

Crash Pulse and DeltaV Comparisons in a Series of Crash Tests with Similar Damage (BEV, EES)

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ABSTRACT

Nine crash tests were conducted at various speeds on three vehicles in three locations under conditions that resulted in similar damage. The objective was to study the differences in crash pulse, ΔV , crush depth, and impact location with change in closing velocity from 20 to 55 mph. Three equal-weight Nissan Sentra vehicles were impacted in the front, rear, and side by an associated narrow object impact device. The three impactors were identically shaped, flat-faced, one-foot wide, and rigid; but each was designed to have a different weight (light, moderate, and heavy weight). The heavy, moderate, and light weight impactors collided with their associated test vehicle at low, medium, and high impacting speeds, respectively, in order to produce damage corresponding to a 20 mph BEV (Barrier Equivalent Velocity) in all nine tests.

Impacts at the same location on the three vehicles produced nearly identical damage yet substantially differed in ΔV . Corresponding crash pulses vary widely in time duration while demonstrating similar deceleration magnitude.

A description of the crash physics behind these observed differences and similarities in the crash pulses provides a basis for pulse shape analysis applicable in biomechanical injury analysis. These tests may also be helpful in explaining the basis for deployment or non-deployment of safety systems.

INTRODUCTION

ACCIDENT SEVERITY AND INJURY EXPOSURE – Historically, much of the crash testing for the purpose of injury assessment and mitigation has been fixed rigid-barrier testing. In such tests a connection between

vehicle damage and potential occupant injury has been observed. Hence the medical literature contains many references to direct correlations between injury potential and descriptions of damage such as BEV (Barrier Equivalent Velocity) or EES (Energy Equivalent Speed). A number of papers in medical journals that refer to BEV or EES are referenced in Appendix A. Such correlations are only strictly correct for fixed rigid-barrier crashes. The more generalized correlations between the potential for injury and a measure of accident severity are with vehicle ΔV and are independent of vehicle damage (for impact injuries).



Figure 1. Nissan Sentra Frontal Impacts at 54 mph, 32 mph, and 21 mph with ΔV 's of 20 mph, 13 mph, and 7 mph. (Matching these speeds to Tests "A", "B", and "C" cannot be based upon observed damage because the damage is essentially the same for each.)

Observed damage to a vehicle involved in an accident tells an incomplete story, Figure 1. Knowledge of the collision partner is essential in order to complete an accident reconstruction. At a minimum, an understanding of the damage to both objects must be available together with the weights of both collision partners and the location of the damage relative to the centers of mass when the objects are collision aligned. In general, it has been shown that in a two vehicle crash the damage to each vehicle is related to the mass ratio

and stiffness ratio of the collision partners as well as to the closing speed [Varat 1996].

As an illustration of this important principle of accident reconstruction, the frontal damage to three test vehicles is shown in Figure 1. Closing speeds and ΔV 's are given. The closing speeds in the tests were between 21 and 54 mph. The ΔV 's produced by the collisions were between 7 and 20 mph. Yet the resulting frontal damage to these Nissan Sentra vehicles is nearly identical.

OBJECTIVES – A series of crash tests was designed to more fully clarify the relationship between vehicle damage and ΔV . What are the conditions that allow three similar vehicles to be damaged nearly identically with a wide difference in impact speed and ΔV ? More interestingly, how does the acceleration crash pulse change in order to accommodate these speed differences? What happens to peak acceleration and pulse time duration? What are the implications for injury? How might crash sensors discriminate between these crash events? These questions, and others, are addressed by the series of crash tests reported hereinafter.

In the sections that follow, the important differences between BEV , ΔV , and closing speed are illustrated by nine crash tests (three frontal, three side, and three rear tests). The three frontal test vehicles are shown in Figure 1. The target test conditions under which these nine tests were conducted were designed such that the damage produced in each of the three comparison test sets was as close to identical as possible. Collision speed conditions covered a broad range. This allowed collection and study of acceleration crash pulses that differ markedly in ΔV yet represent essentially the same damage to the test vehicles.

GOVERNING NEWTONIAN PHYSICS, DEFINITIONS, AND NOTATION – Basic formulas for energy and momentum conservation are well known as applied to accident reconstruction. However, a brief review and discussion of these equations is provided in Appendix A to define notation used herein and to clarify terminology.

The differences between EES (Equivalent Energy Speed) and BEV (Barrier Equivalent Velocity) and its synonyms EBS (Equivalent Barrier Speed) and ETS (Equivalent Test Speed) are discussed in Appendix A. Test results and conclusions apply to both EES and BEV definitions since the difference in damage energy between these two descriptors is only about 1% (for 10% restitution and equal weight vehicles). Hereinafter, a reference to BEV will be understood to also apply to a reference to EES .

COLLISIONS AT CONSTANT DAMAGE AND CONSTANT BEV

BEV AND ΔV CHART – The relationship between BEV and ΔV may be described by a series of charts for specified test vehicle weights. Figure 2 is one such chart for a 4000 pound vehicle. In these theoretical charts a vehicle of known weight collides with a variable weight, rigid, movable impactor. As the weight and closing speed of the impactor are varied the collision characteristics are altered as demonstrated in the chart.

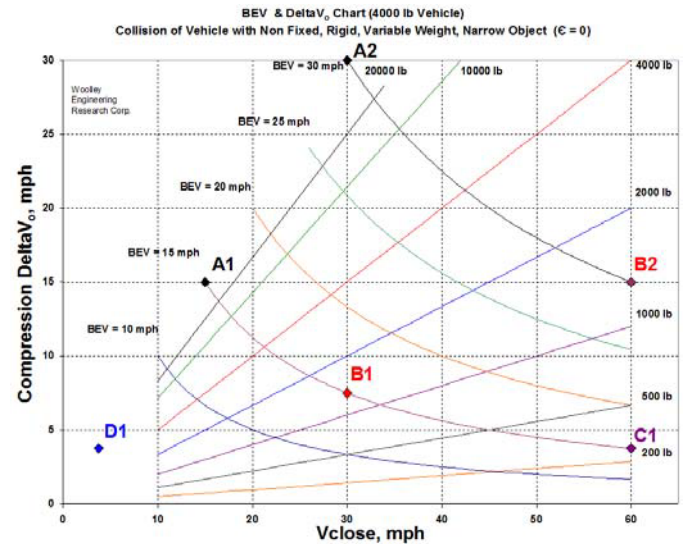


Figure 2. BEV , ΔV_o , and Closing Speed Chart for a 4000 Pound Test Vehicle.

The physics underlying Figure 2 is described below. Restitution is neglected in the formulas that produce the chart. Hence the ΔV shown is the same as the ΔV that takes place during the compression phase of the crash pulse (ΔV_o), also known as the approach or penetration phase (see Appendix A).

Compression ΔV (ΔV_o) is a function of closing speed (V_{CL}). Lines of constant BEV are plotted on the chart by generation of a series of tables in a spreadsheet following a formula relating these two variables. Damage energy is related to V_{CL} (prior to rebound) and the vehicle masses, M_A and M_B . Under test conditions all the impacts are collinear.

$$E = \frac{1}{2} \frac{M_A M_B}{(M_A + M_B)} V_{CL}^2 = \frac{1}{2} M_A BEV^2 \quad (1)$$

The constant BEV formula is derived by first solving the damage energy equation for the necessary weight of the impactor, M_B , for the predefined choice of M_A and the specified constant line of BEV drawn on the chart as a function of V_{CL} .

$$M_B(V_{CL}) = \frac{M_A BEV^2}{(V_{CL}^2 - BEV^2)}$$

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Having found the weight of the impactor, M_B , required to produce the damage to vehicle “A” as specified by the *BEV* parameter, the next step is to define the compression *deltaV* appropriate to the closing speed through application of the momentum equation and the relationship between compression *deltaV* (ΔV_o) and closing speed (V_{CL}).

$$\Delta V_o = V_{CL} \frac{M_B}{M_A + M_B} \quad (3)$$

The tables of ΔV_o as a function of V_{CL} for lines of constant *BEV* are displayed in Figure 2 for damage corresponding to *BEV* = 10, 15, 20, 25, and 30 mph.

Lines of constant impactor mass, M_B , are also drawn on Figure 2 for masses corresponding to M_B = 200, 500, 1000, 2000, 4000, 10000, and 20000 lb. Given a specified M_A for the entire chart and a choice for the constant M_B line, ΔV_o as a function of V_{CL} is defined by the momentum equation for the selected constant value of M_B .

$$\Delta V_o = \frac{V_{CL}}{\left(1 + \frac{M_A}{M_B(\text{cons.})}\right)} \quad (4)$$

BEV AND DELTAV COMPARISONS – Consider theoretical crashes as marked on Figure 2 at positions A1, B1, and C1. These three crash events are on a line of constant *BEV*, meaning that in theory they should all have the same damage if they are the same crash configuration. Crash A1 is a fixed barrier crash at 15 mph with a compression *deltaV* also 15 mph. Crash B1 takes place at a closing speed of 30 mph with an impactor mass of 1333 lb resulting in a *deltaV* during compression of 7.5 mph. Crash C1 takes place at a much higher closing speed of 60 mph but only experiences a compression *deltaV* of 3.75 mph. This is because the impactor mass has dropped to 267 lbs. Even though the *deltaV* of crash C1 is much lower than that of crashes A1 and B1, the theoretical damage should be very similar.

Consider theoretical crashes A2 and B2. These take place at a much higher level of damage, 30 mph *BEV*, yet the *deltaV* is 30 mph for A2 and 15 mph for B2. This is the case because of the differences in mass of the collision partner impactor (fixed barrier for A2 and 1333 lbs for B2).

Crashes B1 and A2 have the same closing speed of 30 mph yet have *BEVs* of 15 and 30 mph with compression *deltaVs* of 7.5 mph and 30 mph.

Crashes C1 and B2 have the same 60 mph closing speed with *BEVs* of 15 and 30 mph yet have compression *deltaVs* of 3.75 and 15 mph.

Crashes A1 and A2 involve an infinite mass impactor (fixed barrier); crashes B1 and B2 involve the 1333 lb impactor; crashes C1 and C2 involve the 267 lb impactor. Crash C2 is off the chart. If it were to be conducted at the same impactor mass as crash C1, damage corresponding to a 30 mph *BEV* would require 120 mph closing speed and would result in a compression *deltaV* of 7.5 mph.

Lastly, crash D1 is a fixed barrier crash at the low closing speed and compression *deltaV* of only 3.75 mph, the *deltaV* of crash C1. Damage in those two tests would be expected to be much different since the *BEV* for crash D1 is 3.75 mph and crash C1 is 15 mph *BEV*.

CONSTANT DAMAGE (BEV) CRASH TEST METHODOLOGY

TEST VEHICLES – Three Nissan Sentras were used as target vehicles in this research program. Prior to the start of the testing each target vehicle was identified with an “A”, “B”, and “C” designation. Test vehicles “A” and “C” were 1995 models and vehicle “B” was a 1996 model year. Model years 1995 through 1999 have the same structure. Each was impacted in the front, then in the rear, and lastly in the passenger side.

Sentra “A” (white) was always impacted at the lowest speed, Sentra “B” (green) at the middle speed, and Sentra “C” Maroon) at the highest speed. The weight of each test vehicle was adjusted to approximately 2400 pounds.



Figure 2. Test Nissan Sentra Vehicles.

IMPACTORS – Three identically shaped impactors were constructed with high, medium and low weight (Figure 3). Each impactor was constructed with a one-foot wide, rectangular, steel, narrow-object impact face.



Figure 3. Impactors for Test Series “A”, “B”, “C”, in Order Left to Right.

SERIES “A” IMPACTOR – In order to achieve a high weight many times larger than the test vehicle the high weight impactor (Figure 4) was mounted to the front of an MMB (massive moving barrier) and weighed 43800 pounds after assembly. This high weight ratio of impactor to target vehicle, 18:1, allowed the MMB (Figure 5) to be driven into the stationary target vehicle (approaching the fixed rigid-barrier test condition). A more detailed account of the use of an MMB in crash testing has been described previously [Woolley 2000].



Figure 4. Impactor Used in Test Series “A”, Prior to Mounting on the Massive Moving Barrier.



Figure 5. Massive Moving Barrier Used in Test Series “A” and as a Tow Vehicle in Test Series “B” and “C”.

SERIES “B” AND “C” IMPACTORS - The impactors for test series “B” and “C” were designed as dollies (Figure 6). The front of each impactor was suspended from a tow boom off the side of the MMB and towed into collision with the stationary Sentra target vehicles.

Both impactors were constructed with a rear axle and two rear wheels to provide stability and tracking during the tow (Figure 7). The “B” series impactor weighed 1605 pounds after addition of concrete. Weight was added as low to the ground as practical and along the length of the impactor (to keep the center of mass below the anticipated resultant force in the crash to minimize pitch motion upon impact). The overall length and track width of the impactor dollies helped minimize yaw motion during towing.



Figure 6. Impactors Used in Test Series “B” and “C”.



Figure 7. Side View of the Light Weight “C” Series Impactor (Foreground) and the Middle Weight “B” Series Impactor.

The lightest weight impactor, Impactor “C” (381 pounds), was the most problematic to tow because of the small amount of weight carried by the rear wheels and the high speed at which it was towed.



Figure 8. Towing Impactor into Stationary Target.

The MMB was driven past the stationary target vehicle following a white line placed on the roadway to establish proper alignment (Figure 8). Impactors were towed by a cantilever beam on the MMB.

Series “B” and series “C” impactors were released by the MMB driver just prior to impact. The release mechanism was hydraulically actuated (Figure 9). The weight of the front of the impactor trailer was carried by a pin on the boom. A target release point was established such that a complete stroke of the hydraulic ram was obtained prior to impact. A wood pencil was inserted in the pin to act as a secondary, frangible, retainer. The speed trap was located such that the speed of the MMB towing vehicle was measured just inches prior to impact.



Figure 9. Release Mechanism.

INSTRUMENTATION – A pair of uniaxial accelerometers were mounted to the “B” pillars of each of the three Nissan Sentra test vehicles (Figure 10). These instruments measured longitudinal or X-axis acceleration in the front and rear impacts. The “B” pillar accelerometers were repositioned and mounted laterally prior to the side impact tests to measure Y-axis acceleration.



Figure 10. X-axis Accelerometers Mounted on “B” Pillars (left shown) for Frontal and Rear Tests; Y-axis Accelerometer Mounted on Left “B” Pillar for Side Tests.



Figure 11. Data Collection Module, “Data Brick”.

Data sets from these instruments were stored in an on-board data acquisition system (Figure 11). Following each crash, the damage profiles were measured using a total station surveying instrument.

TEST PROCEDURE – Several runs were made by the MMB towing and impact vehicle prior to each test to set the speed and alignment of the run. A speed trap was utilized to document the speed of the MMB just prior to impact. MMB engine rpm is governed. Design test speeds were selected to correspond to governed speeds in a defined gear. The driver of the MMB followed a white line placed on the roadway, adjusted speed, and released the impactor at the appropriate position.

Test vehicles were placed in drive gear with the parking brake set.

TEST RESULTS

The nine crash tests in this research program are summarized in Tables 1 and 2. Test Nissan Sentras all weighed close to 2400 pounds (Table 1). The three impactors had a large weight difference; heavy for test “A”, medium for test “B”, and light for test “C” (Table 1).

Table 1. Vehicle and Impactor Test Weights

Vehicle	Test Weight
(A) MMB (Massive Moving Barrier)	43800 Lb (heavy)
(A) Nissan Sentra (white)	2380 Lb
(B) Impactor	1605 Lb (medium)
(B) Nissan Sentra (green)	2400 Lb
(C) Impactor	381 Lb (light)
(C) Nissan Sentra (Maroon)	2400 Lb

Table 2. Test Speed, ΔV , and BEV.

	Closing Speed	Compression ΔV & System V_{MC}	BEV
Frontal A	20.81 mph	19.73 mph	20.27 mph
Frontal B	32.21 mph	12.91 mph	20.39 mph
Frontal C	53.60 mph	7.34 mph	19.84 mph
Rear A	19.76 mph	18.74 mph	19.24 mph
Rear B	32.05 mph	12.84 mph	20.29 mph
Rear C	54.03 mph	7.40 mph	20.00 mph
Side A	19.82 mph	18.80 mph	19.30 mph
Side B	31.90 mph	12.78 mph	20.20 mph
Side C(plan)	52.75 mph	7.23 mph	19.53 mph
Side C (Estimated)	34.03 mph	4.66 mph	12.60 mph

The speed of the MMB (whether used as impactor, as in test “A”, or as the tow vehicle, as in tests “B” and “C”) was targeted at the closing speed that would produce a 20 mph BEV on the test vehicle, Table 2. ΔV is calculated in Table 2 as the compression ΔV , the ΔV prior to rebound (or calculated with $\epsilon = 0$).

This release mechanism functioned as planned in five of the six tests where impactors were towed into contact. On side impact test “C” the ring came off the pin between release and impact, allowing the impactor to contact the pavement before the collision with the target vehicle. Nevertheless, the impact took place only 3 inches forward of the intended target, but at a greatly reduced impact speed. An estimate of the closing speed in side test “C” was therefore made from the acceleration data for that test (Table 2).

FRONTAL CRASH TESTS AT 20 MPH BEV

The position of the three frontal tests (A, B, C) on the test chart is depicted in Figure 12. Test conditions were previously provided in Table 2.

The targeted closing speed for the three frontal tests was selected to produce damage representative of a 20 mph BEV in all three frontal tests over a wide range of closing speeds and ΔV s. Closing speeds span the range from near fixed barrier to 55 mph, Figure 12.

Frontal Tests: BEV & ΔV Chart (2380 lb Test Vehicle)

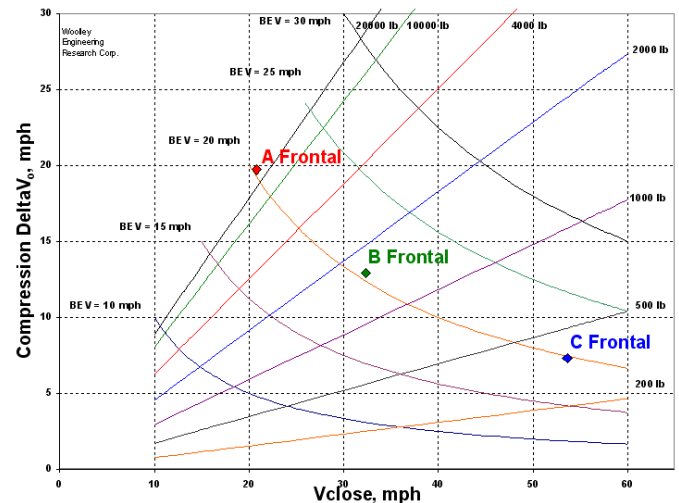


Figure 12. Frontal Crash Test Series Chart.

FRONTAL TEST “A” – Test vehicle “A” was aligned with the MMB such that the heavy weight impactor targeted the centerline of vehicle “A” (Figure 13). The large weight ratio between the impactor, when mounted on the front of the MMB, and the test vehicle resulted in a test condition that approached the fixed barrier test condition. However, test conditions are opposite that of the fixed barrier test in that the test vehicle is stationary and the heavy mass is moving. The ΔV of the MMB in this collision was calculated as 1.1 mph.

Post impact damage in frontal test “A” is shown in Figures 14 and 15.



Figure 13. Frontal Test A, Pre-impact.