

Simulation Model for Low-Speed Bumper-to-Bumper Crashes

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ABSTRACT

The purpose of this study was to develop a numerical analytical model of collinear low-speed bumper-to-bumper crashes and use the model to perform parametric studies of low-speed crashes and to estimate the severity of low-speed crashes that have already occurred. The model treats the car body as a rigid structure and the bumper as a deformable structure attached to the vehicle. The theory used in the model is based on Newton's Laws. The model uses an Impact Force-Deformation (IF-D) function to determine the impact force for a given amount of crush. The IF-D function used in the simulation of a crash that has already occurred can be theoretical or based on the measured force-deflection characteristics of the bumpers of the vehicles that were involved in the actual crash. The restitution of the bumpers is accounted for in a simulated crash through the rebound characteristics of the bumper system in the IF-D function. The output of the model for a numerical simulation is the acceleration vs. time information for each vehicle in the simulated crash. Three low-speed crash tests were performed and the dynamic IF-D curve was measured in each crash. The analytical model was used to simulate the three low-speed crash tests in order to demonstrate the model's ability to describe the vehicle dynamics in a crash that has already occurred. The model is also used to perform parametric studies that show how the structural characteristics of the vehicles' bumpers and the closing speed affect the crash pulse and to demonstrate a technique to estimate the maximum severity of a low-speed crash that has already occurred.

INTRODUCTION

There have been two main approaches to modeling a low-speed collinear crash between two vehicles. The first approach is to treat the vehicles as rigid structures and model the bumpers as spring/dashpot systems and then solve the

governing differential equations with the appropriate initial conditions (1, 3, 4, 7). The solution gives the accelerations of both vehicles during the crash. In order to simulate a specific crash with a spring/dashpot model the appropriate stiffness and damping coefficients must be used. The second approach has been called the Momentum-Energy-Restitution (MER) method. This method is based on rigid body impact mechanics and uses impulse, conservation of momentum, conservation of energy and restitution to determine the ΔV of the vehicles in a low-speed crash (2, 5, 6). In order to estimate the ΔV for a vehicle in a specific crash the MER method requires a value for the coefficient of restitution (ϵ) and an estimate of the energy absorbed by each vehicle during the crash. An analysis of a low-speed crash with the MER method provides a ΔV for the crash but does not provide the acceleration vs. time information for the vehicles during the crash. The peak acceleration in the crash can be estimated by assuming a shape and length for the crash pulse.

Thomson and Romilly (1) treated the vehicle as a rigid mass and the bumper system as a spring/dashpot system in their simulation model. Pendulum-to-car (VW Rabbit) crash tests and static and dynamic compression tests of the VW's piston-type energy absorbers were performed. The simulation model was used to calculate the VW's dynamic response in the pendulum-to-car crash tests. Four different methods were developed to analytically determine the linear coefficients of the spring/dashpot system. The damping and stiffness coefficients that best represented the experimental data were based on an energy analysis of the pendulum-to-car impacts. The calculated accelerations approximated the measured accelerations but did not start at zero because of the constant coefficient for the dashpot.

Bailey et al. (2) performed a series of car-to-car crash tests with vehicles whose bumpers had piston-type energy absorbers. The MER method was used to calculate the ΔV of

the vehicles in the crash tests. In the ΔV calculations ϵ was based on previously performed barrier impacts with the same vehicles and the energy absorbed by each vehicle was estimated from the amount of compression of the piston-type energy absorber in the actual crash test. The ΔV s calculated with the MER method were very close to the ΔV s measured in the crash tests.

Ojalvo and Cohen (3) reviewed vehicle-to-vehicle crash test data of Ford Escorts that had bumpers with piston-type energy absorbers and concluded that a linear spring/dashpot model could be used to represent the dynamic response of these vehicles in low-speed crashes. In their model the vehicles were rigid masses and the bumpers were linear spring/dashpot systems. The simulation model was used to produce closed form solutions of the vehicle accelerations in the vehicle-to-vehicle crash tests. The spring and viscous damping coefficients used in simulations were based on the crash test data. The calculated accelerations matched the measured accelerations very well except at the start of the crash where the calculated accelerations were non-zero because of the constant coefficient for the dashpot. A follow-up study by Ojalvo et al.(4) used this simulation model to simulate low-speed crash tests between cars with bumpers that had foam-type and honeycomb-type energy absorbers as well as the piston-type energy absorbers.

Cipriani et al. (5) used a modified MER method to calculate an upper limit to the ΔV experienced by a vehicle in a low-speed crash. A series of 30 low-speed collinear crash tests were performed with vehicles that had bumpers with foam-type and piston-type energy absorbers. Functions of restitution (ϵ) vs. closing speed were developed for the different bumper configurations based on their crash test data and previously published data. The modified MER method was used to estimate the ΔV s of the vehicles in the crash tests. The estimation of a crash test ΔV was made by obtaining ϵ from the appropriate restitution function and the energy absorbed by each vehicle was calculated using bumper stiffness coefficients (A and B coefficients obtained from published data) and a conservative estimate of the crush on the crash test vehicle. The calculated ΔV s were generally greater than the ΔV s measured in the crash tests (probably because of an overestimate of absorbed energy). This modified MER method provides a technique to estimate the upper limit of the ΔV in a low-speed crash.

Happer et al. (6) developed a technique for quantifying the severity of low-speed impacts involving little or no vehicular damage using the MER method. Sixty-nine barrier tests and vehicle-to-vehicle tests were performed in order to develop and evaluate the technique. The technique to calculate a ΔV for a vehicle in a low-speed vehicle-to-vehicle crash involved nine steps. In the ΔV calculation the appropriate restitution function from Cipriani et al. (5) was used to obtain the value of ϵ and the energy absorbed by each vehicle was determined

by relating the crash test vehicle damage to the damage that same model experienced in the barrier tests. The technique presented in this study provides a good method of estimating the crash severity (ΔV) of vehicles in low-speed collisions.

Brach (7) developed a nonlinear spring/dashpot model of low-speed vehicle-to-vehicle crashes. The nonlinear spring and dashpot each had a coefficient and an exponent in the governing equations. During the development of the model, the author determined that the damping during the restitution (rebound) phase of an impact was greater than the damping during the initial compression phase; therefore the damping coefficient was greater during the restitution phase than the compression phase of a simulated impact. The damping force was also proportional to the product of the relative velocity and the relative displacement of the dashpot so that the damping force did not rise instantaneously once the vehicles made contact. This nonlinear spring/dashpot model was used to simulate published crash test data and the coefficients and exponents were selected so that the calculated accelerations matched the measured accelerations throughout the crash pulse of the simulated crash. In the simulations the accelerations were zero at the time of initial contact because the damping force was proportional to the displacement of the dashpot.

The objective of the research described in this paper was to develop a numerical low-speed impact model that could simulate low-speed collinear vehicle-to-vehicle impacts where the impact force could be directly related to the physical properties of the bumpers that were involved in the crash. This approach allows the crash severity of a low-speed crash involving specific vehicles to be estimated and allows a parametric analysis of the crash to determine how different variables affect the crash pulse. This approach also takes into account the considerable variability of the force-deformation characteristics of the bumper systems that are on present day vehicles.

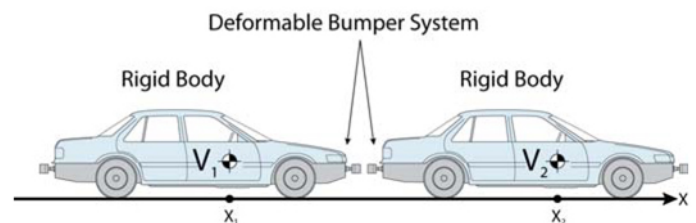


Figure 1. A schematic of the physical system that the model represents.

METHODS

ANALYTICAL MODEL

The model presented is intended to simulate a collinear impact between two vehicles, Vehicle 1 (bullet vehicle) and

Vehicle 2 (target vehicle), with masses M_1 and M_2 . As shown in Fig. 1, the model assumes that the vehicle bodies are rigid structures and the only part of the vehicles that deform are the bumper systems. The numerical simulation satisfies Newton's Second Law at discrete time positions j ,

$$F_j = M_i A_{i,j} = M_i (V_{i,j} - V_{i,j-1}) / \Delta t \quad (i=1,2) \quad (1)$$

where F_j is the impact force, $A_{i,j}$ is the vehicle acceleration, $V_{i,j}$ is the vehicle's velocity, Δt is the numerical time step and the i subscript denotes the vehicle number and the j subscript denotes the discrete time position. The time t is defined as $t = (j-1)\Delta t$ and the crash starts at $t = 0$.

The simulation starts with the vehicles in contact at $t = 0$ and then marches forward in time with time step Δt . The variables calculated at each discrete time position are the location of each vehicle's center of mass ($X_{i,j}$) and each vehicle's velocity ($V_{i,j}$). The impact forces ($F_{i,j}$) and the resulting accelerations ($A_{i,j}$) act on each vehicle during the Δt period between each discrete time position. The structural characteristics of both vehicles' bumpers are combined and input as a system Impact Force-Deformation (IF-D) function where Deformation is the sum of the deformation of the two bumpers. The Impact Force-Deformation function can be a theoretical curve or based on measured force-deflection data for specific bumpers. The output of the simulation is the acceleration versus time information for each vehicle. The algorithm presented here was programmed in MATLAB 7.0 (The MathWorks, Inc).

The numerical simulation starts at $t=0$ ($j=1$) with the vehicles in contact and the initial conditions required are vehicle speeds ($V_{1,1}, V_{2,1}$), and the center of mass positions ($X_{1,1}, X_{2,1}$) along the line the vehicles are traveling. Since the vehicles are in contact but not deformed at time $t = 0$ the undeformed distance (UD) between the two centers of mass is

$$UD = X_{2,1} - X_{1,1} \quad (2)$$

At the first time position $A_{1,1} = A_{2,1} = 0$, and the vehicles move forward through the first time step at their initial velocities and the velocities at the second time position ($j=2$) are the same as the initial conditions, $V_{1,1} = V_{1,2}$ and $V_{2,1} = V_{2,2}$. At the second time position the vehicles' center of mass positions are

$$X_{i,2} = X_{i,1} + V_{i,1} \Delta t \quad (i=1,2) \quad (3)$$

This movement of the center of mass of each vehicle creates an overlap of the vehicles, and the deformation (D_j) at the second and following time positions ($j \geq 2$) is

$$D_j = UD - (X_{2,j} - X_{1,j}) \quad (4)$$

The impact force $F_{i,j}$ that acts on each vehicle during the j^{th} time step ($j \geq 2$) is based on the input IF-D function and Newton's Third Law,

$$-F_{1,j} = F_{2,j} = \text{Function}(D_j) \quad (5)$$

The force $F_{i,j}$ ($i=1,2$) acts on the vehicles during the j^{th} time step where $j \geq 2$. Newton's Second Law is used to calculate the acceleration of each vehicle during the j^{th} time step,

$$A_{i,j} = F_{i,j} / M_i \quad (i=1,2) \quad (6)$$

The impact forces accelerate the vehicles over the j^{th} time step. The time position is incremented, $j = j+1$, and the velocities at the new time position j are calculated,

$$V_{i,j} = V_{i,j-1} + A_{i,j-1} \Delta t \quad (i=1,2) \quad (7)$$

The algorithm then checks to see if the vehicles have reached a common velocity. If the vehicles have reached a common velocity Function (D_j) is changed to represent the rebound phase of the input IF-D function (see Appendix A). The simulation then calculates the vehicle center of mass positions at the new time position,

$$X_{i,j} = X_{i,j-1} + V_{i,j-1} \Delta t + \frac{1}{2} A_{i,j-1} \Delta t^2 \quad (i=1,2) \quad (8)$$

The simulation then recalculates the variables in Eq. 4, 5, 6, 7, Eq. 8 and continues to move forward in time until $F_{i,j}$ ($i=1,2$) in Eq. 5 reaches zero and the crash is over.

The restitution of the crushed structures in a low-speed crash is usually accounted for by assigning a coefficient of restitution (ε) to the crash which is defined as the ratio of the separation velocity to the closing velocity,

$$\varepsilon = (V_1^* - V_2^*) / (V_1 - V_2) \quad (9)$$

where V_1 and V_2 are the pre-crash velocities and V_1^* and V_2^* are the post-crash velocities of the vehicles. The standard method of estimating ϵ for a low-speed crash is to perform a low-speed crash test and calculate ϵ using Eq. 9. Our model accounts for restitution through the Impact Force - Deformation function. This approach is based on the energy definition of ϵ ,

$$\epsilon^2 = E_{afc}^* / E_{afc} \quad (10)$$

where E_{afc} is the energy in the two vehicle system available for crush prior to the crash and E_{afc}^* is the energy available after the crash (8). The theoretical basis for this approach is given in Appendix A.

The accuracy of this numerical analytical model is a function of the magnitude of the time step Δt . A suitable Δt was chosen by using the model to calculate the crash pulse for a purely elastic crash. For this simulation $V_1=10$ ft/sec and $V_2=0$, $M_1 = M_2 = 3500$ lb/g where g is the acceleration due to gravity ($g = 32.2$ ft/sec²). The IF-D function used in this simulation is based on the measured force-deformation curve of the front bumper of a 2007 Ford Edge that is shown in Fig. B3. A description of the Ford Edge's front bumper and the measurement of its force-deformation characteristics are given in Appendix B. For simplicity the force-deflection curve of this bumper is taken to be a straight line that has a slope of 48,000 lbs/ft of deformation. This linear force-deflection curve is shown in Fig. B3 as a dashed line.

Both bumpers in this simulation are taken to have the same structural characteristics. If two bumpers are aligned in series with each other and both have linear force deflection characteristics defined by a slope (S_1 and S_2), then the force-deflection curve of the system has a slope that is defined by,

$$S_{\text{system}} = 1 / (1/S_1 + 1/S_2) \quad (11)$$

Therefore, the system IF-D function for this simulation is a straight line with a slope of 24,000 lbs/ft. This curve is shown in Fig. B3 as a solid straight line.

The crash that was simulated in order to evaluate the magnitude of the time step was taken to be completely elastic. Since the vehicle masses are equal the correct post-crash velocities are $V_1^*=0$ and $V_2^*=10$ ft/sec for this elastic impact. Table 1 shows the pulse durations and the post-crash velocities for a range of Δt s used in this numerical simulation. The magnitude of the time step had little effect on the calculated duration of the crash but it did influence the calculated post-crash velocities. A $\Delta t = 0.00001$ sec provided calculated post-crash velocities with only 0.01% error and

reasonable computing time, therefore this time step was used in the simulations discussed in this study.

TABLE 1. Calculated pulse duration and post-crash velocities for Δt s of different magnitude.

Δt (sec)	Pulse Duration (sec)	V_1^* (ft/sec)	V_2^* (ft/sec)	% Error in V_1^*
0.001000	0.1500	-0.082	10.082	0.82%
0.000500	0.1495	-0.041	10.041	0.41%
0.000100	0.1495	-0.008	10.008	0.08%
0.000050	0.1495	-0.004	10.004	0.04%
0.000010	0.1495	-0.001	10.001	0.01%
0.000005	0.1495	-0.000	10.000	0.00%

LOW-SPEED BUMPER-TO-BUMPER CRASH TESTS

The numerical model does not have to be validated in the sense that it is based on Newton's Second and Third Laws but the model's ability to recreate a crash that has already occurred needs to be demonstrated. The simulation model is used to simulate the dynamics of the target and bullet vehicle in three low-speed bumper-to-bumper crashes. The IF-D function used in the simulations is similar to the IF-D curve measured during the crash. A description of each bumper used in the crash tests is given in Appendix B along with the quasi-static force-deformation characteristics for that bumper.

The low-speed crash tests were performed with two vehicles that had been modified for low-speed bumper-to-bumper impacts. A schematic of the test setup is shown in Fig. 2. Vehicle 1 (bullet vehicle) is a 2003 Ford Explorer that had a test weight of 4246 lbs. The Explorer had a steel plate rigidly attached to the frame at the front and a 2007 Ford Edge front bumper was mounted onto this steel plate. Vehicle 2 (target vehicle) was a buck made from a pickup frame that had a test weight of 3382 lbs. A significant part of the mass of Vehicle 2 came from weights rigidly attached to the pickup frame. Vehicle 2 had a steel plate rigidly attached to the rear of the frame and six load cells (Model 1210AO, 10 klbs, Interface, Inc.) were attached to this plate and a second steel plate was attached to the other end of the load cells. The rear bumper of a 2007 Kia Sportage was mounted onto the rearmost steel plate at a vertical position that provided full engagement with the front bumper on Vehicle 1. A description of the rear bumper of the 2007 Kia Sportage is given in Appendix B. A

Table 2. The pre-impact velocities, the post-impact velocities, the ΔV s experienced by each vehicle in the crash tests and the coefficient of restitution calculated using the velocity and energy definition for ϵ in each of the crash tests.

Test No.	V_1 (ft/sec)	V_2 (ft/sec)	V_1^* (ft/sec)	V_2^* (ft/sec)	ΔV_1 (ft/sec)	ΔV_2 (ft/sec)	$\epsilon_{\text{velocity}}$	ϵ_{energy}
1	2.9	0	0.9	2.7	-2.0	2.7	0.62	0.68
2	4.3	0	1.4	3.8	-2.9	3.8	0.56	0.62
3	5.9	0	2.0	5.0	-3.9	5.0	0.51	0.53

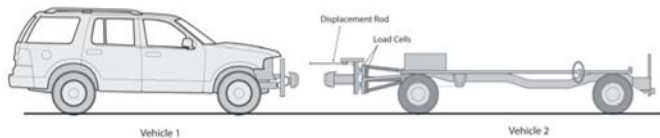


Figure 2. A schematic of the test set up for the low-speed bumper-to-bumper crash tests.

displacement rod extended from the rear plate on Vehicle 2. A string pot (Model PT101, 10 inch, Celesco, Inc.) was mounted on the steel plate and the string was attached to the end of the rod. Just before the vehicles' bumpers made contact the displacement rod contacted the steel plate on the front of Vehicle 1 and the rod was compressed. The string pot measured the distance the displacement rod was compressed. Both vehicles had accelerometers (Model 7596-10/30, Endevco Corporation) mounted on the frames to measure the accelerations in the three vehicle axis. The impact speed of the bullet vehicle (Vehicle 1) was measured with an infra-red sensor (model SM312LVMHS, Banner, Inc.) and retro-reflective tape (Banner, Inc.) and also with high-speed digital video recordings (1000 frames/sec). The data was sampled at 5000 HZ (16-channel TDAS-PRO, DTS, Inc.).

Three low-speed tests were performed. The impact speed of Vehicle 1 (bullet) was 2.9, 4.3 and 5.9 ft/sec. Vehicle 1 achieved its velocity by rolling down a ramp with its engine off. Vehicle 2 was stationary pre-impact for all tests and its wheels were free to roll. The data measured in each test were the impact speed of Vehicle 1, the vehicle accelerations, the impact force (sum of the six load cells), and the distance between the steel plates on Vehicle 1 and 2. The acceleration data were filtered (SAE J211/1, CFC 60). The impact bars on the bumpers were measured after each test with a measuring arm (Model C0605, FARO, Inc), but there was no permanent damage to the impact bars and they were not replaced. The only damage was to the plastic honeycomb energy absorber on the Edge bumper and this was replaced after each test. The foam structure on the top of the Sportage's impact bar was not damaged in any of the crash tests and was not replaced. The vehicle velocities were calculated using the initial speeds and integrating the measured accelerometer data over time. Table 2 is an overview of the velocity measurements made in the three crash tests and the coefficient of restitution calculated using the velocity definition (Eq. 9) and using the energy definition (Eq. 10) with the measured IF-D curves that are shown in Fig. 3. The coefficients of restitution calculated

with the energy definition were slightly higher than the coefficients of restitution calculated with the velocity definition.

<table 2 here>

Figure 3 shows the dynamic IF-D curves created from the measured load cell and displacement rod data for each of the tests. The deformation data is the sum of the deformation of the bumper on the target vehicle and the deformation of the bumper on the bullet vehicle. The slopes of the three curves during the compression phase are very similar. In Tests 1 and 2 the impact force reached a peak and the deformation began to decrease after the peak force was reached. In Test 3 the force remained constant at approximately 9000 lbs then decreased and increased again before the deformation began to decrease. During the rebound phase there was less energy recovered as a percentage of the maximum crush energy as the impact speed increased. This is reflected in the decreasing value of ϵ calculated with the energy definition of ϵ shown in Table 2. The maximum deformation occurred as the impact force was decreasing in the IF-D curves for all these tests.

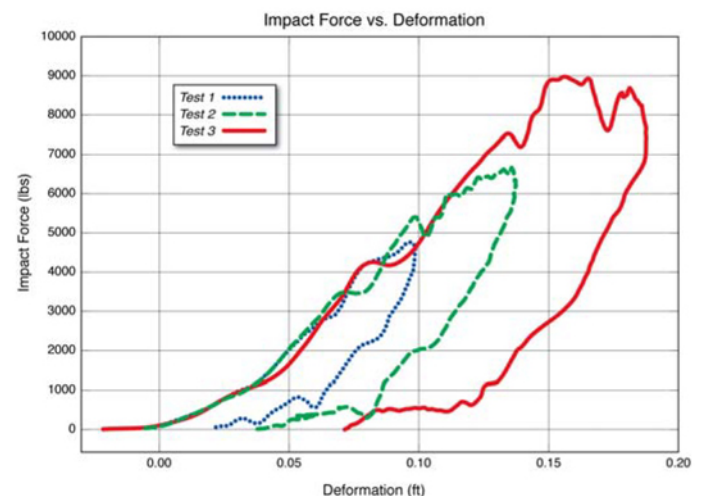


Figure 3. The Impact Force vs. Deformation (IF-D) curves made from the measured load cell data and displacement rod data for Crash Tests 1, 2 and 3.

Figure 4 shows the measured accelerations for the target and bullet vehicles along with the accelerations for each vehicle calculated with the load cell measurements, the vehicle masses and Newton's Second Law. The acceleration data for