

Application of Lateral Pole Impact Force-Displacement Data to the Reconstruction of Side Impacts with Narrow Objects

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ABSTRACT

Reconstruction of passenger vehicle accidents involving side impacts with narrow objects has traditionally been approached using side stiffness coefficients derived from moveable deformable barrier tests or regression analysis using the maximum crush in available lateral pole impact testing while accounting for vehicle test weight. Current Lateral Impact New Car Assessment Program (LINCAP) testing includes 20 mph oblique lateral pole impacts. This test program often incorporates an instrumented pole so the force between the vehicle and pole at several elevations along the vehicle - pole interface is measured. Force-Displacement (F-D) characteristics of vehicle structures were determined using the measured impact force and calculated vehicle displacement from on-board vehicle instrumentation. The absorbed vehicle energy was calculated from the F-D curves and related to the closing speed between the vehicle and the pole by the vehicle weight.

The presented approach resulted in approximately a 2% underestimation of closing speed in large four-door sedans and approximately a 9 to 10% underestimation in large four-door pickup trucks. Accounting for structural restoration is important when assessing accident severity using this methodology. The nominal restoration of the vehicle structures was generally calculated to be in the 17 to 21% range. Furthermore, comparison of F-D curves between vehicle classes and different elevations on a given vehicle is useful for assessment of field crashes, which can occur in various orientations.

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INTRODUCTION

Automobile accident severity is commonly assessed through vehicle crush energy analysis. Based on vehicle residual deformation (or crush) in crash tests, stiffness characteristics are derived. The energy dissipated during deformation of the vehicle's structures during an accident is assessed based on the vehicle's residual crush and derived stiffness coefficients. Using the vehicle mass, a barrier equivalent velocity (BEV), or the equivalent closing speed with a fixed rigid barrier, is then computed. Linear and non-linear approaches to crush energy analysis have been developed and validated [1-4]. Calculation of crush energy due to impact with narrow objects poses a unique challenge in that the majority of available crash testing used to define vehicle stiffness characteristics involves engagement across the entire front of the vehicle or, in the case of side impacts, the majority of the occupant compartment. The distributed impact forces and resulting damage from the wider barriers do not directly apply to narrow object impacts that occur in the field. Additionally, the specific structures contacted (for example, the vehicle body as opposed to the vehicle chassis and suspension components) significantly influence a vehicle's stiffness characteristics [5-7].

Multiple methods for assessment of BEV due to impact with a narrow object are available. One such approach is based on regression analysis of available narrow object crash tests, grouped by vehicle class, and is based on the maximum vehicle residual crush and vehicle mass [8-9]. This method is limited by the range of crash test speeds available and the assumption that each vehicle in a particular class will have similar stiffness characteristics. A second approach utilizes crush stiffness coefficients derived from barrier impact tests and a modified method for quantifying vehicle crush [3, 5]. The planar crush based on the displacement of equally spaced points along the residual crush profile of the vehicle is used as opposed to one-dimensional perpendicular crush measurements. This is intended to account for a reduction in the width of the crush profile due to induced vehicle damage during narrow object impacts.

The National Highway Traffic Safety Administration (NHTSA) maintains a vehicle crash test database accessible to the public. A wide range of vehicle crash types and tested vehicles are included within the database. Historically, there have been limited lateral pole impact tests available. However, 20 mph lateral oblique pole tests have more recently been conducted as part of the New Car Assessment Program (NCAP). The vehicle is accelerated to an initial speed near 20 mph and aligned such that the front of the vehicle contacts a fixed rigid 8 inch diameter pole. The vehicle is oriented at

an angle of 15 degrees from lateral, resulting in a primarily lateral impact with a smaller frontal component (see Figure 1). In addition to an instrumented anthropomorphic test device (ATD), typical vehicle instrumentation includes accelerometers near the vehicle's center of gravity, the struck side hinge pillars and door, and far side rocker and roof rail, approximately in line with the impact point. Furthermore, as part of the test protocol, the rigid poles used in the tests are generally instrumented with eight load cells split between four pole sections at various heights above the ground to allow the forces between the pole and vehicle to be quantified (see Figure 2).

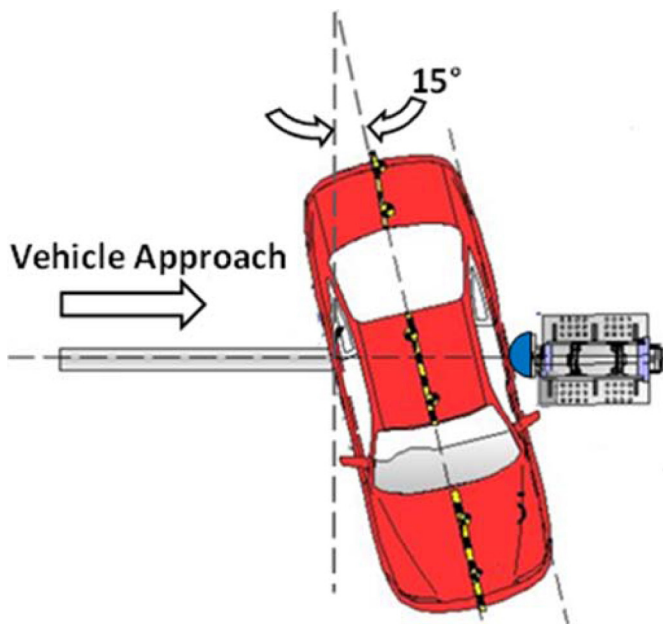


Figure 1. The oblique lateral pole test impact orientation is 15° from perpendicular to the vehicle approach velocity (taken in part from NHTSA test report v08067).

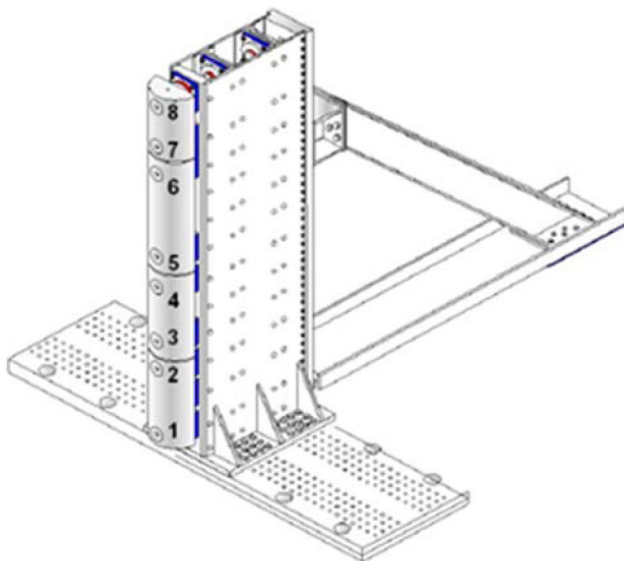


Figure 2. Fixed rigid pole instrumented with eight load cells, two on each of the four pole sections (taken from NHTSA test report v08067).

The accuracy of using test vehicle and pole instrumentation to determine closing speed or BEV in oblique lateral pole impacts was assessed by calculating the absorbed energy due to vehicle deformation at maximum crush. This was accomplished by determining vehicle force - displacement characteristics based on the forces measured at the pole - vehicle interface and through double integration of vehicle acceleration. Multiple approaches to calculating vehicle displacement were assessed using various vehicle accelerometers. Due to the inherent nature of crash testing, not all of the accelerometers were intact after the tests were completed. The accelerometers used as the basis for this method were chosen because of their alignment with the vehicle's center of gravity and their placement away from the crush zone, thus increasing the probability they remained intact and operational throughout the test. The calculated residual deformation was compared to that recorded in the crash test reports and the resulting vehicle restitution was evaluated. In addition to assessing the total force-displacement characteristics, the force-displacement characteristics and the resulting absorbed energy at various vehicle elevations were calculated and compared. The overall responses of large four-door pickup trucks and large four-door sedans were compiled and compared.

METHODOLOGY

The NHTSA crash test database was searched for lateral pole impact tests that incorporated an instrumented pole. Nearly 300 tests were identified by searching the instrumentation database for the presence of pole load cells in the "SENATT" data field. In order to evaluate the proposed reconstruction methodology, a subset of tests was selected by vehicle class. Each test vehicle's class was defined based on the Highway Loss Data Institute's Vindicator software [10]. Large four-door sedans and large four-door pickup trucks were selected for evaluation since they represent two distinctly different vehicle body constructions. This resulted in a total of 30 (18 and 12 respectively) 2011 model year and newer vehicle tests with available test data. Test reports, data and overhead video were downloaded from the NHTSA database for each test. The test vehicle impact speed, maximum residual crush and weight for each test were identified in the crash test database and verified with the reported values in each test report.

The displacement of each test vehicle upon contact with the pole was calculated using data from on-board vehicle instrumentation. As the impacted pole was rigid and stationary, the vehicle motion relative to the pole was equivalent to the pole's penetration into the vehicle side structure which resulted in vehicle crush. Video for each test was reviewed to confirm that the vehicle yaw rotation during the time between contact with the pole and maximum crush was minimal ($< 5^\circ$). Vehicle rotation increased during some tests during the restitution phase and primarily after separation with the pole. The lateral accelerations at the vehicle center of gravity, far side sill, and far side roof rail were assessed. The accelerations were filtered at CFC 180 and then were numerically integrated using the trapezoidal rule to obtain vehicle speed throughout the impact based on the reported initial speed. A second integration was conducted to calculate the vehicle displacement during the impact. It was observed that in several tests, the far side roof rail displacement deviated from the others, likely due to induced roof deformation near the accelerometer mounting location, and was therefore excluded from further analysis.

Additionally, it was observed that in many tests, the validity of the reported center of gravity accelerations was called into question in the test reports because of equipment failure or damage to the accelerometers from the test itself. Results are summarized, both including and excluding these tests.

As the lateral pole impact tests are conducted at an oblique 15° angle from perpendicular to the vehicle, the effect of misalignment between the accelerometers mounted in the vehicle coordinate system and the orientation of the pole load cells was resolved in two ways. First, the acceleration measured by the far side sill lateral accelerometer was divided by the cosine of 15° (Equation 1). This approach assumes that any longitudinal vehicle acceleration is negligible. Second, the longitudinal vehicle acceleration measured at the center of gravity, the nearest longitudinal accelerometer to the far side sill lateral accelerometer, was used in combination with the far side sill lateral accelerometer to calculate the vector sum of acceleration parallel to the vehicle approach direction (Equation 2). Figure 3 is a generic depiction of the general location of these accelerometers relative to the pole and the test vehicle approach velocity.

$$A_{xy} = \frac{A_y (\text{far side sill})}{\cos(15^\circ)} \quad (1)$$

$$A_{xy} = A_y (\text{far side sill}) * \cos(15^\circ) + \dots + A_x (\text{CG}) * \sin(15^\circ) \quad (2)$$

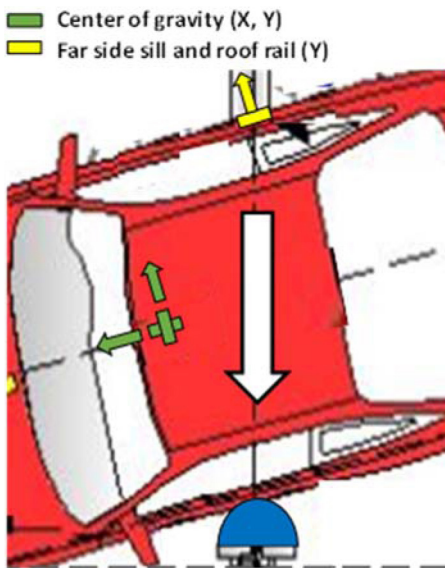


Figure 3. Depiction of the approximate locations and orientations of vehicle accelerometers relative to the fixed rigid pole and the vehicle approach velocity.

For each test, both approaches outlined in equations (1) and (2) were used to calculate vehicle acceleration during impact, and subsequently vehicle velocity and vehicle displacement (crush). Figure 4 presents the acceleration data from one of the chosen tests. Figures 5 and 6, based on the data in Figure 4, depict how both the adjusted far side sill and the combination of the far side sill lateral

acceleration and center of gravity longitudinal acceleration compare to using the unadjusted far side lateral sill acceleration. Both approaches were conducted for each crash test evaluated.

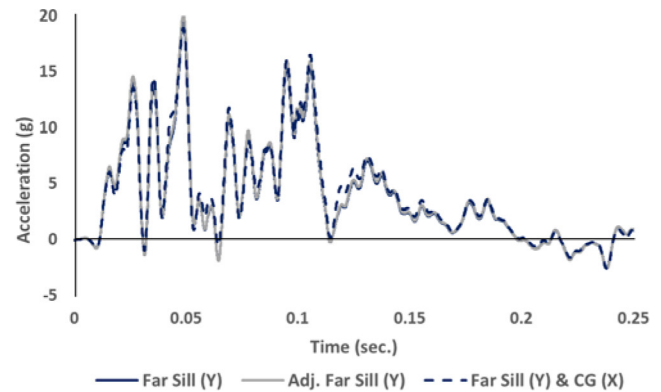


Figure 4. Acceleration (CFC60) versus time plots used with Equations 1 and 2 to compare velocities and displacements calculated to using the far side sill lateral acceleration in test 8067.

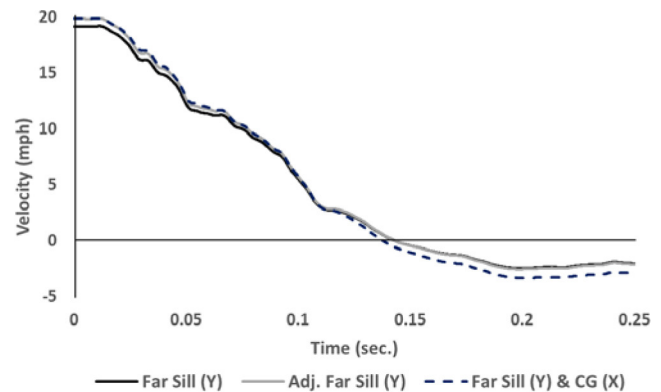


Figure 5. Velocity versus time plots derived using Equations 1 and 2 compared to using the unadjusted far side sill lateral acceleration in test 8067.

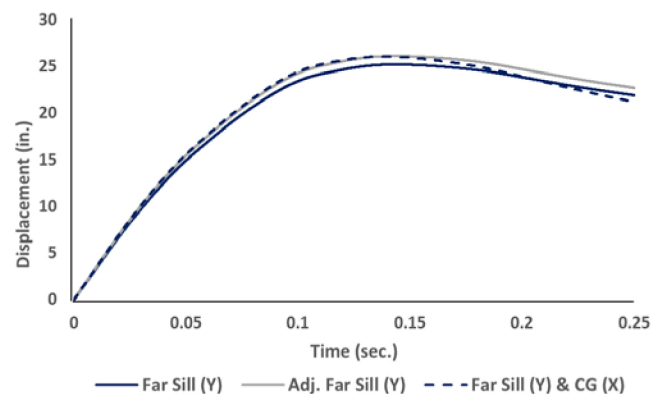


Figure 6. Displacement versus time plots based on results from Equations 1 and 2 compared to using the unadjusted far side sill lateral acceleration in test 8067.

The accuracy of the displacement calculation was assessed by comparing the final displacement or vehicle crush to that reported in each test report. The final displacement, or residual crush, was defined at the time the total force between the pole and vehicle decreased to approximately 1200 lbs. (5.3 kN). This level of force corresponded to the point where the change in velocity from one time

step to the next approached zero, and was confirmed visually by inspecting the overhead crash test videos for the time where the test vehicles separated from the test pole. This same point in time was used to define the maximum rebound velocity. The restoration of each vehicle structure was then assessed by comparing the maximum dynamic crush to the final residual crush. The restitution of each vehicle was assessed by comparing the vehicle rebound velocity to the impact speed.

The fixed rigid pole in each test incorporated eight load cells, two for each of the four pole sections. The measured loads for each pole section were filtered at CFC 60 and summed across the pair of load cells, and also for all eight of the load cells to generate the total reactive force between the vehicle and the rigid pole. Figures 7 and 8 depict each pole section and total pole force versus time and versus crush, respectively, for a sample test.

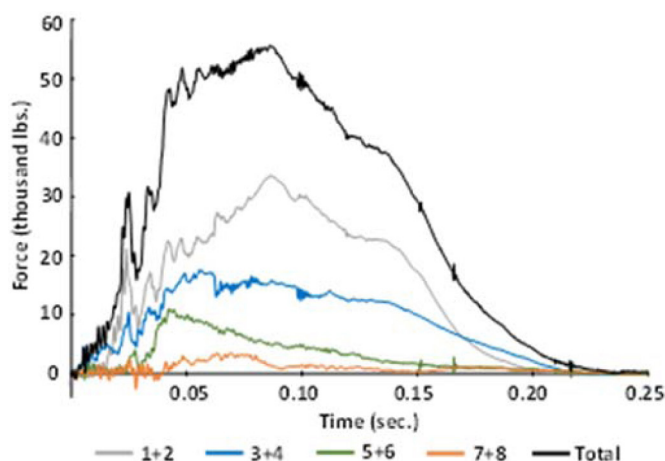


Figure 7. Sample pole force versus time plot for each of the four pole sections and for the total force in test 8067.

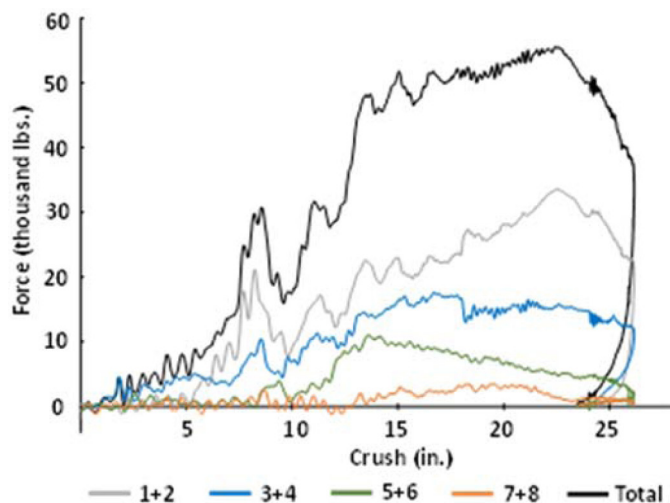


Figure 8. Sample force versus crush plot for each of the four pole sections and for the total force in test 8067.

The absorbed energy was calculated for each test through integration of the force versus crush plot. The integration was conducted from the first contact with the pole to the maximum crush using the trapezoidal rule. This process was conducted for both displacement calculation methods demonstrated previously in Figure 6. The absorbed energy was then related to vehicle closing speed or BEV using the test weight of the vehicle. Figure 9 depicts the relationship between the total force and crush for each of the displacement calculation methodologies for a sample test. Finally, the absorbed energy for each of the four pole sections was calculated for comparison to each other and across vehicle classes. Results are reported based on the average values of vehicle response metrics plus or minus one standard deviation to account for error.

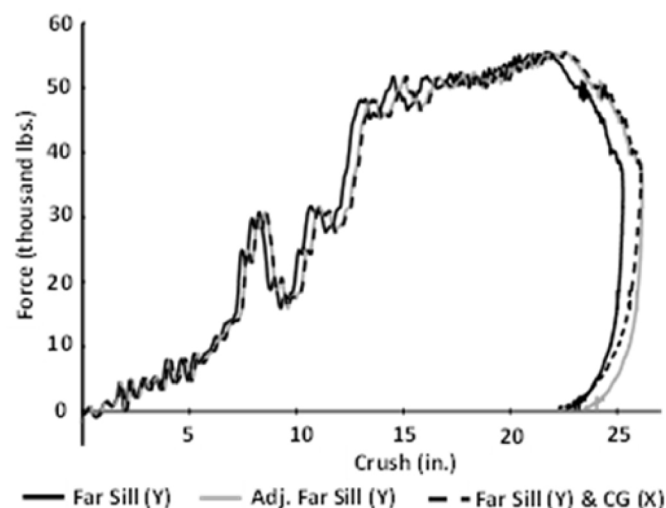


Figure 9. Force versus crush plots comparing the different crush calculation methodologies in test 8067.

RESULTS

The calculated velocities and displacements for each test can be found in [Appendices A](#) and [B](#), respectively. [Table 1](#) outlines the restitution percentages for each calculation method by vehicle class. Similarly, [Table 2](#) reports the calculated structural restoration as a percent of the final displacement or residual crush. After integration of the far side sill accelerometer, it was apparent that in three tests the velocity and displacement values overestimated the actual restitution and structural restoration of the test. Additionally, the crash test reports outlined some tests in which the center of gravity accelerometer data was unreliable because of equipment failure or damage from the test itself. [Tables 1](#) and [2](#) include both a summary of the results including all tests and excluding tests with questionable data. [Figure 10](#) presents a visual representation of the relationship between the calculated residual crush and the maximum dynamic crush for all the tests studied in this paper. The dashed line in [Figure 10](#) represents a 1 to 1 relationship between the calculated residual crush and the maximum dynamic crush.