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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 exceeding 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_y 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.

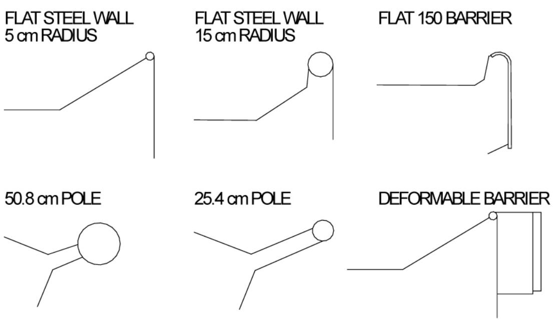

Figure 1. Barrier Types. The front of the vehicle engages the barrier from the right side - see photos below.

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.

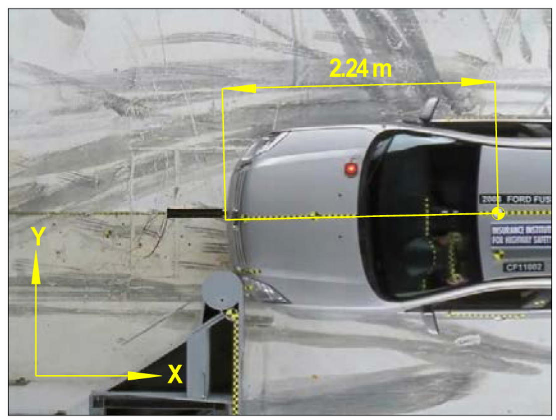

Figure 2. Frame 6 (initial contact), CF11002. 2008 Ford Fusion into 15cm flat steel wall barrier.

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.

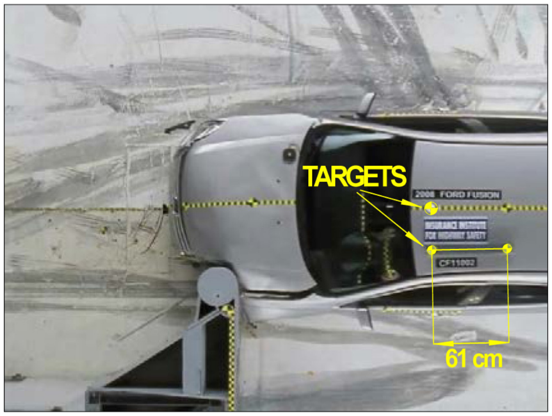

Figure 3. Frame 21, CF11002. 2008 Ford Fusion into 15cm flat steel wall barrier.

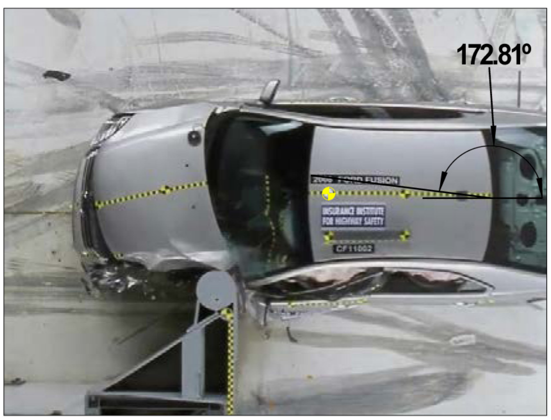

Figure 4. Frame 51, CF11002. 2008 Ford Fusion into 15cm flat steel wall barrier.

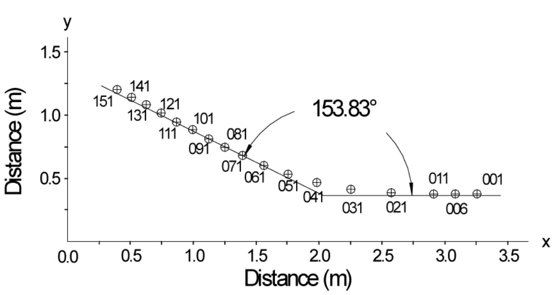

Figure 5. CG locations and departure angle for Test CF11002

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 Ω = 102.75 deg/sec.

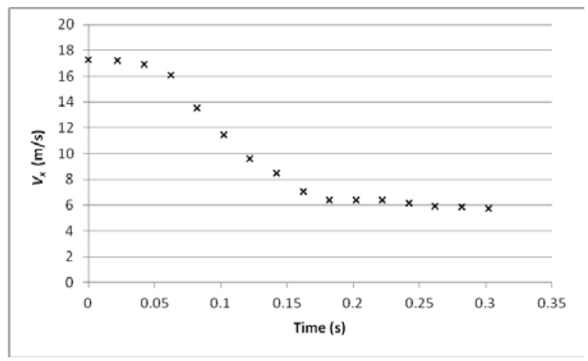

Figure 6. Longitudinal velocity, V_x, vs. Time for CF11002

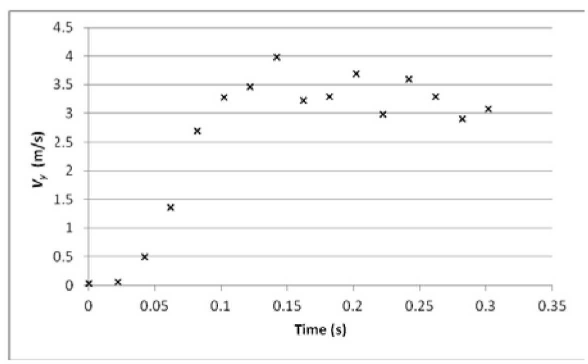

Figure 7. Lateral velocity, V_y, vs. Time for CF11002

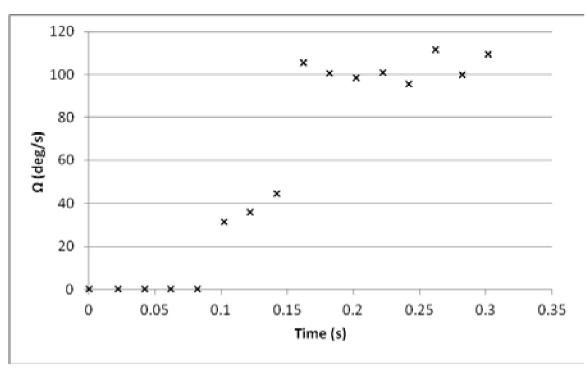

Figure 8. Angular velocity, Ω, vs. Time for CF11002

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:

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

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:

$$I = k^2 m \tag{2}$$

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-m^2, 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-s²/ft)
yaw inertia	I	3166.3 (2336.3)	kg-m² (ft-lb-s²)
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_{1x}	-6.13 (-20.11)	m/s (ft/s)
final lateral velocity	V_{1y}	3.25 (10.69)	m/s (ft/s)
final angular velocity	Ω_1	102.75	deg/s
Varied Parameters			
phi	φ_1	29.00	deg
coefficient of restitution	e	0.00	-
impulse ratio	μ/μ_0	85.18	%
Calculated Parameters			
CG to impact center	d_1	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 vehicle-to-vehicle tests. The input data and the collision parameters resulting from the analyses of all 50 tests are listed in the two tables in Appendix 2.

DATA ANALYSIS

Vehicle-to-Barrier Tests

Test Outlier

IIHS conducted 41 vehicle-to-barrier tests. The optimization analysis described previously determined the collision parameters e, μ, and φ for each test. The data were collected and evaluated, and it was determined that the coefficient of restitution from one of the tests was an outlier. Test CF11006 produced a restitution value of $e = 0.555$, whereas the average of all the restitution values (including Test CF11006) was $e = 0.135$, and the standard deviation was $s = 0.130$. This placed the value for the coefficient of restitution for Test CF11006 more than three standard deviations from the mean of the data. Thus, the data from Test CF11006 was excluded from the following analysis. The average for the test data with the outlier excluded was $e = 0.125$, with a standard deviation was $s = 0.112$.

Significance of Barrier Type

With the crash parameters calculated for the remaining 40 vehicle-to-barrier tests, an analysis of variance (ANOVA) was used to determine if the type of barrier yielded statistically significantly different values of e and μ. No distinction was made in the analysis between collisions that were sideswipes and those that were not. The analysis showed that for both collision parameters, the type of barrier was statistically significant. These results are discussed later.

Sideswipe/Non-Sideswipe

The data were further examined to assess whether any trends could be identified. The vehicle-to-barrier data were separated subjectively (visually) into sideswipe collisions and non-sideswipe collisions. This grouping of the tests was done by viewing the overhead video of each test and subjectively determining whether the striking vehicle's relative tangential velocity ceased. Appendix 2 - Part 1 shows these data separated into the two groups. Analysis of variance was used as a means to check if the subjective separation was supported by the data. ANOVA of the impulse ratio, μ/μ_0, similarly separated into sideswipe and non-sideswipe groups, showed that a significant statistical difference existed for this data, i.e. the subjective groupings corresponding to ranges of impulse ratio values are significantly different.

ANOVA was also used to analyze the data for the coefficient of restitution (separated into the same subjective sideswipe and non-sideswipe groups). This analysis showed that no statistical difference existed for these data, i.e. the coefficient of restitution values were essentially random relative to the sideswipe/non-sideswipe grouping. This result was consistent with expectations that the data are separated into groups based on a parameter characterizing the system behavior along the crush surface, whereas the coefficient of restitution characterizes system behavior perpendicular to the crush surface.

Having established the validity of a sideswipe/non-sideswipe grouping of the data, evaluation of the data shows that the range of values of the impulse ratio (as a percent of μ_0) for the "non-sideswipe" tests is $97.4\% \le \mu/\mu_0 \le 100\%$. The range of values of the impulse ratio (expressed as a percentage) for the "sideswipe" tests is $71.8\% \le \mu/\mu_0 \le 95.9\%$. Several additional observations can be made:

- Small overlap vehicle-to-barrier collisions, of the type studied here, for which the value of $\mu > 0.97\ \mu_0$ can be characterized as a non-sideswipe.
- Small overlap vehicle-to-barrier collisions (of the type studied here) and characterized as a sideswipe will likely have an impulse ratio in the range of $72\% \le \mu/\mu_0 \le 96\%$.
- The entire group of barrier data (all 40 tests) show that the range of the coefficient of restitution is $0 \le e \le 0.3$, with the average value of $e_{AVG} = 0.13$. This range of the coefficient is consistent with published data [1, 13].
- The range of Γ from the sideswipe tests was $70.7° \le \Gamma \le 77.6°$.

Vehicle-to-Vehicle Tests

Sideswipe/Non-Sideswipe

IIHS conducted nine small overlap vehicle-to-vehicle tests with overlaps ranging from 21% to 28% (see Appendix 2 - Part 2 for the data). Using the overhead videos, these data were also separated subjectively (visually) into sideswipe and non-sideswipe collisions, as was done with the vehicle-to-barrier tests. Again, ANOVA was used to analyze the collision parameters to assess whether the subjective grouping was statistically valid. The results of the ANOVA are the same as for the vehicle-to-barrier tests: the analysis shows that the data demonstrate a significant statistical difference between the data sets with respect to the impulse ratio. Analysis with respect to the coefficient of restitution shows no significant statistical difference between the groups.

Having validated the grouping of the data, further evaluation shows that the range of values of the impulse ratio (as a percent of μ_0) for the "non-sideswipe" tests is $96.6\% \le \mu \le 100\%$. The range of values of the impulse ratio (as a percent of μ_0) for the "sideswipe" tests is $81.6\% \le \mu \le 90.0\%$. Several additional observations can be made:

- Small overlap vehicle-to-vehicle collisions (of the type studied here) for which the value of $\mu > 97\%\ \mu_0$ can be characterized as a non-sideswipe. This agrees directly with the conclusion based on the vehicle-to-barrier data.
- Small overlap vehicle-to-vehicle collisions (of the type studied here) that were characterized subjectively as a

sideswipe had an impulse ratio in the range of 82% ≤ % μ_0 ≤ 90%. This range is a subset of the range from the vehicle-to-barrier tests.

- The data from the nine vehicle-to-vehicle tests show that the range of the coefficient of restitution is $0 \le e \le 0.2$, with the average value of $e_{AVG} = 0.06$. This range of the coefficient is a subset of, and is consistent with, the range from the vehicle-to-barrier tests. This range is also consistent with published data [1, 13].
- All of the vehicle-to-vehicle tests were run with the vehicle headings collinear except Tests CF10012 and CF10013. These two tests were run with the vehicle headings at a 15° relative angle (nearly head-on). Neither of these tests was categorized as a sideswipe using the overhead videos.
- A difference is seen with regard to the range of the contact surface angle Γ for these vehicle-to-vehicle tests in comparison to the vehicle-to-barrier tests. For the sideswipe tests, the range is 71.8° ≤ Γ ≤ 80.7°. For the non-sideswipe tests, the range is 0.0° ≤ Γ ≤ 40.9°. Note that for two of the three non-sideswipe tests the headings of the vehicles were not collinear. The non-sideswipe test for which the vehicle headings were collinear produced the largest value of Γ, 40.9°. This value is still 30° to 40° smaller than the values for the sideswipe collisions.

Analysis of Model Sensitivity using Design of Experiments (DOE)

The vehicles used in the IIHS testing included a variety of manufacturers and models. However, sedans were used in the majority of the 50 tests. Vehicle-to-barrier tests involving pickup trucks (2), a minivan (1), a crossover utility (1) and a subcompact (1) are too few to support statistical analysis to identify any vehicle body style differences. Only sedans were used in the vehicle-to-vehicle tests. Thus, the statistical significance of any of the vehicle body styles (or vehicle models) cannot be determined from the current data.

In lieu of this type of information, a sensitivity analysis is presented here for both the vehicle-to-barrier and vehicle-to-vehicle test configurations. The motivation behind this sensitivity analysis is to gain an understanding of the nature of small overlap collisions since little data for this type of collision are available. Part of this understanding is insight into the sensitivity of the PIM model to changes in the parameters. This information will provide guidance to accident reconstructionists analyzing small overlap collisions.

The method used here for the sensitivity analysis follows the presentation showing the use of the DOE methodology in this manner [14] and follows the application of the method to the field of accident reconstruction given elsewhere [15]. (Numerous treatments are available on the topic of Design of Experiments (DOE); see for example [21].) Analysis for both collision configurations is based on the IIHS test data.

In the application of the DOE method to both collision configurations, the process (model) used in the analysis is PIM [1]. The sensitivity analysis is carried out independently for each of two response variables. The response variables used in the study are:

1. The magnitude of the velocity change of Vehicle 1, ΔV_1
2. Total collision energy loss, T_L

For reference, the equations for these two quantities are given below by Equations 3 and 4.

$$\Delta V_1 = \frac{\bar{m}}{m_1(v_{2n} - v_{1n})(1+e)\sqrt{1+\mu^2}} \tag{3}$$

$$T_L = \frac{1}{2}\bar{m}(v_{2n} - v_{1n})^2(1+e)[(1+e) + 2\mu r - (1+e)\mu^2] \tag{4}$$

where r depends on the initial velocity components

$$r = \frac{v_{2t} - v_{1t}}{v_{2n} - v_{1n}} \tag{5}$$

and

$$\bar{m} = \frac{m_1 m_2}{m_1 + m_2} \tag{6}$$

In all cases, the DOE analysis is performed using eight factors with each factor assigned two levels. A fractional factorial design is used consisting of sixteen separate trials. The main effects are tallied allowing for the ranking of effects. The results of this analysis for both collision configurations are presented below.

Vehicle-to-Barrier Collisions

Table 3 shows the eight factors used in the analysis, their nominal values, and the high and low values. The high and low values were selected based on the averages from the data of sideswipe tests where appropriate (e, μ, etc.) and from typical vehicle parameters (m, I, etc.). The preimpact speed of the vehicle in all trials was 18.0 m/s (59.1 ft/s, 40.3 mph), which is the nominal value for the IIHS tests. The barrier was modeled in all trials with a mass of 1.0×10^8 kg and the yaw inertia of the same magnitude with zero initial velocity; the postimpact velocity of the barrier was checked for each trial to ensure the change in velocity was zero.

Table 3. Vehicle-to-Barrier Factors

Parameter	Nominal	High	Low	Units
m_1	1750	1837.5	1662.5	kg
I_1	3.75	3.9	3.6	kN-m-s^2
d_1	1.2	1.4	1.0	m
φ_1	33	40	26	deg
θ_1	0	5	-5	deg
e	0.125	0.250	0.000	-
μ	84	94	74	% μ_0
Γ	74	78	70	deg

The results of the analysis are conveniently evaluated by plotting the main effects on a normal probability plot [14]. The two plots for the vehicle-to-barrier tests, one for each of the two response variables, are shown in Figures 9 and 10.

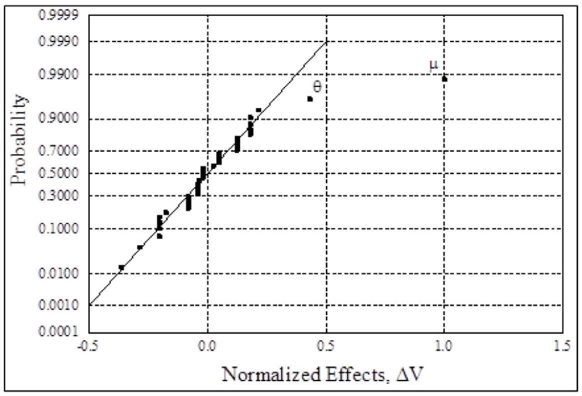

Figure 9. Normal Probability Plot of Main Effects for Response Variable ΔV

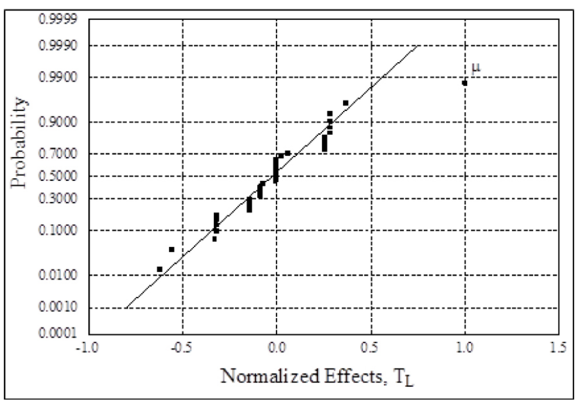

Figure 10. Normal Probability Plot of Main Effects for Response Variable T_L

The results show that in both cases the impulse ratio, μ, is the factor that has the largest (positive) effect. That is, variations in μ affect the response (T_L, ΔV) significantly compared to other factors. This is not surprising since μ is the factor that directly influences that nature of the interaction along the crush surface (in the tangential direction). For the response variable ΔV, the factor θ (vehicle heading) also has a noticeable positive effect. It is worth pointing out that while the coefficient of restitution appears prominently on the right hand of both Equations 3 and 4, for its range in this study and for this type of collision configuration, it does not have a significant effect on these response variables.

Vehicle-to-Vehicle Collisions

Table 4 shows the eight factors used in the analysis, their nominal values, and the high and low values. The high and low values were selected based on the averages from the data of sideswipe tests where appropriate (e, μ, etc.) and from typical vehicle parameters (m, I, etc.). In the nominal case, the two vehicles collide head-on with a narrow offset. The geometric and inertial parameters for nominal vehicle are based on the two Ford Fusions used in Test CF 11017. The preimpact speed of both vehicles in all trials was 18.0 m/s (59.1 ft/s, 40.3 mph), which is the nominal value for the IIHS tests.

Table 4. Vehicle-to-Vehicle Factors

Parameter	Nominal	High	Low	Units
m_1	1700	1785	1615	kg
I_1	3.3	3.5	3.1	kN-m-s^2
d_1	1.7	1.8	1.6	m
φ_1	25	30	20	deg
θ_1	0	5	-5	deg
e	0.1	0.2	0.0	-
μ	87	94	80	% μ_0
Γ	75	80	70	deg

The main effects are plotted on a normal probability plot [14]. The two plots for the vehicle-to-vehicle tests, one for each of the two response variables, are shown in Figures 11 and 12.

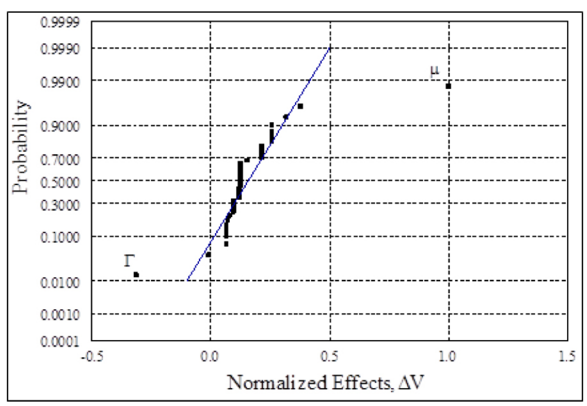

Figure 11. Normal Probability Plot of Main Effects for Response Variable ΔV

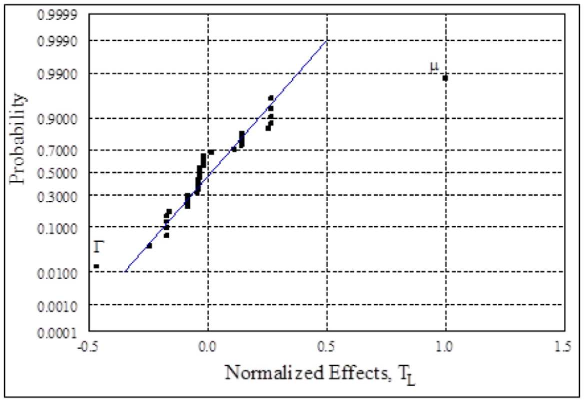

Figure 12. Normal Probability Plot of Main Effects for Response Variable T_L

The results show that in both cases the impulse ratio, μ, is the factor that has the largest (positive) effect. That is, variations in μ affect the response (T_L, ΔV) significantly compared to other factors. As with the vehicle-to-barrier tests, this result is not surprising since μ is the factor that directly influences that nature of the interaction along the crush surface (in the tangential direction). In the case of both response variables, the factor Γ has the largest negative effect.

EXAMPLE RECONSTRUCTION

Collision configurations that give rise to sideswipe conditions, while not nearly as common as non-sideswipe collisions, do arise in practice. One collision configuration in particular that leads to this condition occurs when a vehicle drifts left of the centerline on a two-lane roadway and collides with another vehicle traveling in the opposite direction in which the collision overlap is, perhaps, a little wider than the headlight assemblies of both vehicles. The application of the method presented above and the results of the data analysis are used here to illustrate the reconstruction of such a crash. This type of collision scenario is investigated here through the reconstruction of a crash using PIM.

Figure 13 is a scale diagram that illustrates a crash configuration in which a full-size pickup truck, Vehicle 1 (Veh 1), traveling right to left in the diagram and collides with Vehicle 2 (Veh 2), a crossover utility vehicle, that drifts left of the centerline. The two vehicles collide in the orientations shown in the scale diagram, which also shows the postimpact motion of each vehicle and the rest positions of the vehicles. Also included are the on-road and off-road tire marks that were measured at the scene.

In addition to this physical evidence (vehicle rest positions, tire marks, debris patterns, etc.), Veh 2 was equipped with an air bag control module (ACM) that included an event data recorder (EDR). The data from the EDR were imaged, examined, and deemed reliable. The data from the EDR included the preimpact speed and the maximum recorded longitudinal ΔV, ΔV_{long}. The reconstruction of the collision was undertaken to determine the preimpact speed of Veh 1, which was not equipped with an EDR. The approach used to reconstruct the speed utilized PIM in combination with a least squares optimization strategy to simultaneously meet the various known crash criteria based on the physical evidence (including the EDR data). These criteria were the ΔV_{long} of Veh 2 (from the EDR) and the postimpact vector velocity directions of the center of mass of both vehicles determined from the tire marks. Additionally, the preimpact speed of Veh 2 is known from the data imaged from the EDR.

Method of Least Squares: A reconstruction of the preimpact speed of Veh 1 based on the physical evidence of the postimpact directions of motion of the centers of mass of the two vehicles and EDR data from Veh 2 can be carried out using the method of least squares, described as follows. The quantity Q is defined as the sum of squares of differences between each value of a variable obtained from physical evidence (e.g. the postimpact directions of the CGs of both vehicles) and the value of that same variable that corresponds to the solution of an appropriate physical model; here planar impact mechanics is used. Let:

$$Q\left(s_j\right) = \sum_{i=1}^{n} w_i (u_i - u_i^{data})^2 \tag{7}$$

where n is the number of model variables whose values are to be used from the known data, w_i is a weighting factor, u_i^{data} is the value of variable i from physical evidence and u_i is the corresponding value of variable i that satisfies the physical model. The approach is to minimize Q in a way that determines the values of the variables, s_j, from the model of the physical system. This process satisfies the physical model AND matches the physical evidence in a "best" or "optimal" way. It is not always necessary that the reconstructed/unknown variables, s_j, be the same as the fitted variables, u_i; generally this will not be the case. In this example, the values used from the data are given in Table 5. The variable to be found (reconstructed), s_1, is the initial speed of Veh 1, v_1. All values of the weighting factors, w_i, were chosen to be unity, that is, w_i = 1, i = 1, …,3.

Table 5. Input data for the Least Squares Reconstruction

	Vehicle 1 Full-size Pickup	Vehicle 2 Crossover Utility
ΔV_{long}	TBD	32.5 km/h (20.2 mph)
Departure angle of CG	167.4°	-8.1°
Initial Speed	TBD	109.4 km/h (68.0 mph)

A convenient way to carry out such a reconstruction is to place the PIM impulse-momentum model equations into a spreadsheet [16], set up the computation of Q and let the optimization algorithm of the spreadsheet, in this case Excel *Solver*, carry out the minimization [11]. Figure 14 shows a spreadsheet from the *VCRware* software package [16] that is

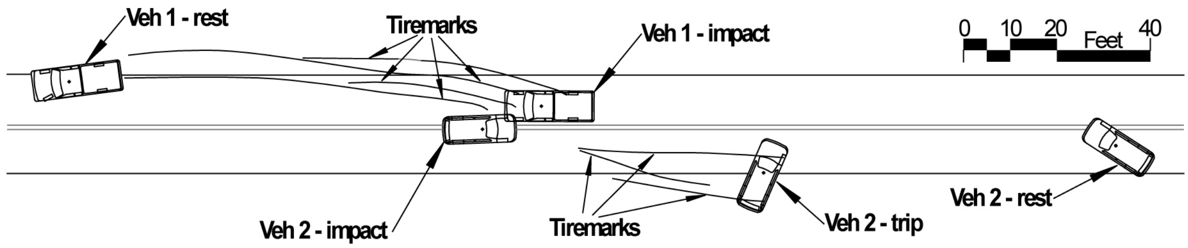

Figure 13. Scale diagram showing the crash scenario

programmed using the PIM impulse-momentum model. The equations in this spreadsheet, by definition, include the coefficient of restitution, *e*, and impulse ratio, μ (implemented in the spreadsheet as a ratio to the critical value as μ/μ_0). Figure 14 also shows the results of the minimization process. Figure 15 shows the input to the spreadsheet's optimization routine (called "Solver Block"), including the "Target" cell which contains the cell reference for the formula *Q* which is to be minimized, the cell numbers of the quantities whose values are to be determined (reconstructed) through the minimization process and the constraints imposed on the process. The suitable ranges for the constraints on *e*, μ, and Γ for a sideswipe collision are established using the test data as outlined above.

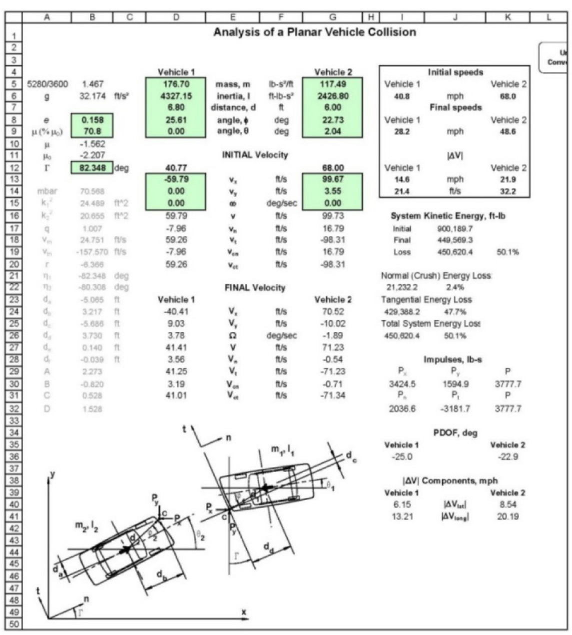

Figure 14. Spreadsheet showing the results of the least squares reconstruction

The reconstructed value of the initial speed of Veh 1 is V_1 = 40.8 mph (59.8 ft/s, 65.6 kph). Note that the coefficient of restitution, cell B8 in Figure 14, and the impulse ratio, cell B9 in Figure 14, are found in the optimization process rather than being specified a priori. The reconstructed values are *e* = 0.158 and μ = 70.8% of μ_0. This value of the coefficient of restitution is consistent with the data from the IIHS testing presented here ($0 \le e \le 0.3$) as well as with other published data [1, 13]. The value of the impulse ratio of 70.8% of the critical value is on the low end of the range for the vehicle-to-barrier tests, and below the range from the six vehicle-to-vehicle tests that were sideswipes. In this situation, confidence in the results (principally the preimpact speed of Vehicle 1) is high for two reasons:

1. The reconstruction is based directly on the physical evidence: the data collected by the EDR during the crash (preimpact speed and ΔV_{long} of Veh 2) and the tire marks, crush of the vehicles, etc., and
2. The values for *e*, μ, and Γ, all determined in the reconstruction by the optimization routine, are consistent with the test data.

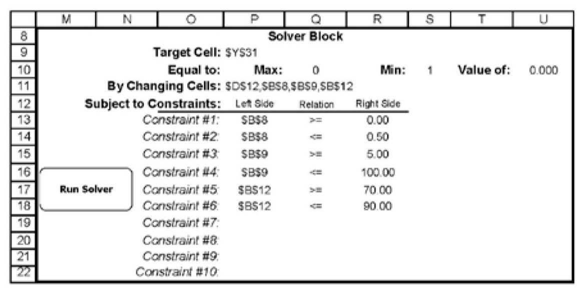

Figure 15. Input to *Solver* optimization routine for minimization of *Q* (calculated in cell Y31, not shown) in order to find the initial speed of Vehicle 1 (cell D12 in Figure 14).

DISCUSSION

This paper presents, for the first time in the open literature, a framework with which to analyze and reconstruct high-speed sideswipe vehicle-to-barrier and vehicle-to-vehicle collisions. This framework stems from a small overlap crash testing program conducted by IIHS. A video analysis routine was developed to extract the required information, primarily the ΔVs of the centers of masses of the test vehicles from the IIHS test video data. The crash parameters, *e*, μ, and Γ were then determined using the test data and the planar impact mechanics (PIM) model.

The data are segregated into sideswipe and non-sideswipe categories. From these categories, suitable ranges of the crash parameters are established for this class of vehicle-to-barrier and vehicle-to-vehicle crashes. In addition to the use of these ranges for selection of the parameters in a reconstruction exercise, the paper includes the presentation of an optimization method in which EDR data and the available physical evidence are used to reconstruct the preimpact speeds of the vehicles in an actual collision. The availability of (reliable) EDR data for use in the reconstruction process includes at least two advantages:

1. It provides a means of calculating the crash parameters for comparison to the ranges eliminating the need to select the values a priori form the appropriate ranges, and
2. It reduces the overall uncertainty in the reconstruction of the speeds of the vehicles.

This approach of calculating the crash parameter values (using optimization methods) is superior to selecting the values merely to facilitate the reconstruction in that, in this manner, the reconstructionist need not make a determination whether the crash is a sideswipe, or not a sideswipe, to reconstruct the crash. Rather, the physical evidence itself (including the EDR data) dictates the nature of the crash. This approach is beneficial as the amount of data pertaining to sideswipe collisions is limited.

In those situations where traditional reconstruction methods are used, the results of the DOE analysis provide the reconstructionist with valuable insight into the sensitivity of the reconstruction to variations in the various parameters. Using the insights provided by this analysis, the reconstructionist can knowledgeably focus the uncertainty calculations on those parameters with the greatest influence on the results.

While the information presented in this paper provides a solid foundation for the reconstruction of this class of high-speed sideswipe collisions, more research will contribute to a better understanding of this topic. In particular, additional data for vehicle-to-vehicle collisions is needed beyond the nine tests (with six classified as a sideswipe) conducted by IIHS.

As the majority of the vehicles used in the IIHS tests were sedans (all the vehicle-to-vehicle tests were sedans), additional tests in which light vehicles other than sedans (pickup trucks, vans, minivans, etc.) are included will provide needed vehicle class specific data related to these collisions and enhance the understanding of this class of collision within the accident reconstruction community. Additionally, analysis based on the currently available data beyond what is presented here is encouraged.

Note that the data from the IIHS tests and the ranges for the impact parameters presented herein apply to this type of high-speed sideswipe collisions. These data and the reconstruction method shown in the example should not be used for analysis and reconstruction of sideswipe collisions different that those addressed in this paper without further consideration.

ACKNOWLEDGEMENTS

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APPENDIX

APPENDIX 1 CONSTRAINING RELATIONSHIP BETWEEN d_1 AND φ_1 FOR VEHICLE-TO-BARRIER TESTS

In this analysis, the value of Γ, the orientation of the crush surface, is defined using the vehicle geometry and the amount of overlap for a given test. The geometry used to define this relationship is shown in Figure A-1. Here A_P is defined as the average of the distance from front bumper to top of windshield and the distance from the front bumper to the bottom of the windshield. The other dimensions, O_W (overall width), O_L, (overlap), G (distance from front bumper to CG), Γ (crush surface angle), d_1 (distance from CG to impact center) and φ_1 (angle of d_1 relative to longitudinal/heading axis of the vehicle) are shown in Figure A-1.

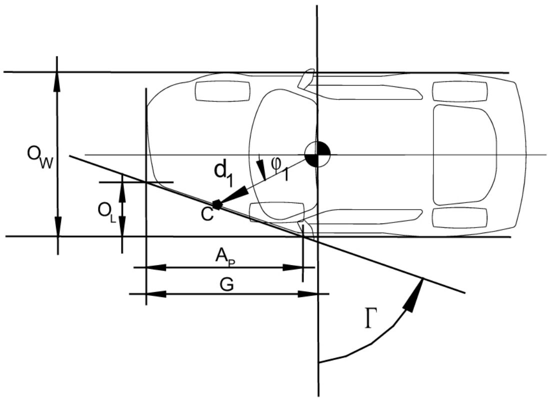

Figure A-1. Diagram of geometric parameters for analysis of vehicle-to-barrier test

The impact center, C, is assumed to be located on the line depicting the crush surface (as shown). An equation relating d_1 and ϕ_1 can be written:

$$d_1 \sin(\phi_1) = -\frac{O_L}{A_p} d_1 \cos(\phi_1) + \frac{O_W}{2} \tag{A1}$$

Solving for d_1:

$$d_1 = \frac{O_W}{2\left(\sin\phi_1 + \frac{O_L}{A_p}\cos\phi_1\right)} = \frac{A_p O_W}{2\left(A_p \sin\phi_1 + O_L \cos\phi_1\right)} \tag{A2}$$

Bounds exist for these values:

$$0 < d_1 \cos\phi_1 < A_p \tag{A3}$$

This can be rewritten as:

$$\frac{O_W}{2} - O_L < d_1 \sin\phi_1 < \frac{O_W}{2} \tag{A4}$$

An expression for the value of the crush angle, Γ, can also be written:

$$\Gamma = \frac{\pi}{2} - \tan^{-1}\frac{O_L}{A_p} \tag{A5}$$

This equation was used to compute Γ for all of the tests.

The terminus of the distance, A_P, at the midpoint of the front windshield, a feature independent of the crush profile, was selected for two reasons:

1. It was near the end of the crush surface for the test crash profiles (as such a "point" can be determined), and
2. It gives a common reference point that can be used in applications of the paper's results to reconstructions.

APPENDIX 2 - PART 1: ANALYSIS RESULTS FOR VEHICLE-TO-BARRIER TESTS (NON-SIDESWIPE TESTS SHOWN IN ITALICS; OUTLIER TEST CF11006 LISTED LAST)

IIHS ID	MY	Vehicle	Vehicle Type	Barrier Type	Overlap	e	μ (% μ_0)	d_1 (ft)	φ (deg)	Γ deg	v_0 ft/s	ΔV_x ft/s	ΔV ft/s	ΔV_y ft/s	Ω, (deg/sec)
CEN1212	*2012*	*Audi A4*	*Sedan*	*Flat 150 barrier*	*25%*	*0.103*	*100.0*	*3.7*	*35.8*	*74.4*	*58.60*	*52.79*	*53.00*	*11.53*	*205.96*
CEN1204	*2012*	*BMW 328i*	*Sedan*	*Flat 150 barrier*	*25%*	*0.039*	*100.0*	*4.3*	*26.6*	*74.8*	*58.60*	*55.37*	*54.60*	*10.61*	*172.85*
CF10017	*2008*	*Ford Fusion*	*Sedan*	*Flat steel wall 5 cm rad*	*25%*	*0.000*	*100.0*	*4.6*	*23.8*	*74.6*	*58.69*	*54.82*	*55.00*	*9.94*	*157.23*
CF10023	*2008*	*Ford Fusion*	*Sedan*	*Flat steel wall 5 cm rad*	*21%*	*0.000*	*97.5*	*4.6*	*26.3*	*77.0*	*58.69*	*46.73*	*48.70*	*10.65*	*196.28*
CF11016	*2009*	*Ford Fusion*	*Sedan*	*Deformable barrier face*	*20%*	*0.147*	*98.9*	*4.4*	*29.3*	*77.6*	*58.60*	*51.20*	*52.90*	*13.11*	*163.11*
CF10001	*2008*	*Honda Accord*	*Sedan*	*25.4 cm pole*	*25%*	*0.000*	*100.0*	*4.4*	*26.3*	*74.2*	*58.60*	*55.36*	*54.30*	*9.38*	*179.40*
CEN1205	*2012*	*Lexus IS 250*	*Sedan*	*Flat 150 barrier*	*25%*	*0.253*	*97.4*	*3.7*	*34.7*	*74.3*	*58.60*	*50.80*	*52.60*	*13.68*	*171.44*
CEN1211	*2012*	*Mercedes-Benz C 250*	*Sedan*	*Flat 150 barrier*	*25%*	*0.159*	*100.0*	*3.8*	*32.7*	*74.8*	*58.60*	*55.32*	*54.20*	*11.75*	*200.71*
CF10005	*2007*	*Mitsubishi Galant*	*Sedan*	*25.4 cm pole*	*25%*	*0.279*	*100.0*	*4.1*	*29.1*	*74.4*	*58.51*	*55.52*	*56.00*	*13.59*	*165.27*
CF10024	*2009*	*Mitsubishi Galant*	*Sedan*	*Flat steel wall 5 cm rad*	*20%*	*0.000*	*100.0*	*3.9*	*36.8*	*77.3*	*58.42*	*54.38*	*51.10*	*9.01*	*243.75*
CF11005	*2009*	*Mitsubishi Galant*	*Sedan*	*Flat steel wall 15 cm*	*27%*	*0.150*	*98.1*	*3.9*	*31.3*	*73.1*	*58.60*	*51.59*	*53.10*	*12.47*	*163.86*
CF11014	*2009*	*Mitsubishi Galant*	*Sedan*	*Deformable barrier face*	*20%*	*0.022*	*100.0*	*4.3*	*30.9*	*77.3*	*58.51*	*52.38*	*53.00*	*11.71*	*188.46*
CF10002	*2010*	*Subaru Forester*	*Cross Utility*	*25.4 cm pole*	*25%*	*0.177*	*100.0*	*4.3*	*24.4*	*73.9*	*58.69*	*57.97*	*56.50*	*11.55*	*163.43*
CEN1203	*2012*	*Volkswagen CC*	*Sedan*	*Flat 150 barrier*	*25%*	*0.150*	*99.3*	*3.8*	*33.7*	*73.6*	*58.60*	*51.80*	*53.30*	*12.75*	*183.91*
CF11001	*2011*	*Volvo S60*	*Sedan*	*Flat steel wall 5 cm rad*	*20%*	*0.000*	*100.0*	*3.9*	*35.6*	*76.9*	*58.42*	*52.70*	*51.70*	*10.11*	*214.00*
CF11015	*2012*	*Volvo S60*	*Sedan*	*Deformable barrier face*	*20%*	*0.231*	*100.0*	*3.7*	*40.3*	*76.9*	*58.51*	*52.25*	*52.30*	*12.75*	*219.38*
				AVERAGE	**23.3%**	**0.107**	**99.5**	**4.1**	**31.1**	**75.3**	**58.6**	**53.2**	**53.3**	**11.5**	**186.8**
				STD DEV	**2.6%**	**0.099**	**0.9**	**0.3**	**4.9**	**1.5**	**0.1**	**2.6**	**1.9**	**1.5**	**24.7**
				MIN	**20.0%**	**0.000**	**97.4**	**3.7**	**23.8**	**73.1**	**58.4**	**46.7**	**48.7**	**9.0**	**157.2**
				MAX	**27.0%**	**0.279**	**100.0**	**4.6**	**40.3**	**77.6**	**58.7**	**58.0**	**56.5**	**13.7**	**243.8**
CEN1201	2012	Acura TL	Sedan	Flat 150 barrier	25%	0.298	76.6	4.3	28.3	74.6	58.51	35.44	38.10	13.94	48.78
CEN1214	2012	Acura TL	Sedan	Flat 150 barrier	25%	0.221	80.7	4.4	27.2	74.6	58.51	37.46	39.60	12.98	61.56
CEN1202	2012	Acura TSX	Sedan	Flat 150 barrier	25%	0.254	89.3	4.1	28.6	74.2	58.51	44.86	46.90	13.58	102.83
CEN1213	2012	Acura TSX	Sedan	Flat 150 barrier	25%	0.304	92.8	3.9	32.5	74.2	58.51	47.72	49.90	14.44	135.93
CN12001	2012	Fiat 500	Subcompact	Flat 150 barrier	26%	0.123	86.2	3.0	37.9	70.7	58.78	43.26	44.40	12.94	166.44
CF10020	2008	Ford Fusion	Sedan	Flat steel wall 5 cm rad	20%	0.000	95.9	3.8	37.5	77.6	58.60	45.57	46.90	10.62	192.50
CF10028	2008	Ford Fusion	Sedan	50.8 cm pole	25%	0.232	71.8	3.9	32.9	74.6	58.51	32.29	34.40	13.70	60.83
CF11002	2008	Ford Fusion	Sedan	Flat steel wall 15 cm	25%	0.000	85.2	4.1	29.0	74.6	58.60	38.49	40.00	10.69	102.75
CF11004	2008	Ford Fusion	Sedan	Flat steel wall 15 cm	25%	0.000	82.3	4.0	31.3	74.6	58.60	36.41	38.10	10.56	103.00
CF11012	2008	Ford Fusion	Sedan	Flat steel wall 15 cm	25%	0.127	86.5	4.0	30.6	74.6	58.69	40.91	42.80	12.51	110.00
CF11013	2009	Ford Fusion	Sedan	Flat steel wall 15 cm	25%	0.000	89.5	3.9	32.9	74.6	58.60	41.95	43.40	9.51	142.19
CF10003	2001	Ford Taurus	Sedan	25.4 cm pole	22%	0.000	93.9	4.6	26.7	76.2	51.22	39.65	40.80	8.86	112.83
CN12002	2012	Ford Taurus	Sedan	Flat 150 barrier	25%	0.084	87.4	4.2	30.1	74.2	58.60	41.47	43.20	12.04	108.30
CN12003	2012	Honda Odyssey	Minivan	Flat 150 barrier	25%	0.230	89.8	3.9	33.0	70.7	58.60	46.40	48.60	14.54	125.54
CEN1209	2012	Infiniti G25	Sedan	Flat 150 barrier	25%	0.252	84.0	3.7	36.0	75.4	58.41	40.16	42.40	13.58	119.00
CF09005	2005	Kia Rio	Sedan	25.4 cm pole	22%	0.064	90.4	3.8	30.4	75.5	51.31	37.32	38.80	10.49	124.83
CN12004	2012	Kia Soul	Sedan	Flat 150 barrier	25%	0.000	86.4	3.2	40.7	71.4	58.51	41.01	42.50	11.03	174.43
CEN1206	2012	Lexus ES350	Sedan	Flat 150 barrier	25%	0.305	89.8	4.1	30.1	74.5	58.60	45.51	47.70	14.20	109.33
CEN1210	2012	Lincoln MKZ	Sedan	Flat 150 barrier	25%	0.145	79.0	3.9	32.1	74.5	58.41	36.13	38.30	12.61	85.28
CF10027	2009	Mitsubishi Galant	Sedan	50.8 cm pole	25%	0.264	89.9	3.9	31.5	74.3	58.60	45.18	47.30	14.00	121.31
CF10029	2009	Mitsubishi Galant	Sedan	50.8 cm pole	25%	0.294	92.8	3.8	33.3	74.3	58.69	47.56	49.70	14.44	142.21
CF10022	2001	Toyota Tundra	Pickup Truck	Flat steel wall 5 cm rad	20%	0.000	95.3	4.2	33.4	76.5	58.51	46.20	47.40	8.71	161.08
CF10025	2001	Toyota Tundra	Pickup Truck	Flat steel wall 5 cm rad	20%	0.000	92.9	4.1	34.5	76.5	58.60	43.84	45.20	9.87	154.69
CEN1207	2012	Volvo S60	Sedan	Flat 150 barrier	25%	0.081	85.6	3.6	39.5	73.5	58.51	40.73	42.40	11.95	146.17
				AVERAGE	**24.2%**	**0.137**	**87.3**	**3.93**	**32.5**	**74.4**	**58.0**	**41.5**	**43.3**	**12.2**	**121.3**
				STD DEV	**1.8%**	**0.121**	**5.99**	**0.34**	**3.72**	**1.6**	**2.1**	**4.24**	**4.21**	**1.88**	**35.9**
				MIN	**20.0%**	**0.000**	**71.8**	**2.99**	**26.7**	**70.7**	**51.2**	**32.3**	**34.4**	**8.71**	**48.8**
				MAX	**26.0%**	**0.305**	**95.9**	**4.55**	**40.7**	**77.6**	**58.8**	**47.7**	**49.9**	**14.5**	**192.5**
CF11006	2012	Volvo S60	Sedan	Flat steel wall 15 cm	25%	0.555	83.3	3.8	34.9	73.7	58.51	43.67	47.20	17.89	95.43

APPENDIX 2 - PART 2: ANALYSIS RESULTS FOR VEHICLE-TO-VEHICLE TESTS (NON-SIDESWIPE TESTS SHOWN IN ITALICS)

IIHS ID	Vehicle	Overlap	e	μ (% μ_0)	Φ (deg)	Γ (deg)	v_0 (ft/s)	ΔV (ft/s)	Ω (deg/sec)
CF09009a	2005 Ford Taurus	28%	0.009	86.2	20.4	74.0	50.94	33.0	64.00
CF09009b	2001 Ford Taurus	28%	0.009	86.2	20.8	74.0	51.12	32.6	75.38
CF10010a	2008 Ford Fusion	28%	0.005	81.6	26.5	71.8	58.69	37.2	94.85
CF10010b	2009 Mitsubishi Galant	28%	0.005	81.6	34.0	71.8	58.51	38.7	63.28
CF11009a	2009 Ford Fusion	27%	0.000	90.0	26.1	77.8	58.42	39.8	132.00
CF11009b	2008 Ford Fusion	27%	0.000	90.0	24.3	77.8	58.60	39.7	130.44
CF11017a	2009 Ford Fusion	21%	0.177	83.5	24.1	80.7	58.51	31.1	67.33
CF11017b	2008 Ford Fusion	21%	0.177	83.5	25.6	80.7	58.60	32.3	85.33
CF11018a	2009 Mitsubishi Galant	21%	0.021	90.0	25.2	77.2	58.51	39.9	117.56
CF11018b	2009 Mitsubishi Galant	21%	0.021	90.0	26.2	77.2	58.69	39.7	116.14
CF11019a	2012 Volvo S60	22%	0.061	89.4	25.1	77.0	58.51	40.7	142.33
CF11019b	2012 Volvo S60	22%	0.061	89.4	27.7	77.0	58.60	40.2	140.83
		AVG	**0.046**	**86.8**	**25.5**	**76.4**	**57.3**		
		STD DEV	**0.065**	**3.5**	**3.5**	**3.0**	**2.9**		
		MIN	**0.000**	**81.6**	**20.4**	**71.8**	**50.9**		
		MAX	**0.177**	**90.0**	**34.0**	**80.7**	**58.7**		
CF11011a	*2012 Volvo S60*	*28%*	*0.098*	*96.6*	*36.1*	*40.9*	*58.51*	*54.9*	*185.67*
CF11011b	*2012 Volvo S60*	*28%*	*0.098*	*96.6*	*37.3*	*40.9*	*58.69*	*54.9*	*192.28*
CF10012a	*2009 Ford Fusion*	*15 ^{o}oblique*	*0.089*	*100.0*	*28.6*	*33.0*	*58.96*	*53.3*	*200.75*
CF10012b	*2009 Mitsubishi Galant*	*15 ^{o}oblique*	*0.089*	*100.0*	*23.1*	*33.0*	*56.23*	*53.0*	*69.88*
CF10013a	*2009 Mitsubishi Galant*	*15 ^{o}oblique*	*0.018*	*100.0*	*15.6*	*0.0*	*56.69*	*49.0*	*204.65*
CF10013b	*2008 Ford Fusion*	*15 ^{o}oblique*	*0.018*	*100.0*	*23.7*	*0.0*	*58.23*	*48.3*	*73.21*
		AVG	**0.068**	**98.9**	**27.4**	**24.6**	**57.9**		
		STD DEV	**0.039**	**1.76**	**8.3**	**19.4**	**1.14**		
		MIN	**0.018**	**96.6**	**15.6**	**0.00**	**56.2**		
		MAX	**0.098**	**100.0**	**37.3**	**40.9**	**59.0**		