WP# 2000-2

The Importance of Crash Pulse Data When Analyzing Occupant Kinematics Using Simulations

Wesley D. Grimes, P.E.
Collision Engineering Associates, Inc.

F. Denny Lee, Ph. D.
F.D. Lee

ABSTRACT

Computer simulations are frequently used to analyze occupant kinematics in motor vehicle crashes, including what they collide with during the crash and the severity of these internal collisions. From study of such occupant simulations, it is then possible to infer how the actual human occupants may have been injured in a crash. When using a simulation to study how occupants react in a vehicle crash, a crash-pulse is usually required as input to the occupant simulation model. This crash-pulse is typically generated from a study of the vehicle motion and acceleration during the crash. There are several different methods for obtaining such a crash-pulse which are in common use. Each of these methods produces a different shape for the crash-pulse, even with identical velocity changes for the vehicle. The time duration, maximum acceleration, and general shape of the crash-pulse may influence the predicted motion of the occupants. In this research, the GATB (Graphical Articulated Total Body) computer simulation model is used to study basic occupant kinematics using a variety of shapes for the crash-pulse, in order to determine how the specific shape of the crash-pulse affects the predicted occupant kinematics.

INTRODUCTION

One of the most obvious reasons that vehicle crashes are analyzed is to determine how people are injured. Computer simulations are frequently used to study how occupants move in a crash, what they collide with during the crash and thus how they are injured. When such a computer simulation is used to analyze occupant kinematics, the vehicle motion is typically defined for the simulation program by specifying a crash-pulse. In other words, most computer models do not calculate both the vehicle motion and the occupant motion at the same time. Usually, the vehicle motion during the crash is modeled separately or else obtained from an actual crash test, and then the crash-pulse from this vehicle motion is used as input for the occupant simulation model in order to predict the occupant motion[1,2].

Analysis of the vehicle motion during a collision produces what is referred to as the crash-pulse. A crash-pulse can be represented as either an acceleration versus time, a velocity versus time, or a position versus time curve. Typically crash-pulse data can be extracted from either instrumented crash test data, or the output from collision models such as EDSMAC4[3] or DYMESH[4], or from approximations based on a given velocity change using specific shapes for the pulse and various time durations.

Unfortunately, a detailed crash-pulse is not immediately available when analyzing most real world crashes. The controlled crash-test data which is publicly available deals with specific vehicles, specific crash orientations, specific crash speeds and specific objects impacted. Such test data is extremely useful for determining vehicle stiffness coefficients, and for analyzing frontal or straight barrier collisions. Crash test data is not as useful when trying to establish a detailed crash-pulse for non-frontal or non-barrier crashes.

It is also possible to obtain general crash-pulse data, by using a crash simulation model. Since there are often many simplifications associated with any such model, care must be taken when using them. Stiffness data, vehicle weights, velocities, and vehicle orientations are some of the factors which will affect the shape of the crash-pulse, and which thus may affect the predicted motion of the occupants.

Yet another method of generating a crash-pulse is to approximate the crash-pulse with a simple mathematical function. Three of the most common approximations involve using 1) a constant, or average, acceleration during the crash, which results in a step function or a square wave for the crash-pulse, 2) a half-sine wave to approximate the crash- pulse, and 3) a triangle wave to approximate the crash-pulse. In each of these cases the analytic procedure consists of calculating the change in velocity due to the crash and then calculating the crash-pulse area by estimating the time duration of the crash. The estimation of the duration of a crash is difficult and critical. Estimating a time duration that is too short will give rise to an excessively large amplitude for the crash-pulse which in turn will predict excessive occupant motion early in the crash. Using a time duration that is too long will predict occupant motion that is delayed and not as severe as actually occurs in the real crash.

This paper reports on research that has been conducted to study how the shape of the crash-pulse affects the predicted occupant motion. The predicted occupant behaviors obtained using various approximations for the crash-pulse are then compared with the predicted occupant behaviors using the crash-pulse obtained from an actual instrumented crash test.

RESEARCH PROCEDURE

The research was conducted in the same manner that an ordinary reconstruction analysis would be conducted. In this case however, there was also an actual crash test which was used as a base with which to compare the final results from the various tests. The simulated occupant motion results from using this crash test acceleration pulse were used for comparison purposes only.

The GATB (Graphical Articulated Total Body) computer simulation model was used to model occupant motion during a frontal impact. These simulations were set up and executed under the HVE (Human-Vehicle-Environment) system[5].

Crash-pulse duration is a critical component of the crash-pulse data. In real-world crashes this time interval is an unknown and can only be estimated. Typically such estimates show a rather wide variation.[6] Actual crash testing has shown that indeed, the duration of a crash does in fact vary from crash to crash but typically falls into the 100msec to 200msec range. In this analysis three different time intervals were selected to cover this range. The three time intervals which were selected were 100msec, 150msec, and 200msec.

Computer simulations were executed using a variety of sources for the crash-pulse data. The initial GATB run was made using the crash-pulse which was obtained from the acceleration-time pulse taken from the actual crash test. The results from this base run were then compared with the results from other sources for the crash-pulse. For example, a GATB run was made using the crash-pulse determined by the EDSMAC4 model. Other GATB runs used crash-pulses which were generated using a half-sine wave pulse, a square-wave pulse, and a triangle-wave pulse.

To keep the research focused on the effect of the crash-pulse shape on occupant motion, the actual pulse shape was extracted from the test report, as shown in Figure 1. This was then used to establish the velocity change in the crash, which in turn was used to define the other test crash-pulse shapes.

CRASH TEST

A vehicle-to-barrier crash test report was obtained from Neptune Engineering, Inc.[7] The report documents a crash test conducted at TRC in East Liberty, Ohio. In this test a 1990 Chevrolet Lumina 4-door sedan was made to collide with a fixed barrier at a speed of 29.6 mph. The velocity change of the Lumina (including restitution) was determined to be approximately 34.8 mph from the analysis of the crash test data set. Since the two acceleration vs time curves which were used (Left-rear seat and Right-rear seat) produced slightly different values for delta-V (33.3 mph and 37.6 mph respectively), the two acceleration-time curves were first averaged and then integrated to arrive at the 34.8 mph figure. This number was the only data used from the crash test at this point.

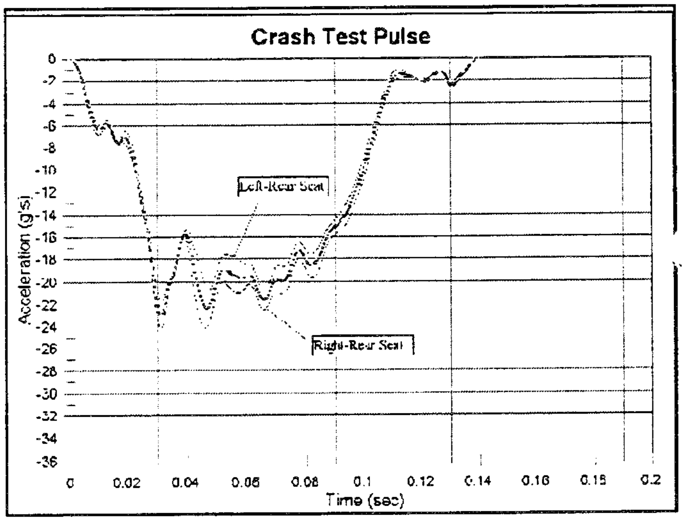

Figure 1 - Crash test pulse data.

EDSMAC4 RUN

A crash simulation run was set up in EDSMAC4. The vehicle selected from the HVE vehicle database [8] was a Chevrolet Lumina 4-door. The vehicle weight and its impacting speed were set in accordance with the crash test. That is, a value of 3663lbs for the weight, and a value of 29.6 mph for the impact velocity were used.

The front stiffness coefficients were obtained from Neptune Engineering, Inc. using the air-gap adjusted data[9]. It was of interest to note in passing that if the data is not adjusted for the air-gap correction, the B-stiffness coefficient is 81 lbs/in^2, whereas it drops to 59 lbs/in^2 after adjustment fc the air-gap.[10,11]

The EDSMAC4 run was set up as a vehicle-barrier impact in an effort to duplicate the conditions of the actual barrier crash test. EDSMAC4 predicted the vehicle velocity change to be approximately 35 mph, which is good agreement with the actual TRC barrier crash test.

From this EDSMAC4 run, an acceleration crash-pulse was generated at 0.002 second intervals. This crash-pulse was then used by the GATB model as the vehicle prescribed motion. The acceleration vs time curve produced by the EDSMAC4 run is shown in Figure 2.

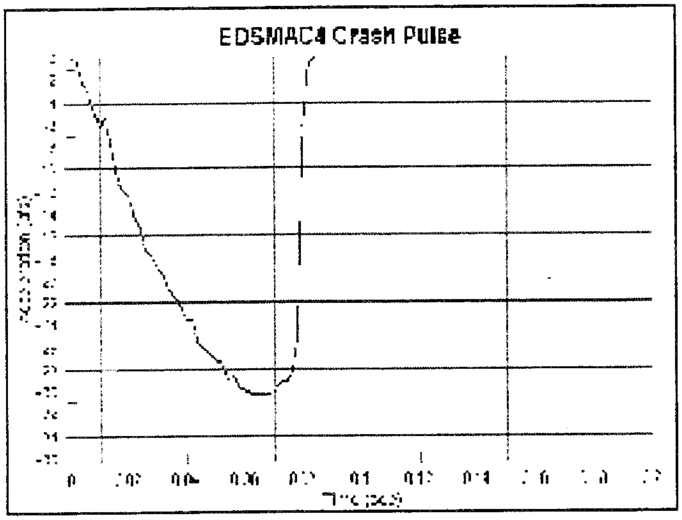

Figure 2 - Crash-pulse from EDSMAC4 simulation.

SQUARE-WAVE PULSE

Using the velocity change of 34.8 mph as the target, three separate square wave pulses were generated. The three pulses differ by the time duration and pulse height. The time intervals chosen were 100msec, 150msec, and 200msec. The square-wave pulses used are shown in Figure 3.

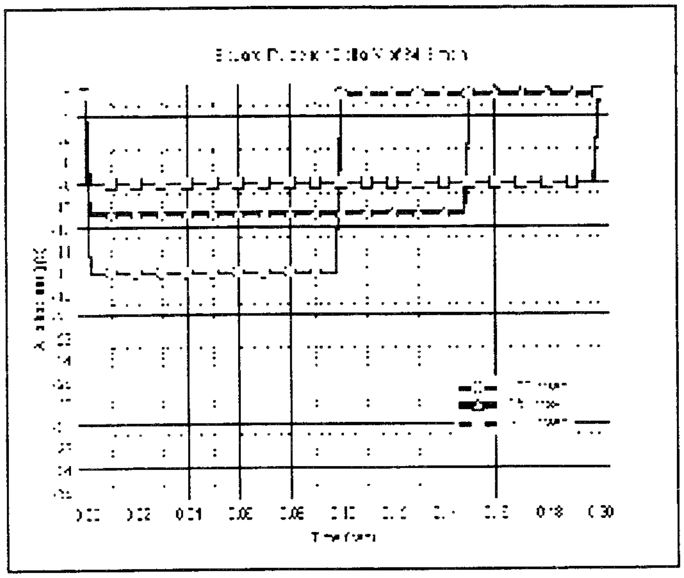

Figure 3 - Square wave crash pulse data.

HALF-SINE WAVE PULSE

Using a half-sine wave shape to approximate the crash-pulse required adjustment of the amplitude of the sine wave to be such that the specified speed change of 34.8 mph was produced during the specified time interval. Three separate half-sine pulses were constructed each with the appropriate duration of 100msec, 150msec, and 200msec. The half-sine pulses are shown in Figure 4.

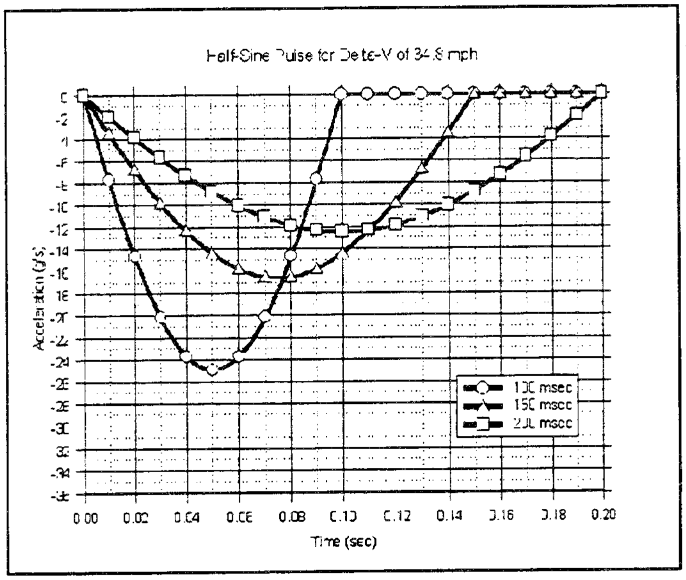

Figure 4 - Half-sine wave crash pulse data.

TRIANGLE-WAVE PULSE

Using the specified speed change of 34.8 mph, along with the three estimated time intervals, three different triangular-shaped pulses were calculated. Here again, the time intervals chosen were 100msec, 150msec, and 200msec. The triangle wave pulses used are shown in Figure 5.

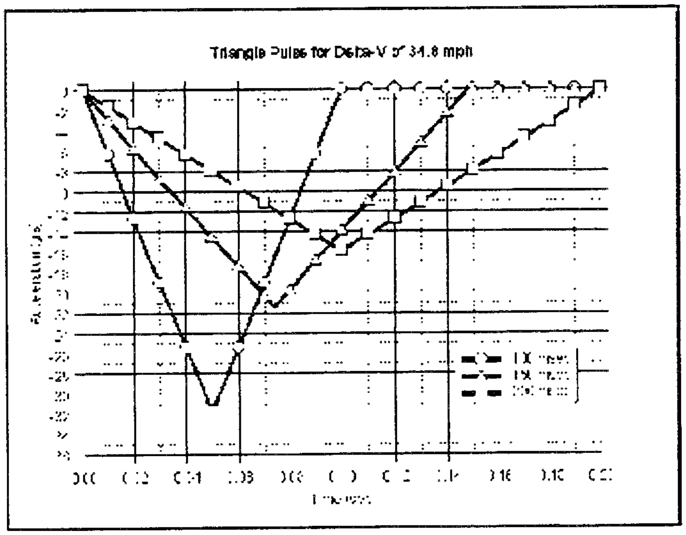

Figure 5 - Triangle wave crash pulse data.

GATB RUNS

Version 5.124 of the GATB program was used. A 50th percentile (height and weight) adult male was selected from the HVE human database [12]. The human was placed in the right-front seat position and approximate equilibrium was established by positioning the human visually. Several short duration runs were then made in order to examine the equilibrium forces acting on the human and thereby balancing the gravitational forces acting on the occupant with appropriate contact forces. An isometric view of the human model at the beginning of a GATB run is shown in Figure 6.

Occupant in GATB

Since the purpose of the study was to determine how occupant motion is affected by crash pulse differences, the human-vehicle contacts were chosen so as to have minimal effect on subsequent occupant motion. Thus, in order to avoid any unnecessary influences from extraneous factors, only the minimal contacts required to establish initial equilibrium were used.

The human occupant was thus unrestrained with the exception of the specified equilibrium contacts shown in Table 1 below. In each run, the position, velocity, and acceleration data for the different occupant segments were stored for examination and comparison among the various cases. The pelvis (lower-torso) segment position, with respect to the vehicle, is used for comparison in the following graphs and tables.

Use of crash-pulse data in GATB

The GATB simulation model was set up to use a cubic polynomial fit to the acceleration data. The GATE simulations were run for a total time interval of 60ms. First the base run was established using the TRC test crash data, and then additional runs were made using the various other crash-pulse shapes. All other parameters were held constant from one run to the next.

Table 1 - List of occupant contacts

Segment	Contacts
Pelvis	Seat Bottom, Back
Abdomen	Seat Back
Chest	Seat Back
Right Upper Leg	Seat Bottom Right Lower Arm
Left Upper Leg	Seat Bottom Left Lower Arm
Right Foot	Floor
Left Foot	Floor

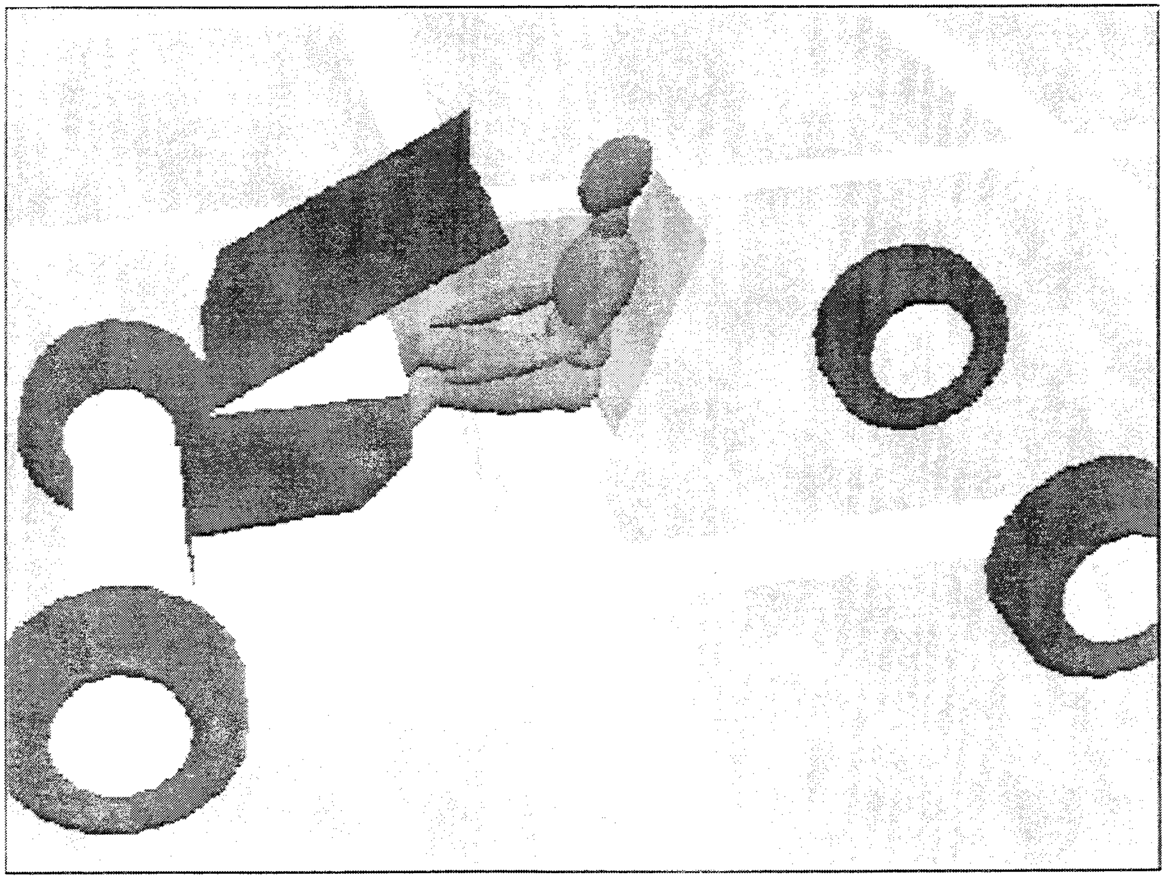

Figure 6 - GATB initial position setup.

ANALYSIS

This study focuses on how a simulated occupant moves during the first 50msec following an impact. Such a time interval is an important first phase of the crash, since during these first 50msecs, the simulated occupant is beginning to move relative to the vehicle as the vehicle changes its velocity while the simulated occupant continues on its pre-impact path with a velocity which is approximately equal to its initial velocity.Occupant contact with the vehicle interior depends on many factors. Some of the factors which influence this contact include the interior geometry and seat position, occupant size and seating posture, and crash-pulse magnitude and duration. Clearly, the actual crash-pulse greatly affects not only when and where the occupant strikes the interior, but also the predicted speed of the simulated occupant relative to the interior when such a collision occurs.

If the occupant is restrained with a belt system for example, it is during this initial 50msec that the occupant begins to load the belt and to start the ride-down. If pre-impact belt slack is increased, this ride-down is delayed. The crash-pulse determines the time versus distance relationship between the occupant and the vehicle and also the distance versus speed relationship. In other words, if a crash pulse has an unrealistic magnitude and shape it will most likely affect not only the prediction of when an occupant loads the belt, but also the predicted speed differential between the occupant and the vehicle.

In the analysis which is presented here, only a frontal impact is considered. However, in a real-world crash any rotation of the vehicle will also affect where the occupant strikes the inside the vehicle. For example, if the occupant begins moving to the left at an angle of 30 degrees, then they will strike the dash at a certain place if the vehicle does not rotate during the time interval in which the occupant is moving toward the dash. If the vehicle rotates during that time interval however, the location of the dash will have moved, and hence the point of contact and the relative speed will be different. In short, in a crash when rotation occurs, the projected target has moved by the time the occupant reaches it. Thus it is clear that the crash-pulse shape will also affect how occupants move in crashes including rotation, since the pulse shape determines at what instant in time the occupant will arrive at a certain position.

It is important to note that the results of this study cannot be used to predict the occupant motion after the 50msec duration. Typically there will be a greater deviation between the actual motion and the predicted motion of an occupant, the longer the duration of the simulation. This study shows the general accuracy and effects within the first 50msec, and should not be extrapolated to a longer duration. The occupant motion as predicted by the GATB model using the TRC crash test pulse is shown in Figures 7 and 8. Basic results are summarized in Table 2. Using these values as the base data, comparisons can now be made with the other crash-pulse shapes in order to examine how the different crash-pulse shapes affect the predicted occupant motion.

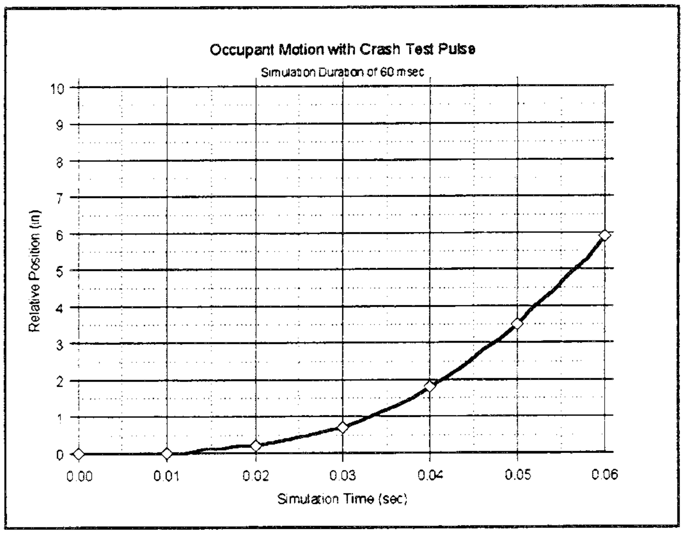

Figure 7 - Position vs time using TRC crash test pulse in GATB.

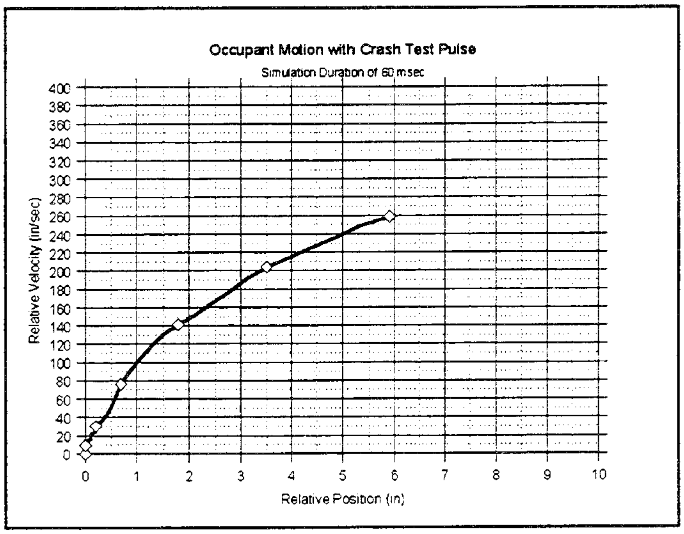

Figure 8 - Velocity vs position with TRC crash test pulse.

Table 2 - Results of GATB runs with crash test pulse.

Time (sec)	Relative Position (in)	Relative Velocity (in/sec)
0.020	0.2	30
0.033*	1.0	99
0.040	1.8	141
0.0413*	2.0	148
0.0473*	3.0	187
0.050	3.5	204
0.052	4.0	216

(* Values are interpolated)

EDSMAC4 RESULTS

The EDSMAC4 crash pulse, shown in Figure 2, together with the base data produces the results shown in Figures 9 and 10 and summarized in Table 3 below.

Comparing this data to the values from the base run gives insight into how the GATB predictions are affected by approximating the crash with the EDSMAC4 model. Table 3a summarizes this comparison, based only on relative position.

The time required for an occupant to cover a certain distance in space is also likely to be affected by the crash-pulse shape. In frontal impacts the time required to reach the dash does not greatly affect the impact location on the dash. In crashes where rotation is occurring however, the dash will also be moving laterally relative to the occupants motion. In such a case a delay in occupant arrival time of say 10msec, will mean the predicted location of the hit on the dash will be in quite a different location due to the rotation. Hence it is important to study the time versus distance predictions for the various pulse shapes as well.

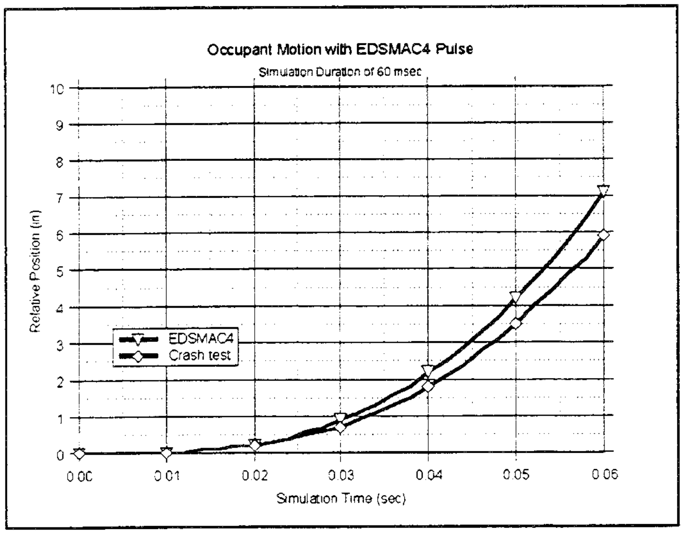

Figure 9 - Position vs time using EDSMAC4 crash-pulse data.

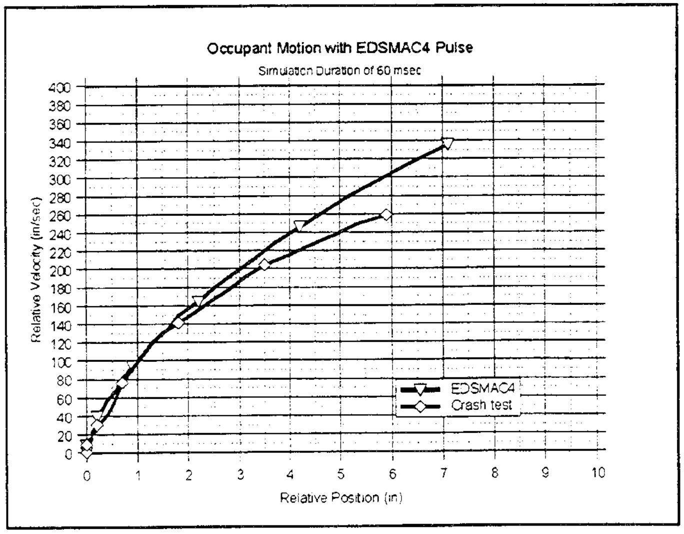

Figure 10 - GATB results using EDSMAC4 crash-pulse data.

The time to reach a fixed total distance for the GATB runs with the EDSMAC4 crash-pulse is compared with that from the TRC crash test pulse in Table 3b.

Table 3 - Results of GATB runs with EDSMAC4 pulse.

Time (sec)	Relative Position (in)	Relative Velocity (in/sec)
0.020	0.2	39
0.031*	1.0	100
0.039*	2.0	157
0.040	2.2	164
0.0445*	3.0	200
0.0492*	4.0	239
0.050	4.2	246

(* Values are interpolated)

Table 3a - Velocity - EDSMAC4 vs Crash Test pulse.

Relative Position (in)	Crash Test Rel. Velocity (in/sec)	EDSMAC4 Rel. Velocity (in/sec)	Relative Deviation (%)
1.0	99	100	1
2.0	148	157	6
3.0	187	200	7
4.0	216	239	11

Table 3b -Time - EDSMAC4 vs Crash Test pulse.

Relative Position (in)	Crash Test Time (msec)	EDSMAC 4 Time (msec)	Relative Deviation (%)
1.0	33	31	6
2.0	41.3	39	6
3.0	47.3	44.5	6
4.0	52	49.2	5

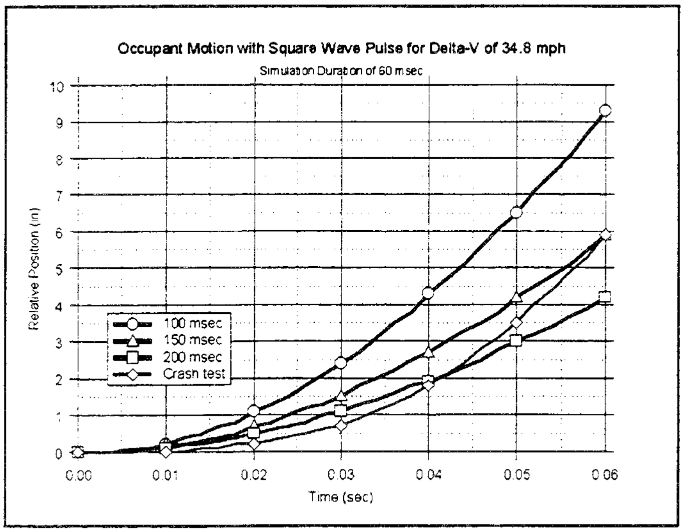

Figure 11 - Position vs time results for square-wave

SQUARE PULSE RESULTS

The square-wave crash pulse data, shown in Figure 3, together with the base data produce the results shown in Figures 11 and 12 and summarized in Table 4 below. Comparing this data to the base values gives insight into how the GATB results are affected by approximating a crash pulse by using a square wave pulse assumption. Table 4 summarizes this comparison, based on relative positions as well as the time to reach a fixed distance comparison between the GATB runs with the square wave pulse and the TRC crash test pulse.

Reading the tables

Tables 4 through 6 present data comparing the results from different pulse shapes to those using the crash test pulse data. These tables include a summary of the results as well as a comparison of times to reach a relative position and the relative velocity at that relative position. For example, Table 4 shows that in the GATB runs using the 100msec square pulse it took 0.0193 seconds to reach 1 inch and the relative velocity was 106 in/sec at that point.

Table 2 shows the results using the crash test pulse, where it took 0.033 sec to reach the same relative position, with a relative velocity of 99 in/sec. Thus, the 100 msec square pulse shows 0.0193 sec (Table4) and the crash test pulse shows 0.033 sec (Table 2) to reach 1 inch relative position. Table 4 shows this to be a deviation of approximately 42%, shown in parenthesis next to the time. Similarly, Table 2 shows a relative velocity of 99 in/sec at this point while Table 4 shows 106 in/sec, which is a deviation of approximately 7%, as shown in the parenthesis next to the relative velocity value in Table 4.

Table 4 - Summary of GATB runs with square pulse - with a comparison (as deviation) to data in Table 2.

Time (sec)	Relative Position (in)			Relative Velocity (in/sec)		
	100 (msec)	150 (msec)	200 (msec)	100 (msec)	150 (msec)	200 (msec)
0.0193* (42 %)**	1.0			106 (7%)**		
0.020	1.1	0.7	0.5	109	70	50
0.024 (27%)**		1.0			83 (16%)**	
0.0273* (34%)**	2.0			148 (0%)**		
0.028 (15%)**			1.0			69 (30%)**
0.0335* (29%)**	3.0			178 (5%)**		
0.034 (18%)**		2.0			115 (22%)**	
0.0388* (25%)**	4.0			202 (6%)**		
0.040	4.3	2.7	1.9	208	131	94
0.041* (0.7%)**			2.0			96 (35%)**
0.042 (11%)**		3.0			137 (27%)**	
0.0490* (6%)**		4.0			154 (29%)**	
0.050 (6%)**	6.5	4.2	3.0	250	157	111 (41%)**
0.0587* (13%)**			4.0			127 (41%)**

(* Values are interpolated) **(Relative deviation)

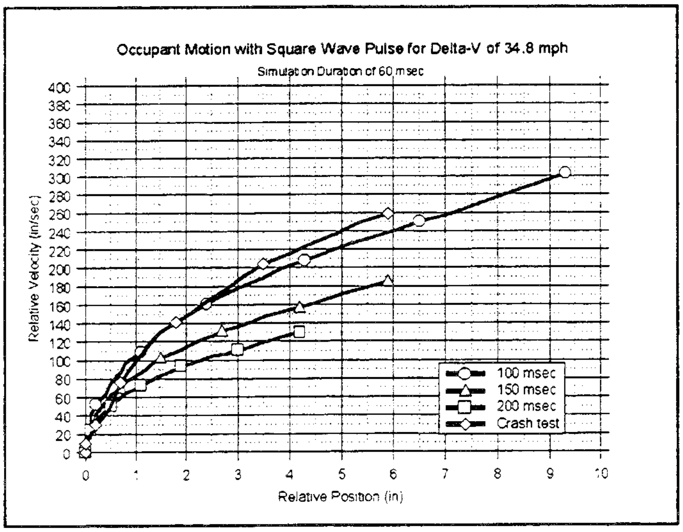

Figure 12 - Velocity vs position results for square-wave.

HALF-SINE PULSE RESULTS

Using the half-sine wave pulse as shown in Figure 4, the GATB model produces the results shown in Figures 13 and 14 and which are summarized in Table 5 below.

Close examination of the Figure 13 and comparison with Figure 7 illustrate that if the time duration could be determined accurately, the half-sine pulse would generate results very close to the actual crash pulse results. (Approximate linear interpolation on Figure 13, assuming a duration of 125 msec.)

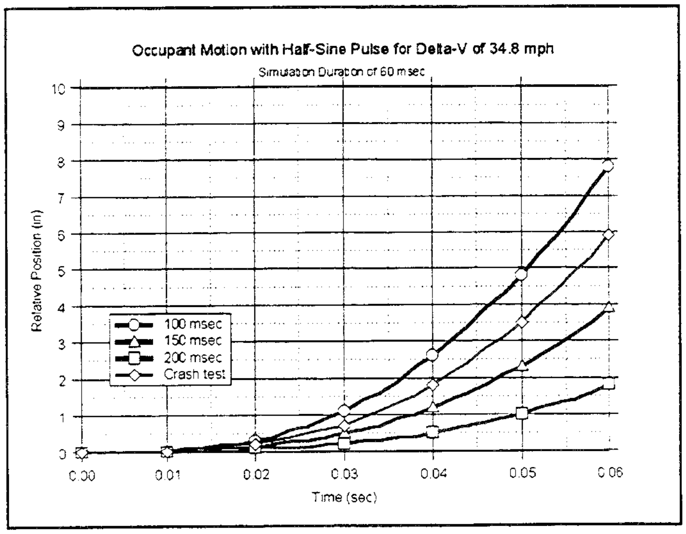

Figure 13 - Position vs time results for half-sine wave.

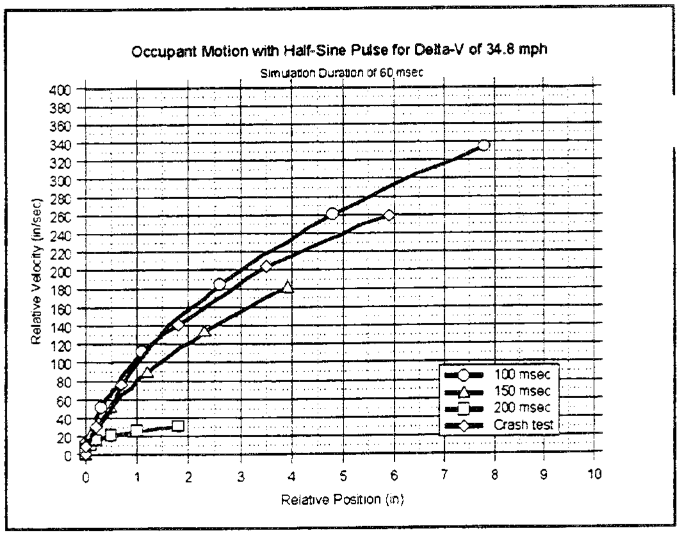

Figure 14 - Velocity vs position results for half-sine wave.

TRIANGLE PULSE RESULTS

Using the triangle wave pulse as shown in Figure 5, the GATB model produces the results shown in Figures 15 and 16, and which are summarized in Table 6.

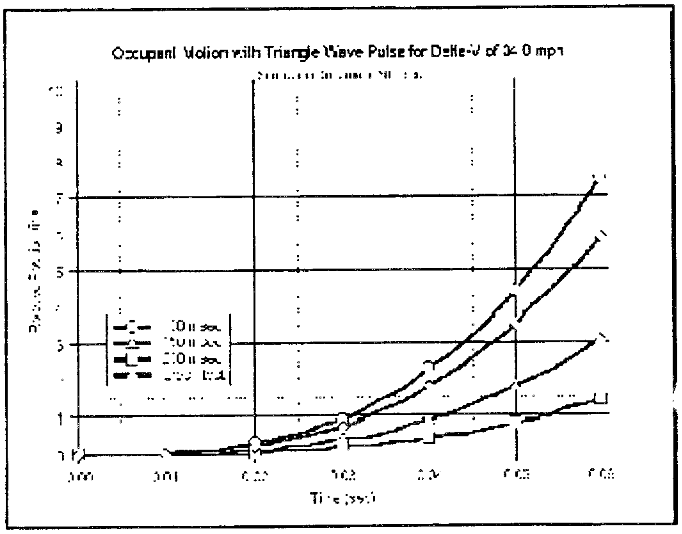

Figure 15 - Position vs time results for triangle-wave.

Table 5 - Summary of GATB runs using half-sine pulse - with a comparison (as deviation) to data in Table 2.

Time (sec)	Relative Position (in)			Relative Velocity (in/sec)		
	100 (msec)	150 (msec)	200 (msec)	100 (msec)	150 (msec)	200 (msec)
0.020	0.3	0.1	0.1	51	23	10
0.029* (12%)**	1.0			105 (6%)**		
0.0365* (12%)**	2.0			158 (7%)**		
0.038 (15%)**		1.0			81 (18%)**	
0.040	2.6	1.2	0.5	185	89	40
0.042 (11%)**	3.0			200 (7%)**		
0.0465* (11%)**	4.0			235 (9%)**		
0.0473* (15%)**		2.0			121 (18%)**	
0.050 (52%)**	4.8	2.3	1.0	261	133	62 (37%)**
0.0547* (16%)**		3.0			155 (17%)**	

(* Values are interpolated) **(Relative deviation)

Table 6 - Summary of results using triangular pulse - with a comparison (as deviation) to data in Table 2.

Time (sec)	Relative Position (in)			Relative Velocity (in/sec)		
	100 (msec)	150 (msec)	200 (msec)	100 (msec)	150 (msec)	200 (msec)
0.020	0.3	0.1	<0.1	4	16	7
0.031* (6%)**	1.0			103 (4%)**		
0.0385* (7%)**	2.0			158 (7%)**		
0.040	2.3	0.9	.04	171	69	32
0.042 (27%)**		1.0			77 (22%)**	
0.044 (7%)**	3.0			206 (10%)**		
0.0484* (7%)**	4.0			247 (14%)**		
0.050	4.4	1.8	0.8	264	108	50
0.052 (26%)**		2.0			117 (21%)**	
0.054 (64%)**			1.0			59 (40%)**
0.0593* (25%)**		3.0			152 (19%)**	

(* Values are interpolated) **(Relative deviation)

CONCLUSIONS

This work is a baseline for additional research. The results of this research could, in fact, be achieved by using simple hand calculations; although this could require some time. This research was an effort to define and exhibit the problems associated with making simplifying assumptions about the crash pulse shape and duration when studying occupant kinematics.

After analyzing the results from all the simulations completed and studying the graphs and tables presented, the following conclusions are presented:

- The shape and duration of a crash-pulse does affect the position and velocity time-history of the occupant.
- When the time duration of the crash is known, a half-sine wave pulse produces good results on this 30 mph frontal barrier crash (interpolating approximately 125msec pulse on Figure 13). However, it is clear that assuming different time durations may greatly affect the position and velocity time-history of the occupant.
- Occupant position and velocity time-history predictions are affected by assuming different crash pulse time durations for square, half-sine, and triangular wave shapes. The crash-pulse time duration assumed is critical in accurately simulating occupant motion when using one of these pulse shapes.
- For the first 50msec of this frontal impact scenario the occupant simulations based on the EDSMAC4 crash-pulse closely match the occupant simulations based on the actual crash-pulse.
- Additional work must be completed to study the effect of crash pulse shape on non-frontal impacts.

CONTACT

Wesley Grimes received his B.S. in mechanical engineering from Arizona State University. He investigates and analyzes motor vehicle crashes. Based in Mesa, Arizona he may be contacted at wgrimes@cea-az.com.

Denny Lee received his B.S. degree in Physics from the University of Kansas. He received his Ph.D. degree from the same institution. He is an accident reconstructionist and an Emeritus Physics Professor at Montana State University. He may be contacted at fdlee@mcn.net

REFERENCES

1. Obergefell, L.A., Gardner, T.R., Kaleps, I., and Fleck, J.T., "Articulated Total Body Model Enhancements, Volume 2: User's Guide", Report No. AAMRL-TR-88-043, Armstrong Laboratory, Dayton, Ohio, January 1988 (NTIS No. A203 566).
2. *GATB User's Manual, Third Edition*, Collision Engineering Associates, Inc., Mesa, AZ, 1999.
3. Day, T.D., "An Overview of the EDSMAC4 Collision Simulation Model", SAE Paper No. 1999-01-0102, 1999.
4. York, A.R., Day, T.D., "The DyMesh Method for Three-Dimensional Multi-Vehicle Collision Simulation", SAE Paper No. 1999-01-0104, 1999.
5. *HVE User's Manual, Version 2*, Engineering Dynamics Corporation, Beaverton, OR 1998.
6. Kerkhoff, J.F., Husher, S.E., Varat, M.S., Busenga, A.M., Hamilton, K., "An Investigation into Vehicle Frontal Impact Stiffness, BEV and Repeated Testing for Reconstruction", SAE Paper No. 930899, 1993.
7. Crash test report Chevrolet Lumina crash test: NHTSA #1378
8. Day, T.D., "An Overview of the HVE Vehicle Model", SAE Paper No. 950308, 1995.
9. Neptune, J.A., "A Comparison of Crush Stiffness Characteristics from Partial-Overlap and Full-Overlap Frontal Crash Tests", SAE Paper No. 1999-01-0105, 1999.
10. Crush Stiffness Coefficients For Vehicle Model Years 1960-1997, Neptune Engineering, Clovis, CA, 1996.
11. Air-gap adjusted data obtained from Neptune Engineering, Clovis, CA.
12. Day, T.D., "An Overview of the HVE Human Model", SAE Paper No. 950659, 1995.