

Analysis of High-Speed Sideswipe Collisions Using Data from Small Overlap Tests

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ABSTRACT

Little experimental data have been reported in the crash reconstruction literature regarding high-speed sideswipe collisions. The Insurance Institute for Highway Safety (IIHS) conducted a series of high-speed, small overlap, vehicle-to-barrier and vehicle-to-vehicle crash tests for which the majority resulted in sideswipe collisions. A sideswipe collision is defined in this paper as a crash with non-zero, final relative tangential velocity over the vehicle-to-barrier or vehicle-to-vehicle contact surface; that is, sliding continues throughout the contact duration. Using analysis of video from 50 IIHS small overlap crash tests, each test was modeled using planar impact mechanics to determine which were classified as sideswipes and which were not. The test data were further evaluated to understand the nature of high-speed, small overlap, sideswipe collisions and establish appropriate parameter ranges that can aid in the process of accident reconstruction. An example reconstruction of a small overlap, sideswipe collision using optimization methods based on the planar impact mechanics model is included in the paper. The results of the example reconstruction show that the reconstruction method developed in the paper, using the physical evidence and EDR data, produces useful results.

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INTRODUCTION

It is possible to categorize vehicular collisions into those that are sideswipe collisions, and those that are not. The notion of a sideswipe collision has been defined quantitatively [1] and is discussed in more detail in the following section.

Much has been written over the last five decades about vehicular impact. The vast majority of these articles consider non-sideswipe collisions with comparatively few articles dealing explicitly with sideswipe collisions. One of the earliest articles that considered sideswipe collisions was by Woolley [2]. In that paper, the "IMPAC" collision model is presented and its capability to model sideswipe conditions in vehicle-to-vehicle collisions is described. A comment is made in that paper that the sideswipe feature of the software was not validated due to the absence of test data. Two papers [3, 4] consider the determination of the relative speed of two vehicles based on the pattern created on the side of one of the vehicles by the protruding lug nuts of the other vehicle (typically a truck tractor) as the two vehicles "swipe" past one another. Another paper [5]

considers the low-speed sideswipe interaction between a crane truck and a passenger car using data from two tests. Test data are also presented for eleven tests for two different pairs of vehicles over a range of preimpact speeds from 5 kph to 27 kph (3 mph to 17 mph) [6]. The paper also considers occupant response through the use of the vibration dose value (VDV). Two papers [7, 8] present models of sideswipe collisions including validation to test data. The approach used in each paper to model the tangential interaction between the vehicles during contact is Coulomb friction. Both papers acknowledge that the use of this "sliding" model for intervehicular contact precludes the use of the model for sideswipe collisions in which the vehicles "snag" one another during contact. Thus, these models are applicable to vehicular collisions with relatively limited intrusion and low relative normal approach speeds.

Generally speaking, experimental data are not available to analyze or reconstruct high-speed sideswipe collisions. This type of collision occurs, for example, when a light vehicle traveling at high speed (an initial closing speed of approximately 20 mph or higher) engages a stationary, off-road

object (pole, etc.) at the front headlight area and continues traveling past the object after sustaining a change in velocity. Data recently became available from a series of tests for this type of collision.

In 2012, the Insurance Institute for Highway Safety (IIHS) conducted numerous tests between various light vehicles into a variety of fixed barriers and light vehicles into light vehicles [9]. They referred to these tests as “small overlap” frontal collisions due to the small amount of vehicle-to-barrier (or vehicle-to-vehicle) offset. IIHS intended for the data from these tests to assist consumers in selecting the safest vehicles. However, due to the nature of the small overlap between the vehicle and the barrier or between vehicles, a large number of the tests were sideswipes (i.e. non-zero final relative tangential velocity). This appears to be the first set of experimental tests to provide data suitable for gaining insight into this class of collision and for determination of the collision parameters.

This paper is divided into three main analysis sections followed by an example reconstruction application and then discussion of the topic. Following a formal definition of a sideswipe collision, the first main section describes the process used to extract the information from the video of each test. This analysis is necessary to determine the change in velocity of the vehicle (or vehicles) (ΔV_x , ΔV_y , and Ω_{final}) to facilitate the determination of the crash parameters for each test trial. The second main section describes the process used to determine the crash parameters. Statistical analysis of the output data, which provided the relationships between the parameters for the various test factors, is in the third main section. This is followed by an example reconstruction illustrating the use of the concepts presented in the paper. The paper concludes with a discussion of the data, the analysis of the data and comments for its use in reconstructing crashes.

Definition of a Sideswipe Collision

In order to analyze sideswipe collisions, it is necessary to define the term in a specific and quantitative fashion. Numerous definitions, or descriptions, of a sideswipe collision have been presented in the past, including:

- a crash in which contact occurs only along the side(s) of the vehicle(s)
- a crash with sliding contact, usually occurring at low speed resulting in minor damage
- a crash in which the directions of the approach and departure vectors are approximately equal
- a crash with prolonged sliding contact, often with very little structural damage [8].

A more meaningful definition is that a sideswipe collision is a vehicle crash with a non-zero final relative tangential velocity [1]. That is, the vehicles continue to slide relative to each other (along the contact surface) throughout the entire duration of contact. For some time, the concept and method of planar

impact mechanics (PIM) has been in common use for the analysis of vehicle crashes [1, 2, 17, 18]. Planar impact mechanics is based on the idealization of a common vehicle-to-vehicle or vehicle-to-barrier planar (vertical) crush surface. The directions perpendicular to and along this surface are used to define normal and tangential components of the contact velocities and impulses. The ratio of the tangential impulse component, P_t , to the normal impulse component, P_n , generated in a crash is defined as the impulse ratio, $\mu = P_t/P_n$ [1]. Based on Newton's laws, the impulse ratio attains a critical (maximum) value, μ_0 , when sliding ends at or before separation. Thus, a sideswipe collision is defined quantitatively as a collision for which $\mu < \mu_0$.

Previous analyses of experimental data have determined values of the impulse ratio, μ , for a number of crash tests. Brach [19] analyzed the crash tests titled Research Input for Computer Simulation of Automobile Collisions [RICSAC] conducted by the National Traffic Highway Administration [20]. The findings showed that all eleven of the RICSAC (vehicle-to-vehicle) tests resulted in a critical value, μ_0 , meaning that sliding ended at or before separation for the RICSAC collision configurations. Additionally, the behavior of the critical value of the impulse ratio has been validated experimentally [22].

VIDEO ANALYSIS

A small overlap vehicle-to-barrier test is designed to evaluate the performance of a vehicle's forward outer structure in colliding with a fixed, roadside object, such as a tree, or in the case of the vehicle-to-vehicle test, with another vehicle that encroaches into the travel lane of a vehicle traveling in the opposite direction and engages the front corner of the vehicle.

IIHS [9] used overlaps in the range of 20% to 28% of overall vehicle width. This paper analyzes 41 vehicle-to-barrier and 9 vehicle-to-vehicle small overlap frontal tests to assess whether each of these collisions can be classified as a sideswipe or non-sideswipe collision. The method of extracting the data used in making this determination is described in this section. IIHS Test CF11002, involving a 2008 Ford Fusion colliding with a flat barrier, will be used to demonstrate portions of the analysis process.

Due to the volume of data related to the 50 tests, the test reports, test video and all related data and reports were provided to Brach Engineering directly by the IIHS rather than downloading this information from the IIHS web site. The video files were provided to Brach Engineering in AVI format with the frame rate described in the documentation.

IIHS used five different barrier designs in the 41 vehicle-to-barrier tests. Figure 1 shows the plan view of each barrier type. Each barrier type is labeled with the name used by the IIHS in referring to the barrier.

Multiple video cameras were used to record each crash from various angles. The overhead video, taken with a high-speed camera (500 fps), was used in the analysis described in this study. This camera position provided the most direct means to calculate the change in translational velocity of the center of gravity (CG) of the vehicle and the change in the rotational velocity. To perform an analysis using planar impact mechanics, initial velocities, v_x , v_y and ω and final velocities, V_x , V_y and Ω are needed. Figure 2 shows the x-y coordinate system. The initial values v_x and ω are zero by virtue of the manner in which the vehicle was propelled into the barrier/vehicle. The initial speed, v_x , was measured by IIHS instrumentation. This leaves measurement of V_x , V_y and Ω for the video analysis.

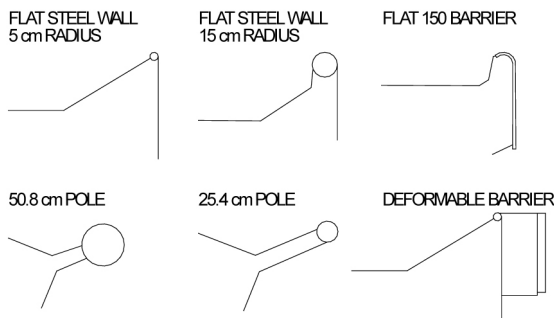


Figure 1. Barrier Types. The front of the vehicle engages the barrier from the right side - see photos below.

IIHS collected crash data from accelerometers mounted on the floor behind the driver's seat. This acceleration data was not useful in the analysis to determine the translational velocity changes of the vehicle because the data was not collected at the CG of the vehicle. Moreover, the angular velocities of the test vehicles were not measured by IIHS. Thus, the final velocity components, necessary for the determination of the velocity changes, were determined using video analysis. Analysis of the video provided both the translational velocity changes of the center of gravity of the vehicle and the change in the angular velocity.

Each crash test video was first trimmed to begin at five frames before first contact with the barrier and end at a point where the vehicle's CG, as indicated by a target on the vehicle roof, was no longer visible in the video frame or had reached a significant distance away from the barrier. This typically provided over 200 total frames for the video analysis of each test. The frame showing initial contact was determined by the illumination of the red indicator light on the hood of the vehicle that was activated by a contact switch located on the front bumper. Every frame from this trimmed video was extracted using automated video frame extraction software [10]. Frames 1, 6, 11, and every tenth frame thereafter were used for the video analysis. Analysis using every tenth frame from the high-speed video proved sufficient to calculate the changes in velocity of the vehicles.

The CG of the test vehicle was marked by IIHS with a black and white target superimposed on the inch tape fixed along the longitudinal centerline of the roof of the vehicle (see Figure 2). This CG location was confirmed from IIHS measurements of vehicle front and rear weight distribution, reported as a percentage of the total weight. Table 1 shows the parameters for calculating the CG for vehicle used in Test CF11002.

Table 1. Parameters for Test CF11002 [12]

Front Weight Distribution	55%
Rear Weight Distribution	45%
Wheelbase	2.72 m (8.92 ft)
Front Bumper to Front Axle	1.02 m (3.35 ft)
CG Location behind Front Bumper	2.24 m (7.35 ft)

The extracted video frames were imported into CAD software (AutoSketch by Autodesk) for scaling and measurement of the images. Figure 2 shows the CG target on the 2008 Ford Fusion in test CF11002 and the distance behind the front bumper as measured on the CAD image.

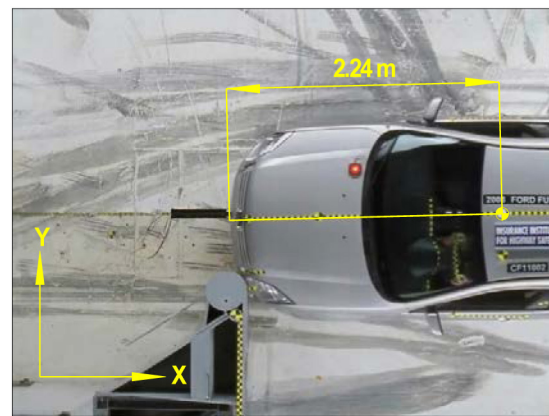


Figure 2. Frame 6 (initial contact), CF11002. 2008 Ford Fusion into 15cm flat steel wall barrier.

The scale for the images was determined using the known distance between two yellow and black targets (see Figure 3) on the driver's side of the roof of the vehicle. This distance was specified by IIHS as 61 cm (2.0 ft) [9]. This scaling was typically done on one of the first frames where the 61 cm strip is fully visible and prior to any deformation of the roof. Once the scale was set, it was applied to all frames for a given test.

The angular velocity, Ω , is calculated by determining the change in the angular orientation of the vehicle as a function of time. Therefore, a line was marked on the roof between two distinct points in the CAD image. These points varied between tests and were selected based primarily on providing as large a separation as possible and how easily identifiable they were from frame to frame. The line was scribed between the same two points on the roof of the vehicle on each successive frame, and its angle relative to the horizontal axis was measured in each successive frame. The change in this angle over time was used to calculate the angular velocity. The pre-impact angular velocity of the vehicle was assumed to be zero in all

cases. In the case of Test CF11002, this line was drawn between the upper left corner of the black and white vehicle identification label and the lower right corner of the square on the inch tape on the roof closest to the backlight, as seen in Figure 4.

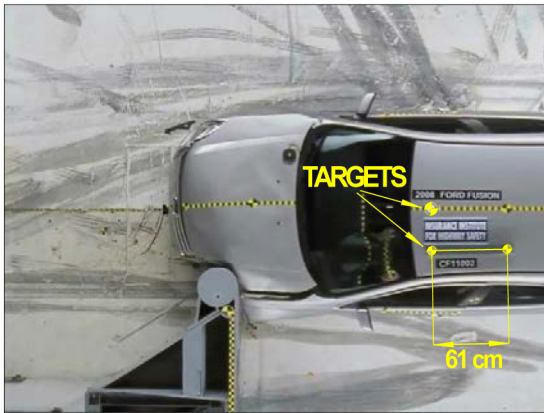


Figure 3. Frame 21, CF11002. 2008 Ford Fusion into 15cm flat steel wall barrier.



Figure 4. Frame 51, CF11002. 2008 Ford Fusion into 15cm flat steel wall barrier.

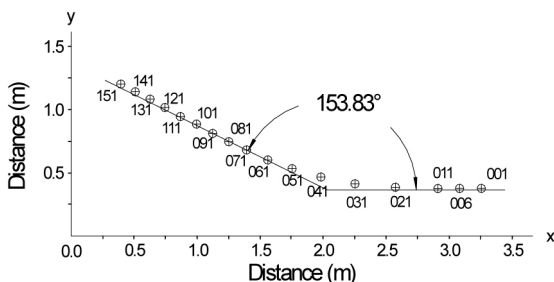


Figure 5. CG locations and departure angle for Test CF11002

The locations of the CG markers for each of the frames were plotted on a horizontal plane with a common origin. Each CG location was identified by its video frame number (see Figure 5). The vertical and horizontal distance between each point was measured and used with the video frame rate to calculate

V_x and V_y . The departure angle is the included angle between the horizontal axis and the path taken by the CG after the collision, as seen in Figure 5. The departure angle was measured for each test. The velocities, V_x , V_y , and Ω , were calculated for each frame and then plotted with respect to time as shown in Figures 6, 7, and 8.

Mean values for the each of the three velocity components were calculated after they began to stabilize around a particular value. For Test CF11002, the velocities were stable from approximately 0.15 s through the last data points. These values were averaged and used as the final post-collision velocity values, V_x , V_y , and Ω . In Test CF11002, $V_x = -6.13$ m/s (-20.11 ft/sec), $V_y = 3.25$ m/s (10.69 ft/sec), and $\Omega = 102.75$ deg/sec.

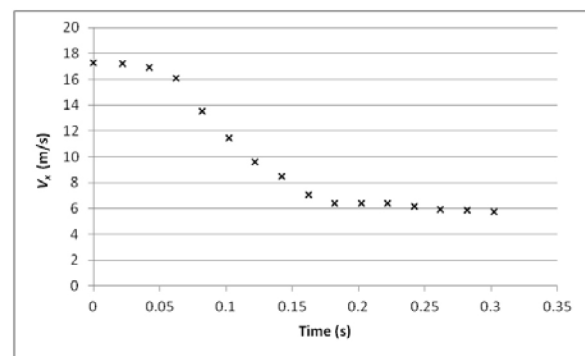


Figure 6. Longitudinal velocity, V_x , vs. Time for CF11002

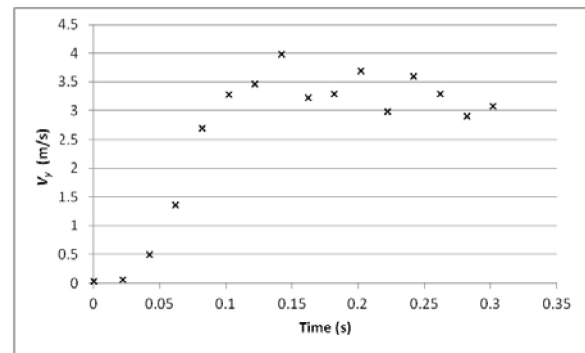


Figure 7. Lateral velocity, V_y , vs. Time for CF11002

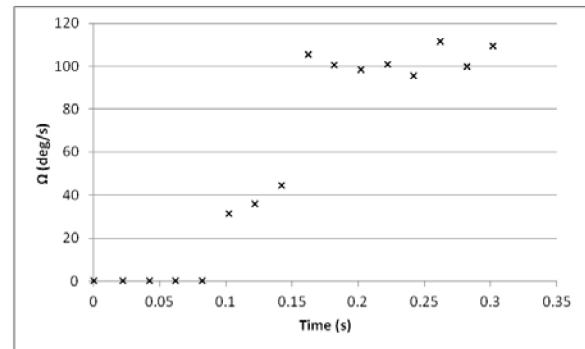


Figure 8. Angular velocity, Ω , vs. Time for CF11002

CALCULATION OF COLLISION PARAMETERS

Planar impact mechanics (PIM) [1] was used to calculate the collision parameters for each crash test. The method utilizes the nonlinear optimization algorithm of Microsoft Excel [11], known as *Solver*, to fit the test data, in a least squares sense, to the model. The method minimizes the sum of the squares of the differences between the three components of the **measured** postimpact velocity of the vehicle and the **calculated** postimpact velocity of the vehicle (calculated by the PIM model). In the implementation of the least squares method here, a quantity Q is defined as the sum of squares of the differences between each value of a variable obtained from test measurements and the value of that same variable that corresponds to the solution of an appropriate physical model (i.e. PIM). Let Q be defined as:

$$Q = \sum_{i=1}^n w_i (u_i - u_i^{data})^2 \quad (1)$$

where u_i is the corresponding value of a particular variable from the physical model. For the IIHS testing, $u_1 = V_x$, $u_2 = V_y$ and $u_3 = \Omega$. The variable n is the number of variables whose values are to be used from the experimental data ($n = 3$ in this application), w_i is a weighting factor, and u_i^{data} is the value of the same variable from the test data. The approach is to minimize Q in a way that determines the “best”, or “optimal”, values of the desired parameters from the planar impact mechanics model. In the analysis performed here, three parameters were allowed to vary to achieve the least squares fit to the data. Two different sets of parameters were used for the vehicle-to-barrier tests and the vehicle-to-vehicle tests, and the details are described below. In the analysis here, the weighting factors, w_i , were all 1.

Vehicle-to-Barrier Tests: For the analysis of these tests, three parameters varied in the optimization method. These parameters were e , μ and ϕ where e is the coefficient of restitution, μ is the impulse ratio, and ϕ is the angle that locates the impact center on the crush surface. As a means of simplification, a relationship was introduced that defined the value of Γ , which describes the angular orientation of the crush surface as a function of the overlap of the car with the barrier and the geometry of the vehicle. [Appendix 1](#) provides the details of this relationship and the rationale for its use.

Vehicle-to-vehicle Tests: For this analysis, the three parameters varied in the optimization scheme were e , μ and Γ . Due to possible asymmetries of the crush of the two vehicles, the values of ϕ and d were defined for each vehicle based on the crush profiles visible in the overhead view of the vehicles in the video.

In addition to the geometric parameters of the test vehicles, the PIM analysis requires that the inertial parameters of the vehicles (mass and yaw inertia) be known for each vehicle tested. While IIHS measured the weight of each vehicle in the as-tested condition, the yaw moments of inertia of the vehicles were not measured (for practical reasons). Yaw inertia values for the as-manufactured vehicle are available [12]. They are based on the curb weight of the vehicle, which is also reported [12]. The as-manufactured yaw inertia values were modified to accommodate the change in the weight/mass of the vehicle from the curb weight to the test weight. This modification uses the relationship between mass, m , yaw inertia, I , and the radius of gyration, k :

$$I = k^2 m \quad (2)$$

In this modification process, the radius of gyration for a given vehicle is assumed to remain essentially constant for small changes in mass. Therefore, its value can be calculated from the vehicle's curb weight and inertia [12]. Once k is known for a given vehicle, the inertia of the test vehicle can be calculated using [Equation 2](#) and the test mass listed in the IIHS report. These scaled values for the vehicle inertias were used in the PIM analysis.

Note that in the least squares analysis for the vehicle-to-barrier tests, the barrier is considered immovable. To model this condition in the analysis, the mass and inertia for the barrier are both set to 1×10^6 kg and 1×10^6 kg-m², respectively. The validity of this approach is confirmed by the fact that the preimpact velocity of the barrier, which was set to zero, remains zero after the impact.

Table 2. Parameters for Test CF11002 [9]. See [Figure A-1](#) for definition of parameters.

CF11002 - 2008 Ford Fusion - Input Parameters:			
initial horizontal velocity	v_x	17.89 (58.60)	m/s (ft/s)
initial lateral velocity	v_y	0 (0)	m/s (ft/s)
mass	m	1619 (111)	kg (lb-s ² /ft)
yaw inertia	I	3166.3 (2336.3)	kg-m ² (ft-lb-s ²)
heading angle	θ	0.0	deg
front bumper to CG	C	2.24 (7.36)	m (ft)
overall width	O_W	1.83 (6.00)	m (ft)
base of windshield	W_B	1.24 (4.08)	m (ft)
top of windshield	W_T	2.08 (6.83)	m (ft)
front to A pillar	A_P	1.66 (5.46)	m (ft)
overlap	O_L	0.46 (1.50)	m (ft)
final horizontal velocity	V_{fx}	-6.13 (-20.11)	m/s (ft/s)
final lateral velocity	V_{fy}	3.25 (10.69)	m/s (ft/s)
final angular velocity	Ω_f	102.75	deg/s
Varied Parameters			
phi	ϕ	29.00	deg
coefficient of restitution	e	0.00	-
impulse ratio	μ/μ_0	85.18	%
Calculated Parameters			
CG to impact center	d_i	1.26 (4.14)	m (ft)
crush angle	Γ	74.63	deg

Table 2 shows the input parameters used to determine the collision parameters for Test CF11002. Similar analyses were performed for the remaining 40 vehicle-to-barrier tests and 9