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A Test for Evaluating the Rearward Amplificiation of Multi-Articulated Vehicles

Foreword—This SAE Recommended Practice is intended as a guide toward a standard practice and is subject to change to keep pace with experience and technical advances.

This procedure 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 1. 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 vehicle motion. This input is quantified by computing its root-mean-square (rms) value over the lateral maneuvering section of the test course.[1] 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 is the ratio of (a) the value of the ouput 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 10% of the average value with a confidence of 90% that the true value lies within this band. This level of confidence can be obtained using the results from five repeats of the test. The following statement of this test procedure for evaluating obstacle evasion capability contains sections entitled:

1. Scope
1.1 Purpose
2. References
3. Statement of the Test Procedure
3.1 Test Course
3.2 Vehicle Condition and Preparation
3.3 Instrumentation Requirements
3.4 Data Acquisition and Processing Requirements
3.5 Requirements for Proper Execution of the Test Maneuver
3.6 Analysis of the Test Data
3.7 Interpretation of the Results

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1. After investigating several possibilities for quantifying the input motion (including peak measured values of lateral acceleration, for example), it was found that the rms value of the lateral acceleration of the front axle of the tractor was a good indicator of the magnitude of the input, and when this rms value is used, the variability of the test results is less than that obtained using other possibilities

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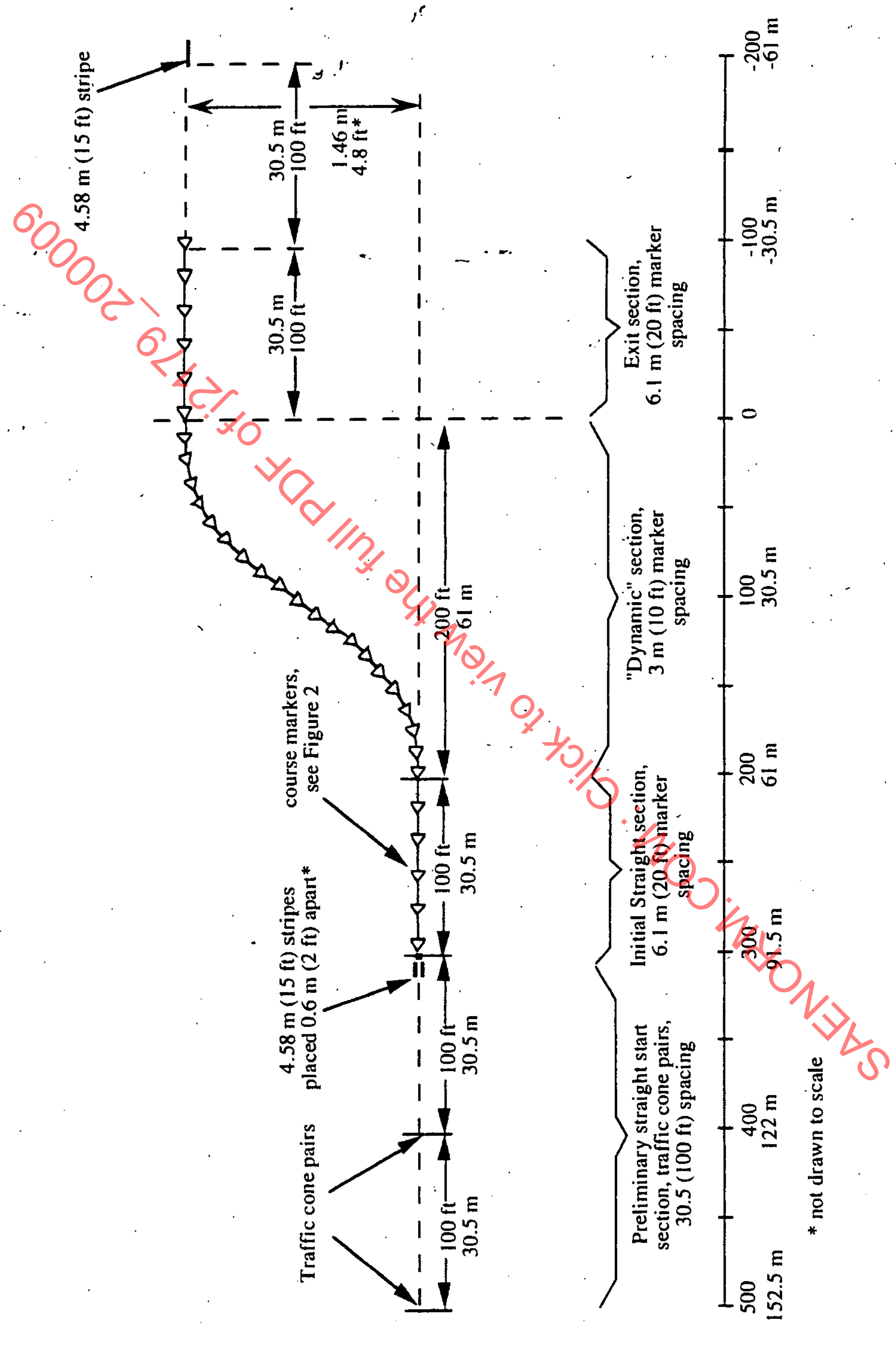


FIGURE 1—LAYOUT OF THE TEST COURSE

The procedure, which is presented next, is intended to meet the following general requirements:

To be able to:

a. Distinguish reliably between vehicles with different levels of performance in obstacle avoidance maneuvers.
b. Perform the tests using reasonable instrumentation and data processing requirements.
c. Attain repeatable results.
d. Perform the tests correctly in a relatively easy manner.

1. ***Scope***—The procedure applies to heavy vehicles weighing more than 11 800 kg (26 000 lb) and particularly to those vehicles having two or more articulation joints that allow rotation in a horizontal plane. The procedure pertains to the lateral directional response of multi-articulated vehicles in avoidance maneuvers performed at highway speeds without braking.

1.1 Purpose—This test procedure is intended to be used for determining the rearward amplification and dynamic offtracking qualities of multi-trailer commercial vehicles (heavy trucks and buses).

2. ***References***

2.1 Applicable Publications—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated, the latest revision of SAE publications shall apply.

2.1.1 SAE Publication—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J2180—A Tilt Table Procedure for Measuring the Static Rollover Threshold for Heavy Trucks

2.1.2 FMVSS Publications—Available from the Superintendent of Documents, U. S. Government Printing Office, Mail Stop: SSOP, Washington, DC 20402-9320.

FMVSS 105—Hydraulic Brake Systems
FMVSS 121—Air Brake Systems

3. ***Statement of the Test Procedure***

3.1 Test Course—The test involves the course illustrated in Figure 1. (Also see Appendix A.) The test driver is to follow this course in a manner that meets the requirements of 3.5. As shown in Figure 1, there is a straight section 91.5 m (300 ft) long, leading up to a maneuvering section that attains a 1.46 m (4.8 ft) lateral displacement in a longitudinal distance of 61 m (200 ft). After the "dynamic" maneuvering section, the course remains parallel to the original direction of travel for an additional 61 m (200 ft).

The lateral displacement of the course in the maneuvering section represents the motion of a point that is traveling at 88 km/h (55 mph) for 2.5 s with a lateral acceleration of the form $-A[\sin(2\pi/2.5)]$ where t is time in seconds (t = 0 at the beginning of the maneuvering section) and A = 0.15 g.

The test course should be laid out on a proving ground or other facility with adequate room to allow a heavy truck to reach 88 km/h (55 mph) (or its maximum speed on level ground if that speed is less than 88 km/h (55mph)).

The facility must provide sufficiently large space to allow the driver to recover control of the vehicle in the event control is lost during the prescribed obstacle avoidance maneuver occurring on the maneuvering section. Additional course space is also required for the driver to steer and/or brake to exit from the maneuver.

The test course should be nearly level (planar with a uniform grade) in all directions with a maximum slope that is no greater than 1% in any direction.

Ambient wind conditions should be less than 24 km/h (15 mph). Surface and wind conditions should be entered into the data sheets for each test.

The skid number of the dry test surface shall exceed 56 when measured at 64 km/h (40 mph).[2] If available, the skid number of the surface should be recorded.

3.2 **Vehicle Condition and Preparation**—The results of this test are known to be sensitive to how the vehicle is loaded and the condition of its tires. Also there is a danger that unrestrained vehicles may rollover in this test.

The condition of the vehicle's tires needs to be controlled. If the vehicle is to be operated with bias ply tires, it should be tested with new (broken in) bias ply tires installed on the vehicle. Otherwise, the vehicle is to be tested with new radial ply tires.

The tires should be broken in with at least 50 miles of running. Also the tires should be exercised by driving through the test course at least five times before taking any data. (The test driver will probably need at least this many practice runs to become used to the vehicle and the test course.)

Tire wear should be less than 2 mm (3/32 in). That is, the tread depth should be no less than the new tire tread depth minus 2 mm. If the vehicle is tested at other states of tire wear, those tread depths shall be reported.

The tire inflation pressures shall be set at the manufacturer's recommendations or the Tire and Rim Association specifications for the tire loads involved. Tire condition and inflation pressure shall be recorded on the data sheets. The tires shall be identified on the data sheets. Ideally the cornering stiffness for the tires will have been measured and these values will be recorded to aid in identifying the vehicle. Identification of the tires is very important because the shear force capabilities of the tires (particularly cornering stiffness) may have a large influence upon the results of these tests.

Unless special test loads are specified, the vehicle should be uniformly loaded to the maximum weight that it is expected to carry. Ordinarily (unless otherwise specified) this will be at the GCWR with axle loads close to their GAWR. The height of the center of gravity (cg) of the test load should be set to a height specifically chosen for the test. (If practical, a tilt table test (SAE J2180) may be used to identify the rollover threshold of vehicles that are to be tested for rearward amplification.) The cg height and rollover threshold, if available, for the vehicle in the condition used in testing for rearward amplification shall be recorded on the data sheets. The axle loads and the payload's cg height shall also be recorded on the data sheets identifying the vehicle.

Since how the load is distributed is important, the load used in the test needs to be described carefully. Ideally this description will either give the dimensions and location of the load or the moments of inertia of the load about horizontal, lateral, and vertical axes through the center of gravity of the load plus the location of the center of gravity of the payload. To the extent feasible, the moments of inertia of the load used in testing should be representative of the intended load to be carried in service.

The fill level of tank vehicles is important. Vehicles with partially filled tanks may not perform as well as vehicles with full tanks. The fill level shall be recorded when testing tank vehicles.

(In summary, and to aid in defining and identifying the vehicle being tested, Appendix B provides a list of pertinent vehicle properties that should be described and included with the test results.)

2. For directions on measuring dry surface skid numbers, see Federal Motor Vehicle Safety Standard FMVSS 105 or 121. These measurements follow ASTM procedures for measuring skid number except that the pavement is not wetted.

Since an unconstrained vehicle may roll over in this maneuver, the test vehicle shall be equipped with outriggers. (Information on outriggers is presented in Appendix C.)

3.3 Instrumentation Requirements—Transducers—Transducers shall be provided for measuring:

a. Forward Velocity (V) with an accuracy of ±0.5 mph over a range from 80 to 100 km/h (50 to 60 mph).
b. The time period of the maneuver (T) from the moment the front axle reaches the first plate of the maneuvering section until it reaches the last plate of the maneuvering section with an accuracy of ±0.03 s for time periods ranging from 2.0 to 3.0 s. (The idea here is to provide an event recorder that will determine the start and the end of the maneuvering section. This has been done with a laser optical device mounted on the front axle. The device discerns marks placed on the pavement indicating where the dynamic section begins and ends. Any other scheme that records the times when the front axle enters and leaves the dynamic section of the course will suffice.)
c. Lateral acceleration of the center of the front axle (AYX) with an accuracy of ±0.01 g over a range from 0.0 to 0.2 g. (This accelerometer may be attached to the axle and need not be mounted on a stabilized platform.)
d. Lateral acceleration of the center of mass of the sprung mass of the last semitrailer (AYT) with an accuracy of ±0.01 g over a range from 0.0 to 0.5 g. This accelerometer may be mounted upon a stable platform to eliminate the influence of vehicle roll upon the measurement of lateral acceleration, or trailer roll angle may also be measured to compensate for gravitational effects of a rigidly mounted accelerometer.

Measurements from the transducers listed previously are sufficient to determine rearward amplification. The following instrumentation is needed to determine the quality of the driver's steering and to evaluate the level of transient high-speed (dynamic) offtracking.

The test course is marked by "plates" that have five sides and a point as illustrated in Figure 2. The point is placed on the test course. A water-jet attached at a selected point on the front axle may be used to mark the vehicle's path. (See Appendix D.) Alternatively, a laser system or some other system may be used to measure the distance from the vehicle's path to the desired path (the test course). The test driver shall be capable of following the desired path within 15.2 cm (6 in). Any test run that does not meet this requirement is unsatisfactory and must be rejected.

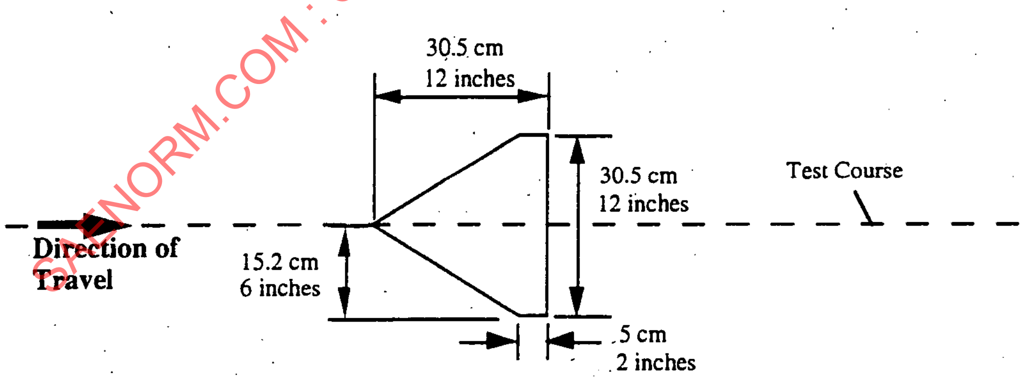
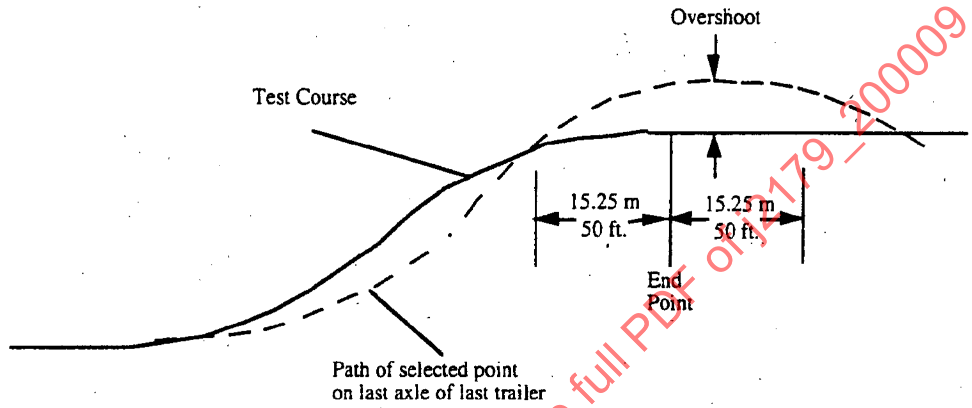


FIGURE 2—"HOME" PLATES USED TO MARK THE TEST COURSE

To determine transient high-speed offtracking, a water-jet or alternative device shall be attached to the rear axle of the last trailer at a point that corresponds to the selected 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 section (1.46 m (4.8 ft) from the original direction of travel) is measured. If the last trailer overshoots the tangent line in the region from 15 m (50 ft) before the end of the maneuvering section to 15 m (50 ft) after the end of the maneuvering section, the maximum level of overshoot shall be recorded. If the last trailer's path does not overshoot in this region, the amount of "undershoot" at the end of the maneuvering section shall be recorded. (See Figure 3.)



a. Overshoot

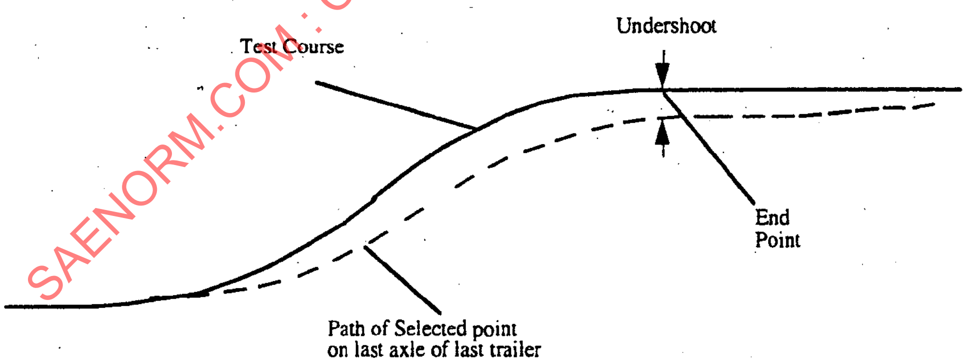


FIGURE 3—TRANSIENT HIGH-SPEED OFFTRACKING: OVERSHOOT AND UNDERSHOOT

3.4 Data Acquisition and Processing Requirements—The data from the transducers described in 3.3 shall be gathered as the test vehicle traverses the test course. The data should be recorded at a rate of 80 samples per second (or faster). At approximately 88 km/h (55 mph) there will be approximately 10 s of data for each channel. The data channels that need to be recorded are as follows:

a. Time, t.
b. Time of the start of the maneuvering section and time of the end of the maneuvering section, with the difference being the period, T.
c. Velocity, V.
d. Lateral acceleration of the front axle, AYX.
e. Lateral acceleration of the last trailer, AYT.

These signals need to have zero and full-scale calibration levels recorded and they need proper anti-aliasing filters. Low pass filters with cutoffs at 15 Hz are suitable.

The data processing system shall be capable of smoothing these signals using a 0.2 s uniformly weighted moving average. (A 0.2 s uniformly weighted moving average means replacing each data point with the average of all data points within a band of ±0.1 s about the original data point.)

The root-mean-square (rms) value of AYX from the start to the end time of the maneuvering section will need to be computed. The maximum absolute value of AYT occurring during the test will need to be determined also.

The data processing system shall be capable of computing means, standard deviations, and confidence intervals for sets of runs.

3.5 Requirements for Proper Execution of the Test Maneuver—For a test run to be properly executed, the driver shall follow the test course so that a selected point on the front axle of the vehicle does not deviate more than ±15 cm (±6 in) from the desired path defined by the test course. (The selected point may be located to aid the driver in following the course. A marker over the hood on the truck may aid the driver in sighting along the course. See Appendix D for more detail.)

The vehicle's average velocity shall be within ±1.6 km/h (±1 mph) of the selected speed over the maneuvering section. Nominally, the selected test speed will be 88 km/h (55 mph); however, lower speeds may be selected if the vehicle is not capable of traveling at 88 km/h (55 mph) on the test course. (For example, if the vehicle is only capable of traveling at approximately 85 km/h (53 mph), a set of five runs at 85 km/h ± 1.6 km/h (53mph±1mph) are needed to have a valid test sequence.) Higher speeds may also be run but the course is intended for use at 88 km/h (55 mph).

The vehicle's velocity should be as constant as possible throughout the entire test course but a ±3 km/h (±2mph) deviation from the selected speed is permissible on the initial and exit sections of the course if this helps the driver in executing the maneuver.

The period of time, T, taken from the start to the end of the maneuvering section shall be used to determine the average velocity over the maneuvering section. The average velocity is given by using Equation 1:

$$V = 61/T\,(m/s) \text{ or } (3.6)\,61/T\,(km/h) \qquad \text{(Eq. 1)}$$

A set of five acceptable runs is required to establish vehicle performance. In addition to the velocity (that is, period) requirements prescribed previously, the consistency of AYX should not be excessively erratic. The effective value of AYX (that is, 1.414 times its rms value) should not have a sample standard deviation greater than 0.02 g in a set of five runs. Ideally, the average value of AYX will be 0.15 g at 88 km/h (55 mph). At speeds other than 88 km/h (55 mph), the ideal level of AYX is given by using Equation 2:

$$AYX = 0.15(2.5/T)^2 \quad \text{(Eq. 2)}$$

The effective value of AYX should be greater than 0.1 g for a run to be acceptable.

3.6 Analysis of the Test Data—The test data is analyzed as follows:

First the checks for each test run as described in 3.5 are applied and bad runs are screened out.

For each test run that passes the checks, the average value of AYX is computed over the entire test course and this average is subtracted from AYX to remove any bias. Then the resulting signal is filtered twice using a moving average smoothing filter with a time width of 0.2 s. (This means that the signal is passed through the moving average algorithm once and then the result is passed through the algorithm once again.) Then the rms value of this signal is computed from the time at the start of the maneuvering section to the time at the end of the maneuvering section. The effective value of AYX is 1.414 times the rms value. This effective value is saved to be used in the denominator of the calculation of rearward amplification.

The signal AYT is filtered twice using a uniformly weighted moving average with an averaging width of 0.2 s. (The zero value of AYT needs to be carefully controlled since there is no easy way to remove any bias in the recording.) Then the peak value of this signal in the vicinity of the time of the end of the maneuvering section is read. This value is used as the numerator of the calculation of rearward amplification.

The value of rearward amplification is computed and stored for each run that has been found to be acceptable per the requirements of 3.5. (That is, the checks on V and AYX as specified in 3.5 are applied.) Once a set of five acceptable runs is obtained, the mean value (RAM) and the standard deviation (S) of the sample are computed. The result for the five acceptable runs is stated by Equation 3:

$$RA = RAM \pm 0.953\,S \quad \text{(Eq. 3)}$$

where:

$RAM = \Sigma\, RAi/5$
$S^2 = \Sigma\, (RAi - RAM)^2/4$
RAi represents the individual values of rearward amplification measured in each of the five acceptable test runs,[3] where RAi = AYTi (peak filtered)/AYXi (effective)

These values are to be used to determine whether the vehicle meets design targets or other target values of performance.

3.7 Interpretation of the Results—The value of RAM + 0.953 S represents an upper bound on the level of rearward amplification. From a statistical point of view and based upon the test results, there is a 5% chance that the mean rearward amplification for five runs is greater than RAM + 0.953 S.

To aid in interpreting results for various vehicles, an example based upon results for a typical Western double might be useful for comparison purposes. Results obtained by applying this test procedure to a heavily laden 36000 kg (80 000 lb) Western double with a rollover threshold of 0.35 g and equipped with modern radial truck tires indicate that its mean rearward amplification is approximately 2.0. For a vehicle to have a mean rearward amplification that is no higher than 2.0, the following inequality is based upon 95% confidence:

$$RAM + 0.953\,S < 2.0$$

3. 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

In summary, if the previous inequality is satisfied, one can say with 95% confidence that RA is less than 2.0.[4] (It should be clear that 2.0 is simply an example value and that it could be replaced by any other performance target one chooses to use.)

The same set of five runs used to determine rearward amplification can be used to determine the mean and sample standard deviations of overshoot or undershoot. The mean values of undershoot or overshoot can be used to determine the performance level for dynamic (transient high-speed) offtracking.

This ends the specification of this test procedure.

PREPARED BY THE SAE TRUCK AND BUS DYNAMICS SUBCOMMITTEE
OF THE SAE TRUCK AND BUS TOTAL VEHICLE SYSTEMS COMMITTEE

4. See, for example, Paul G. Hoel, Introduction to Mathematical Statistics, John Wiley & Sons, New York, 1984, pp. 146-149 for a discussion of "A Confidence Interval for a Normal Mean."

APPENDIX A

A.1 The test course for measuring rearward amplification consists of a "lane-change-like" maneuver in which the vehicle is required to move laterally 1.46 m (4.8 ft) as it moves forward 61 m (200 ft) at 88 kph (55 mph). (Figure 1 diagrams the course.) Table A1 details the specific distances for marking the initial straight, "dynamic," and exit sections of the course. The plate orientation is such that the course always passes through the tip of the plate and the center of the edge opposite the tip. (Plate geometry is detailed in Figure 2.)

TABLE A1—X, Y COORDINATES OF THE COURSE

X in meters	Y in centimeters	X in feet	Y in inches
–30.48	0.0	–100	0.0
–24.38	0.0	–80	0.0
–18.29	0.0	–60	0.0
–12.19	0.0	–40	0.0
–6.10	0.0	–20	0.0
0	0.0	0	0.0
3.05	0.3	10	0.1
6.10	1.3	20	0.5
9.14	3.3	30	1.3
12.19	7.1	40	2.8
15.24	12.7	50	5.0
18.29	20.3	60	8.0
21.34	30.0	70	11.8
24.38	42.2	80	16.6
27.43	55.9	90	22.0
30.48	70.6	100	27.8
33.53	84.8	110	33.4
36.58	100.3	120	39.4
39.62	112.8	130	44.4
42.67	123.4	140	48.6
45.72	132.3	150	52.1
48.77	138.7	160	54.6
51.82	143.0	170	56.3
54.86	145.3	180	57.2
57.91	146.3	190	57.6
60.96	146.3	200	57.6
67.06	146.3	220	57.6
73.15	146.3	240	57.6
79.25	146.3	260	57.6
85.34	146.3	280	57.6
91.44	146.3	300	57.6

To measure transient high-speed offtracking, it is convenient to add an additional reference line placed parallel to the exit section of the course. Use this line to measure the paths of the front axle and the rear axle separately. A convenient reference line is 30.5 m (100 ft) long with its center offset laterally from the last plate in the "dynamic" section of the course. The lateral offset of the line is 259 cm (102 in). The location of the reference line may be adjusted to accommodate the performance of the vehicle being tested.

Following is a list of the materials used to mark the test course:

a. Thin Sheet Metal—used to cut out the plates that marked the path.
b. Putty—used to secure the plates to the road surface. This has proved to be a very convenient way of temporarily securing the plates.
c. Heavy String—used as a reference marker for the offtracking measurement.
d. Paint—used to permanently mark the plate, traffic cone, stripe, and string locations.
e. Bright Durable Material—used to mark the entry and exit of the path. These help the driver align the vehicle with the path.
f. Traffic Cones—used to mark the course entry and exit.

APPENDIX B

B.1 This appendix provides a list of items pertaining to vehicle properties that have an important influence on rearward amplification. These properties should be described carefully so that persons examining the data from this test will be able to identify the vehicle being tested and know its pertinent mechanical properties. Items to be described and transmitted with the data include the following:

a. General identification of the tractor or truck towing the combination. Include items such as year, make, model, mileage, VIN, style, engine, powertrain, and other items that will serve to identify the power unit and its components.
b. General identification of all semitrailers, full trailers, dollies, and innovative dollies. Including year, make, model, etc., much like previous with the exception of power-related items.
c. Major dimensions including the locations (vertical, horizontal, and lateral) of all axles, tires, hitches, springs, etc. (A side view drawing is a good way to show the vertical and horizontal dimensions.) Also the locations and sizes of all of the cargo containers and load beds should be specified.
d. A description of the load. Its dimensions and weight and/or density. The distribution of loads on the tires. (The axle loads, as determined from scale readings perhaps, is a good way to show the distribution of load on the various wheels.) If available, measured values for center of gravity heights of the loads and their moments of inertia should be provided.
e. Dimensions and specifications of pertinent major components such as suspensions, springs, axles, wheels, and tires. There should be sufficient information so that the same (that is, a very similar) vehicle could be assembled and tested again.
f. Tire condition and state of use. The make, model, size and load range, tread depth, and hot or cold inflation pressure should be recorded for each tire. Tread depths before and after testing are desirable.
g. Any unique or unusual factor that would make the test vehicle behave differently from traditional highway trucks should be described.
h. If available results of tilt table tests for rollover threshold are useful information to include with the results of this test.

APPENDIX C

C.1 Outriggers are lateral extensions added to both sides of a unit to prevent it from rolling completely over. They are usually adjusted to allow the unit to roll beyond its "recoverable" roll angle before touching the ground and supplying a righting moment to prevent rollover. Figure C1 offers some detail of the outriggers used by UMTRI to measure rearward amplification and high-speed transient off-tracking of double and triple truck combinations.

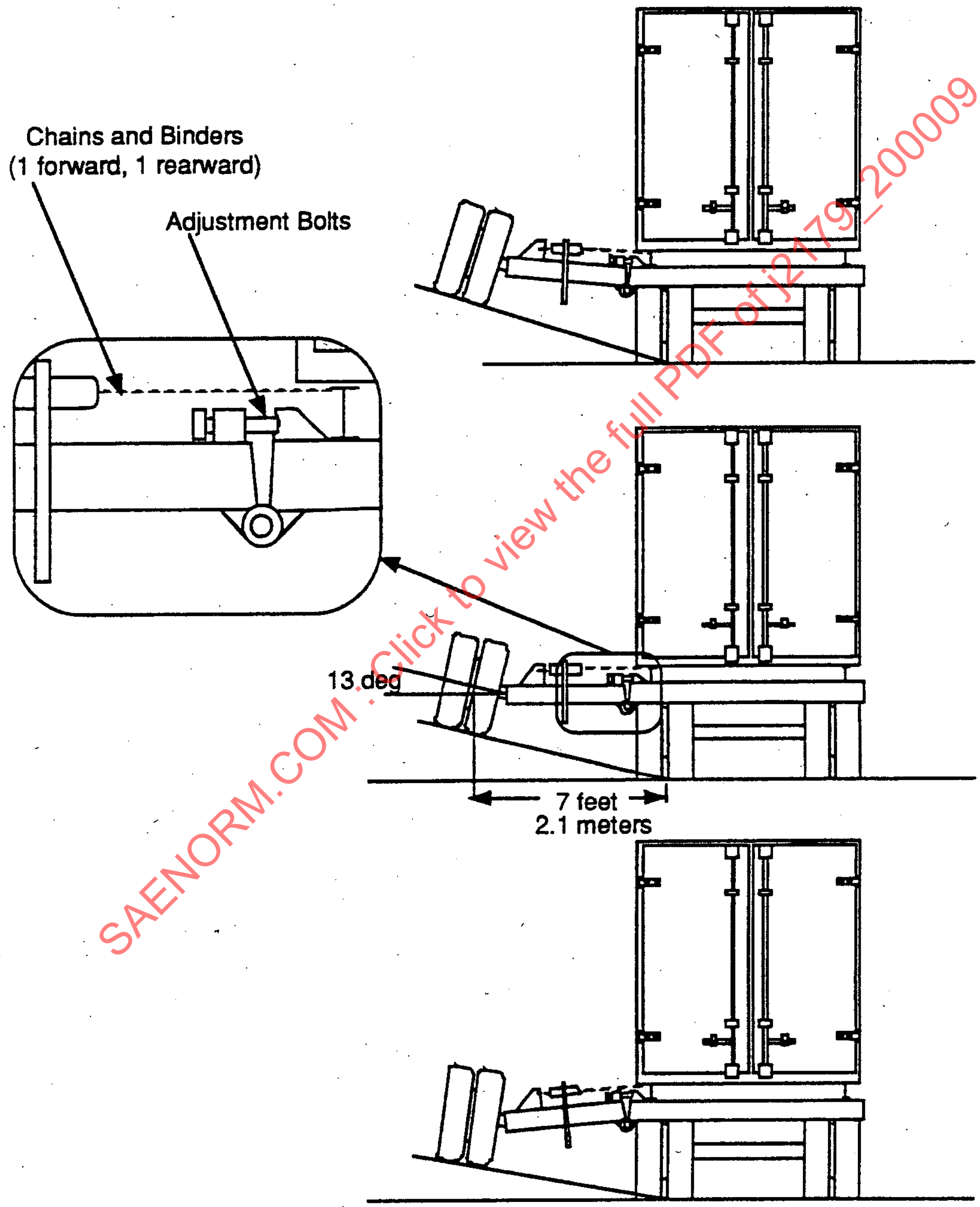


FIGURE C1—OUTRIGGER CONCEPT