Evaluation of Small-Sign Systems from Existing Crash Test Data

L. Dwayne Breaux and James R. Morgan

Small signs and small-sign support systems account for a substantial investment by federal, state, and local agencies. For the past 20 or more years these systems have been tested for crashworthiness. Many small-sign systems had been tested and approved on the basis of previous specifications. For the most part, these tests were conducted with different vehicles and sometimes at different impact speeds than those required by current specifications. Retesting of current systems will undoubtedly be required as new specifications are released. A rationale that can be used to predict impact performance for sign installations that have been tested previously with a different size and class of vehicles is presented. In spite of the variability in test parameters, it appears that an energy formulation will provide estimates, not only for the current standard, but also for any future vehicle weights or impact speeds. Most sign systems, breakaway or not, appear to follow a linear relationship between kinetic energy and impact velocity. Recent tests, for the most part, support this theory. The one notable exception to the linear fit is the triangular slip base. This system, because of its unique failure mechanism, is more appropriately modeled by a cubic equation of best fit. The estimated changes in velocity could be useful for recertification of existing sign systems as well as for extrapolation between single- and multiple-post systems. If additional tests are required, the estimated changes in velocity will indicate which tests are critical, thereby allowing for the possibility of fewer certification tests.

Unfortunately, the need for retesting will resume at the end of the current grace period.

The primary focus of the specifications has been the changes in velocity during impact and the integrity of the occupant compartment. The current standard addresses these areas as follows. First, the change in velocity of an unrestrained occupant should not exceed 15 ft/sec (extended to 16 ft/sec by 23 CFR 625) during the impact. Second, there can be no penetration of the occupant compartment. The report includes other test specifications, but for a given sign system, it is generally these two criteria that determine the acceptability of a sign installation for crash performance.

The most significant difference between the 1,800-lb and 2,250-lb cars has been the change in velocities. Vehicle stability and occupant compartment integrity are also major considerations, but these are usually linked to the change in velocity. Unfortunately, there has been no acceptable method for comparing or predicting the crash performance of the 1,800-lb car versus the 2,250-lb car. To complicate the problem, many of the previous tests included cars of weights other than 2,250 lb, various impact speeds, different crush characteristics, and test matrices with multiple posts as well as single-post sign systems.

A rationale that can be used to predict impact performance for sign installations that have been tested previously with a different size and class of vehicles is presented. In spite of the variability in test parameters, it appears that an energy formulation will provide estimates, not only for the current standard, but also for any future vehicle weights or impact speeds. The estimated changes in velocity will be useful for recertification of existing sign systems as well as for extrapolation between single- and multiple-post systems. If additional tests are required, the estimated changes in velocity will indicate which tests are critical, thereby allowing for the possibility of fewer certification tests.

DATA COLLECTION

This study began with a compilation of recent crash test data to try to validate some of the small-sign supports currently used by the Texas State Department of Highways and Public Transportation. It soon became obvious that the data that could be classified as recent were limited in quantity. Therefore, the data search was expanded to include all previous crash tests for which the sign installation was well defined and the vehicle weight, impact speed, and change in velocity were accurately known. The data collected are given in Table 1 (5–12) by sign classification.
TABLE 1  CRASH DATA

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Each crash test supplied the following three data points:
1. $M_1$, the vehicle mass;
2. $V_i$, the impact velocity; and
3. $\Delta V_i$, the change in velocity.

The direct comparison of the changes in velocity for a particular sign installation type showed no apparent trend. The only general tendency was a decrease in the change in velocity for a corresponding increase in impact velocity. These data confirmed the observation that the actual failure mechanism varied for different impact speeds. At this point two different methods, the conservation of energy and the principle of impulse and momentum, were incorporated to further reduce the data to find a relationship that overrides the physical differences.

**DATA REDUCTION**

In review, the mass (weight) of the vehicle, impact speed, and change in velocity ($\Delta V$) during impact were all known for specific tests. However, the challenge was to predict the change in velocity for a vehicle of any mass, $M_1$, striking at any velocity, $V_i$, in a future impact.

The first approach was to use the principle of impulse and momentum, which can be expressed as

$$(M_1)V_i + (M_2)V_2 - \int F \, dt = (M_2)V_2 + (M_3)V_3$$

where
- $M_1$ = mass of automobile,
- $M_2$ = mass of sign system,
- $V_2$ = initial velocity ($V_i$),
- $V_3$ = final velocity ($V_3$), and
- $\int F \, dt = \text{impulse or impact force}.$

Assuming that $M_2$ is negligible compared with $M_1$ gives the following:

$$(M_1)V_i = \int F \, dt = (M_2)V_2$$

or

$$\int F \, dt = (M_{\text{CAR}}) \cdot (\Delta V) = \text{change in momentum} \quad (1)$$

This is the formulation used to calculate change in momentum from the $\Delta V$ supplied from the crash tests.

Then, for a known change in momentum with a new car mass or a new impact velocity, or both, the equation can be written:

$$(M_1^*)(V_1^*) = \int F \, dt = (M_1^*)V_1^*$$

or

$$V_1^* = \frac{1}{M_1^*}(M_1^*)V_1^* = \int F \, dt$$

(2)

This is the formulation that is used to predict final velocity and change in velocity for a sign system with a known change in momentum.

The next approach was to enforce conservation of energy. The total energy is expressed as the sum of the kinetic energy...
(T) and the potential energy (V). Energy is conserved when the change in the total energy of a system, represented by the prefix $\Delta$, is equal to zero. This can be stated as $\Delta T + \Delta V_g + \Delta V_e = 0$. Note that the change in potential energy is subdivided into gravitational and elastic potential, designated by the subscripts $g$ and $e$, respectively.

Again, assuming that the mass of the sign system is negligible compared with the automobile's mass greatly simplifies the energy expression. The only term contributing an appreciable amount is the change in kinetic energy of the car. This term is written

$$\Delta T = 1/2 \left( M_{\text{Car}} \right) \left[ V_f^2 - V_i^2 \right] = \Delta KE$$

This equation is used to calculate the change in kinetic energy ($\Delta KE$) from the crash test data.

Then, for a known change in kinetic energy with a new car mass or a new impact velocity, the equation can be written

$$V_f = \sqrt{V_i^2 + 2(\Delta KE)/M_{\text{Car}}}$$

Therefore, if the change in kinetic energy is known for a particular sign system, the car's final velocity and its change in velocity can be predicted.

As noted in the footnote to Table 1, many of the tests involved multiple-post installations. Once the change in momentum or kinetic energy was calculated, the values were divided by the corresponding number of posts to obtain an extrapolated value for a single-post installation.

### MOMENTUM VERSUS KINETIC ENERGY

Basic engineering mechanics provides two equations that can be used to predict the vehicle's final velocity. The questions remain as to what values for the change in either momentum or kinetic energy to use and whether either equation is appropriate.

Noting the previous trend (that the $\Delta V$ seemed to vary with impact velocity), the changes in both momentum and kinetic energy were plotted versus velocity. To find a general trend for all breakaway systems, all the data points were combined as indicated in Figures 1 and 2. The plot using momentum showed too much scatter to detect any general trend. On the other hand, the plot using kinetic energy did indicate a generally increasing trend. To qualify this trend a least-squares fit for a line was done. The corresponding equation and line are indicated in Figure 2.

The comparison between the two approaches was then narrowed to a single class of small-sign support system, the 3-lb/ft U-post that uses breakaway mechanisms. Again a least-squares fit was done (see Figure 3). The data suggest that a linear fit is reasonable, but momentum was plotted in Figure 4 as a check. After these two comparisons, it was decided that the best approach would be to use kinetic energy to predict the change in velocity. Although this model neglects many variables (vehicle crush, etc.), when limited to systems with similar strength and breakaway characteristics it shows good correlation with experimental data.

The 3-lb/ft nonbreakaway U-posts (Figure 5) and the sets of 4-lb/ft U-posts (Figures 6 and 7) exhibit similar linear behavior. It was noted that the line for the nonbreakaway systems was generally steeper than for the breakaway systems. The greater slope corresponded to the greater stiffness of the nonbreakaway systems.

During the data search, many data points were found for 8-lb/ft U-post systems. The data were plotted in Figure 8 because of the number of data points and the variety of impact speeds even though this system is no longer used. Figure 8 clearly illustrates the linear relationship between impact velocity and change in kinetic energy. Two additional graphs are included with linear relationships. The 2½-in. pipe with frangible connectors, Figure 9, and the 2-in. x 2-in. square perforated steel tube, Figure 10, exhibit good approximations to linear relationships.

One other system, a 3-in. pipe on a triangular slip base, is shown in Figure 11. This is certainly a breakaway system, but

![Impulse vs. velocity](image-url)
it differs from all the others considered in its failure mechanism. This system uses friction to facilitate breakaway. Such a difference could mean that the relationship between velocity and change in kinetic energy is not linear but perhaps cubic, as indicated in Figure 12. Considering the limited number of data points available, it would be inappropriate to use any "recommended" best-fit curve for this system.

The diamond data points were not used in obtaining the best-fit curves shown in Figures 6, 7, 9, 11, and 12.

PREDICTING CHANGE IN VELOCITY

Although many factors (such as vehicle crush, post impact stability, size of sign, mounting height, variability in material properties, etc.) influence the behavior of breakaway sign-support systems, the significant feature is the change in kinetic energy of the vehicle. It is a great simplification to ignore all other effects, and these analyses indicate good agreement with experimental data.

The least-squares fit of the data (square data points only) shown on each of the graphs now provides a value for the change in kinetic energy for any impact velocity. One would expect the curves to tend toward zero, as is the case for all curves presented. However, these curves are valid only for systems (and impact speeds) for which a breakaway will occur. Obviously, as the impact speed decreases, at some point there will not be enough energy for a breakaway to occur. This information, taken from previous crash tests, can then be used to estimate the final velocity of a car of any mass and any
impact velocity from Equation 4. The difference between the final and initial velocities is the change in velocity of the vehicle during impact provided that a breakaway of the sign support does indeed occur.

This approach can be extended from a single post to multiple posts by assuming linear interpolation. That is, the $\Delta KE$ taken from the graph is simply multiplied by the number of posts. The product is then substituted into Equation 4 for $\Delta KE$.

**ACCURACY OF PREDICTIONS**

This research predated the FHWA’s design standards (23 CFR 625), so as part of a Texas project, additional crash tests (12) were required to certify several small-sign supports. This project also provided an excellent opportunity to check the validity of the assumptions on change in kinetic energy (none of these new tests were included in the curve fits). First a 40-ft^2 sign supported by three 4-lb/ft rail steel U-posts (Tests 3 and 4) was tested at 20 and 60 mph. Table 2 compares the actual changes in velocity with the values predicted using the principles presented herein. The values for $\Delta KE$ were calculated directly from the least-squares equation in Figure 7 for 4-lb nonbreakaway posts. This system was classified as nonbreakaway because large soil deformations prevented actuation of the bolted splice. Also, values for the single post in the “actual” column were extrapolated using linear interpolation.

The model was not able to predict a specific value for the change in velocity for three posts at an impact speed of 20
mph. This problem occurred because the calculated change in velocity was greater than the initial velocity. Therefore, our calculations agreed well with the first set of tests.

The next set of tests involved two 4-lb/ft U-posts with ground splices (Tests 6 and 7). The changes in kinetic energy were calculated from the line fit in Figure 6 and the changes in velocity listed in Table 2. Again there is good correlation (less than 10 percent difference) between the predictions and the actual values.

Tests 8 and 9 involved single 2½-in. standard steel pipe in a threaded coupler. Figure 9 provided the equation to predict the changes in kinetic energy. The comparison indicates that the calculated values do not agree very well with the actual values (see also Table 2). However, an upper bound estimate can be calculated from the scatter in the data. The largest vertical error between the crash test data and the "best-fit" line was used to construct a parallel offset line that provides a much better estimate.

The final set of tests, 10 and 11, involved a 3-in. pipe tree mounted on a triangular slip base. The changes in velocity were calculated using the linear and the cubic fits from Figures 11 and 12, respectively. As originally thought, the linear fit
did not come close to predicting the car's performance even with an offset. However, the data supported the third-order fit much more closely. The low-speed prediction came within about 3 percent of the actual change in velocity. The high-speed prediction with only one previous data point estimated the change in velocity to within 19 percent.

CONCLUSIONS

The technique presented provides a method for predicting vehicle performance from existing crash data. It appears that the change in kinetic energy during impact, for specific sign systems, follows a consistent trend compared with the impact velocity regardless of vehicle size, sign mounting height, size of sign, and so forth.

The relationship between kinetic energy and impact velocity appears to be linear for most sign systems, breakaway or not. The 8-lb/ft U-post data demonstrate this trend for a wide range of intermediate impact speeds. This trend also is supported by recent tests (72). When there are few data or large scatter in the data, the method may not provide reasonable predictions. In these cases, use of a parallel offset line should provide adequate estimates for determining the critical tests.
In one such case, the predicted changes in velocity were high, and in fact when the system was tested it proved to be marginal.

The one notable exception to the linear fit was the triangular slip base. This system, because of its unique failure mechanism, is more appropriately modeled by a cubic equation of best fit. Including the new test data would certainly improve the predictions; however, use of the current cubic equation is not recommended.

One key observation from the new tests is that breakaway systems that do not actuate should be included as nonbreakaway systems for analysis. Examples of this type of behavior may result from improper installation, excessive material strength, or large soil deformation. As data become available, this method of analysis could be extended to weak-soil applications and systems with characteristically large soil deformation. For now, it only applies to the existing crash test data base which, until recently, only included strong-soil tests.

More tests would increase confidence in the estimates provided using these energy calculations. However, a good deal of information already exists for many types of sign-support systems. The calculations of change in kinetic energy indicate that many systems have a large margin of safety (so that further testing should not be needed). For the systems that are borderline, or for extending the allowable number of posts,
Delta \text{K.E.} = -3.63 + 1192V - 51.1V^2 + 0.666V^3

![Graph showing change in kinetic energy versus velocity for 3-in. pipe on triangular slip base—cubic relationship.](image)

**FIGURE 12** Change in kinetic energy versus velocity for 3-in. pipe on triangular slip base—cubic relationship.

**TABLE 2** COMPARISON OF CHANGES IN VELOCITY

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<th>( \Delta V ) (ft/sec)</th>
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\(^a\)Three nonbreakaway 4-lb/ft posts.

\(^b\)Two breakaway 4-lb/ft posts.

\(^c\)Two and one-half in. pipe with threaded coupler, offset = 4,660 ft-lb.

\(^d\)With offset.

\(^e\)Three-in. pipe on triangular slip base.

\(^f\)Linear.

\(^g\)Cubic.

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REFERENCES


The contents of this paper reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. This paper does not necessarily reflect the official views or policies of the Texas Transportation Institute, the Texas State Department of Highways and Public Transportation, or the Federal Highway Administration.