Evaluation of Small-Sign Systems from Existing Crash Test Data

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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.

Small-sign systems include everything from Stop signs and delineator posts to signs up to about 25 ft^2. In some cases multiple small-sign support systems are used to support much larger signs (40 to 50 ft^2). Therefore, this broad class of sign is prevalent in every state, county, and municipality in the country.

To ensure the safety of vehicle occupants, specifications, guidelines, and recommendations have been written that define acceptable vehicle performance criteria (*1,2*). In 1981 *NCHRP Report 230* (*3*) became the standard for measuring crashworthiness. The NCHRP report with modifications from AASHTO (*4*) is the current standard; however, a new standard is unquestionably in the future.

Many small-sign systems had been tested and approved under the TRB specification using a 2,250-lb vehicle. However, AASHTO requires the use of an 1,800-lb vehicle tested at 20 and 60 mph. Thus, the more recent specification required additional testing for systems that had previously been tested and approved. Several recertification tests were done showing that most previously approved systems passed with the 1,800-lb cars. With these considerations, the Federal Highway Administration ruled (23 CFR 625) that it is not currently necessary to retest systems approved with 2,250-lb vehicles. 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.

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TABLE 1 CRASH DATA

Test Number	Vehicle Weight (lb)	Impact Velocity (mph)	Change Velocity (ft/s)	Change[1] Momentum (lb-sec)	Change Kin. Energy (ft-lb)
3 lb/ft U - Post Ground Splice (Rail Steel Post)					
3491-1	2250	22.7	2.7	190	6070
3491-2	2250	59.6	2.5	179	15420
3491-3	2250	17.2	5.2	368	8323
3491-4	2250	16.6	5.1	358	7807
3 lb/ft U - Post High Splice (100 ksi) -Single Post					
7024-7	1800	60.5	3.1	169	14740
7024-8	1800	19.9	6.0	339	8866
Three Posts					
7024-9	1800	59.3	10.6	197	16067
7024-10	1800	19.4	23.9	445	7348
3 lb/ft U - Post High Splice (80 ksi) Three Posts					
7024-16	1800	20.0	27.9	511	7983
7024-17	1800	62.0	18.9	353	28732
7024-18	1800	19.5	24.9	465	7496
7024-21	1800	61.5	22.9	412	32585
Two Posts					
7024-22	1800	20.0	9.4	267	6557
7024-23	1800	62.8	11.7	334	28768
3 lb/ft U - Post Ground Splice (Three High Carbon Billet Post)					
7024-26	1800	21.7	12.6	235	5998
7024-27	1800	61.6	9.1	169	14530
4 lb/ft U - Post High Splice (High Carbon Billet Post) -Two Posts					
7024-11	1800	20.2	12.5	327	7766
7024-12	1800	60.9	10.3	295	24753
-Single Post					
4 lb/ft U - Post Ground Splice (Three Rail Steel Post)					
7024-24	1800	20.6	28.0	522	8460
7024-25	1800	62.6	13.2	246	20962
8 lb/ft U - Post					
1817-4	3500	37	16.6	1810	30664
1817-25	3600	31.5	16.9	1890	71343
1817-29	3550	24	15.4	1700	46733
1817-31	3900	36	14.9	1810	82043
2466-1	4100	29.3	9.3	1180	45241
2466-2	4100	43.7	12.6	1610	93011
2466-3	4400	43.9	12.4	1700	98883
2466-4	4400	30.4	15.0	2050	76025
2466-5	3880	45.8	14.8	1780	106421
2466-6	3750	49.5	13.5	1570	103399
2466-7	3850	31.7	16.7	2000	76259
2466-8	3850	45.6	18.1	2170	125438
2466-9	3800	47.8	15.0	1770	110815
2 - 1/2 inch Pipe w/Frangible Connector					
3254-14	2250	20.3	11.4	802	19316
3254-15	2250	63.3	5.4	379	34167
3254-16	2250	19.2	9.1	638	15079
0941-3	2270	29.2	7.3	514	20139
2 x 2 inch Square Perforated Steel Tube -Single Post					
7024-3	1800	20.0	3.5	193	5328
7024-4	1800	56.8	8.5	468	37028
-Two Posts					
7024-5	1800	19.7	20.7	575	10699
7024-19	1800	18.9	14.7	413	8391
7024-20	1800	57.5	17.9	503	37860
-Three Posts					
7024-6	1800	59.3	26.3	486	35951
3 inch Pipe on Triangular Slip Base					
0941-1	2270	60.8	5.5	386	33364
0941-4	2270	45.4	3.0	209	13637
S-8	3970	46.0	1.1	136	9100
S-18	4170	31.3	1.3	168	7603

[1]NOTE: All values for Change in Momentum or Kinetic Energy are given for a single post and obtained by linear interpolation.

Each crash test supplied the following three data points:

1. M_1, the vehicle mass;
2. V_1, the impact velocity; and
3. ΔV_1, 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 (ΔV) 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_1^*, in a future impact.

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

$$(M_1)V_1 + (M_2)V_2 - \int F\,dt = (M_1)V_1' + (M_2)V_2'$$

where

M_1 = mass of automobile,
M_2 = mass of sign system,
$V_\#$ = initial velocity (V_i),
$V_\#'$ = final velocity (V_f), and
$\int F\,dt$ = impulse or impact force.

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

$$(M_1)(V_i) - \int F\,dt = (M_1)(V_f)$$

or

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

This is the formulation used to calculate change in momentum from the ΔV 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:

$$(M_1^*)(V_i^*) - \int F\,dt = (M_1^*)(V_f)$$

or

$$V_f = (1/M_1^*)[(M_1^*)V_i^* - \int F\,dt] \quad (2)$$

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 Δ, 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

$$\Delta T = 1/2\,(M_{\mathrm{CAR}})\,[V_f^2 - V_i^2] = \Delta KE \qquad (3)$$

This equation is used to calculate the change in kinetic energy (ΔKE) 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

$$V_f = [V_i^2 + 2(\Delta KE)/M_{\mathrm{CAR}}]^{1/2} \qquad (4)$$

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 ΔV 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. × 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

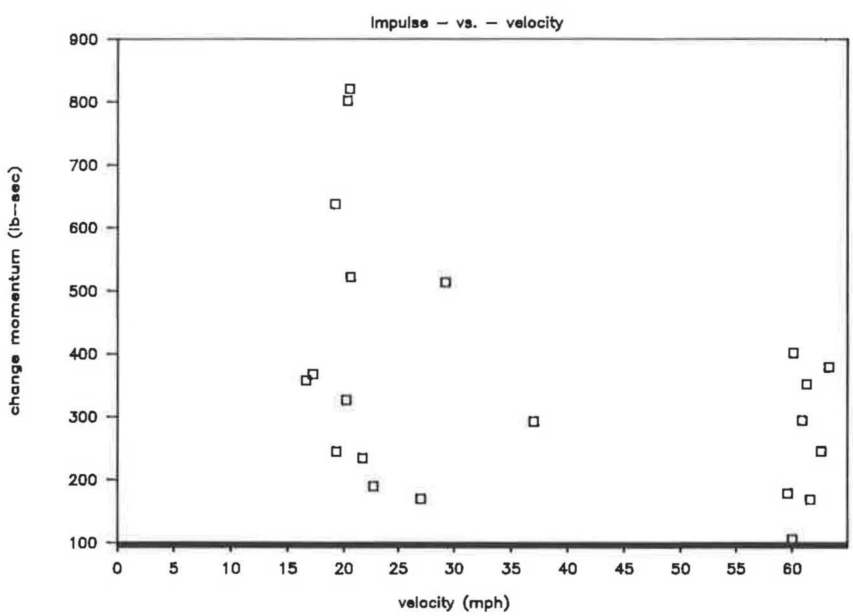

FIGURE 1 Breakaway connections—change in momentum versus velocity.

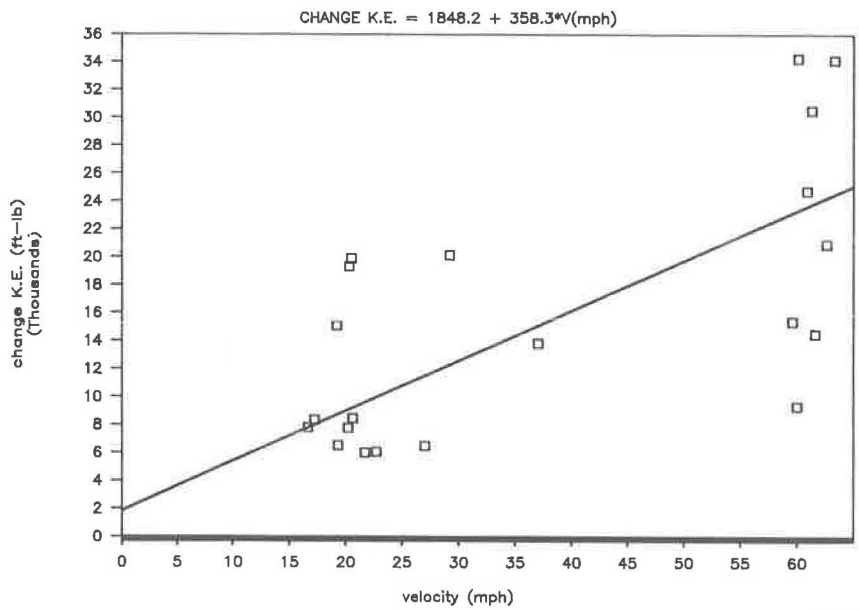

FIGURE 2 Breakaway connections—change in kinetic energy versus velocity.

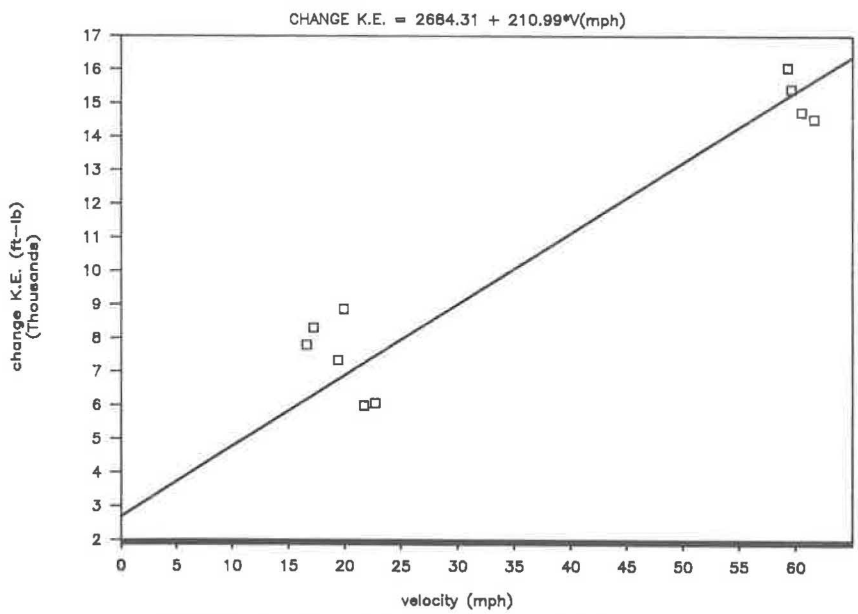

FIGURE 3 Breakaway steel U-post (3 lb/ft)—change in kinetic energy versus velocity.

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

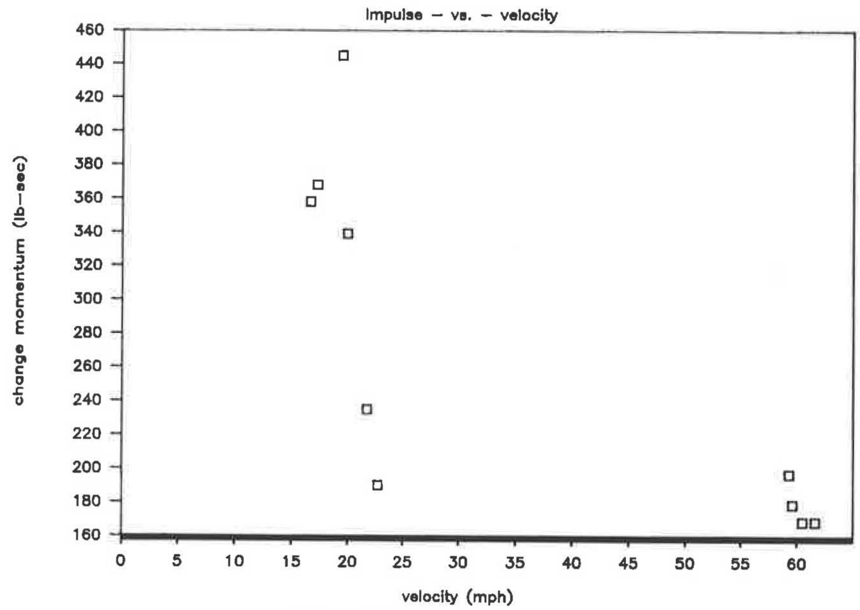

FIGURE 4 Breakaway steel U-post (3 lb/ft)—change in momentum versus velocity.

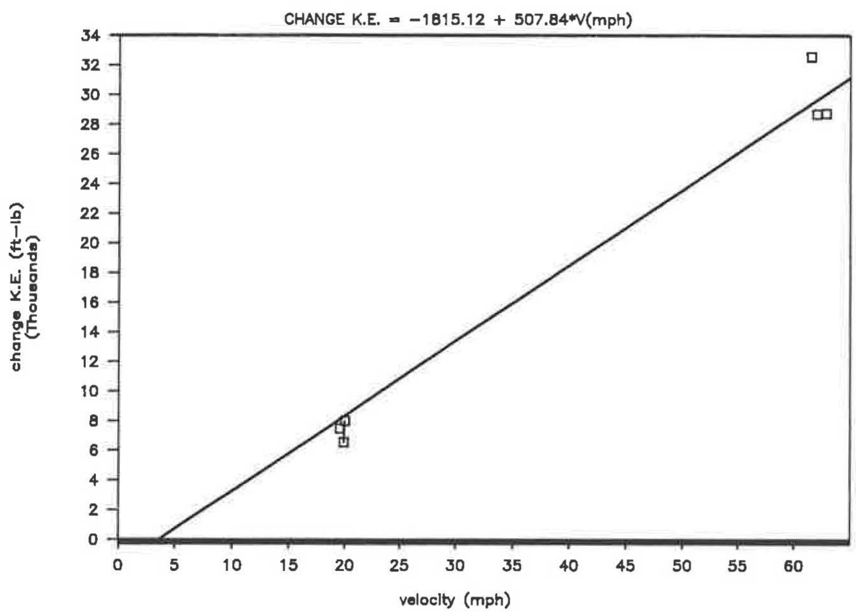

FIGURE 5 Nonbreakaway steel U-post (3 lb/ft)—change in kinetic energy versus velocity.

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 ΔKE taken from the graph is simply multiplied by the number of posts. The product is then substituted into Equation 4 for ΔKE.

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 ΔKE 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

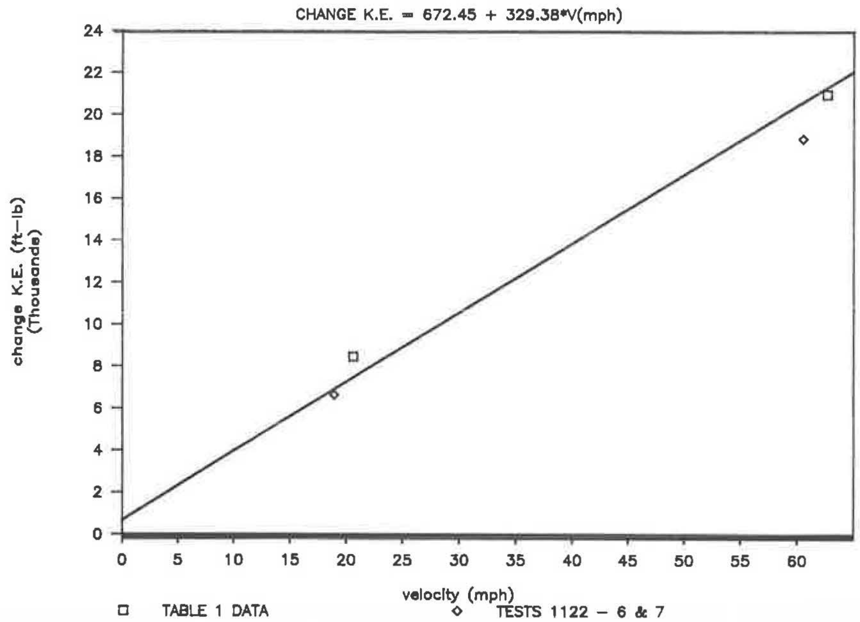

FIGURE 6 Breakaway steel U-post (4 lb/ft)—change in kinetic energy versus velocity.

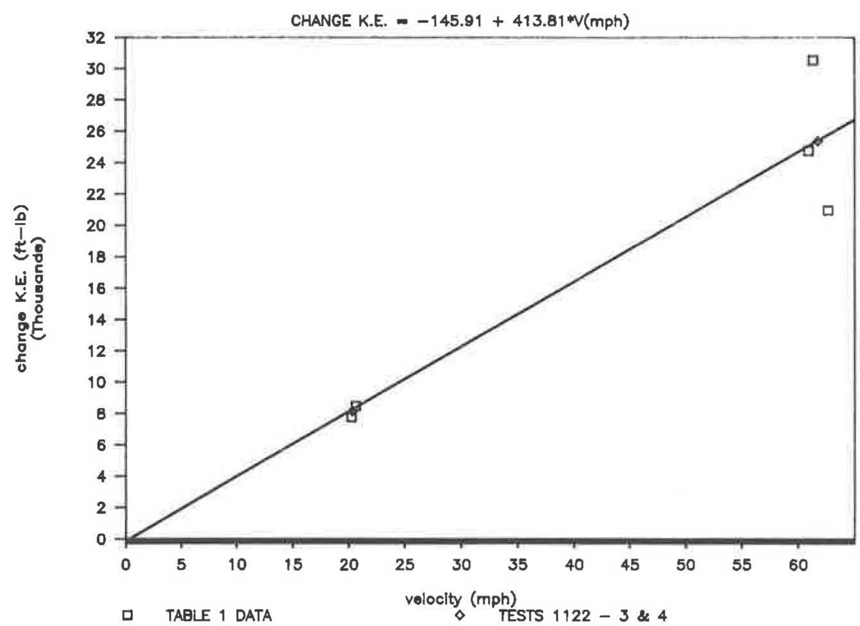

FIGURE 7 Nonbreakaway steel U-post (4 lb/ft)—change in kinetic energy versus velocity.

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

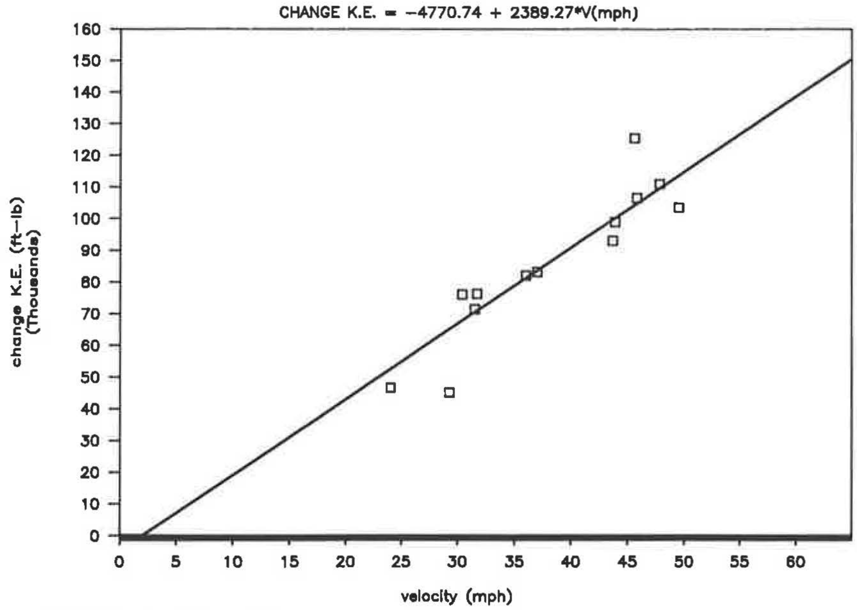

FIGURE 8 **Steel U-post (8 lb/ft)—change in kinetic energy versus velocity.**

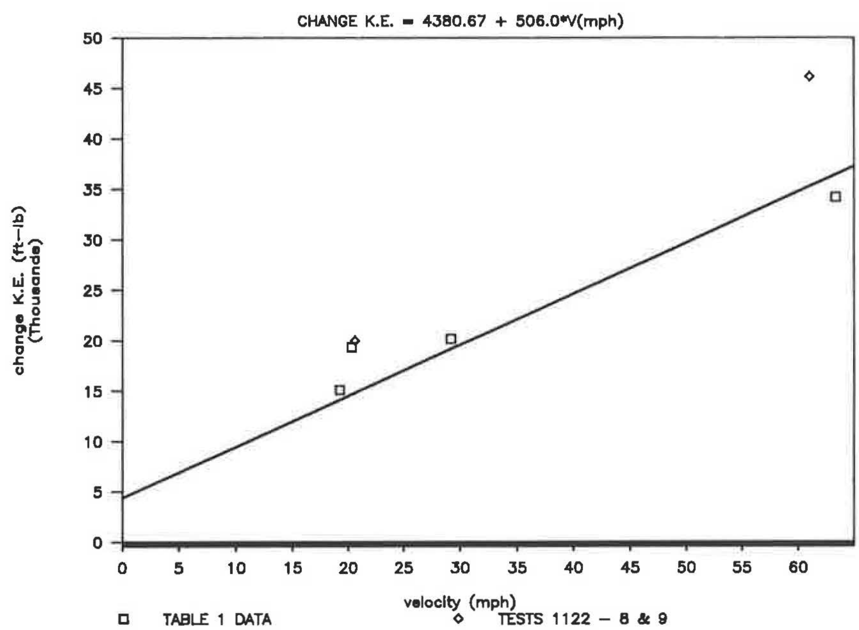

FIGURE 9 **Breakaway 2½-in. standard steel pipe—change in kinetic energy versus velocity.**

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 (*12*). 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.

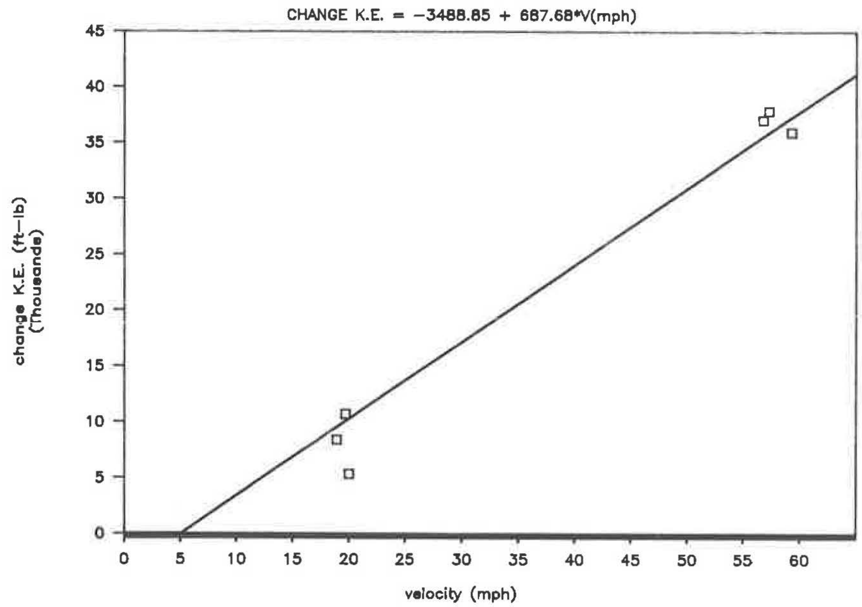

FIGURE 10 Unistrut post (2 in. × 2 in.)—change in kinetic energy versus velocity.

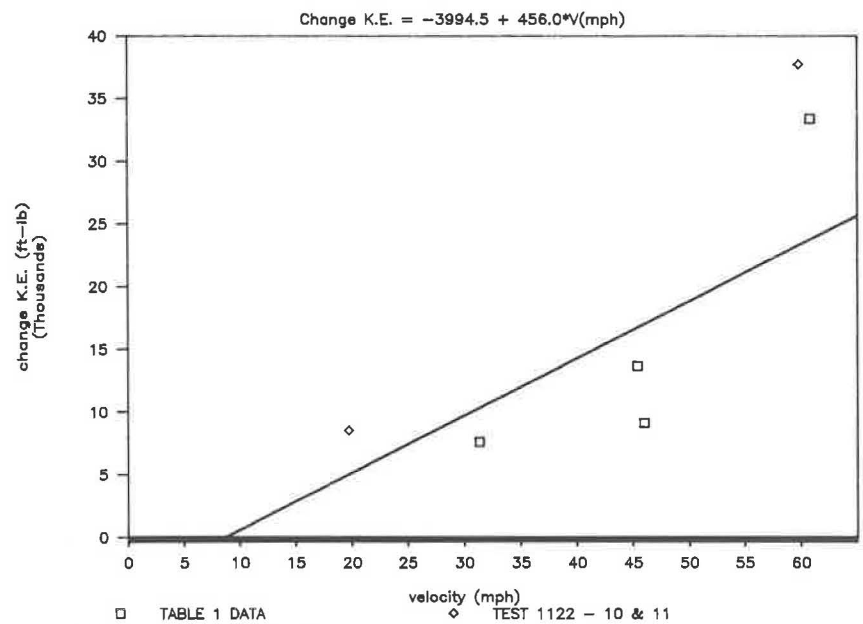

FIGURE 11 Change in kinetic energy versus velocity for 3-in. pipe on triangular slip base—linear relationship.

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,

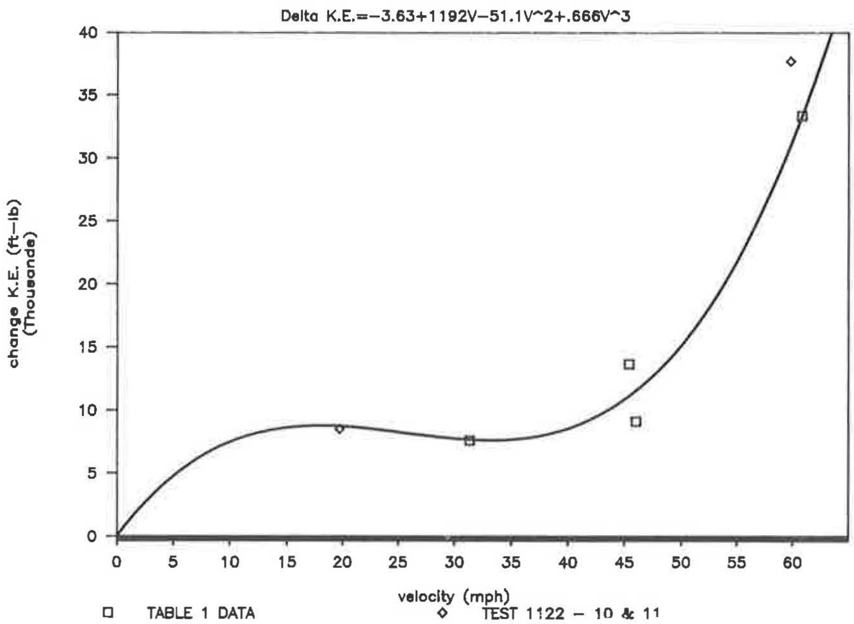

FIGURE 12 Change in kinetic energy versus velocity for 3-in. pipe on triangular slip base—cubic relationship.

TABLE 2 COMPARISON OF CHANGES IN VELOCITY

V_i (mph)	No. of Posts	ΔV (ft/sec) Actual	Estimated
Tests 3 and 4[a]			
20.27	3	33.25	>29.73
20.27	1	5.37	5.46
61.67	3	16.56	16.56
61.67	1	5.16	5.16
Tests 6 and 7[b]			
18.89	2	10.60	11.14
18.89	1	4.68	4.88
60.46	2	7.96	8.74
60.46	1	3.89	4.25
Tests 8 and 9[c]			
20.58	1	16.16	10.65
20.58	1	16.16	15.52[d]
61.03	1	9.75	7.63
61.03	1	9.75	8.37[d]
Tests 10 and 11[e]			
19.67	1	5.87	3.27[f]
19.67	1	5.87	6.06[g]
59.77	1	8.07	4.88[f]
59.77	1	8.07	6.55[g]

[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.

this method can at least identify the critical tests and possibly reduce the number of tests required.

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