Innovative Dollies: Improving the Dynamic Performance Of Multi-Trailer Vehicles

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ABSTRACT

This paper reviews the finding of a two year research program conducted by the UMTRI and sponsored by the Federal Highway Administration of the US DOT. The goal of the project was to identify and evaluate innovative dollies or coupling mechanisms which could improve the dynamic performance of multi-trailer commercial vehicles when compared to the conventional A-dolly. Performance measures of interest included rearward amplification, dynamic rollover limit, and low speed offtracking. A survey of innovative ideas being applied throughout the world was conducted, and the concepts identified were screened using computer simulation analysis techniques. Three of the more promising innovative concepts were selected for further study. These were (1) the four-bar linkage dolly, (2) the linked-articulation dolly, and (3) the "auto-steering" B-dolly. In addition, the researchers developed a forth dolly concept, the controlled-steering B-dolly, to be studied along with the other three. These four dolly concepts were subject to a more extensive computer simulation study, and full scale dynamic performance testing was conducted on examples of each. Each of the four concepts was found to provide substantial improvement in dynamic performance in comparison to the conventional A-dolly.

INTRODUCTION

This paper reports some of the findings of a research project entitled "Techniques for Improving the Dynamic Ability of Multi-Trailer Combination Vehicles". (1) The project was conducted by The University of Michigan Transportation Research Institute (UMTRI) and was sponsored by the Federal Highway Administration (FHWA) of the U.S. Department of Transportation under Contract No. DTFH61-84-C-00026.

The Surface Transportation Assistance Act of 1982 allows the use of doubles combination vehicles nationwide in the U.S. on the federal highway system. This Act is generally expected to result in a major increase in the number of multi-trailer commercial vehicles in use throughout the U.S. At the same time, pressure for allowing the use of triples is increasing. In light of the fact that multi-trailer vehicles are known to suffer from special dynamic characteristics that can limit their stability and emergency maneuverability characteristics, vis-a-vis the tractor-semitrailer, these developments have led to concern over the potential for degradation of the safety quality of the U.S. commercial vehicle fleet. The primary purpose of this research study was to obtain information on developments in heavy-vehicle technology which might provide improvement in the dynamic performance of multi-trailer vehicles. A major goal of the project was to develop safer, practical coupling mechanisms for multi-trailer combination vehicles.

For purposes of this study, the goal of "improving the dynamic performance" of multi-trailer vehicles was taken to imply that the conventional "A-train doubles" vehicle be used as the reference. It is well established in the literature that maneuvering quality of the tractor-semitrailer portion of an A-train doubles combination vehicle is virtually unaffected by the presence of the full trailer, but that, in emergency maneuvers, the second trailer of the doubles suffers from a "crack-the-whip" phenomenon in which the second trailer substantially exaggerates, or amplifies, the motions of the tractor. (2-16) The major safety consequence of this "rearward amplification" is the premature rollover of the second trailer. Rearward amplification and the resulting propensity toward

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rollover of the second trailer is generally recognized as the property of the double which distinguishes (and degrades) its dynamic performance capability from that of the tractor-semitrailer combination vehicle.

The major effort of this project, then, involved identification, analysis, and further development of innovative dolly and trailer hitching hardware showing potential for the reduction of rearward amplification and prevention of rollover of the second trailer. Specifically, the project (1) reviewed the current state-of-the-art in innovative coupling mechanisms, (2) examined the performance of combination vehicles equipped with existing and proposed coupling mechanisms through the use of computer simulation methodology, (3) developed a new type of dolly believed to provide superior safety performance, (4) conducted full-scale tests of combination vehicles using various dollies, including a prototype of the new dolly, and (5) examined the potential operational impact of the use of innovative dolly hardware. This paper reports on some of the findings derived from the first four tasks listed.

A SURVEY OF INNOVATIVE DOLLIES AND COUPLING MECHANISMS

The first task of this study was a survey effort intended to identify new, innovative, trailer-to-trailer hitching mechanisms available or being developed worldwide. In conducting this survey, contact was made with many individuals or organizations in the U.S. and Canada who were involved in the development and/or manufacture of innovative dollies or hitching hardware. In addition, letters of inquiry were mailed out worldwide. Responses were received from North and South America, Europe, Asia, and Australia.

The survey identified many individual examples of innovative dollies in use or under development. To bring order to the simulation study which would follow, the individual dollies were organized into two major categories and several subcategories, according to generic design qualities. These were:

Modified A-Dollies

- Shifted-IC Dollies
- Forced-Steering Dollies
- Linked-Articulation Dollies
- Skid-Steer Dollies
- Roll-Stiffened Pintle Hitch
- Extending-Drawbar Dollies
- Locking A-Dolly

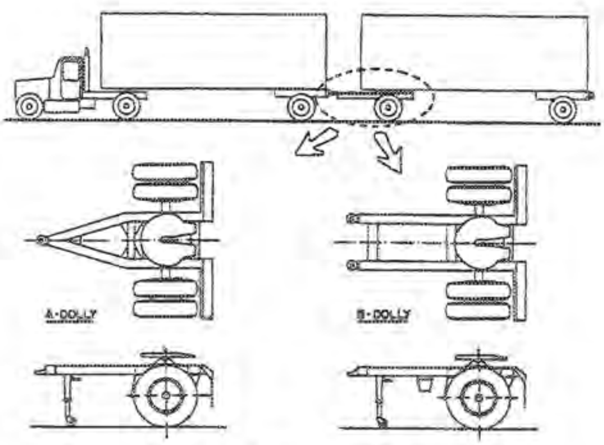
B-Dollies

- Non-Steering B-Dollies
- Self-Steering B-Dollies

The dollies identified are listed by these generic groupings in Table 1. The table also shows the inventor or commercial enterprises associated with the dolly where applicable.

MODIFIED A-DOLLIES

The so-called A-dolly is, of course, the conventional single-drawbar dolly, which connects to the first semitrailer trailer with a single pintle hitch and to the second trailer with a conventional fifth wheel (converter dolly) or with a turntable bearing (turntable dolly). Modified A-dollies are dollies which retain the pintle hitch, or other form of single-point coupling which permits yaw articulation between the dolly and the first trailer. B-dollies, on the other hand, are dollies which practically eliminate yaw motions between the first trailer and the dolly, usually by using rigid double drawbars and two pintle hitch connections. The "basic" A-dolly and B-dolly configurations are illustrated in Figure 1.



The A-dolly and B-dolly

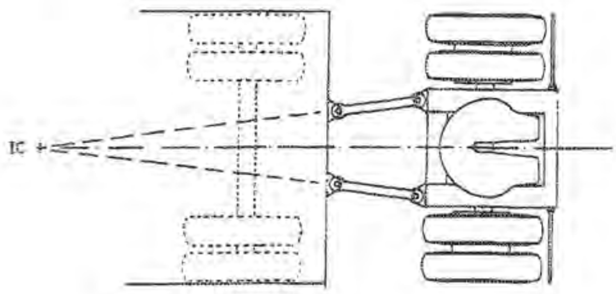
FIGURE 1

Table 1 — Innovative dollies and hitching hardware

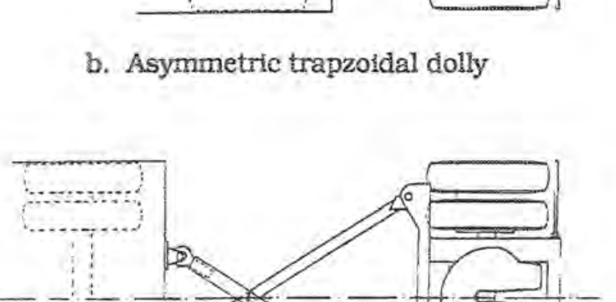
Dolly type	Description	Inventor, commercial interest or manufacturer
Modified A-Dollies	Dollies which retain yaw articulation capability between the first trailer and the dolly.	
Shifted IC Dollies	Dollies whose "pintle" hitch hardware causes a shift in the center of rotation of the dolly and the first trailer away from the hitch point.	
Symmetric Trapezoid hitch	Double drawbars, hinged at both ends, form a symmetric trapezoid about the longitudinal centerline in the plan view with the narrower end forward. The IC is forward of the physical hitch point.	Used by Michelin test fleet. No known active producer.
Asymmetric Trapezoid hitch	Double drawbars, as above except on bar on centerline.	Norman Gallatin. Trapezoid Corp.
Converter, trapezoid hitch	Symmetric trapezoid, converts to rigid connection for low speed maneuvering.	Marcard Trailer Services
Double-crossed hitch	Double drawbars, hinged at both ends, criss-cross in plan view. The IC is at the cross point, rearward of the physical hitch point.	Arnies Welding. Hamelex Transport.
Roller cam hitch	Cam surface of the hitch provides forward IC at small articulation angles, rearward IC at large articulation angles.	A. Pavluk, L. Segel, P. Fancher.
Forced Steer Dolly	The wheels of the dolly are forced to steer as a function of pintle articulation angle. Different types are produced with a variety of steering linkages. Used in Europe for "close-coupling".	Royce Currey, ASTL. Doll "AVL". Kogel Kassbohrer. Wackenhut. Ackermann-Fruehauf.
Linked Articulation Dolly	A-dolly with an additional linkage attached directly from trailer to trailer. A fixed relationship between the pintle and fifth wheel articulation angles results.	Truck Safety Systems.
Skid steer dolly	The yaw articulation joint at the dolly fifth wheel is eliminated. This is, the front tires of the full trailer do not steer at all.	Doetcker Industries.
K-Train	Modification of the skid steer concept. An "auto-steer", self steering axle is used for the dolly axle, so that the front tires of the full trailer steer by caster.	Knight Industries.
Roll stiffened pintle hitch	Fifth wheel-like device is used at the draw bar hitch	Truck Safety Systems.
Extending Drawbar dollies	The drawbar is caused to lengthen as either pintle articulation or fifth wheel articulation angle increases. For "close-coupling".	Blumhart. Pietz. Meier-Bürstadt. Eck.
Locking A-dolly	Single point drawbar equipped with device which can "lock-out" yaw articulation. Operates as an A-dolly when "unlocked" as a B-dolly when "locked".	VBG, Sweden
B-Dollies	Dollies which eliminate the yaw articulation between the first trailer and the dolly by using a rigid, double drawbar.	
Slider B-dolly	B-dolly with fixed, non-steering axles which "slides under the cargo area of the first trailer when the second trailer is absent.	Arquin, Trailer. Monon Trailer. Fruehauf Corp. E. Tenn. Transport.
Auto-steer B-dolly	A B-dolly with a self-steering axle. The dolly axle is equipped with "automotive style" steering knuckles on positively castered kingpins. The steering system has a centering spring mechanism.	Royce Curry. ASTL. Knight Industries. Sterling Axle. Independent Trailer.
Turntable steer B-dolly	A B-dolly with a self-steering axle. Steering results from the rotation of a solid axle about a positive castered steering pivot located on the dolly centerline. The steering system has a centering spring mechanism.	ASTL. Arnies Welding. Westank-Willock. Knight Industries.

Shifted IC Dollies

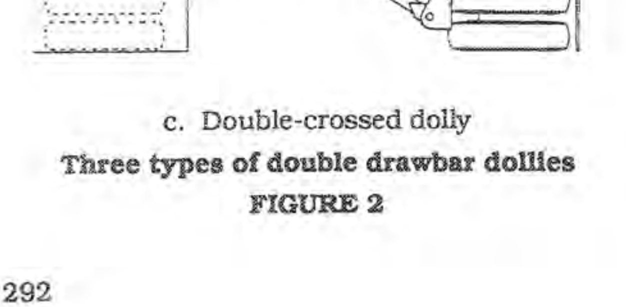
In the parlance of the mechanical engineer, the pintle connection point between the first trailer and the dolly can be identified as the "Instant Centre of Rotation" (IC) of the relative motion of these two bodies. The technical literature establishes that the location of the pintle hitch can have an important influence on the dynamic behaviour of doubles. (5,11,13,14,16) Further, it has been recognized that the importance of the pintle hitch location in this regard is not so much in the location of the actual physical connection, but rather in the location of the IC, in yaw, of the first trailer and the dolly.



a. Symmetric trapezoidal dolly



b. Asymmetric trapzoidal dolly



c. Double-crossed dolly

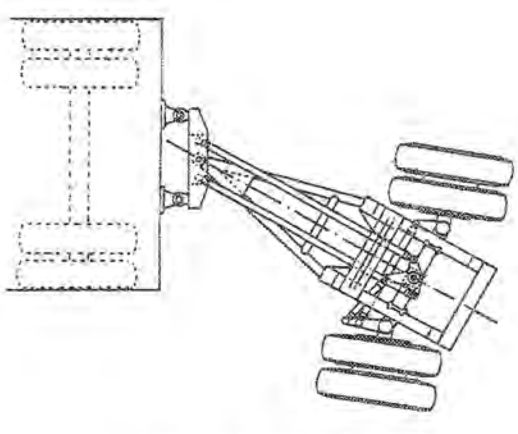
Three types of double drawbar dollies

FIGURE 2

Several dolly types, or hitching mechanisms, which effectively shift the IC away from the location of the actual physical connection point, were identified in the survey. Most of this class of dolly use two, hinged drawbars. As shown in Figure 2, these arrangements produced an IC at the intersection of the projection of the axis of the drawbars. The so-called "trapezoidal" dollies have an IC shifted forward from the usual position and the "double-cross" results in a rearward IC location. It is well established in the technical literature that IC's which are well forward in the first trailer are advantageous for reducing rearward amplification. (11,13,14,16) However, IC's which are well forward in the trailer exaggerate low-speed offtracking. One advantage of the trapezoidal design is that the IC can be purposely relocated to a more rearward position under low-speed operating conditions by providing a mechanism for sliding the forward drawbar hitching points closer together.

The Forced-Steer Dollies

The survey identified a number of commercially available A-dollies which provide for controlled steering of the dolly tires as a function of pintle hitch articulation. Most but not all of the known examples of these dollies are European developments where the primary interest lies in providing advantageous steering geometry for close-coupling trailers. These designs generally cause the tires of the dolly to steer to a greater angle (relative to the first trailer) than they would by dolly articulation alone. However, a Canadian, forced-steer dolly (by ASTL), shown in Figure 3, causes the dolly tires to steer in the other direction.



A forced-steer dolly

FIGURE 3

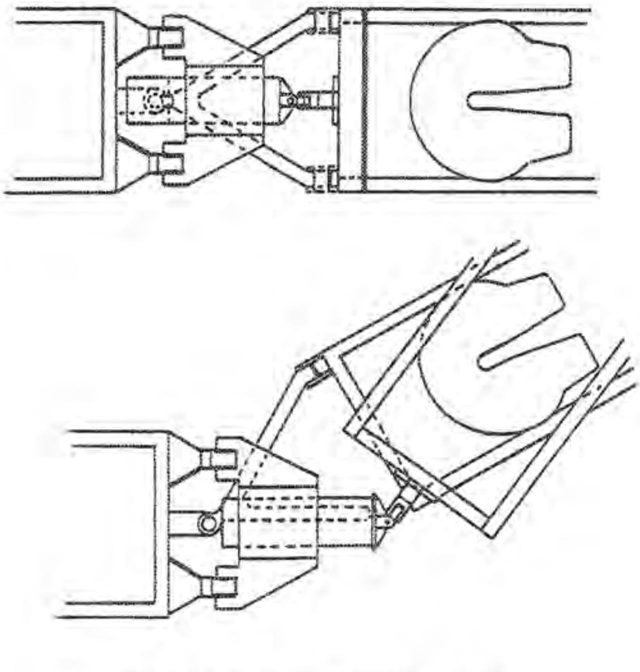
The Linked-Articulation Dolly

In the normal operation of the conventional A-dolly, the yaw articulation that occurs between the first trailer and the dolly (about the pintle connection) and the yaw articulation which occurs between the dolly and the second trailer (about the fifth-wheel connection) are independent of one another so that, within the range allowed, any pintle angle can exist with any fifth-wheel angle. The system is said to have "two degrees of freedom" in yaw.

A class of hitching hardware was identified which "linked" the two articulation angles of the dolly. An example is shown in Figure 4. These devices cause a specific relationship to exist between the articulation angle between the first trailer and dolly and the articulation angle between the dolly and second trailer. Even though two articulation joints exist, the mechanical system is reduced to one degree of freedom. The elimination of a degree of freedom represents a fundamental change to the vehicle system, and significant changes in dynamic performance can be expected to follow.

The Skid-Steer Dollies

The "skid-steer" dolly is similar to an A-dolly with a normal pintle hitch, except that yaw articulation about the fifth-wheel connection with the second trailer has been eliminated. That is, the skid-steer dolly converts the second semitrailer to a full trailer whose front axle does not steer. Skid-steer dollies have been operated in the Canadian Province of Saskatchewan.



The linked articulation dolly

FIGURE 4

At least one working example of the so-called K-train also has been operated in Saskatchewan. The K-train is a modification of the skid-steer dolly concept. That is, there is no fifth wheel on the second full trailer, but the front axle of the full trailer is an "auto-steer," self-steering axle. As will be discussed in more detail later, the wheels of these axles are allowed to steer by castering action after overcoming a "centering spring," or steering-resisting mechanism. With a very high level of steering resistance, the K-train would behave as a doubles using a skid-steer dolly.

The Roll-Stiffened Pintle Hitch

Truck Safety Systems of Michigan has marketed a dolly hitching device which provides a roll-resistant coupling between the dolly and the first trailer. This device replaces the usual pintle hitch connection with a fifth-wheel-like coupling. In dynamic turning maneuvers, when the roll motions of the two trailers of the doubles are out of phase, the roll coupling between trailers serves to improve the roll stability of each trailer. Depending on the tires used, rearward amplification behaviour may be modified due to the change in dynamic tire loads.

Extending-Drawbar Dollies

Extending-drawbar dollies are another type of close-couple dolly available in Europe. These dollies are, in effect, straightforward A-dollies with the exception that their drawbar length adjusts automatically as a function of pintle articulation angle. That is, the drawbar, in one manner or another, telescopes such that it is shortest at zero articulation, and increases in length in off-centre conditions. This allows for close coupling the trailers in straight running while avoiding trailer-to-trailer interference in tight maneuvering.

The Locking A-Dolly

This dolly is being developed by VBG of Sweden. It is the only European device identified that exists specifically to enhance the dynamic performance of multiply articulated vehicles. The dolly uses a drawbar which can provide yaw articulation at the pintle, or "lock out" that motion. In its "locked" configuration, this dolly functions as a simple B-dolly, and in its unlocked configuration, it acts as a conventional A-dolly. The dolly is "locked" at highway speeds to provide good dynamic performance, and unlocked at low speeds to provide good maneuverability and prevent high frame stresses.

B-Dollies

All the preceding devices are considered to be "modified" A-dollies, in that they retain a pintle-hitch-like yaw articulation joint. B-trains and B-dollies, on the other hand, have the major identifying property of eliminating the yaw articulation which otherwise occurs at a pintle joint.

B-dollies are actually a development following as a extension of the B-train concept. The B-train is a multi-trailer vehicle employing only semitrailers, i.e., no full trailers. Each towing trailer is equipped with a rigid frame extension aft of its cargo area which is fitted with a fifth wheel for coupling to the following semitrailer. The fifth wheel may be conventional, but often, and particularly on tank trailers, a so-called compensating fifth wheel may be used to reduce stresses imposed on the frame. The improved rearward amplification performance of this vehicle in comparison to the A-train is well documented. (6,7,10,15) Roll stability, per se, is also improved, particularly with the rigid fifth wheel. Offtracking performance is somewhat degraded relative to the A-train, and many practical considerations of cost, frame stressing, incompatibility of existing trailers, etc., serve to limit the applicability and acceptance of the B-train.

Non-Steering B-Dollies

Non-steering B-dollies provide a "first approximation" of the B-train. Rather than having a single-point pintle hitch, B-dollies are equipped with a forward frame extension, or "double drawbar," which connects to the lead trailer at two points separated laterally at about the spacing of the frame rails. In yaw, then, the B-dolly is effectively a rigid frame extension of the lead trailer. In pitch, however, it maintains the pintle-like articulation joint, and from a strictly practical view, it is a separate, detachable piece of hardware.

Sliding B-dollies are a modification of the simple, non-steering B-dolly. When used between trailers in multi-trailer trains, these devices function equivalently to standard B-dollies. When not in use, however, sliding B-dollies remain part of the towing trailer, and, in a manner similar to the operation of sliding trailer suspensions, the dolly may be slid forward under the cargo area of the towing trailer. The practical advantages of sliding dollies have to do with times when the doubles vehicle is "broken down." The dolly is no longer a "loose" piece of equipment, but conveniently remains with the first trailer. It can serve to "convert" the first trailer from a single- to a tandem-axle trailer. When slid underneath the cargo area, it does not interfere with backing the trailer into loading docks.

Steerable B-Dollies

"Steerable" B-dollies are a major variation of the B-dolly which are rapidly gaining popularity in Canada. Their structure and coupling mechanism are similar to the non-steering B-dolly, but the axle or axles on the dolly are equipped with a caster steering mechanism. With the so-called "auto-steering" (i.e., "automotive") style (Figure 5), the steering freedom is provided by a kingpin and steering knuckle arrangement similar to that found on truck steering axles. "Turntable"-style steering (Figure 6), on the other hand, allows for a rigid axle to pivot, relative to the dolly frame, about a central, castered kingpin. In practice, both types of steering mechanisms are generally equipped with a "centering" spring device of some sort. These mechanisms, along with varying levels of Coulomb friction developed in the kingpin joints, provide a torque which is resistant to steering and which must be overcome by tire forces acting about the caster pivot in order to induce steering of the dolly tires. The general theory of operation, then, is that resistance to steering is sufficiently high that, at highway speeds, little or no steering takes place, and dynamic performance is effectively that of a B-train. But steering is also sufficiently free as to significantly mitigate low-speed offtracking, tire scuffing, and frame stress problems that otherwise arise in the operation of B-trains and non-steering B-dollies. In practice, the quality of the performance of the steerable B-dolly depends on the compromise implied by these requirements.

The steerable B-dollies are susceptible to a unique performance problem related to braking. The B-dolly axles steer in response to torque about the steering pivot which results from tire forces acting at some distance from the pivot. Normally, the force of interest is tire side force acting at the caster length, and generally the steering motivation provided by left- and right-side tire forces will be additive. But steering moment may also be generated by braking force acting at the kingpin offset dimension. Normally, left- and right-side torques of this sort have canceling influences, but if brake force is unbalanced side-to-side, a net steering torque will result.

Brake force imbalance of 20% is not uncommon due to brake property variations, and much greater imbalances may result from differences in tire/road friction side to side. Given a certain level of brake imbalance, the sensitivity of the system response will depend, in large part, on the kingpin offset dimension. Accordingly, the turntable steering mechanism is seen as the far more sensitive type of design, since its kingpin offset dimension is equal to half of the track width of the axle.

The devices listed in Table 1, then, constitute the innovative hitching mechanisms which were candidates for study. The candidates fall into two major groupings, viz., modified A-dollies and B-dollies. Modified A-dollies retain the yaw articulation degree of freedom at the first trailer-to-dolly connection, while B-dollies eliminate this articulation. Subgroups, defined by generic operating concepts, have been identified for each of the major categories. In many cases, a number of specific mechanical designs are known to exist within each subgroup. However, the interest herein will focus on the performance potential of the concept, rather than on the performance of any specific design example.

SIMULATION STUDY

The initial phase of the dynamic performance study consisted of a screening activity in which the performance qualities of the dollies identified in the survey were evaluated using computer simulation techniques. Later, the performance of three specific selected dollies, and a new dolly concept developed during the study, were examined in more depth.

The "Western Double," shown in Figure 7, served as the "test vehicle" throughout this research study. The geometry shown in the figure is typical of this type of vehicle. Most simulation runs were conducted with the vehicle "fully loaded." Other runs were made with one or the other, or both, trailers empty. The payload parameters used, as shown in the figure, are for a full load of medium-density freight. Data derived from test of the Michelin 10.00 R 20 G steel radial were used to describe the tires of all simulated vehicles.

THE SCREENING STUDY

The basic approach in conducting the screening portion of the study was to evaluate the performance potential of each of the generic types of dollies rather than the specific examples that had been identified. UMTRI's Yaw/Roll simulation model was altered to include generalized features which would allow representation of each of the dolly types. For each dolly type, the characteristic property of the dolly was varied over a broad range, so that the performance potential of the concept could be evaluated.

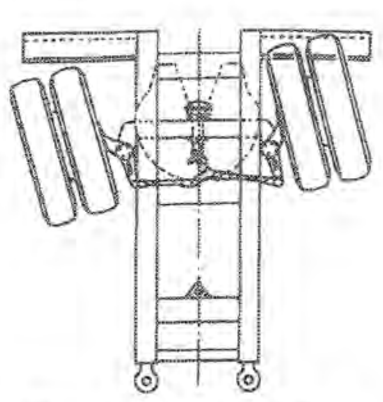
Although all the dolly types identified in Table 1 were investigated, some are not reported on here for reasons of space. Table 2 identifies the dollies considered here. The table names the vehicle, or dolly, and gives a description of the generic quality and associated simulation parameter of interest. The "shorthand" code used to identify the specific simulation "test vehicles" is given, as is the parameter value which distinguishes that vehicle.

Figure 8 aids in defining the characteristic parameters of IC-group, forced-steer, and linked-articulation dollies. Figure 9 shows the reference steering resistance characterization of self-steering axles. The steering resistance properties shown, combined with 5 inches of mechanical caster of the steering system and approximately 2 inches of pneumatic caster of the tires, provide a steering resistance function which effectively resists steering of the B-dolly tires until lateral tire forces on the B-dolly total about 5,200 lbs, representing a lateral friction utilization coefficient of about 0.3, given an axle load of 17,500 lb.

The dynamic portion of the screening study consisted of a set of simulation runs planned to produce measures of both rearward amplification and dynamic roll stability for each of the subject vehicles. The matrix consisted of (1) a "frequency sweep" of lane-change-like maneuvers, conducted at 55 mi/h and at low levels of lateral acceleration, for characterizing rearward amplification, and (2) an excursion into higher levels of lateral acceleration, using the same maneuver, to examine dynamic rollover stability limits. All these maneuvers were conducted with the fully loaded test vehicle. Example data showing the paths and the acceleration time histories of the tractor and second trailer during such a maneuver are shown in Figure 10. The definition of rearward amplification is illustrated in the figure.

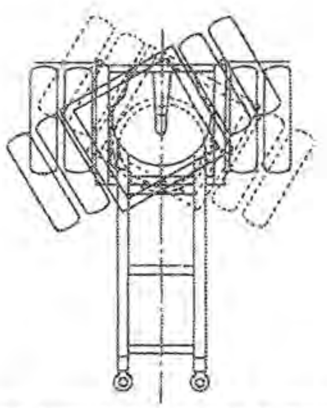
Rearward Amplification

The results of the screening study simulation runs examining rearward amplification are shown in Figure 11. The figure presents rearward amplification of the test vehicles as a function of



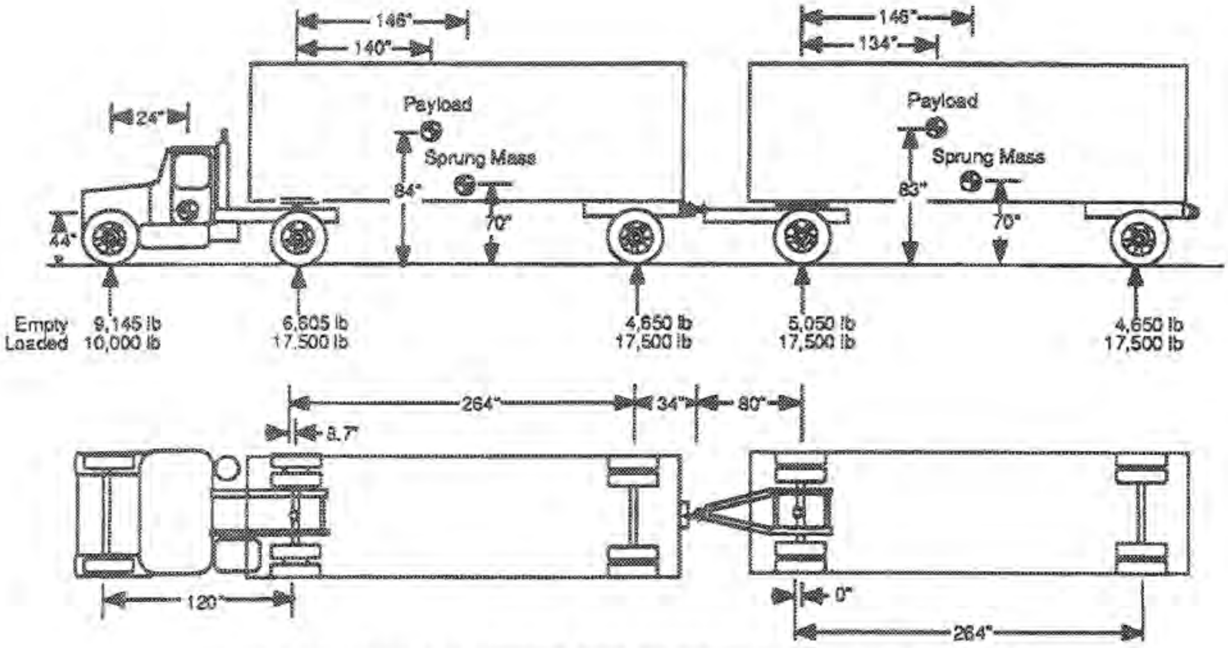
The auto-steer B-dolly

FIGURE 5



The turntable-steer B-dolly

FIGURE 6



The baseline simulation test vehicle: the western double

FIGURE 7

maneuvering frequency. Each individual plot shows the rearward amplification performance of a specific group of test vehicles (Table 2).

The performance of the A-train is given in each plot as a reference. The rearward amplification performance of the A-train, as shown in these plots, is indicative of "the doubles problem." At very low frequencies, both trailers follow the path of the tractor virtually exactly, so that rearward amplification is unity, but at both 3 and 4 rad/sec the rearward amplification of the A-train reaches 2.37. Thus, at these frequencies, the second trailer experiences maneuver levels which are more than twice as severe as those experienced by the tractor.

Regarding the study vehicles, the data in Figure 11 indicate the following:

- *The IC Dollies* (Figure 11a): The results shown in the figure confirm the previously known fact that as the instant centre of rotation (the "effective hitch point") of the dolly moves forward in the frame of the first trailer, rearward amplification of the train is reduced. Fancher (13,14) has clearly shown that the more important influence is the location of the

IC in the first trailer, not the effective lengthening of the towbar. Rearward amplification is reduced at all frequencies by moving the IC forward, with the strongest influence at high frequencies.

- *The Forced-Steer Dollies* (Figure 11b): The rearward amplification of each of the forced-steer dollies examined is slightly larger than the rearward amplification of the A-train. Since the steering gain of the dollies examined were all of the polarity in which the dolly tires steer toward the outside of a steady turn (and their slip angle and level of side force generation thereby tend to be reduced), the polarity of this finding is as would be expected. Nevertheless, the sensitivity of performance to steering gain is small and appears to be "saturating." This observation, and further analysis, led to one of the more interesting findings of the study, viz., the development of the "steer-point" concept, to be discussed below.

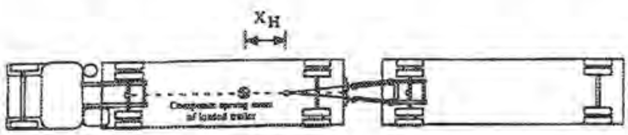
- *The Roll-Stiffened Pintle Group* (Figure 11c): These results indicate that providing realistic levels of roll coupling at the pintle hitch tends to decrease rearward amplification very slightly, but if a hitch (and frame) very rigid in roll could be applied, rearward amplification could be reduced appreciably. The explanation lies in nonlinear tire properties. It is well known (18) that the nonlinear sensitivity of cornering stiffness of truck tires to vertical load results in a reduction of the total cornering stiffness of all the tires on a given axle as load is transferred from side to side due to rolling motions. In dynamic maneuvers, the roll

Table 2 – The screening study vehicles

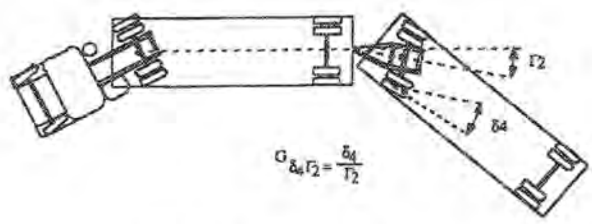
Dolly type	Generic description and simulation parameter of interest	Simulation study code	Parameter value
A-trains			
A-dolly	Baseline vehicle, twin 18' van trailer, 5-axle A-train	AT	Baseline parameter set $x_{IC} = 0$
Shifted IC dollies	Pintle hitch mechanism causes the instate center of yaw rotation of the dolly and the first trailer to shift away from the hitch point. The parameter variation of interest is the longitudinal position of this instant center of rotation (IC) in the first trailer coordinate system, xIC.	IC1 IC2 IC3 IC4	$x_{IC} = 0$ $x_{IC} = 62$ $x_{IC} = 124$ inches $x_{IC} = 200$ inches
Forced-steer dollies	Steering linkage provided which causes the tires of the dolly to steer as a direct result of yaw articulation at the pintle. The parameter variation of interest is the steering system gain, $G_{\delta 4\Gamma 2}$.	FS1 FS2 FS3 FS4	$G_{\delta 4\Gamma 2} = 0.75$ $G_{\delta 4\Gamma 2} = 1.50$ $G_{\delta 4\Gamma 2} = 2.25$ $G_{\delta 4\Gamma 2} = 3.00$
Linked-articulation dollies	A linkage is added to the basic A-dolly which causes a fixed relationship to be established between the yaw articulation angle at the pintle and the yaw articulation at the dolly fifth wheel. The parameter variation of interest is the gain of the articulation angle relationship, $G_{\Gamma 2\Gamma 3}$.	LA1 LA2 LA3 LA4	$G_{\Gamma 2\Gamma 3} = 0.6$ $G_{\Gamma 2\Gamma 3} = 1.3$ $G_{\Gamma 2\Gamma 3} = 2.0$ $G_{\Gamma 2\Gamma 3} = 2.6$
Roll stiffened pintle hitches	The standard A-dolly is equipped with a pintle hitch providing roll coupling between the dolly and first trailer. The parameter variation of interest is the level of roll stiffness across the hitch, K_{2xx}.	RR RC1 RC2 RC3	$K_{2xx} = 106$ in-lb/deg (Roll rigid) $K_{2xx} = 60{,}000$ in-lb/fdeg $K_{2xx} = 30{,}000$ in-lb/deg $K_{2xx} = 15{,}000$ in-lb/deg
B-trains			
B-train	A tractor-semitrailer-semitrailer doubles with no separate dolly and with conventional fifth wheel couplings between units. Virtually equivalent to a non-steering B-dolly with rigid roll coupling.	BT	$K_{2xx} = \infty$
Steering axle B-dolly	As above, but the tires of the dolly axle are allowed to steer by caster. A steer centering-spring mechanism is included. The steering resistance of the centering mechanism must be overcome for steering to occur.	SA1 SA2 SA3	Reference steering resistance. 1/2 of reference steering resistance. No steering resistance.

response of the tractor-semitrailer and of the full trailer of the doubles tends to be substantially out of phase. Therefore, coupling the two units together in roll tends to reduce the maximum roll of each. As a result, the extent of cornering stiffness reduction is also reduced. Fancher (11,13,14,16) and Ervin (17) have both shown that the reduction of cornering stiffness of the tires of a double generally tends to increase rearward amplification.

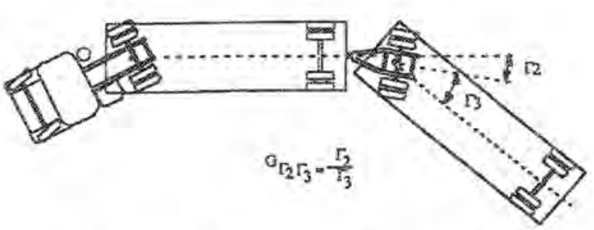
- *The Linked-Articulation Dollies* (Figure 11.d): In addition to the four linked-articulation (LA) dollies of varying linkage gain, and the reference A-train, the performance of both the B2 dolly (a non-steering B-dolly with no roll coupling) and the skid-steer dolly (SS) are included in this figure. This is done since it has been observed that the B2 dolly is conceptually the equal of the linked-articulation dolly with an articulation gain of zero ($G_{\Gamma 2\Gamma 3} = 0$), and the skid-steer dolly is conceptually the equal of the linked-articulation dolly with an infinite gain ($G_{\Gamma 2\Gamma 3} = \infty$). In general, the data show that removing a yaw degree of freedom at the dolly, either at the drawbar (B2), at the fifth wheel (SS), or "in between" (LA), aids in reducing rearward amplification. Judged by rearward amplification alone, the reduction of yaw articulation at the drawbar is preferable (and, as will be seen, other performance measures strongly support this choice). Linked articulation gains in the vicinity of unity and less achieve nearly the level of improved performance as can be attained by elimination of pintle yaw articulation.



a. The shifted IC dollies



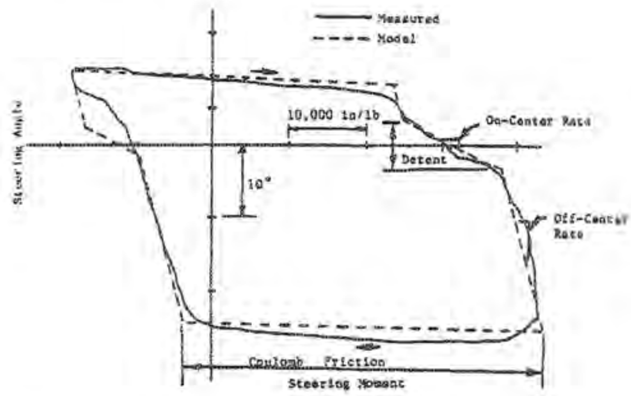
b. The forced steer dollies



c. The linked articulation dolly

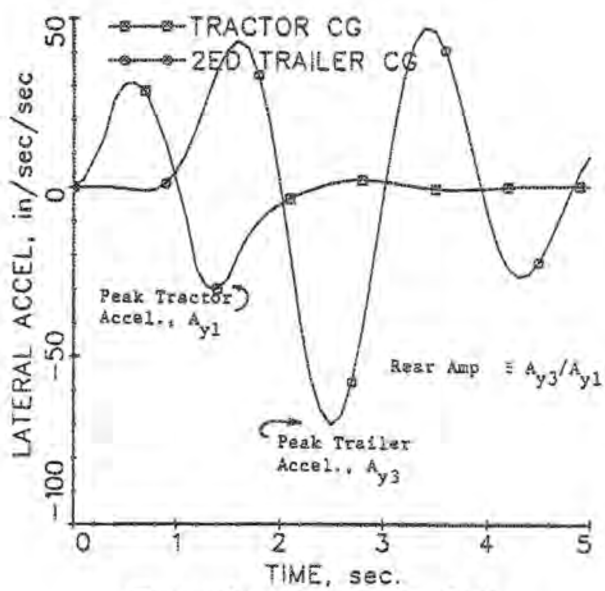
Characteristic parameters of three types of screening study dollies

FIGURE 8



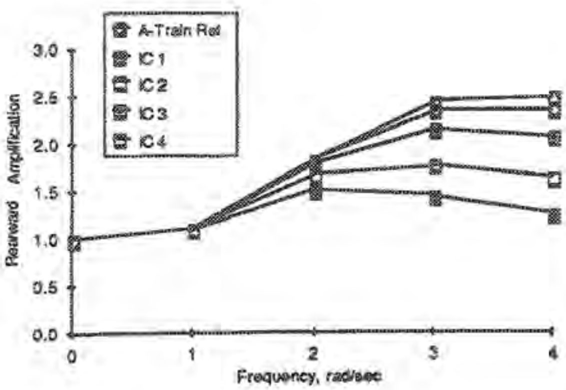
Steering resistance of the reference self-steering axle

FIGURE 9

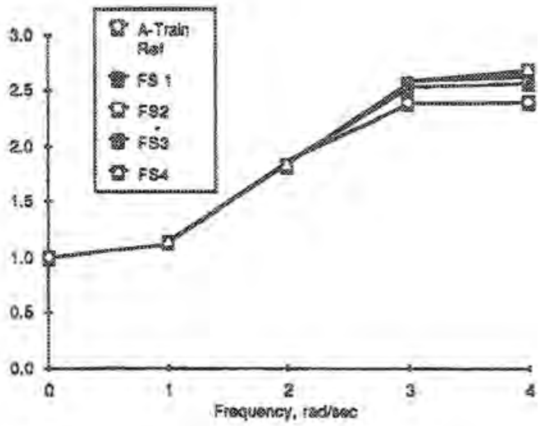


Example acceleration data from a lane-change maneuver

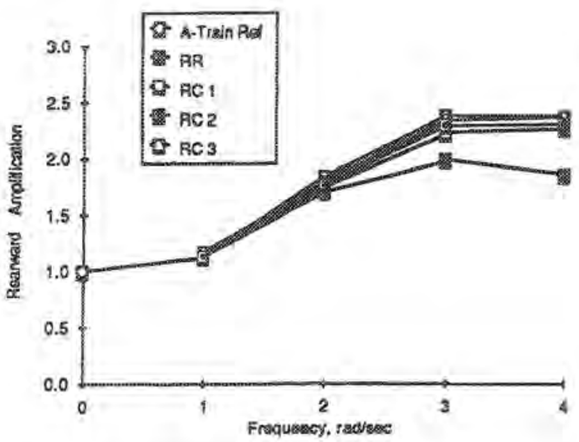
FIGURE 10



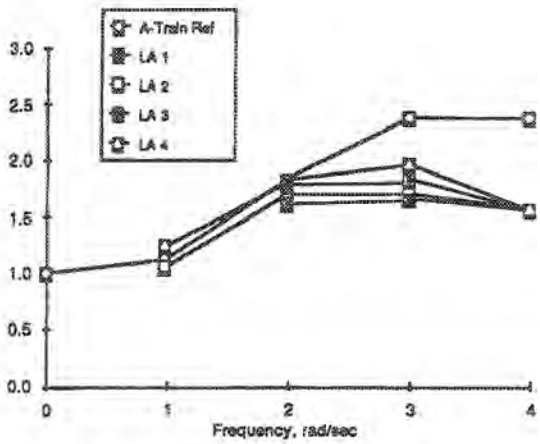
a. The Shifted IC Dollies



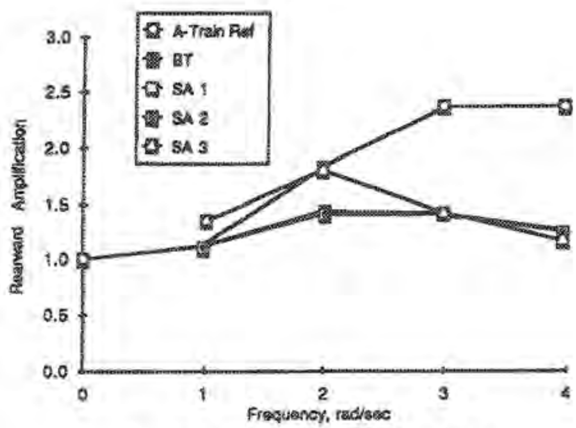
b. The Forced-Steer Dollies



c. The Roll-Stiffened Pintle Hitches



d. The Linked Articulation Dollies



e. The Self-Steering B-Dollies.

Rearward amplication in the frequency domain at 55 mph

FIGURE 11

- *The Steerable-Axle B-Dollies* (Figure 11 e): As was the case with the skid-steer dollies, the highly nonlinear quality of the steering-resistance feature of the SA1 and SA2 dollies means that the results shown are in part, dependent on the amplitude of the maneuver, and may vary for more severe maneuvers. At the low levels experienced here, virtually no self-steering action occurred on either the SA1 or SA2 vehicles, so that their performance is virtually identical to the B-train. When the B-dolly axle has no resistance to steer (SA2), rearward amplification in the 2 rad/sec range degrades to that of the A-train, but remains low at higher frequencies. Like the K2 vehicle, however, it will be seen that other performance measures of the B-dolly vehicle can be seriously degraded when steering resistance of the self-steering axle is very low.

The Steer-Point Concept

Before proceeding with other specific findings of the screening study, an explanation of a finding of a more general nature, viz., the concept of the "steer-point" of the full trailer, will be presented. The impetus for developing this concept derived from the somewhat surprising rearward amplification performance of the forced-steer dollies, as noted above.

Fancher (11,13,14,16) and others have noted that trailing elements of the multi-trailer train may be mathematically decoupled from the lead elements at the single-drawbar hitch point. In physical terms, this mathematical decoupling is equivalent to the fact that lateral forces at the drawbar hitch point are so small as to be insignificant with regard to motivating lateral or yaw motions of either elements. Rather, hitch forces provide only the power necessary to steer the front axle tires of the trailer; the trailer tires (front and rear), in turn, provide the lateral forces that actually motivate trailer lateral or yaw motions. As noted earlier, Fancher has also shown that the location of the hitch point in the towing vehicle is very significant to rearward amplification.

Adding the simple observation that, for a conventional A-train and trailer, the "steering geometry" is such that the front axle of the trailer is always steered to point toward the hitch point, suggests that the significance of hitch point geometry in the lead unit is not actually associated with the location of the "hitch" point, but with the location of the "steering" point. If, indeed, the significance of the hitch point is its "steering" function rather than its "hitching" function, it follows that a similar affect on rearward amplification should be obtainable by other mechanisms which steer the full trailer front axle such that it points toward a "steer point" located forward in the towing trailer.

The model of Figure 12 can be used to illustrate that a mechanism which steers the tires of the dolly axle as a linear function of the yaw articulation angle at the drawbar hitch point can provide either a forward or rearward shift of the dolly axle "steer point" away from the drawbar hitch point. That is, if H marks the towbar hitch point and S marks the dolly "steer point," the dolly axle steering gain of:

$$G = \delta_4/\Gamma_2 = a/b \qquad (1)$$

can be shown, assuming small angles, to result in:

$$x_S = x_H + G\ /\ (1 + G)\ L \qquad (2)$$

From Equation (2):

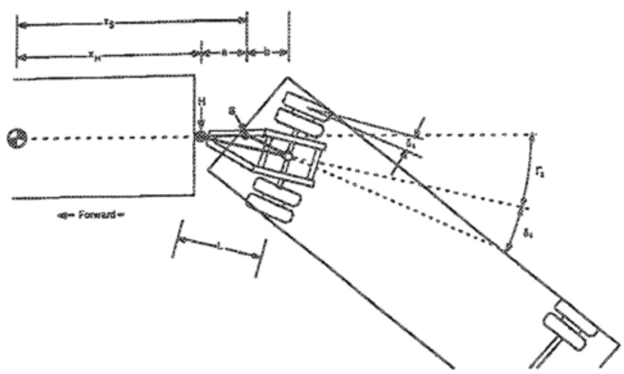
if	$G < -1$	then	$x_S > x_H + L$	(3a)
if	$G = -1$	then	$x_S = \pm\infty$	(3b)
if	$-1 < G < 0$	then	$x_S < x_H$	(3c)
if	$G = 0$	then	$x_S = x_H$	(3d)
if	$G > 0$	then	$x_S > x_H$	(3e)
if	$G \to \infty$	then	$x_S \to x_H + L$	(3f)

Figure 13 presents simulation results that support the premise that it is the steer point, rather than the hitch point, or even the instant centre of rotation of the dolly in the towing vehicle, that is the truly significant factor of A-dolly design influencing vehicle performance. The data presented in this figure derive from the performance of twelve test vehicles, viz., the reference A-train (AT), the four shifted-IC and the four forced-steer (FS) vehicles, and three additional special (SP) vehicles. The SP1 vehicle has both shifted-IC and forced-steer properties combined in one dolly. The SP2 and SP3 vehicles have IC's in the normal position, but use a negative steering gain to produce a forward steer-point position. The figure shows that the rearward amplification and the low-speed offtracking of these twelve vehicles are a linear function of steer-point location, regardless of the specific mechanical mechanism which establishes the steer point.

Equations (3e) and (3f) provide the explanation for the performance of the forced-steer dollies as presented in Figure 11 b. Each of the forced-steer dollies shows rearward amplifications greater than the reference A-train, because each has a positive steering gain producing a steer point aft of the hitch point (3e). The increase in rearward amplification is limited as steering gain increases because, as equation (3f) shows, the limit position of the steer point is the position of the dolly axle centerline.

These findings suggested that the study of the IC dollies and the FS dollies was redundant. Therefore, three of the FS dollies were discarded, and only the FS4 dolly was retained (since it provides the most rearward steer point of the original set) for study along with the IC dollies.

Dynamic Roll Stability Limit
The second portion of the screening study examined the dynamic roll stability limit of the study vehicles in the emergency lane-change maneuver.



Schematic diagram illustrating the location of the steer point for forced steer dollies

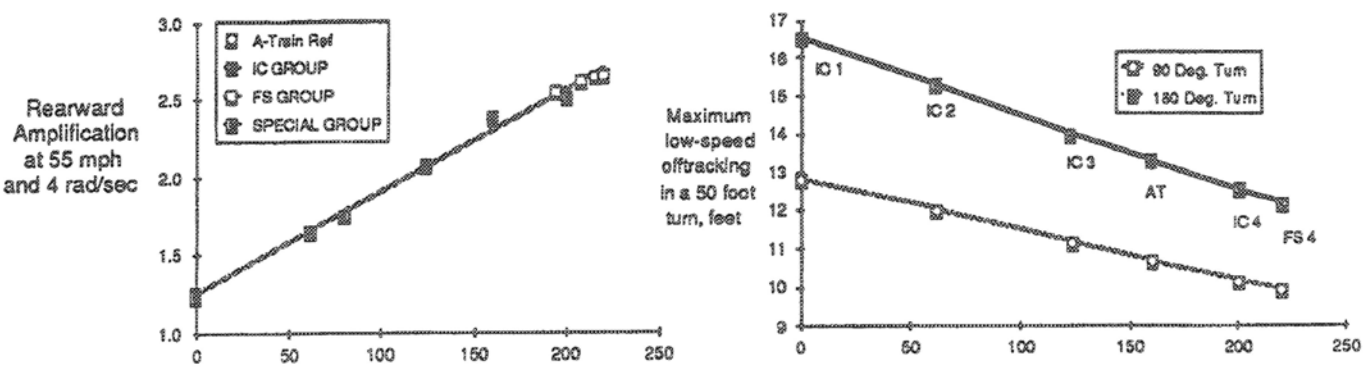
FIGURE 12

With each dolly, the test vehicle was subjected to an iterative series of severe lane-change maneuvers, until the rollover limit of the vehicle (second trailer) was determined to within 0.015 g of peak tractor lateral acceleration. This exercise was conducted at only one frequency of lane change for each dolly. The frequency used for each dolly was the one at which that dolly had displayed its greatest rearward amplification. Unfortunately, it became clear later that the roll response of the second trailer, per se, was more sensitive to excitations in the 2 rad/sec frequency range. Thus, in interpreting the following results, vehicles tested at 3 and 4 rad/sec should be "derated" relative to those tested at 2 rad/sec. Further, it should be remembered that the fidelity of the measure for each vehicle is in the vicinity of 0.015 g.

Regarding the dynamic rollover threshold of the study vehicles, Figure 14 indicates:

- *The Shifted-Steer-Point Dollies* (Figure 14a): Accounting for the differences in test frequency, the relative roll stability of these vehicles is as would be expected from our understanding of steer point and its influence on rearward amplification. That is, the vehicle with the most forward steer point has the highest dynamic rollover threshold, and rollover threshold declines as the steer point moves aft.

- *The Roll-Stiffened Pintle Group* (Figure 14b): These data clearly show the advantage of roll coupling between trailers in dynamic maneuvering. Although roll coupling had only a modest influence on rearward amplification,

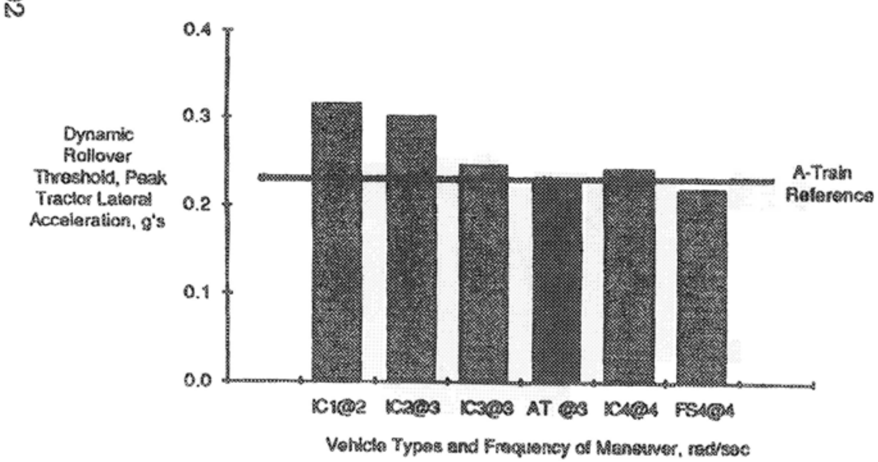


a. Rearward Amplification

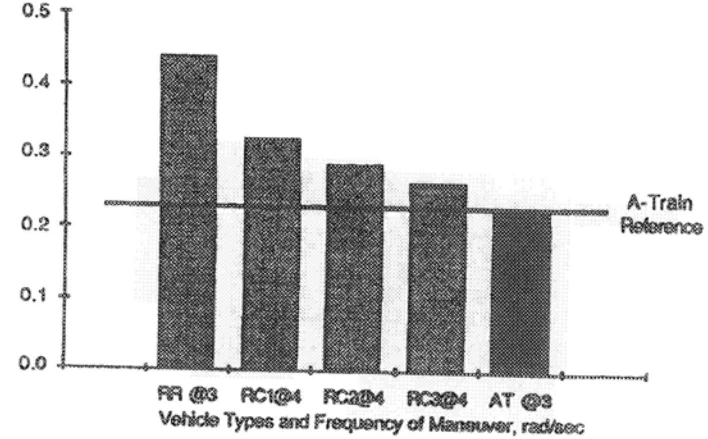
b. Low-Speed Offtracking

Performance as a function of steer point position

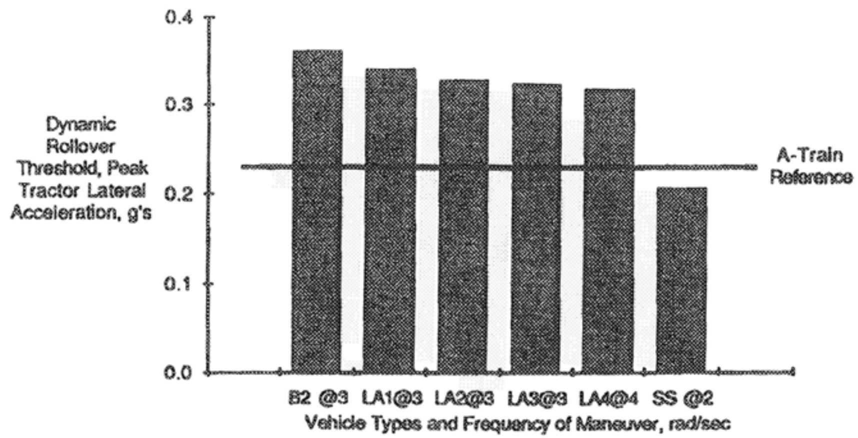
FIGURE 13



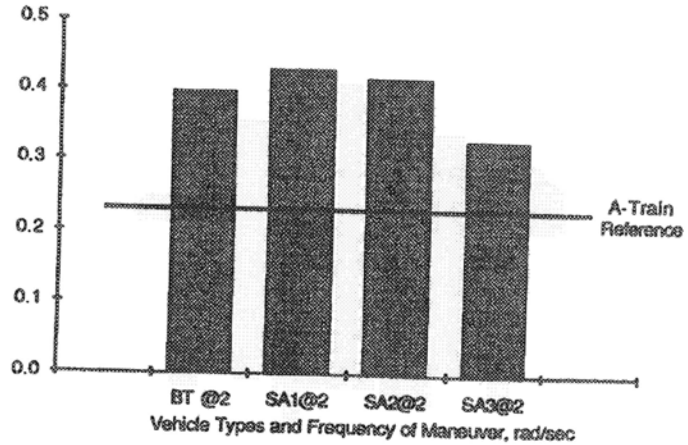
a. The Shifted Steer Point Dollies



b. The Roll Stiffened Pintle Hitches



c. The Linked Articulation Dollies.



d. The Self-Steering B-dollies

Dynamic rollover threshold in an emergency lane change

FIGURE 14

it can significantly raise the rollover limit by directly improving roll stability. The A-train with a roll-rigid hitch was actually the most stable vehicle in roll which was simulated. Unfortunately, an A-dolly hitch/frame which is even as rigid as that of RC1 is probably not practically attainable.

- *The Linked-Articulation Dollies* (Figure 14c): (The B2 and SS are included, since they represent the "limit" cases of linked articulation.) Except for the SS dolly, the relative rollover threshold of these vehicles can be seen to derive directly from the rearward amplification results. The B2 and the LA1 dollies show the highest rollover threshold of all dollies without trailer-to-trailer roll coupling. The skid-steer dolly suffers somewhat from the 2 rad/sec test frequency, but also from the fact that yaw motions of the second trailer are very lightly damped for this type of vehicle.

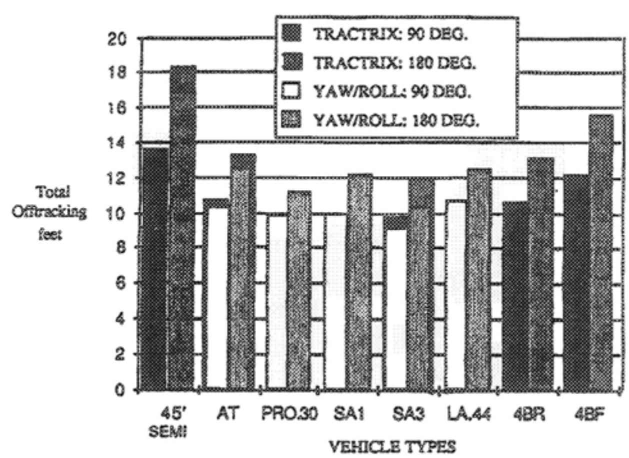
- *The Steerable-Axle B-Dollies* (Figure 14d): The rollover threshold of the steerable-axle B-dollies improves as steering resistance increases. The slightly poorer performance of the B-train (with non-steering axle) is surprising. However, note that the thresholds of the BT, SA1, and SA2 vehicles are all virtually within the fidelity of the measure. The only other ready explanation is that the B-train used a slightly different axle layout than the other configurations.

Low-Speed Offtracking

The screening study also examined the low-speed offtracking performance of the study vehicles. The obvious advantage of the doubles configuration (over a single-trailer vehicle providing equal cargo-carrying capacity) is the improved low-speed offtracking performance which allows such a long vehicle to be practical. Although the main goal of this study was to determine methods of improving dynamic performance of the double, attaining that goal should not be allowed to seriously degrade this performance advantage of the double.

The low-speed offtracking performance was examined in 90- and 180-degree turns of 50-foot radii. The maximum offtracking between the first and last axle of the train in turns of these types was determined. To be cost effective, a simplified Tractrix offtracking model was used when appropriate. However, it was necessary to use the Yaw/Roll model for any dolly configuration which might produce tire "scuffing" in a low-speed maneuver. The Tractrix model predicts the offtracking performance that would result at very low speed; i.e., it assumes zero lateral acceleration. The Yaw/Roll model, however, does not make this simplifying assumption. Runs using Yaw/Roll were conducted at 10 ft/sec forward velocity (0.06 g lateral acceleration in a 50-ft radius turn). The influence of this speed produces discrepancies between the predictions of the simple model and the Yaw/Roll model. The reference A-train (AT) vehicle and the SA3 vehicle were simulated with both models to provide a comparison of the models.

Figure 15 summarizes the results of the offtracking runs. The shifted-steer-point vehicles (IC's and FS4) show, as expected, that offtracking degrades as the steer point moves forward and improves as it moves rearward. The linked-articulation vehicles show some improvement in offtracking relative to the A-train, except for LA4 in the 180-degree turn. We note here that the 180-degree turn is a "better" measure of steady-state offtracking, while the 90-degree turn is influenced more by the spatial lag characteristic of transient offtracking performance (14,16,19). The suggestion is that the steady-state performance of LA4 is poor, but that the linked-articulation character "stretches out" the transient performance so that the vehicle is not penalized in the shorter turn. As expected, the B-train (BT) offtracks slightly more than the A-train. The vehicles with the self-steering B-dollies (SA's) show slightly improved offtracking, with that improvement increasing as the steer resistance of the self-steering axle decreases.



Maximum low-speed offtracking in 50 foot radius turns

FIGURE 15

THE IN-DEPTH STUDY

The objectives of this portion of the simulation study were (1) to provide a more complete performance analysis of the several specific dollies brought forward from the screening study, and (2) to provide an "optimum" parametric description of a dolly which could serve as a guide in the design of the prototype dolly to be constructed in this project. Actual samples of the dollies selected for the in-depth study would later be subjected to performance testing on the test track.

In the in-depth study, the investigation of rearward amplification was expanded to include the examination of influences of various vehicle loading conditions and changes in velocity. Variations in loading consisted of the four possible combinations of full and empty trailers (F/F, F/E, E/F, and E/E). The influence of velocity was examined in lane changes conducted at 25, 40, and 55 mi/hr. As in the screening study, the dynamic rollover threshold of the test vehicle in the fully loaded condition was determined, but this measure was taken for both 2 and 3 rad/sec lane-change maneuvers. The yaw damping performance was also examined using simulated "pulse-steer" maneuvers.

All of these simulation activities were conducted with three dolly types brought forward from the screening study, plus a "prototype" concept dolly developed within the study.

Commercial Dollies Selected from the Screening Study

Three "commercial" dollies were selected from the screening study vehicles for further study. Selections were made on the basis of (1) predicted performance quality as indicated by the screening study, (2) a reasonable expectation for obtaining or fabricating a working example, and (3) background theoretical and practical knowledge of the field.

The dollies selected were (1) the (ASTL) auto-steer-style, self-steering B-dolly, (2) the (Truck Safety Systems) linked-articulation dolly, and (3) the (Trapezoid Corp.) asymmetric trapezoidal-drawbar dolly.

The results of the screening study clearly indicated that the selection of a B-dolly for further study was in order. Again, since only one set of steering resistance data was available, it was used as the reference. (This dolly continued to be designated as SA1.) Some runs were also conducted with low steering resistance (SA3). In the screening study, the steerable-axle B-dollies had been simulated with infinite roll coupling stiffness. In the in-depth study, these dollies were simulated with a more realistic value of 30,000 in-lb/deg of roll coupling stiffness.

Of all of the modified A-dollies in the screening study, the linked-articulation style appeared to be among the more promising. The rearward amplification performance of this modified A-dolly approached that of the B-dollies. In contrast to the shifted-steer-point dollies, the low-speed offtracking performance of the linked-articulation dolly is not degraded as rearward amplification improves. The apparent drawbacks of this dolly were the lack of trailer-to-trailer roll coupling, and the practical problem of the "extra hardware" which could make coupling and uncoupling difficult, and restrict rear access to the first trailer cargo area.

The only examples of linked-articulation dollies known to exist in practice are in use in the Michigan petroleum tanker fleet, and it was determined that the linked-articulation hardware was no longer in production. It was felt that for the testing program to come later, hardware could be fabricated and adapted to the "Western Double" test vehicle. The articulation angle gain to be used in the in-depth study could be established by choice.

The articulation gain chosen was that which establishes, within the small angle approximation, "Ackerman" geometry between the axles of the dolly and the two trailers. The so-called Ackerman steering relationship is established when the projection, in the plan view, of all of the wheels in question intersect at a common point, which is the turn centre. Ackerman steering assures that, during low-speed turning, all tires track with no slip and no resulting side force. Tire scuffing and wear are minimized, as are structural loading on the steering system and frame. It is worth noting that at low speed, the A-dolly maintains Ackerman geometry through its natural tracking behaviour.

Ackerman geometry of the dolly and two trailers is illustrated in Figure 16. A system gain (G_{LA}) of 0.44 establishes Ackerman geometry given the dimensions of the "Western Double" used in the simulation study. In the in-depth study, this vehicle was designated as LA.44.

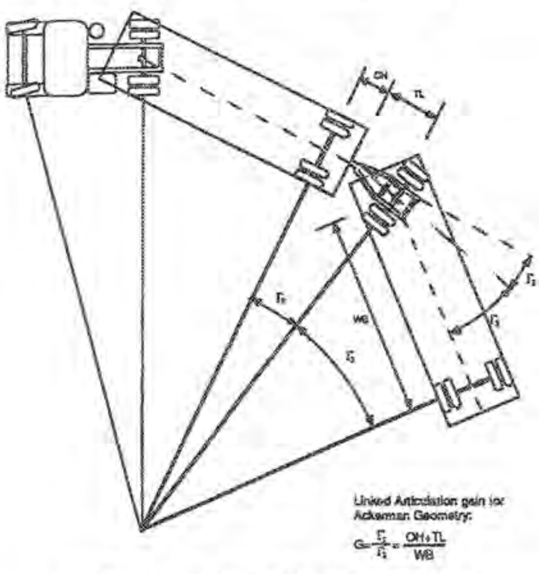
The asymmetric trapezoidal dolly was selected as the third commercial dolly. This design was seen as one which could take advantage of the good dynamic performance which results from dollies whose steer point is forward, and the good offtracking performance resulting from a rearward location of the steer point. The major shortcoming of this design is that it lacks trailer-to-trailer roll coupling. It has the advantage of simplicity, and it is probably inherently the lightest of all the dollies included in the in-depth study. The Trapezoid Corporation design allows for adjusting the geometry of the secondary towbar so that the IC may be forward for travel at highway speeds and rearward for low-speed maneuvering. Using the design parameters provided by Trapezoid, these conditions corresponded to values of 41 inches and 168 inches, respectively (reference Figure 12).

The Prototype Dolly, a Controlled-Steering B-Dolly

A new type of dolly, which became known as the "controlled-steering B-dolly" (CSB), evolved during the progress of the in-depth study and was subjected to the same investigations as the other subject dollies. This dolly represents an attempt to embody the attractive properties of both the B-dolly and linked-articulation dolly in one device.

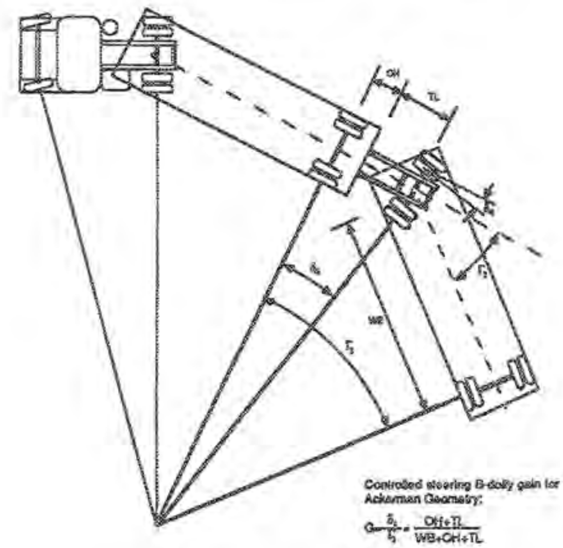
The rigid double-drawbar concept of the B-dolly is seen as extremely attractive, in that it (1) eliminates the yaw degree of freedom at the drawbar hitch point, and (2) provides strong trailer-to-trailer roll coupling. The first is the best-known method for improving rearward amplification, and the second is very powerful in providing dynamic roll stability. The biggest drawback of the double drawbar is the introduction of large hitch loads which result from the new yaw and roll constraints, and the related tire scuffing and wear problems that result from the yaw constraint. To relieve the yaw-related problems somewhat, the self-steering axle has been applied to the B-dolly. In general terms, the theory of operation of the steerable-axle B-dolly is that resistance to steering should be sufficiently high that, at highway speeds, little or no steering takes place, thus assuring good dynamic performance, but, at the same time, steering should be sufficiently free as to significantly mitigate tire scuffing and frame stress problems that would otherwise occur, particularly in low-speed, tight-turning maneuvers. In practice, this compromise can be difficult to attain.

On the other hand, it was observed that the linked-articulation dolly concept (1) eliminated a yaw degree of freedom at the dolly in a manner which resulted in improved rearward amplification, but (2) retained positive control of the yaw angle orientation ("steer") of the dolly tires. As explained above, the establishment of Ackerman "steer" geometry in a linked-articulation dolly results in dynamic performance in the yaw plane which is comparable with that of fixed-axle B-dollies, while minimizing hitch loads, frame stressing, and tire scuffing during low-speed maneuvering.



Ackerman steering geometry: the linked articulation dolly

FIGURE 16



Ackerman steering geometry: the controlled steering B-dolly

FIGURE 17

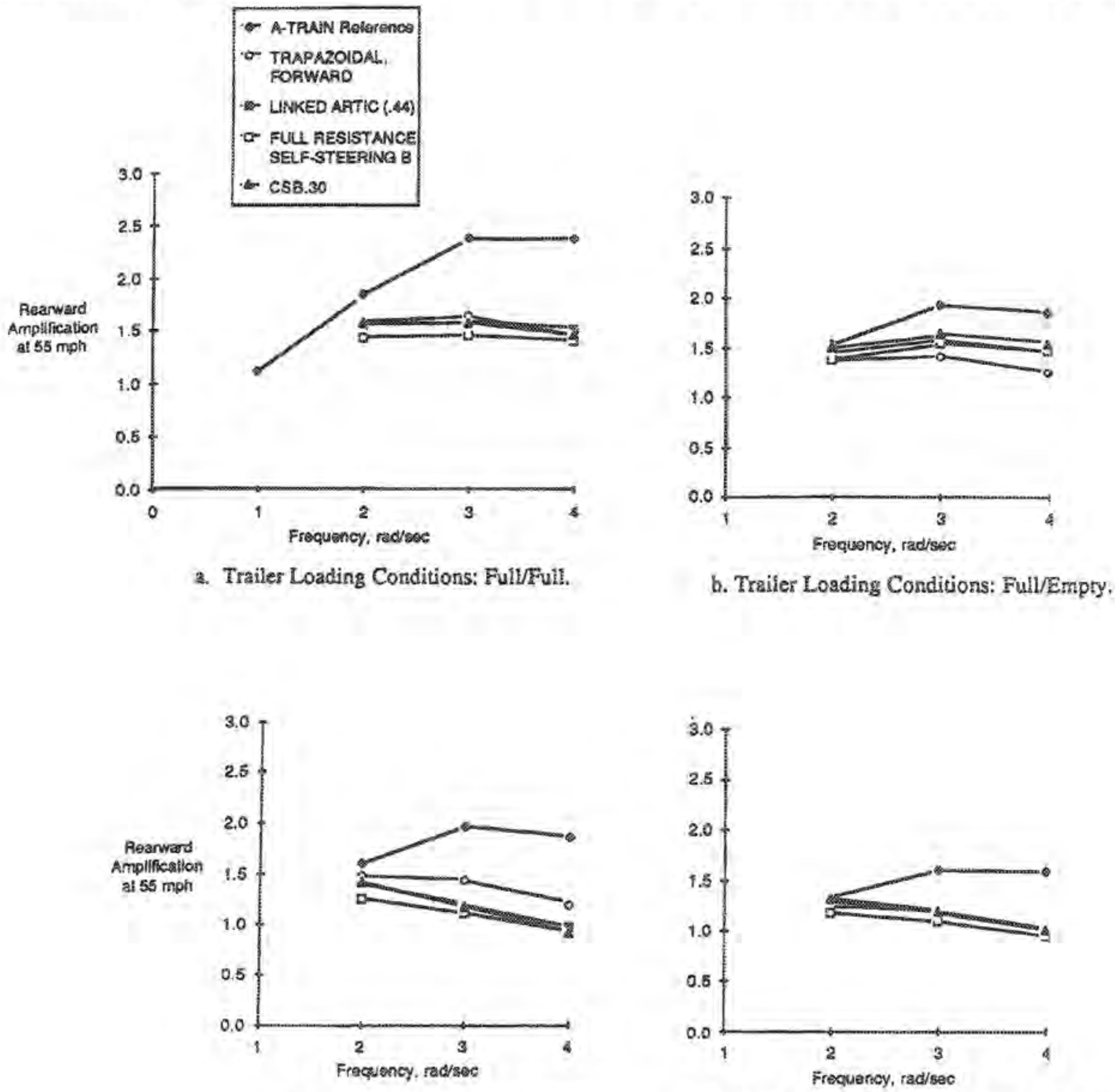
The goal in developing the prototype was to combine the attractive elements of these two approaches into one concept. The result is the controlled-steering B-dolly (CSB-dolly). In this concept, the dolly is a double, rigid drawbar style which eliminates the yaw degree of freedom at the drawbar hitch and provides trailer-to-trailer coupling in roll. The tires of the dolly steer relative to the dolly frame in a controlled manner as a function of the yaw articulation angle between the dolly and the following trailer, i.e., the dolly fifth wheel articulation angle. As defined in Figure 17, the characteristic parameter of this dolly is the steering system gain ($G_{\delta 4 \Gamma 3}$). For small angles, Ackerman steering geometry results when:

$$G_{\delta 4 \Gamma 3} = \frac{\delta_4}{\Gamma_3} = \frac{OH + TL}{WB + OH + LT} \qquad (4)$$

For the geometry of the simulation test vehicle, $G_{\delta 4 \Gamma 3} = 0.3$ produces Ackerman steering. This is the steering gain used for the CSB-dolly in the in-depth study. The dolly is designated as CSB.30.

Rearward Amplification

Figure 18 shows the rearward amplification performance of the in-depth study vehicles in the four loading conditions. These data show that the four "improved" dolly types have remarkably similar performance. In the critical full/full loading condition, three of the dollies are virtually



a. Trailer Loading Conditions: Full/Full.

b. Trailer Loading Conditions: Full/Empty.

c. Trailer Loading Conditions: Empty/Full.

d. Trailer Loading Conditions: Empty/Empty.

Rearward amplification of the improved dollies under four loading conditions

FIGURE 18

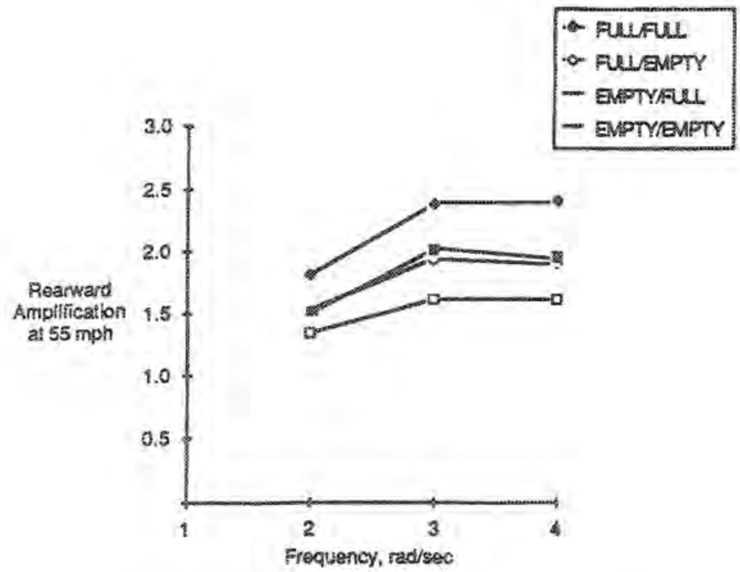
indistinguishable, while the full-resistance self-steering B-dolly is slightly better in this condition. The ranking of the dollies shifts in other loading conditions, but these four dollies remain very close in their rearward amplification performance. In general, removing load from either trailer tends to reduce rearward amplification.

Figure 19 shows the rearward amplification performance of the trapezoidal dolly and the self-steering B-dolly in their less favorable (for dynamic performance) states. The trapezoidal dolly shows the expected high levels of rearward amplification when the hitching linkage is arranged for the rearward IC position. With very low steering resistance, the B-dolly shows a wide range of response, depending on loading. In the empty/full condition, rearward amplification is very low. Rearward amplification of less than unity indicates that the second trailer is "under-responding" and not following the path of the tractor. Without the cornering power of the dolly tires, the lightly loaded tires of the first trailer are insufficient to guide both the rear of the first trailer and the front of the second trailer.

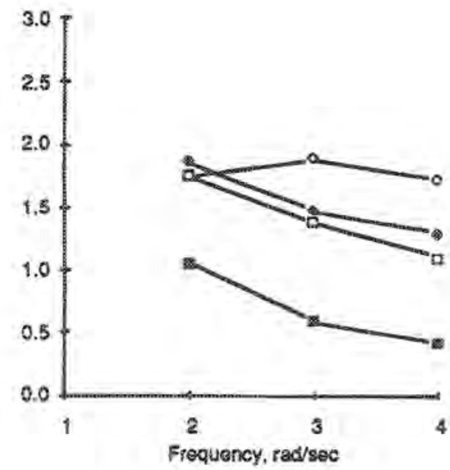
The results of simulation runs investigating the influence of forward velocity on the rearward amplification confirmed what is well established in the literature, viz., that rearward amplification is a strong function of speed and that it increases as speed increases. None of the "improved" dolly types violate this tenant. For each, the sensitivities of rearward amplification to speed were approximately linear and range from about 0.025 to 0.055 mph, depending on load, frequency, and the type of dolly.

Dynamic Rollover Threshold

The dynamic rollover threshold in the emergency lane-change maneuver of the four improved dolly types is shown in Figure 20 in comparison to that of the A-train. In this portion of the study, this measure was taken at maneuvering frequencies of both 2 and 3 rad/sec. The measure was taken only in the full/full loading condition. The figure indicates that each of the improved dolly styles provides significant improvement in rollover threshold relative to the A-train. The two B-dollies clearly benefit from trailer-t-trailer roll coupling, and the full-resistance B-dolly is the best performer in this regard. Each of the vehicles is more resistant to rollover at the higher frequency. At 3 rad/sec, both of the B-dolly-equipped vehicles were still successfully resisting rollover at tractor maneuvering levels of 0.45 g. This was judged to



a. The Trapazoidal Dolly, Rearward IC Position.



b. The Self-Steering B-dolly, Low Steering Resistance.

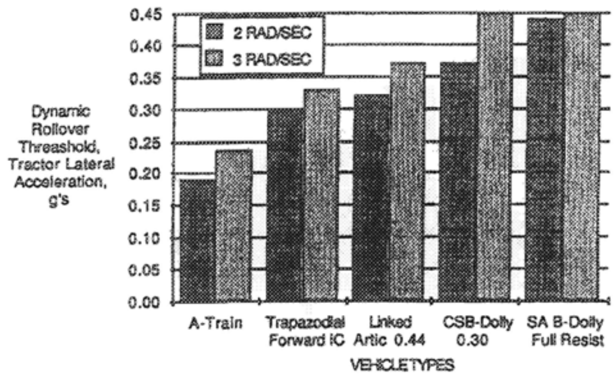
Less favorable rearward amplification performance

FIGURE 19

be a reasonable maximum limit, and the exercise was stopped without obtaining rollover of these vehicles at this frequency.

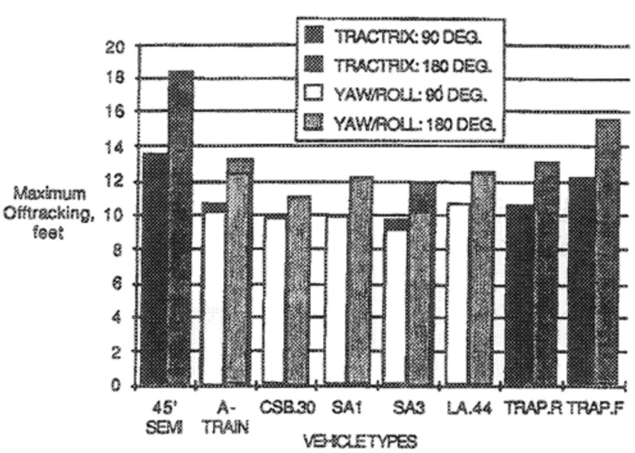
Low-Speed Offtracking

The low-speed offtracking performance of the test vehicle equipped with the selected dollies is shown in Figure 21. The performance of the A-train is shown as the usual reference, and the performance of the typical tractor-semitrailer with a 45-foot trailer is also shown. The test vehicle performance is comparable or slightly better with each of the selected dollies than it is with the A-dolly, except for the trapezoid dolly in its forward IC position state. All of the doubles exhibit better performance than the single-trailer vehicle, pointing out the advantage of the double configuration in this area.



Dynamic rollover threshold of the improved dollies

FIGURE 20



Low speed offtracking performance of the selected dollies

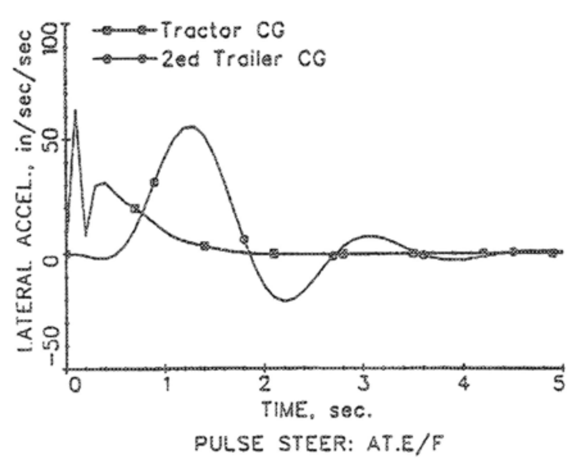
FIGURE 21

Yaw Damping Behaviour

Some configurations of multi-trailer vehicles may display very lightly, or even negatively, damped (unstable) dynamic modes of motion. The eigenvector of these modes is usually dominated by yaw motions of the last trailer so that, in practice, these modes are revealed as seemingly unprovoked "wagging" of the last trailer during normal running. One fatal accident of a doubles using a steerable-axle B-dolly, which occurred in Saskatchewan, is strongly suspected of being caused by a similar phenomenon.

Simulation runs of a so-called "pulse-steer" maneuver were used to evaluate the influence of the dolly on yaw damping quality. The steering pulse consisted of 2 degrees of (roadwheel) steer for 0.2 sec duration. Figure 22 shows the lateral acceleration response of the tractor and second trailer of the A-train in such a maneuver. The tractor shows a sharp response to the pulse which generally excites the system. The oscillatory response of the second trailer then decays quickly, showing that the system is fairly well damped. The effective damping of the second-trailer lateral acceleration response was determined from response data of this form using the logarithmic decrement technique.

Loading is known to be influential to multi-trailer vehicle damping (6,7,9), so this investigation included the four loading conditions. Further, a general understanding of vehicle dynamics suggests that, for B-dollies, steering properties and drawbar length of the dolly should also be very influential. The influence of these properties was investigated.



Lateral acceleration response to a steering pulse: A-train

FIGURE 22

Table 3 shows the calculated damping ratios for all of the runs conducted on the A-train and improved dollies. The test vehicles all displayed good damping properties with all of these dolly types in all the loading conditions tested. (As a point of reference in interpreting the values of Tables 3 and 4, Klein and Szostak (20) have recommended minimum damping ratios of 0.15 for passenger cars towing trailers.) The trapezoidal dolly showed performance very near to the baseline A-train in both the forward and rearward IC conditions. Damping with the linked-articulation dolly, the self-steering B-dolly, and CSB-dolly was improved over the A-train.

Table 3 — The dampling ratio of the test vehicle in a 55 mph pulse-steer maneuver

Dolly type	Load condition	Damping ratio
A-Train reference	F/F	0.32
	E/F	0.31
Trapezoidal dolly, Forward IC position	F/F	0.37
	E/F	0.35
Trapezoidal dolly, rearward IC position	F/F	0.32
	E/F	0.31
Linked articulation dolly, 0.44 system gain	F/F	0.59
	F/E	0.72
	E/F	0.37
	E/E	0.50
Self-steering B-dolly,	F/F	0.68
	E/F	0.51
CSB-Dolly,	F/F	0.55
	F/E	0.74
	E/F	0.34
	E/E	0.45

As noted, it is to be expected that the level of steering resistance and the tongue length would have considerable influence on yaw damping performance of B-dolly equipped vehicles. To demonstrate this influence, pulse-steer runs were conducted using the self-steering B-dolly with very low steering resistance and with long-drawbar B-dollies (160 inches from pintle to dolly axle, rather than the baseline dimension of 80 inches). The long drawbar was applied to the self-steering B-dolly with both full and low levels of steering resistance and to the CSB-dolly. The damping ratios calculated for these vehicles appear in Table 4. These data show that, with the low-steering-resistance B-dolly, the fully loaded test vehicle is very lightly damped, and with load in the rear trailer only, the vehicle is unstable. Adding the long drawbar makes the performance of the vehicle still worse, so that it also becomes unstable in the full/full loading condition. Figure 23 shows an example of unstable response in a pulse-steer maneuver.

The data of Table 4 also reveal the influence of long-drawbar geometry on the performance of the CSB-dolly configuration. Applying the long drawbar to the CSB-dolly with a steering system gain of 0.30, reduces the damping coefficient from 0.55 to 0.48. However, to "accurately" apply the CSB-dolly concept to the longer drawbar configuration requires a change in the steering gain to accommodate the change in longitudinal axle geometry. The appropriate steering gain to maintain Ackerman steering for the long-drawbar condition is 0.43. With this change, the damping ratio reduces to 0.32. While the system remains reasonably well damped, it appears that increasing the length of the drawbar of the CSB-dolly tends to reduce yaw damping of the vehicle.

Table 4 — The influence of dolly drawbar length and steering properties on yaw damping ratio

Dolly type	Load condition	Steering property	Drawbar length, in.	Damping ratio
Self-steering B-Dolly	F/F	Full resistance	80	0.68
		Full resistance	160	0.65
		Low resistance	80	0.11
		Low resistance	160	-0.10*
	F/E	Low resistance	80	0.51
	E/F	Low resistance	80	-0.16*
	E/E	Low resistance	80	0.16
CSB-Dolly	F/F	$G_{\delta 4 \Gamma 3} = 0.30$	80	0.55
	F/F	$G_{\delta 4 \Gamma 3} = 0.30$	160	0.48
	F/F	$G_{\delta 4 \Gamma 3} = 0.43$	160	0.32

* Negative damping indicates an unstable system.

VEHICLE TESTING

A program of full-scale vehicle tests was conducted to confirm the findings of the simulation activity. The test vehicle used was a "Western Double" composed of UMTRI's two-axle, COE Ford tractor and two short-wheelbase trailers, on loan from the Fruehauf Corporation, to form the Western Double used in this project. (The trailers are each 26 feet in length, i.e., slightly shorter than those of the simulation program.) Each of the trailers was equipped with outriggers to prevent actual rollovers during testing. Each of the yaw articulation joints was equipped with chains to limit yaw articulation angle and prevent damage due to jackknifing. Most of the testing was conducted with the trailers in the fully loaded condition. Loading was such that (1) GVW ≈ 80,000 lbs, (2) tractor front-axle load was approximately 10,000 lbs and all other axle loads were approximately 17,500 lbs, and (3) the composite sprung mass c.g. height of each trailer was approximately 80 inches. All axles of the test vehicle, including all dollies, were equipped with Michelin 10.00R20 G, steel-belted radial tires.

Five types of dolly/hitch hardware were included in the test program, viz.:

(1) The conventional A-dolly (AT)

(2) An asymmetric trapezoidal hitch dolly (TRAP.F and TRAP.R)

(3) A "linked-articulation" dolly (LA.8)

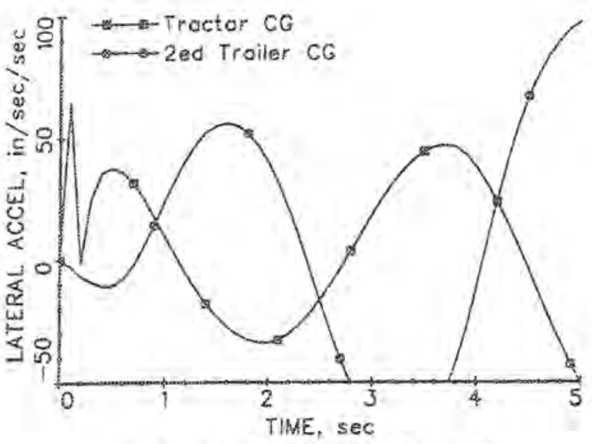
(4) A steerable axle B-dolly (SA.60 and SA.0)

(5) The prototype, Controlled Steering B-dolly (CSB.30)

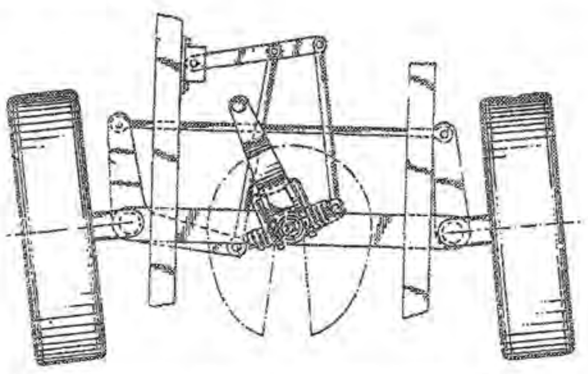
The parenthetical notation will be used to reference these dollies.

The Trap-dolly is a prototype dolly manufactured by Trapezoid Corporation of Cedar Rapids, Iowa, and is the invention of Mr. N. Gallatin. Although the four-bar hitch concept is the best known of the non-conventional concepts to be tested, this was the only version identified which was currently intended for the marketplace. The double-drawbar, trapezoidal-hitch design is of the asymmetric style. Two hitching configurations were tested, viz., the "forward IC" (TRAP.F) and "rearward IC" (TRAP.R) positions. These provided IC positions which were 198 and 71 inches ahead of the dolly axle, respectively. (A hoped for automatic device for switching the hitch configuration based on speed of the vehicle was not available for the test program.)

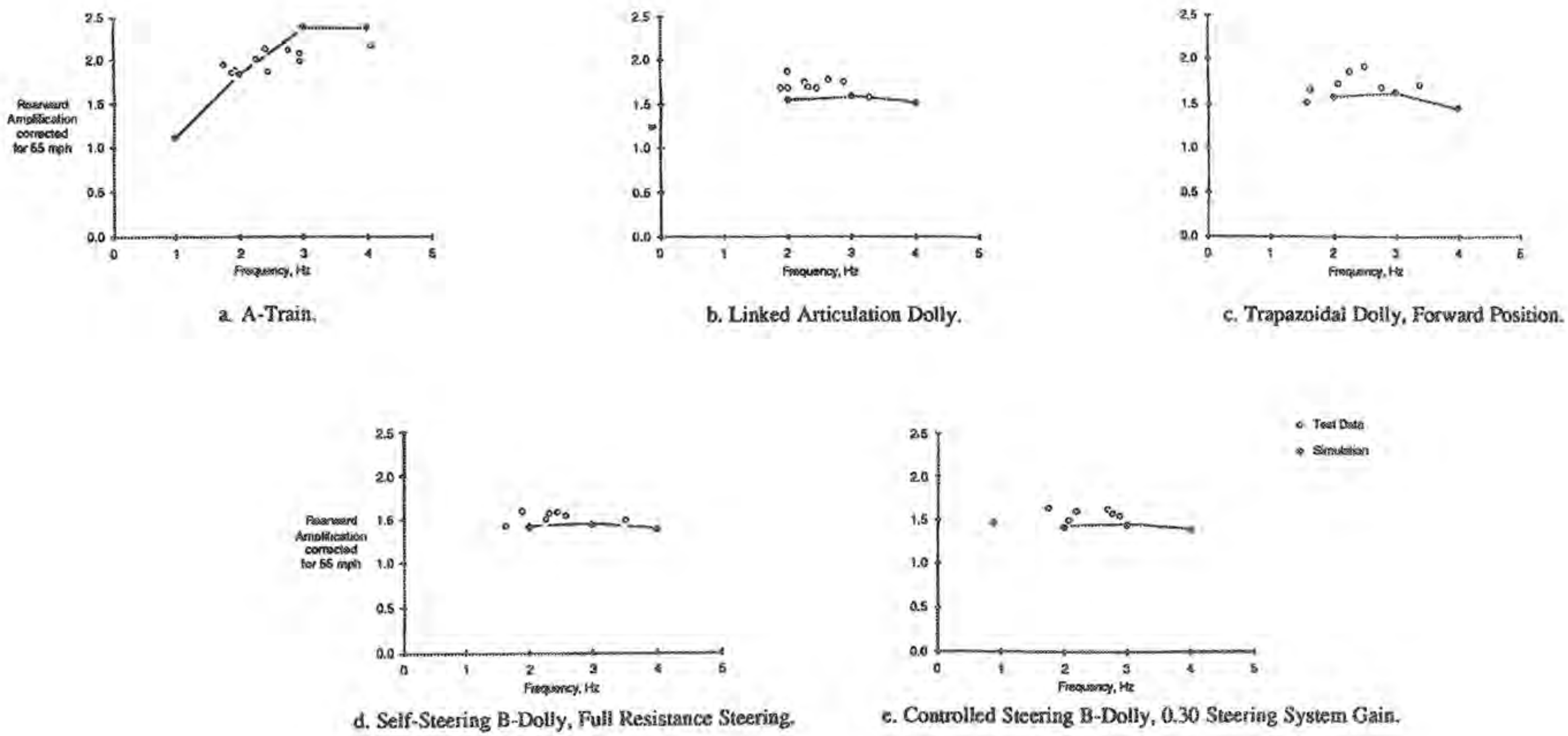
The LA-dolly hardware tested was an adaptation of commercially available hardware, fabricated by UMTRI. This hardware is patented and has been marketed for use on "Michigan double" tankers by Truck Safety Systems (TSS) of Tecumseh, Michigan. Adaptation to the 80-inch A-dolly and van trailers provided some difficulty. Although a system articulation gain of about 0.5 was desirable for "Ackerman steering," a gain of about 0.8 (LA.8) was actually used.



Lateral acceleration response to a steering pulse: self-steering B-dolly, low steering resistance, long drawbar
FIGURE 23



Schematic diagram of the CSB-dolly steering linkage
FIGURE 24



Comparison of rearward amplification performance measured in tests and simulations

FIGURE 25

that this self-steering B-dolly has sufficient steering system friction to retain well-damped responses in this low-level maneuver even with no air pressure supplied to the centering device.

OFFTRACKING

Low-speed offtracking was measured in experiments which mimicked the 50-foot radius turning maneuvers of the simulation study. The results are shown in Figure 27. These data are superimposed on the corresponding simulation study results. The absolute differences between simulation and experiment result largely from the shorter trailers used in the experiment. The relative performance qualities generally hold.

CONCLUSION

The results of the simulation study reported herein suggest that it is both reasonable and practical to develop commercial vehicle dollies which can significantly improve the dynamic performance of the multi-trailer combination vehicle. Four different innovative dolly designs have been shown to be capable of substantial improvements in rearward amplification and dynamic rollover threshold without degrading the desirable qualities of conventional multi-trailer vehicles. Full-scale vehicle testing has confirmed the findings of the simulation study.

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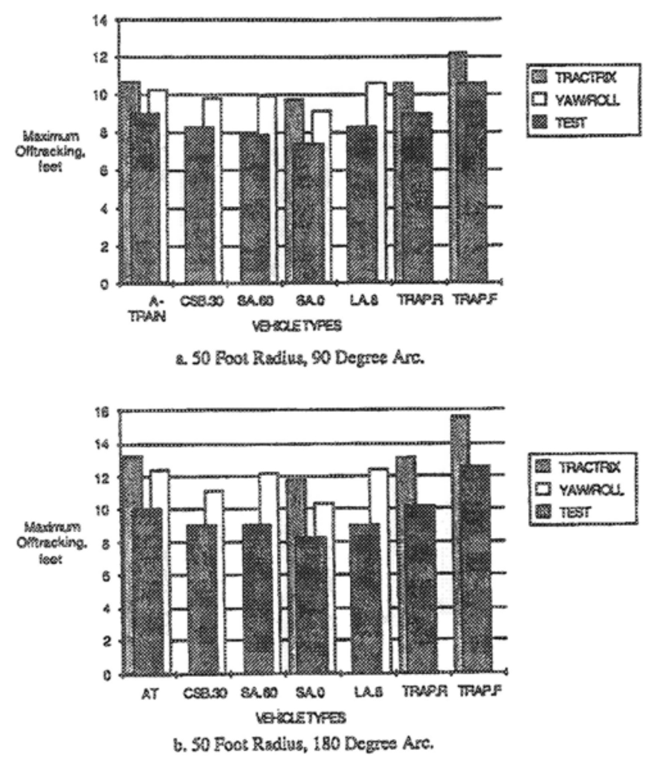
Table 5 — Damping ratio measured in vehicle tests

Test dolly type	Run number	Damping ratio
A-Dolly	56	0.206
A-Dolly	57	0.173
A-Dolly	58	0.334
LA.80	92	0.343
LA.80	93	0.256
LA.80	94	0.267
TRAP.R	169	0.134
TRAP.R	170	0.066
TRAP.F	198	0.150
TRAP.F	199	0.230
TRAP.F	200	0.258
SA.60	250	0.665
SA.60	251	0.464
SA.0	264	0.619
SA.0	265	0.392
CSB.30	323	0.536
CSB.30	324	0.435



a. 50 Foot Radius, 90 Degree Arc.

b. 50 Foot Radius, 180 Degree Arc.

Low-speed offtracking in fifty foot radius turns

FIGURE 27

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