the tractor avoided the other vehicle, the last trailer rolled over spilling gasoline and catching fire. Events of this type happened in seven of thirteen accidents that happened in 1977.

In a more recent study [11], an attempt was made to associate differences in trailer lengths with involvement in single vehicle accidents on high-speed roads. Although there are little data on the safety record of doubles combinations, analyses of crash and exposure data show that vehicles with short trailers are much more likely to be involved in these types of crashes than vehicles with longer trailers. Specifically, vehicles with trailers that are 7.3 meter (24 foot) or less are 3.8 times more likely to be involved in single vehicle accidents on high speed roads than vehicles with 8.5 meter trailers. These crash data are consistent with analytical results showing that rearward amplification tends to increase as trailer wheelbases decrease.

In addition to longer trailers, special hitching arrangements, such as using double drawbar dollies or other types of innovative dollies [8], are effective in lowering rearward amplification. The results of analytical studies show that these dollies tend to reduce rearward amplification by a factor of approximately 1.35 over a wide range of conditions for vehicles like the Western double—twin 8.5-meter trailers in the United States [12]. Furthermore, recent detailed analyses of vehicles performing obstacle avoidance maneuvers show that the roll characteristics of the vehicle can have a significant influence on rearward amplification for vehicles with heavy loads and high centers of gravity [13].

Given the safety concerns and the known influences of vehicle properties on rearward amplification, the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation sponsored the development of testing and screening procedures for use in regulating the rearward amplification performance of longer combination vehicles [14]. This paper describes the procedure developed for quantifying rearward amplification.

2.0 RATIONALE FOR A PATH FOLLOWING TEST

Although tests for demonstrating rearward amplification and the influence of vehicle properties on rearward amplification have been performed in the past (see [2] and [8], for example), there has been no generally accepted test procedure for quantifying rearward amplification. Since 1989, the International Standards Organization (ISO) and the Society of Automotive Engineers (SAE) have been considering tests for heavy vehicles. The ISO proposal for new work entitled "Road vehicles - Heavy commercial vehicle combinations - Lateral stability test procedure," contains a "sinusoidal steer" test in which one cycle of a sine wave is applied at the steering wheel. Originally, a similar test was proposed to SAE. However, based upon Canadian experience with a sinusoidal steer test and results obtained at UMTRI, it was observed that a sine wave of steering at the steering wheel (no matter

how well done) could result in (1) asymmetric levels of lateral acceleration at the tractor and (2) responses at the last trailer that are difficult to interpret given that the first peak of the tractor acceleration is often much larger than the second peak.

Subsequently, various schemes for defining rearward amplification, depending upon the amplitudes of the first and second half cycles of the lateral acceleration at the tractor and at the last trailer, were used to describe the results of the tests. However, it is difficult to know if these results are meaningful in comparing vehicles. Perhaps one vehicle might be rated higher than another due to properties that have more to do with the test input than with the performance of the vehicle in a sudden swerving maneuver. It is clear that freeplay and other factors in the steering system can have a lot to do with the results if they depend upon an open-loop input at the steering wheel. Because of these concerns, it was proposed that a path-following test be tried.

Conceivably, a path-following test might be very simple in terms of the instrumentation required, the area of the facility needed, and techniques for ensuring that driver inputs are repeatable. Ideally, for regulation purposes, the test need only be a pass/fail test. It might be based upon a "cone course" that would require the lead unit to follow a tightly constrained path. The only instrumentation might be a fifth wheel for measuring velocity although accelerometers could be used to verify acceleration levels. The measure of success or failure would simply depend upon whether the vehicle rolled over onto its outriggers or the last trailer swept out cones that marked the allowable bounds of the swept path. While these hopes were not realized, the test procedure discussed in section 4 was developed from these ideas. The primary differences are (1) accelerometers are used to measure rearward amplification and (2) the vehicles are expected to have passed a tilt table test [14, 15] thereby assuring a static rollover threshold of at least 0.35g.

3.0 CONCERNS WITH LOAD DISTRIBUTION AND TIRE PROPERTIES

Rearward amplification depends upon tire properties and roll properties associated with load distribution. Clearly, test results are highly dependent upon the conditions pertaining to the vehicle being tested.

For example, the differences in cornering stiffnesses between radial and bias ply truck tires are large enough to have a major influence on rearward amplification. The cornering stiffness of a bias ply tire might be approximately 5/7 of the cornering stiffness of a radial ply truck tire at comparable loads. This could make the difference between a rearward amplification of 2.0 for a Western double with radial tires and a rearward amplification over 2.3 for a Western double with bias ply tires. In addition, the cornering stiffness of tires worn to 1/3 tread is much larger than that of new tires. The point being that obtaining repeatable results from one test exercise to another depends upon having close to the same tire properties for the two test exercises.
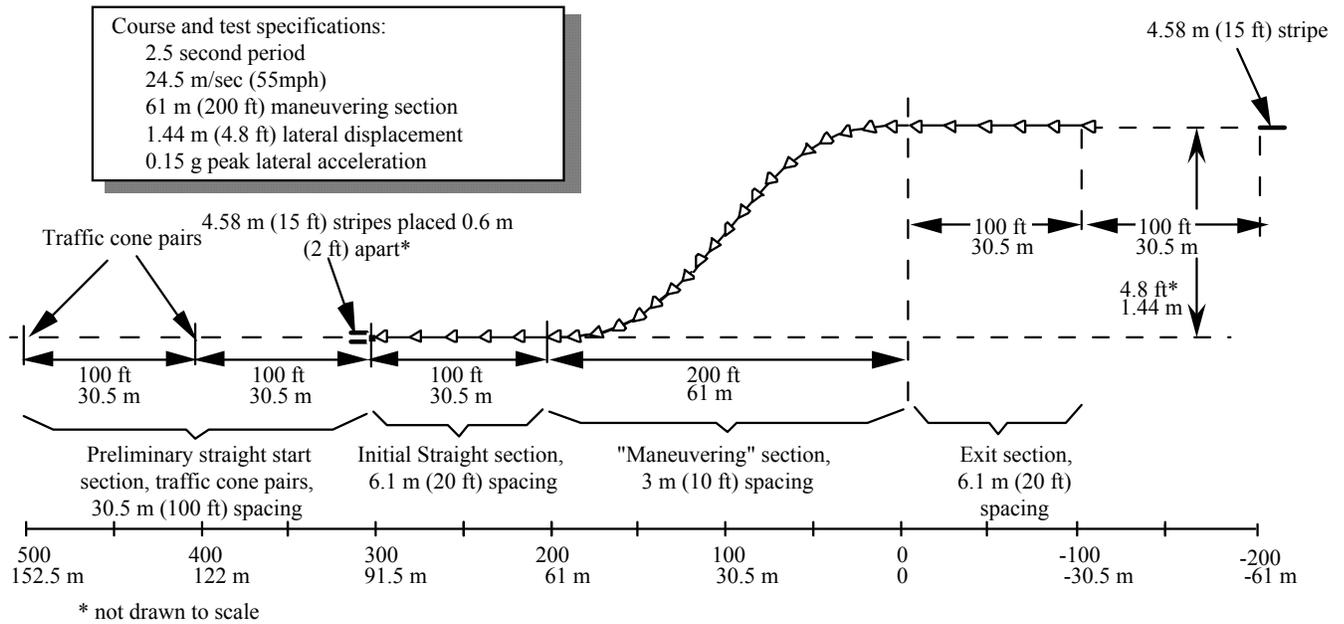
Course and test specifications:
2.5 second period
24.5 m/sec (55mph)
61 m (200 ft) maneuvering section
1.44 m (4.8 ft) lateral displacement
0.15 g peak lateral acceleration

4.58 m (15 ft) stripe

4.58 m (15 ft) stripes placed 0.6 m (2 ft) apart*

Traffic cone pairs

100 ft 30.5 m   100 ft 30.5 m

4.8 ft* 1.44 m

100 ft 30.5 m   100 ft 30.5 m   100 ft 30.5 m   200 ft 61 m

Preliminary straight start section, traffic cone pairs, 30.5 m (100 ft) spacing

Initial Straight section, 6.1 m (20 ft) spacing

"Maneuvering" section, 3 m (10 ft) spacing

Exit section, 6.1 m (20 ft) spacing

500 152.5 m   400 122 m   300 91.5 m   200 61 m   100 30.5 m   0 0   -100 -30.5 m   -200 -61 m

* not drawn to scale

Figure 2. Layout of the test course

Similar remarks can be made about the differences between a load that is concentrated along the trailer bed and one that has a center of gravity height that is close to the height of the center of the van, for example [13,16]. The complete test procedure [14] contains sections for describing the pertinent mechanical properties of the vehicle being tested to help in ensuring that tests for certifying vehicles specify the conditions under which acceptable performance is obtained.

4.0 DESCRIPTION OF THE MEASUREMENT METHOD

4.1 Introductory Summary of the Method

The measurement method involves a test course especially laid out to excite the rearward amplification tendencies of multi-articulated heavy trucks. The form of the course is illustrated in figure 2. The test driver follows this course in performing the test.

The vehicle is instrumented to measure lateral accelerations at the tractor's front axle and at the center of gravity of the sprung mass of the last trailer. The lateral acceleration of the tractor is the input that excites the trailer motions. As will be explained later, this input is quantified by computing its root-mean-square (rms) value over the lateral maneuvering section of the test course. The value of the input is obtained by multiplying the rms value of the input by the square root of 2 to provide an estimate of the amplitude of an equivalent sinusoid of lateral acceleration. The output is quantified by measuring the maximum absolute value of the lateral acceleration of the last trailer. The rearward amplification (RA) is the ratio of (a) the value of the output divided by (b) the value of the input.

Studies of various methods of processing the data have led to a technique that can be used to measure rearward amplification to within approximately ten percent of the average value with a confidence of ninety percent that the true value lies within this band.

Typically, this level of confidence can be obtained using the results from five repeats of the test.

4.2 The Path and Path-Following

The path chosen for use in the method is designed to correspond to one cycle of a sine wave of lateral acceleration. That is, the following relationships apply to the maneuvering section of the test course shown in figure 2:

$$A_y = A \sin(2\pi t/T) \tag{1}$$

$$V_y = [A/(2\pi/T)][1 - \cos(2\pi t/T)] \tag{2}$$

$$y(t) = [A/(2\pi/T)][t - (\sin(2\pi t/T)/(2\pi/T))] \tag{3}$$

where:

t   is time,
T   is the period,
A   is the amplitude in feet per second squared,
V_y is the time rate of change of y, and
y   is the lateral position of the path along the ground.

Equations 1, 2, and 3 pertain to a situation in which the longitudinal distance, x, is traversed at a constant forward velocity, V, such that:

$$x(t) = Vt \tag{4}$$

Let X be the longitudinal coordinate at the end of the maneuvering section of the obstacle avoidance path, that is, the longitudinal coordinate of the path at t = T. For a forward velocity, V, X = VT. Using these relationships yields the following important simple relationship:

$$y(X) = AT^2/2\pi \quad (\text{or } y(X) = AX^2/2\pi V^2) \tag{5}$$

This means that the displacement at the end of the avoidance maneuver depends upon the period and the level of lateral acceleration. For example, if A = 0.15 g, that is, 1.47 m/sec² (4.824 ft/sec²) and T = 2.5 seconds; y(X) = 1.44 m (4.80 ft.). (See figure 2.)

The simple relationships for the path (equations 1 to

5) make it easy to specify courses of different amplitudes and periods. However, an amplitude of 0.15 g was found to be a reasonable level for investigating vehicles with RA =2.0 and greater. (For RA = 2.0 and Ay = 0.15 g, the lateral acceleration of the last trailer will be 0.3 g which is approaching the rollover threshold of many heavy trucks. Hence, outriggers for preventing rollovers are necessary.) If amplitudes lower than 0.15 g are used, measured RA tends to increase because the phenomenon is nonlinear.[1] Using 0.15 g provides a test that challenges the safety qualities of heavy truck combinations (particularly those qualities related to rolling over) and allows those qualities to be compared to those of the Western double.

Rearward amplification is known to depend upon the period of the maneuver [5]. Previous procedures [8] have involved tests at various periods. In this study, paths with periods of 2.0, 2.5, and 3.0 seconds were laid out and investigated at a speed of 88 kph (55 mph). The results of experimenting with these different paths indicated that the end of each path could be superimposed on the others with little other difference between them. In practice, the course with a 2.5 second period tended to evoke the most RA and to be the easiest to perform satisfactorily. Based upon this experience, the 2.5 second period has been recommended in specifying the test procedure. (Of course, it is a simple matter to use other periods and, if this path is driven at speeds differing from 88 kph, the period and lateral acceleration will be different.)

To aid in measuring the deviation between the path taken by the vehicle and the course, the course was marked with five-sided plates as illustrated in figure 3. The shape of these plates was associated with an on-board, laser-based, instrument system which could be used to measure the deviations from the ideal path. An equally effective, but much simpler, method of checking whether the vehicle stayed close to the path was to use a water jet system to mark the path taken by the first axle of the vehicle [14].

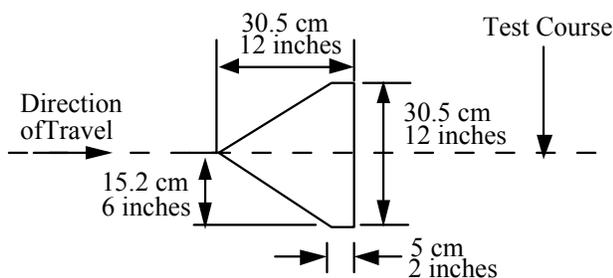To insure that the test is performed accurately, it is

Figure 3. "Home Plates" used to mark the test course

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[1] At a maneuver amplitude of 0.15 g, the lateral response of the last trailer can be large enough that the rearmost tires can approach the limits of friction. This can limit the lateral acceleration peak reached by this trailer.

stipulated that a specific point on the front axle must pass over each plate. A procedure for marking the pavement with the path of a point on the front axle has been developed for checking that the driver steers to stay within ± 15 cm (6 inches) of the prescribed path. It was found that with the aid of a sighting strip on the hood the driver could follow the ideal path within these limits on the majority of test runs.

Even when the reference point on the front axle stays within ± 15 cm of the ideal path, the lateral acceleration of the tractor can differ significantly from run to run and may not be exactly sinusoidal in form. The peak values of the lateral accelerations corresponding to the path that the tractor actually follows do not always provide a good indication of the magnitude of the maneuver. After investigating several possibilities for quantifying the input motion, it was found that the rms value of the lateral acceleration measured along the front axle of the tractor was a good indicator of the magnitude of the input. The rms value times 1.414 is now used to describe the magnitude of the input. This procedure provides results that substantially improve the run-to-run repeatability of the measured RA ratio.

4.3 Instrumentation and Data Processing for Quantifying the Motion of the Last Trailer

The lateral acceleration of the center of gravity of the last trailer is the output of the test and the numerator of the RA ratio. For this quantity, the peak reading of the lateral acceleration transducer (mounted upon a stable platform) proved to be satisfactory. The wave form is "clean" and passes through relatively smooth peaks because the trailer's dynamics tend to filter out any irregularities. Simple digital filtering techniques have been used to provide repeatable readings of the peak values obtained in vehicle tests. This is fortunate because the response of the last trailer is asymmetric and there is nothing (that we know of) to warrant using an assumed shape or an rms reading or any other method for averaging over time.

The data processing used to determine the peaks involves using a 0.2 second moving average on samples that are taken at a rate of at least eighty samples per second. The moving average smoothing filter is used twice by making two passes over the data. This procedure, that is simple to describe, has been compared with other more sophisticated types of filters and the results are the same. The smoothing is sufficient to cancel high frequency variations while not reducing the peak significantly.

If one desires to determine transient high-speed offtracking, a water-jet or alternative device can be attached to the rear axle of the last trailer at a point that corresponds to the selected reference point on the front axle. The distance from the path of this axle (as determined by the water mark, for example) from a line tangent to the test course at the end of the maneuvering
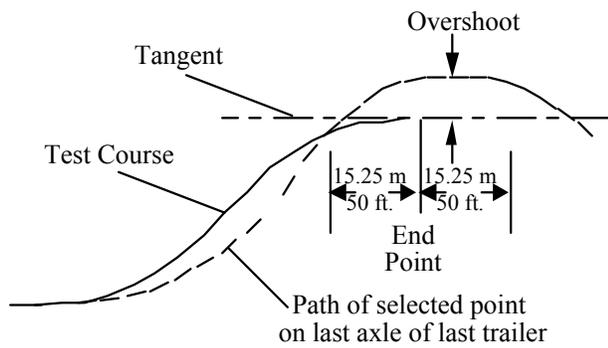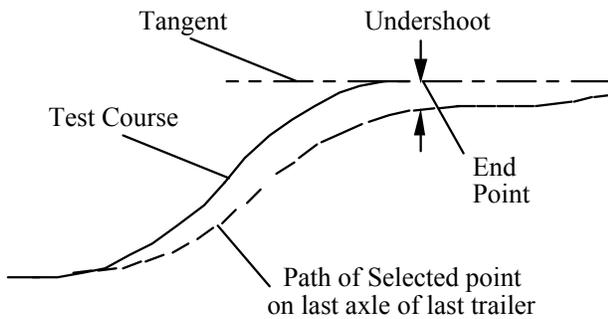
a. Overshoot

b. Undershoot
**Figure 4 Transient high speed offtracking:
overshoot and undershoot**

section is measured. If the last trailer overshoots the tangent line in the region from 15 meters (50 feet) before the end of the maneuvering section to 15 meters after the end of the maneuvering section, the maximum level of overshoot can be measured. If the last trailer's path does not overshoot in this region, the amount of "undershoot" at the end of the maneuvering section can be measured. (See figure 4.)

4.4 Further Information On The Methodology

The pertinent requirements for performing the new test procedure are summarized in table 1. This table highlights the essential features of the transducers, data processing, performance evaluation, and quality checks. These features form the foundation of the steps involved in measuring RA. (See figure 5.) A key idea portrayed in table 1 and figure 5 is to check the quality of each test run to see that the test was performed properly.

The results from five good runs are processed to provide the measure of rearward amplification performance obtained by the vehicle in this obstacle avoidance maneuver. If the tests are done properly, the standard deviation of a sample of five runs should be less than ten percent of the mean of the five runs. Sensitivity analyses, using UMTRI's Yaw/Roll simulation [17] and considering changes in vehicle parameters, test velocity, and amplitude and period of input (while still requiring the reference front axle point to pass over the plates), showed that it is reasonable to expect this quality of results for vehicles with acceptable dynamic properties. Full-scale vehicle tests [14] support this conclusion.

The results are presented as follows:

$$RA = m \pm 0.953\ S \qquad (6)$$

where:

m   is the sample mean (the average of 5 runs), and

S   is the sample standard deviation where $S^2 = (\sum (RA_i - m)^2) / 4$.

(Note: S, as used here, is a numerical property of the data, which fits the needs of the method. Further, the value of 0.953 is appropriate only with a procedure constrained to five repeats.)

A requirement for "passing" the test might be based on the performance of the Western double [14]; viz.,

$$m + 0.953\ S \leq 2.0 \qquad (7)$$

The idea behind this requirement is that $m \pm 0.953\ S$ are the ninety percent confidence limits on the mean result of a large number of tests. Or, in other words, satisfying the above inequality implies a ninety-five percent confidence that the mean rearward amplification does not lie above 2.0.

4.5 Example Results For A- And C-Train Doubles And Triples

The new procedure has been used to quantify the performance of a Western double and a triple trailer combination. Both of these vehicles were evaluated in A-train and in C-train configurations. Figure 6 illustrates the dollies used in the A-train and C-train configurations. The results of this initial test program (see figure 7) show that the confidence bands are small. They also show that the C-dolly provides an improvement factor of 1.35 when the performances of the C-trains are compared to those of the A-trains. This same level of improvement factor has been predicted by simulation [12], not only for these combinations, but also for a variety of different doubles combinations. It is interesting to observe that the rearward amplification for the A-train triple went from 2.5 to 1.8 for the C-train triple when C-dollies were used in place of the A-dollies in the same vehicle. In addition, the 2.0 level found for the Western double corresponds to the results predicted by simulations. These results indicate that the rationale behind the new procedure is sound and that one can expect to obtain repeatable and predictable results.
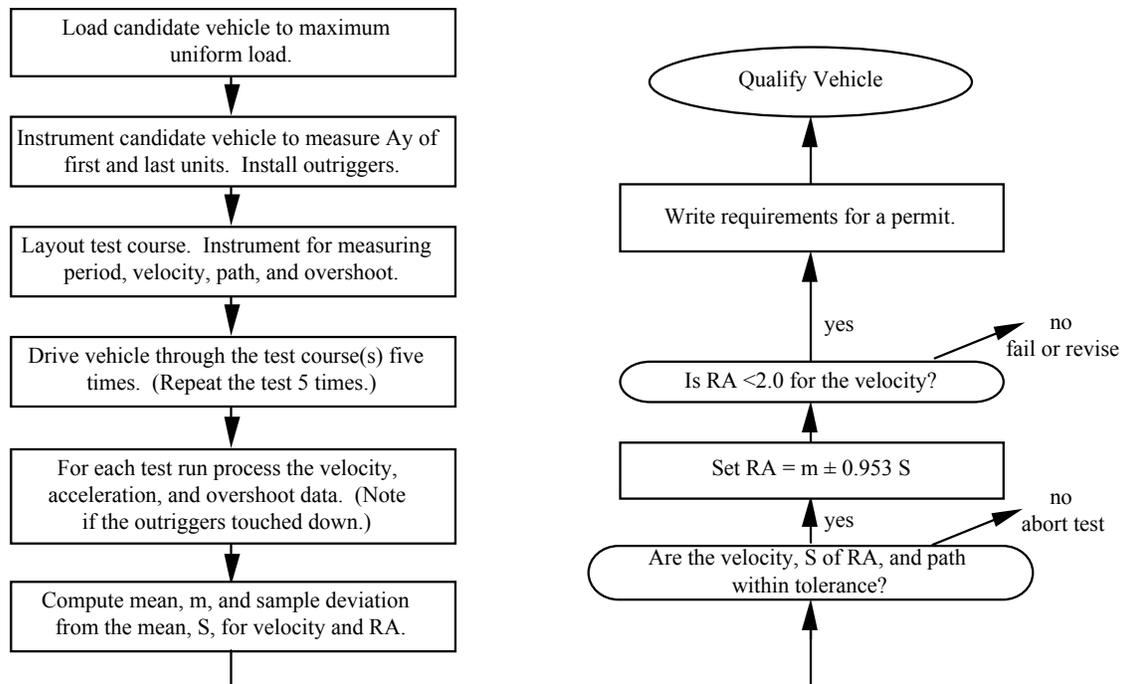

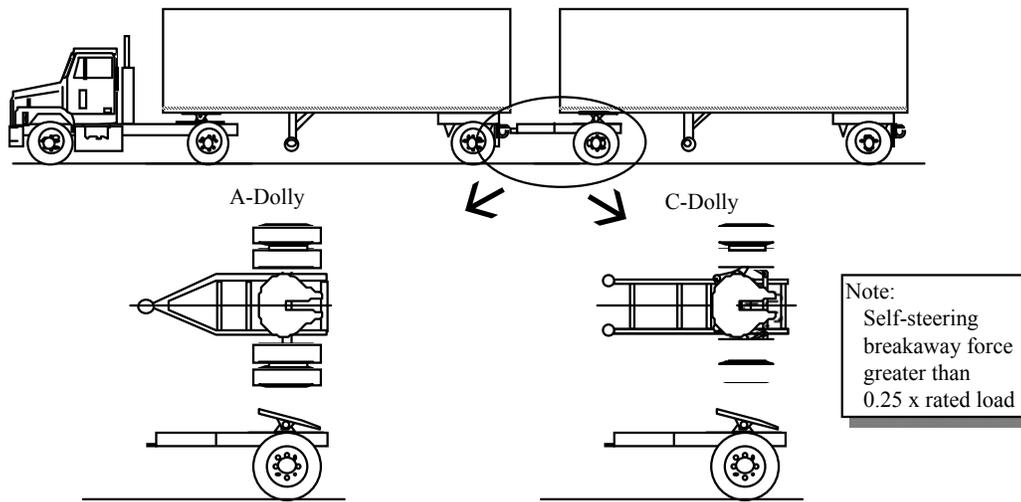**Figure 5. Block diagram of testing for obstacle avoidance capability**

Figure 6. The single draw-bar A-dolly and the double draw-bar C-dolly

5.0 CONCLUDING STATEMENT

A new type of objective test procedure has been developed for assessing the obstacle avoidance capabilities of heavy trucks. The measures of rearward amplification determined by this procedure are in close agreement with those predicted by the Yaw/Roll simulation [17], thereby aiding to verify the simulation. In addition, the improvement measured when double drawbar dollies are used is the same as predicted by the

Figure 7. Test results indicating influences of changing sprung mass cg height and changing dolly types

Yaw/Roll model. Since (1) it has been demonstrated

that the test results are repeatable and (2) the correspondence with simulation results indicates that the phenomena involved with developing rearward amplification are adequately understood, it appears reasonable to use the test methods described here to certify the level of performance of vehicles with respect to a design or regulatory target.

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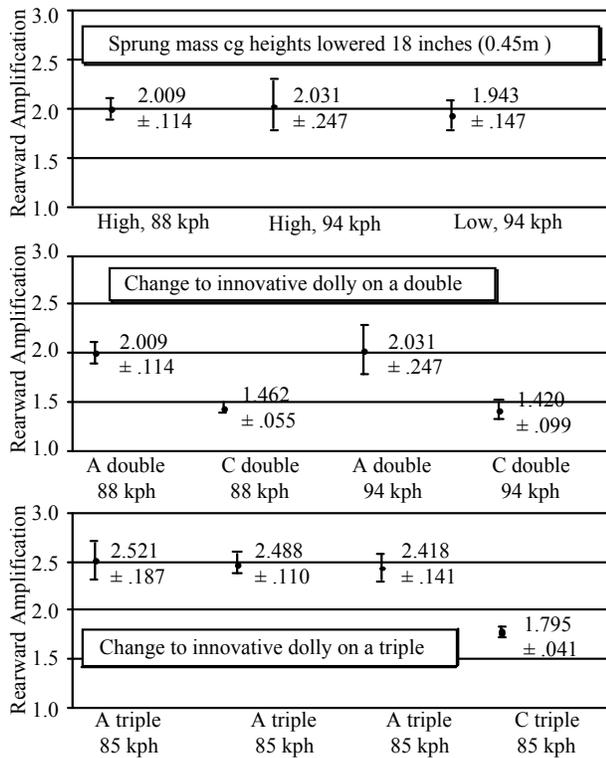
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