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Restitution in Frontal Impact Simulations Using the EDSMAC4 and SIMON/DyMESH Collision Models

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ABSTRACT

In this study, the restitution (i.e., structural recovery) models within the EDSMAC4 and SIMON (via DyMESH) physics modules of the HVE program are examined. By way of background, the methodologies for handling structural recovery within these physics modules are reviewed. Results from simulation studies using these modules are presented. In these simulation studies, the effective coefficient of restitution values from a series of frontal vehicle-to-barrier impact simulations and a series of vehicle-to-vehicle collinear frontal impact simulations are determined from the program output and compared to results from publicly available full-scale vehicle crash tests. Studies were also conducted to evaluate simulation sensitivities vis-à-vis changes of the user-supplied parameters that directly control the respective structural recovery algorithms.

INTRODUCTION

EDSMAC4 is a two-dimensional automobile collision analysis module within the Human•Vehicle•Environment (HVE) software program, available from Engineering Dynamics Corporation (EDC). Though EDC has instituted some changes, the basic collision algorithm of the EDSMAC4 program is essentially unchanged from that of the original Simulation Model of Automobile Collisions (SMAC) program developed in the early 1970's [1-3]. The manner in which it handles structural recovery, and therefore effective restitution, during the collision phase of an automobile accident simulation remains an unchanged aspect of the program. EDSMAC4 is a widely used accident reconstruction tool; however, studies published in the open literature related to the actual restitution response calculated by the program, or its predecessors EDSMAC and SMAC, are scarce.

SIMON is a three-dimensional, multi-purpose automobile analysis software module within HVE. Through the use of SIMON, various automobile analyses can be conducted including, but not limited to, vehicle handling, hydroplaning and rollovers. Vehicle-to-vehicle and vehicle-to-object collisions can also be simulated with SIMON by using a sub-module called DyMESH. Commercially available starting in 2004, DyMESH is a relatively new accident reconstruction tool. To date, available studies that examine the actual structural recovery characteristics of this model are largely limited to those published by EDC - the proprietors of the program.

In this study, we review the EDSMAC4 and SIMON/DyMESH collision and structural recovery algorithms, and present the results of vehicle-to-barrier and vehicle-to-vehicle impact simulation studies conducted with the purpose of examining the actual restitution response these programs produce. We then compare these results to those of full-scale vehicle crash testing available through the National Highway Traffic Safety Administration (NHTSA) crash test database.

THE EDSMAC4 COLLISION MODEL

A fundamental aspect of the EDSMAC4 collision model is that the periphery of a vehicle in a potential impact zone is represented by an array of radial vectors emanating from the center of gravity of the simulated vehicles. A graphical representation of this is depicted in Figure 1.

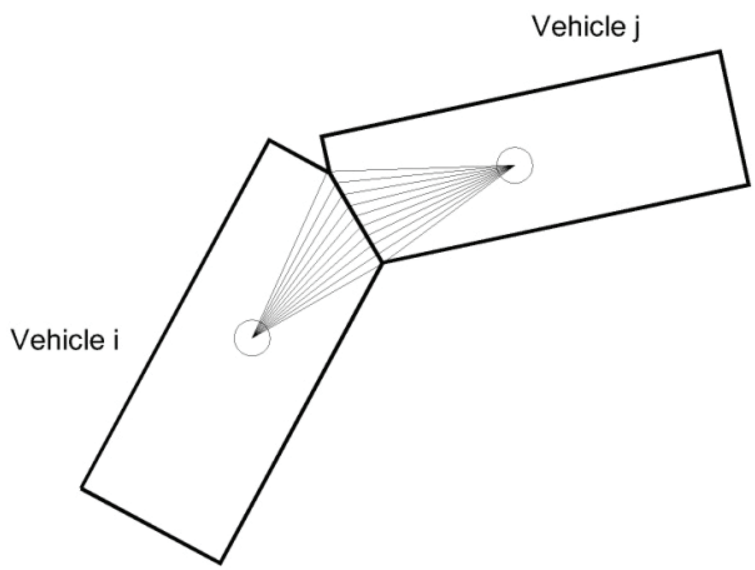

Figure 1: *SMAC Radial Damage Vectors.*

For a given radial vector of what is designated within the program as the base vehicle (vehicle i) - both vehicles are, in turn, treated as the base vehicle in the collision algorithm - the endpoint is constrained to move along the line from its original location on the periphery of the vehicle toward the center of gravity. A corresponding vector for the non-base vehicle (vehicle j) is established between the current endpoint of the base vehicle radial vector and the non-base vehicle center of gravity, as depicted in Figure 2.

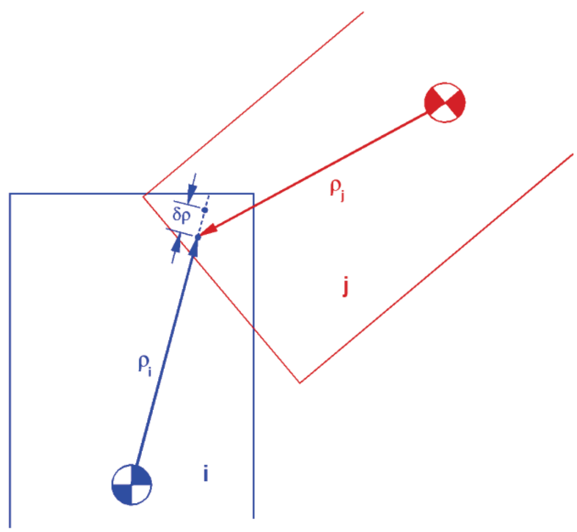

Figure 2: *Radial Vector Endpoint Motion.*

Once the endpoint positions of the vectors have been established, "pressure" values, considered to act at the endpoints of the radial vectors, are calculated for each vehicle. The calculated pressure at the endpoints of the vectors is based on the crush stiffness values (A and B) entered by the user and the displacement of the radial vector endpoints for each vehicle. The pressure equation is defined as [4],

$$P = \begin{cases} A\left(\dfrac{\delta}{\xi}\right), & \text{for } \delta \leq \xi \\ A + B(\delta - \xi), & \text{for } \delta > \xi \end{cases} \tag{1}$$

In equation (1), δ is the change in rho-vector length from its original length. The parameter ξ is the "null distance" for reaching the full value of A and has a fixed value of 0.5 inches.

Once the pressures for both vehicles at a given displacement point have been determined, the EDSMAC4 algorithm checks for equilibrium. The check for equilibrium is accomplished by comparing the difference between the calculated pressure for vehicle i against that for vehicle j to a user-defined tolerance (λ). If equilibrium does not exist, the radial vector for the base vehicle is adjusted by $\delta\rho$, a user-defined increment with a default value of 0.2 inches, in the direction of the center of gravity (see Figure 2) and the pressure calculation process is repeated.

When equilibrium has been found for each of the radial vectors in the damage zone, the pressures are converted to surface segment forces both normal and tangent to the surface segment. A surface segment is defined as the line between the current endpoints of adjacent radial vectors. These segment forces are then resolved to vehicle longitudinal and lateral components and used in the numerical integration of the equations of motion.

STRUCTURAL RECOVERY IN EDSMAC4

At each time-step in the numerical integration of the equations of motion, the collision algorithm controls the structural recovery of the individual rho vectors through the use of a control parameter designated "C." This parameter is expressed as a function of user-supplied constants C_0, C_1 and C_2, and the maximum displacement (at the current time-step) as follows,

$$C = C_0 - C_1\delta_m + C_2\delta_m^2 \tag{2}$$

Thus, the parameter C is not fully defined until δ_m is determined through the pressure-balancing iteration algorithm.

The approach used in EDSMAC4 to incorporate structural recovery in the collision routine is to, after the inter-vehicle collision forces have been calculated at each time-step, adjust the length of the current rho-vector from its maximum displaced length (ρ_m) to a slightly longer length (ρ_f) based on the control parameter C as follows,

$$\Delta\rho_R = C\delta_m = C_0\delta_m - C_1\delta_m^2 + C\delta_m^3 \tag{3}$$

Thus, the "structural recovery" for each rho-vector at each time-step is based on a cubic relationship of the maximum deformation of that vector.

The idea behind adjusting the rho-vectors is to define a new vehicle body perimeter for vehicle-to-vehicle overlap determination at the next time step. This process is shown in Figure 3 where a vector ρ_f from time-step i-1 is shortened to its maximum displacement ρ_m as a result of the pressure equilibrium algorithm and then relaxed to its final length ρ_f at the current time-step i. The result of this process is to provide additional vehicle-to-vehicle overlap at each integration time step, thereby producing additional "rebound" forces at the end of the compression phase of the collision.

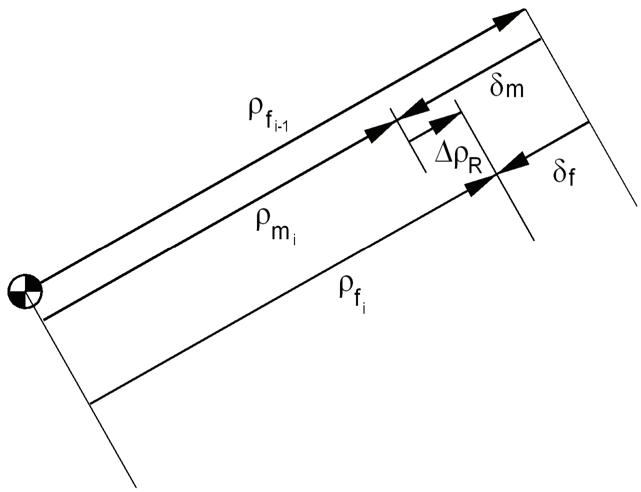

Figure 3: *Rho-vector adjustment diagram.*

Equation (3) can be rearranged to express C as a function of the rho-vector maximum and final displacement, as follows,

$$C = 1 - \frac{\delta_f}{\delta_m} \tag{4}$$

Using a single-parameter, constant-stiffness model, and assuming the loading and unloading force-deflection slopes are the same, McHenry derived a theoretical relationship between the coefficient of restitution and the parameter C as follows [5],

$$\varepsilon^2 = \frac{E_R^2}{E_A^2} = \frac{\frac{1}{2}k\left(\delta_m^2 - \delta_f^2\right)}{\frac{1}{2}k\delta_m^2} = 1 - \left(\frac{\delta_f}{\delta_m}\right)^2 \tag{5}$$

Combining equations (4) and (5), the theoretical coefficient of restitution is then found to be,

$$\varepsilon = \sqrt{2C - C^2} \tag{6}$$

Substituting equation (2) into (6), and expanding, yields the following lengthy expression relating the theoretical coefficient of restitution to the maximum rho-vector displacement,

$$\varepsilon = \sqrt{C_0(2 - C_0) - 2C_1(1 - C_0)\delta_m + \left(2C_2 - C_1^2 - 2C_0C_2\right)\delta_m^2 + 2C_1C_2\delta_m^3 - C_2^2\delta_m^4} \tag{7}$$

A plot of the coefficient of restitution versus the maximum rho-vector deformation using the SMAC/EDSMAC default values for C_0, C_1 and C_2 is shown in Figure 4.

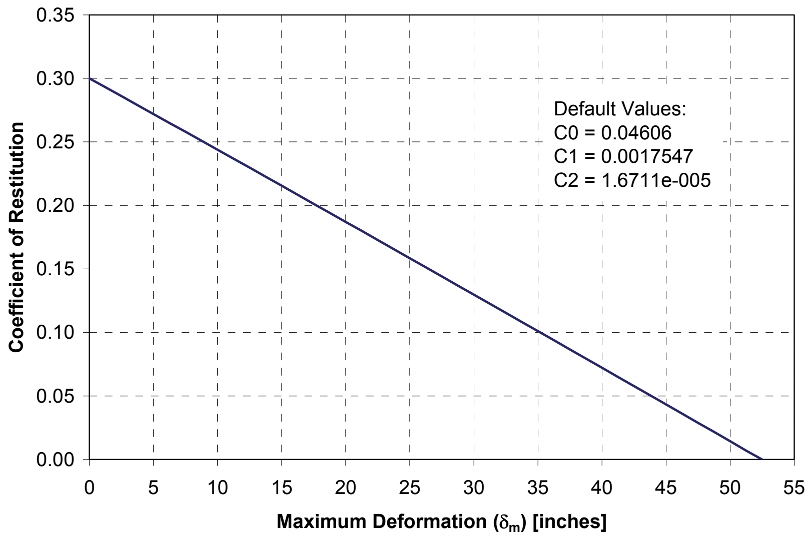

Figure 4: *Theoretical Coefficient of Restitution vs. Maximum Deformation.*

It is evident from equation (7) that it is difficult for a user of the program to discern what effective restitution value will result for a given selection of control parameter constants as the user will not typically have an *a priori* knowledge of what the maximum displacement will be for any given rho-vector. Furthermore, the theoretical relationship of equation (7) (displayed in Figure 4) is for a single rho-vector, whereas in a collision simulation, numerous rho-vectors are involved, all with potentially differing maximum deformation within the impact zone making an estimate of the actual, in-practice restitution all but impossible to predict.

It is interesting to note the evolution of the recommended values for the constants C_0, C_1, and C_2. In one of the earliest reports published by McHenry in 1971 [1] on the development of the SMAC program, the recommended values were described as a "Typical Automobile Frontal," and quantified as,

$C_0 = 0.115$
$C_1 = 5.100\text{x}10^{-3}$
$C_2 = 5.679\text{x}10^{-5}$

In a 1973 report by McHenry, et al. [2], these "typical" values were subsequently altered, though with no discussion in Reference [2] as to what prompted the change in values. These new coefficients were defined to be,

$C_0 = 0.06423$
$C_1 = 3.5417\text{x}10^{-3}$
$C_2 = 4.7381\text{x}10^{-5}$

Ultimately, in a 1975 report by McHenry et al. [3], these values were changed to,

$C_0 = 0.04606$
$C_1 = 1.7547\text{x}10^{-3}$
$C_2 = 1.6711\text{x}10^{-5}$

It is in this report that we see the theoretical coefficient of restitution value being compared to actual frontal crash test data. The values established in 1975 have, to date, been retained as the default values in the EDSMAC and EDSMAC4 programs.

SIMON/DyMESH COLLISION MODEL

Whereas EDSMAC4 utilizes a two-dimensional collision model in which the vehicle is idealized as a rectangular box whose deformable surfaces are defined by radial springs, the SIMON/DyMESH model utilizes a three-dimensional wireframe representation of a vehicle as depicted in Figure 5. The deformable surfaces in the SIMON/DyMESH model are defined by the vertices of the wireframe vehicle surface constructed using triangular polygons (i.e., each facet of the wireframe model comprises three vertices).

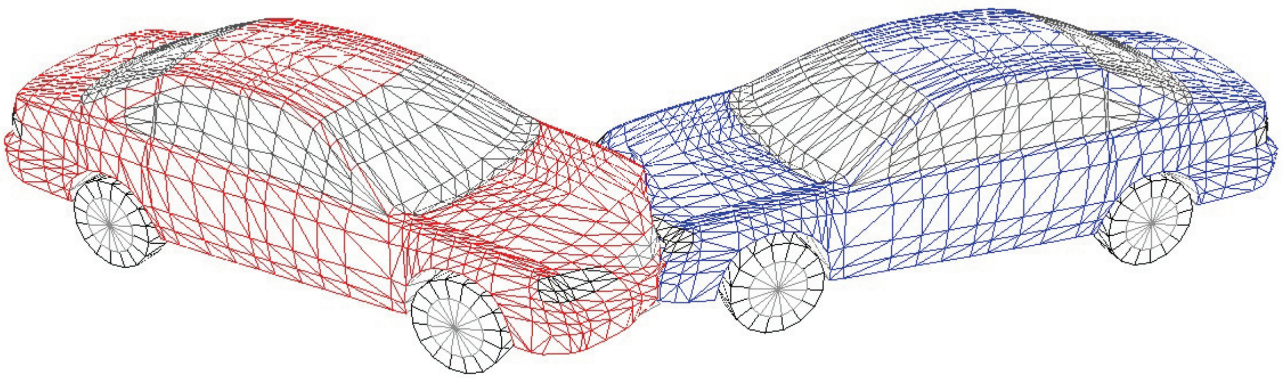

Figure 5: *Wireframe vehicle representations used in SIMON/DyMESH collision model.*

Collision detection is accomplished by first establishing a bounding box defined by the overall length, width and height of a given vehicle. Based on the relative position of these bounding boxes, intersection lines are determined between the interacting objects and a volume defined by those lines defines the space inside which respective vehicle polygon surfaces may be interacting (i.e., colliding). Wireframe vertices inside this potential-damage volume are catalogued and a search over that listing is conducted to determine which, if any, vertices of the "Slave" vehicle have progressed inside the "Master" vehicle. The Slave vehicle vertices are then adjusted back to the surface of the Master vehicle and a displacement value (δ) is determined [6]. A two-dimensional representation of this process is depicted in Figure 6.

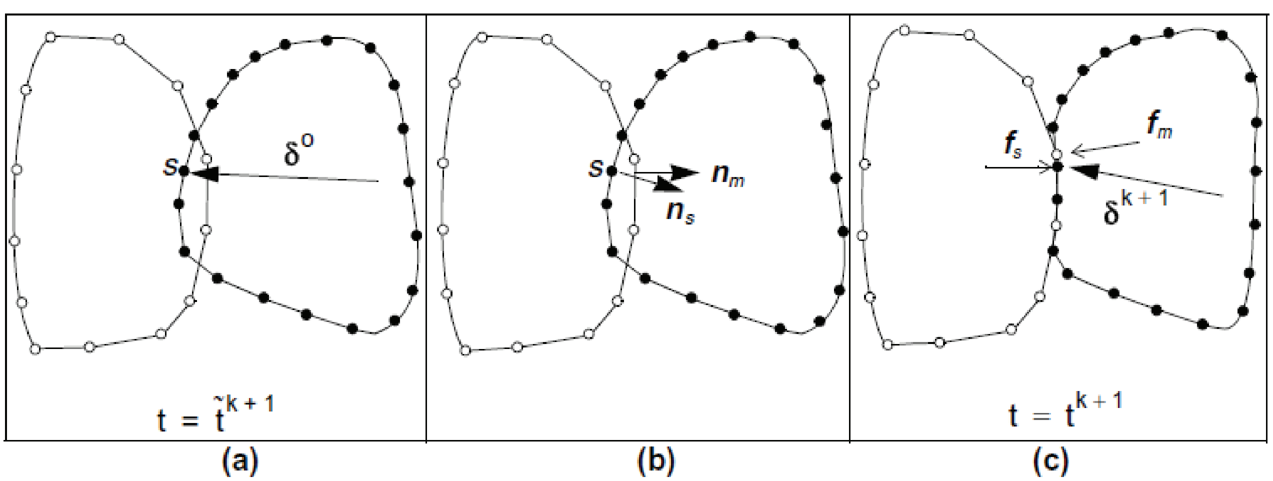

Figure 6: *Representation of vertex displacement process in SIMON/DyMESH (SAE 1999-01-0144).*

The force calculation for a given Slave vertex displacement is a third-order relationship expressed as,

$$F = \left(A' + B'\delta + C'\delta^2 + D'\delta^3\right)\left(Area\right) \tag{8}$$

In equation (8), A′, B′, C', and D' are coefficients defined by the user in the HVE Vehicle Editor, divided by a Stiffness Conversion Factor that is an effective height parameter that converts the A, B, C, and D values from a crush-area basis to a crush-volume basis; the default value for this factor is 30 inches but can be changed by the user of SIMON/DyMESH. The SIMON/DyMESH force-displacement model also allows for the user to define a point at which the force saturates (i.e., becomes constant for all subsequent displacement values). All simulations conducted in this study used only the A' and B' values (C' and D' were set to zero) with the default effective height value. Additionally, the force saturation option was not used in any of the simulations.

The "Area" quantity used in equation (8) is an effective area associated with the particular vertex undergoing displacement and is based on the surface areas of the wireframe polygons that share that vertex, and δ is the difference between the current vertex position and its original position relative to the vehicle (i.e., its deformation). SIMON and DyMESH are three-dimensional models and the direction of the force applied at each vertex is based on a weighting of the normal vectors of the polygon surfaces which share that particular vertex. This vertex adjustment and force calculation process is repeated for every Slave vehicle vertex that has been determined to have penetrated the periphery of the Master vehicle. These forces are then resolved into vehicle-fixed coordinate system components, summed and used in the numerical integration of the equations of motion. The "Slave" and "Master" designation alternates between collision partners at every time-step. That is, if at some time-step k vehicle 1 is the Master vehicle then at time-step k+1 it will become the Slave vehicle for the vertex adjustment procedure at that time-step.

SIMON/DYMESH STRUCTURAL RECOVERY

Early publications regarding DyMESH described the potential for substantial user flexibility in handling structural recovery [7] (definition of unloading slope, a relaxation length parameter, etc.). Ultimately, EDC settled on a single method to incorporate structural recover in the DyMESH algorithm. The current user of DyMESH can define the value for a single parameter called the 'relaxation length parameter.' The default value for this parameter is 0.05 and is dimensionless.

The process for structural recovery in DyMESH is similar in approach to that of EDSMAC4 in that, at the end of each time-step, the collision algorithm allows some "grow-back" for each deformed vertex. Thus, the periphery of the vehicle is increased in size leading to increased vehicle interaction and additional forces at the end of the compression phase of the collision. The grow-back amount for each vertex is dependent on the maximum deformation for that time-step and the relaxation length parameter through the following relationship,

$$\Delta\delta = R_L \delta_m \tag{9}$$

In equation (9), $\Delta\delta$ is the amount the given vertex grows-back (i.e., relaxes), δ_m is the maximum displacement for that vertex at the current time step, and R_L is the relaxation length parameter.

Noting that $\Delta\delta$ is also equal to δ_m - δ_f, we can arrive at equation (10) below and notice right away that this equation is very similar in form to equation (4). The relaxation length parameter is thus analogous to the restitution control parameter C in the EDSMAC4 collision algorithm; the primary difference being the control parameter C is a function of the user-defined constants (C_0, C_1, and C_2) and maximum rho-vector displacement, whereas the relaxation length parameter is simply a constant value regardless of the maximum vertex displacement.

$$R_L = 1 - \frac{\delta_f}{\delta_m} \tag{10}$$

The theoretical relationship for restitution, given similar assumptions used to arrive at equation (6), would be,

$$\varepsilon = \sqrt{2R_L - R_L^2} \tag{11}$$

For the default relaxation length parameter of 0.05, the theoretical restitution value based on equation (11) is a constant of approximately 0.3 for all maximum deformation values. This is not a realistic value for medium- and high-severity automobile collisions, and, as will be shown below, not the result one gets in practical application of the SIMON/DyMESH model.

RESTITUTION STUDY DESCRIPTION

To study the effective restitution values that result from the above-described structural recovery models, a series of vehicle-to-barrier and vehicle-to-vehicle collisions were simulated using the EDSMAC4 and SIMON physics modules of HVE. Within each physics module, a series of simulated impacts were conducted using the 2001-2005 Toyota Camry LE vehicle model available in the HVE vehicle database (see Table 1 for database-provided vehicle details). This particular vehicle was chosen because it is a fairly popular in the United States and there are barrier crash tests available in the NHTSA database over a relatively large range of impact energies [8 – 16]. For each impact configuration, and for each physics module, the impact speed of the test vehicle(s) was varied from 5 mph to 50 mph at 5 mph increments. Images of the vehicle-to-barrier and vehicle-to-vehicle impact configurations are provided in Figures 7 and 8, respectively.

Table 1: *2001-2005 Toyota Camry LE.*

Vehicle Weight [lb]	3203
Overall Length [in]	189.0
Wheelbase [in]	107.1
Front Overhang [in]	37.1
Overall Width [in]	70.7
Crush Coefficient A [lb/in]	325.8
Crush Coefficient B [lb/in/in]	117.4

Note: Values in table rounded to indicated significant digit

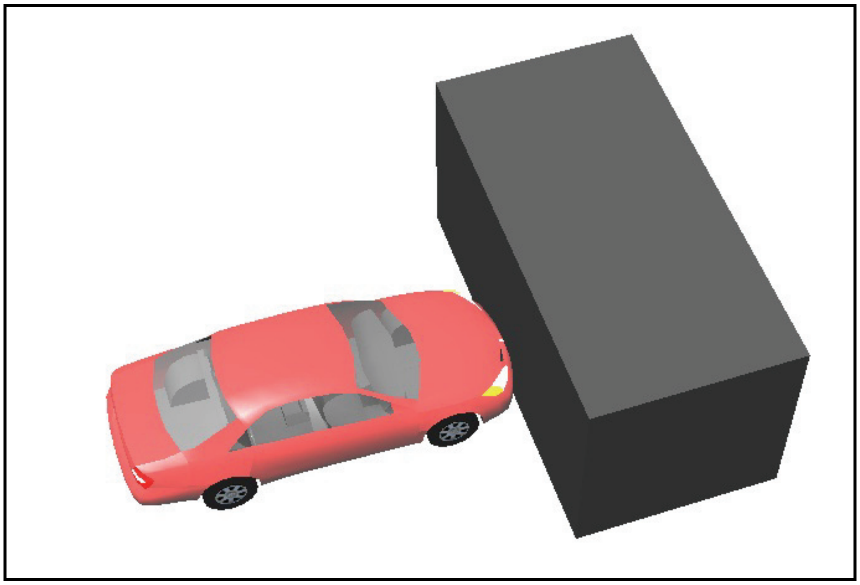

Figure 7: *Vehicle-to-barrier impact configuration.*

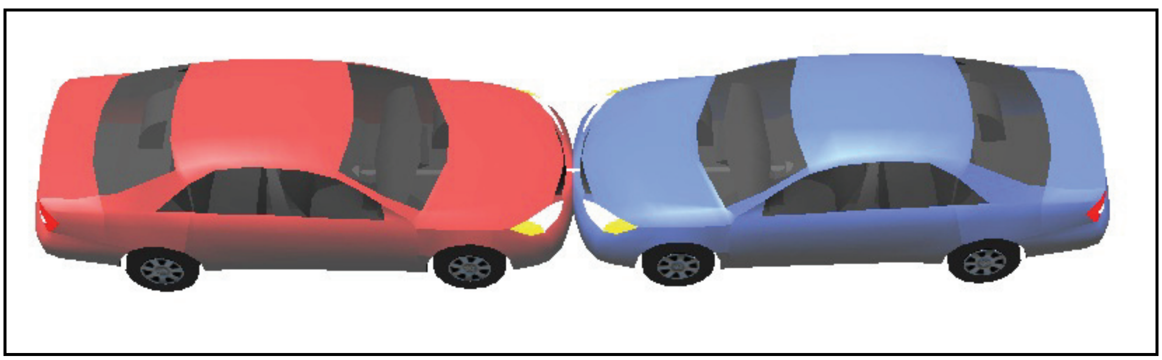

Figure 8: *Vehicle-to-vehicle collinear impact configuration.*

In this study the classical kinematic definition (Newton's coefficient) for the coefficient of restitution was used and is defined as,

$$\varepsilon = \frac{V_{2s} - V_{1s}}{V_{1i} - V_{2i}} \tag{12}$$

Where V_{1i} and V_{2i} are the initial velocities of vehicles 1 and 2, respectively, and V_{1s} and V_{2s} are the separation velocities. In the case of barrier impacts, the velocities V_{2i} and V_{2s} were simply set to zero as the barrier did not move as a result of the impact.

The separation velocity values used in the calculations based on equation (12) were those found in the *Variable Output* table of the HVE *Playback Editor* and selected at a time concurrent with when the longitudinal acceleration fell below 0.1g.

RESTITUTION STUDY RESULTS

Results of the vehicle-to-barrier simulations using default structural recovery values are shown in Figures 9 and 10.

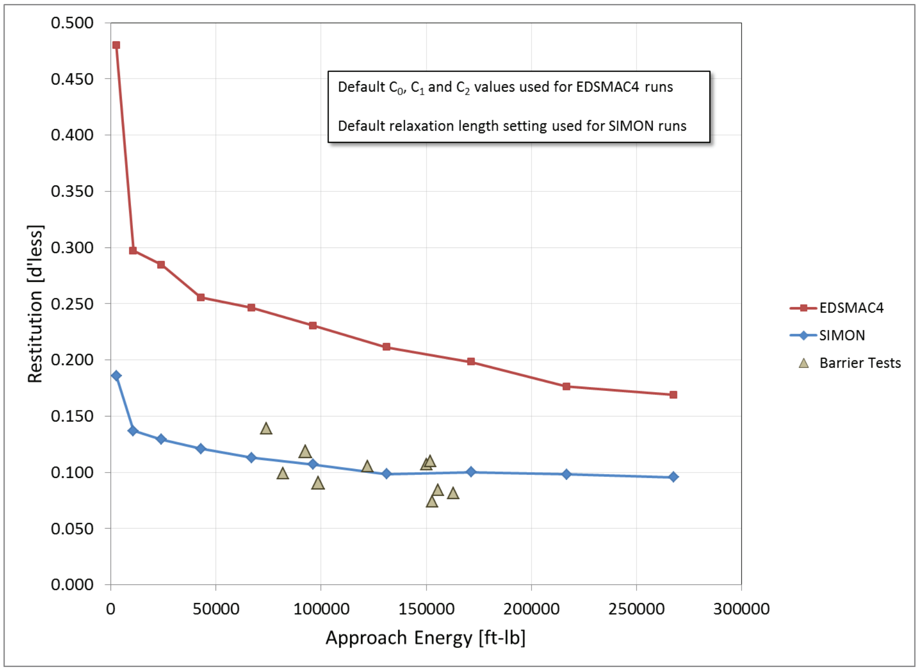

Figure 9: *Restitution versus approach energy – vehicle-to-barrier simulations – default restitution parameters.*

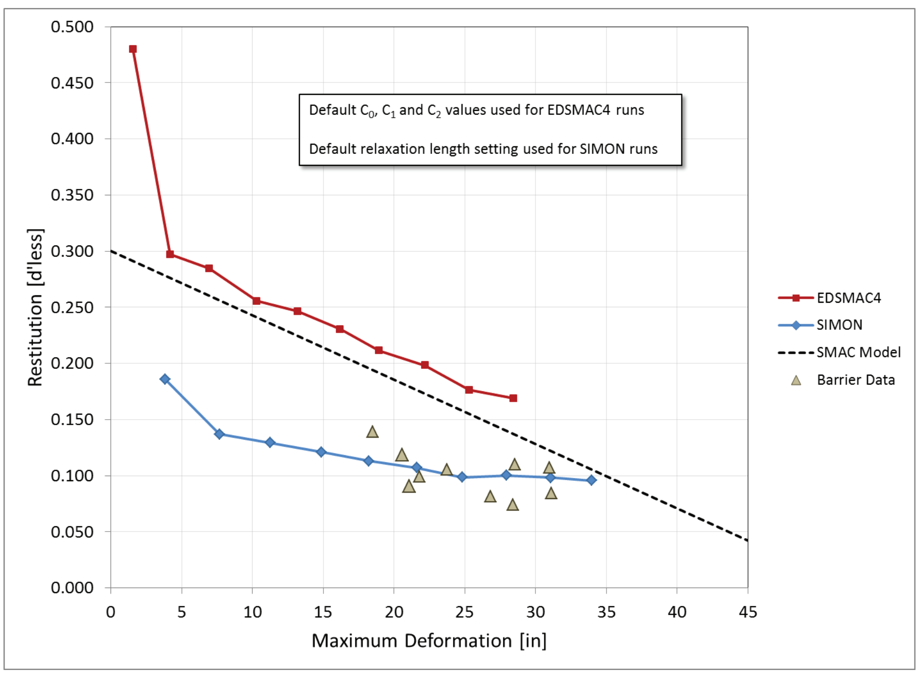

Figure 10: *Restitution versus maximum deformation – vehicle-to-barrier simulations – default restitution parameters.*

The results of the vehicle-to-vehicle simulations using default structural recovery values are shown in Figures 11 and 12. In these figures we include the restitution data found from the available barrier crash tests. The basis for the inclusion of this data is that, in previous studies, researchers have derived restitution equations for the situation where two vehicles impact one another. Two of these equations are provided below.

Stiffness-Based Combined Restitution [17]:

$$\varepsilon = \sqrt{\frac{k_2 \varepsilon_1^2 + k_1 \varepsilon_2^2}{k_1 + k_2}} \tag{13}$$

Mass-Based Combined Restitution [18]:

$$\varepsilon = \sqrt{\frac{m_2 \varepsilon_1^2 + m_1 \varepsilon_2^2}{m_1 + m_2}} \tag{14}$$

ε_1, ε_2:	Restitution values determined from barrier crash tests
k_1, k_2:	Vehicle crush stiffness values
m_1, m_2:	Vehicle masses of collision partners

By inspection of equations (13) and (14), one can see that, for identical vehicles striking one another in a head-on impact configuration, the combined restitution value simply reduces to that found from barrier impact testing. Thus, the barrier crash test data was included for comparison with the vehicle-to-vehicle simulations.

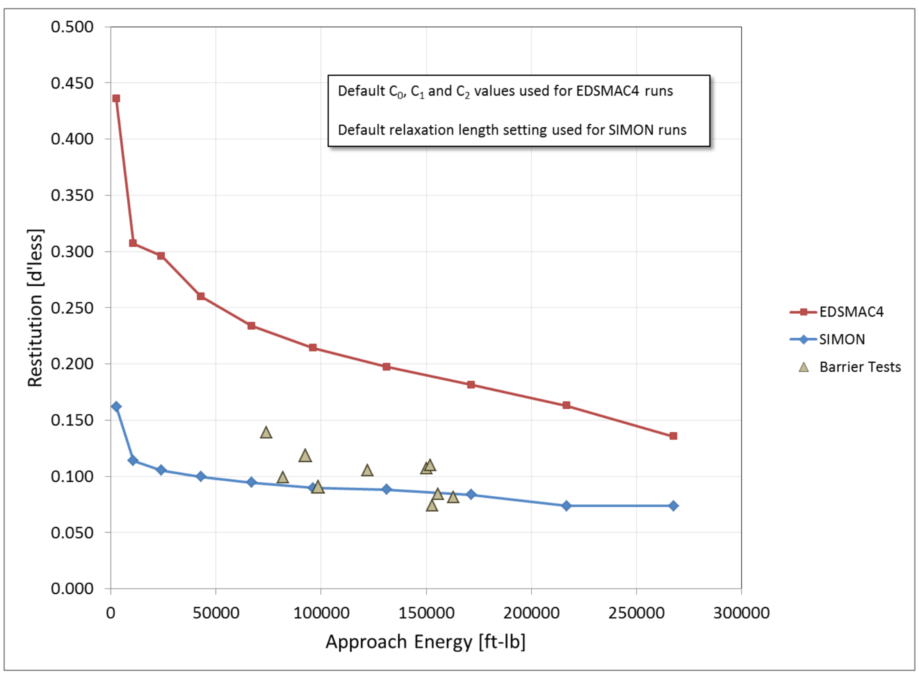

Figure 11: *Restitution versus approach energy – vehicle-to-vehicle simulations – default restitution parameters.*

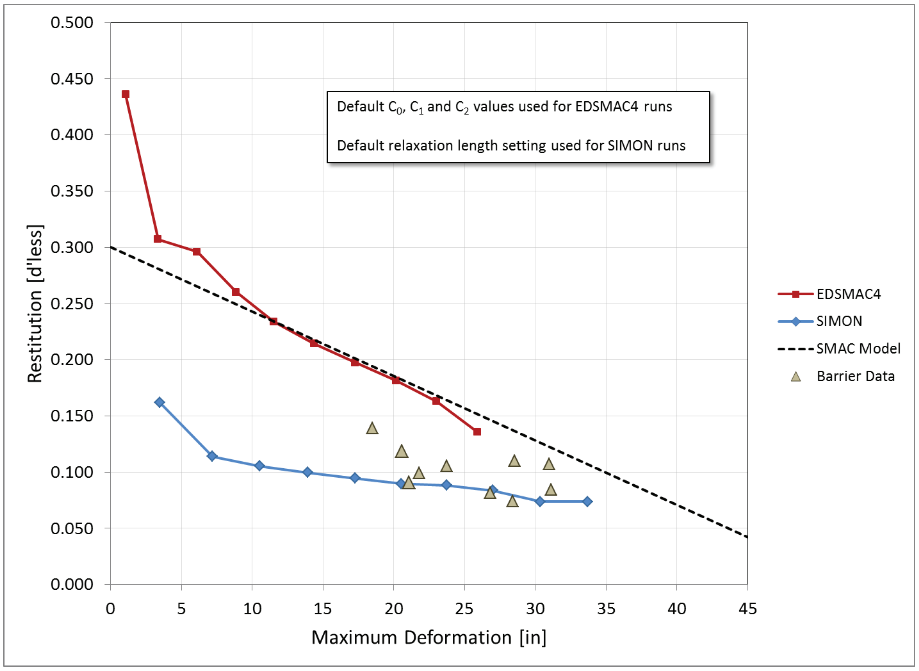

Figure 12: *Restitution versus maximum deformation – vehicle-to-vehicle simulations – default restitution parameters.*

DISCUSSION

It is clear from Figures 9 and 11 (EDSMAC4 simulation runs with the default restitution values) that the effective coefficient of restitution is significantly over-predicted for both the vehicle-to-barrier and vehicle-to-vehicle impact modes relative to the available full-scale vehicle crash testing for the selected vehicle. In fact, in both vehicle-to-barrier and vehicle-to-vehicle modes, the values predicted by EDSMAC4 are roughly double those found from the crash test data – with the vehicle-to-barrier simulation values and the vehicle-to-vehicle simulation values similar to one another over the range of impact severities. In reviewing Figures 10 and 12, we see that the maximum deformations were well below those of the full-scale crash test data for both the vehicle-to-barrier and vehicle-to-vehicle simulations. Furthermore, the maximum deformation of the 50 mph simulations well under those of the 35 mph full-scale crash tests (approximately 3 inches for the vehicle-to-barrier simulations and approximately 5 inches for the vehicle-to-vehicle simulations).

The SIMON/DyMESH vehicle-to-barrier simulations using the default relaxation length parameter value resulted in coefficient of restitution values that matched the full-scale crash test data rather well in the range in which data was available. The vehicle-to-vehicle simulations resulted in restitution values that were within the range of the full-scale data though the resulting values were on the low end of that range. As with the EDSMAC4 simulations, the SIMON/DyMESH simulations resulted in maximum deformation values less than those of the full-scale crash tests, though to a lesser extent. The simulated 50 mph maximum deformations for both the vehicle-to-barrier and vehicle-to-vehicle values were approximately 3 inches greater than the 35 mph.

Based on the above observations regarding the EDSMAC4 simulations results, additional simulations using lower structural recovery constants (C_0, C_1, and C_2) were conducted in an attempt to better approximate the real-world test data. For the SIMON/DyMESH physics module, as the vehicle-to-vehicle simulations resulted in restitution values at the lower range of real-world values, additional simulations were conducted using an increased value for the relaxation length parameter to attempt to achieve more realistic restitution values for the vehicle-to-vehicle impact mode and to examine the sensitivity of the vehicle-to-barrier impact mode to an increased relaxation length value.

Data from the modified-value simulations (vehicle-to-barrier and vehicle-to-vehicle) are shown in Figures 13 through 16. For the EDSMAC4 runs, the constants C_0, C_1, and C_2 were all set to zero. For the SIMON/DyMESH simulations the relaxation length parameter was increased to 0.06.

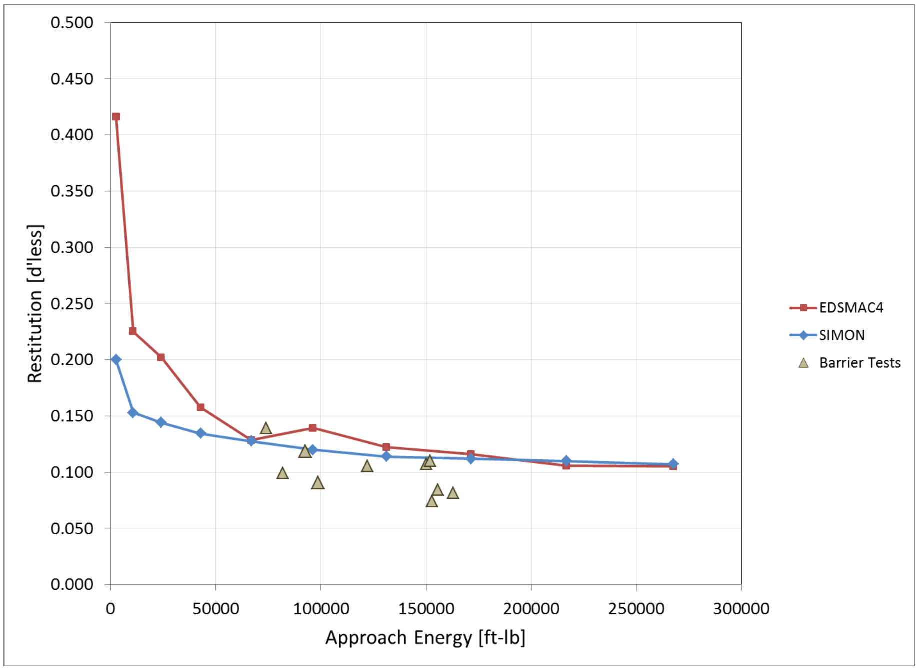

Figure 13: *Restitution versus approach energy – vehicle-to-barrier simulations – modified restitution parameters*

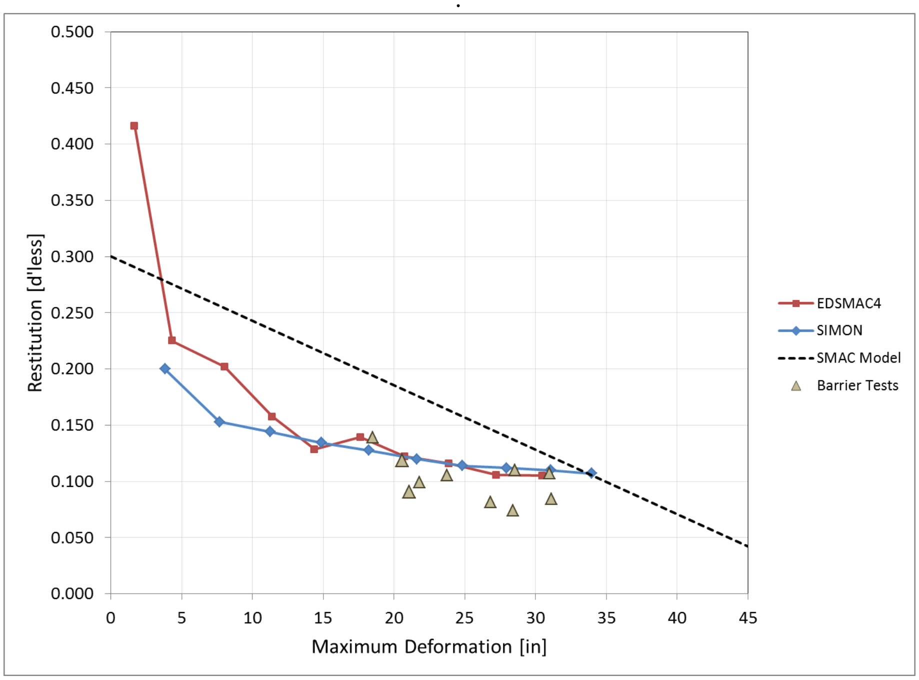

Figure 14: *Restitution versus maximum deformation – vehicle-to-barrier simulations – modified restitution parameters.*

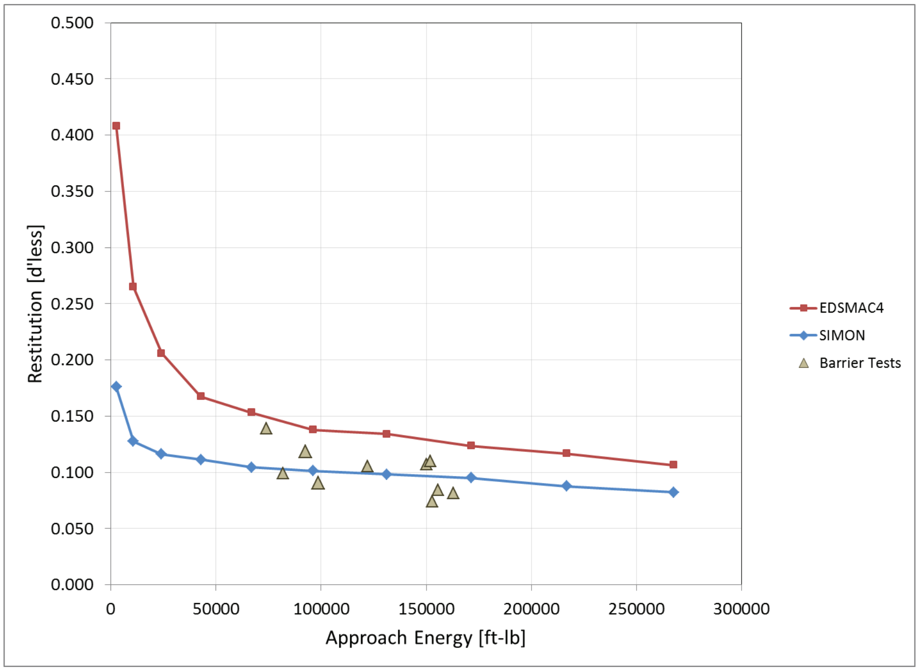

Figure 15: *Restitution versus approach energy – vehicle-to-vehicle simulations – modified restitution parameters.*

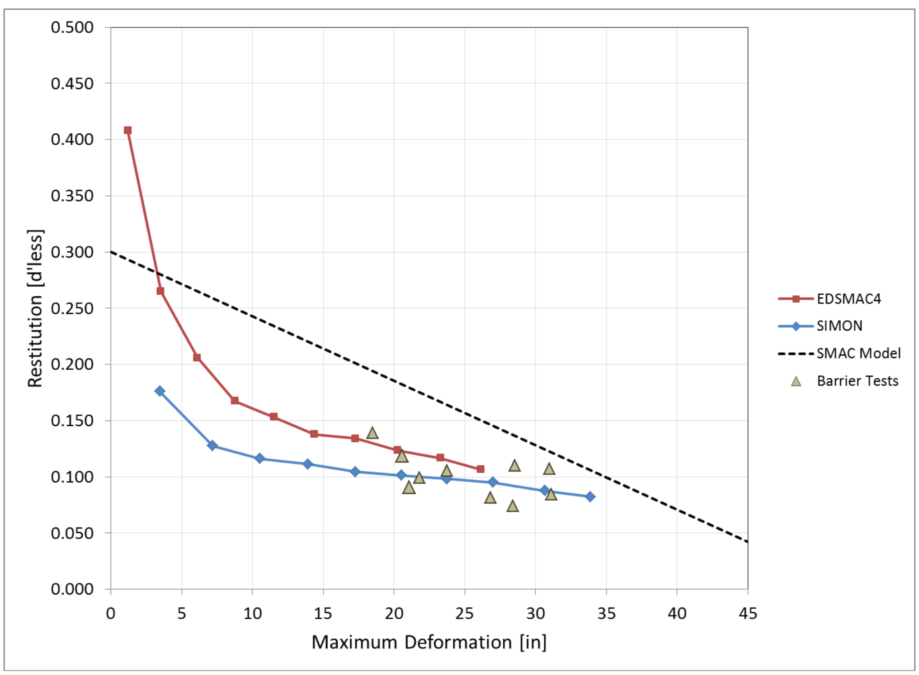

Figure 16: *Restitution versus maximum deformation – vehicle-to-vehicle simulations – modified restitution parameters.*

From Figures 13 and 14, we observe that, with all structural recovery constants set to zero, the resulting restitution values for the EDSMAC4 vehicle-to-barrier simulations are still generally greater than those of the full-scale barrier crash tests, though they approach the upper range of the full-scale data. Note that, in comparing Figures 10 and 14, in addition to a lowering of the resulting simulation restitution values, the maximum deformation for a given approach energy has increased slightly with the use of the modified parameters. This result is understandable given the rho-vector "grow-back" process in the force-displacement-recovery algorithm – i.e., less grow-back at each time-step.

Interestingly, even with the structural recovery constants all set to zero, there is still an indicated grow-back at the end of the impact. For instance, in the 30 mph simulation, the ultimate structural recovery (the maximum displacement minus the residual crush at the vehicle centerline listed in the damage data playback window) for the default structural constants is 1.1 inch whereas, for the zeroed constants, the recovery was found to be 0.8 inch.

For the SIMON/DyMESH simulations the increased relaxation length parameter increased the restitution values relative to those using the default value. For the vehicle-to-barrier simulations, the restitution values no longer matched the real-world data as well as those found when using the default value, producing restitution values at the upper range of the real-world data. However, in the vehicle-to-vehicle simulations, the increased relaxation length parameter resulted in a much better match than that produced by the default value. For both the vehicle-to-barrier and vehicle-to-vehicle simulations, the resulting restitution values at the lower severity impacts are lower than what the experience of the authors would suggest should be expected. Fittanto and Rodowicz [19] examined the SIMON/DyMESH model at low impact severities. They found that, for vehicle-to-vehicle impacts, the relaxation length parameter had to be made larger to match full-scale crash test results. To replicate a 5.5 mph closing speed front-to-rear impact, they found that the relaxation length parameter had to be increased to 0.25 in order to replicate a measured coefficient of restitution of 0.44. For a 20.5 mph closing speed the relaxation length parameter was increased to 0.06 (slightly above the default value) to achieve a coefficient of restitution of 0.17.

To further investigate the sensitivity of the SIMON/DyMESH structural recovery algorithm to changes in the relaxation length parameter, we conducted a series of vehicle-to-barrier simulations in which the relaxation length parameter was varied from zero to 0.15 at three different impact speeds (10mph, 30mph and 50mph). The results of this evaluation are shown in Figure 17 and demonstrate a non-linear trend of increasing coefficient of restitution with increasing values of the relaxation length parameter. Also of note in Figure 17 is that, though the restitution decreases as the impact speed increases (a result that is to be expected), at relaxation length parameter values greater than the default value, the difference in coefficient of restitution values between the various impact speed data trends become roughly constant (a notable exception is the 10 mph data point at a relaxation length parameter value of 0.075) indicating little speed sensitivity to increasing relaxation parameter value.

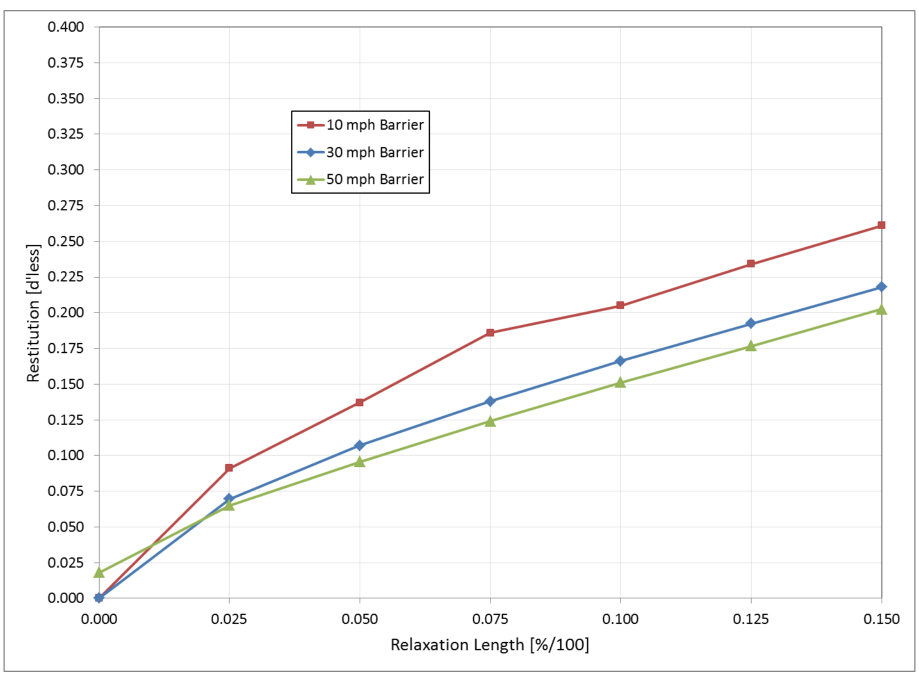

Figure 17. *Restitution versus Simon/DyMesh relaxation length parameter.*

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