

Passenger Car Response to Interaction with Tractor-Trailer Steer Tire Lugs

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ABSTRACT

Performing a reconstruction of sideswipe interactions is difficult due to the lack of permanent crush sustained by the vehicles involved. Previous studies have provided insight into the forces involved in creating various types of damage for vehicle-to-vehicle interactions during a sideswipe interaction. However, these data may not be applicable to the interaction that occurs when a tractor-trailer steer tire is involved. As demonstrated in previous studies, steer tire interaction produces a unique pattern of markings on the struck vehicle by the protruding lugs (wheel stud) of the steer tire. These studies have demonstrated that the pattern of cycloidal marks created by the wheel lugs can be used to calculate the relative speeds of the vehicles. While this is helpful in understanding the relative motion of the vehicles, it does not provide information regarding the forces applied at the point of contact. The purpose of this study is to assess the structural response of passenger cars during a sideswipe event involving a tractor-trailer steer tire. The study consists of quasi-static and dynamic tests performed using a stationary tractor-trailer tire spinning at an equivalent speed of 55 mph. A total of 20 quasi-static tests were performed using 3 separate vehicles by forcing the spinning tire against the side of a stationary vehicle. The force and displacement necessary to cause various levels of damage to the passenger car was measured to develop an understanding of the stiffness response at different locations along the side of the vehicle. A range of contact stiffness was achieved by forcing the tire against areas around the door pillars and at the center of the door panels which produced stiffer and softer responses respectively. A total of 8 dynamic tests were performed by driving the side of the same 3 vehicles against the rotating steer tire. The vehicle acceleration and change in speed (Delta-V) associated with contact were measured. Peak forces during the quasi-static testing ranged from 500 to 2,600 lbs with a range of deflection of 0.5 to 3.6 inches. The data provided by the quasi-static testing can be used to assess the lateral forces applied to passenger vehicles based on the level of damage sustained. The dynamic testing was performed at speeds of 4.5 to 6.5 mph and resulted in peak vehicle accelerations of 0.1 to 1.4 g in the lateral and 0.1 to 0.6 in the forward direction. The patterns created by the wheel studs were similar to those presented in previous studies. The results of the dynamic testing can be used to assess vehicle acceleration based on the severity of the damage observed.

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INTRODUCTION

Sideswipe collisions present a unique problem to an accident reconstructionist. Sideswipe collisions generally do not result in the vehicles reaching a common velocity during impact and, therefore are considered partial impacts. As a result of the shallow nature of the interaction between the two vehicles, sideswipes are characterized by a sliding interaction. The forces imposed between the vehicles are developed through a normal force against the side of the vehicle structure and a longitudinal force dependent on the frictional forces between the surfaces. Understanding the forces involved during a sideswipe based on post-impact evidence has received little attention. Several studies have performed sideswipe tests which provide some information that can be used to quantify the severity of a sideswipe event. Toor et al. [1] performed a series of barrier (n=19) and vehicle to vehicle (n=4) sideswipe

tests to assess the performance of an analytical model for sideswipes. Their analytical model was based on vehicle stiffness (A and B values) and an assumed inter-vehicular friction of 0.6. Only change in velocity of the test vehicles were reported and compared to the model results. Acceleration values and approach angles to the barrier or vehicle were not reported. The authors concluded that the predicted results from the model were relatively consistent with the values measured during testing. Vehicle to vehicle side-swipe impacts were performed by Bailey et al. [2] to assess vehicle response and the resulting damage. Their study provided acceleration profiles for a wide range of vehicle acceleration. They observed that characterizing sideswipes using change in velocity, or Delta-V and acceleration is difficult. The long pulse durations can produce moderate Delta-Vs with a low acceleration and the acceleration profile demonstrates peak values with a

duration less than 50 ms which may not influence occupant response due to the short duration. Their data demonstrated that higher longitudinal accelerations (3 to 4g) were produced when vehicle structures snagged during contact. Considering the levels of acceleration using during human volunteer studies, the occupant response is expected to be minimal from similar collisions [3, 4, 5, 6, 7]. In an effort to develop a mathematical model of a sideswipe collision Funk et al. [8] performed a series of sideswipe tests using a striking vehicle equipped with an instrumented bumper. The bumper was equipped with load cells which allowed the normal and tangential force to be measured during each test. Based on the results of the testing, a mathematical model was developed and validated. A comparison to standard stiffness values using EDSMAC was also performed demonstrating the overestimate of impact severity generated by using stiffness values derived from high-speed crash tests. Force-displacement data were also gathered which provided a lateral stiffness value for the vehicle within the sideswipe model.

Several studies have examined sideswipe events involving tractor-trailers. Previous analyses have been performed using the cycloidal marking created by tractor steer tire lugs to calculate the relative speeds between the vehicles involved [9, 10]. Varat et al. performed dynamic testing to generate the cycloidal markings and expanded on the general equations developed by Levy et al. Their analysis produced a range of lug patterns and their meaning with respect to relative vehicle velocity magnitude and direction. The data from the vehicle instrumentation demonstrates the long duration associated with Varat et al.'s sideswipe events. More recently, Pearce and Parker (2011)[11] demonstrated a step-by-step procedure for applying the equations developed by Varat et al. Their study also included three examples demonstrating how to apply the equations describing the shape of the lug nut marks to real-world incidents. Focusing on occupant response to tractor-trailer sideswipes, Fittanto et al. [12] performed a series of sideswipes using three different Ford Taurus sedans. Occupant response was assessed using a 50th percentile Hybrid III dummy. The study provided valuable data with respect to vehicle damage, vehicle acceleration and occupant response. A more detailed analysis of occupant response was reported in a companion paper [13]. Consistent with previous studies on sideswipe events, the authors found that the extent of damage during a sideswipe event is not directly comparable to damage sustained during a full vehicle to vehicle impact because the damage is associated with longer impact durations.

The previous work involving sideswipe events provide valuable data regarding vehicle and occupant response. The findings of the previous research consistently demonstrate the minor nature of these events which results from their long duration which allows energy transfer or a velocity change to occur over an extended period thereby reducing vehicle acceleration and relative occupant motion. The purpose of the current study is to evaluate passenger car response to a tractor steer tire.

METHODOLOGY

The test series was performed using three passenger vehicles, a 2006 Ford Crown Victoria, a 2008 Honda Civic and a 1993 Toyota Tercel (Appendix A). Each vehicle was evaluated under quasi-static and dynamic testing which will be described separately.

Quasi-Static Testing

The quasi-static testing was performed by exposing the left side of each vehicle to the lugs of a spinning tractor-trailer steer tire. An apparatus was constructed that would allow the tire to spin at a rate equivalent to a speed of 55 mph while being forced against the vehicle (Figure 1). The tractor tire had an overall diameter of 43 inches and was mounted 1.5 inches above the ground. The wheel lugs had an outer diameter of 12 inches. The tractor tire was accelerated up to speed using a 3-phase electric motor which drove a smaller tire that had an interference fit with the tractor tire. The steer tire was mounted to a movable platform controlled by hydraulic cylinders which were mounted in-line with the line of action of the steer tire against the vehicle. Each cylinder was equipped with a load cell (1210AO, Interface, Scottsdale, AZ) that measured the applied load. A displacement transducer (E-Series, MTS, Cary, NC) was attached to the platform to record the motion of the wheel toward the vehicle. The motion of the vehicle was measured using video (Phantom 7.3, Vision Research, Wayne, NJ) as well as a string potentiometer (PT101, Celesco, Chatsworth, CA) mounted to the opposite side of the vehicle and the location of the tire contact. The data from the video and string potentiometer were used to calculate the actual deformation sustained by the vehicle during each test. The locations of the tests were chosen to assess the relative stiffness of the stronger structural components (hinge pillars) and the more cosmetic (door shell, fender) components of the passenger vehicles.



Figure 1. Apparatus used to move spinning tractor tire into passenger vehicles.

Dynamic Testing

A series of dynamic tests were performed using the opposite side (right) of the vehicles tested under the quasi-static conditions. The dynamic tests were performed by driving each vehicle against the spinning tire in a rearward direction. During each test, vehicle acceleration was measured using an accelerometer array (7290E-R-S-10, Endevco, Irvine, CA) mounted on the center tunnel and sampled at 10 kHz. Vehicle coordinates are per SAE J211. Vehicle position was recorded by video (Phantom 7.3, Vision Research, Wayne, NJ). Vehicle velocity was calculated from integration of the accelerometer data and was checked against video data when available. A range of contact angles were achieved by using varying amounts of steer into the tractor steer tire. During the dynamic tests, the steer tire platform was stationary and due to the dynamic nature of these tests, the load cell data would have been altered by the inertia of the steer tire and, therefore, were not recorded during the dynamic test series.

RESULTS

Quasi-Static Testing

A total of 20 quasi-static tests were performed on the three vehicles ([Appendix A](#)). Overall, peak forces ranged from 465 to 2,620 lbs and varied with test location. Several repeat tests were performed on the same location on the Crown Victoria to provide a range of force-displacement curves at a range of deflection values. A series of repeated tests were initially performed at the A-hinge pillar of the Crown Victoria (Tests 1-6). These tests produced peak deflections of 0.6 to 3.6 inches. Since these tests were performed at the same location, the force-deflection data were merged by plotting subsequent tests such that the force at the maximum deflection value of the previous test equaled that of the subsequent test ([Figure 2](#)). The first four of these tests were performed using lug-nut covers with a rounded tip. These tests produced little permanent crush to the vehicle, but did result in a flattening of the lug nut covers ([Figure 3](#)). After exposure to a force of 1,520 lbs (Test 4), the lugs wore through the thin covers and were no longer used. The remaining tests were performed without lug nut covers.

The Ford Crown Victoria response was assessed by location ([Figure 4](#)). Tests were performed at the A and B - hinge pillars which are essentially the junction between the driver door and the front fender and the junction between both left side doors. The junction between the rear door and the rear wheel well was denoted as the C-post. The combined A-hinge pillar tests produced a peak force of 2,620 lbs at a deflection of 1.7 inches. The single test performed at the B-hinge pillar produced a peak force of 2,570 at a deflection of 1.8 inches. These tests represent a linear stiffness of 1,550 and 1410 lb/in respectively. The B-hinge pillar produced a similar response up to a deflection of 1 inch, beyond which it produced a relatively flat force response until a deflection of 2 inches. A subsequent

test (Test 10) of the same location demonstrated an increased stiffness after exceeding the previous deformation resulting in a peak force of 2,300 lbs at 2.5 inches of deflection.

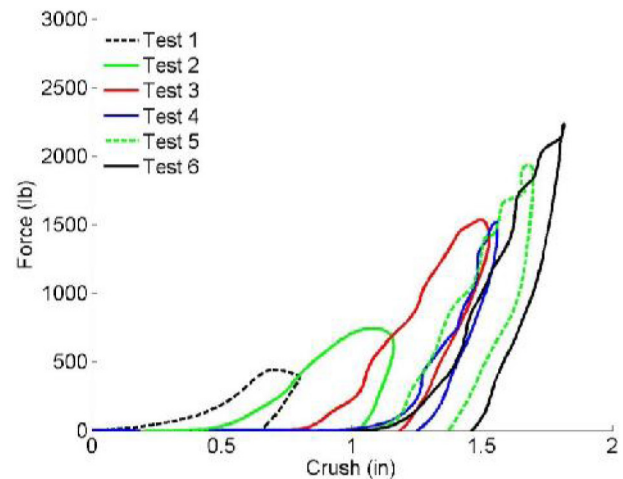


Figure 2. Repeated tests on Ford Crown Victoria A-hinge pillar.



Figure 3. Post-test 4 demonstrating flattening of lug nut cover and corresponding damage to A-hinge pillar.

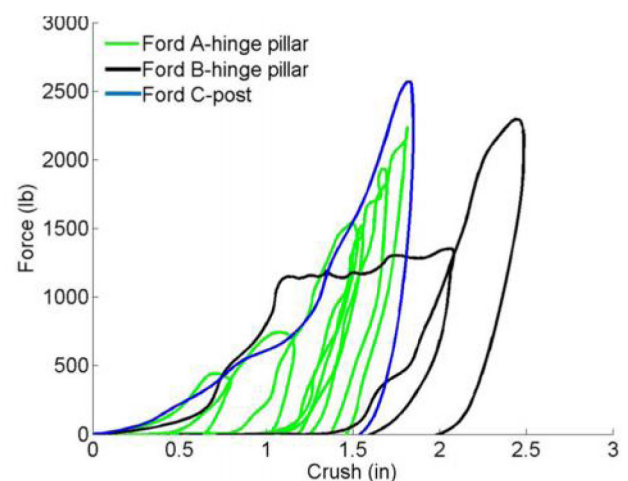


Figure 4. Ford Crown Victoria hinge pillar tests.

Single tests were performed on various body panels of each vehicle (Figure 5). Two tests performed on the Honda driver door produced nearly identical results demonstrating an initial stiffness of 796 lbs/in on average. Both tests demonstrated a loss of structural integrity at approximately 1 inch of crush. During these tests, tears and holes in the door panel were created, particularly around the side door beam. The Ford driver door exhibited a slightly softer response with an initial stiffness of 510 lbs/in.

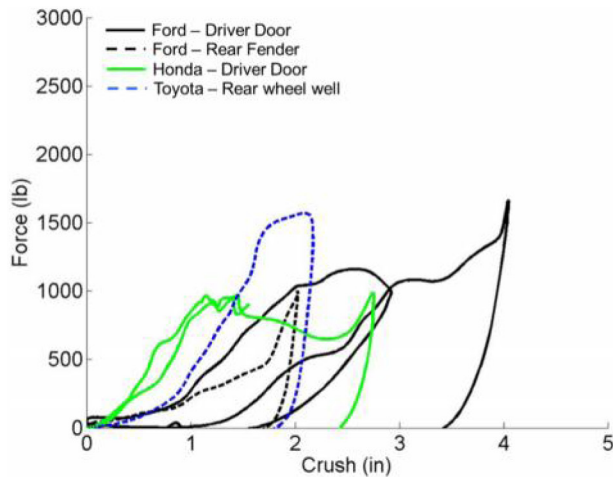


Figure 5. Crush for tests performed on body panels for each vehicle.

Hinge pillar response during non-repeated tests was compared between vehicles (Figure 6). Except for the Honda B-hinge pillar, all other vehicles and pillars produced similar initial stiffness. The Toyota and Ford B hinge pillars exhibited a loss of structural support at 1.1 and 1.4 inches respectively. Both vehicles exhibited a relatively flat force response despite crush of 2 inches and greater.

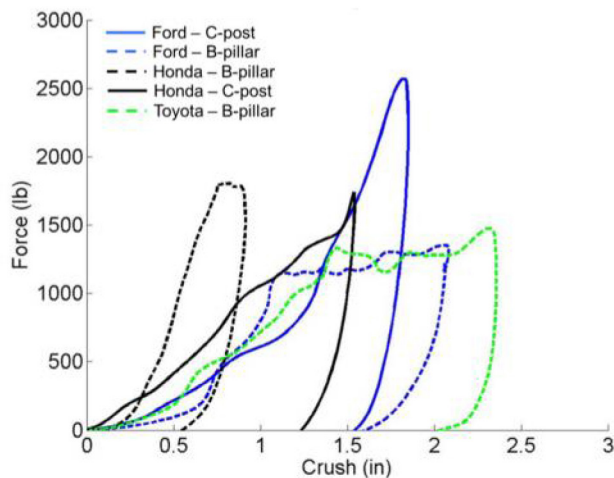


Figure 6. Force-displacement response of pillar tests for all three vehicles.

In test 20, the Toyota A-hinge pillar was tested with the vehicle unsupported, allowing the rear of the vehicle to rotate (Table 4 Appendix A). This test resulted in smearing of the damage pattern across a wider area as the vehicle rotated away from the tire. This test was not included in the force-displacement plots due to the excessive rotation which precluded the actual crush from being calculated accurately.

Dynamic Testing

A total of 8 dynamic tests were performed on the right side of each vehicle which is opposite to the side exposed to the quasi-static testing described above (Appendix B). All tests were performed at a shallow angle of approach ranging from 0.5 to 2 degrees. This angle was achieved by manually steering the vehicle toward the tractor tire to produce contact at the desired location. The approach speed was achieved by manually pushing the vehicle at speeds of 4 to 6 mph. All tests were performed with the vehicle initially moving rearward toward the tire. One test resulted in a velocity change such that the vehicle changed direction. This occurred in the first dynamic test (Test 1) and was caused by the rear wheel well snagging on the steer tire lugs. This test produced a peak acceleration of 1 g which was the highest longitudinal acceleration measured for all dynamic tests. During the dynamic tests, the steer tire lugs produced the characteristic cycloidal markings demonstrated by the previous studies on steer tire interaction (Figure 7). The acceleration data demonstrated low level variation with local short duration peaks (Figure 8).



Figure 7. Post-test photograph of Honda Civic after dynamic Test 5.

Overall, vehicle acceleration had no significant correlation to the change in velocity experienced (Figure 9). In general, higher accelerations were associated with a higher change in velocity. Lateral and longitudinal acceleration values were also correlated; however a significant trend was not seen, mostly due to the high lateral acceleration experienced during Test 8.