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of Transportation

National Highway
Traffic Safety
Administration



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June 1987

# CRASH III Model Improvements: Vehicle Categorization for Stiffness Parameters, Volume I

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16. Abstract

The CRASH III computer model uses physical evidence, such as various vehicle parameters and vehicle damage measurements, to reconstruct highway accidents. When damage measurements are used in a reconstruction, the model assumes a set of stiffness parameters which represent the resistance to crush for a group of vehicles. The set of parameters assumed is dependent on both the type of impact (frontal, side, or rear) and the type of vehicle(s) in the reconstruction. In the current model, stiffness parameters for passenger cars are categorized by wheelbase.

This report is divided into two volumes. Reported in this volume, Volume I, are the results of an investigation which explored the possibility of another categorization method producing CRASH III results that are more reliable than those from the current method.

Correlations were done to determine if any of the standard vehicle parameters, such as curb weight, length, width, etc., relate to the damage a vehicle sustains in a collision. Stiffness parameters were derived based on a few different methods of categorizing vehicles. These were used in the CRASH III model and comparisons were made.

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Report Author(s)

Donald T. Willke and Michael W. Monk


The CRASH III computer model was developed for use in highway accident reconstruction. The model uses physical evidence such as various vehicle parameters, vehicle trajectory information, and vehicle damage measurements. The primary outputs of the model are the vector changes in velocity ($\Delta v$) of the vehicles resulting from the collision and impact speeds (only if trajectory information is available).

When damage measurements are used in a reconstruction, the model assumes a set of stiffness parameters which represent the resistance to crush for a group of vehicles. The set of parameters is dependent on both the impact mode (frontal, side, or rear) and the type of vehicle(s) in the reconstruction. In the current model, stiffness parameters for passenger cars are categorized according to wheelbase.

This report is divided into two volumes. Reported in this volume, Volume I, are the results of an investigation which explored the possibility of another categorization method producing CRASH III results that are more reliable than those from the current method.

Correlations were done to determine if any of the standard vehicle parameters relate to the damage a vehicle sustains in a collision. For each case, fifteen vehicle parameters were used including weight, wheelbase, length, width, height, track widths, engine displacement, drive configuration, and several combinations of the above. Vehicle damage was represented by an average crush measurement, a derived stiffness factor, and the stiffness factor per unit width, for each case.

Stiffness parameters were derived based on the current wheelbase categories, based on the vehicle parameter with the highest correlation, and by combining all vehicles into one group (ie. no categories). These parameters were then used in the CRASH III model to predict velocity changes.

The model's current formulation for crush resistance was also examined and recommendations were made for future efforts on updating the CRASH III model.

# CRASH III MODEL IMPROVEMENTS:
## Vehicle Categorization for Stiffness Parameters

### 1.0 INTRODUCTION

The CRASH III* computer program was developed for use in highway accident reconstruction. The model uses physical evidence such as various vehicle parameters, vehicle trajectory information, and vehicle damage measurements. In the absence of trajectory measurements, the reconstruction is based solely on vehicle damage measurements, and vice versa. In the absence of both trajectory and damage measurements, reconstruction is based on the Collision Damage Classification (CDC). The primary outputs of the model are the vector changes in velocity ($\Delta v$) of the vehicle(s) resulting from the collision and impacts speeds (only if trajectory information is available).

When damage measurements are used in a reconstruction, the model assumes a set of stiffness parameters which represent the resistance to crush for a group of vehicles. The set of parameters assumed is dependent on both the type of impact (frontal, side, or rear) and the type of vehicle(s) in the reconstruction. In the current model, stiffness parameters for passenger cars are based on wheelbase.

The issue was raised as to whether a different method for categorizing passenger cars would produce more reliable results. Also, if wheelbase is an appropriate measure, is it necessary to adjust the existing categories to reflect the current fleet size. This report summarizes the work done to address these issues and offers recommendations on re-categorization of vehicles for the determination of stiffness parameters.

* Calspan Reconstruction of Accident Speeds on the Highway, Version 3

## 2.0 OBJECTIVES

The purpose of this investigation was to examine the current method of categorizing passenger cars for the selection of stiffness parameters and to determine if another method would produce more reliable results from the CRASH III model.

## 3.0 BACKGROUND

As mentioned previously, the CRASH III computer program was developed for use in highway accident reconstruction. When damage measurements are used for reconstructions, as they were in this study, the model assumes the form of crush resistance shown in Figure 3.1. For this formulation, it is necessary to know the values of three stiffness parameters, A, B, and G, which are defined in the figure. There are a total of 33 sets of these parameters in the CRASH III model, one for each of the eleven stiffness categories in each of the three impact modes (front, side, and rear).

The current values for the six passenger car categories in each impact mode were derived in an earlier study (1). These categories represented the passenger cars and were divided by wheelbase as follows:

| Category | Classification | Wheelbase |
|---|---|---|
| 1 | minicar | 80.9 to 94.8" |
| 2 | subcompact | 94.8 to 101.6" |
| 3 | compact | 101.6 to 110.4" |
| 4 | intermediate | 110.4 to 117.5" |
| 5 | full size | 117.5 to 123.2" |
| 6 | large | 123.2 to 150.0" |

The derivation of the stiffness parameters A, B, and G for CRASH III was as follows: First, vehicles previously crash tested were divided by wheelbase as indicated above. The data from each test were then entered into the CRUSH algorithm. These data included vehicle

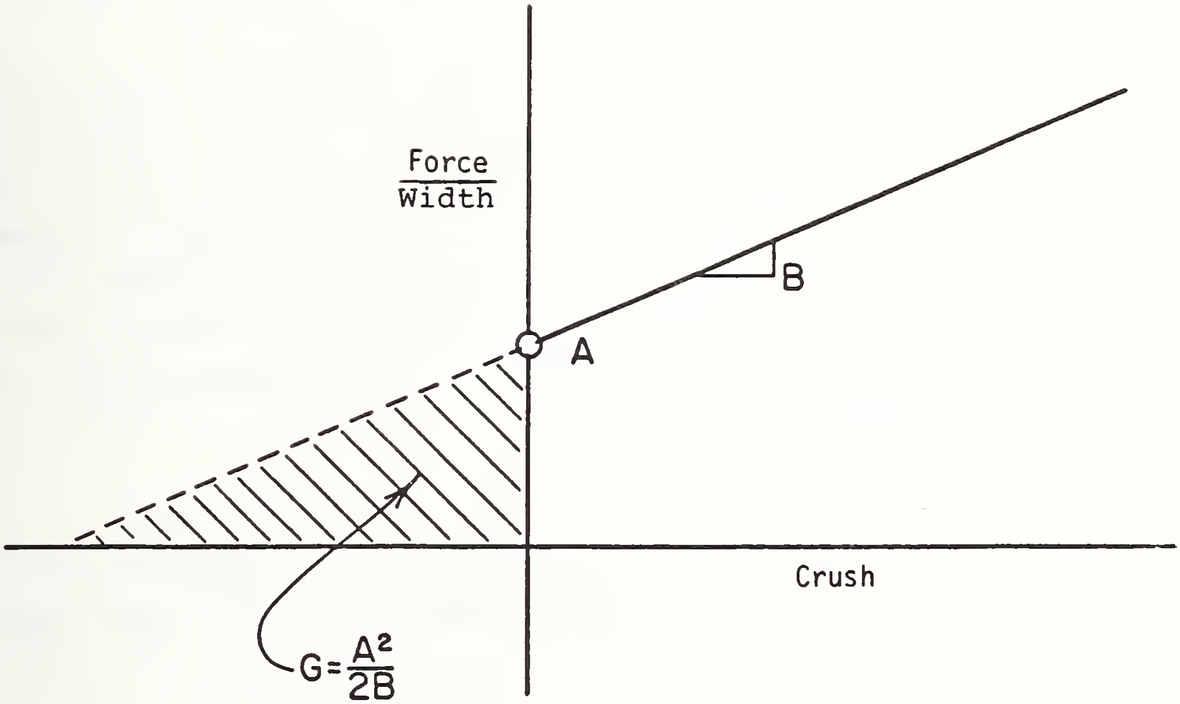



Figure 3.1. Current Formulation for Crush Resistance

weight, impact speed, principal direction of force, damage width (L), damage depths (C1 to C6), and damage offset (D). From this information, three parameters were calculated, E, $\alpha$, and $\beta$. E is the energy absorbed in the collision (in·lbs). $\alpha$ is the area of damage assuming a uniform vertical damage profile ($in^2$). $\beta$ is the first moment of this damage area about the line defining the original (undeformed) surface ($in^3$).

Once these CRUSH parameters were found for all the cars in a given category (for a particular impact mode), they were entered, as a group, into the NLIN routine from the Statistical Analysis System (SAS) package. Also entered was the damage width, or L, for each test. This routine then calculated the stiffness parameters A and B, and thus G, for this category. These were found such that the following equation was fit, to meet a given convergence criterion, for each individual test:

$$E = A\alpha + B\beta + GL$$

Due to the lack of lower speed test data, these values for A and B were adjusted such that a more realistic A value, or onset of permanent deformation, was achieved.

Figures 3.2 through 3.4 display the current model values for these parameters for the six passenger car categories in all three impact modes. Note that these parameters follow no trend based on vehicle size. In addition, Figures 3.5 and 3.6 show E vs. $\alpha$ and E vs. $\beta$, respectively, for the rear subcompact collisions used in Reference 1. These indicate that even within a specific wheelbase category, there is no correlation between the level of crush and the energy absorbed in a collision. The information from these five figures seems to imply that wheelbase is not a good indication of vehicle stiffness.

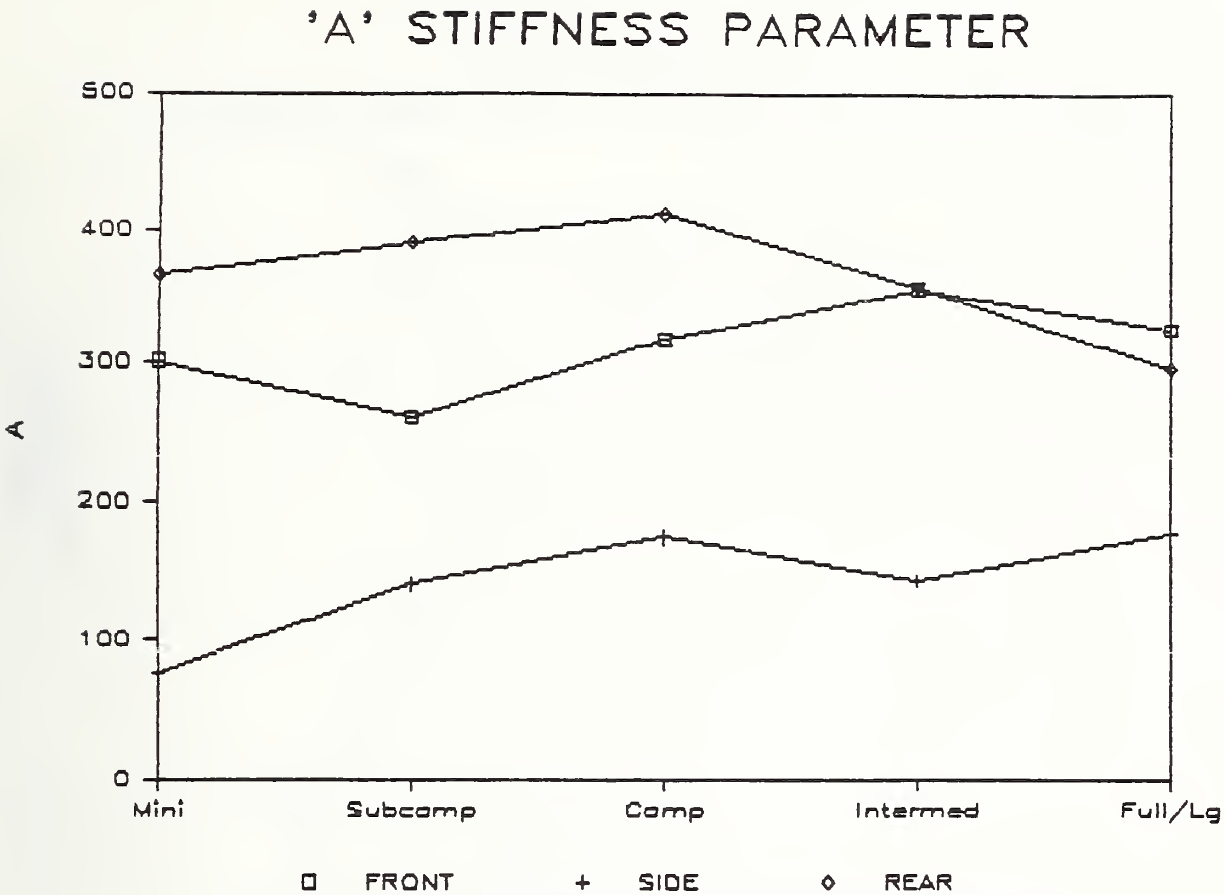



Figure 3.2. Current 'A' Stiffness Parameters

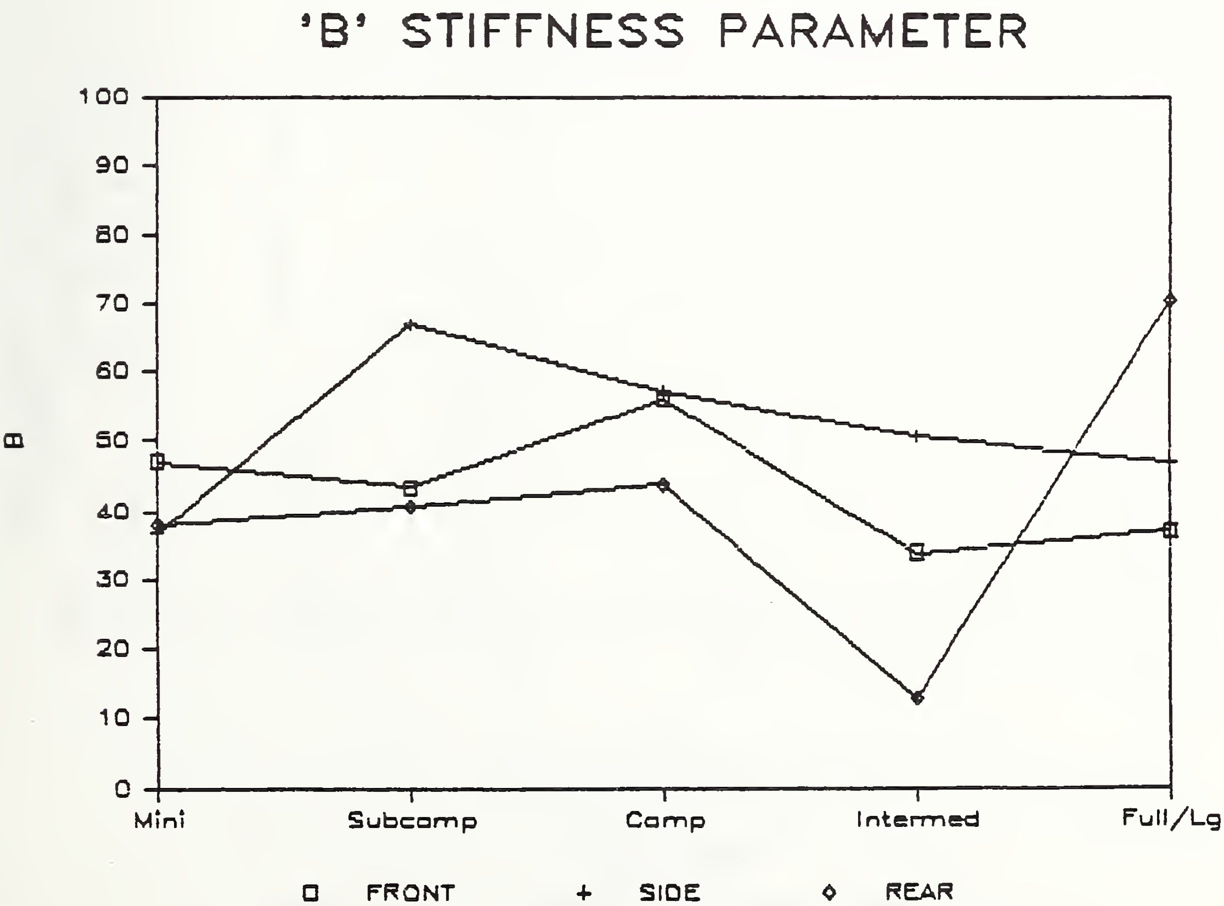



Figure 3.3. Current 'B' Stiffness Parameters

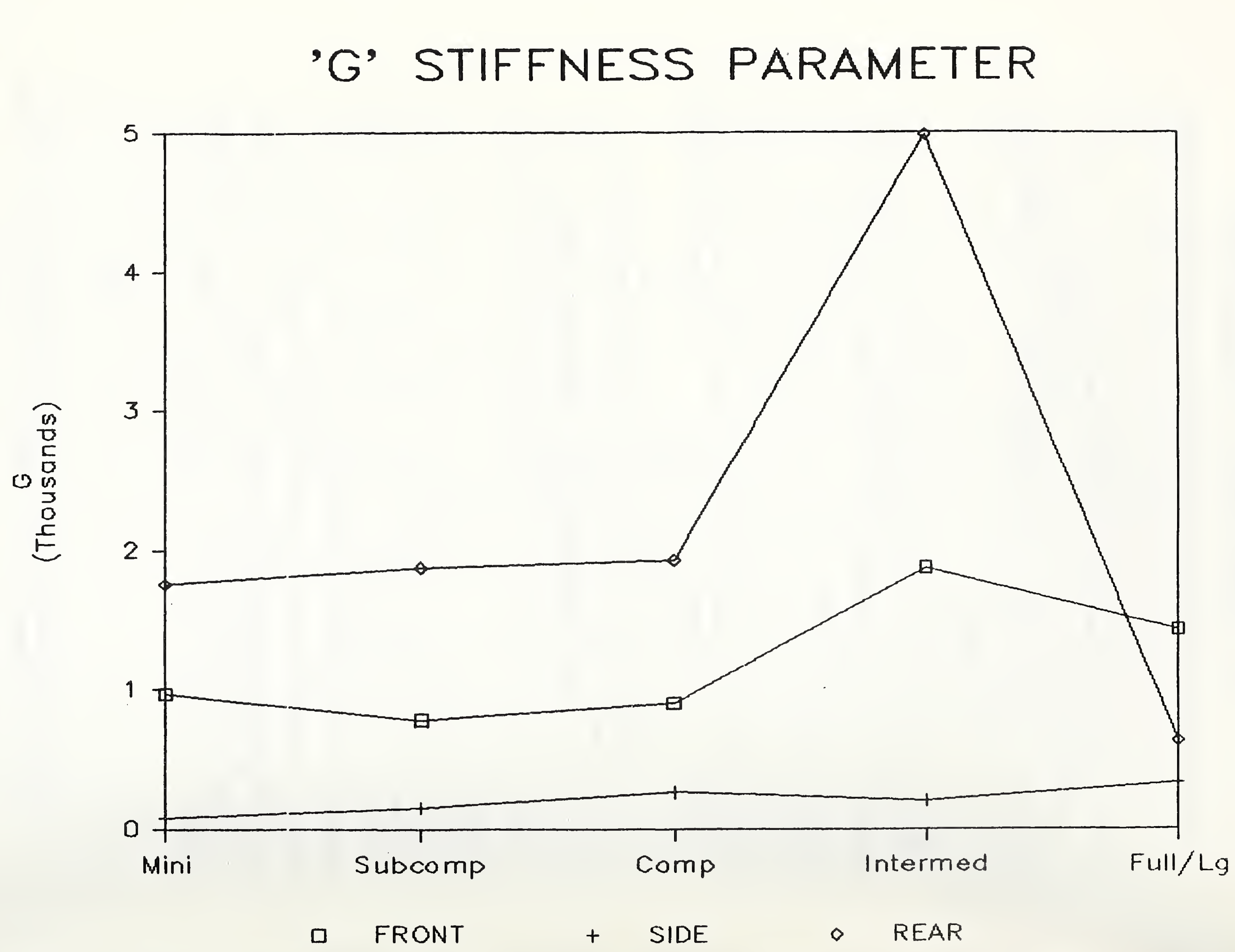



Figure 3.4. Current 'G' Stiffness Parameters

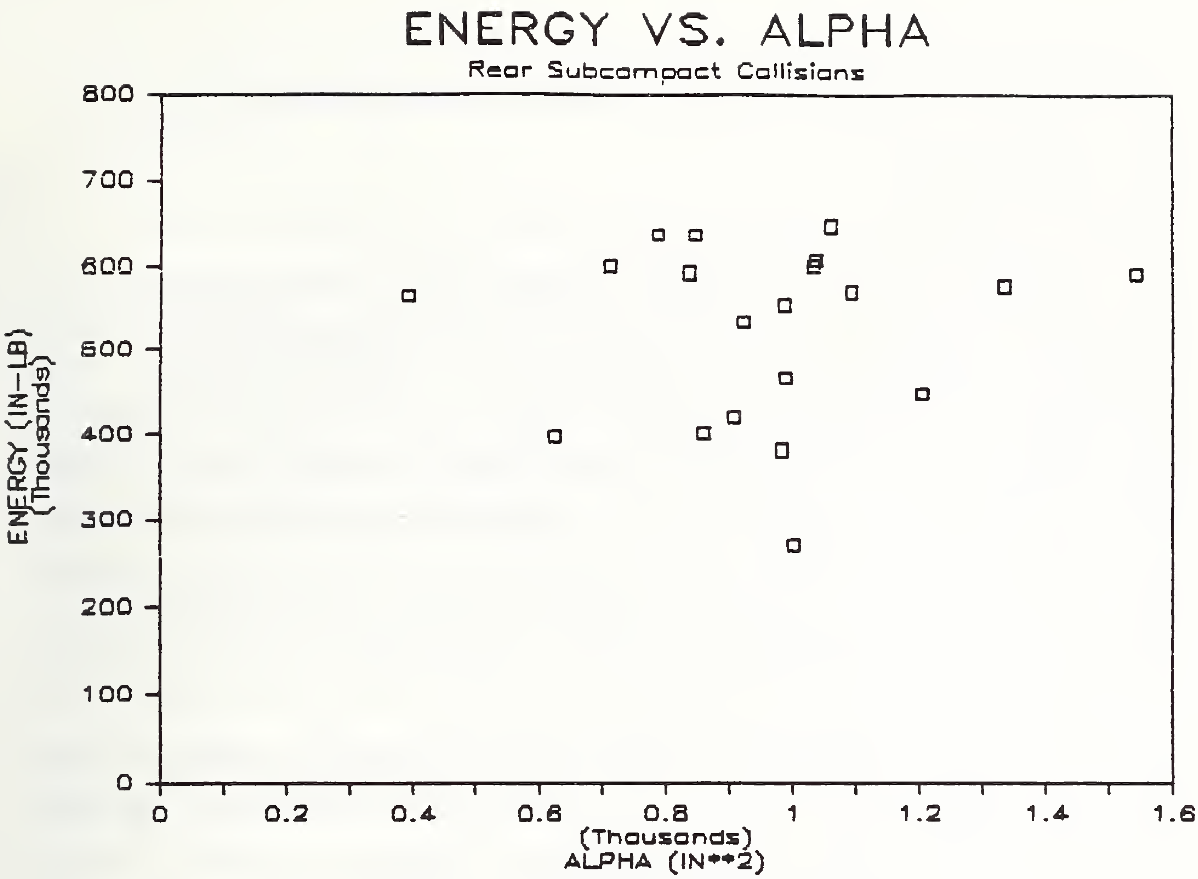



Figure 3.5. Energy vs. CRUSH Value Alpha

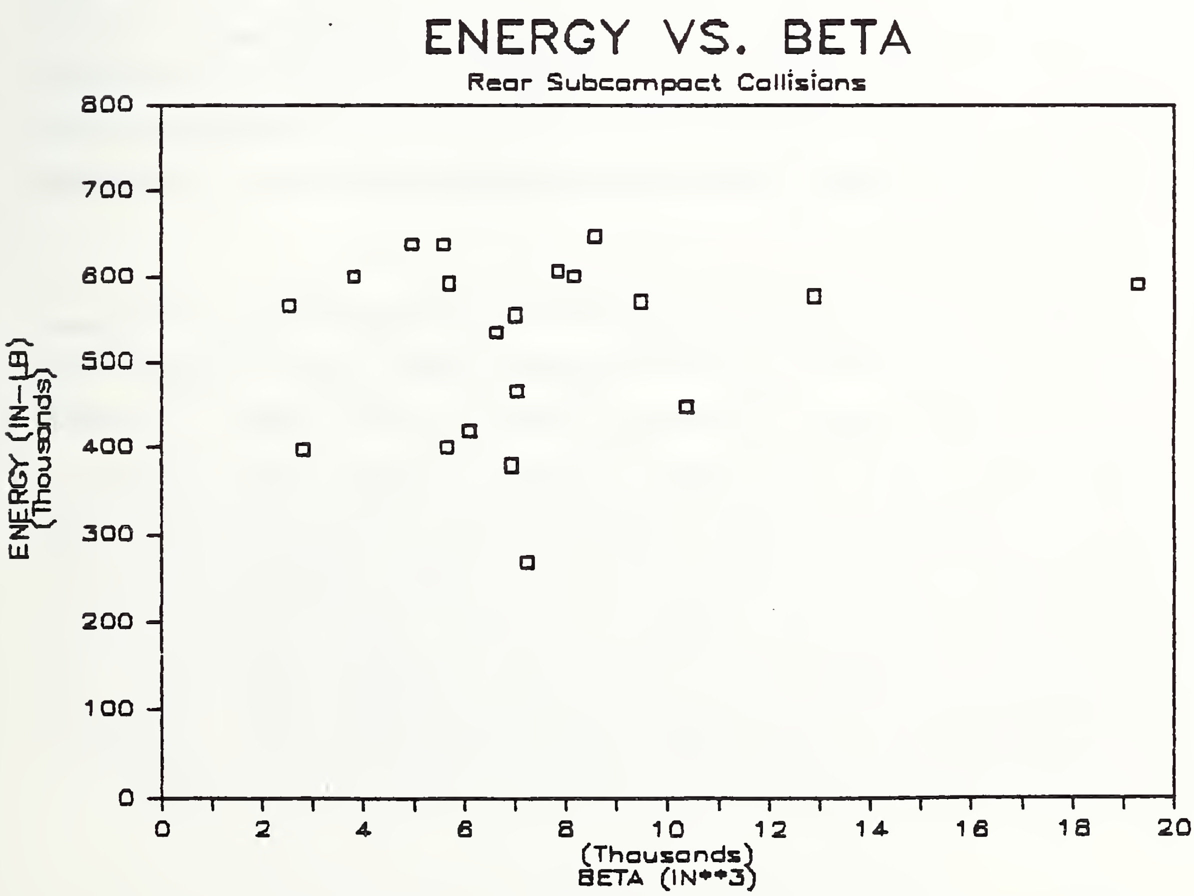



Figure 3.6. Energy vs. CRUSH Value Beta

## 4.0 INVESTIGATION OF STIFFNESS PARAMETER CATEGORIZATION

### 4.1 Correlations

The first step in the re-categorization investigation was to determine if any of the standard vehicle parameters relate to the damage a vehicle sustains in a collision. To accomplish this, it was necessary to obtain crash test damage data as well as vehicle specification data for many vehicles. While data were collected for both front and rear impacts at a few different impact speeds, the work outlined in this section concentrated on the 35 mph car-to-barrier frontal crash tests. There were 73 of these tests, performed on cars ranging from 1980 to 1985 model years.

A table of data was compiled which included the depth of crush (CR) measurement for each of the tests. If more than one such measurement was given for a particular test, the average value was used. A stiffness factor (K) was calculated for each test and entered into this table. The Appendix contains this table as well as a sample calculation of this factor. Since one of the model parameters (B) is actually a stiffness per unit crush width, the above stiffness factor was divided by the overall width of the car (KW) and also entered into the table. These three quantities were considered to be the dependent variables.

Also included in this table were various vehicle specifications. These included curb weight (WT), wheelbase (WB), front and rear track width (TF & TR), overall length (L), width (W), and height (H), engine displacement (ED), and drive configuration (DR - front or rear). A few combinations of these were also added. These were curb weight divided by the overall length (WTL), curb weight divided by the wheelbase (WTWB), and curb weight divided by the overall width (WTW). Finally, each vehicle represented in the table was grouped by its manufacturer, using three different methods (MAK1, MAK2, MAK3), with the corresponding code being included in this table (see Appendix).

These fifteen quantities were considered to be the possible independent variables.

SAS was then used to examine the correlation of the three dependent variables to the possible independent variables. The table of data described above was used in the RSQUARE routine of SAS. Each of the dependent variables was correlated to the possible independent variables for one, two, and three variable models. The output of this routine was simply the coefficient of determination, or the $r^2$ value, for each regression performed.

The $r^2$ value measures the portion of the variation in the response that is attributed to the model rather than to random error. An $r^2$ value of 0.70 (1.0 being the maximum) is generally considered to be the onset of meaningful correlation between the dependent variable and the independent variable(s).

**TABLE 4.1 -- Regression Results**

| Dependent Variable | Variables per Model: 1 | 2 | 3 |
|---|---|---|---|
| CR | ED<br>0.22 | L, H<br>0.24 | ED, H, L<br>0.26 |
| K | WTL<br>0.34 | WTL, ED<br>0.39 | WTL, ED, H<br>0.41 |
| KW | WTL<br>0.19 | WTW, ED<br>0.30 | WTL, ED, H<br>0.31 |

Table 4.1 lists the best results from each regression performed. As can be seen, none of the independent variables correlated well with any of the dependent variables. The best results were obtained from a three variable model using K as the dependent variable and WTL, ED, and H as the dependent variables. This regression produced an $r^2$ value of 0.41, which is poor. The best single variable model had an $r^2$ value of 0.34 with K and WTL as the dependent and independent

variables, respectively. Note that this same regression done with wheelbase as the independent variable produced an $r^2$ value of only 0.26. The Appendix contains a complete listing of both the input and output from these SAS regressions.

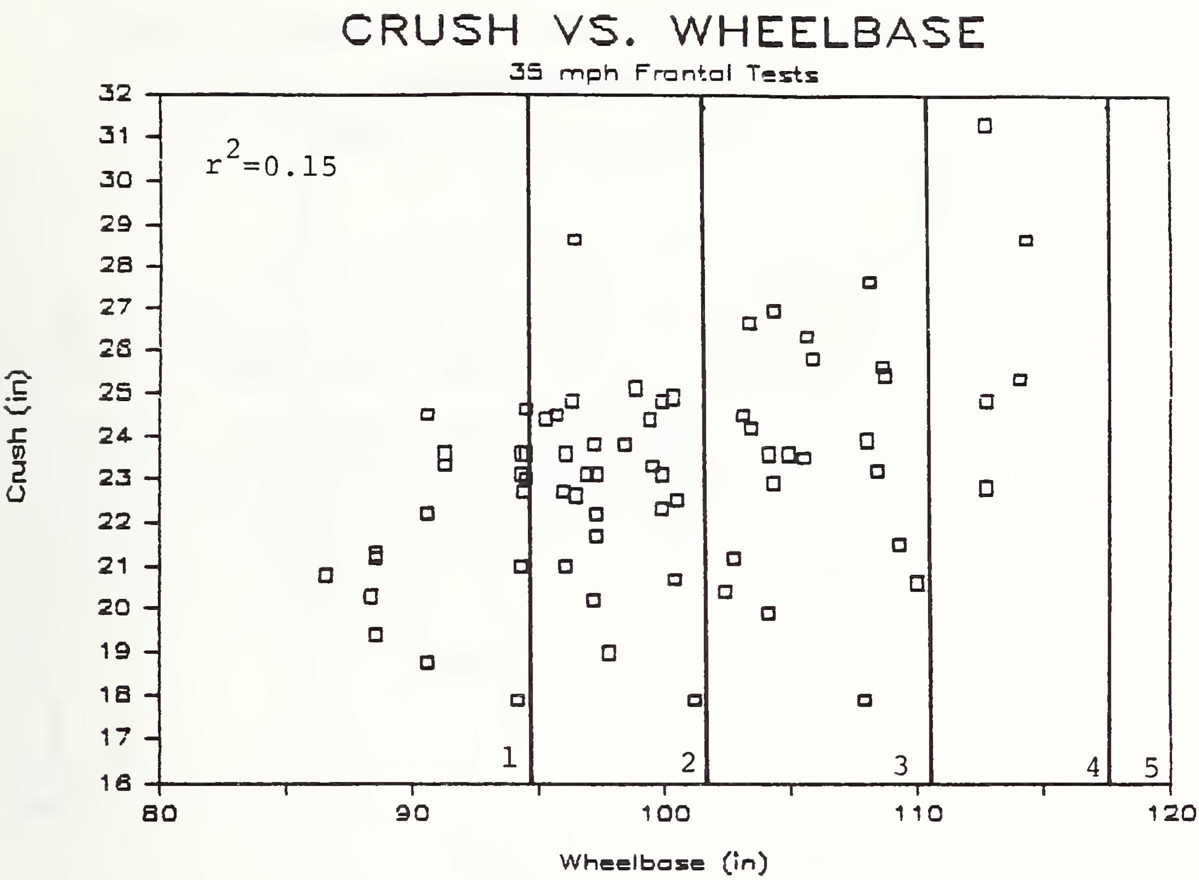
Figures 4.1 and 4.2 illustrate the lack of correlation for a few of the regressions performed. In the first of these, crush is plotted against WB and WTL, separately, while Figure 4.2 shows a plot of K with these same variables. The vertical lines on the two plots involving WB indicate the divisions of the existing stiffness categories. Although there seems to be a slightly increasing slope in each case, the scatter was considerable. Note that the regression of K versus WTL produced the highest $r^2$ value for the single variable models attempted (0.34).

## 4.2 Comparison of Stiffness Parameters

The observation of such poor correlation between the damage a vehicle sustains in a collision and the various dimensional and inertial parameters of that vehicle indicated the following: 1.) the present categorization by wheelbase does not appear to be very effective, and 2.) re-categorization by one or more of the other vehicle parameters would offer no significant improvement. To further explore these tentative results, two studies were done, involving the two extremes for categorizing stiffness parameters. The first was to lump all passenger cars into one category, having just one set of these parameters. The second was to have a different set of stiffness parameters for each individual vehicle model.

### 4.2.1 One Category For All Cars

This investigation was done to determine the effectiveness of having just one set of parameters rather than categorizing vehicles. Results ($\Delta v$) from the CRASH III model were compared to actual measured velocities from several tests. Three sets of stiffness parameters were used in the model; a set of parameters found from combining all



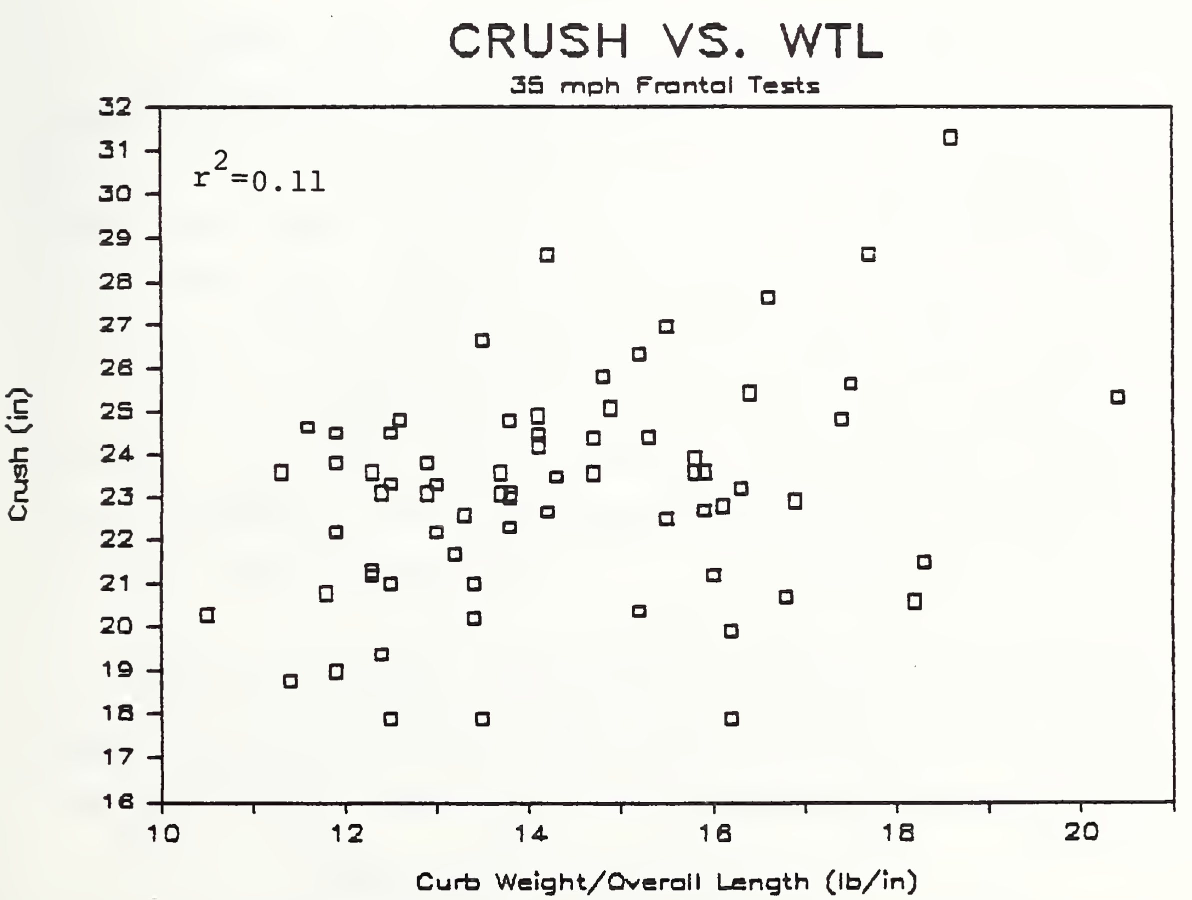
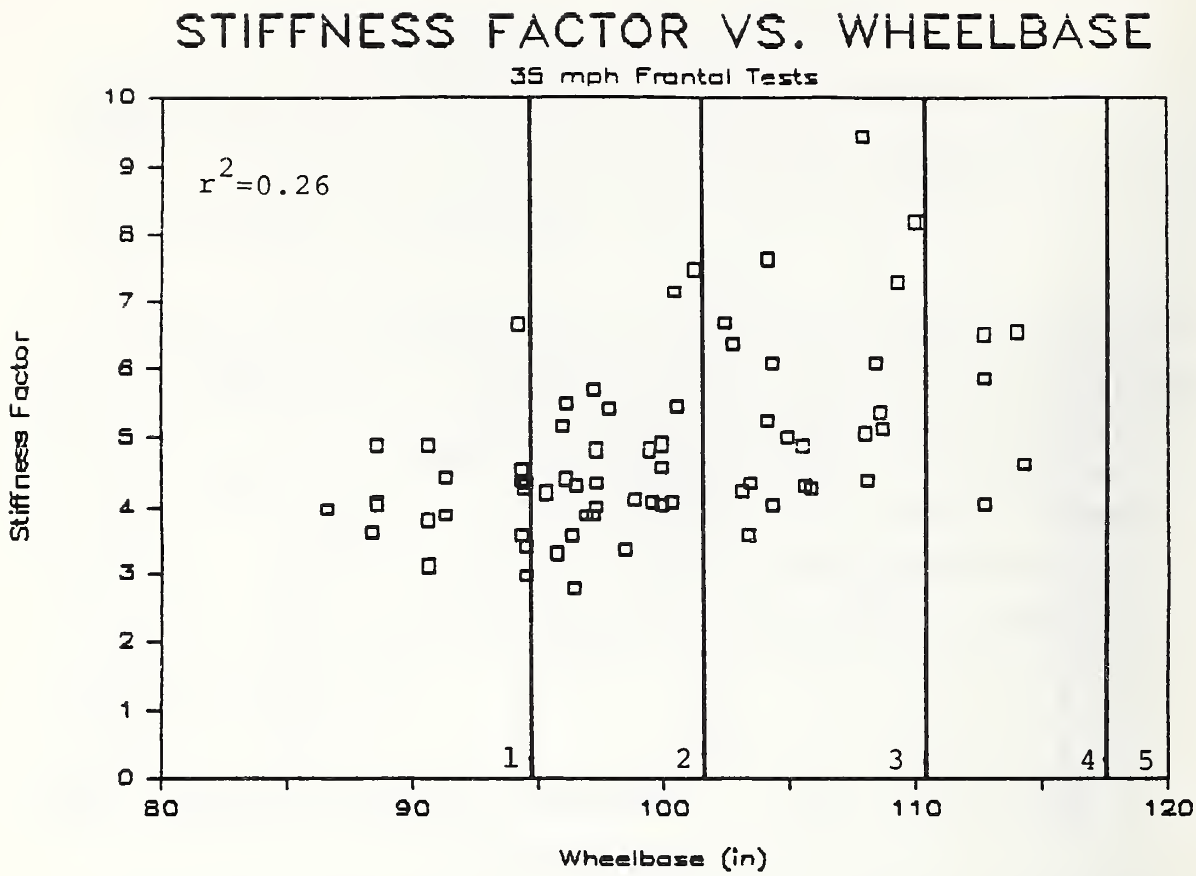




Figure 4.1. Regression Results on the CRUSH Variable



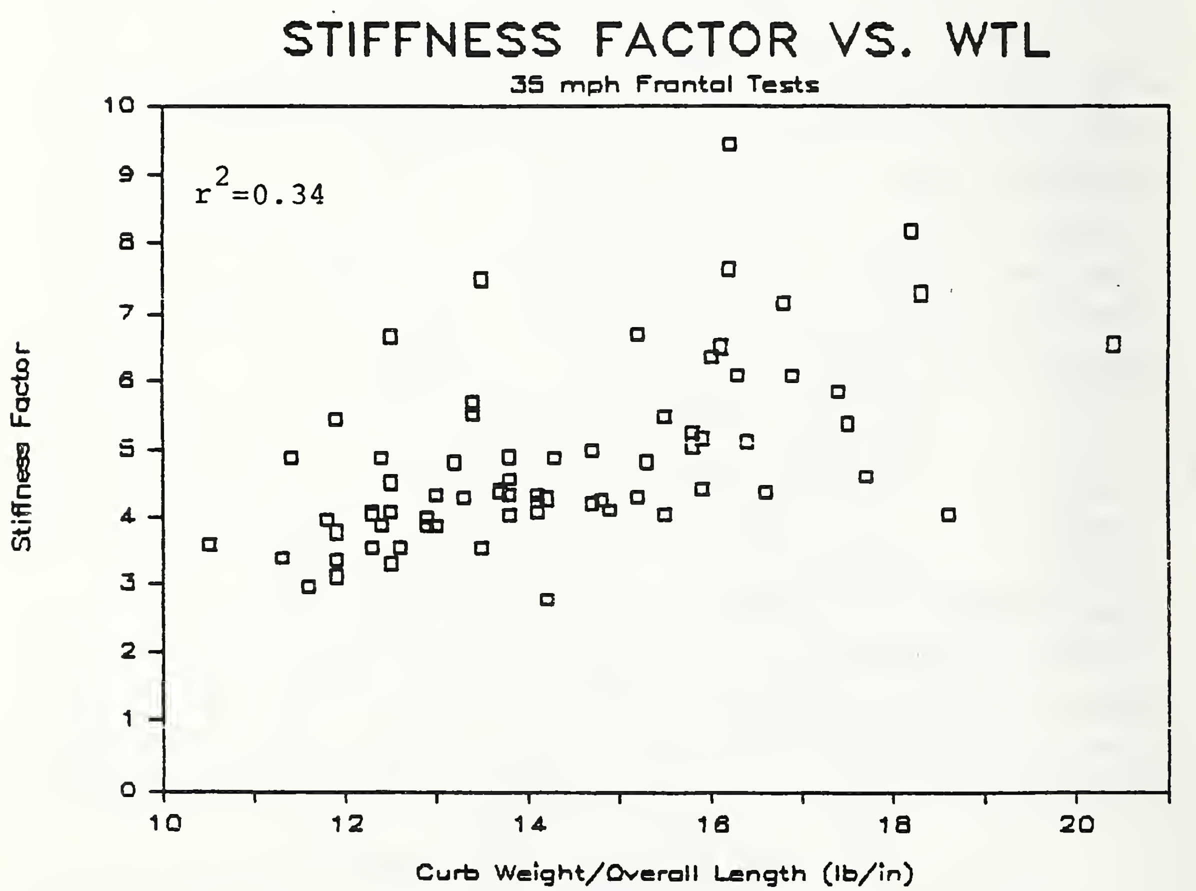




Figure 4.2. Regression Results on the STIFFNESS FACTOR Variable

vehicles into one group, the current parameters categorized by wheelbase, and new parameters categorized using the best correlating variable.

As outlined previously, the vehicle parameter which correlated best with vehicle stiffness was curb weight divided by overall length (WTL). Therefore, categories based on this parameter were established. This was done by finding the range of WTL for the cars of model years 1976, 1977, 1985, and 1986. The minimum was 10.55 and the maximum was 25.57. This range was then simply divided into six equal categories as follows:

| Category | WTL |
|---|---|
| 1 | 0 to 13.05 |
| 2 | 13.05 to 15.56 |
| 3 | 15.56 to 18.06 |
| 4 | 18.06 to 20.56 |
| 5 | 20.56 to 23.07 |
| 6 | 23.07 and up |

Eight passenger car models were found that had been frontally crash tested at both a lower speed (5 to 15 mph) and a higher speed (30 to 35 mph). The data from these tests were then entered into the CRUSH routine and values for E, $\alpha$, and $\beta$ were calculated for each case (see Chapter 3). The CRUSH results were then run through the NLIN routine of the SAS package to find the stiffness parameters A, B, and G, using two procedures: 1.) combined as one group, thus resulting in one set of stiffness parameters for all cars, and 2.) divided by WTL category, as listed above, resulting in an A, B and G for each of three categories. (There were no category 3, 5, or 6 vehicles among the eight vehicle models used.)

Thirteen additional frontal crash tests were then chosen, which included both high and low speed tests, for reconstruction using the CRASH III model. In each case, the $\Delta v$ predicted by the model was compared to the actual $\Delta v$ measured during the test. Each collision was reconstructed three times, using the current stiffness parameters categorized by wheelbase, the new parameters categorized by WTL, and the new parameters found by combining all the vehicles into one group. Table 4.2 list the stiffness parameters obtained from all three procedures.

**TABLE 4.2 -- Frontal Stiffness Parameters**

| WB/WTL Category | Stiffness Parameter | Current WB Parameters | New WTL Parameters |
|---|---|---|---|
| 1 | A | 301.5 | 269.9 |
| | B | 47.0 | 57.4 |
| | G | 966.7 | 634.9 |
| 2 | A | 259.4 | 254.8 |
| | B | 43.2 | 49.3 |
| | G | 778.1 | 658.2 |
| 3 | A | 317.4 | ---- |
| | B | 55.9 | ---- |
| | G | 901.1 | ---- |
| 4 | A | 355.9 | 195.1 |
| | B | 33.8 | 52.6 |
| | G | 1873.7 | 361.9 |
| 5 | A | 325.2 | ---- |
| | B | 37.0 | ---- |
| | G | 1429.1 | ---- |
| 6 | A | 325.2 | ---- |
| | B | 37.0 | ---- |
| | G | 1429.1 | ---- |
| Combined | A | 282.8 | |
| | B | 48.4 | |
| | G | 825.7 | |

Table 4.3 lists the results of these reconstructions. Along with the actual and predicted $\Delta v$'s for each test, the difference between the actual and the model results is listed. Note, that on average, there was virtually no difference in the accuracy of the model when WTL categorized stiffness parameters were used and when the combined parameters were used. This would indicate that categorization produces a more complicated model without any increase in reliability.

Note that the accuracy obtained by using the WTL and combined parameters was slightly better than that obtained using the current model configuration.

TABLE 4.3 -- Reconstruction Results (mph)

| Vehicle | Actual | Current Model | | New Parameters | | | |
|---|---|---|---|---|---|---|---|
| | | | | Categorized | | Combined | |
| | Δv | Δv | \|Δ\| | Δv | \|Δ\| | Δv | \|Δ\| |
| Escort | 4.88 | 8.8 | 3.9 | 7.3 | 2.4 | 8.2 | 3.3 |
| Escort | 10.03 | 10.3 | 0.3 | 8.8 | 1.2 | 9.6 | 0.4 |
| EXP | 34.96 | 26.7 | 8.3 | 27.4 | 7.6 | 26.4 | 8.6 |
| Accord | 10.00 | 14.7 | 4.7 | 15.0 | 5.0 | 15.3 | 5.3 |
| LeBaron | 35.05 | 32.1 | 3.0 | 35.5 | 0.5 | 33.8 | 1.3 |
| Prelude | 34.92 | 35.3 | 0.4 | 34.7 | 0.2 | 35.2 | 0.3 |
| Horizon | 10.02 | 8.9 | 1.1 | 8.5 | 1.5 | 9.3 | 0.7 |
| Stanza | 35.19 | 27.3 | 7.9 | 28.3 | 6.9 | 28.8 | 6.4 |
| Thunderbird | 4.96 | 7.5 | 2.5 | 6.5 | 1.5 | 7.2 | 2.2 |
| Grand Am | 5.01 | 9.9 | 4.9 | 8.7 | 3.7 | 9.4 | 4.4 |
| Century | 34.83 | 33.1 | 1.7 | 30.6 | 4.2 | 31.0 | 3.8 |
| Seville | 34.74 | 28.5 | 6.2 | 28.8 | 5.9 | 29.7 | 5.0 |
| Imperial | 35.00 | 32.0 | 3.0 | 33.4 | 1.6 | 34.0 | 1.0 |
| average | | XX | 3.7 | XX | 3.2 | XX | 3.3 |

### 4.2.2 Individual Stiffness Parameters For Each Car

The possibility of having a separate set of stiffness parameters for each individual vehicle model was also explored. This option seemed attractive, provided the stiffness of any single vehicle was reasonably constant over a speed range. Since stiffness parameter computation is best done with pairs of tests at different speeds, it would require that such data were available for a sufficient number of individual models. In order to investigate this, it was necessary to find multiple tests on the same model car, at different speeds, and calculate a set of stiffness parameters for each pair. Four frontal crash tests performed on Chevrolet Citations were chosen. The first test had a velocity of about 10 mph. The other three had nominal test velocities of 35, 40, and 48 mph. The results of these last three tests had previously been addressed in the study of Reference 1, and the crush measurements used for that study were used here. Similarly, four frontal crash tests on Ford Torinos, also from the study of

Reference 1, were chosen. These had nominal test velocities of 15, 25, 35, and 40 mph.

As before, the results of these eight tests were run through the CRUSH routine, producing the E, $\alpha$, and $\beta$ values for each. These were then entered into the NLIN routine, in high/low speed pairs, resulting in a set of stiffness parameters for each pair. These parameters are listed in Table 4.4. Figures 4.3 and 4.4 show the crush resistance curves derived from these parameters for the Citation and Torino tests, respectively. Also plotted on these are the crush resistance curves derived from the stiffness parameters of the current wheelbase categories 3 and 4. These were chosen since they contain the extremes of the current passenger car slopes (B-parameters).

**TABLE 4.4 -- Citation & Torino Stiffness Parameters**

| Vehicle | lo/hi test speeds | Stiffness Parameters | | |
|---|---|---|---|---|
| | | A | B | G |
| Citation | 10/35 | 237.6 | 44.8 | 630.7 |
| | 10/40 | 241.7 | 48.8 | 598.6 |
| | 10/48 | 214.8 | 29.8 | 774.0 |
| Torino | 15/25 | 243.4 | 31.0 | 955.5 |
| | 15/35 | 195.1 | 52.6 | 361.9 |
| | 15/40 | 211.5 | 47.0 | 476.1 |

In these figures, note that for each car, two of the three curves are similar with the third being much flatter. There was no pattern to this, though, as stiffness did not consistently increase or decrease with velocity. Most notable was the spread in the stiffnesses. For both the Citation and the Torino, the spread beteen the crush resistance curves derived for the individual vehicle was as large as that between the various existing vehicle categories. This would indicate that the stiffness of a car either varies with speed or the model's method for formulating stiffness is not adequate.

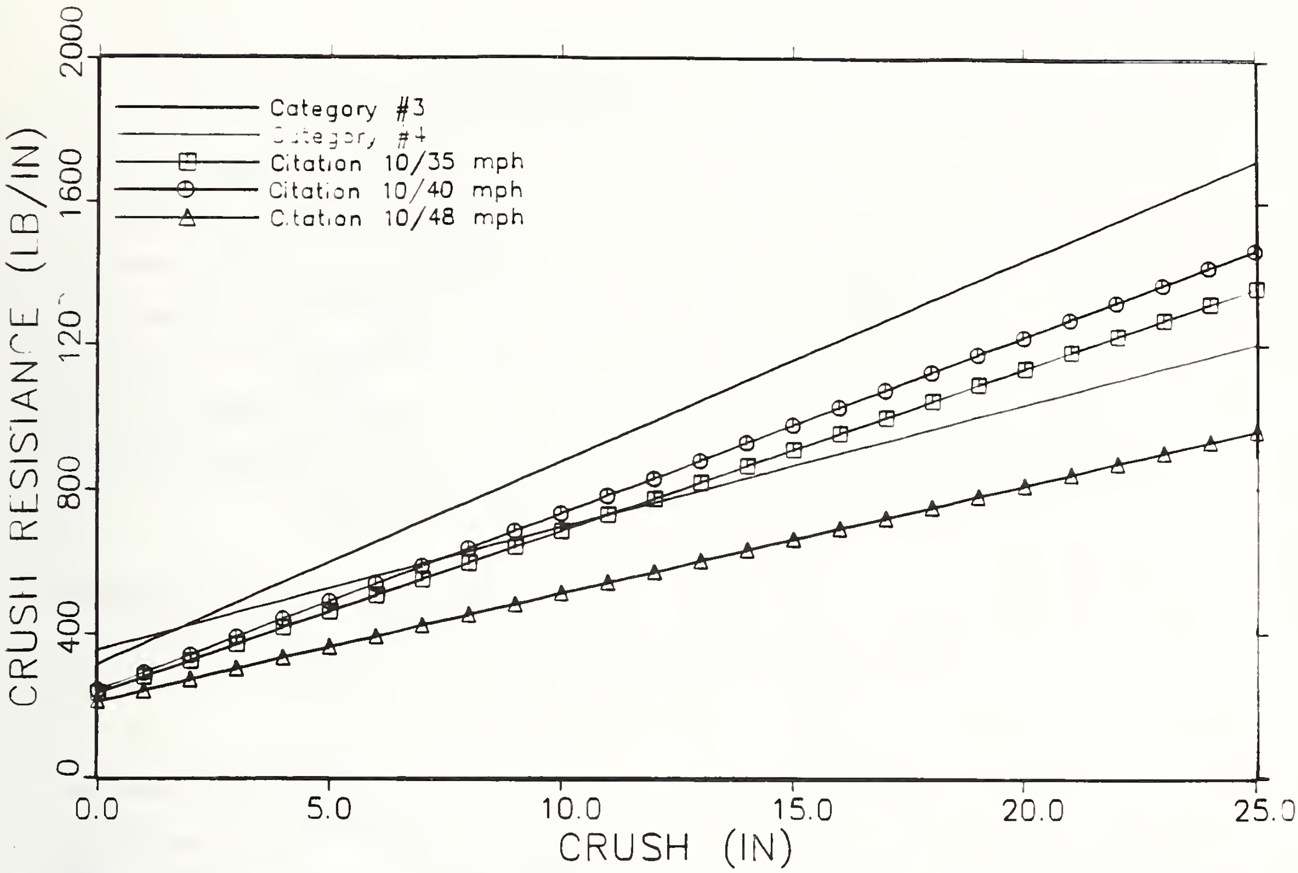



FIGURE 4.3. CITATION CRUSH RESISTANCE

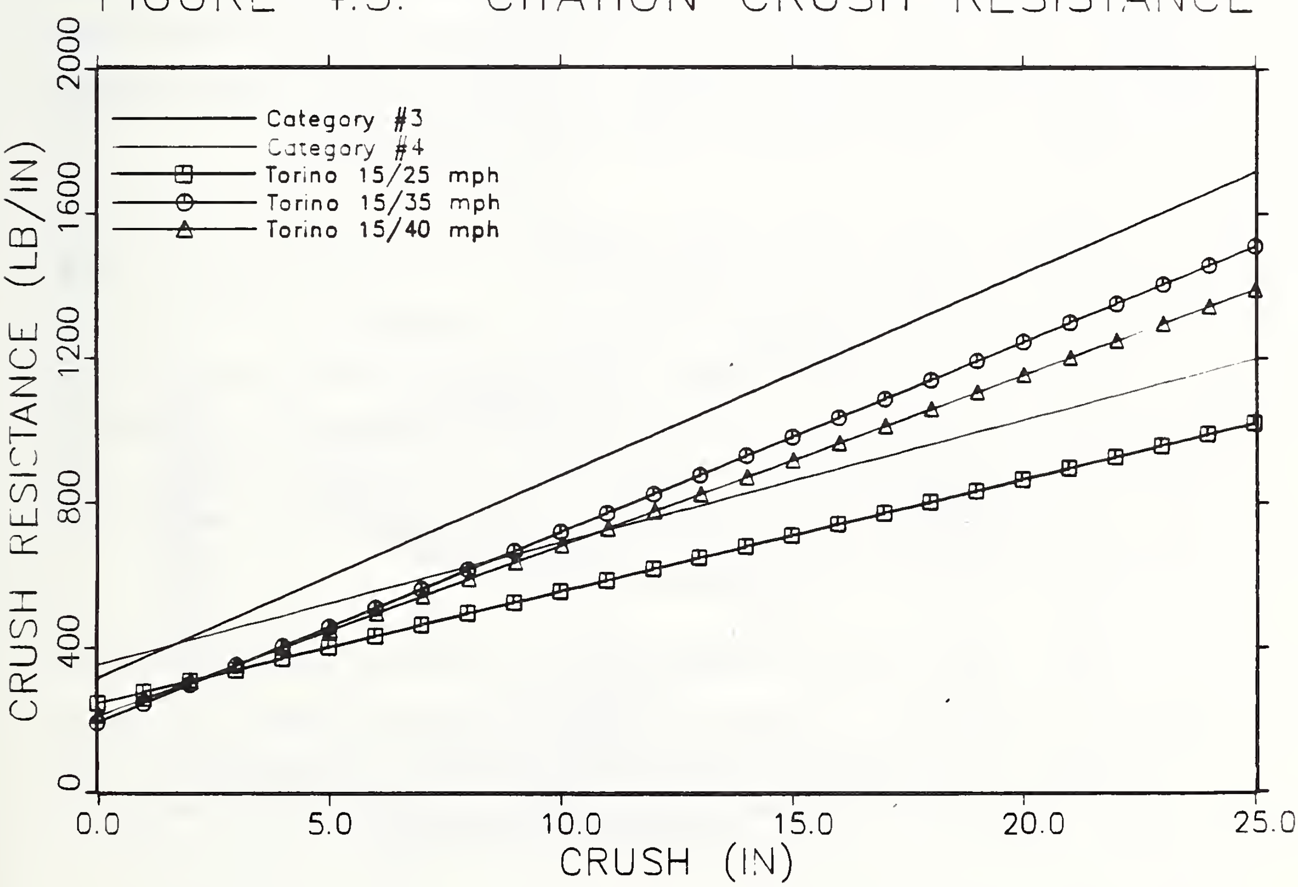



FIGURE 4.4. TORINO CRUSH RESISTANCE

## 4.3 Discussion of Crush Resistance Formulation

As presented in Chapter 3, the CRASH III model assumes a linear crush resistance as shown in Figure 3.1. The shaded area defined by the 'G' parameter represents the energy absorbed prior to the onset of permanent deformation. Note that the current formulation assigns the same crush resistance, or slope, to this elastic region as it does to the plastic portion of the curve. Typically, materials such as steel (and engineering structures such as automobiles) have different deformation characteristics in the elastic and plastic ranges.

This current formulation of the crush/energy relationship might be a contribution to the spread in the stiffness parameters calculated for the Citation and Torino.

Figure 4.5 shows the force vs. dynamic deflection curves from the three higher speed Citation tests examined in the previous section. Note that all three have similar shapes, the differences being the amounts of crush. Therefore, it did not seem reasonable that when each of these tests was individually matched with the same low speed test, widely varying stiffness parameters were produced.

The data from the three higher speed Citation tests were run through the CRUSH program and then as a group through the NLIN routine, producing the following stiffness parameters: A = 456.1, B = 12.33, G = 8433.5. The straight line representing these parameters is also shown on Figure 4.5. While this approximation does a reasonably good job of estimating the energy/crush relationship for impacts near this level of severity, its accuracy decreases greatly as tests with lower crush levels are modelled.

This trend can be explained if the current formulation of the model is examined. As shown in Figure 3.1, the area under the 'tail' of the crush resistance curve, or G, represents the energy (per unit width) required to produce permanent deformation. If all energy is

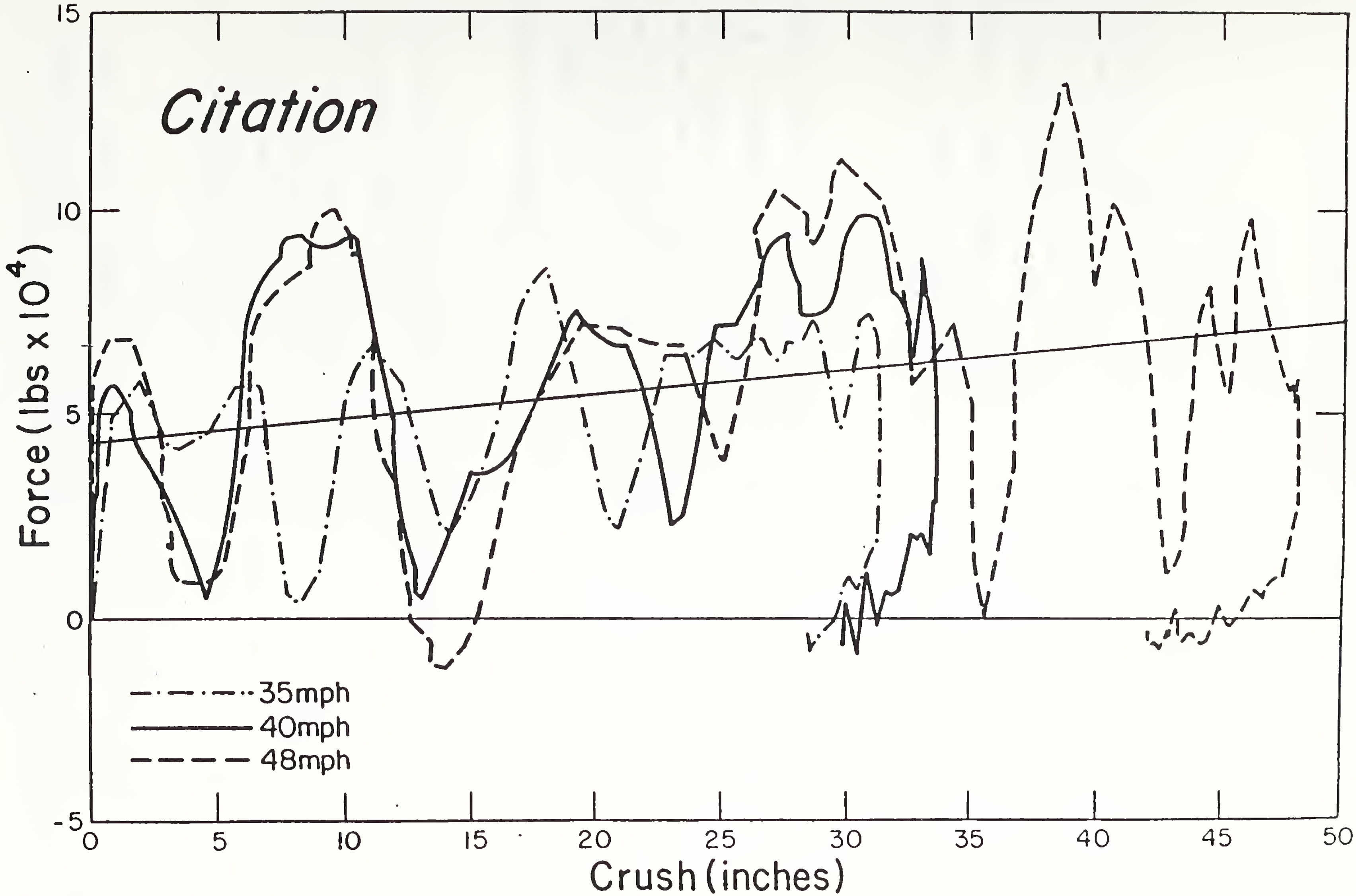



Figure 4.5. Citation Crush Responses

assumed to be kinetic, L is the crush width, and m is the mass of the car, then the following energy equation can be written:

$$E = \frac{1}{2}m(\Delta v)^2 = GL = \frac{A^2 L}{2B}$$

where $\Delta v$ is the velocity change required to produce permanent deformation. Note that this is a shortened form of the energy equation presented in Chapter 3. Substituting in the stiffness parameters (as represented by the straight line of Figure 4.5) and the appropriate vehicle parameters, this relationship predicts that a $\Delta v$ of about 21 mph would be required to produce permanent damage in the Citation. This is much too high, as the actual value is probably about 5 mph.

To counteract this effect, low speed data points have been used in conjunction with the higher speed points to draw the intercept, A, down, thus increasing the slope, B, and reducing the area under the tail, G (see Table 4.4). The slope and intercept values derived in this manner are not representative of the true crush characteristics of the vehicle. While this tends to improve the model's ability to predict $\Delta v$'s near both the low and high speed data points used to determine the parameters, it does a poor job of modelling tests that fall between or beyond these.

The current assumption in the model is that the tail of the curve has the same slope, B, as the positive, or plastic, crush portion of the curve. In many cases, as for the Citation, this results in a large area under the tail, G. Since all the energy represented by the area under the tail is used for elastic deformation of the vehicle, unrealistically high $\Delta v$'s for the onset of permanent deformation often result.

More realistically, the tail of the curve probably has a steeper slope, B′, than the positive crush portion of the curve (see Figure 4.6). This would decrease the area under the tail, thus reducing the

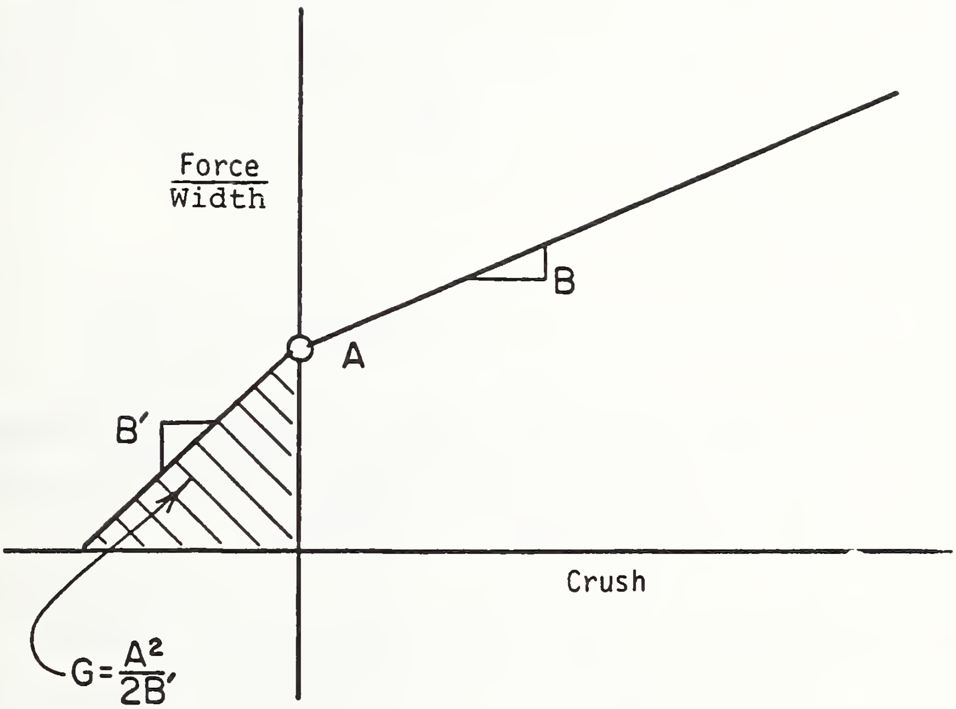



Figure 4.6. Alternate Formulation for Crush Resistance

$\Delta v$ required to produce permanent deformation. At the same time, the plastic crush region of the curve could still be modelled using the B value more realistic for that portion.

If such a re-formulation of the CRASH III model was done, the variability in the stiffness parameters found from multiple tests on the same model car, as presented in the previous section, would be expected to decrease. While this would not necessarily increase the chance that vehicles may be categorized based on some vehicle parameter, it would increase the chance that using stiffness parameters for individual car models would improve the model's accuracy.

## 5.0 CONCLUSIONS

The following conclusions were made from this study:

1. No vehicle parameters were found which correlated well with either the amount of crush a vehicle sustains in a collision or the crush stiffness of that vehicle.
   - An $r^2$ value of 0.41 was the highest found when correlations to crush and stiffness were attempted. In this case, stiffness was the dependent variable and curb weight divided by overall length (WTL), engine displacement, and overall height were the independent variables. Only one, two, and three variable models were attempted.
   - An $r^2$ value of 0.22 was the highest found when single variable correlations to crush were attempted. In this case, engine displacement was the independent variable.
   - An $r^2$ value of 0.34 was the highest found when single variable correlations to stiffness were attempted. In this case, WTL was the independent variable.

2. The CRASH III model predicted velocity changes as accurately when all passenger cars were combined into one stiffness

category as it did when they were divided into six categories.

- The model was run using stiffness parameters found by categorizing cars by WTL, by using just one category for all cars, and by categorizing cars by wheelbase (current). The average difference between predicted velocity change and actual for each of these was as follows:

  WTL categories - $|\Delta| = 3.2$ mph
  Combined - $|\Delta| = 3.3$ mph
  Wheelbase categories - $|\Delta| = 3.7$ mph

3. It did not appear reasonable to compute stiffness values for individual vehicle models. The variations in stiffness parameters found from multiple pairs of tests on the same vehicle model were larger than the variation in the six sets of stiffness parameters currently used for passenger cars. (note: c.v. $= \sigma/\bar{x}$)

- The slope, or B, parameters in the curent model formulation varies from 33.8 to 55.9 (c.v. = 20.0%).

- The B parameters found using three pairs of Citation tests varied from 29.8 to 48.8 (c.v. = 24.4%).

- The B parameters found using three pairs of Torino tests varied from 31.0 to 52.6 (c.v. = 25.8%).

4. In the current formulation of CRASH III, it is assumed that the stiffness is the same during the elastic portion of the crush as it is once plastic deformation begins. This can lead to unrealistically high velocities required for the

onset on permanent deformation unless low speed test data are used.

## 6.0 RECOMMENDATIONS

In the short term, the use of categories to determine stiffness parameters for passenger cars could be eliminated[1].

In the long term, a re-formulation of the CRASH III model should be considered[2]. One focal point of this re-formulation should be the current assumption that the stiffness of a vehicle during the elastic crush portion of a crash is the same as that during the plastic crush portion.

## 7.0 REFERENCES


1. M.W. Monk, D.A. Guenther; "Update of CRASH II Computer Model Damage Tables"; NHTSA final report number DOT-HS-806-446; March 1983.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[1] The response from question number 2 in the CRASH III program is used to determine default values for vehicle geometric and inertial parameters, while the response from question number 5 is used to determine vehicle stiffness parameters. Eliminating stiffness categories should not affect the default values of the second question.

[2] This is currently under way at the VRTC in project number VRTC-87-0053, "CRASH III - Crush Model Reformulation."

# APPENDIX

## Correlation Parameters and Results

## 1. Calculation of Stiffness Factor

Assumptions:

a. All energy in the system is kinetic

b. The vehicle crushes linearly at a constant rate, k.

c. All the energy of the system goes towards crushing the vehicle.

then,

$$E = \frac{1}{2}mv^2 = \frac{1}{2}kx^2$$

where m is vehicle mass, v is impact velocity, and x is the dynamic crush.

Solving for k, we get,

$$k = \frac{mv^2}{x^2}$$

If the tests are grouped by impact speed, then the $v^2$ term is essentially a constant. Also, since $m = wt/g$, the above expression can be rewritten as follows:

$$k = \frac{v^2}{g} \dot{o} \frac{wt}{x^2}$$

or

$$k = (C)\frac{wt}{x^2} \propto \frac{wt}{x^2}$$

Since dynamic crush was not available, the measured static crush from each test was used. A stiffness factor, K, was then calculated for each test as follows:

$$\text{Stiffness factor, } K = \frac{\text{curb weight}}{(\text{static crush})^2}$$

2. Vehicle Manufacturer Codes

MAK1:

0 - American

1 - Japanese

2 - European

MAK2:

0 - General Motors

1 - Ford

2 - Chrysler

3 - Toyota

4 - Honda

5 - Mitsubishi

6 - Volkswagen

7 - Renault

8 - Other American

9 - Other Japanese

10 - Other European

MAK3:

1 - General Motors

2 - Ford

3 - Chrysler

4 - AMC

5 - Japanese

6 - European

3. Table of Parameters/SAS Input and Output

```
  T FRONT35.SAS
* FRONT35.SAS;
* Partial command file to put CRASH III data into;
*      SAS program. Frontal car/barrier data @;
*      35 +/-0.5 mph.;
DATA CRUSHCOR;
INPUT CR WT WB   TF    TR    L     W     H    ED  DR  K   WTL  WTWB  WTCR  KW MAK1 MAK2 MAK3 WTW;
CARDS;
22.7 2665   96.0 58.1 57.0 167.2 71.9 51.5 151 0  5.1  15.9 27.8 117.4 0.072 0  8 3 37.1
21.5 3361  109.3 59.6 57.5 184.0 71.0 55.1 258 1  7.27 18.3 30.8 156.3 0.102 0  8 3 47.3
25.4 3299  108.7 60.0 59.5 201.2 74.2 53.4 225 0  5.11 16.4 30.3 129.9 0.069 0  2 2 44.5
24.8 3602  112.7 60.0 59.5 206.7 74.2 55.3 225 1  5.86 17.4 32.0 145.2 0.079 0  2 2 48.5
28.6 3780  114.3 62.2 62.0 214.0 77.5 55.2 302 0  4.62 17.7 33.1 132.2 0.060 0  1 1 48.8
17.9 2135   94.2 54.7 56.0 170.3 65.9 50.5  98 1  6.66 12.5 22.7 119.3 0.101 0  1 1 32.4
25.6 3521  108.6 58.4 59.0 201.2 73.6 54.9 302 0  5.37 17.5 32.4 137.8 0.073 0  1 1 47.8
23.2 3270  108.4 58.1 57.0 200.4 74.1 53.0 302 0  6.08 16.3 30.2 140.9 0.082 0  1 1 44.1
23.6 2780  104.9 58.7 57.0 189.1 67.7 53.7 181 1  4.99 14.7 26.5 117.8 0.074 0  0 0 41.1
27.6 3333  108.1 58.5 57.7 200.4 71.3 53.0 350 0  4.38 16.6 30.8 120.8 0.061 0  0 0 46.7
25.3 4185  114.0 59.3 60.6 204.8 71.4 54.3 350 1  6.54 20.4 36.7 165.4 0.092 0  0 0 58.6
23.6 1990   94.3 51.2 51.2 161.9 61.8 52.3  98 0  3.57 12.3 21.1  84.3 0.058 0  0 0 32.2
23.1 2135   97.3 51.2 51.2 164.9 61.8 52.9  98 0  4.00 12.9 21.9  92.4 0.065 0  0 0 34.5
22.2 2138   97.3 51.2 51.2 164.8 61.8 52.8  89 0  4.34 13.0 22.0  96.3 0.070 0  0 0 34.6
23.3 2206   99.5 55.1 55.9 176.7 66.2 53.7  97 0  4.06 12.5 22.2  94.7 0.061 2 10 5 33.3
28.6 2285   96.4 55.1 55.5 161.0 64.9 53.0  91 1  2.79 14.2 23.7  79.9 0.043 2 10 5 35.2
20.6 3465  110   58.6 56.9 190.9 70.3 56.6 168 0  8.17 18.2 31.5 168.2 0.116 2 10 5 49.3
23.9 2890  108   56   53.5 182.4 66.7 56.4 120 0  5.06 15.8 26.8 120.9 0.076 2 10 5 43.3
17.9 3020  107.9 57.5 56.5 186.7 68.4 56.4 120 0  9.43 16.2 28.0 168.7 0.138 2 10 5 44.2
21.0 2426   96.1 55.7 53.4 181.5 66.5 55.2 132 1  5.50 13.4 25.2 115.5 0.083 2  7 5 36.5
24.4 2876   99.4 55.9 56.3 187.6 66.5 55.9 121 1  4.83 15.3 28.9 117.9 0.073 2 10 5 43.2
23.6 1892   94.5 54.7 53.5 167.8 63.4 55.5 105 1  3.40 11.3 20.0  80.2 0.054 2  6 5 29.8
22.7 2204   94.4 54.7 53.5 155.3 63.4 55.6  97 1  4.28 14.2 23.3  97.1 0.068 2  6 5 34.8
23.0 2293   94.5 54.7 54.3 165.7 64.0 51.4 105 1  4.33 13.8 24.3  99.7 0.068 2  6 5 35.8
24.5 1865   90.6 53.9 52.8 156.9 62.4 50.0  86 1  3.11 11.9 20.6  76.1 0.050 1  5 4 29.9
25.1 2595   98.8 53.9 54.3 173.8 65.4 53.3 120 0  4.12 14.9 26.3 103.4 0.063 1  9 4 39.7
20.2 2325   97.2 56.3 55.5 173.4 65.6 54.7 120 1  5.70 13.4 23.9 115.1 0.087 1  9 4 35.4
21.0 1987   94.3 54.1 53   159   63.8 53.5  85 1  4.51 12.5 21.1  94.6 0.071 1  9 4 31.1
22.6 2200   96.5 49.8 49.4 164.8 61   56.7  97 1  4.31 13.3 22.8  97.3 0.071 1  9 4 36.1
23.6 2921  104.1 54.7 54.5 184.8 66.5 54.3 168 0  5.24 15.8 28.1 123.8 0.079 1  3 4 43.9
23.8 1905   98.4 52.3 51.7 160.0 61.0 52.6  89 1  3.36 11.9 19.4  80.0 0.055 1  3 4 31.2
23.1 2135   97.3 51.2 51.2 164.9 61.8 52.9  98 0  4.00 12.9 21.9  92.4 0.065 0  0 0 34.5
24.5 1865   90.6 53.9 52.8 156.9 62.4 50.0  86 1  3.11 11.9 20.6  76.1 0.050 1  5 4 29.9
24.8 2476   99.9 57.6 57.0 179.7 68.5 52.6 135 1  4.03 13.8 24.8  99.8 0.059 0  2 2 36.1
25.6 3521  108.6 58.4 59.0 201.2 73.6 54.9 302 0  5.37 17.5 32.4 137.5 0.073 0  1 1 47.8
23.5 2703  105.5 57.9 56.9 188.9 69.6 54.7 131 0  4.89 14.3 25.6 115.0 0.070 2 10 5 38.8
23.6 2450   96.1 55.7 53.4 178.7 66.5 55.3 101 0  4.40 13.7 25.5 103.8 0.066 2  7 5 36.8
21.3 1822   88.6 53.5 54.3 148.0 62.2 53.0  91 1  4.02 12.3 20.6  85.5 0.065 1  4 4 29.3
21.2 1822   88.6 53.5 54.3 148.0 62.2 53.0  91 1  4.05 12.3 20.6  85.9 0.065 1  4 4 29.3
31.3 3961  112.7 60.0 59.5 213.3 72.7 53.2 318 0  4.04 18.6 35.1 126.5 0.056 0  2 2 54.5
18.8 1730   90.6 50.8 50.2 152.2 60.0 54.3  79 0  4.89 11.4 19.1  92.0 0.082 1  3 4 28.8
20.8 1713   86.6 51.5 55.7 144.6 63.9 50.8  82 1  3.96 11.8 19.8  82.4 0.062 1  4 4 26.8
22.5 2775  100.5 56.6 57.0 179.1 69.1 59.1 140 0  5.48 15.5 27.6 123.3 0.079 0  1 1 40.2
24.8 2182   96.3 55.5 54.1 173.0 65.4 51.6 110 1  3.55 12.6 22.7  88.0 0.054 1  5 4 33.4
24.5 1985   95.7 54.5 53.9 158.7 63.6 54.7  88 1  3.31 12.5 20.7  81.0 0.052 1  3 4 31.2
26.3 2981  105.6 56.6 57.0 196.5 71.0 53.6 200 0  4.31 15.2 28.2 113.3 0.061 0  1 1 42.0
23.3 2106   91.3 55.1 55.5 161.4 64.4 51.0 107 1  3.88 13.0 23.1  90.4 0.060 1  4 4 32.7
19.4 1835   88.6 53.5 54.3 148.0 62.2 53.0  81 1  4.88 12.4 20.7  94.6 0.079 1  4 4 29.5
22.8 3380  112.7 60.0 59.5 209.5 72.7 53.3 225 0  6.5  16.1 30.0 148.2 0.089 0  2 2 46.5
23.1 2070   96.9 52.4 53   167.3 63.4 53.7  97 1  3.8  12.4 21.4  89.6 0.061 1  9 4 32.6
19.0 1957   97.8 55.2 52.8 163.8 65.0 51.3  85 1  5.42 11.9 20.0 103.0 0.083 2  7 5 30.1
24.9 2516  100.3 57.6 57.2 178.6 68.0 52.7 135 1  4.06 14.1 25.1 101.0 0.060 0  2 2 37.0
22.3 2438   99.9 54.7 57.6 176.2 68.3 52.7 140 1  4.90 13.8 24.4 109.3 0.072 0  1 1 35.7
```

```
24.2 2542 103.4 55.5 55.2 180.0 67.7 52.1 151 0  4.34 14.1 24.6 105.0 0.064 0  0 0 37.5
22.9 3188 104.3 56.3 53.5 188.8 67.2 57.5 141 0  6.08 16.9 30.6 139.2 0.091 2 10 5 47.4
19.9 3020 104.1 54.7 54.9 186.2 66.5 54.3 168 0  7.63 16.2 29.0 151.8 0.115 1  3 4 45.4
26.9 2919 104.3 56.3 53.5 188.8 67.2 56.2 141 0  4.03 15.5 28.0 108.5 0.060 2 10 5 43.4
24.5 2535 103.1 57.6 57.2 180.4 68.3 53.0 135 1  4.22 14.1 24.6 103.5 0.062 0  2 2 37.1
26.6 2527 103.3 57.6 57.2 186.6 68.0 53.1 135 1  3.57 13.5 24.5  95.0 0.053 0  2 2 37.2
23.1 2438  99.9 54.7 57.6 176.2 68.3 52.7 140 1  4.57 13.8 24.4 105.5 0.067 0  1 1 35.7
25.8 2844 105.8 57.8 57.8 192.7 71.4 55.7 136 1  4.27 14.8 26.9 110.2 0.060 2 10 5 39.8
17.9 2395 101.2 55.4 55.7 176.8 64.8 54.3 108 0  7.47 13.5 23.7 133.8 0.115 2 10 5 37.0
23.1 2335  94.3 51.4 51.4 170.7 61.8 53.5 111 0  4.38 13.7 24.8 101.1 0.071 1  9 4 37.8
21.2 2853 102.7 57.2 57.8 178.4 68.0 54.8 140 1  6.35 16.0 27.8 134.6 0.093 2 10 5 42.0
24.4 2500  95.3 55.9 55.1 170.1 65.7 49.6  80 0  4.20 14.7 26.2 102.5 0.064 1 10 4 38.1
22.2 1865  90.6 54.1 52.8 156.9 62.4 50.0  90 1  3.78 11.9 20.6  84.0 0.061 1  5 4 29.9
20.4 2778 102.4 56.9 55.3 183.1 66.7 51.6 143 1  6.68 15.2 27.1 136.2 0.100 1  5 4 41.6
20.7 3060 100.4 57.5 53.9 181.7 66.5 55.1 151 0  7.14 16.8 30.5 147.8 0.107 1  9 4 46.0
24.6 1808  94.5 54.7 54.3 155.9 63.6 52.0  90 1  2.99 11.6 19.1  73.5 0.047 1  9 4 28.4
23.8 2190  97.2 56.1 56.1 170.0 65.4 52.5 109 1  3.87 12.9 22.5  92.0 0.059 1  9 4 33.5
20.3 1488  88.4 52.4 51.2 141.1 60.3 53.2  61 1  3.61 10.5 16.8  73.3 0.060 1  9 4 24.7
23.6 2459  91.3 56.7 56.7 154.5 65.6 49.2  97 0  4.42 15.9 26.9 104.2 0.067 1  3 4 37.5
21.7 2275  97.3 56.3 56.0 171.7 65.5 55.7 109 1  4.83 13.2 23.4 104.8 0.074 2  6 5 34.7
;
PROC RSQUARE;
MODEL CR=WT WB TF TR L W H ED DR WTL WTWB MAK1 MAK2 MAK3 WTW/STOP=3;
MODEL  K=WT WB TF TR L W H ED DR WTL WTWB MAK1 MAK2 MAK3 WTW/STOP=3;
MODEL KW=WT WB TF TR L W H ED DR WTL WTWB MAK1 MAK2 MAK3 WTW/STOP=3;
$
$
$
$ T FRONT35.LIS
```

N=73 REGRESSION MODELS FOR DEPENDENT VARIABLE: CR MODEL: MODEL1

| NUMBER IN MODEL | R-SQUARE | VARIABLES IN MODEL |
|---|---|---|
| 1 | 0.00020525 | H |
| 1 | 0.01651766 | DR |
| 1 | 0.05193623 | MAK2 |
| 1 | 0.07749807 | MAK1 |
| 1 | 0.08779410 | MAK3 |
| 1 | 0.11204859 | WTL |
| 1 | 0.13388773 | WTW |
| 1 | 0.13749980 | TF |
| 1 | 0.13807575 | TR |
| 1 | 0.14784693 | WTWB |
| 1 | 0.15044023 | WB |
| 1 | 0.16131965 | WT |
| 1 | 0.17682311 | W |
| 1 | 0.19619053 | L |
| 1 | 0.21523408 | ED |
| 2 | 0.21558952 | ED WB |
| 2 | 0.21641323 | ED WTW |
| 2 | 0.21697232 | L MAK2 |
| 2 | 0.21730948 | ED MAK2 |
| 2 | 0.21764898 | ED TF |
| 2 | 0.21803687 | ED TR |
| 2 | 0.21884416 | ED W |
| 2 | 0.21922089 | L MAK3 |
| 2 | 0.21925774 | ED MAK1 |
| 2 | 0.21968134 | ED MAK3 |
| 2 | 0.22080150 | ED WTL |
| 2 | 0.22384384 | L MAK1 |
| 2 | 0.22560292 | ED L |
| 2 | 0.23153440 | ED H |
| 2 | 0.24365115 | L H |
| 3 | 0.24367385 | L H WTWB |
| 3 | 0.24372966 | L H TF |
| 3 | 0.24379759 | ED L WTW |
| 3 | 0.24380652 | L H TR |
| 3 | 0.24389284 | L H W |
| 3 | 0.24396907 | L H WTL |
| 3 | 0.24436386 | L H WTW |
| 3 | 0.24532239 | L H DR |
| 3 | 0.24555146 | ED WTL WTWB |
| 3 | 0.24561082 | L H WB |
| 3 | 0.24828790 | L H MAK2 |
| 3 | 0.24999615 | L H MAK1 |
| 3 | 0.25031738 | L H MAK3 |
| 3 | 0.25184935 | WT WTL H |
| 3 | 0.25980864 | ED H L |

```
N=73         REGRESSION MODELS FOR DEPENDENT VARIABLE: K  MODEL: MODEL2

NUMBER IN    R-SQUARE    VARIABLES IN MODEL
  MODEL

    1       0.00091371    MAK3
    1       0.00424020    MAK1
    1       0.01390398    MAK2
    1       0.08168057    DR
    1       0.11285000    TR
    1       0.12082336    ED
    1       0.15651330    H
    1       0.16845426    W
    1       0.17223619    TF
    1       0.20518847    L
    1       0.25696690    WB
    1       0.29986201    WT
    1       0.30117910    WTWB
    1       0.32898034    WTW
    1       0.33819796    WTL
----------------------------
    2       0.34723903    WTW L
    2       0.34762429    WTL W
    2       0.35019996    WTL WTWB
    2       0.35154740    WTWB ED
    2       0.35270539    WTW H
    2       0.36265813    WTW MAK2
    2       0.36400337    WTW MAK1
    2       0.36625504    WTW MAK3
    2       0.36831815    WTL MAK2
    2       0.36964139    WTL H
    2       0.37045656    WTL MAK3
    2       0.37655644    WTL MAK1
    2       0.37859860    WT ED
    2       0.38202110    WTW ED
    2       0.38559850    WTL ED
-------------------------------
    3       0.38674520    WTW ED MAK1
    3       0.38795006    WTL MAK3 H
    3       0.38826096    WTL MAK1 H
    3       0.38865615    WTW ED MAK3
    3       0.38883670    WT ED H
    3       0.38942809    WTL ED MAK2
    3       0.39047564    WTL FD MAK3
    3       0.39092512    WTW ED H
    3       0.39300387    WT ED L
    3       0.39335562    WTL ED L
    3       0.39428056    WTL ED WT
    3       0.39438392    WTL ED MAK1
    3       0.39568808    WTL ED WTW
    3       0.40481369    WTL ED WB
    3       0.40588434    WTL ED H
----------------------------------
```

N=73 REGRESSION MODELS FOR DEPENDENT VARIABLE: KW MODEL: MODEL3

| NUMBER IN MODEL | R-SQUARE | VARIABLES IN MODEL |
|---|---|---|
| 1 | 0.01232300 | MAK3 |
| 1 | 0.02178958 | MAK1 |
| 1 | 0.02533339 | TR |
| 1 | 0.03003203 | MAK2 |
| 1 | 0.03354352 | ED |
| 1 | 0.04618858 | W |
| 1 | 0.05692360 | TF |
| 1 | 0.05864276 | DR |
| 1 | 0.08375182 | L |
| 1 | 0.12282210 | WB |
| 1 | 0.13381037 | H |
| 1 | 0.15154950 | WT |
| 1 | 0.15798459 | WTWB |
| 1 | 0.19118125 | WTW |
| 1 | 0.19353178 | WTL |
| 2 | 0.23510303 | WTW W |
| 2 | 0.23628191 | WTL H |
| 2 | 0.24008483 | WTL MAK2 |
| 2 | 0.24128431 | WTW MAK2 |
| 2 | 0.24330144 | WTW L |
| 2 | 0.24353266 | WTWB ED |
| 2 | 0.24498566 | WTL MAK3 |
| 2 | 0.24809770 | WTW MAK3 |
| 2 | 0.24850512 | WTL W |
| 2 | 0.25012316 | WTW MAK1 |
| 2 | 0.25339083 | WTW WT |
| 2 | 0.25548651 | WTL MAK1 |
| 2 | 0.26287319 | WT ED |
| 2 | 0.28493321 | WTL ED |
| 2 | 0.29504313 | WTW ED |
| 3 | 0.29509721 | WTW ED WB |
| 3 | 0.29523250 | WTW ED DR |
| 3 | 0.29549111 | WTW ED TF |
| 3 | 0.29550893 | WTL ED MAK1 |
| 3 | 0.29557584 | WTW ED TR |
| 3 | 0.29717936 | WTW ED W |
| 3 | 0.29777914 | WTW ED WT |
| 3 | 0.29793750 | WTW ED MAK2 |
| 3 | 0.29828107 | WTW ED WTWB |
| 3 | 0.30037195 | WTW ED MAK1 |
| 3 | 0.30088372 | WTW ED MAK3 |
| 3 | 0.30205867 | WTL ED WTW |
| 3 | 0.30602098 | WTW ED H |
| 3 | 0.30921862 | WTW ED L |
| 3 | 0.30981010 | WTL ED H |