Determination of Impact Force and Crush Energy Using Abductive Networks

Oren Masory

Mechanical Engineering Department, Florida Atlantic University

Nicolas Putod

IFMA – Institut Francais De Mechanique Advancee, Les Cezeaux

ABSTRACT

Sensory based methods as well as approximation methods are currently being used to determine the impact force and the crush energy pertained to vehicles' collision. This paper describes a method, based on Abductive Networks that can be used to develop explicit models by which the above quantities can be estimated. Similar to Neural Networks Abductive Networks are "trained", using experimental data and upon convergence, a model is established. Comparisons between the results, obtained by the different methods, indicate that the models obtained with this method provide more accurate results.

INTRODUCTION

The values of the impact force and the crush energy, generated in cars' collisions, are used to determine the vehicles' pre and post crash speeds as well as the severity of the accident from the passengers' injuries point of view. Both quantities can be calculated using a set of coefficients, which characterize the stiffness of the vehicle's structure and were predetermined experimentally and the measurements of the crush in both vehicles [2, 4]. If sensory data are provided, in particular accelerometers' readings from the airbag module, the value of the impact force is readily available and the crush energy can be calculated [5].

The difficulties with the first method include inaccurate stiffness coefficients [4] and simple models for the impact force and the crush energy. As a result, large errors in the estimation of the vehicles' speeds are expected. To improve accuracy, stiffness coefficients are provided for different categories of vehicles, such as passenger car or van, and within each category for different range of wheel bases dimension.

This paper proposes a different approach by which models for the impact force and the crush energy will be obtained automatically by training Abductive networks using a set of experimental data. Once the model is obtained it can be used to determine these quantities for cases which were not included in the training set.

In this study one set of crush and sensory data from crash tests, performed by NHTSA, were used for training and another set for verification of the model. The results obtained by this model were compared with the results obtained by CRASH3 both relative to the actual sensory data. To demonstrate this method this study deals only with front collision with a fixed rigid barrier covering the whole width of the vehicle.

The results indicate that the estimation for the impact force and the crush energy obtained by the proposed method is more accurate than the ones obtained by CRASH3 method.

AIM OVERVIEW

AIM is a powerful supervised inductive learning tool for automatically synthesizing network models from a database of input and output values. The model emerging from the AIM synthesis process is a robust and compact transformation implemented as a layered Abductive network of feed-forward functional elements as shown in Figure 1.
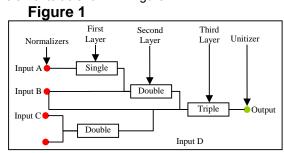
Figure 1

Figure 1 - Example Abductive Network.

All the functional and connection elements are learned from the input data. Currently AIM has seven types of elements. The algebraic form of each element is a polynomial where W_n are the coefficients determined by AIM and X_n are the input variables (Table 1 shows sample elements).

1

All terms in an element's equation may not appear in a node since AIM will throw out or carve terms which do not contribute significantly to the solution.

Table 1: Examples of elements definition.

Single	$W_0 + W_1 * X_1 + W_2 * X_1^{\ 2} + W_3 * X_1^{\ 3}$
Double	$W_0 + W_1 * X_1 + W_2 * X_2 + W_3 * X_1^{\ 2} + W_4 * X_2^{\ 2} +$ $W_5 * X_1 * X_2 + W_6 * X_1^{\ 3} + W_7 * X_2^{\ 3}$

The eligible inputs for each layer and the network synthesis strategy are defined in a set of rules and heuristics which are an inherent part of the synthesis algorithm.

AIM automatically determines the best network structure, element types, coefficients and connectivity by minimizing a modeling criterion which attempts to select as accurate a network as possible without over fitting the data. The modeling criterion used within AIM is the Predicted Squared Error (PSE). The PSE is a heuristic measure of the expected network squared error for independent data not in the training database. The PSE is given by:

$$PSE = FSE + KP \tag{1}$$

where FSE is the fitting squared error of the model on the training data and KP is a complexity penalty term determined in AIM by the equation:

$$KP = CPM * \frac{2K}{N} s_p^{\ 2} \tag{2}$$

where K, N and $s_p^{\ 2}$ are determined by the database of examples used to synthesize the network and CPM, the Complexity Penalty Multiplier, is a variable the user can select. The default value of CPM is 1; a lower value decreases the complexity penalty impact and results in a more complex network and inversely for a higher value.

To create a model using AIM one has to follow these steps:
1. Decide what are the inputs and the output of the model.
2. Create a database which includes sets of inputs and the corresponding outputs from the process being modeled.
3. Train the Abductive network using the above database.
4. Evaluate model performance of the model using sets of inputs/outputs which were not used to train the network.
5. Once the network (model) performs to satisfaction an explicit model can be derived and implemented.

CURRENT ESTIMATION METHODS

Method based on crush measurements

CRUSH3 algorithm [2] is a simple, most commonly used, model for the estimation of the impact force and the crush energy during collision.

The estimation is based on measurements of the actual crush depths and a set of stiffness coefficients characterizing the particular vehicle. It is assumed that these coefficients are roughly the same for each class of cars, characterized by wheelbase dimensions.

Different stiffness coefficients, A and B that were found experimentally [3], are used to accommodate frontal, side or rear impacts.

The impact force, F, is determined by:

$$F = L(A + B\overline{C}) \tag{3}$$

where L is the crush indentation width and $\overline{C}$ is the average depth of crush, measured according to a protocol detailed in [1].

The crush energy, E, is given by:

$$E = \frac{L}{30}\left[\begin{array}{l} 3A(C_1 + 2C_2 + 2C_3 + 2C_4 + 2C_5 + C_6) + \\ B(C_1^{\ 2} + 2C_2^{\ 2} + 2C_3^{\ 2} + 2C_4^{\ 2} + 2C_5^{\ 2} + C_6^{\ 2} + \\ C_1 C_2 + C_2 C_3 + C_3 C_4 + C_4 C_5 + C_5 C_6) + 30\frac{A^2}{2B} \end{array} \right] \tag{4}$$

where C_i are equally spaced crush indentation values along the indentation length.

The accuracy of this algorithm depends on the accuracy of the stiffness coefficients as well as the accuracy of the crush indentations. The stiffness coefficients as well as the vehicles classification are being updated from time to time to accommodate for major changes in vehicle's structure designs and the introduction of new designs [4].

Sensory Based Method

This method is based on the crash test experiments realized by the NHTSA or acceleration data available from the airbag module. It is assumed that the acceleration signal is sampled with sufficient rate to capture the actual acceleration the vehicle has experienced at impact. The maximum value of impact force can be obtained directly from this signal:

$$F_{max} = m \cdot a_{max} \tag{5}$$

where m is the vehicle's mass

Similarly, the average value of the impact force can be obtained by:

$$F_{average} = ma_{average} = \frac{m}{\Delta T} \sum_{i=0}^{N=\frac{\Delta T}{T}} a(iT) \qquad (6)$$

where a is the acceleration, N is the number of samples and T is the sampling period and ΔT is the impact duration time

The acceleration signal can be integrated with respect to time in order to determine the vehicle velocity, v. The sampling rate is usually very high, so any numerical integration method can be used. Using trapezoidal integration, the velocity at instant k, is given by:

$$v(kT) = v_0 + \frac{T}{2} \sum_{i=1}^{k} \langle a(iT) + a[(i-1)T] \rangle \qquad (6)$$

where v_0 is the approach velocity

A second integration will yield the vehicle displacement $s(kT)$:

$$s(kT) = \frac{T}{2} \sum_{i=1}^{k} \langle v(iT) + v[(i+1)T] \rangle \qquad (7)$$

Using the above results, the crush energy, E, can be determined by:

$$E = m \sum_{i=1}^{k} a(i)[s(iT) - s\langle(i-1)T\rangle] \qquad (8)$$

where kT is the time when the vehicle's velocity is zero.

This method has been demonstrated in [5] using sensory data provided by NHTSA. In this particular reference, it has shown that most of the signal energy is contained in very low frequencies (below 50 Hz) and therefore in this study a Low Pass Filter with a cutoff frequency of 100 Hz was used to filter the raw acceleration signal.

THE MODEL PROCESS

Create a database

A data base, which contains the information items shown in Table 2, for 50 different passenger vehicles, was constructed. Vehicle information and the crush indentation were extracted directly from NHTSA data base and the impact force and crush energy was calculated using acceleration data given at the same data base. The assignment of these items as input to or output from the model is also indicated in the table.

Table 2: Data base information.

Parameters	Symbol	Unit	State
Wheelbase	Wheelbase	mm	Input
Weight	Weight	kg	Input
Indentation Length	Indentation	mm	Input
Crush Depth 1	C1	mm	Input
Crush Depth 2	C2	mm	Input
Crush Depth 3	C3	mm	Input
Crush Depth 4	C4	mm	Input
Crush Depth 5	C5	mm	Input
Crush Depth 6	C6	mm	Input
Maximum Force	Force	N	Output
Crush Energy	Energy	Joules	Output

Obtaining models through Training

The network was trained using 50 sets of data from the data base. The best models have been obtained by adjusting the CPM value. The effect of the CPM values on the models' performance is shown in Tables 3 and 4. The errors indicate the model capability to predict the output given data which was used for training,

Table 3: Impact Force

CPM	1	0.5	0.25	0.1
Average Error (%)	11.99	11.14	9.68	9.65
Max Error (%)	31.7	29.27	31.71	32.49
Min Error (%)	0	0.08	0	0

Table 4: Crush Energy

CPM	1	0.5	0.25	0.1
Average Error (%)	10.53	8.45	7.86	7.46
Max Error (%)	37.58	28.02	27.57	24.44
Min Error (%)	0.00	0.00	0.00	0.00

Based on the results in Tables 3 and 4, for impact force model the CPM value was set to 0.25 and for crush energy to 0.1.

COMPARISON WITH OTHER METHODS

To compare the performance of the Abductive network model to other methods the following steps were taken:
1. A new set of 50 passenger vehicles was selected and the relevant data was extracted from the NHTSA data base.
2. The impact force and the crush energy were determined using the three methods mentioned above.
3. The results from by the CRUSH3 method and the model obtained from the trained Abductive network were compared to each other using the result obtained by the sensory method as a reference.

The reason for selecting the results obtained by sensory method as a reference is to due the fact that the values were obtained directly from sensors that were mounted on the vehicle during the collision. These sensors were carefully calibrated and were mounted on the vehicles' chassis and as result the acceleration readings are very accurate.

Figure 2 illustrates the absolute error in percentage of the impact force between the results obtained by CRUSH# and the results obtained by Abductive model with respect to the results obtained by the sensory method. As shown for most cases the Abductive model provides slightly better results and its average error is about 3% lower than the average error produced by the CRUSH3 method.

Table 5 provides the statistics related to these results.

Figure 3 demonstrates the direct relationship between the results obtained by the sensory and the Abductive methods.

Table 5: Comparison results

	Force		Crush Energy	
	Crush3	AIM	Crush3	AIM
Average =	21.34	18.15	22.87	16.74
Maximum =	60.28	86.00	61.71	47.77
Minimum =	0.06	0.20	1.86	0.83

Similarly, Figure 4 shows the absolute errors obtained by both methods in the estimation of the crush energy. In this case the Abductive method provides better result than the CRUSH3 method. On the average, the Abductive method error are 6% lower than the ones produced by Crush3 one.

Similar to Figure 3, Figure 5 shows the relationship between the results obtained by the sensory and the Abductive methods.
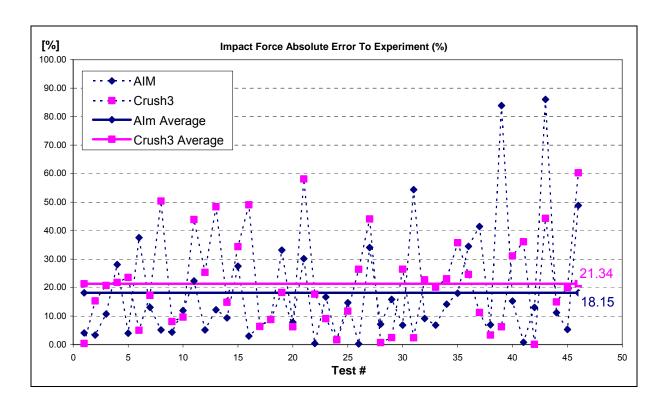

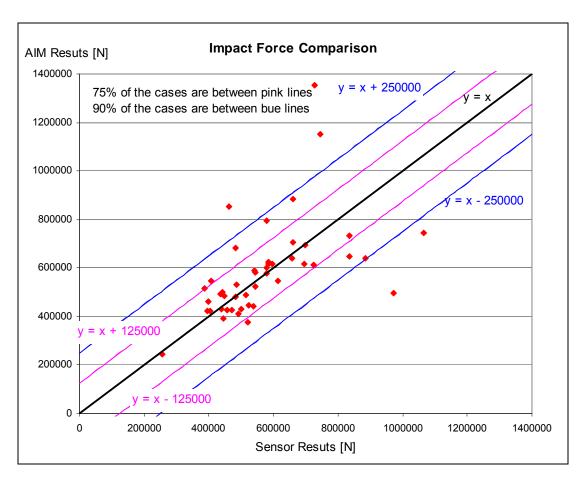Figure 2: Impact Force absolute error relative to experimental data.

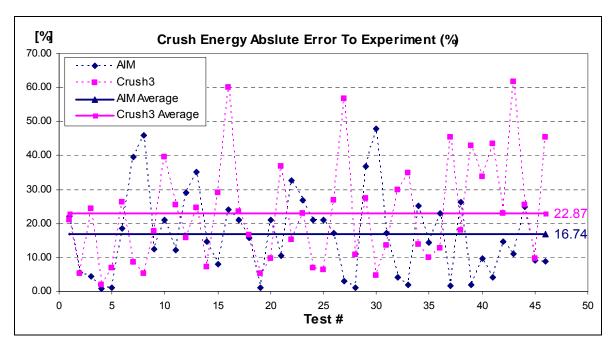Figure 3: Impact force results – Abductive method versus Sensory method.

Figure 4: Crush Energy absolute error relative to experimental data.
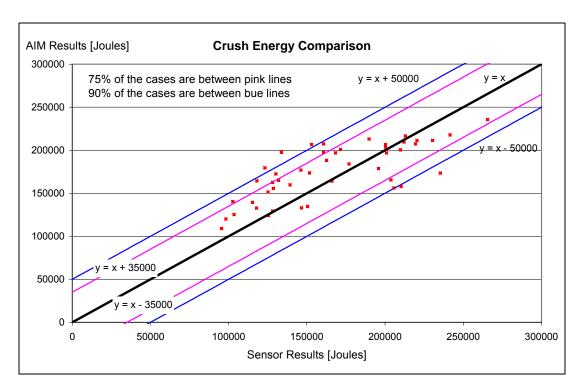
Figure 5: AIM/Sensor Comparison

IMPACT SPEED CALCULATIONS

In most accident reconstruction cases the pre-collision speed is sought. The Principle of Energy Conservation is used for this purpose and it is formulated for this case as follows:

$$E_{K,Initial} = E_{Crush} + E_{K,Final} \qquad (9)$$

where E_k is the kinetic energy and E_{Crush} is the crush energy. Explicitly it is given by:

$$\frac{1}{2} m \cdot V_{Initial}^2 = E_{crush} + \frac{1}{2} m \cdot V_{Final}^2 \qquad (10)$$

where $V_{initial}$ and V_{final} are the pre and post collision speeds of the vehicle. Arranging Eq. 11 yields the required speed:

$$V_{Initial} = \sqrt{2 \frac{E_{Crush}}{m} + V_{Final}^2} \qquad (11)$$

In most cases, the kinetic energy that corresponds to the post impact speed is very small (few percents) and can be neglected. Thus, the initial speed value is determined by:

$$V_{Initial} = \sqrt{2 \frac{E_{Crush}}{m}} \qquad (12)$$

The crush energy results obtained by the Abductive and the CRUSH3 methods the corresponding pre-speeds were calculated by Eq. 13. These results were compared with the pre-speed information that is provided in the NHTSA database. The errors in the pre-speed estimation are shown in Figure 6. As indicated the average error produced by the Abductive model is below 5% while the average error produced by the CRUSH3 model is above 14%.

CONCLUSION

The results obtained in this paper indicate:
1. The estimated values for the impact force and the crush energy obtained by the Abductive model are more accurate than the ones obtained by the CRUSH3 model.
2. It is important to empahzise that even though the Abductive model is by far more complex than the simple linear model it does not provide substantially more accurate results.
3. The development process of the Abductive model is straight forward and does not require any assumptions.
4. The results obtained by the Abductive model can be improved by including additional inputs, e.g. vehicle classification by wheel base.
5. Since the model development process is so easy it will be possible to update the model as more experimental data become available.
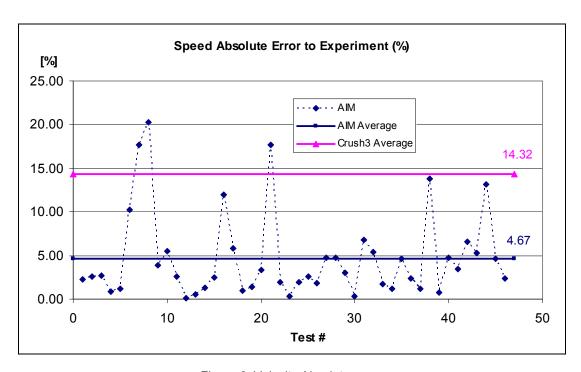
6

Figure 6: Velocity Absolute error.

REFERENCES

1. AIM User's Manual, AbTech Corporation, 1990

2. CRASH3 User's Guide and Technical Manual, NHTSA, 1981

3. NHTSA Web site: www.nhtsa.com

4. Donald E. Siddall, Terry D. Day, "Updating the Vehicle Class Categories", SAE Paper #960897, 1996

5. O. Masory, C. Favrot, "Determination of Impact Forces and Crush Energy Using Sensory Data and Comparison with Other Algorithms", Proc. 15th Florida Conference on Recent Advances in Robotics, May 23-24, 2002.