

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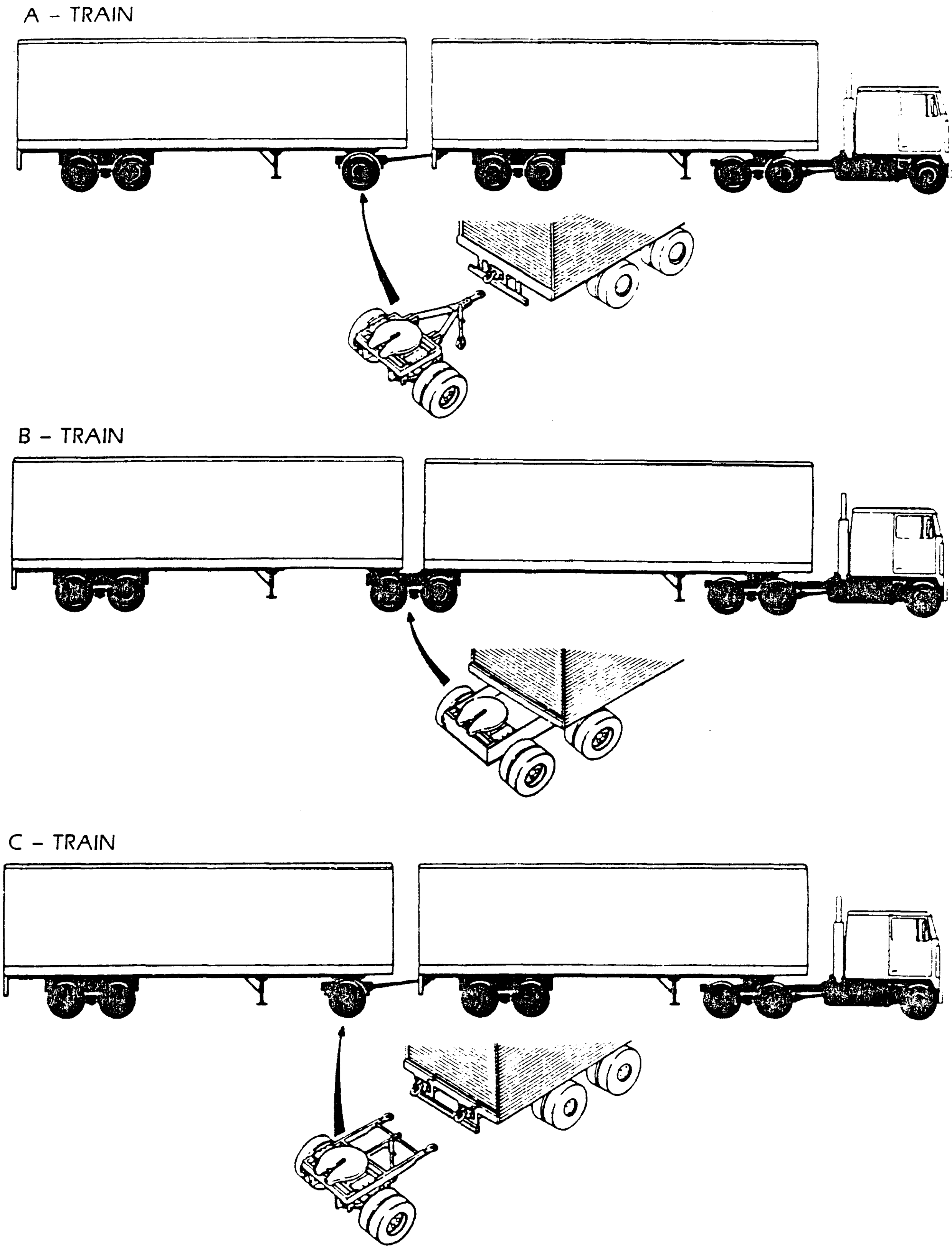

Figure 1. Illustration of the Three Vehicle Combination Currently in Use in Canada

the National Research Council of Canada (NRCC). It was undertaken to examine the dolly and its components as well as the vehicle combination it is used with. It puts forward the necessary design and performance criteria to ensure safe application of this device.

2.0 Description of the C-dolly and its Components

2.1 General Description of the C-Dolly

The first C-dolly was developed in Canada by Auto Steering Trailers Ltd. (ASTL) about 1980. The dolly consisted of a rigid structural steel frame, a fifth wheel for attachment to the following trailer and a self-steering axle assembly suspended by a leaf spring suspension. Attachment to the lead trailer was achieved with two steel eyes fixed to the arms of the dolly on 30" centres and two corresponding pintle hooks with vertical latches attached to the rear apron of the lead trailer.

Presently there are many manufacturers of C-dollies each with some unique design feature. All models use one of two types of self-steering axle assemblies, shown in Figure 2.

THE TURN TABLE SELF-STEERING AXLE ASSEMBLY shown in Figure 2 consists of a large diameter roller bearing or turn table which allows for relative rotation parallel to the ground plane between the main frame of the dolly and the suspension sub frame. The axle is set aft of the centre of rotation of the turn table thereby providing caster kinematics essential to self-steering operation.

THE AUTOMOTIVE STEERING AXLE shown in Figure 3 utilizes kingpins and a tie rod assembly similar to that of a heavy truck front end. Both steer systems utilize a centre seeking or zero steer biased forcing system. The centring force system is probably the most varied component among dolly and axle manufacturers. All axles have a locking mechanism to lock the axle in the zero steer position which is desirable when the vehicle travels on adverse road conditions or when the vehicle travels in reverse.

2.2 Self-steering Axles

Self-steering axles were first developed in the northen Italian city of Verona, home to Romeo and Juliette. They were designed to be used as the second axle of a tandem axle suspension of straight trucks to improve off-tracking and reduce tire scuffing in tight turns which affected both the vehicle and the cobblestone roadways. Used in a tandem axle system, the load equalization of the two axles was biased in favour of the fixed lead axle which carries at least 60% of the tandem axle group load. Since the

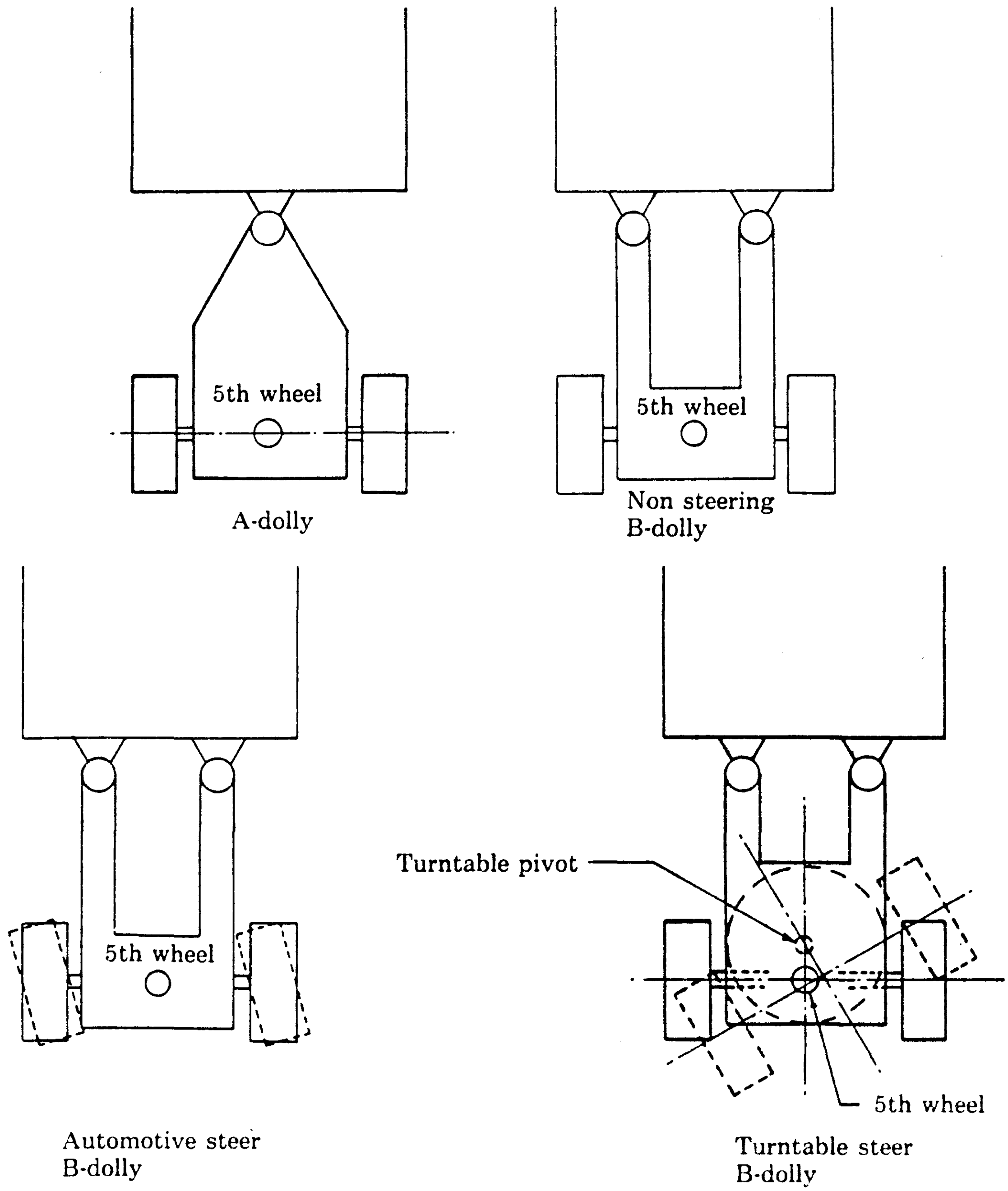

Figure 2. Schematic of A-dolly and Different C-dolly Types

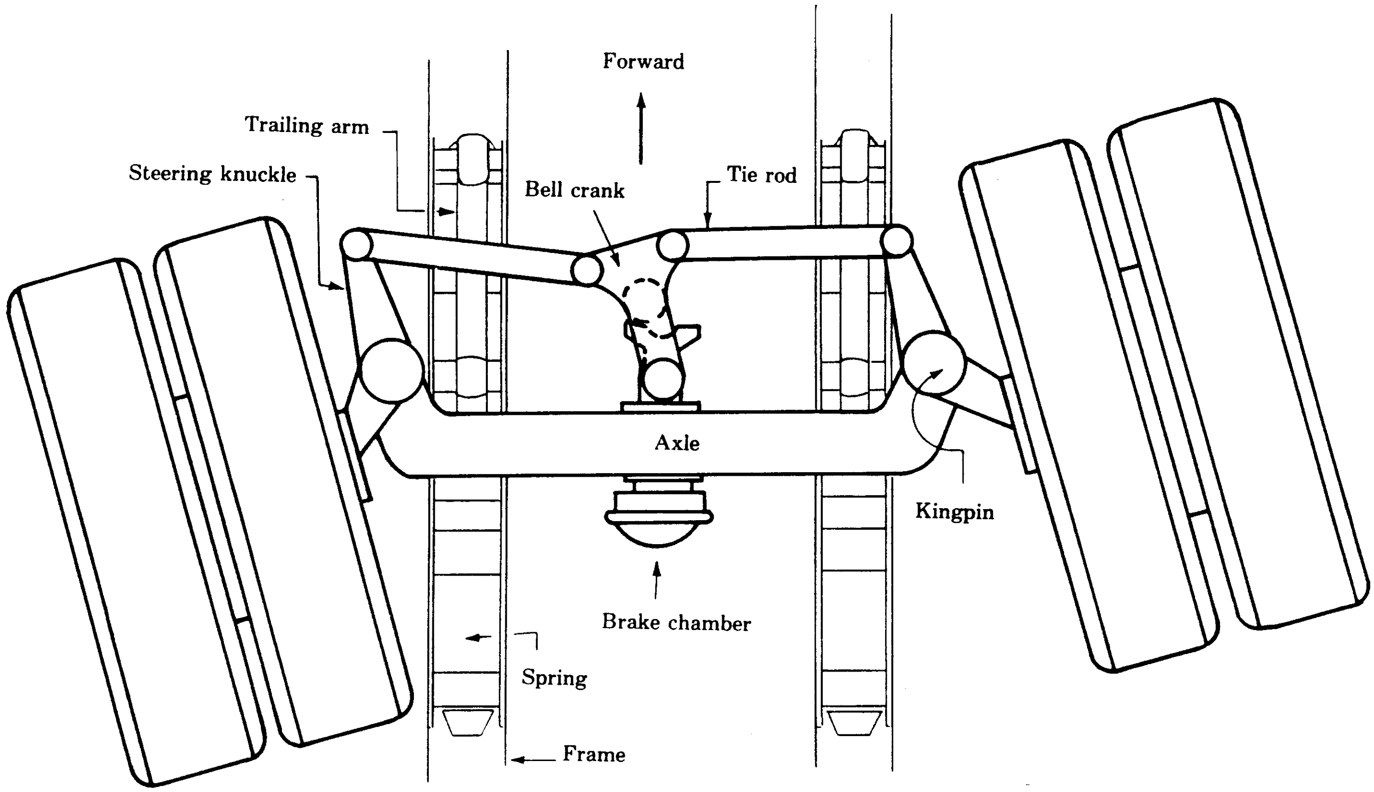

Figure 3. Main Components of the BPW Self Steering Axle Tested in 1983 (1)

suspension design ensured that the lead axle always carried the majority of the load of the axle group, it was assured that this fixed axle could provide the cornering force requirement of the vehicle. The self-steering axle was not designed to produce primary cornering forces for the vehicle during high speed turns.

The self centring or zero steer angle biased forcing system found on most self-steering axles is used to offset the effects of unbalanced braking between wheels of the axle and as an assistance mechanism that returns the steering axle to the zero steer position quickly and smoothly. Without this centring assistance device, the internal friction within the self-steering axle would freeze the axle in a steered position until the slip angles of the tires on the self-steering axle were large enough to overcome these friction forces. Because of the "stiction" phenomenon associated with sliding or Coulomb friction, and considering that the side force characteristic of a tire is analogous to a spring, once sufficient side force has been generated to overcome the friction in the system, there is a rapid change in steer angle of the self-steer axle resulting in a lateral force impulse, or jerk which is transmitted to the vehicle.

The C-train places unique demands on the self-steering axle. The C-dolly effectively de-couples the two trailers vertically, i.e. there is little or no vertical load transfer between the leading and following trailers. But the C-dolly is rigidly coupled laterally so that lateral cornering forces can be transferred from the following trailer to the leading trailer. If the self-steering axle is castering freely, thereby providing no cornering forces, approximately half of the lateral force required by the following trailer during cornering is transferred through the dolly to the tires of the lead trailer.

Under certain conditions this extra force demand on the tires of the lead unit can result in excessive high speed out-board offtracking and possible yaw divergence of the trailers. One such condition that could lead to this occurrence is when the lead trailer is lightly loaded and the following trailer is full. Since there is no vertical load transfer between the trailers, the tires of the lead trailer would be lightly loaded therefore incapable of generating much cornering force yet the fully loaded following trailer would have high cornering force requirements which would have to come from the lead trailer tires. This weakness associated with free castering self-steering axles can be overcome by using a centring force system.

Self-steering axles are also vulnerable to unequal longitudinal forces acting through the wheels of the axle. This could occur because of frozen or poorly adjusted brakes, failure of brakes on one side of the axle or variations in the road surface friction between each side of the axle during heavy brake applications. A very high level of longitudinal force unbalance between tires of a self-steering axle can be experienced when one side of the axle is on a paved part of the road and the other is on soft material such as a soft shoulder or on slushy high density snow. If sufficiently high, the force unbalance can result in an axle steer angle relative to the vehicle velocity vector which will produce lateral forces that can, in some cases, change the direction of travel of the trailers.

The weaknesses associated with the free castering self-steering axles can be offset with the use of an appropriate centring force system. The force requirements are higher than those associated with self-steering axles in the traditional straight truck application. Most of the analysis conducted during this research project focused on this issue. Because of the complexity and length of the analysis, it could not be included in this paper. It can be found in the main report (6).

Manufacturers of self-steering axles offer a wide range of axle load capacities and axle track dimensions. Axle capacities range between 6 and 15 tonnes. Track width is dependent on the requirements of the customer; however, both 2.4 and 2.6 meter outer dimension track widths are common. For the automotive steer type axle the caster dimension is approximately 150 mm and the lateral moment arm from the kingpin to the centre of the dual tire contact area, referred to as kingpin offset dimension, varies between 370 mm to 430 mm depending on manufacturer or the requirements of the purchaser. All automotive self-steering axles examined use kingpins with virtually no inclination. Some manufacturers set about 1° of camber in the axle to allow for slight bending of the axle under rated load. This ensures that both ties of a dual pair will be normal to the road surface when fully loaded.

The alignment of the axle and the toe in adjustment is achieved with a threaded sleeve coupler or with an eccentric bushing and lock nut assembly. All manufacturers recommend toe in settings varying from 0.05 to 0.15 degrees measured with respect to the rotational plane of the wheel and the centre line axis of the vehicle.

Maximum steer angles of the axles vary between models and manufacturers. They range from about 14 to 24° off centre. Along with the centring force system, automotive type self-steering axles are often fitted with shock absorbers to dampen out steer impulses and to retard the dynamic steer response of the system.

Spring centres on automotive style axles are generally quite narrow because of interference allowances required by the tires of the steer axle as they steer. For a steering axle fitted with dual tires on a 2.6 meter track, typical spring centre dimensions range from 0.69 to 0.75 meters. If super singles are used, the spring centres can be increased to about 1.0 meters.

The turn table type steer axle has much larger spring centres because the tires do not steer relative to the suspension. The tires, suspension and sub-frame all rotate with respect to the main frame, therefore spring centres can be as wide as 1.1 meters.

2.3 Locking Mechanism

Self-steering axles require locking mechanisms to immobilize the steering action of the axle on centre when the vehicle moves in reverse. Without it the axle will instantly steer to its limit of travel and the high forces generated by the tires can result in mechanical failure of the steering system. The lock is a pin type device which engages into a hole in steel plate attached to the tie rod assembly. The turn table type dolly has a similar device which pins the main dolly frame and the sub-frame together. The locking devices can be controlled from the tractor cab if fitted with the appropriate hardware.

For a short time a particular turn table dolly was produced with a unique locking feature that injected a pin into one of a series of locking holes when the dolly brakes were applied. The locking holes were arranged in a circular fashion allowing for locking of steer axle system at steer angles other than zero. Because of the design of the pin it would occasionally jam in the locking hole while the axle was in a steered position despite the vehicle having re-aligned itself. The problems associated with such a failure are obvious and the practice was curtailed. It is worth noting that this idea may not be without merit. Since the steer axle is sensitive to imbalance longitudinal wheel forces of the type experienced during heavy brake applications of split friction surfaces, it may be beneficial to have a locking device immobilize the axle when high brake forces are required. If this device took the form of lock which could not jam in the locked position, it could prove to be an effective means of preventing unwanted steer due to differential break forces.

Upon inspection of different units in the field it is clear that some locking pin assemblies are of better quality and strength than others. It can be expected that as these devices mature, more unformity in quality and performance can be expected.

2.4 Tires

Virtually all C-dollies in Canada operate with dual tires ranging in sizes from 10:00 x 20 to 11:00 x 24.5. Tire considerations for self-steering axles are no less important than the front steering axle of heavy trucks. The fact that dual tires are used is a significant point. Dual tires produce high aligning moments not seen in single tires. These aligning moments must be considered when analyzing the self steering axle as they are contradictory to the preferred caster action of the axle as they work to keep the wheel running tangent to the curve. Similarly, if there is an effective rolling radius differential between the dual pair such as could occur in rutted road conditions, there is a moment referred to as the spin moment which also works against the preferred alignment of the axle. If the tires of a dual pair were of different radius or tread type or inflation pressure or construction such as radial and bias ply, the relative rolling resistance between tires would also produce a counter productive spin moment. It is important that dual tires on a self steering axle be matched as closely as possible in both tire type, size, state of wear, and inflation pressure. The tires of a self steering axle need not be of the same construction type as the rest of the vehicle as the self steering axle is in effect partially decoupled from the vehicle. Therefore there is no technical reason related to vehicle control requiring that uniformity of tire type between the vehicle and the self steering axle be regulated.

The use of re-caps in the trucking industry has at times prompted heated debates regarding safety and damage resulting from tread failures at high speeds. In the case of self steering axles re-cap tires are clearly undesirable. Should a tire failure occur on the inside tire of a dual pair, the kingpin offset dimension could be increased by as much as 40%. For a normal balanced brake application where both brakes produced the same retarding force, the longitudinal force induced moments on the steering system would be out of balance, and the axle could steer out of control as a result of large brake applications.

When mounting tires on the C-dolly, care is needed to ensure minimal run-out or wobbling of the wheels as this results in inbalanced tire forces being imposed on the centering force system of the axle. A run-out variation value in excess of 1/8 inch indicates an improperly mounted rim according to the Erie Wheel Catalogue (5). Based on this source, the recommended maximum variation in run-out for the C-dolly steering axle shall be 4 mm.

2.5 Hitches and Fifth Wheels

Since the C-dolly couples the two trailers in roll, it transfers high torsionally induced vertical forces through the hitch points. High vertical forces especially in the upwards direction are unusual for truck hitches and most are incapable of handling these forces. This presents a major problem for the C-dolly and must be addressed through regulation. The hitches presently used with the C-dolly are pintle type hitches equipped with a latch mechanism which prevents the draw bar eye from escaping vertically from the hitch. These hitches were not developed specifically for C-dolly use but do offer positive upward restraint which is deemed acceptable in the absence of something better. Discussions with carriers and operators who use C-dollies revealed concern over the adequacy of the hitches. It is felt that the C-dolly hitches require further development.

Previous research and testing of the C-dolly has also concluded that the hitches require special attention. The critical points regarding hitch performance can be summarized as follows:

1. The hitch and the eye must be capable of withstanding high vertical loads in both directions. Forces of 66.9 Kn (15,000 lb) are possible (1).

2. The hitch and the eye must be capable of withstanding very high drawbar tensile and compressive loads due to yaw induced moments. During violent maneuvers of the vehicle, longitudinal hitch forces associated with yaw moments can be as high as 134 kn (30,000 lb).

3. Hitch slack particularly in the longitudinal direction must be minimized as it permits a small amount of yaw freedom to the dolly which is undesirable. The hitches currently in use restrict slack by means of a pneumatic plunger which forces the eye of the draw bar against the pintle hook. The force generated by the plunger is in the order of 13.4 kn (3,000 lb) which represents an improvement over a free slack system but is insufficient to overcome the longitudinal hitch forces associated with the yaw moment of the dolly resulting from steer axle forces.

4. The hitch must be operable in severe climatic conditions, have some fail safe mechanism to prevent unwanted disengagement and it must maintain its reliability over the long term, at least equal to the life expectancy of the trailer to which it is attached.

5. The trailer backing plate to which the hitch is attached must provide at least the same minimal force requirements as the hitch.

During the course of the investigation into hitch requirements and the availability of hitch hardware for the C-dolly application, it became apparent that Canada is lagging behind most nations with regard to hitch regulations.

ISO Standards 1102 and 3584 have been developed for truck and trailer hitches and mounting requirements. The hardware that these standards specify is in the opinion of the authors a considerable improvement over what exists in Canada now. Some of these hitches have ratings sufficiently high to be suitable for C-dolly applications. Unfortunately, we have no experience with these hitches and cannot state absolutely that there would be no unforeseen operational problem associated with their use.

It would be beneficial to embark immediately on a program to review hitch standards and to develop standards for all hitches used in Canada. It will also be necessary to establish a committee or appoint an organization to approve hitches for C-dolly use.

3.0 Field Experience

The most concentrated use of the C-dolly is found in the Province of Saskatchewan. The Transportation Agency of Saskatchewan has gained a great deal of experience and knowledge about C-train operations through experimental and analytical studies of C-trains in connection with their special permit program. This agency along with some key trucking operations were consulted regarding operational problems with the C-dolly. From these sources emerged the following findings.

1. There is a general lack of confidence in the pintle type hitches currently used to connect the dolly to the lead trailer. There has been at least one case of a hitch eye disengaging from the pintle hook during normal use. There are also concerns about the long term performance of these hitches where wear and fatigue may effect performance.

2. C-dollies with centring force mechanisms which produce low centring forces to the self-steering axle are highly susceptible to road irregularities and unbalanced braking. These conditions cause the axle to steer uncontrollably.

3. C-dollies that produce high centring forces have performed very well; however, high centring forces result in higher stress in C-dolly frame and higher longitudinal forces at the hitch points.

4. The unlocked self-steering axle of the C-dolly performs poorly on very soft ground particularly on the extreme edges of roadways or on very poor gravel or dirt roads. A number of vehicle roll-over accidents have been traced to this problem and it appears to be equally as serious at slow speed. This is a particular concern.

5. The steer axle locking pins of some axles have been found to be too weak for long service duty.

6. Axle beams and/or kingpins in some automotive steer axles are prone to wear or fatigue cracking after lengthy service. It has been suggested that (axle beams), kingpins and other critical components be inspected annually or after 500,000 km whichever comes first. It is also imperative that lubrication and inspection maintaince similar to the front end of a truck be applied to the self steering axle.

There has been one documented case (7) of a C-train that became dynamically unstable in a classic yaw divergent manner which eventually overpowered the tractor resulting in a jackknife. The dolly was unusual in that it had two self-steering axles. The dolly also had a very long drawbar and the lead trailer was equipped with a tridem axle group. The distance from the dolly fifth wheel to the centre of the lead trailer tridem was large in comparison with the lead trailer wheelbase. This resulted in high side force demands at the tractor drive axles which was reflected by the tractor jackknife. Excessive vehicle speed and hitch slack were cited as the two main causes of the initial instability.

4.0 Practical Considerations Pertaining to Self-Steering Axle Centring Force

4.1 Differential Brake Forces

It is clear that self-steering axles used in the C-dolly application must be capable of generating some magnitude of side force and must resist steering action due to differential brake or rolling resistance loads. Examining the service record of the C-dolly, the common problem with the axle is related to steer action due to imbalanced brake or rolling resistance forces. There have been at least three accidents attributed to this problem. It is appropriate therefore that along with lateral force requirements resistance these longitudinal unbalanced forces must also be among the performance criteria of self-steering axles. By differentiating between these two forces, the designers of self-steering axle are given some creative latitude which will allow for the development of self-steering systems specifically geared the C-dolly application.

The Transportation Agency of Saskatchewan now referred to as Transportation Systems Branch, Saskatchewan Department of Highways and Transport initiated a requirement that the self-steering axle assembly of the C-dolly should be capable of generating side force of at least 0.3 g (based on static vertical wheel loads). After this requirement was put in place, the occurrences of unwanted steer from unbalanced longitudinal loads, particularly in turntable type dollies, were effectively reduced to zero. This field experience provides the input needed on which to base the calculation of steer force requirements.

Since differential longitudinal loading is the primary cause of unsatisfactory C-dolly performance, and with the knowledge that the turntable type steer dolly is more susceptible to this form of behaviour, the force available to resist steer from longitudinal forces can be calculated as follows.

For a turn table type steer dolly the principle dimensions are as follows:

MECHANICAL CASTER TRAIL 12 in (305 mm)

TRACK WIDTH MOMENT ARM $\frac{77}{2}$ = 38.5 in (978 mm)

The requirement of 0.3 g lateral force simply means that the steer axle system must resist a minimum lateral force equal to 30% of the vertical load 89.1 kN (20,000 lb). The measurement must be corrected to account for pneumatic trail. Pneumatic trail is related to the mechanics of rolling tires and occurs as the tire/road contact patch migrates rearward as the vehicle velocity increases. This has the effect of increasing the caster dimension which in effect erodes the centering force due to the extension of the total caster trail moment arm. Pneumatic trail varies considerably with tire type, and pressure; however, a value of 2 inches or 50 mm has become the accepted value

Therefore, for the dolly above, the corrected caster trail

305 + 50 = 355 mm (14 in).

To determine the equivalent longitudinal force required to cause the axle to steer the ratio of the moment arms is multiplied by the lateral side force requirement.

$$\text{TOTAL LONGITUDINAL FORCE IMBALANCE} = \frac{\text{CORRECTED CASTER TRAIL}}{\text{TRACK WIDTH MOMENT ARM}} \times 0.3 \times \text{MAXIMUM VERTICAL AXLE LOAD}$$

For the axle specified above, complying to the 0.3 g requirement with a maximum vertical axle load of 89.1 kN (20,000 lb) the axle can resist the following longitudinal force imbalance.

$$\frac{355}{978} \times 0.3 \times 89.1 = 9.73 \text{ kN}$$

or 10.9% of the vertical axle load.

As mentioned above, this level of centring force is sufficient to correct the common problem of unwanted axle steer. To put this in perspective, early production dollies having the same corrected caster trail and track width moment arm were not capable of resisting a longitudinal force imbalance greater than about 3% of the vertical load. It is not surprising that these early dollies were prone to unbalanced longitudinal force induced steer. When fitted with new centre force mechanisms, these particular dollies improved their resistive capability to 9.1% which has been found to be satisfactory.

From practical experience, therefore, it can be stated that an axle centring force which provides longitudinal force capability of 9.1 to 10.9% of total vertical axle load produces satisfactory results.

4.2 Cornering Forces

As outlined in earlier, it is important for vehicle control during cornering, that the self-steering axle generate side force. A reasonable level of side force for C-train configuration is about 0.25 g or 25% of the maximum vertical axle load. There is natural aligning moment that occurs when an axle with wide or dual tires negotiates a curve. As the axle follows the curve radius, the path followed by the outside tire is of different length per unit of arc as the path followed by the inside tire. This results in differential longitudinal tire forces on the dual pair which produces a moment that is in conflict with the dolly centring force mechanism. The magnitude of this moment is inversely proportional to curve radius and takes the form of

$$M = \frac{17000}{R}$$

where R is in meters and M is in Newton/meters.

The above relationship shows that for a curve radius of 30 meters, a pair of typical dual tires will produce a total aligning moment of 573 N-m which on a turntable steer axle is equivalent to a centring force of 0.02 g or 2% of the vertical axle load. The effect of this aligning moment on an automotive type steer axle is .03 or 3% of the vertical load. If the curve radius were reduced by half to 15 m, the aligning moment would be increased by a factor of 2. This moment is small; however, it does demonstrate why the early designers of these axles incorporated centring devices in their products.

The characteristics of the centring force returning to the zero steer position should also be specified because Coulomb friction in some axles can be quite high. It would appear from an intuitive point of view, that a lower centring force on the return action of the steer axle may be beneficial to the vehicle as it reduces the total side force generated by the axle group and therefore acts to reduce lateral accelerations attributed to overshoot of the vehicle. This phenomenon was observed during field tests (1).

On the other hand, one would not want a large "negative" side force as the axle could get hung up in the steer position. Respecting these two somewhat contradictory factors, it is recommended that the axle be capable of returning to within 1° of the zero steer position on its own.

4.3 Hitch Forces

There is sufficient documentation in previous work to establish the magnitude and direction of possible hitch loads. Referring in part to Winkler (4), the maximum loading predicted at the hitches is as follows.

*Longitudinal	F_x	= 220 kN (49,400 lb)
Vertical	F_z	= 100 kN (22,400 lb)
Lateral	F_y	= 38.5 kN (8,660 lb

*This value does not include normal towing forces or safety factors. It is derived from an assumption of a dolly with a 2.0 m draw bar and a locked steer axle being skidded laterally under maximum load at 0.8 surface friction.

These hitch loads represent maximum expected values which would be the result of a worst case incident.

With any vehicle coupling system, the elimination of hitch slack is beneficial as it reduces longitudinal action of the vehicle. Because of the unique geometry of the C-dolly, hitch slack cannot only produce longitudinal action but it can also provide unwanted yaw action of the frame. This yaw freedom is in fact the same as steer freedom at the axle. A given dolly having 10 mm of slack in both hitches will result in 1.5 degree of steer freedom. This steer freedom is at odds with the centering requirement of the steering system by defeating its purpose within this limited slack range. It is important therefore that slack be removed from the hitches.

The mounting position of hitches would benefit from uniformity. Failure to do so could result in variations from the level position which would result in king pin inclination of the steering axle. The current lateral centre to centre mounting position of hitches is 762 mm (30 inches). The mounting height of the hitches as measured from the ground to the centre of the drawbar eye on an unloaded vehicle is approximately 914 mm (36 inches).

It would seem appropriate, if for nothing more than metric round-off convenience, to propose a standard hitch mounting recommendation as follows.

Lateral centre to center hitch spacing	760 mm
Vertical centre of eye mounting height of unloaded vehicle	900 mm

4.4 Roll Coupling/Drawbar Torsion

In general, roll coupling of the trailers of a C-train is beneficial to roll stability of the vehicle. The C-dolly frame structure and the lateral positioning of the hitch points provides this torsional coupling. Torsional flexibility between trailers is also of great importance in reducing the magnitude of forces and stresses within the trailer and dolly frame members during normal operations. Without flexibility, unnecessarily high loads will frequently occur which can lead to fatigue failure of components. Industry has recognized the benefits of torsional flexibility by adding compensating fifth wheels and pitch pivoting or "limp wrist" drawbar eye assemblies. To arrive at a conclusion on roll coupling, it is necessary to consider the basics of roll stiffness particularly as it relates to the C-dolly. Roll stiffness is a term which relates primarily to the vertical stiffness of the suspension and the lateral distance between spring centres. Apart from these two parameters, suspension roll stiffness can be increased with the addition of a separate device such as a torsional stabilizer bar referred to in more exacting terms as an auxiliary roll stiffness device.

It is important, in any vehicle design, to incorporate as much roll stiffness as possible to maximize roll stability. It is also important in a multiple trailer vehicle such as a C-train, that each vehicle unit develop its own roll stiffness and not depend on a torsional link to the preceeding trailer to make up the roll stiffness shortfall of the following trailer.

There is a roll stiffness shortfall inherent in the design of the automotive type self-steering axles because the spring centres have to be kept narrow (approximately 0.7 m) to allow room for the intrusion of the tires while turning and because of the physical obstruction on the axle of the kingpin assemblies. On the other hand the turntable steer dollies have normal spring centres (approximately 1.1 m) because there is no relative yaw or steerage of the axle with respect to the suspension or the subframe. By virtue of this spring centre difference, the automotive dolly would have approximately 35% less roll stiffness then the turntable dolly if both dollies were fitted with the same suspension.

A compensating fifth wheel allows for some roll flexibility relative to the dolly suspension, and therefore by definition lowers the roll stiffness of the trailer. In some applications, such as its use in the B-train where a common rigid bogie assembly joins both trailers, the compensating fifth wheel seems to work well in providing the torsional flexibility between trailers needed to reduce fatigue cracking of the frame structure. However, it was thought that fitting a compensating fifth wheel to the C-dolly may further reduce its roll stiffness and shift the burden for the provision of roll stiffness to the lead unit and then onto the tractor which can be undesirable. To satisfy this concern, a tilt test was conducted to determine the effect of a compensating 5th wheel on the roll over threshold of a C-train. The results of the test proved that if the compensating fifth wheel has a roll centre near that of the trailer mass centre, no appreciable reduction in roll stiffness was measured. It follows, therefore, compensating 5th wheels of the type having the roll centre near the mass centre of the trailer can be used on C-dollies. It is important that particular attention to design be given to roll stiffness considerations of the C-dolly so as to ensure adequate stability performance of the vehicle.

The torsional flexibility required between trailers can also be provided through some well-engineered design of the dolly frame structure. Torsional stiffness need not be linear and if it is nonlinear, it should be biased towards increased stiffness as a function of rotational displacement. The frame must also be capable of transmitting a minimum level of torque to the system.

There is limited literature available to help support the declaration of an appropriate minimum torsional compliance value for the C-dolly frame. This being a requirement, an engineering judgment is necessary.

The torsional stiffness of heavy truck frames ranges between 900 Nm/deg and 1800 Nm/deg (8000 and 16000 in-lb/deg) as reported by Fancher et al (8). It is well known that for purposes of improved steering control, truck frames are inherently weak in torsion. This is made possible by the fact that the drive axle group of the tractor provides all the roll stiffness for the front end of the semitrailer. Considering that the C-dolly must provide adequate roll coupling between the trailers without excessive torsional compliance, the net torsional stiffness of the C-dolly frame must be greater than that of a tractor. As mentioned earlier in this section, a significant amount of torsional flexibility particularly at low relative roll angles would be helpful in reducing hitch loads during maneuvers in rough freight yards or during curb climbing. These seemingly contradictory requirements can be accommodated by specifying both a minimum torsional stiffness and a minimum torsional strength value which would give the designers of frame structures some freedom for innovation.

The principle asset of roll coupling is seen during sinusoidal or evasive maneuvers of a loaded vehicle on high friction surfaces. There is a phase shift in the roll action of the two trailers. Under these conditions the coupling of the trailers in roll helps to counter balance the relative roll of the trailers allowing the kinetic energy of roll to be transferred between trailers and equalized, thereby increasing the probability of a successful maneuver. In consideration of this fact, the maximum relative roll that can be expected between trailers is about 15 degrees.

5.0 CONCLUSIONS OF THE STUDY

C-dollies like most heavy truck components must endure very rough service in extreme environmental conditions over a very long period of time. In establishing performance criteria and regulatory principles for the C-dolly it is important to be as clear, simplistic and straightforward on the requirements and to address the appropriate issues so as not to constrain further innovations. It is also important to keep any control systems on the C-dolly foolproof and simple, bearing in mind the effects of neglect and long term abuse. This is in view of the fact that a dolly may exceed five million kilometers during its service life.

What follows is a point summary of relevant findings of the study pertaining to either hardware or performance of the dolly or its mechanisms.

5.1 Self Steering Axle Centering Forces

Caster steering systems must contribute to the cornering force requirements of the C-train. They must also resist unwanted steer due to imbalanced brake or rolling resistance forces. **This leads to a requirement that the caster steering system must generate a minimum lateral force equal to 25% of specified axle load capacity and a minimum longitudinal force of 10% of the same specified axle load.** The lateral force measurement shall include a correction to account for pneumatic trail which will be taken as a 50 cm addition to the mechanical caster trail dimension. No correction factor is required for the longitudinal force measurement. **The minimum force requirement must be attained within the 1.0 degree of steer on either side of the zero steer position. The angular displacement over which the minimum force requirement must be maintained is 15° relative to the zero steer position. On return of the axle from 15° to the zero steer position, the axle must return on its own within 1° of centre.** The compliance test must be conducted with a vertical load on the axle equal to 10 tonnes which is equivalent to the legal single axle load limit for the C-dolly plus 10% of that value. The tires of the axle must be supported by frictionless pads or the equivalent to eliminate tire friction forces and tire aligning moments during the test.

Forces must be applied to each stub axle or wheel at a point of known distance from the king pin thereby yielding steering moment vs steer angle. The required lateral and longitudinal force characteristics are then calculated by dividing the steer moment by a) the corrected caster trail dimension yielding the lateral force and b) the king pin offset yielding the longitudinal force. The caster trail dimension is defined as the distance parallel to the longitudinal axis of the dolly measured from the stub axle king pin or turn table rotational centre to the axial centres of the wheels of the dolly.The CORRECTED CASTER TRAIL DIMENSION is defined as the caster dimension plus 50 mm correction for pneumatic trail.

The king pin offset is defined as the distance perpendicular to the longitudinal axis of the dolly measured from the stub axle king pin or turn table rotational centre to the geometric centre of the contact patch of the wheel. For dual wheels the contact patch centre is taken as the midpoint between both contact patches. For both tests balance forces on the left and right of the axle acting in the opposite direction producing a pure moment is preferred.

5.2 Centring Force Control

Most C-dollies have controls which allow an operator to change the magnitude of the self steering centring force. Varying the magnitude of centring force allows the steering system to function during cornering when the vehicle is empty. The need for the axle to steer in the empty condition is questionable as the consequences of no steer action during cornering with an empty vehicle are minor. These include a slight increase in tractive effort of the power unit and tire scuffing of the trailer and C-dolly, and a marginal increase in vehicle offtracking. Because of the low axle loads in the unloaded condition, there are no significant stresses imposed on the vehicle when compared with the loaded condition.

By comparison, the consequences of a low centring force, whether by choice or by accident, on the behaviour of a loaded vehicle can be quite severe as revealed by previous research. **It is recommended therefore that in the interest of road safety, controls on the C-dolly which allow for variations in the magnitude of steer centring force should be prohibited. It is also recommended that centring force systems that operate by compressed air or hydraulic pressure should be equipped with a pressure gauge to display at the C-dolly, the amount of pressure at the centring device. Adjacent to the gauge should be a label clearly indicating the minimum design pressure that the C-dolly must have to comply with the centring force requirements.**

5.3 Self Steering Axle Lock

Locking the self steering axle in the zero steer position is required when reversing the vehicle as caster steering systems are absolutely unstable when travelling in reverse. Most self steering axles are fitted with electric or pneumatic actuated locking pins. Locking the steer axle at highway speeds has merit in that the axle performs like a non steering axle and does not respond to lateral inputs.

Operators should be encouraged to lock the steering axle at highway speeds especially when operating under adverse weather conditions, or on gravel or icy roads, or when travelling sections of highway that are very rough or under repair. Since any of these factors can occur during the course of a trip, it would be beneficial to the operator if the axle lock system could be activated from the cab. **Therefore it is recommended that**

all C-dollies be equipped with steer locking systems that can be activated by the driver in the cab of the tractor and that C-train tractors be equipped with the necessary switch hardware.

For emergency purposes, the C-dolly must also be equipped with a separate manual locking mechanism that allows the steering to be locked independently of the remote locking system.

Automatic locking systems activated by a speed threshold or activated by keying to a particular gear shift, would be viewed favourably. Because these locking systems would leave the axle unlocked at lower speeds, perhaps 40 km/hr, they could not be used in place of the recommended centring force requirements of the axle. However, if a C-dolly were to be used in heavy duty haul on poor quality roads, it may be appropriate to request that speed activated locking systems be installed as a pre-condition to the issuance of a special permit.

5.4 Frame and Hitch Considerations

The two hitches or equivalent mechanism and backing plate assembly that attach the C-dolly to the lead trailer will require the following working load rating.

Longitudinal Fx	**220 Kn (49,400 lb)**
Vertical Fz	**100 Kn (22,400 lb)**
Lateral Fy	**40 Kn (9,000 lb)**

Where possible and practical the lateral centre to centre mounting position of the hitch should be 760 mm and the mounting height as measured from the ground to the centre of the draw bar eye on an unloaded vehicle should be 900 mm. Longitudinal slack or free play between the hitch and the draw bar eye should not exceed 5mm.

The means by which the drawbar eye and the hitch connect is a matter which will require consideration. There are very few hitches on the market suitable for the C-dolly. There are however, ISO Standards 1102 and 3584 which specify hitches and mounting details and serve as examples of the kind of hitch design and performance specifications that would be beneficial to the industry.

With regards to the torsional stiffness and strength of the C-dolly drawbar frame structure, the minimum torsional stiffness provided about the hitch point of the C-dolly should be 3,000 Nm/deg (26,550 in.lb/deg) of roll and the drawbar and dolly structure should be capable of at least 45,000 Nm (398,300 in.lb) torque within 15° torsional displacement without permanent deformation.

5.5 Tires

Tires fitted to the steering axles of trucks require special considerations. Self steering axles must be treated in a similar manner; however, there are some unique considerations.

As shown earlier, dual tires impose an aligning moment on the steering axle when curving. This is due to the fact that in a curve the tire of a dual pair on the outer radius of the curve will travel further than the tire on the inner radius of the curve. Since the dual pair cannot rotate with respect to each other, an aligning or steering moment is generated by the longitudinal slip characteristic of the tire. If the tires are not matched in both diameter and inflation pressure, this aligning moment will conflict with the steer centring force mechanism. It is therefore important that the pair of tires forming a dual tire set should be matched in terms of size and state of wear.

Because different manufacturers produce slightly different tread design and rubber compounds which will have an effect on the longitudinal stiffness of the tires, it is important to require that self steering axles be fitted with matched tires. **This implies that the tires of a self steering axle should be of the same manufacturer, size, tread, style and tread wear.** It is recommended that rib style tread be used on the self steering axle and that re-capped tires be prohibited from use on self steering axles.

5.6 Vehicle Configuration

The C-train is a unique vehicle combination. Because the C-dolly eliminates the yaw articulation at the hitch point, it can be thought of as an extension of the lead trailer frame. The significant measure of this extension is from the turn centre of the lead trailer to the steering axle of the C-dolly. The longer this dimension, the larger the aligning forces associate with the lead trailer which must be counteracted by the tires of the tractor. As demonstrated by Ervin and Guy (2), increased axle spread results in increased tractive efforts at the tractor which is of particular concern during cornering on low friction surfaces. In addition, a large overhang requires greater steer angles from the dolly. By all accounts it is an advantage from a vehicle stability point-of-view to minimize the distance between the lead trailer turn centre and the dolly axle. Minimizing the draw bar length is also beneficial as it reduces the tensile and compressive forces at the hitches resulting from lateral forces originating from the tires of the dolly.

The C-dolly has been used recently in straight truck full trailer applications. This configuration does not qualify as a C-train and has proven to be an inappropriate use of the C-dolly. Unlike the tractor semi trailer, the straight truck receives all its directional force input from the steering axle. By comparison, the tractor semi trailer receives its cornering input from both the tractor steering axle and the tractor drive axles. The principle task of the tractor steering axle is to provide a relative yaw displacement between the tractor chassis and the semi trailer. It is the tractor drive axles that actually provide the cornering force input to the trailer. This fundamental difference between these two vehicle classes provides the rationale for prohibiting the use of C-dollies in straight truck full trailer applications on the grounds that on lower friction surfaces, the tires of the straight truck steering axle can be overpowered by lateral forces originating at the trailer and being transferred forward to the steer axle resulting in loss of directional control.

The use of the C-dolly in straight truck and trailer applications should be strictly prohibited. The C-dolly affects the cornering force demand on the steering axle of the truck to such an extent that controllability becomes grossly impaired, especially on low friction surfaces.

In C-train applications the distance from the turn centre of the lead trailer bogie to the C-dolly steering axle must be minimized. In addition, the distance from the turn centre of the lead trailer to the lead trailer kingpin should be maximized. The reason for this dimensional preference is to reduce tire side force demands at the tractor which have an effect on both high speed and low speed performance.

With respect to the current C-train doubles dimensional layout contained in "The Memorandum of Understanding on Interprovincial Vehicle Weights and Dimensions" (9), the following suggestions can be made with regard to specifying allowable dimensional limits.

a) **C-dolly drawbar length should be limited to 2.0 m maximum. The current hitch offset of 1.8 m maximum should remain. This requires that the tandem axle spread maximum values of the lead trailer be reduced from 1.85 to 1.60 m to eliminate dimensional contradiction.** This allows the C-train to comply with the 3 m interaxle spacing requirement which qualifies the C-dolly to carry 9,100 Kg. It also ensures that the distance from the turn centre of the lead trailer to the C-dolly steering axle can be held to 3.8 m. A 2.0 m drawbar maximum will improve fleet compatibility. If in place of a drawbar length specification, the single dimensional limit of 3.8 m from the C-dolly axle to the turn centre of the lead trailer were chosen, there would be potential for dimensional conflict within the fleet. Exchanging equipment would result in a high level of incompatibility as some unit combinations could have the distance from the turn centre of the lead trailer to the C-dolly steering axle as high as 4.4 m. Provisions should be made to allow the C-dolly with an interaxle spacing dimension of less than 3 m to be treated as the third axle of a tridem. Much can be gained by keeping these axles as tightly spaced as possible.

b) There is an advantage to vehicle handling if the wheelbase of the lead trailer is equal to or greater than that of the following trailer. **The wheelbase of the following trailer should never be greater than the wheelbase of the leading trailer.** The wheelbase is defined as the distance from the king pin of a given trailer to the geometric centre of the axle group of that trailer.

c) Since there is no vertical load transfer from the following trailer to the leading trailer, **it is necessary to ensure that the weight of the following trailer never be greater than that of the lead trailer.** For example a C-train with an empty lead trailer and a loaded following trailer would be considered dangerous.

d) Examined in isolation there is no apparent disadvantage to increasing the box length of the C-train from 18.5 to 20 meters. However, if an overall vehicle length limit of 23 meters were to apply, this would result in a reduction of the tractor wheelbase. Short wheelbase tractors are known to have poor handling characteristics independent of what vehicle combination that they are connected to. Further study is warranted to determine whether design parameter resrictions should apply to shorter wheelbase tractors. If such a study could establish design criteria addressing such parameters as wheelbase, drive axle spread and fifth wheel settings and if these prove compatible with the 20 m box length and the 23 m overall vehicle length rule, then there would be no vehicle dynamic concerns about a C-train with a 20 m box length.

e) By definition the C-train is a more complex vehicle than the B-train. Considering factors such as self steering axle control, hitching systems and the lack of load transfer from the following trailer to the lead trailer, one cannot consider the C-train to be equal in performance to the B-train. It is clear, however, that the C-train represents a significant improvement over the A-train. There is good technical rationale to support an increase in the gross vehicle weight of C-trains from the present 53,500 kg. However, there is equally good technical rationale for not allowing the C-train to achieve as high a gross vehicle weight as that allowed for the B-train (62,500 kg). From a technical perspective, a maximum gross combination weight of approximately 58,000 kg, which is midway between the current A- and B-train values, would seem appropriate. It is also appropriate tha the C-dolly axle qualify as a single axle with a maximum load of 9,100 kg given compliance with th 3.0 m interaxle spacing rule. If the interaxle spacing were less than 3 m, consideration should be given to treating the C-dolly axle as the third axle of a tridem because this tighter axle spread is highly beneficial to the C-train.

f) There may be situations where C-trains will be configured outside of the dimensional limits agreed upon by the provinces. In such cases, it is recommended that proposed vehicle layout satisfy the following design rule. This design rule is a crude approximation which respects the dimensional preference of the C-train in light of the findings of this study.

The ratio of the lead trailer wheel base to the distance from the lead trailer suspension geometric centre to the C-dolly self steering axle should be greater than or equal to 1.5

$$\frac{\textbf{LEAD TRAILER WHEEL BASE}}{\textbf{DIST. FROM THE LEAD TRAILER GEOMETRIC CENTRE TO SELF STRG. AXLE}} \geq 1.5$$

g) **Lift axles or self steering belly axles must not be used in any C-train application.** The presence of a self steering belly axle on any element of a C-train including the tractor would degrade the net cornering force available to the vehicle. Non steering lift axles on any element of a C-train would increase cornering force demands due to high aligning moments which can be critical to C-train performance.

h) All self steering axles examined were of the non-inclined king pin type. However, an analysis was conducted on the characteristics of self steering axles with inclined king pins and these were found to be undesirable. It is recommended therefore that only axles with vertical king pins be used for heavy vehicle self steering axle applications. The turntable bearing used on some axles is considered to be a vertical king pin.

i) Controls on the C-dolly which allow for variations in the magnitude of steer centring force should be prohibited. It is also recommended that centring force systems that operate by compressed air or hydraulic pressure should be equipped with a pressure gauge to display at the C-dolly, the amount of pressure at the centring device. Adjacent to the gauge should be a label clearly indicating the minimum design pressure that the C-dolly must have to comply with the centring force requirements. The label should also include a warning that the axle must be locked when the vehicle is operating on anything other than hard, dry road. Devices that automatically lock the axle beyond a given speed, 40 km/hr, should be encouraged.

j) Because of the unique performance and design requirements imposed on the C-dolly, there should be an annual inspection program established to certify that the dolly is in good working order.

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