Measurement of Changes to Vehicle Handling Due To Tread-Separation-Induced Axle Tramp

Mark W. Arndt and Michael Rosenfield
Transportation Safety Technologies, Inc.

Stephen M. Arndt
Safety Engineering & Forensic Analysis, Inc.

ABSTRACT

Tests were conducted to evaluate the effects of the tire-induced vibration caused by a tread separating rear tire on the handling characteristics of a 1996 four-door two-wheel drive Ford Explorer. The first test series consisted of a laboratory test utilizing a 36-inch diameter single roller dynamometer driven by the rear wheels of the Explorer. The right rear tire was modified to generate the vibration disturbance that results from a separating tire. This was accomplished by vulcanizing sections of retread to the prepared surface of the tire. Either one or two tread sections covering 1/8, 1/4, or 1/2 of the circumference of the tire were evaluated. The results demonstrated that a tire modified with two bonded-on tread sections driven at half speed replicated axle tramp characteristics of a modified tire with a single bonded-on tread section at the peak axle tramp speed. A second test series consisted of low speed vehicle handling tests with a right rear tire modified with two bonded-on tread sections. The on-road testing showed that the modified right rear tire caused axle tramp and associated vehicle skate at the peak axle tramp speed. A 1999 four-wheel drive Ford F-250 truck was tested with a tire modified by cutting away 1/4 of the tread and outer belt at two locations. The modified tire was placed at the left front position and low speed vehicle handling tests were conducted at the peak axle tramp speed. Test results show front-axle tramp induced an increase in steer gradient and significantly reduced turning capability.

INTRODUCTION

Road-induced vibrations in vehicle suspension systems are a topic of considerable interest in motor vehicle design. Dixon, in his book The Shock Absorber Handbook (1), describes a tire discomfort value derived from the r.m.s. value of the vertical force fluctuations divided by the mean vertical force. Dixon states, “a high tire discomfort value causes significant deterioration of the tire mean shear-force capability and therefore [causes significant deterioration] of the vehicle[‘s] cornering and handling capability.” Hop, according to SAE J670e - SAE Vehicle Dynamics Terminology (10), is the vertical oscillatory motion of a wheel between the road surface and the sprung mass. Axle tramp occurs when the right and left side wheels oscillate out of phase (10). Axle tramp as a self-exciting oscillation under conditions of acceleration and braking was studied by Sharp (2, 3). It was also studied by Kramer (4) who linked axle tramp to the occurrence of vehicle skate. Kramer stated that “skate occurs when the rear of the vehicle moves laterally while traveling over rough road surfaces.” Skate is described in materials provided for the Monroe® [shock absorber] Ride Control Seminar as “A condition where the rear of the vehicle moves laterally over rough surfaces. Typically caused by wheel shake which reduces the traction of the wheel…” (5). Skate is typically associated with rough roadway conditions and is not defined by SAE J670e - Vehicle Dynamics Terminology (10). Search of the SAE Handbook yielded no hits for the word skate. For the purpose of this paper skate will be defined as: a condition where the rear of a vehicle moves from a straight line direction without change to the steering wheel angle made possible by rear wheel hop (or a form of rear wheel hop) oscillation. A vehicle motion called “dart” is described as identical to skate but related to the front end of the vehicle.

A tire-tread separation event results when the tread either partially or completely peels away from the carcass of the tire while driving. Noise, vibration, and the vehicle pulling to the side of the separating tire have been a consistently reported vehicle response by researchers conducting tread separation event tests. The vibration is caused by a number of factors including: 1) a tire which is no longer round, 2) an imbalance of the tire, and 3) the vertical step that occurs as the tire rolls from a position on the tire surface where there is tread to a position where the tread has peeled off and back to where there is tread again. The step described in three (3) above is also influenced by flailing detached tread folding under the tire as it rolls. All of these factors tend to occur at the rotational frequency of the tire. The
tire induced vibration has been modeled as a sinusoidal vertical force lasting the duration of the tread separation event at the rotational frequency of the tires in a simulation study preformed by the USDOT (6).

As a result of a right rear partial tread separation event, an experienced and trained test driver lost control and rolled over the test vehicle during a vehicle handling test program while driving a 1996 four-door two-wheel drive Ford Explorer. This event was documented in a previously published paper without an explanation of why the loss of control occurred (7). It was hypothesized following this loss of control event that the type of suspension and type of tread separation may have been the key factors contributing to the loss of control. The 1996 Ford Explorer was equipped with a live rear axle with leaf spring suspension. The test involved a partial tread separation event where approximately half of the right rear tire’s tread separated, but was still attached. Analysis of test data shows no turning of the hand wheel prior to and during the initial stages of the tread separation event, yet the vehicle yawed rapidly clockwise, resulting in loss of control.

Quasi-steady state testing of the 1996 Explorer pursuant to the procedures dictated by SAE J266, method 1 (9) documented a reduction to the vehicle’s understeer gradient when equipped with either a complete or partial tread-separated rear tire. The understeer gradient was measured to be 1.5 deg/G for a 50% tread-separated tire when located at the rear of the vehicle on the outside of the turn. A range of forces and force durations have been shown to act on a vehicle during a tread separation event with the maximum forces typically occurring during long events (greater than 1.5 seconds) (8). An analysis of the effect of the maximum magnitude and duration of these forces on the Explorer with a 1.5 deg/G understeer gradient does not explain the severity of the turn documented in the test that produced the loss of control described above.

PURPOSE

The question posed at the beginning of the project described in this paper was, “Could a tire tread separation event produce axle tramp oscillations that result in measurable and destabilizing changes to a vehicle’s handling?” Two types of tests were designed to answer this question: 1) a laboratory based dynamometer (roller) test to evaluate tire conditions that would produce tramp mode oscillations, and 2) a full-scale handling test to determine whether tire caused tramp-mode-induced axle motion substantially changes the vehicle’s steer properties and cornering capabilities.

The roller test had two objectives: 1) to demonstrate and document tramp mode rear axle oscillations at highway speeds due to a rotating tire prepared to simulate the vertical input of a partial tread-separated tire, and 2) to demonstrate and document that the tramp mode oscillations can be induced at half the vehicle speed with a tire prepared to provide a vertical input two times per tire revolution. By meeting the goal of the second objective, the full-scale handling tests could be safely performed at half the speed required of a typical partial tread separation event.

Handling tests were completed on two vehicles: a 1996 four-door two-wheel drive Ford Explorer and a 1999 four-wheel drive Ford F-250 pickup truck. The Explorer tests evaluated the handling characteristics of a vehicle experiencing rear axle tramp, and the F-250 tests evaluated the handling characteristics of a vehicle experiencing front axle tramp.

METHOD – LABORATORY TEST

A 1996 4-door 2-wheel drive Ford Explorer at curb weight was positioned on the rear tires centered on a 36-inch diameter freely turning steel surfaced single roller. Vehicle test configurations included a control condition with four unmodified tires and a variety of experimental conditions with modified tires at the right rear.

The vehicle was secured in place with the rear wheels resting on the roller and the front wheels resting on a platform that maintained a proper trim condition. Tires were inflated to the manufacturer's specification of 26 psi. OEM wheels and recommended tires were used. OEM rear shock absorbers that had been in service prior to the testing were installed. The vehicle was constrained at the front by a standard tow bar that allowed for all natural roll and pitch motions and limited yaw movement. The tow bar would not allow forward or sideward movement of the front of the vehicle. The steering wheel was unlocked and no vehicle brakes were applied. The rear of the vehicle was not constrained by any physical attachment. Vertical movement of the vehicle was allowed. A safety chain was employed to stop excessive rear lateral or vertical vehicle motion but was never brought to bear. The roller was driven by the vehicle’s engine through the drive train. Throttle and braking were applied through an umbilical remote control.

Tires were prepared by first machining off most of the existing tread. This created an even surface for the attachment of sections of retread to the tire by vulcanization. The retread averaged 0.575 inches thick and covered the full width of the tire. The retread sections were varied in length to cover 1/8, 1/4, or 1/2 of the tire’s circumference. The vulcanized retread sections were rectangular in shape with both the leading and trailing edges beveled at 45 degrees.

Tires were prepared by vulcanizing either one or two sections of retread onto the tire. For tires on which two retread sections were attached, either 1/8 or 1/4 tread sections were used, and the sections were centered 180° apart from each other. Modified tires with one retread section are referred to as bonded 1/2 single tires. Modified tires with two retread sections are referred to as bonded 1/8 or 1/4 double tires.
Parameters measured during the laboratory test included speed (measured from the surface of the roller), right rear wheel RPM, left and right rear frame vertical displacement from the ground, left and right axle vertical displacement from the frame, and left and right axle vertical acceleration. Data was collected at 400 samples per second. Five real-time video cameras were used to document the test. Cameras documented an overall view, a close-up view of the left and right tires’ interaction with the roller, and an overall view of the rear suspension.

Each test was conducted by slowly applying throttle to increase wheel speed to over 80 mph. Deceleration of the tires was achieved by reducing throttle until the vehicle speed was less than 30 mph. The vehicle brakes were applied to bring the tires and roller to a stop. Axle tramp displacement and axle tramp acceleration was calculated by subtracting the left measurement from the right measurement in the time domain.

METHOD - HANDLING TEST

Two vehicles were tested to evaluate handling changes due to tread-separation-induced axle tramp. The Ford Explorer utilized in the laboratory test was again used in the handling test to investigate rear axle tramp, and the 1999 Ford F-250 four-wheel drive extended cab super-duty pickup truck was used to investigate front axle tramp.

The Explorer weight configuration was curb weight plus driver plus instrumentation. Two modified tire configurations were evaluated at the right rear wheel position. The modified tires used were bonded 1/8 and 1/4 doubles.

The F-250 had aftermarket equipment that included a rear suspension pitch stiffener and Rancho® Brand adjustable shock absorbers at all four wheels. The vehicle was ballasted with a driver, instrumentation that approximates a second occupant, and 205 lb in the truck bed centered over the rear axle. Tires on the truck were all terrain LT285/75R16 load range D, inflated to the vehicle placard pressure of 55 psi. The modified tire was evaluated at the left front wheel position. The modification consisted of removal of the tread and outer steel belt from two symmetrically opposite sections, each covering 1/4 of the tire’s circumference. These modified tires are referred to as cut 1/4 double tires. The leading and trailing edges of the remaining tread sections were not beveled. The truck was tested with all four shock absorbers adjusted to two positions: 1) maximum stiffness and 2) minimum stiffness.

Handling test instrumentation included that used in the laboratory test with the following changes and additions: speed was measured with respect to the ground instead of the roller; and vehicle slip angle, hand wheel angle, yaw rate, roll rate and accelerations at the center of gravity (CG) were added. Data was collected at 400 samples per second in the rear axle tramp test and 200 samples per second in the front axle tramp test. Different sample rates were dictated by different data acquisition hardware. Since the anticipated response of the axle was in the range of 10 Hz to 15 Hz a maximum sample rate of 200 samples per second was deemed acceptable. The comparability of the 400 samples per second versus 200 samples per second data in shown in the detail traces of Appendix A by contrasting the results of Explore laboratory testing (figure A1 and A2) to F250 handling testing (figure A6) respectively.

Handling tests were conducted in a control condition with four unmodified tires on both vehicles. The Explorer was tested with bonded 1/8 and 1/4 double tires at the right rear wheel position. The F-250 was tested with cut 1/4 double tires at the left front wheel position. Straight-line slowly increasing speed tests were completed first to determine if tramp mode oscillation occurred and the speed at which it peaked. This was accomplished by in-the-field analysis of the data. The second phase of the handling test protocol included Constant Speed Slowly Increasing Steer (CSSIS) tests and dropped-throttle 180 degree step steer (J-turn) tests, run at a speed that produced peak tramp mode oscillations. CSSIS tests of the Explorer were run with the driver providing the hand wheel input at a rate that approximated 20 degrees per second up to the limit of the vehicle’s turning capacity. CSSIS tests of the F-250 were made with a steering robot providing the hand wheel input at a rate of 13.5 degrees per second up to 270 degrees steer magnitude.

Figure 1. Unmodified tires Explorer laboratory (control) test’s calculated rear axle tramp acceleration versus measure speed.

RESULTS

Effective speed was calculated by multiplying the measured speed by two (2) for low speed tests run with the bonded and cut double tires. This was done so that a direct comparison could be made with high speed tests using bonded 1/2 single tires. The unmodified tire laboratory test’s (control) calculated rear axle tramp acceleration versus measure speed is shown in Figure 1. Calculated rear axle tramp acceleration versus
Figure 2. Bonded 1/2 single tire Explorer laboratory test’s calculated rear axle tramp acceleration versus measure speed.

Figure 3. Bonded 1/4 double tire Explorer laboratory test’s calculated rear axle tramp acceleration versus effective speed.

Figure 4. Unmodified tire Explorer handling control test’s calculated rear axle tramp acceleration versus effective speed.

Figure 5. Bonded 1/4 double tire Explorer laboratory test’s calculated axle tramp displacement versus effective speed.

Figure 6. Bonded 1/4 double tire Explorer handling test’s calculated rear axle tramp acceleration versus effective speed.

Figure 7. Hand wheel angle and vehicle slip angle in straight-line slowly increasing speed tests for the Explorer with unmodified tires.
measured speed for laboratory tested bonded 1/2 single tires is shown in Figure 2. Calculated rear axle tramp acceleration versus effective speed for laboratory tested bonded 1/4 double tires is shown in Figure 3. An example of calculated axle tramp displacement from the laboratory test with a bonded 1/4 double tire is shown in Figure 5. The unmodified tire handling control test's calculated rear axle tramp acceleration versus measure speed is shown in figure 4. Calculated rear axle tramp acceleration versus effective speed for handling tested bonded 1/4 double tires is shown in Figure 6.

Figures 7 and 8 show hand wheel angle and vehicle slip angle measured during straight-line slowly increasing speed tests for the Explorer in the control configuration and with a bonded 1/4 double tire respectively.

The Explorer spun out rapidly during J-turn tests conducted at a target speed of 30 mph and a left-hand wheel angle of 180° with bonded 1/8 and 1/4 double tires. The Explorer did not spin out in an identical J-turn test of the control configuration.

The calculated front axle tramp acceleration versus effective speed plots for unmodified tires and shock absorbers at minimum and maximum stiffness is shown for the 1999 Ford F-250 truck in Figures 9 and 10, respectively. The calculated front axle tramp acceleration versus effective speed plots for cut 1/4 double modified tire left front are shown for shock absorbers adjusted to minimum and maximum stiffness in Figures 11 and 12, respectively.

Summary understeer gradient results from the CSSIS tests are presented in Table 1 for the Explorer and Table 2 for the F-250. Appendix A contains a one second clip near the point of peak tramp response for each tests' result shown in figure 2, 3, 6 and 11. The one second clip demonstrates the opposite phase vertical oscillation at the left and right side of the axle. The recorded motion is consistent with observations during testing and video recordings of the axle motion.

DISCUSSION

The Modified tires used in the reported test were different from many tread separating tires because there was not a flailing piece of tread. A flailing piece of tread, due to contact with the vehicle and ground, would cause noise and longitudinal and lateral forces and damage. The magnitude and duration of forces have been previously studied and reported (8). The experiments described in this paper limited focus to the response caused by detaching tread induced vibrations.

For a tire that is in the process of a tread separation event the radius of the tire where tread has detached is different than the radius where the tread is still attached. The difference in radius is at least the thickness of the detaching tread and if flailing tread is attached may be up to two times the tread thickness. The difference in radius is effectively a bump in the tire and will affect balance, effective circumference, structure and vibration characteristics.

Bonded tires were used during the Explorer test series because of concerns about the durability of cut tires used for the laboratory test when run at high speed on the roller. Flailing detaching tread has produced significant damage to vehicles including broken brake components, fuel system components and wiring for lighting systems. There were no tire failures or tread detachments during any of the laboratory or handling test runs. Once it was proven that a consistent and valid low speed handling test could be successfully executed, a question was raised about whether bonded tires would produce different results than cut tires because tread separation events involve detachment and loss of tread, not addition of tread.

A comparison test was completed on a 1991 Ford E-350 15-passenger van. Both bonded and cut modified tires were run at the left rear wheel position for comparison. Results of a control, bonded and cut tire are shown in Appendix B. The results show that both bonded and cut tires produce a similar axle tramp versus speed response. The cut tire peak tramp oscillation occurred at a slightly higher speed when compared to the bonded tire. The cut tire tramp acceleration amplitude was lower compared to the bonded tire. The magnitude of the left and right axle acceleration shown in the one second clip near peak axle tramp response is approximately equivalent and in opposite phase. Differences were probably due to a changed structure and vibration characteristics caused by a weakening of the tire structure associated with the cut-away tread and outer belt sections.

REAR AXLE TRAMP LABORATORY TESTS

The dynamometer used in laboratory testing was used to determine if axle tramp motion could be recreated

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**Figure 8.** Hand wheel angle and vehicle slip angle in slowly increasing speed tests for the Explorer with right rear bonded 1/4 double tire.
using a modified tire with two symmetrically opposite bumps at half the speed of a modified single bump tire. All tires were balance before modification. Tires with a single bump were grossly unbalanced compared to the two bump tires. No attempt was made to rebalance the two bump tires. Because of symmetry two bump tires were not influenced by the same unbalancing effects present in a single bump tire.

The bonded 1/4 double tires' tramp mode oscillation peaks at an effective speed approximately 5 mph lower than the measured speed of the bonded 1/2 single tires. The shape of the two curves is similar up to the peak response speed. Figure A1 in Appendix A shows a one second clip for the bonded ½ single tire near the peak tramp response. Left and right measure responses were in opposite phase, had similar magnitude and the magnitude of the calculated tramp response was significantly larger compared to the magnitude of any one measured response.

The axle tramp of a bonded 1/2 single tire does not drop off above the peak response speed (Figure 2) while the bonded 1/4 double drops off gradually (Figure 3). Figure A2 in Appendix A shows a one second clip for the bonded ½ single tire at a measured speed of approximately 74 mph. Tramp was present at 74 mph for the bonded ½ single tire in that vertical motion of the left tire is upward when the right tire is moving downward, however, right displacement was much less than right displacement. Left and right acceleration were consistent with the measured displacements. The absence of tramp drop off at high speed for the bonded 1/2 single tire may be caused by the grossly unbalanced tire and driving forces transmitted through the drive train at higher speed in combination with other vehicle body vibrations. At speeds different from the peak tramp response speed, hop of the wheel with the bonded ½ single tire is similar to the combined out of phase displacements with the bonded ¼ double tire. Regardless of speed, a tramp response is measurable due to the connection between right and left wheels in a live axle equipped vehicle.

REAR AXLE TRAMP HANDLING TESTS

Rear axle tramp induced skate was observed in the straight-line slowly increasing speed test data. Skate used here is a condition where the rear of a vehicle moves from a straight line direction without change to the steering wheel angle made possible by rear wheel hop (or a form of rear wheel hop) oscillation. The vehicle began to develop a side slip which oscillated between positive and negative as the test driver steered the vehicle to maintain a straight ahead path (Figure 8). The data was confirmed by the test driver who reported that the vehicle required constant steering correction to maintain a straight path at peak tramp-inducing speeds. A maximum speed of 28 mph (56 mph effective speed) was achieved during the straight line tests. The effective peak axle tramp speed is between 52 and 56 mph (Figure 3).

The peak tramp response effective speed in the handling test is approximately 3 mph higher than in the laboratory test (Figures 3 and 6). The shape of the response up to the peak is similar. The maximum speed of the handling test was limited because of space and the need to maintain test driver safety.

While there may be many factors that influence the difference in peak tramp response effective speeds between a stationary vehicle and a driven vehicle, one measurable factor is the vehicle pitch and associated rear suspension deflections that occur during acceleration, deceleration and turning. The plots of axle vertical acceleration and vertical displacement during laboratory testing both show the peak tramp response effective speed to be 50 mph (Figures 3 and 5). The axle tramp acceleration plot displays a much larger and more distinct peak than the axle tramp displacement plot. These plots demonstrate that axle tramp acceleration is a good surrogate for determining the speed of peak tramp oscillation response that the displacement transducers measure.

The influence of rear axle tramp on vehicle handling is shown by the degraded vehicle turning response in the CSSIS tests. The understeer gradient decreases significantly (up to 90%) at speeds at or near the peak axle tramp response speed when compared to the control test condition (Table 1). The maximum hand wheel angle achieved during 28 mph (56 mph effective speed) CSSIS runs was substantially reduced with a bonded 1/8 or 1/4 double tire mounted at a rear wheel position on the outside of the turn. The peak hand wheel angle was limited in these cases because the vehicle spun out early during both runs. The understeer gradient is calculated using the same method for each test run. The method used measured data for the 0.1 G to 0.3 G range of lateral acceleration. The calculation forces a linear fit in the calculated range. The response is linear at speed below the peak tire-induced tramp speed, but is not linear at the peak tire induced tramp speed. The non linear response is due to impending spinout of the test vehicle subjected to tire induced rear axle tramp. Based upon the test results, vibrations consistent with a tire tread separation event produced wheel hop and axle tramp oscillations that resulted in measurable and destabilizing changes to a vehicle's handling.

The CSSIS tests with the modified tire at the inside of the turn did not result in spinout at any speed (right turn tests). For these tests there was a reduction of up to 56% in steer gradient when compared to the control test configuration (Table 1). Body roll and weight transfer to the outside (unmodified) tires reduced axle tramp. The unmodified outside tires gained authority as lateral acceleration increased during the turning maneuver which reduced the axle tramp effect and increased vehicle stability. In contrast to the result at peak tramp speed, the understeer gradient increased for each test conducted at the 20 mph target speed. This test speed
Table 1. Results from the Explorer handling test’s constant speed slowly increasing steer tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Speed (mph)</th>
<th>Measure Speed (mph)</th>
<th>Tires</th>
<th>Steer Direction</th>
<th>Spinout</th>
<th>Max Steer (deg)</th>
<th>Raw Steer Gradient (deg/G)</th>
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Figure 9. Unmodified tire F250 at minimum shock stiffness handling test’s calculated front axle tramp acceleration versus effective speed.

Figure 10. Unmodified tire F250 at maximum shock stiffness handling test’s calculated front axle tramp acceleration versus effective speed.

Figure 11. Cut ¼ double left front tire F250 at minimum shock stiffness calculated front axle tramp acceleration versus effective speed.

Figure 12. Cut ¼ double left front tire F250 at maximum shock stiffness calculated front axle tramp acceleration versus effective speed.
Figure 13. Steer gradient for front axle tramp handling testing comparing unmodified condition to cut ¼ double left front tire. The influence of shock absorber stiffness on the peak tramp response effective speed can be seen in the results of the Ford F-250 truck test using a cut 1/4 double tire at the left front wheel position. When this configuration was tested with all four shock absorbers in the minimum stiffness position, the peak axle tramp effective speed was found to be approximately 70 mph (Figure 11). When the four shock absorbers were adjusted to their maximum stiffness setting, the peak axle tramp effective speed increased to approximately 73 mph (Figure 12).

Large increases in steer gradient were measured with a cut 1/4 double tire on the left front of the F-250 (Figure 9). As shown is Figure 13, compared to the vehicle with four unmodified tires, approximately four times more rotation of the hand wheel was required to produce an identical right turn of the F-250 traveling at a speed that produced peak front axle tramp.

CONCLUSIONS

- Tires modified to replicate the vibration present in partial tread separation events were shown to induce wheel hop and tramp mode oscillations in solid axle equipped vehicles.
- Above the speed of peak tire-induced tramp response axle tramp motion is present due to the presence of a live axle.
- For the Explorer above the speed of peak tire-induced tramp response left and right wheel hop was in opposite phase but different magnitude. At higher speed modified right rear tire wheel hop was equivalent or greater than the tramp response calculated at peak tramp speed.
- The use of bonded or cut 1/4 or 1/8 double tires is a valid method to replicate peak tire-induced axle tramp at effective speeds. Effective speed refers to the test speed multiplied by two.
- Tire-induced axle tramp response observed during laboratory testing was replicated during handling tests.
- Peak tire-induced axle tramp speed can easily be determined from the axle tramp acceleration data collected with accelerometers located on each side of the axle. This is an effective alternative to the more complicated task of measuring axle displacement.

### Table 2. Results from the F250 constant speed slowly increasing steer tests with front axle tramp

<table>
<thead>
<tr>
<th>Shock Absorber Stiffness</th>
<th>Turn Direction</th>
<th>Tire Condition</th>
<th>Steer Gradient (0.1 - 0.3, deg/G)</th>
<th>Steer Gradient (0.1 to max, deg/G)</th>
<th>Max lateral G (G's)</th>
<th>Max steer (deg)</th>
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Figure 13. Steer gradient for front axle tramp handling testing comparing unmodified condition to cut ¼ double left front tire.

was significantly below the peak tramp speed of 27 mph to 28 mph measured in the straight-line slowly speed test (Figure 3, 40 mph effective speed). Out-of-balance and out-of-round vibrations were present in the vehicle at 20 mph. The increased understeer gradient at 20 mph may be caused by a whole-body vehicle vibration decreasing the ability of the vehicle to turn.

FRONT AXLE TRAMP

The influence of shock absorber stiffness on the peak tramp response effective speed can be seen in the results of the Ford F-250 truck test using a cut 1/4 double tire at the left front wheel position. When this configuration was tested with all four shock absorbers in
Tire-induced rear axle tramp required significant steer input to maintain vehicle control at the relatively low test speeds (skate).

The tire-induced rear axle tramp handling test shows significant reductions in vehicle directional stability at effective speeds near the peak axle tramp response speed.

The ability of a typical driver to control a vehicle with tire-induced rear axle tramp-induced skate while traveling at highway speeds will be diminished from what was demonstrated under these test conditions. Under most circumstances, maintaining vehicle control with a persistent tire induced rear axle tramp would not be expected.

The degradation in steer gradient was greater for the test vehicle experiencing tire-induced rear axle tramp than for a test vehicle fitted with a rear tire whose tread and outer steel belt had been completely removed.

As a vehicle turns, body roll and weight transfer effects reduce suspension symmetries, affecting axle tramp and steer response. Straight-line longitudinal acceleration and deceleration can also influence axle tramp.

The tire-induced front axle tramp tests show significantly higher steer gradients. At the peak axle tramp speed, the steering sensitivity was reduced to 1/4 of the value measured for the control vehicle.

A significantly reduced turning response occurs for a vehicle traveling at a speed that produces tire-induced front axle tramp. If a vehicle is steered consistent with what is normally required when tire-induced front axle tramp is not present, it will follow a significantly reduced turning radius when tire-induced front axle tramp is present.

REFERENCES


DEFINITIONS AND ACRONYMS

**CSSIS:** Constant Speed Slowly Increasing Steer.

**Hop:** According to SAE J670e (10), the vertical oscillatory motion of a wheel between the road surface and the sprung mass.

**Skate:** a condition where the rear of a vehicle moves from a straight line direction without change to the steering wheel angle made possible by rear wheel *hop* (or a form of rear wheel *hop*) oscillation.

**Steering Sensitivity:** According to SAE J670e (10), the change in steady-state lateral acceleration on a level road with respect to change in steering wheel angle at a given trim and test condition

**Tramp:** According to SAE J670e (10), tramp is the form of wheel hop in which a pair of wheels *hop* in opposite phase.

**Tramp Acceleration:** Calculated by subtracting the vertical acceleration measurement at one side of the axle from the vertical acceleration measurement of the opposite side.

**Tramp Displacement:** Calculated by subtracting the vertical displacement measurement at one side of the axle from the vertical displacement measurement of the opposite side.
Figure A1. Corresponding to Figure 2, Bonded 1/2 single tire Explorer laboratory test's measured and calculated rear axle displacements and accelerations versus time at peak tramp response measured speed.
Figure A2. Corresponding to Figure 2, Bonded 1/4 double tire Explorer laboratory test's measured and calculated rear axle displacements and accelerations versus time at speed equal to approximately 74 mph measured speed.
Figure A3. Corresponding to Figure 3, Bonded 1/4 double tire Explorer laboratory test’s measured and calculated rear axle displacements and accelerations versus time at peak tramp response effective speed.
Figure A4. Corresponding to Figure 6, Bonded 1/4 double tire Explorer handling test's measured and calculated rear axle accelerations versus time at peak tramp response effective speed.
Figure A5. Corresponding to Figure 11. Cut ¼ double left front tire F250 at minimum shock stiffness measured and calculated front axle displacements and accelerations versus time at peak tramp response measured speed.
Figure B1. Unmodified tire Van handling control test's calculated rear axle tramp acceleration versus effective speed.

Figure B2. Cut double tire Van handling test's calculated axle tramp acceleration versus effective speed.

Figure B3. Bonded double tire Van handling test's calculated axle tramp acceleration versus effective speed.
Figure B4. Corresponding to Figure B2. Cut double left rear tire Van measured and calculated rear axle accelerations versus time at peak tramp response measured speed.
Figure B5. Corresponding to Figure B3. Bonded double left rear tire Van measured and calculated rear axle accelerations versus time at peak tramp response measured speed.