AN OVERVIEW OF NHTSA'S CRASH RECONSTRUCTION SOFTWARE WinSMASH

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ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) uses WinSMASH computer software to estimate the change in velocity, delta-V, of the vehicles involved in crashes. The software uses detailed measurements from the crash scene, vehicle damage and vehicle stiffness characteristics to compute energy absorbed by the vehicle and estimate the delta-V and Barrier Equivalent Speed (BES). The WinSMASH is a Microsoft Windows based, enhanced and updated version of the accident reconstruction software CRASH3 previously used by NHTSA. The purpose of this paper is to describe the new enhancements in the program.

The damage algorithm used in CRASH3 has been reformulated in WinSMASH. The new damage algorithm in WinSMASH is based on an assumed linear relationship between crash energy and crush and uses intercept d_0 and slope d_1 to describe vehicle stiffness. The software uses generic vehicle size and stiffness categories based on the vehicle's wheelbase. However, the program also allows the users to enter the vehicle specific stiffness coefficients. The stiffness coefficients for a large number of vehicles have been calculated from crash test results and integrated into WinSMASH. An automated procedure to select the vehicle specific stiffness coefficients is currently under development. A statistical model is also being developed for estimating the stiffness coefficients of a vehicle that is not crash tested. The paper provides an overview of these procedures.

The WinSMASH estimated delta-V of the vehicles is compared with the corresponding delta-V obtained from the Event Data Recorder (EDR) installed in the crashed vehicles to assess the accuracy of the software. The staged crash tests used to validate the software are also discussed in the paper.

INTRODUCTION

The NHTSA's National Center for Statistics and Analysis (NCSA) has been collecting nationally representative data on motor vehicle traffic crashes through the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS), since 1979. The purpose of this data collection effort is to understand the real world motor vehicle crash performance and the injury risk as a function of crash severity. The most commonly used measure of crash severity is the change in velocity, delta-V of vehicles involved in a collision. It is defined as the change in velocity of the crashed vehicle during the collision phase. The delta-V is considered a good indicator of the crash severity because it is related to the impact forces of the collision and to the vehicle deceleration.

In the 1970s, Calspan Corporation developed the program CRASH (Calspan Reconstruction of Accident Speeds on the Highway) for NHTSA to assist SMAC (Simulation Model of Automobile Collisions) users in determining a first estimate of impact speeds. It was subsequently utilized as stand-alone software to estimate the delta-V of the vehicles involved in a crash and make a standardized assessment of the severity of an impact. The program had two separate and independent methods, trajectory analysis and damage analysis. The trajectory analysis method required detailed measurements from a crash scene and vehicle to compute the delta-V using the principle of conservation of linear momentum for the collision.

The damage analysis method was based on Campbell's observation that for full frontal impacts into a fixed rigid barrier, the delta-V has a linear relationship with residual crush [1]. It used detailed measurements of the structural deformation of each vehicle to estimate the approach energy, which was then used to estimate the delta-V.

The NASS/CDS began coding the delta-V of crashed vehicles in 1979 using the CRASH program. The program was updated and revised several times in the 1980s to a widely used and distributed mainframe version:CRASH3. In the late 80s, the program was migrated to a DOS based PC platform and the version was called CRASHPC. No algorithm changes were made in the translation. The CRASH3 program was

based on crash tests conducted on older (1971-1974) GM full frame body cars. Later model year cars have significant changes in the structure and materials and many have a unitized body. In the 1990s, the NHTSA Vehicle Research and Test Center (VRTC) used repeated test techniques on later model year (1980-1992) cars to verify the relationship between the crush energy and residual crush. Based on these results the damage analysis algorithm of the CRASH3 program was reformulated and the new program was called SMASH. The SMASH program was written for the Microsoft Windows environment. Finally, in 1995, Volpe National Transportation System Center made some user-friendly enhancements to SMASH and integrated the program with the NASS/CDS data entry software and called the program WinSMASH. Since then several versions of the program were released for internal use, but all of those releases were mostly cosmetic changes and error corrections. The WinSMASH is written in the Delphi programming language under the Microsoft windows environment. One of the key features of the WinSMASH software is the user-oriented, menu-driven, interactive input mode. The interactive input option allows the user to supply all input data, edit the data and run the program. A mouse can be used to navigate through the program. The results of the analysis are displayed in numerical and graphical forms. The NASS/CDS system began using SMASH/WinSMASH in 1995. This paper describes WinSMASH version 2.42, which is currently being used by NHTSA.

The new additions in WinSMASH, since the last version of CRASH3 was released, include:

- Reformulated damage algorithm
- Updated stiffness coefficients
- Input fields for substitution of default data including stiffness coefficients
- New algorithm for missing vehicle reconstruction
- Estimation of Barrier Equivalent Speed

OBJECTIVES

The purpose of this paper is to describe the new enhancements in the WinSMASH software since the last PC-based version of CRASH3 was released. This paper provides an overview of different calculation procedures of WinSMASH and their application in the NASS/CDS. The accuracy of the program is assessed by comparing the WinSMASH estimated delta-V with the corresponding delta-V obtained from the EDR installed in the crashed vehicles and with the delta-V from staged crash tests. The use of vehicle specific stiffness is proposed and a statistical method for estimating the stiffness coefficients of a vehicle model that is not crash tested is being developed and is discussed here briefly.

WinSMASH PROCEDURES

The WinSMASH software has two separate and independent algorithms (Trajectory Analysis and Damage Analysis) to estimate the delta-V of the vehicles involved in a crash. Each method has options to reconstruct vehicle-to-vehicle and vehicle-to-object crashes. The software also has a reformulated missing vehicle algorithm that is used to estimate the delta-V when the damage to one of the vehicles is unknown.

All of the simplifying assumptions of CRASH3 remain in WinSMASH. The algorithms assume the impact was instantaneous and at some point during the impact both vehicles reached a common velocity. Due to these assumptions, WinSMASH can not be used for rollovers, sideswipes, non-horizontal forces, severe over-ride/under-ride, under-carriage impacts, multiple impacts to the same area, and towed trailer or vehicles.

The WinSMASH algorithms are discussed in the following sections.

Trajectory Analysis Algorithm

The trajectory analysis algorithms of WinSMASH and CRASH3 are identical. The algorithm is based on work-energy relationships for the spinout and the conservation of linear momentum for collisions. It estimates the vehicle separation speed from the information about the rest position, skid marks, coefficient of friction, and point of collision. The momentum equations are then used to compute the impact speed and delta-V of the vehicles.

For oblique impacts where the line of action of the collision force is not perpendicular to the damaged side or end, the algorithm uses spinout and the conservation of linear momentum to compute the delta-V and impact speeds. For those impacts, WinSMASH also computes the delta-V using the damage analysis algorithm. The delta-V from the two algorithms will seldom be precisely equal. However, the NASS researcher assumes that a satisfactory agreement exists between the two estimates when their delta-V components differ by no more than 4 kmph or ten percent, whichever is greater.

For the axial impacts, delta-V is computed using the damage analysis algorithm. The trajectory algorithm then uses separation conditions and damage delta-V to compute the impact speeds of the vehicles.

The Trajectory Simulation Option of CRASH3/CRASHPC is also available in WinSMASH. This option can be used to improve the agreement between the predicted post crash trajectory and documented physical evidence. The algorithm changes the magnitude and direction of linear velocity of the vehicles at separation until agreement is reached between the predicted and actual rest positions and heading angles. In WinSMASH, the users have control of the number of trajectory runs, instead of up-to-5 automatic runs completed in the trajectory simulation option of CRASH3.

Required Input

To use the trajectory option in WinSMASH, the NASS researcher thoroughly examines the crash scene for physical evidence, and obtains coordinates of the rest and impact positions, heading angle, slip angle, rotation direction, end rotation position, coordinates of a point on the path if the trajectory is in a curved path, friction coefficients and rolling resistance at each tire, for each vehicle. The vehicle damage data, described later in this paper, are also required for axial impacts.

NASS/CDS Application

Due to the statistical case selection process of the NASS program, a lag time exists between the crash date and the date the crash researcher begins data collection. Scene evidence, tire marks, and other witness marks tend to diminish with time. Moreover, Anti-lock Braking System (ABS) equipped vehicles generally do not leave readily visible skid marks at the scene. As such, this evidence may be overlooked or not documented. Due to the difficulties associated with the scene data collection, the trajectory option is rarely used by the NASS researcher. Less than one percent of the coded delta-Vs in NASS/CDS are computed using the trajectory algorithm. Since the trajectory option is rarely used, no initiative was taken to update this portion of the algorithm in WinSMASH.

The major enhancements to the trajectory option in WinSMASH are the implementation of a user friendly interface and graphical output. The detailed description of the trajectory analysis algorithm can be found in the CRASH3 manual [2].

Damage Analysis Algorithm

The damage analysis algorithm uses the damage measurement of the vehicle to estimate the approach energy absorbed by the vehicle, which is then used to estimate the delta-Vs by using the principal of conservation of momentum. The damage algorithm of CRASH3 was based on the assumed linear relationship between the impact velocity and crush and was derived from the crash tests conducted on old (1971-1974) General Motors full frame body cars. The later model year cars have unitized body and have significant changes in material and structures. Similar crash tests on late model year cars were needed to study their crush behavior.

In the 1990s, VRTC performed several crash tests on late model year cars [1980-1992] at delta-V in the range of 16-64 kmph [4,5,6]. A repeated test technique was used to confirm the linear relationship between the terms $\sqrt{\frac{2E_A}{w}}$ and crush. Where E_A is the energy absorbed by the vehicle structure and w is the width of the crush. The technique was based on the assumption that the vehicle deforms under repeated impacts in a manner similar to that of a single test at higher speeds having the same absorbed impact energy [3]. Based on the results from the crash tests, the damage analysis algorithm of CRASH3 was reformulated in WinSMASH. The new damage algorithm in WinSMASH is based on an assumed linear relationship between crash energy and crush [4,5,6].

The linear relationship between $\sqrt{\frac{2E_A}{w}}$ and residual crush is represented by Figure 1. In this model two parameters intercept, d_0 and slope, d_1 characterize the vehicle stiffness.

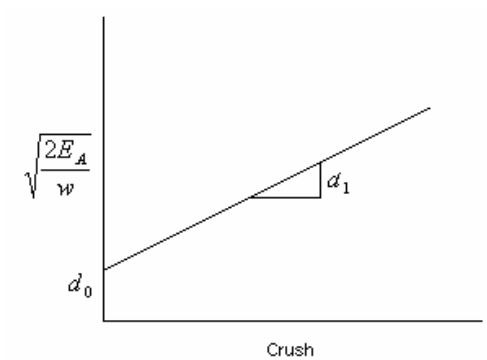

Figure 1. Assumed linear relationship between crush and crash energy.

The expression for the straight line in Figure 1 is given by:

$$\sqrt{\frac{2E_A}{w}} = d_0 + d_1 \times C \qquad (1).$$

Where C is the residual crush.

The energy absorbed during the approach period that is defined as the time between the initial contact and the time when common velocity is achieved, can be calculated by integrating the expression over the crush profile C(w):

$$E_A = \int_0^w \frac{1}{2} \times (d_0 + d_1 \times C)^2 \, dw \qquad (2).$$

In WinSMASH the integration is performed numerically by assuming piecewise linear approximation of the crush profile. The crush profile can be defined by two, four, or six equidistant points along the damage plane.

Equation (2) is used to compute the absorbed energy (E_A) for each vehicle. The total energy (E_T, sum of energy absorbed by each vehicle) is then used to compute the delta-V of each vehicle at the center of gravity (c.g.) using the principle of conservation of linear momentum. The delta-V of the approach period is given by:

$$\Delta V_1 = \sqrt{\frac{2E_T\gamma_1}{M_1\left(1 + \frac{\gamma_1 M_1}{\gamma_2 M_2}\right)}} \qquad (3).$$

$$\Delta V_2 = \sqrt{\frac{2E_T\gamma_2}{M_2\left(1 + \frac{\gamma_2 M_2}{\gamma_1 M_1}\right)}} \qquad (4).$$

M_1 and M_2 are the masses of the vehicles and

$$\gamma_1 = \frac{k_1^2}{k_1^2 + h_1^2} \quad \text{and} \quad \gamma_2 = \frac{k_2^2}{k_2^2 + h_2^2} \qquad (5).$$

Where:
k_1 and k_2 are the radius of gyration of vehicles 1 and 2
h_1 and h_2 are the moment arm of impact force [Figure2].

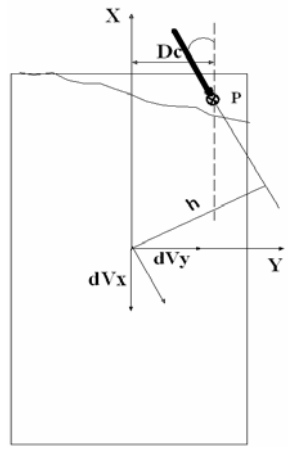

Figure 2. Moment Arm in non-central collision

The moment arm of impact force depends on the location of the centroid of the damage area relative to the center of gravity of the vehicle and the Principal Direction of Force (PDOF). For central impacts, where the line of action of the collision force passes through the center of mass of the two vehicles, the moment arms are zero, and γ_1 and γ_2 are equal to 1. The procedure to determine the h_1 and h_2 can be found in the CRASH3 Technical Manual [2].

The stiffness coefficients A, B and G used in CRASH3 are replaced by d_0 and d_1 in WinSMASH. The new coefficients are conceptually more direct and simpler. It avoids the need to reduce the experimental results to force-deflection formulation and models the energy crush behavior directly. The WinSMASH stiffness coefficients can be converted to CRASH3 coefficients A and B as follows:

$$A = d_0 \times d_1 \quad \text{and} \quad B = d_1^2 \qquad (6).$$

The WinSMASH damage reformulation consists mainly of the addition of new crash test data points and a rework of the formula to use different symbols [7]. Nonetheless, the updated algorithm allows a general procedure for front, rear, and side impacts. The observed improvement in results of the WinSMASH is due to the use of vehicle-specific dimensions, inertial properties, and updated stiffness coefficients.

The damage algorithm in WinSMASH only estimates the velocity change in the approach period. The velocity change during the separation period defined as the period between the maximum crush and complete separation of the vehicles is not considered in the analysis. The residual crush is used to compute the energy absorbed to the point of common velocity.

Required Input

The input required to use damage analysis option are Field L, Damage Offset, Crush Profile, PDOF, heading angle, Collision Deformation Classification (CDC), and Stiffness Coefficients. The NASS/CDS uses SI units for all measurements. The following sections briefly describe the input variables.

Field L and Field L-D

The Field L, also known as damage length or width, is defined as the length of the direct and induced damage measured parallel to the damage plane. The Field L is used for Damage Length in WinSMASH for side plane impacts and for end plane impacts where the damage does not extend across the entire end plane. For end impacts where contact and induced damage includes the entire width of the end plane, the undeformed end width (UEW) of the vehicle is entered as the Damage Length in WinSMASH. The UEW is the distance on an undamaged end plane measured bumper corner to bumper corner from an exemplar vehicle.

The Field L-D (D_{FL}) is the distance from the center of the Field L to vehicle's damaged end plane center or the damaged wheelbase center, measured parallel to the vehicle's lateral or longitudinal axes for front and side impacts, respectively [Figure 3]. The Field L-D measurement is primarily used to specifically locate the damage on the vehicle diagram.

Damage Offset

The damage offset also known as Direct D (Dc) is the distance from the center of the direct damage width to either the vehicle's damaged end plane center or the damaged wheelbase center [Figure 3]. It is measured along the general slope of the damaged plane. The center of gravity (c.g.) of the vehicle is typically located forward of the center of the wheelbase. For side plane damage, the WinSMASH program adjusts the D_C to account for different location of c.g. and the center of wheelbase. The D_C measurement is used to compute the moment arm of the impulse force.

In non-central frontal collisions (i.e. offset), the line of action of the collision forces passes through a point P in the region of direct contact [Figure 2]. This point P (centroid of direct damage area) is at a distance, Dc, away from the c.g. of the vehicle in a lateral direction. The point is between the undamaged plane (undamaged box) and damage plane (damaged box) in the region of direct contact. The force acting at a distance from the c.g. creates a moment arm and in turn affects the calculated delta-V of the vehicles, since this moment arm tends to produce rotation as well as translation. Assuming the same force is acting, a larger moment arm produces a lower delta-V but a higher rate of rotation.

Crush Profile

In NASS/CDS the basis for field data collection is the point-to-point vehicle measurement technique which specifies the actual distance a specific component moved within its damage plane. The crush profile measurements are obtained by establishing a reference line, measuring residual crush, and subtracting the undeformed bumper/body taper to obtain the resultant crush profile. The emphasis is placed on the damage level at which the stiffness coefficients were determined. For end impacts, measurements are taken at bumper level and for side impacts the measurements are typically taken along the door guard beam. Typically, the crush measurements are taken at six equidistant points obtained by dividing the Field L into five equal lengths [Figures 3, 4]. The depths of the crush are measured from the original outline of the vehicle to the final crush position in the perpendicular direction.

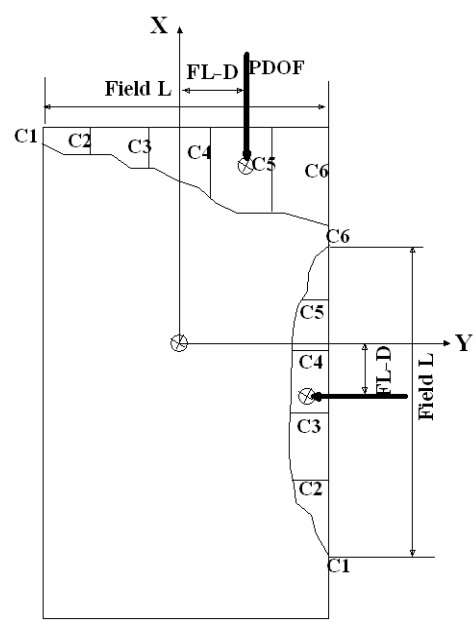

Figure 3. Crush Profile Approximation

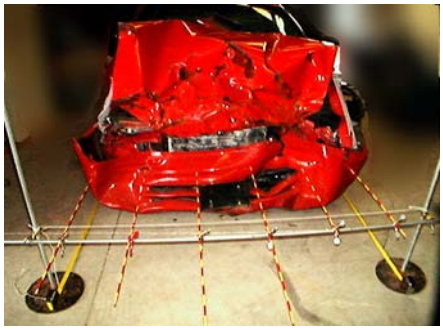

Figure 4. Measurement taken during vehicle inspection

PDOF and Heading Angle

The PDOF is defined as the angle of the direction of Impulse Force acting on the vehicle, measured relative to the longitudinal axis. It determines the direction of delta-V. The delta-V computed by WinSMASH is most sensitive to PDOF and yet it is the most difficult measurement to obtain. The NASS investigator considers the general flow of sheet metal crush of the vehicle, weight and impact speed, pre and post impact trajectories and occupant kinematics to determine the PDOF. In NASS/CDS, PDOF is estimated to the nearest 10 degrees and entered as an improved PDOF to the clock direction specified in columns 1 and 2 of the CDC. The PDOF estimated from the CDC clock direction may be off by as much as 30 degrees.

The heading angle is the direction of travel and it specifies the orientation of the vehicle at the impact location. For vehicle-to-vehicle impacts, the WinSMASH requires that the Force Vectors on the vehicle must be within 15 degrees of perfectly collinear or along the same line. The WinSMASH performs a collinearity check before proceeding with the calculation and an error message is displayed if the PDOFs are apart by more than 15 degrees.

CDC

The CDC value is used to determine the type of collision that occurred in the crash, e.g. frontal, side, rear or rollover. The CDC is a seven character alpha-numeric code that describes the vehicle deformation detail concerning the direction, location, size of the damage area, and extent of damage. A CDC is required for each vehicle for a WinSMASH run. The program uses CDC information to validate the consistency of PDOF and crush measurements. The information is also used to properly locate the damage on the vehicle diagram. If the vehicle is not available for measurement, WinSMASH has an option to use CDC information to compute a crude estimate of delta-V. The CDC is completely described in SAE Recommended Practice (SAE J224 MAR 80).

Vehicle Stiffness Coefficients d_0 and d_1

In WinSMASH, the stiffness characteristics of vehicles are defined by coefficients d_0 and d_1 as opposed to A, B and G in CRASH3. The stiffness parameters for passenger cars are categorized according to the wheelbase in similar ways as in CRASH3. The stiffness category automatically assigns the generic d_0 and d_1 according to the general structural characteristics of the vehicle.

The CRASH3 assumption, vehicles of similar size have similar stiffness characteristics, also applies to WinSMASH. The program assumes a homogeneous stiffness along the front, side and rear structures of the vehicle. The vehicles are divided into nine sets of stiffness coefficients (d_0, d_1) corresponding to seven vehicle size categories. The data from NHTSA's crashworthiness database that contains data from mostly New Car Assessment Program (NCAP) and Compliance crash tests is used to compute the stiffness coefficients for each category. First, a method developed by Prasad [4,5,6] is used to compute the d_0 and d_1 values for each vehicle in the database. The method is based on using two data points on the straight line describing $\sqrt{\frac{2E_A}{w}}$ vs. crush to determine the intercept d_0 and slope d_1. A zero crush intercept is used for the low speed data point and the high speed data point is obtained from the NHTSA's crash test. For frontal impacts, a low speed data point is assumed to be zero crush at 12 kmph. The NCAP tests at 56 kmph and Federal Motor Vehicle Safety Standard (FMVSS) No. 208 tests at 48 kmph are used for the high speed data point. For rear impacts, a low speed data point is assumed to be zero crush for the impactor speed of 16 kmph (i.e. delta-V of 8 kmph). The FMVSS No. 301 tests at 48 kmph and 80 kmph are used for the high speed data point. For side impacts FMVSS No. 214 tests at 54 kmph are used for the high speed data point. The value of d_0 is assumed to be $63.3\sqrt{\text{Newton}}$ (which is equivalent to a barrier approach velocity of approximately 16 kmph with vehicle and barrier weighing 1360 kg. each) [6]. This data point provides a reasonable estimate for low speed impacts and avoids the errors introduced by curve-fitting multiple data points clumped together at 48-56 kmph.

Figure 5 shows the crush energy relationship for a 2005 Volvo V70 which is a NHTSA frontal NCAP test number 5242.

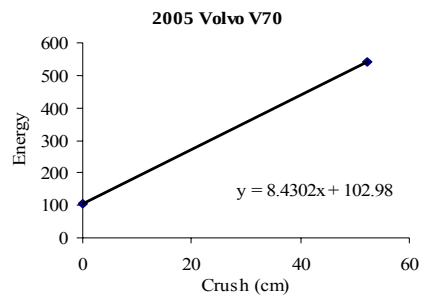

Figure 5 Crush Energy plot for NHTSA test 5242

Once the stiffness coefficients for all the vehicles are computed, the vehicles are then assigned to six passenger car categories (1 to 6) according to wheelbase and two categories for vans (category 7) and pickups (category 8). A generic set of d_0 and d_1 values are computed for each category by averaging the known values in that category. The generic stiffness coefficients used in WinSMASH are listed in Tables 1 and 2. For frontal impacts, a separate stiffness category (category 9) is used for front wheel drive (FWD) vehicles. The stiffness in category 9 is the average of all the front wheel drive passenger cars.

For side impacts, all vehicles including pickup trucks and vans are divided into six stiffness categories based on wheelbase size.

The NHTSA' crashworthiness database is constantly updated as newer models are tested by NHTSA for Compliance and NCAP. The generic stiffness coefficients shown in Tables 1 and 2 were created in 1995 using test data from NHTSA's crashworthiness database. The stiffness coefficients are currently being updated to include later model year vehicles which have been crash tested by NHTSA.

Table 1.
Vehicle Size Categories

Category	Wheelbase (cm)
1	<= – 240.8
2	240.8 – 258.0
3	258.0 – 280.4
4	280.4 – 298.4
5	298.4 – 312.9
6	> – 312.9
7 (vans)	276.8 – 330.2

Table 2.
Generic Vehicle Stiffness Categories

Cat.	Front		Rear		Side	
	d_0 $\sqrt{\text{Newton}}$	d_1 $\frac{\sqrt{\text{Newton}}}{\text{cm}}$	d_0 $\sqrt{\text{Newton}}$	d_1 $\frac{\sqrt{\text{Newton}}}{\text{cm}}$	d_0 $\sqrt{\text{Newton}}$	d_1 $\frac{\sqrt{\text{Newton}}}{\text{cm}}$
1	91.4	6.7	93.88	5.43	63.3	6.83
2	97.0	7.22	96.23	5.28	63.3	8.02
3	102.1	7.25	99.49	5.56	63.3	7.50
4	107.0	6.36	99.99	5.37	63.3	7.21
5	109.6	6.18	99.97	4.50	63.3	5.19
6	116.0	5.75	74.86	6.94	63.3	5.69
7 (vans)	109.7	8.51	98.69	7.79	-	-
8 (pickup)	105.7	7.98	101.42	7.77	-	-
9 (FWD)	99.18	6.46	-	-	-	-

NASS/CDS Application

The damage analysis option is used most often by NASS investigators to estimate the delta-V because it can be accomplished from the vehicle inspection alone and it does not require scene data. It is a practical means of independently determining the delta-V of a vehicle when good accident site data are unavailable. For 2000-2005 NASS/CDS cases, fifty-three percent of the highest severity impacts (by vehicle) have delta-V values. The other unknown delta-Vs could not be computed for reasons including non-horizontal impacts, side swipe, rollover, severe over-ride, overlapping damage, insufficient data, vehicle beyond scope, and no vehicle inspection. Ninety-nine percent of those coded delta-V are computed using one of the options of the damage analysis algorithm including Standard (vehicle-to-vehicle impacts), Barrier (vehicle-to-object impacts), Missing Vehicle or CDC-Only. Of those coded delta-Vs, about fifty-eight percent are calculated using the standard or barrier option also known as Damage-Only in NASS/CDS.

Input Fields for Substitution of Default Data

The CRASH3 program used generic vehicle parameters based on vehicle size category. These data represent an average within a specified wheelbase range. A specific vehicle sometimes has properties which differ significantly from the generic data. The vehicle dimension can result in incorrect computation of damage offset, h. These inaccuracies can cause inaccuracy in the computed delta-V. The

WinSMASH has a facility to substitute for the generic data.

The use of vehicle-specific dimensions and inertial properties has improved the WinSMASH results. The radius of gyration used in the reformulated damage algorithm of WinSMASH is based on an investigation done at VRTC as a part of the Crash Avoidance Inertial Parameter Measurement Program and is given by

k = 0.3 x (vehicle length) (7).

The generic d_0 and d_1 stiffness coefficients automatically assigned by the crush stiffness category may not apply for all collisions. As in the case of bumper over-ride and under-ride crashes, the frames of one vehicle engage with the softer part of the other vehicle. The WinSMASH allows for replacement of generic coefficients with the vehicle specific stiffness coefficients. The NHTSA's Special Crash Investigation (SCI) teams use vehicle specific coefficients when available. However, NASS/CDS only uses generic stiffness coefficients in WinSMASH for delta-V estimations.

Correction Factor

During the vehicle inspection, the depths of the crush are measured from the original outline of the vehicle to the final crush position in a perpendicular direction. However, in oblique impacts the distance through which the PDOF act is greater than the measured crush. Therefore, in CRASH3 the value of the energy absorbed by the vehicles is multiplied by a correction factor given by ($C_f = 1 + \tan^2 \alpha$) where α is the angle between the PDOF and surface normal. The usage of correction factor (C_f) increases the value of absorbed energy (E_A) and therefore, causes CRASH3 to over-predict the value of delta-V in the oblique side impacts. In reconstructing an oblique side impact that has α of 45°, eliminating the correction factor reduced the delta-V error to less the 10 percent from 40 percent [5].

In WinSMASH, the user can specify whether to use or ignore the correction factor. An option "End Shift" can be checked to include the correction factor in the damage algorithm of WinSMASH. In NASS/CDS the end shift is only used for oblique impacts where the vehicle end structure (both frame rails) shifts more than 10 cm.

Missing Vehicle Option

The missing vehicle option is used to estimate the delta-V when the damage to one of the vehicles is unknown in a vehicle-to-vehicle impact. The missing vehicle algorithm, OLDMISS of CRASH3 has been reformulated and completely integrated in WinSMASH. The new algorithm uses a simple expression directly relating the energies absorbed by the known vehicle and missing vehicle, bypassing the need to estimate the crush profile of the missing vehicle, and then integrate across that profile. The method also accounts for the energy absorbed by the induced damage. The new algorithm is based on crash tests conducted at VRTC to update the CRASH3 damage algorithm [8]. The new missing vehicle algorithm uses the following expressions to estimate the energy of the missing vehicle:

For an impact involving damage to only the front or rear of vehicle:

$$E_{missing} = \frac{(d_1^2)_{measured}}{(d_1^2)_{missing}} E_{measured} \quad (8).$$

For an impact involving damage to sides and front of the vehicles:
Case 1: Vehicle with front/rear damage available, side damage missing:

$$E_{missing} = 2.1 \frac{(d_1^2)_{measured}}{(d_1^2)_{missing}} E_{measured} \quad (9).$$

Case 2: Vehicle with side damage available, front/rear damage missing

$$E_{missing} = \frac{(d_1^2)_{measured}}{(d_1^2)_{missing}} \frac{E_{measured}}{(2.1)} \quad (10).$$

The damage analysis algorithm is used to compute the absorbed energy for the measured vehicle. Once the energy absorbed by the missing vehicle is computed, the total energy (E_T) is used in equation 3 and 4 to estimate the delta-V. In NASS/CDS thirty seven percent of the coded delta-Vs are computed using the missing vehicle option of WinSMASH. This option only requires the vehicle specifications and damage location for the un-inspected or missing vehicle.

CDC-Only Option

The CDC-Only option is used for vehicle-to-vehicle collisions when insufficient damage data are documented for one of the vehicles. The option requires a complete CDC for both vehicles, and complete damage data for one vehicle. The algorithm computes the crush profile of the second vehicle by using the damage length and damage extent coded in CDC. Only four percent of the coded NASS delta-Vs are computed using the CDC-Only option of WinSMASH.

Barrier Equivalent Speed

The WinSMASH also estimates the Barrier Equivalent Speed (BES) for each vehicle. The BES is defined as the speed with which a vehicle would have to collide with a fixed barrier in order to absorb the same amount of energy or produce same amount of crush to the vehicle as in the crash. The BES is a direct representation of the amount of energy the vehicle structure has to absorb and therefore approximates the amount of crush sustained by the vehicle. The same energy absorption could come out of collisions with different delta-Vs, leading to different potential for injuries. The BES therefore is typically a more appropriate way of comparing collisions with similar struck objects.

Nonetheless, BES is also considered a reliable indicator of crash severity. The NASS/CDS cases are used in Figure 6 to show the injury relationship with the delta-V and BES. The cumulative frequency of MAIS 2+ injuries to the belted occupant in crashes that have an air bag deployment is plotted against delta-V and BES of the vehicles. The chart shows sixty percent of the MAIS2+ injuries occurred at BES of 34 kmph and less. Similarly, sixty percent of the MAIS2+ injuries occurred at Delta-V of 38 kmph and less.

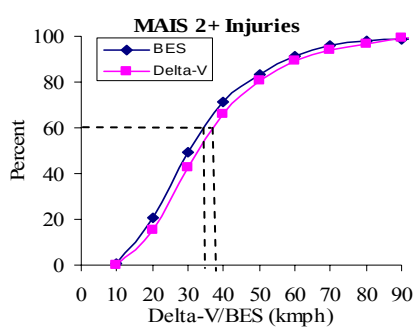

Figure 6. The cumulative distribution of MAIS 2+ injuries .vs. delta-V and BES.

The BES is calculated using mass and energy absorbed by each vehicle. No information is required of collision partner for BES calculations. Whereas, total amount of energy (both vehicle 1 and vehicle 2) is required to calculate approach delta-V.

For each vehicle the BES is given by,

$$\mathrm{BES} = \sqrt{\frac{2 E_A \gamma}{M}} \qquad (11).$$

Since 1995 the NASS/CDS was coding BES for all cases where delta-V estimates were available. The vehicle collisions with yielding objects, moving trains, larger trucks, large animals, pedestrians and cyclists that results in a measurable crush to the vehicle are set-up with the Barrier option and only the BES is coded for the vehicle.

Pole Option

The WinSMASH also has an option to set up vehicle impacts with a pole. This option uses the same damage analysis algorithm described above. However, the categorical stiffness coefficients are modified by multiplying the values by a correction factor. These factors are computed based on a series of repeated centered pole impact tests carried out on eight late model year (1987-1992) vehicles. The results were compared to the performance of these vehicles in full frontal impacts. An examination of the d_0 data showed that the values for pole impacts are much smaller than the values for full front impacts. For the pole option d_0 is set to zero and value for d_1 is multiplied by 1.5 for small cars and 2.0 for all other cars.

The pole option is not validated and is not used by the NASS researchers to calculate delta-V. All pole impacts are set up with barrier option in NASS/CDS.

Validation of Damage Algorithm
<u>Staged Crash Tests</u>

The accuracy of the reformulated damage algorithm of WinSMASH was assessed by comparing the delta-V estimates from the software with the delta-V from the crash tests conducted under controlled conditions. These staged crash tests were based on both vehicle-to-barrier impacts and vehicle-to-vehicle impacts. The vehicles were instrumented with accelerometers at various locations for direct computation of delta-V. The algorithm was validated by reconstructing nine staged vehicle-to-vehicle impacts and five crash tests involving oblique and

rear impacts. The details of validation are available in a report by VRTC [5]. Since, the damage algorithm in WinSMASH only estimates the velocity change in the approach period, delta-V at the point of common velocity was compared for validation.

For frontal impact tests, overall on average, the WinSMASH underestimated the delta-V by 5 percent. For 10 of 11 frontal impact tests, the errors in delta-V from WinSMASH were well below 10 percent.

For rear impact tests, overall on average, the WinSMASH underestimated the delta-V by 11 percent. For two of the three rear impact tests, the errors in delta-V from WinSMASH were less than 5 percent.

For validating the WinSMASH in side impacts, seven vehicle-to-vehicle 270 degree side impacts and five oblique impacts were reconstructed. These tests involved both vehicles moving prior to the impact. In eight of the twelve tests the percent errors in delta-V were less than or close to 10 percent. Overall on average, WinSMASH overestimated the delta-V by 12 percent for side impacts.

Real World Collisions

The real world collisions are complex and very seldom match the perfect configuration of staged collisions used for software validation. The WinSMASH software was developed to compute the delta-V estimates of the vehicles involved in real world collisions and hence, the accuracy of the program should be assessed for these crashes. The EDR now installed as standard equipment by several vehicle manufacturers, provide a direct measurement of the delta-V of the crashed vehicle. Several authors have investigated and written about the accuracy of delta-V estimates from EDR [9,10].

In a study of 121 real world crashed vehicles, Niehoff and Gabler compared the delta-V measured by EDRs with the delta-V estimated by WinSMASH, and found that WinSMASH underestimates longitudinal delta-V by 25 percent on average [12]. A similar analysis was carried out in parallel at NHTSA using 135 NASS files from year 1997-2003. In this analysis, the NASS cases with questionable WinSMASH delta-V estimates were excluded. The delta-V estimates ranged from 20 kmph to 50 kmph. The overall average difference between the WinSMASH and EDR delta-V was about 21 percent. Figure 7 compares the delta-V estimated by WinSMASH using generic stiffness coefficients [Table 2] with the corresponding delta-V computed from EDR data. The symbols falling on the dotted line drawn diagonally across the plot are cases where the EDR and WinSMASH delta-V perfectly matched with each other. The symbols falling below this line represent underestimated WinSMASH delta-V, that is, the WinSMASH delta-V estimate is lower than the EDR delta-V. The other two dashed lines correspond to +/- 20 percent difference between the WinSMASH and EDR delta-V.

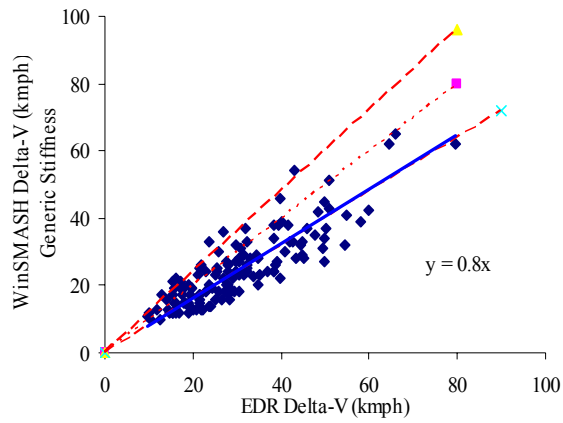

Figure 7. EDR vs. WinSMASH delta-V using generic stiffness.

The average difference was lower in NHTSA's analysis because the cases with questionable WinSMASH runs were excluded in their analysis. As mentioned earlier in the paper, the damage algorithm in WinSMASH only estimates the delta-V in the approach period, i.e. at the point of common velocity. This may have contributed to the difference seen in the comparison of delta-V from WinSMASH and EDR. The consideration of restitution may improve the WinSMASH results.

The stiffness coefficients of WinSMASH are best applicable to crash configurations that match with the crash tests used to develop the coefficients. The offset impacts, side impacts at the wheel and axle, under-ride and over-ride impacts should be examined carefully. The WinSMASH was not designed to be a simulation program but rather a consistent, uniform method of judging accident severity in terms of the change in velocity. It should be emphasized that the WinSMASH program, as CRASH3, should be statistically valid for a large number of cases; it may not provide accurate results in a particular case. The software should only be used with caution for individual cases. Good engineering judgment must always be used to ensure the validity of any simulation results.

RECENT DEVELOPMENTS IN WinSMASH

Abandoning Stiffness Category 9

In WinSMASH, for frontal impacts, a separate stiffness category (category 9) is used for front wheel drive passenger cars. The stiffness coefficients for category 9 are computed by averaging the known stiffness coefficients of all the front wheel drive passenger cars.

The data used to compute the average generic stiffness for each category suggest that drive axle (front or rear) is no longer a distinguishing feature. The larger cars tend to be rear wheel drive cars and smaller cars tend to be front wheel drive. In WinSMASH, the average stiffness in each category is calculated from crash tested vehicles that are mostly front wheel drive. To test the applicability of the category representing the front wheel drive vehicles, the NHTSA barrier crash tests of front wheel drive vehicles from size categories 2, 3 and 4 [Table 1] were reconstructed with WinSMASH. Each crash test was reconstructed twice, first using stiffness category based on wheelbase size and again using stiffness category 9. All data except the stiffness category were the same for both reconstructions. The delta-V estimates from using category 9 were six percent lower than the delta-V estimates using size based stiffness categories 2 and 3 [Table 2].

Based on these observations, the category 9 has been eliminated in NASS/CDS since data collection year 2006. The category 9 is absorbed in wheelbase size.

A new class of vehicles known as Sports Utility Vehicles (SUV) has emerged since the WinSMASH categories were developed. The computed average stiffness coefficients for SUVs matched closely to the stiffness coefficients of vans. Therefore, category 7 is currently used for SUVs until a separate category is created for SUVs.

Using Vehicle Specific Stiffness Coefficients

The 135 NASS/CDS cases used in the real world collision validation were selected to study the effect of replacing the generic stiffness coefficients with the vehicle specific coefficients in WinSMASH. Figure 8 compares the delta-V estimated by WinSMASH using vehicle stiffness coefficients with the corresponding delta-V computed from EDR data. Again symbols falling on the dotted line drawn diagonally across the plot are cases where the EDR and WinSMASH delta-V perfectly match with each other. The other two thin lines correspond to +/- 20 percent difference between the WinSMASH and EDR delta-V estimates. The plot clearly shows that more cases moved between the 20 percent error bounds (dashed lines) after the vehicle specific coefficients were used in the WinSMASH runs.

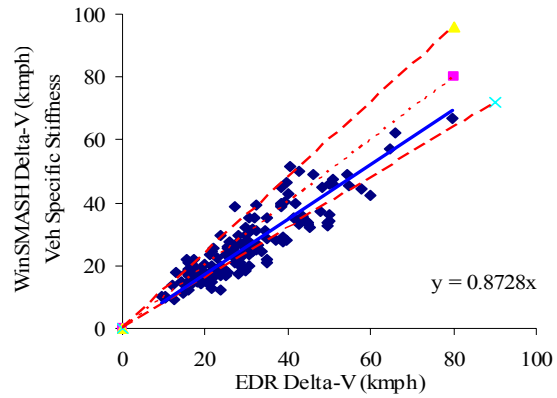

Figure 8. EDR vs. WinSMASH delta-V using vehicle specific stiffness.

The overall average difference between the WinSMASH and EDR delta-V is reduced to about 17 percent from 21 percent. This accounts for an improvement of about 4 percent, when vehicle specific coefficients were used in the WinSMASH software. The study also examined and compared the data by different impact and crash configurations including front-to-front, front-to-side, and front-to-barrier and pole crashes. In those cases, the WinSMASH delta-V estimates in longitudinal direction improved by about 4 percent on average for different crash configurations.

Various studies have shown that a high degree of variation exists in the stiffness characteristics of different vehicles. The results from this study also suggest that using the same stiffness coefficients for different vehicles with the same wheelbase may underestimate the WinSMASH delta-V. The results of this analysis suggest the advantage of the use of vehicle specific coefficients.

The WinSMASH was developed to utilize the vehicle specific stiffness coefficients. The main source of vehicle stiffness data is NHTSA's vehicle crash test database which contains detailed information on over 5000 crash tests involving primarily the vehicle models from year 1975 to current model year. The vehicle specific coefficients for front, side, and rear structure are computed for more than 2000 vehicle models from year 1975 to 2006. Additionally, since the main body structure of the vehicle model does not change every year, the same stiffness coefficients can

be used for the years during which the model structure has not changed. The stiffness coefficients for the tested vehicles can also be applied to its sister/clone models.

The frontal stiffness coefficients of 1395 vehicles, rear stiffness coefficients of 299 vehicles, and side stiffness coefficients of 600 vehicles have been computed. However, it represents only a fraction of the number of vehicles in the current fleet. There is a need to be able to reconstruct impacts involving vehicle models not tested by the agency.

Estimating d_0 and d_1 for vehicle not tested

In 1991, Prasad proposed a linear regression model based on the correlation between the vehicle parameters and stiffness coefficients of crash tested vehicles to estimate the stiffness coefficients of non-tested vehicles [6]. Since then the crash test data on more vehicles has become available in the NHTSA data base. The use of a statistical modeling scheme is examined to improve the estimates of the frontal stiffness coefficients for vehicles that are not crash-tested.

Twelve variables from 1300 frontal vehicle crash tests with computed d_0 and d_1, are used for this analysis. The variable chosen for this study are: Vehicle Age (w.r.t. model year 2006), body type (BT), distance between the side rails (E), engine displacement (ENGDSP), front overhang (F), C.G. (VEHCG), length (VEHLEN), width (VEHWID), weight (VEHWT), wheelbase (WHLBAS), d_0 and d_1.

An exploratory data analysis is performed by using scatter plots, correlation coefficients and descriptive statistics in SAS to see if there are any patterns, relationships, or trends the variables might hold. Then, a general linear model is fitted to predict d_0 and d_1. From the full model with all independent variables, statistically insignificant independent variables are removed one by one by using Multivariate Analysis of Variance until all independent variables are statistically significant in a fitted model. A final fitted general linear model is developed to predict d_0 and d_1 from predictor variables including vehicle age, length, weight, wheelbase, width, c.g., front overhang and body type. The body type is a categorical variable that divides the vehicles into four categories: passenger cars, pickup trucks, SUVs and vans.

For passenger cars the fitted general linear model for d_1 is:

$$d_1 = 14.4057 - 0.1307*AGE - .00001665*VEHLEN + 0.0018371*VEHWT - 0.0003816*WHLBAS - 0.0006609*VEHWID - 0.0010748*VEHCG - 0.0453959*F$$

The estimates produced by the fitted model are evaluated through simulation study. A sub-sample of 100 cases is randomly selected from the set of 1204 crash tested vehicles with known d_0 and d_1. Those 100 tests are treated as non-tested vehicles and are not used in the general linear model for the simulation study. The fitted model developed in the above analysis is used to predict the stiffness coefficients of selected cases. The actual values are compared with the model predicted coefficients and with the current wheelbase based categorical coefficients.

The average difference between the model based predicted and actual was 0.9 percent for d_0 and 13 percent for d_1. The average difference between the current categorical based and actual was 4 percent for d_0 and 17 percent for d_1. Figure 9 compares the actual d_1 with the d_1 predicted by the general linear model and d_1 from the wheelbase based category for passenger cars. The wheelbase based d_1 is shown by triangular symbols.

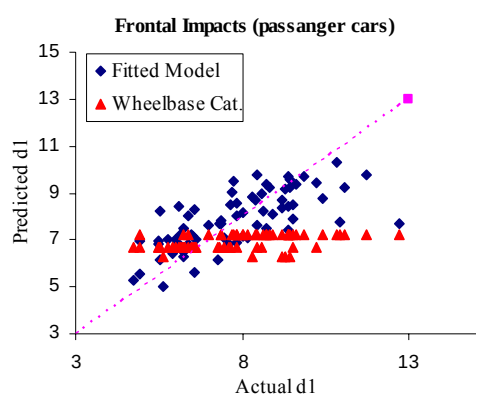

Figure 9. Comparison of d_1 predicted by general linear model and wheelbase base category.

A similar analysis is currently being carried out for side and rear stiffness coefficients. The details of the general linear models will be presented in a separate paper.

The analysis showed that the general linear model is a better predictor of the stiffness coefficients of non-tested vehicles than the average values used over a wheelbase category. In the current model for stiffness category, a wrong stiffness could be assigned to a vehicle if its wheelbase is close to the upper or lower end of the wheelbase range. The vehicle's other characteristics such as weight, length,

and front overhang could match with the cars in the next higher or lower size category. The new method considers four categories of vehicle body type namely, passenger car, pickups, SUVs, and vans. For each category, relevant vehicle parameters are used to compute the stiffness coefficients of the vehicle. It eliminates the errors associated with assigning a stiffness category to the vehicles that fall in the upper or lower range of wheelbase size. If all the vehicle parameters used in the general linear model are known, the model will give a better estimate of stiffness coefficients of a vehicle than the average stiffness coefficients obtained from wheelbase based categories.

A database of stiffness coefficients is currently under development and will be integrated into WinSMASH. An automated selection procedure based on the vehicle parameters such as make, model, year wheelbase and weight, is being implemented. The software will use the vehicle specific stiffness coefficients for damage analysis, if available. The modeling scheme briefly discussed in the paper will be used if the vehicle is not in the database. If the stiffness and vehicle parameters needed to either lookup or estimate the stiffness coefficients are unknown, then the updated wheelbase based categorical stiffness coefficients will be used.

CONCLUSIONS

The paper presented an overview of NHTSA's crash reconstruction program WinSMASH. The software replaced the CRASH3 program and has been used by NASS/CDS investigators since 1995 to compute the delta-V of vehicles involved in crashes. At present, some programming errors are being resolved and new features including an automated scheme to select the stiffness coefficients, and new graphics enhancements are being implemented. The new stiffness selection method entails:

1) Use of vehicle specific stiffness, if available.
2) If the search process in step 1 does not reveal any vehicle, sister/clone information will be used to obtain stiffness of a compatible vehicle.
3) Otherwise, use the general linear model to estimate stiffness coefficient.
4) Use wheelbase based categories, if 1, 2 and 3 above can not be used.

The software is currently being tested and will be made available to the public once all features are implemented.

As with CRASH3, NHTSA maintains that WinSMASH is intended as a statistical tool to identify and isolate problems in motor vehicle safety, not as a simulation program, and should be used accordingly.

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