



**THE HANDLING AND STABILITY OF
DOUBLES DURING EMERGENCY
STEERING MANUEVERS**

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A SPECIAL PROGRAM DEVELOPMENT REPORT

**TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
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I. INTRODUCTION - OBJECTIVES AND PROBLEM STATEMENT

Over the past four years the use of doubles has increased rapidly. The legalization of doubles on the Interstate highway system by the Surface Transportation Act of 1982 has generated a rapid increase in this extrapolation of the classic 18 wheeler, to the point that doubles now represent a significant part of the interstate truck commerce. Even though doubles have been used in the far west of the U.S. for more than 35 years, there are still some concerns about their handling and stability characteristics.¹ In the nine midwest states the increase in accidents which involve doubles is about 50 percent greater than the increase in double mileage.

Perhaps the most significant of these is the problem of "rearward amplification" of turning maneuvers. A potentially more severe situation is brought about when quick avoidance maneuvers are attempted. These maneuvers require a reverse steering input over a short time period by the driver and much higher lateral acceleration may be encountered on the last trailer than on the first. In the extreme condition the last trailer may even roll over in response to the "rearward amplification phenomenon." Rearward amplification is a well documented safety problem. Overturning of the rear trailer leads quickly to a complete loss of control of the entire rig. This overturning of the rear trailer may occur before a significant feeling of instability is transmitted to the driver. This is documented in a motion picture recently produced by the University of Michigan Transportation Research Institute.²

A common steering maneuver is a lane change, but this is probably not the most important from the viewpoint of vehicle stability, since most lane changes tend to take place over periods of time long enough that rearward amplification is not a severe problem.

The element of doubles that is most susceptible to modification to alleviate the problem of rearward amplification is the dolly connection between the first and second trailer units. There are a wide variety of dollies either in use or in the development stage, many of which have some significant advantage in reducing rearward amplification. Most of these can be classified within two generic types referred to as A-dollies or B-dollies. Many of these different dolly systems have been described in a recent report by Winkler.³ Figure 1 is from Winkler's report illustrating the primary difference between A-dollies and B-dollies. Simply stated, the A-dolly has a single point of connection resulting in a center of rotation about the rear of trailer 1. The hitch mechanism is most often a pintle hook. The B-dolly has two points of connection resulting in either no rotation or extremely limited rotation of the B-dolly with respect to trailer 1. As documented by Winkler using both full-scale testing procedures and computer simulations, B-dollies are in general much more successful in reducing rearward amplification than are A-dollies.

The purpose of the work described in this report was to conduct a series of tests on a particular B-dolly, referred to as Straight Train. This particular B-dolly will be referred to in

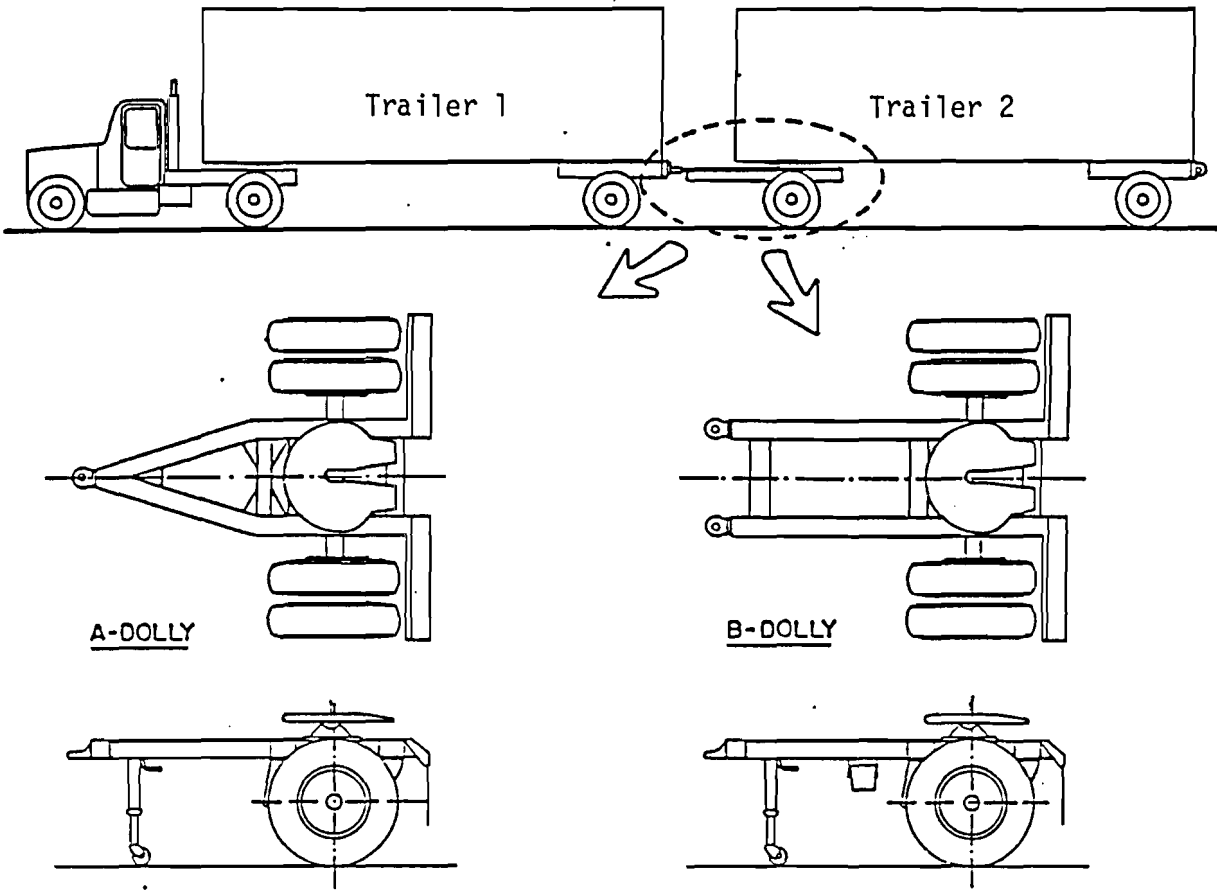
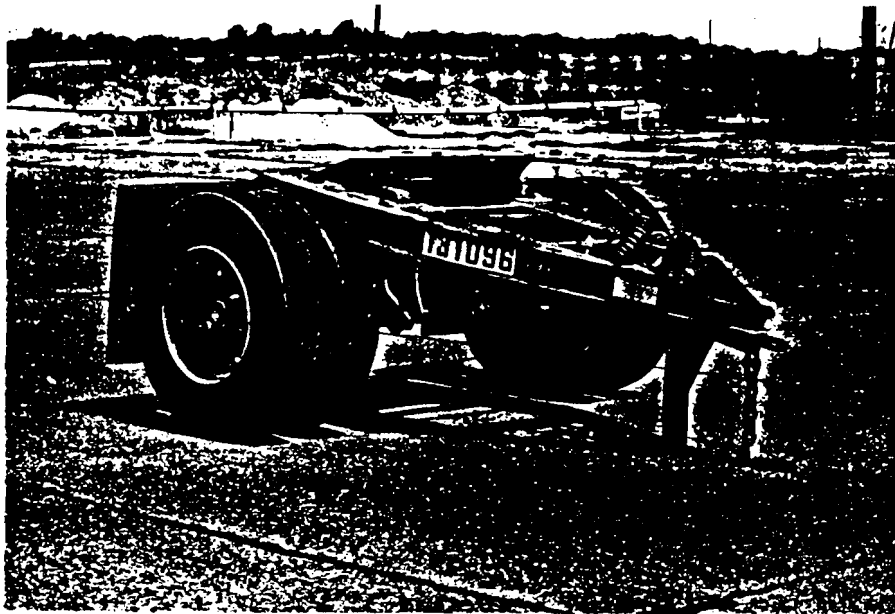


Figure 1. The A-dolly and B-dolly.
(After Winkler³)

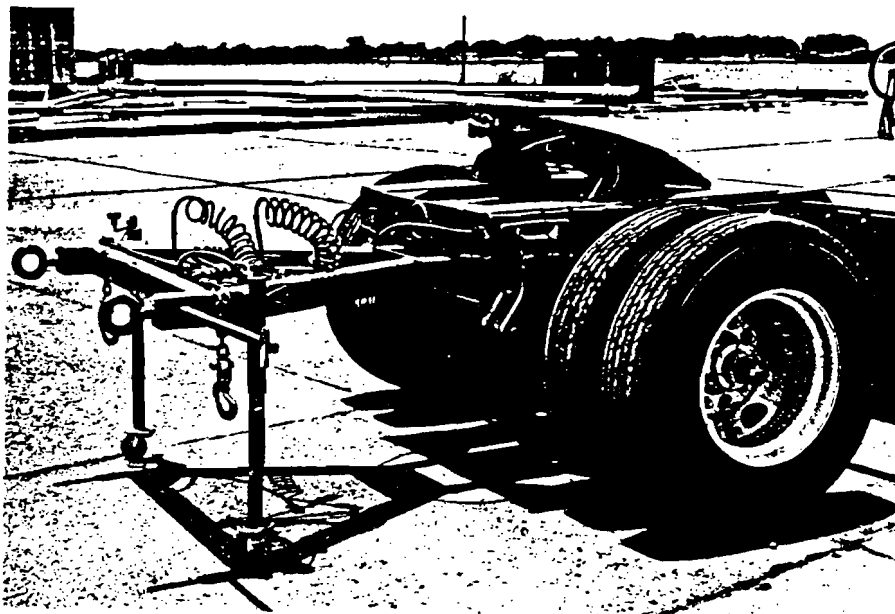
this report as ST-dolly. Examination prior to testing would indicate straight train has the advantages in reducing rearward amplification that would be expected of B-dollies as well as other advantages related primarily to the ease of attachment to trailer 1, and ease of coupling to trailer 2. These projected advantages include a unique way of attaching the straight train dolly to trailer 1, and the fact that the trailer 1, ST-dolly combination can be backed with approximately the same degree of ease as backing a conventional 18 wheeler, in order to engage and connect with the second trailer unit, trailer 2. A further advantage a ST-dolly appears to have over the conventional A-dolly is that the entire four segment doubles unit can be backed by a practiced driver with much greater ease than can a doubles unit which includes an A-dolly. In order to better describe the performance of ST-dollies in the three areas of interest, 1) reduction of rearward amplification or stable tracking, 2) hitching and 3) backing, a modern conventional A-dolly was also tested. The two dollies which were studied are illustrated by Figure 2.

In order to determine the characteristics of an ST-dolly with respect to tracking during highway maneuvers, three types of tests were run. The first was a simple lane change. Vehicle speeds covered a range from 30 to 45 mph and the lane change was fairly rapid, taking place in approximately 180 feet longitudinally.

The second maneuver was a quick avoidance maneuver requiring a sinusoidal steering input. This was produced by rotating the steering wheel approximately 90 degrees in one direction then rotating back 180 degrees in the opposite direction then rotating



A-Dolly



ST-Dolly

Figure 2. Test dollies.

back to center 90 degrees. This took place in periods from 2 to 6 seconds.

The final maneuver was to simulate a low speed exit ramp. The vehicle was driven through a 20 degree curve with a total change in direction of 90 degrees at speeds from 20 to 30 mph. In the areas of hitching convenience and backing, objective testing was not attempted but demonstrations were conducted to illustrate advantages which seem apparent on examination of the ST-dolly system.

B. TEST VEHICLE

1. C-Train

Full-scale testing of the ST-dolly, Figure 2, was conducted at the TTI Proving Ground with the C-train type vehicle shown in Figure 3.

a. Tractor

The tractor was a standard 1984 cab-over Mack Model MH612.

b. Trailers

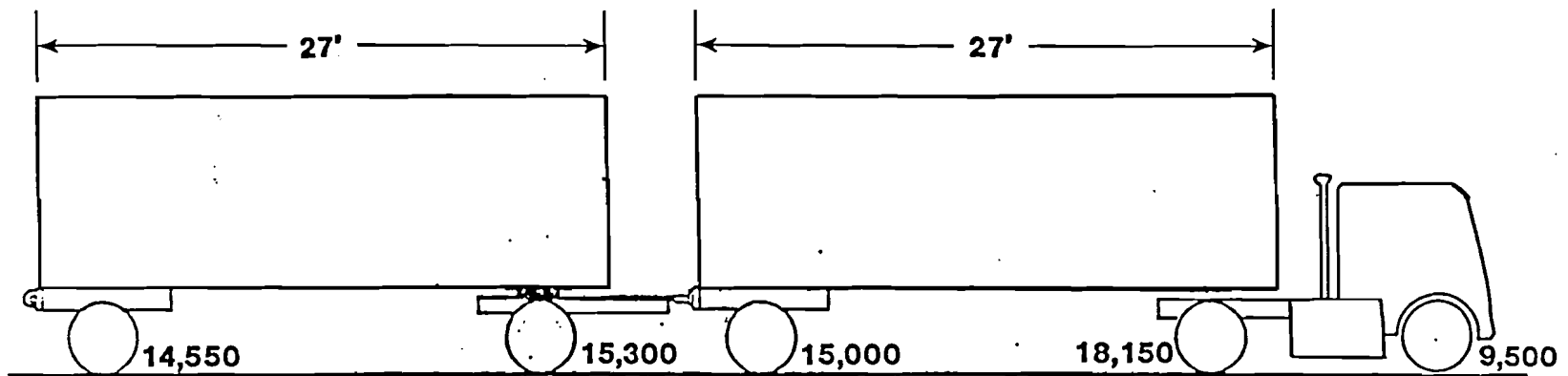
The two trailers by UTILITY were 96 inches wide, 27 feet long with a GVWR rating of 37,000 lbs. each. Weights and dimensions of the system are shown in Figure 4.

2. A-Train

The conventional A-dolly was tested in an A-train configuration. It had an axle to pintle distance of 80 inches and an unsupported tongue weight of 230 lbs. It is shown in Figure 2. It was tested using the same Mack tractor but with THEURER trailers. These trailers were 102 inches wide, 28



Figure 3. C-Train test vehicle using ST-dolly.



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Figure 4. C-Train test vehicle using ST-dolly.



Figure 5. A-dolly test vehicle.

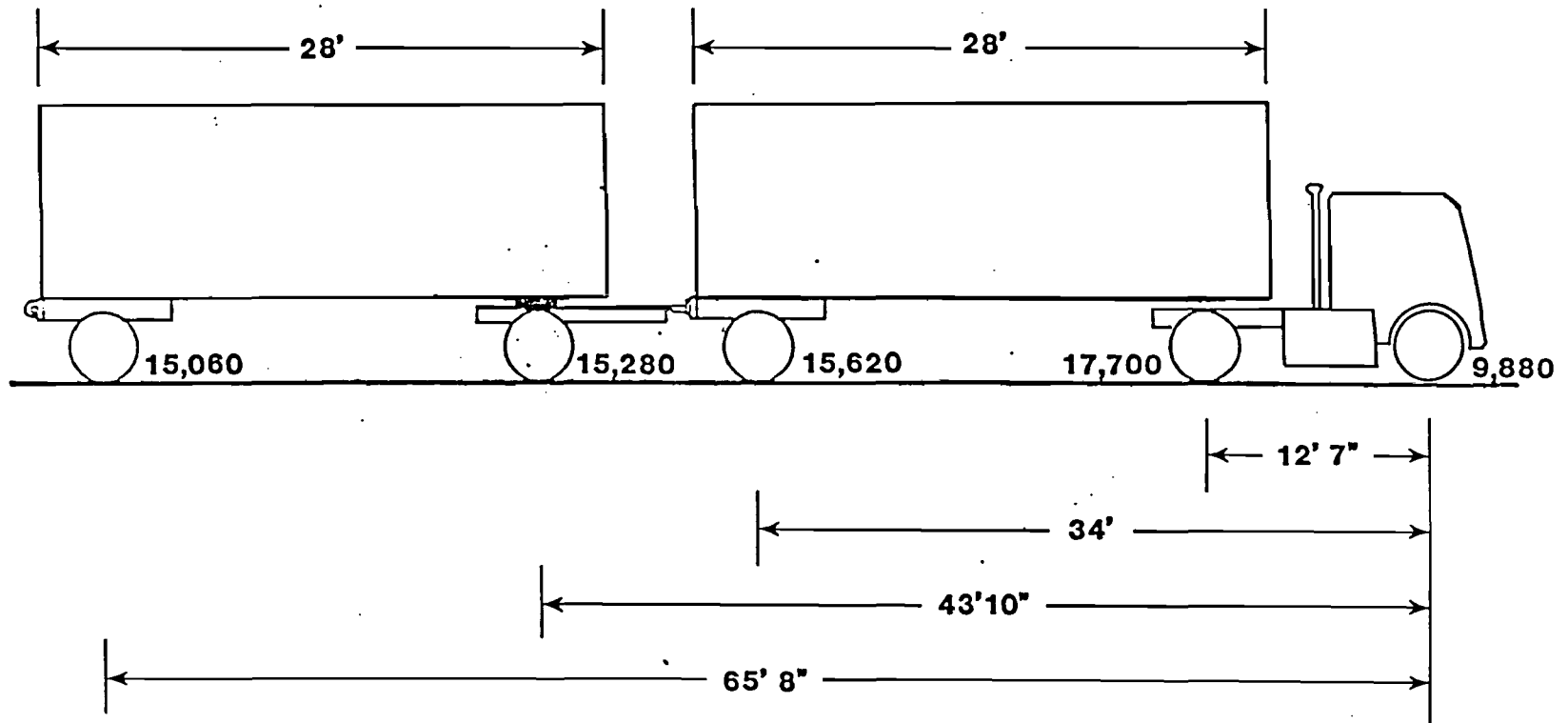


Figure 6. A-Train test vehicle using A-dolly.

feet long with a GVWR rating of 42,850 lbs. The complete test vehicle is shown in Figure 5 with the dimensions and weights shown in Figure 6.

3. Loading

The vehicles were tested both in an empty configuration and again with a full load of books on pallets. Each trailer contained 14 stacks which were 45 inches high, 31 inches long and 41 inches wide. Each stack contained 32 boxes at 41 lbs each or a total of 1,312 lbs per stack. These stacks were evenly distributed fore and aft, and right to left but not necessarily touching. This produced a load in each of the two vans of 18,368 lbs with the load center of gravity approximately 28 1/2 inches above the van floor, Figure 7.

4. Instrumentation

Accelerometers

Measurement of the rearmost lateral acceleration was provided by a Servo accelerometer located near the rear door of the second trailer at the floor level. This type of accelerometer provides infinite resolution with a frequency response above 100 hz. Calibration was performed before each test series by tilting the accelerometer to very accurate angles and using the relationship of the sine of the angle to fractions of one gravity or 'g'.

Articulation Angle

The angle between the first and second trailer was measured by a device called a "string pot" shown in Figure 8. This device measured the distance between the right most point



Figure 7. Full load test conditon.

of each trailer. As the vehicle turned this distance would become smaller on a right turn and larger on a left turn. The distance change was then converted into degrees of articulation. This method did have some error at large angles but at the small angles encountered at test speed the error was insignificant.

Recorder

Acceleration, articulation angle and time were permanently recorded on a Brush 222 Strip Chart Recorder located in the cab of the tractor. Chart speed of 5 mm per second was chosen for all testing.

C. STRAIGHT TRAIN DOLLY (ST-DOLLY)

1. Hitching Features

The ST-dolly is hitched between trailer 1 and trailer 2 in the following way.

- a. Trailer 1 is backed to the dolly. A guide target is located at the side of ST-dolly so that trailer 1 can be aligned accurately by the driver.
- b. The individual towing eyehooks of ST-dolly are then positioned vertically by the two independent jacks. Modest lateral adjustments can be made to produce the final alignment.
- c. Trailer 1 is then backed the final foot or less to engage the eyehooks. As the eyehooks penetrate the V-latches at the rear of the trailer, horizontal pins, 1.5 inches in diameter, are then pneumatically pushed through the arm end holes by means of a lever located adjacent to the V-latches.

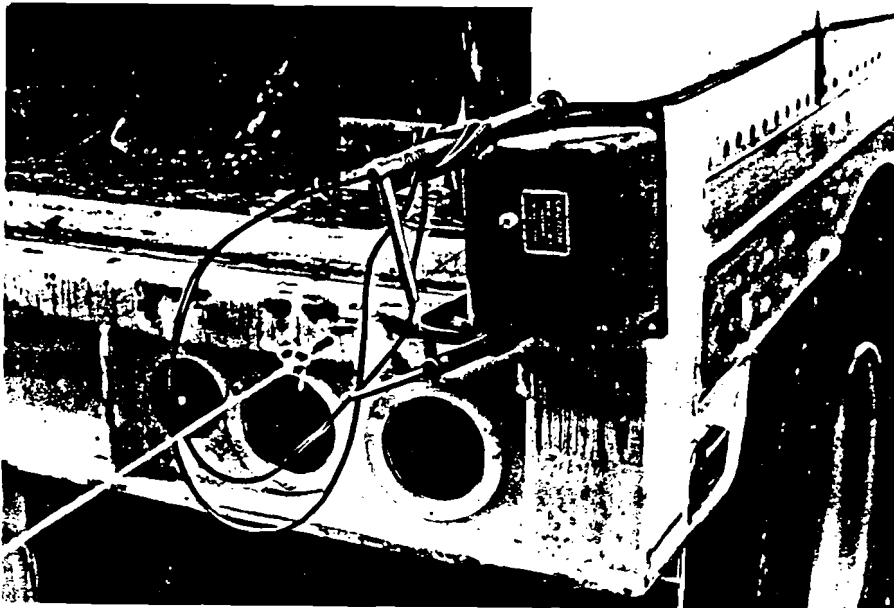


Figure 8. Articulation angle transducer.
(String pot)

- d. Safety keys are then placed in the horizontal pins.
- e. After raising the jacks the combination of tractor, trailer 1 and ST-dolly can then be accurately backed into trailer 2 to connect the fifth wheel of ST-dolly to the king pin of trailer 2.

A primary feature of ST-dolly is the ease of connection to trailer 1, due to the flexibility of vertical adjustment by independent jacks, and the fact that ST-dollies can be conveniently backed after the connection is made. The ease and flexibility of the first connection is especially important when attempting to connect on unlevel terrain. Coupling this feature with the ease of backing, virtually eliminates the need to move the dolly by hand during hitching operation.

2. Backing Features

Once all elements of the double bottom rig are connected the ST-dolly has an additional feature that is also common to most B-dollies. The rig can be backed. By eliminating one degree of rotational (yaw) freedom, the rotation between trailer 1 and ST-dolly, a coupled vehicle results that is susceptible to backing by an experienced driver. Most drivers realize that a long trailer can be backed with greater ease than a short one. ST-dolly eliminates the "short" trailer in the train, resulting in the need to back only two long trailers. Backing is still not comparable to the relative ease of backing a conventional 18 wheeler, but with care and practice it can be accomplished.

D. CONVENTIONAL DOLLY (A-DOLLY)

1. Hitching Features

The A-Dolly used in this test series is hitched between trailer 1 and trailer 2 in the following way.

- a. A-dolly must be moved by hand to a position just in front of trailer 2 in a position so that it can be shoved directly under the king pin after it is connected to trailer 1. Since the tongue weight of the A-dolly used was 230 lbs this placement would normally require two men. A single man would have difficulty maneuvering and positioning the A-dolly and might under some circumstances sustain injury in the attempt. This problem could of course be alleviated by placing a jack with roller on the A-dolly tongue.
- b. Trailer 1 is then backed to a position in line with trailer 2 and maneuvered to place the hitch ring of the A-dolly into the pintle hook. The hook is then latched.
- c. Trailer 1 and the A-dolly are then backed so that the A-dolly fifth wheel latches on the trailer 2 king pin. It is essential this backing take place over a very short distance (probably not more than five feet) or the A-dolly will be likely to start jackknifing, thus violating alignment necessary for the connection. If the A-dolly does not latch on the first rearward movement, it may be virtually impossible to regain alignment without detaching the dolly and re-aligning the A-dolly by hand. The inexperienced driver may require several trials before achieving a successful connection.

2. Backing Features

The fully connected double bottom rig including a conventional A-dolly cannot be backed a significant distance. If this is attempted with the rig in an initially straight condition, the A-dolly will normally jackknife within about thirty feet. Any original misalignment will result in a dolly jackknife in a shorter distance. The same is true of the tractor, trailer 1, A-dolly assembly. The tongue length is simply so short on an A-dolly that it cannot be backed by even experienced drivers to preselected positions and/or for significant distances.

E. TYPES OF TESTS

In order to assess the dynamic stability and subsequent safety of the dollies, these maneuvers are typical of those encountered in typical driving and would hopefully produce any inherent instabilities or indications that instabilities would appear at higher speeds. Care was taken so as not to produce known dangerous levels of lateral acceleration since outriggers were not employed during this testing.

Each maneuver was completed at low speeds initially so as to observe any incipient instabilities and to discontinue the maneuver if safety became a question. Since no outriggers were used the highest test speed was 45 mph.

1. Lane Change

Two 12 foot traffic lanes were laid out on the test track to simulate a typical roadway. The maneuver involved changing from the right lane to the left in a distance of 180 feet

which for consistency, was delineated with red highway cones. The driver was instructed to maintain the test speed in a straight path until reaching the cones. At that time he would follow the path to the left and assume a straight path in the adjacent lane at the same test speed.

2. Avoidance Maneuver

The avoidance maneuver simulated an emergency maneuver by the driver to avoid a hazard in the roadway. He would do this by rapidly moving the steering wheel approximately 90 degrees counter-clockwise, then immediately through 180 degrees to the 90 degrees clockwise position and back to the straight ahead position. This maneuver, which required a minimum of two seconds, was intended to apply a rapid disturbance to the entire vehicle system followed by a rapid return to a normal straight ahead condition.

3. 'J' Curve

An existing 20 degree 'J' curve was used for the final maneuver. This curve has a straight approach leading into a constant 286 foot radius turn to the left, hence the term 'J'. Even though the curve is flat with no super elevation, it could be considered similar to a low speed exit ramp. This maneuver theoretically applied a steady state lateral acceleration to the total vehicle system. The level of the acceleration was varied by varying the test speed.

II. TEST RESULTS

The peak values of articulation angle between the two vans and the lateral acceleration of the rear van are shown in Tables 1, 2, 3, and 4 for each of the maneuvers with Tables 1 and 2 describing ST-dolly tests and Tables 3 and 4 the A-dolly tests. The angle and acceleration columns indicate the peak values for the left and then right turn. The period is the time required to execute the maneuver, i.e. starting from a straight condition and returning to a straight condition. The 'Stability Problem' column reflects any problem observed from electronic or photoinstrumentation data during the maneuver.

A. ST-DOLLY TESTS

1. Lane Change Maneuver

The lane change maneuver was run several times in the empty condition at 40 and 45 mph and again in the loaded condition at the same speeds. This maneuver was rather mild as far as 'g' levels were concerned with a range from 0.06 to 0.13 g at the rear trailer. No stability problems were detected by the instrumentation system and no problem with the tracking or lane keeping ability was detected by observers or video tape.

2. Avoidance Maneuver

The avoidance maneuver was designed to produce higher 'g' levels than the lane change. These avoidance maneuvers produced g levels from 0.15 to 0.25 g at the rear van. Figure 9 shows typical data curves of acceleration and articulation angle during one of these maneuvers. The driver turned the steering wheel approximately ± 90 deg which resulted in an

DYNAMIC HANDLING TESTS

Dolly Type Straight Train

Trailer Type Tandem Van

MANEUVER	LOADING	VELOCITY (MPH)	ARTICULATION ANGLE		REAR ACCELERATION		PERIOD (SEC)	STABILITY PROBLEM
			LEFT	RIGHT	LEFT	RIGHT		
Lane Change	Empty	40	0.6°	1.6°	0.06 g	0.06 g	6.5	None
Lane Change	Empty	45	0.63°	1.9°	0.08 g	0.12 g	9.0	None
Avoidance	Empty	40	1.26°	2.5°	0.15 g	0.17 g	3.0	None
Avoidance	Empty	40	1.26	2.5°	0.13 g	0.16 g	3.0	None
'J' Curve	Empty	25	6.3°	----	0.21 g	-----	---	None

TABLE 1

DYNAMIC HANDLING TESTS

Dolly Type Straight Train

Trailer Type Tandem Van

MANEUVER	LOADING	VELOCITY (MPH)	ARTICULATION ANGLE		REAR ACCELERATION		PERIOD (SEC)	STABILITY PROBLEM
			LEFT	RIGHT	LEFT	RIGHT		
Lane Change	Full	40	1.1°	1.2°	0.1 g	0.13 g	2.5	None
Lane Change	Full	45	1.0°	1.4°	0.1 g	0.13 g	5.0	None
Avoidance	Full	40	1.89°	1.6°	0.2 g	0.2 g	2.0	None
Avoidance	Full	45	1.7°	2.5°	0.22 g	0.25 g	2.5	None
'J' Curve	Full	30	6.3°	----	0.35 g	-----	---	None
'J' Curve	Full	25	6.3°	----	0.21 g	-----	---	None

TABLE 2

STRAIGHT TRAIN - 40 MPH

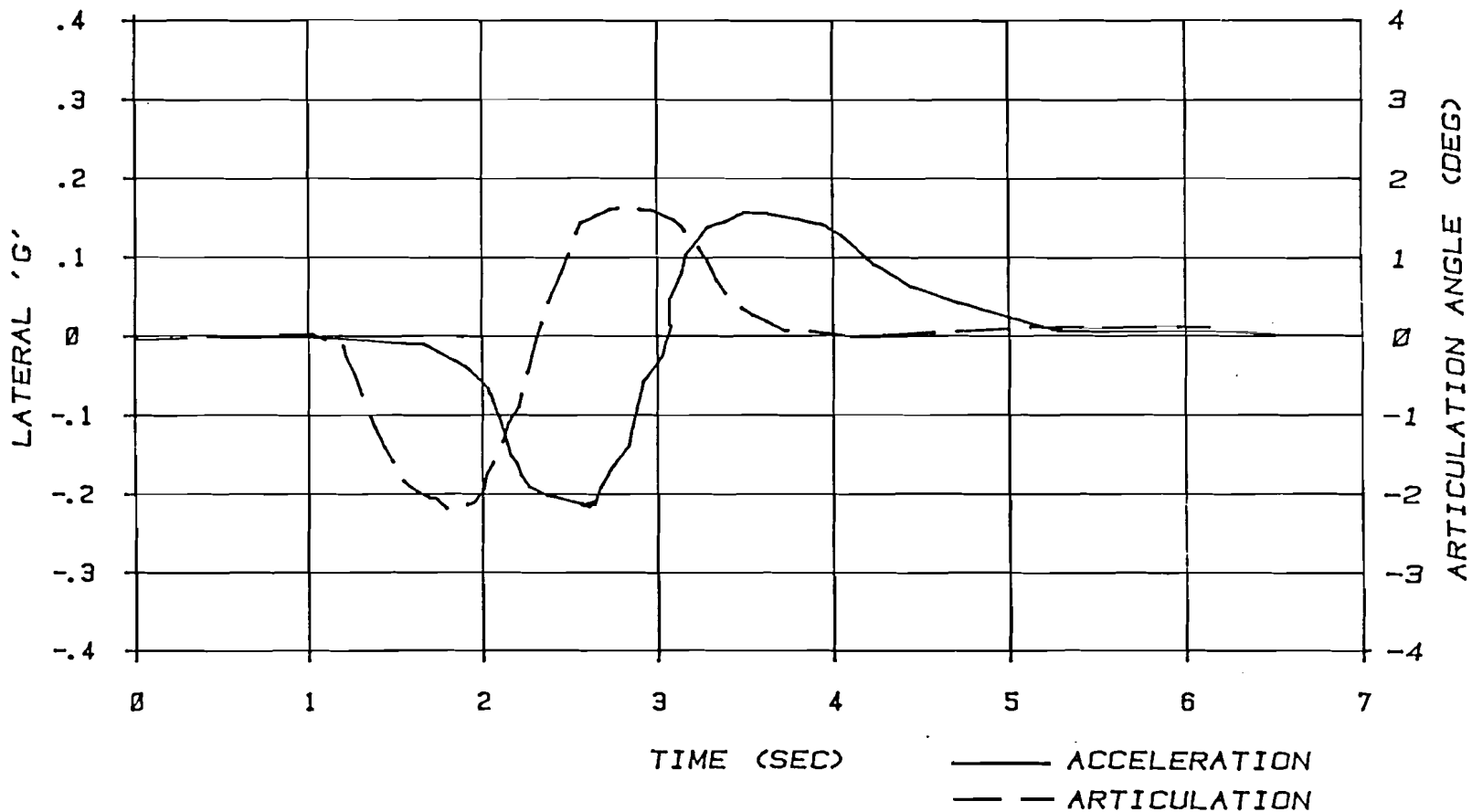


Figure 9. Avoidance maneuver with ST-dolly.

articulation angle of approximately ± 2 deg, followed one second later by the rear trailer lateral acceleration of approximately ± 0.2 g. It is important to note that after the maneuver both traces smoothly returned to zero without crossing indicating a well damped system. None of the 25 avoidance maneuver tests with the ST-dolly indicated any instability problems.

3. 'J' Curve

The 'J' curve test produced a high steady state lateral acceleration on the whole vehicle system ranging up to 0.35 g at 30 mph. Typically these tests were run at 25 mph producing 0.21 g lateral acceleration for about 7 seconds. These tests with the ST-dolly produced very smooth traces with no anomalies or instability problems.

B. A-DOLLY TESTS

Tables 3 and 4 indicate test results for the empty and full load testing of the A-train vehicle.

1. Lane Change

This maneuver was conducted at speeds of 30, 35, 40, and 45 mph with the A-train full and empty. As expected the values were low with the rear van lateral acceleration increasing with test speed up to 0.15 g which was somewhat dependent on the drivers open loop steer inputs. Both the electronic and photoinstrumentation indicated no stability or lane tracking problem at the levels tested.

DYNAMIC HANDLING TESTS

Dolly Type A-Dolly

Trailer Type Tandem Van

MANEUVER	LOADING	VELOCITY (MPH)	ARTICULATION ANGLE		REAR ACCELERATION		PERIOD (SEC)	STABILITY PROBLEM
			LEFT	RIGHT	LEFT	RIGHT		
Lane Change	Empty	35	0.6°	1.6°	0.03 g	0.09 g	8.0	None
Lane Change	Empty	40	0.6°	1.2°	0.05 g	0.08 g	7.0	None
Lane Change	Empty	45	0.9°	1.6°	0.1 g	0.15 g	6.2	None
Avoidance	Empty	30	0.5°	0.6°	0.12 g	0.12 g	3.6	None
Avoidance	Empty	40	1.9°	2.8°	0.15 g	0.2 g	4.6	None
'J' Curve	Empty	20	6.6°	---	0.14 g	----	---	None
'J' Curve	Empty	25	6.9°	---	0.18 g	----	---	None

TABLE 3

DYNAMIC HANDLING TESTS

Dolly Type A-Dolly

Trailer Type Tandem Van

MANEUVER	LOADING	VELOCITY (MPH)	ARTICULATION ANGLE		REAR ACCELERATION		PERIOD (SEC)	STABILITY PROBLEM
			LEFT	RIGHT	LEFT	RIGHT		
Lane Change	Full	30	1.3°	1.3°	0.03 g	0.03 g	9	None
Lane Change	Full	40	1.3°	1.8°	0.1 g	0.12 g	6.5	None
Lane Change	Full	45	1.3°	0.88°	0.12 g	0.05 g	6.5	None
Avoidance	Full	30	3.2°	4.4°	0.15 g	0.2 g	4.0	0.9° Overshoot
Avoidance	Full	40	3.2°	3.5°	0.26 g	0.26 g	4.0	1.3° Overshoot
'J' Curve	Full	20	6.9	----	0.18 g	----	----	None
'J' Curve	Full	25	6.9	----	0.25 g	----	----	None

TABLE 4

2. Avoidance Maneuver

A total of 32 avoidance or quick 'S' turns were made with the A-Train vehicle in the empty and full load condition from 30 to 45 mph. In the empty condition no stability problem was observed up to the 0.17 g level tested. In the full load condition some overshoot was noted when at the end of the maneuver the steering wheel was returned to straight ahead the rear van would not immediately return to a straight path. This condition is illustrated in Figure 10 with the articulation angle overshooting zero at the 3 seconds point. This condition was not as evident at lower levels of steer input which indicates the amount of overshoot would probably continue to increase as the severity of the maneuver increased. The motion does dampen out which is a relative stable condition as opposed to underdamping where each cycle is larger than the preceding one. Other than the small overshoot no other potential stability problems were observed.

3. 'J' Curve

The 'J' curve test produced a high, steady state lateral acceleration on the whole vehicle system ranging up to 0.25 g. Typically these tests were run at 25 mph producing 0.18 g to 0.25 g lateral acceleration on the rear van for about 7 seconds. These tests with the A-dolly produced smooth traces with no anomalies or instability problems.

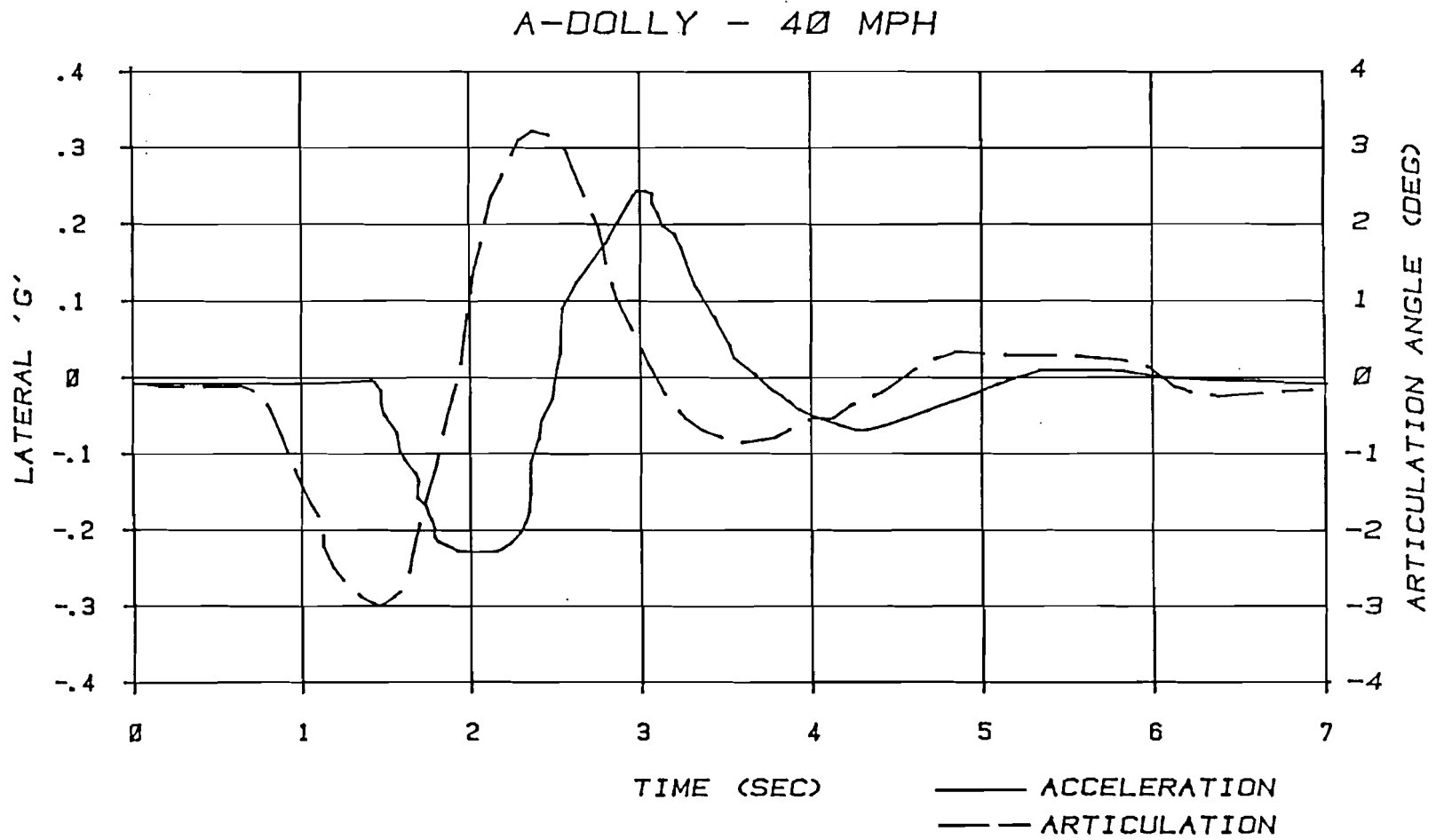


Figure 10. Avoidance maneuver with A-dolly.

CONCLUSION

It is concluded that ST-dolly does offer significant advantages in terms of hitching and backing features when compared to those same characteristics of conventional A-dollies. While a detailed analysis was not conducted in this study, simply working with both types of dollies was sufficient to make these advantages clear. The net result of both these features is to reduce the necessity of moving the ST-dolly by hand and much greater ease in maneuvering both the three and four segment trains during backing.

The stability of a double bottom connected by ST-dolly in forward maneuvers, maneuvers that would be expected to excite many double bottom systems appears excellent. In all maneuvers, including lane change, emergency avoidance and J curve, smooth cornering and quick damping of oscillations were apparent. Rearward amplification seemed minimal.

While the magnitude of the cornering maneuvers were not sufficient to create a significant safety problem with the A-dolly, overshoot of the rear trailer shown in two instances in Table 4, gave warning that an oscillation problem might be developing and that significant rearward amplification could be imminent. The likelihood of these developing problems is illustrated by tests in both Michigan and Canada using vehicles with outriggers to prevent overturning.^{2,4} The major differences between A-dollies and B-dollies, (ST-dolly is a type of B-dolly) is summarized by Woodrooffe and Billings as follows.⁴

The B-dolly has shown the capability to improve the performance of combination vehicles. The considerations required in the design of such a device to attain this performance are complex. While the strength requirements of the attachment points and frame structure can be

understood, the stiffness and damping parameters of the steering system can vary in many ways without detracting from vehicle stability.

The major criteria of design suitability are hitching strength and effective steering stiffness during high speed operation. With these two criteria satisfied, the B-dolly presents a very appealing alternative to the A-dolly in terms of dynamic performance

The ST-dolly, without a designed self steering mechanism maximizes the "effective steering stiffness." This feature is probably the primary feature promoting stability during high speed operation.

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