Computer-Based Methodology for the Generalized Design of the Connecticut Impact Attenuation System

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Impact attenuation devices are employed to minimize the adverse effects of a run-off-the-road accident. In particular, crash cushions should trap or redirect the errant vehicle without subjecting its occupants to unacceptably high dynamic forces. This paper describes the development of the Connecticut Attenuator Design System (CADS,) which implements a design strategy for a generalized version of the Connecticut Impact Attenuation System (CIAS) when supplied with basic information concerning the dimensions of the site and the design speed of the roadway. The program incorporates the crash testing guidelines and performance requirements of *NCHRP Report 230*, along with an accurate mathematical model of the vehicular and occupant impact responses. Turbo Pascal is employed as the implementation language using an object-oriented programming approach. The knowledge used to design the impact attenuator as well as the knowledge representation are described. The validity of the techniques is demonstrated by comparing the mathematical simulation to actual full-scale crash test results. An example problem involving 60-mph impacts with 1,800- and 4,500-lb vehicles is presented in which the crash cushion configuration and individual energy dissipating components are designed in such a way that the occupant risk parameters are minimized.

Crash cushions are impact attenuation devices used in highway safety applications to shield errant vehicles from rigid objects along the roadside where head-on impacts are possible. Examples of crash cushion locations include

- Exit ramps and gore areas,
- The ends of longitudinal barriers such as bridge rail ends, and
- In front of abutments, retaining wall ends, and bridge piers.

Crash cushions are designed to bring errant vehicles to a controlled stop in head-on impacts. Under side-impact conditions, crash cushions either redirect or contain the vehicle, depending on the design of the system.

In 1980, the California Department of Transportation completed 5 years of monitoring impact attenuators with video systems (*1*). Its report strongly recommended that further design work be done to make all crash cushions more energy absorbent when struck along the side. A recently developed crash cushion that possesses this characteristic is the Connecticut Impact Attenuation System (CIAS) (*2–4*). The CIAS traps the errant vehicle when it impacts the unit on the side unless the area of impact on the device is so close to the back of the system that significant energy dissipation and acceptable deceleration responses are unobtainable because of the proximity of the hazard. Only in this situation will the impact attenuation device redirect the vehicle into the traffic stream. The CIAS, shown in Figure 1, employs steel cylinders as the energy dissipation components. These cylinders are bolted together, rest on a concrete pad, and are attached to an appropriate backup structure. Steel tension straps (ineffective under compressive loading) and compression pipes (ineffective in tension) are employed to effect redirection when the unit is impacted near the backup structure. This bracing system ensures that the crash cushion will stiffen when subjected to an oblique impact, providing the necessary lateral force to redirect the errant vehicle. On the other hand, the braced cylinders retain their unstiffened response when the attenuation system is crushed by impacts away from the back of the device (*5,6*). In 1986, following an 18-month in-service evaluation of four CIAS installations in Connecticut, FHWA declared the CIAS to be an operational crash cushion. It is currently being employed in the states of Connecticut and Tennessee as well as in the District of Columbia.

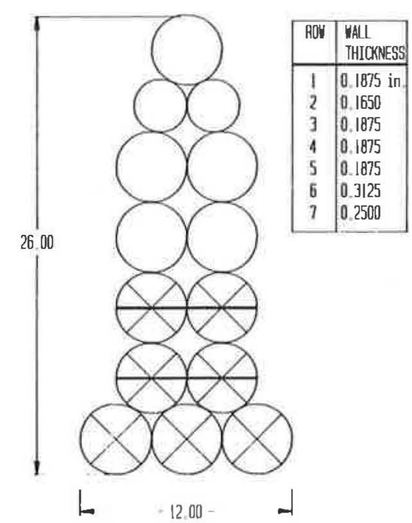

FIGURE 1 Connecticut Impact Attenuation System.

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One drawback with the installation of the CIAS is the fact that site limitations sometimes restrict its use. The currently operational system was designed for 60-mph impacts and is 12 ft wide at the rear and 26 ft long. Some sites require a narrower crash cushion or have lower design speeds. A generalized design of the CIAS, possessing all of the innovative features of the original CIAS and the added flexibility of variable geometry and design speed, could be installed in a much wider range of locations. In this paper, a methodology is described that optimizes the design of a site-specific CIAS. The program contains an impact response model that predicts the post-impact behavior of a hypothetical occupant in conformance with recommended crash testing guidelines (*7*). The design strategy is described in the following sections, and the accuracy of the impact response model is demonstrated. This is followed by a detailed example illustrating the individual steps in the generalized design process.

CRASH TESTING GUIDELINES AND PERFORMANCE GOALS FOR CRASH CUSHIONS

The effectiveness of a crash cushion is ultimately determined by means of a full-scale crash testing program and an analysis of its performance in the field. The required crash testing guidelines are contained in *NCHRP Report 230* (*7*).

As stated in that report, the performance objective of a roadside safety appurtenance is to "minimize the consequences of a run-off-the-road incident (*7*)." The goal is to bring the errant vehicle to a controlled stop or to redirect the vehicle away from the hazard without subjecting its occupants to serious injury. The performance of a device is judged on the basis of three criteria:

- Structural adequacy,
- Occupant risk, and
- Vehicle trajectory after collision.

The structural adequacy of an appurtenance is determined by its ability to interact with a selected range of vehicle sizes and impact conditions in a predictable and acceptable manner. The unit should remain intact during impact so detached debris do not present a hazard to traffic.

The occupant risk evaluation of a highway appurtenance when subjected to a high-speed impact involves the dynamic interaction of the vehicle and occupant. An essential crash test requirement of *NCHRP Report 230* is that the impacting vehicle remain upright during and after collision and that the integrity of the passenger compartment be maintained. In addition, the occupant-vehicle interior impact velocity and the maximum occupant ridedown acceleration must be less than certain limiting values (*7*).

The vehicle trajectory after collision is also of concern because of potential risk to other traffic. An acceptable vehicle trajectory after impact produces minimal intrusion into adjacent traffic lanes.

The crash test conditions for the minimum crash cushion matrix are presented in Table 1 (*7*). Occupant risk criteria are of particular concern in impact tests involving the front (or nose) of the system. These criteria include a hypothetical occupant impact velocity and subsequent ridedown acceleration. It is assumed that, following impact, the vehicle compartment surface accelerates toward the occupant, who is moving with the vehicular pre-impact velocity. After occupant impact with the vehicle interior, it is assumed that contact remains and the occupant experiences the same deceleration forces as the vehicle. The specific occupant risk requirements are given in Table 2, where F_1, F_2, F_3, and F_4 are usually assigned values between 1 and 1.33.

TABLE 1 REQUIRED CRASH CUSHION TEST MATRIX

Vehicle Type	Impact Speed (mph)	Impact Angle (deg)	Target Impact Severity (ft-kips)	Impact Point
4500S	60	0	541	Center nose of device
1800S	60	0	216	Center nose of device
4500S	60	20	63	Alongside, midlength
4500S	60	10-15	541	0-3 ft offset from center of nose of device

TABLE 2 OCCUPANT RISK REQUIREMENT (*7*)

Impact velocity of hypothetical front seat passenger against vehicle interior, calculated from vehicle accelerations and 24 inch forward and 12 inch lateral displacements, shall be less than:

Occupant Impact Velocity-fps	
Longitudinal	Lateral
$40/F_1$	$30/F_2$

and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger impact should be less than:

Occupant Ridedown Accelerations — g's	
Longitudinal	Lateral
$20/F_3$	$20/F_4$

where F_1, F_2, F_3, and F_4 are appropriate acceptance factors.

The design system to be described bases the acceptability of a CIAS design on the results of simulations of the zero-degree impact tests. The two-angle impact tests are not directly considered. The performance of a CIAS when struck at an angle does not hinge on its energy dissipation capability but, rather, on its redirectional capability. The redirectional capability of a CIAS is a result of the lateral stability produced by the triangular shape of each device and the bracing system. Incorporating these characteristics into each generalized CIAS ensures a response similar to the original CIAS, which met the performance criteria in each case.

CONNECTICUT ATTENUATOR DESIGN SYSTEM

Knowledge of crash cushion design is generally limited to those who specialize in the research and development of such devices. Heuristic knowledge of hundreds of crash tests, knowledge of the impact performance of materials, as well as knowledge of the required performance standards is not readily accessible to typical engineers in state departments of transportation. Typically, demand for highway impact attenuators arises from state or federal jurisdictions. Once an engineer concludes that a roadside hazard warrants a crash cushion, the problem of choosing a specific type remains. This choice is based primarily on cost, availability, and performance. There are a variety of competing attenuation systems available from private manufacturers that meet the criteria in some respect. The engineer supplies the manufacturer with the site characteristics; however, these characteristics may not correspond to the dimensions of one of the manufacturer's standard models. If a program were available that could design a competitive impact attenuator, the field engineer could assume a more active role in the selection, manufacture, and installation. The Connecticut Attenuator Design System (CADS) allows a state engineer to formulate the design of a CIAS specifically suited to a particular site.

Because the engineers do not typically have the detailed knowledge required to design a CIAS, CADS must act as an independent designer that, when given the site-specific parameters, can completely design the attenuator. The engineer has the option of performing the design manually after becoming familiar with the strategy. The reliability of the design is based on a mathematical model that accurately predicts the performance of a particular CIAS. CADS justifies its design by demonstrating that it meets the occupant risk criteria recommended by *NCHRP Report 230*.

The basic organization of CADS is shown in Figure 2. The system is made up of four main modules:

- Data acquisition,
- Design,
- Output, and
- Explanation.

Before the design process can begin, the engineer must provide the specific characteristics of the intended attenuator site. The data acquisition module of CADS gathers such information as the required width of the rear of the system and the design speed. Any conflict between this information and the limits set for a CIAS application is checked at this point. This module also contains error-handling routines and functions performing standard calculations, such as total length of the CIAS or the weight of an individual cylinder.

The design module comprises the bulk of CADS. It is made up of subblocks corresponding to the various steps in the design, which are discussed later in detail. In short, there are four steps in the design:

1. Configuration of cylinder diameters,
2. Satisfaction of energy dissipation criteria,
3. Selection of the braced components, and
4. Installation details.

First, the configuration step involves specifying the diameters of the cylinders so the plan view of the CIAS maintains a triangular shape. Next, cylinder thicknesses are chosen based

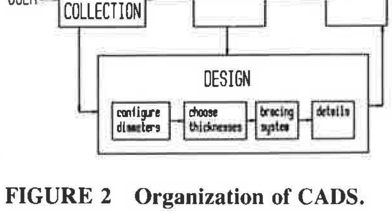

FIGURE 2 Organization of CADS.

on the occupant safety criteria of *NCHRP Report 230*. Once designed for the zero-degree impact, the CIAS is fitted with the proper bracing system so the system has the stiffness for redirectional capabilities. The final step consists of providing design details such as the cylinder connections, backup structure, and base pad.

The output module contains the procedures for graphical displays and output file creation. Details of the design are presented in tabular form on the display as the design progresses, and a drawing of the completed CIAS design is displayed. The design can be documented in permanent disk file storage. This documentation is sufficiently detailed that the attenuator can be manufactured by a third-party vendor.

The explanation block can be employed whenever the user is prompted. At selected stopping points, information relevant to that stage of the design is available. These points include the beginning of the program, when the user is prompted for data, the beginning and end of subblocks of the design module, and the completion of the design. For instance, if a design speed of 60 mph were input in the data-acquisition module, a minimum of approximately 25 ft of length would be required for installation. If the user indicated this length was not available, an explanation stating the conflict would be activated. Also, during the design the user may access material containing more specific information about a step. The user is informed in situations when the CIAS is not the definitive choice for a given site.

KNOWLEDGE REPRESENTATION AND IMPLEMENTATION

Since state DOTs are the intended end users, IBM-PC compatible computers have been selected as the implementation hardware. This type of computing machinery is available to most state engineers. Initially, an implementation was attempted using a rule format as the knowledge representation paradigm. A prototype system was implemented in the rule-based expert system shell Insight 2+ (*8*). Insight 2+ is characterized by a simple syntax and user friendliness, which makes it a useful development tool. It became apparent, however, that as the knowledge base grew and the iterative nature of design problems became evident, a simple rule-based approach would lack versatility and speed.

An effective design system should be able to represent its design graphically. This is necessary to enhance user friendliness and reduce the amount of textual material required for some explanations. Other PC-based packages lacked graphics facilities or the ability to interface with graphics software. The Turbo Pascal language (*9,10*) is currently being used and has proven to have the necessary requirements. Also, applications developed with Turbo Pascal can be compiled into executable files resulting in software independent of copyright and licensing difficulties.

The implementation follows an object-oriented style of programming. This programming paradigm has been found to be ideal for problems where the programmer must represent a collection of interacting objects, such as in a simulation (*11*). Object-oriented programming involves decomposing a problem into a class hierarchy of objects (*12*). Each object has a number of attributes that define its characteristics. For example, Figure 3 shows the two main objects involved in the problem: the attenuator and the vehicle. The object class "Attenuator" is then broken into subobjects or subclasses, which more specifically describe the attenuator. The class "Cylinder" is a subclass of "Row," which is itself a subclass of Attenuator. A cylinder has attributes including a diameter and a thickness. These attributes are used by Row to calculate its attributes of weight or energy dissipation capability. Similarly, Attenuator needs information about each of its rows to find values for its attributes, such as total attenuator length and weight.

In a design problem, the objects to be designed are incomplete until the proper values for all attributes are selected. Object-oriented terminology defines a method as a block of code containing certain instructions. The methods used to design the object are the knowledge base. When a method is called to act on an object, it is said that a message is sent to that object. Objects and methods comprise the basic elements of object-oriented programming.

In the attenuator design application, objects are defined using the Pascal record data structure in the type declaration. As seen in the example of the automobile class in Figure 4, attributes of varying types are easily defined. When all objects in the problem have been defined, variables are then declared and termed "Instances" of a class, such as

VAR LTCAR, HYCAR : AUTO;
CIAS : ATTENUATOR;

where LTCAR and HYCAR are the 1,800- and 4,500-lb automobiles, respectively, and represent instantiations of the class "Auto." CIAS is a particular instantiation of the class Attenuator. Since the vehicles are not being designed, values of their attributes pertinent to the design of the CIAS are assigned via an initialization procedure. Pascal procedures parallel methods in functionality. That is, the procedures in CADS contain the knowledge necessary to design the CIAS.

In languages specifically designed for object-oriented programming, the methods are defined similarly to attributes of an object such that they are internal to the object. The object-oriented program is driven by messages sent between the objects, which triggers the application of methods. In CADS, since the objects and procedures are separate, the main program is the controlling module and acts as the message sender. That is, the controller calls the proper procedures based on the algorithm that describes the design process, thus activating the main blocks of CADS.

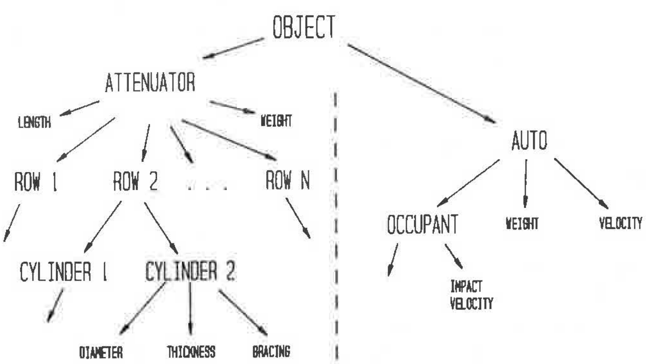

FIGURE 3 Representation of object class hierarchy.

```
TYPE
occupant = record                                   {OCCUPANT CLASS}
        ov : array[1..5] of real;                   {occupant velocity change}
        vaccuum:array[1..5] of real;                {accumulated occupant velocity}
        d:array[1..5] of real;                      {distance traveled inside compartment}
        daccum : real;                              {accumulated distance traveled}
        impvel : real;                              {impact velocity}
        impt : real;                                {time of impact}
        impact : boolean;                           {occupant impact}
end;

auto = record                                       {AUTO CLASS}
        occup: occupant;                            {occupant becomes subclass of auto}
        w:real;                                     {weight}
        v:array[1..maxrows] of real;                {velocity}
        waccum:array[1..maxrows] of real;           {accumulated weight}
        e:array[1..maxrows] of real;                {energy of automobile}
        dv:array[1..maxrows] of real;               {change in velocity}
        dc:array[1..maxrows] of real;               {deceleration}
        t:array[1..maxrows] of real;                {time to crush a row}
        taccum:array[1..maxrows] of real;           {accumulated time of crash event}
        stopped : boolean;                          {energy of auto dissipated}
end;
```

FIGURE 4 Example of object class declaration in Turbo Pascal.

DESIGN STRATEGY

The CIAS design process can be divided into several well-defined steps. The first is to obtain the correct width and length for the given site conditions. The width at the rear of the attenuator is based on the width of the backup structure, which is given the same width as the hazard. In order for the attenuator to redirect vehicles impacting near the rear of the device, it must be slightly wider than the backup structure. Testing has shown that the attenuator-backup connection must be offset from the edge of the backup by 6 in to prevent a failure of the connection. This offset is shown in an example system later in this paper. Imposing this constraint, the width of the CIAS is:

$$WA = 3(WB - 1)/2 \tag{1}$$

where WA and WB are the widths of the attenuator and backup in feet, respectively.

The factors used to determine the necessary length are much less concrete. A rough estimate of the distance required to stop a vehicle can be calculated when the design speed and a maximum average deceleration are given. For example, a 60-mph design speed and a 5-g maximum deceleration (one-third the maximum for the 10-ms window) gives a required stopping distance of 24 ft. Since the light and heavy cars cannot both use the entire length of the attenuator, their differing energies must be taken into account. Also, there is an upper bound on the attenuator length beyond which the device becomes impractical. By weighing these factors and drawing on experience, a length on the order of 25 ft was chosen for the 60-mph case. Lengths for other design speeds are chosen proportionally to this standard.

The next step is to choose the proper configuration for the cylinders. Given that the back row has three cylinders and the front row a single cylinder, diameters of the cylinders are chosen from back to front. The back row, by default, has a diameter equal to one-third of the width. The two variables available are the number of rows and the increment in which adjacent rows differ in diameter. Initial values are chosen and then adjusted until the length constraint is satisfied. A minimum constraint of 2 ft is also imposed on the cylinder diameter. Using this process, the plan view of the attenuator attains a triangular shape. This triangular shape is desired for the stability and stiffness of the system during impacts other than head-on.

After the configuration of the system has been determined, the designer module can specify the thickness of each cylinder such that the kinetic energy of the vehicle is dissipated in an acceptable manner. Ten standard cylinder thicknesses are available to CADS ranging from ⅛ to ⅜ in. A preliminary design is developed by setting all thicknesses to the ⅛-in minimum. This ensures that the occupant impact velocity criteria is initially satisfied. The task, then, is to dissipate the energies of the light and heavy vehicles while not violating this safety constraint. Each change to the design must be tested with the mathematical model simulating the crash event.

Complications arise when considering both the 1,800-lb car and 4,500-lb car cases and the safety of passengers in each case. The attenuator must possess the energy dissipation capacity to stop the large car (structural adequacy criteria) while remaining flexible enough to ensure the safety of the light car's occupant (occupant risk criteria). To solve this problem, CADS must dissipate as much energy at the front of the system as possible; therefore, the impact velocity of the occupant of the light car will be as close to the maximum as possible. Later, after designing for the dissipation of the heavy car's energy, the impact velocities of the passengers are reduced if possible.

VALIDATION OF THE CRASH TEST MODEL

To develop CADS, it was necessary to uncover the underlying process governing the behavior of the CIAS. The mathematical model of the zero-degree test incorporates both heuristic knowledge obtained from experimentation and basic knowledge of engineering and science. This model is used to predict the crashworthiness of a trial CIAS design. For instance, it is known from experiments involving individual steel cylinders that the energy dissipation capability of an individual cylinder is significantly increased under dynamic loading conditions (*6*). Using this information, the designer is able to predict, with a high degree of confidence, how much energy a row of cylinders in the system will absorb when crushed by the vehicle. Also, full-scale crash tests revealed that, as a vehicle impacts the attenuator, the rows crush independently from front to back. These two pieces of information allow the crash event to be divided into individual impacts of each row.

The model keeps track of the state of the crash event as the vehicle crushes a row. Initially, the vehicle impacts the attenuator with a kinetic energy given by

$$E_0 = 1/2\ m\ v_0^2 \tag{2}$$

where

E_0 = initial energy,
m = mass, and
v_0 = initial velocity of the vehicle.

After a row is crushed, the energy of the vehicle is decreased by the energy absorbing capacity of that row. Because the collision is plastic, the mass of each row is added to the mass of the vehicle as they are collapsed. The new velocity of the vehicle is derived using the law of conservation of energy as

$$\left\{\frac{m + dm}{2}\right\} v_f^2 = \frac{m\ v_i^2}{2} + E_{row} \tag{3}$$

where

dm = change in mass,
v_i = initial velocity,
v_f = final velocity, and
E_{row} = energy absorbed by the row.

Assuming the change in velocity is linear over a row, the average deceleration can then be found from

$$a = (v_i^2 - v_f^2)/2s \tag{4}$$

where a (in this case negative), is acceleration and s is the distance traveled. The time it takes to crush a row is the change in velocity over the row divided by the deceleration that occurred, which can be shown as

$$t = dv/a \tag{5}$$

The actual time, then, is the accumulation of the relative times.

Occupant risk data is typically generated from the impact event acceleration-time data acquired in a full-scale crash test. Occupant risk predictions are made in much the same way in the mathematical model. The motion of the passenger is described relative to the vehicle; therefore, the increase in the relative passenger velocity is equal to the decrease in the vehicle velocity. The distance the passenger moves forward in the vehicle compartment is the average velocity of the passenger over a row multipied by the time elapsed. The position and velocity calculations are continued until the passenger has traveled over the 2-ft limit recommended by *NCHRP Report 230*. Straight-line interpolation is used to predict the impact velocity and time of impact at 2 ft.

Proving that the numerical model does, in fact, simulate an actual crash involved a comparison of full-scale test data and the predictions of the model. The results of three such tests involving different vehicle weights and slight variations in the original CIAS design were analyzed. A 5,400-lb pickup, 4,500-lb Plymouth Fury, and 1,800-lb Honda Civic were used in head-on impacts at 60 mph. High-speed film and accelerometer output were used to generate velocity-versus-time plots.

The film analyses were conducted on a NAC motion analyzer interfaced with a SUN workstation. The location of the vehicle is defined relative to a stationary point on the film, such as the backup structure, light post, or any stationary object in view throughout the entire crash event. This relative location is then measured at regular intervals (e.g., five frames equals 0.01 sec at a film speed of 500 ft/sec) until the forward motion of the vehicle stops. Hence, a deformation-versus-time plot of the crash event can be generated. By calculating the film speed and a conversion factor to translate film analyzer units to feet, the data can be converted to units of feet and seconds. From this data, velocity-versus-time plots, decelerations, and occupant impact velocities are obtained.

The next step is to input the CIAS design used in each full-scale test into the CADS model. The simulations generated are then compared with the actual data. Figures 5, 6, and 7 show a velocity-versus-time plot for each vehicle. The predictions of the model are in close agreement with the full-scale tests, especially early in the crash event—before the occupant has impacted the interior of the vehicle compart-

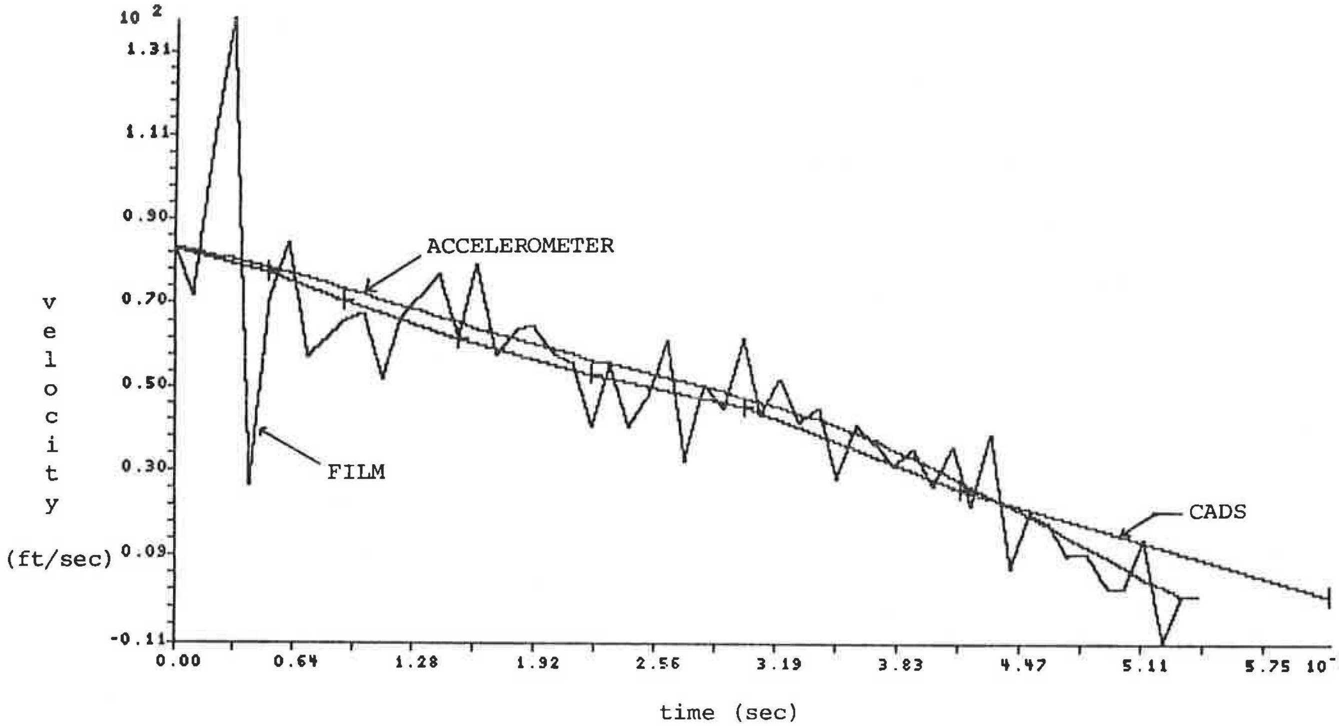

FIGURE 5 Velocity vs time plots for the 5,400-lb pickup crash test.

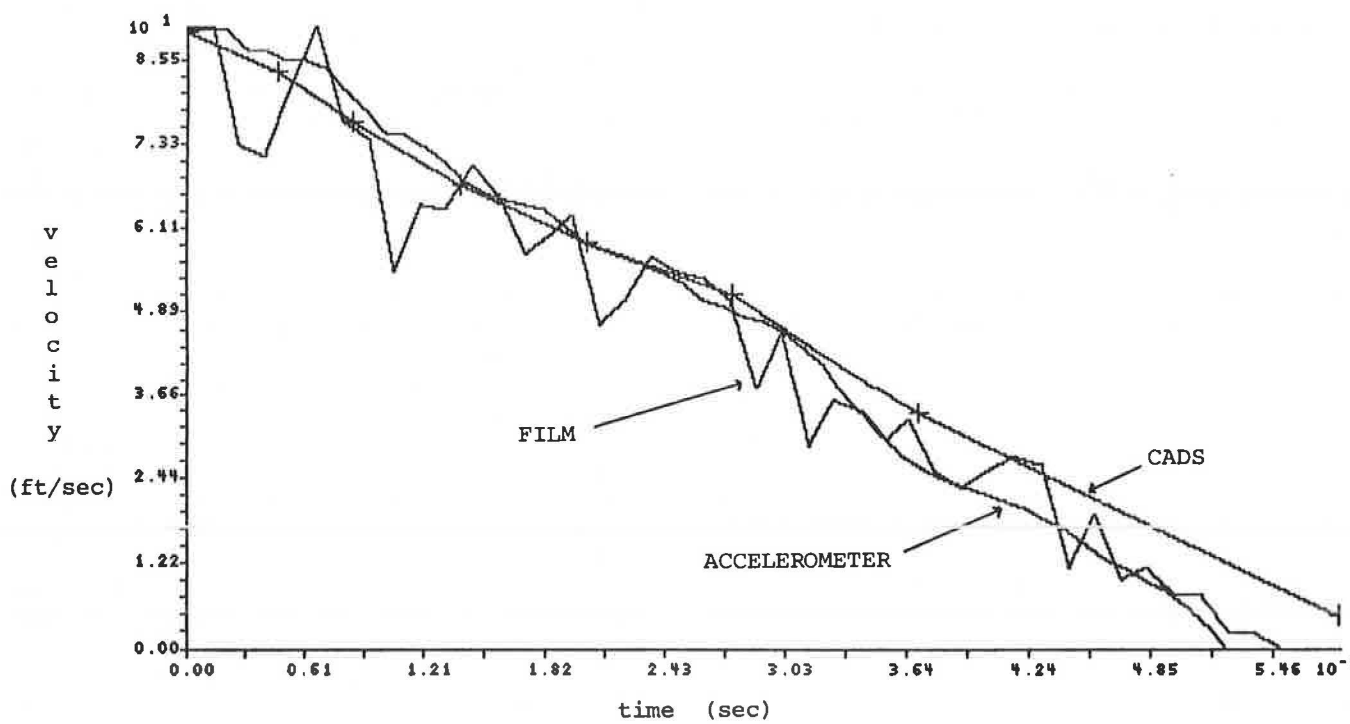

FIGURE 6 Velocity versus time plots for the 4,500-lb Plymouth Fury crash test.

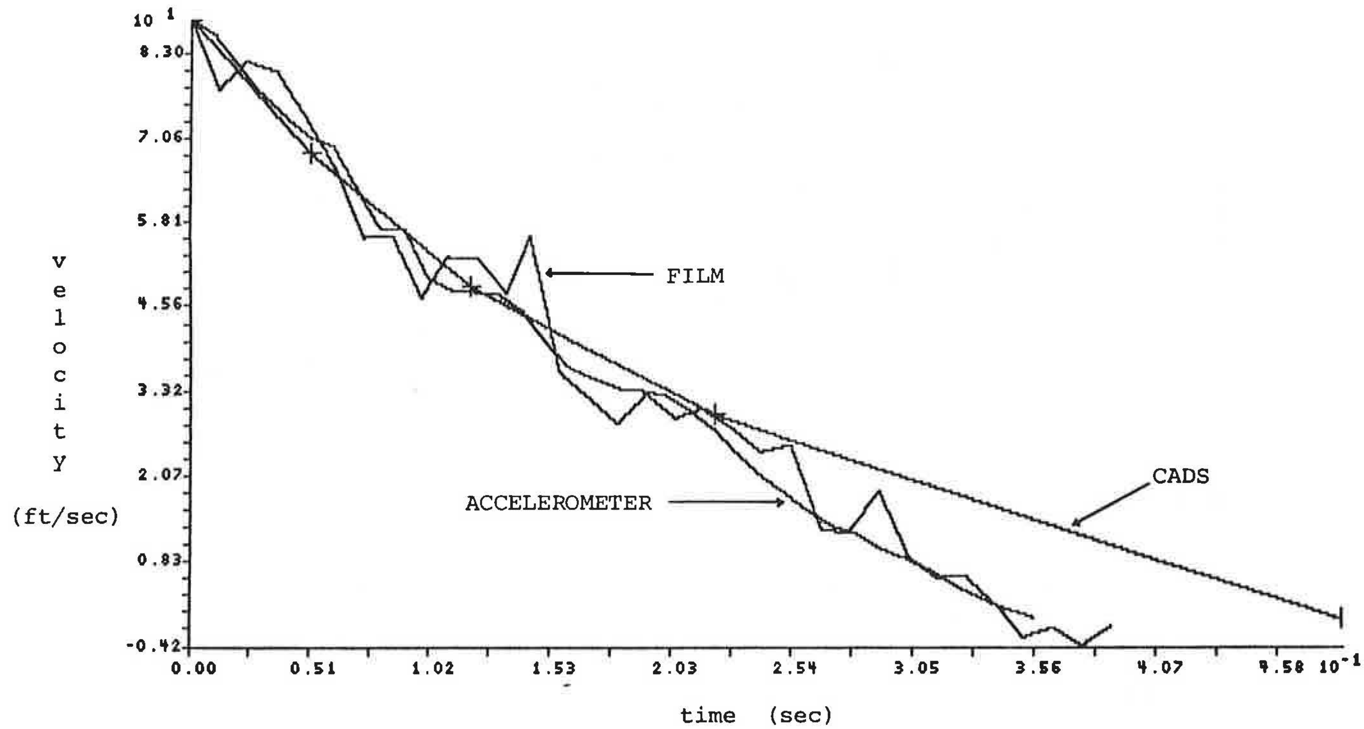

FIGURE 7 Velocity vs. time plots for the 1,800-lb Honda Civic crash test.

TABLE 3 OCCUPANT IMPACT VELOCITY PREDICTIONS (ft/sec) FROM FULL-SCALE TEST DATA AND CADS

	ACCELEROMETER	CADS
1800-lb HONDA CIVIC	39.25	37.97
4500-lb PLYMOUTH FURY	25.70	25.84
5400-lb PICKUP	23.02	24.95

ment. This is an important characteristic of the model because, after occupant impact (which generally occurs at or before the fourth row), the only concern is the ridedown deceleration. These decelerations are kept well below *NCHRP Report 230* guidelines as a factor of safety. Table 3 shows the predictions of occupant impact velocity from accelerometer data and the mathematical model. In all three cases, the CADS prediction is within 2 ft/sec of that calculated from accelerometer data.

Generalized CIAS designs are being manufactured for testing in the near future. The results of these will further verify the validity of the CADS crash test model.

EXAMPLE: 10-FT WIDE CIAS

Assume a site exists that warrants the installation of an impact attenuation device and the engineer chooses to investigate the use of the CIAS. The roadway design speed is 60 mph, and the hazard is 7 ft 8 in wide. Based on these site characteristics, CADS initially configured a 10-ft-wide system with a length of approximately 26 ft. Figure 8 shows the final configuration. The length had to be increased after the ridedown deceleration constraint could not be satisfied. The design has the proper plan view conforming to the width constraint and triangular shape for stability. The engineer must decide if this configuration is compatible with the intended site.

CADS iteratively determined the cylinder thicknesses using the crash event model. Table 4 shows a description of the design along with simulation data for each vehicle. Notice that the model determines the state of the vehicle before impact with the system and between rows thereafter. The values in the rows labeled "energy," "velocity," and "time" represent the state of the vehicle before the collapse of that row. For example, under the column for the first row, the values are the pre-impact conditions.

Occupant impact velocities and decelerations in rows where occupant impact has occurred are the most significant values. The maximum allowable occupant impact velocity was set at 30 ft/sec. The rows of the CIAS prior to the occupant impact row absorb as much energy as possible without violating this constraint. As shown previously, the CADS occupant impact velocity prediction would be very close to a prediction made with actual data. Also, because the model assumes constant decelerations, the actual values of a 10 ms deceleration may be significantly higher than the model reveals. For this reason, a maximum of 6.5 g was set. Figure 9 shows the velocity-versus-time plot of simulation data for each vehicle impacting the example design. The slope of the curves represents the deceleration of the vehicle. Comparing these curves with the corresponding curves for the Honda and Plymouth full-scale tests shows that the behavior of the new design closely resem-

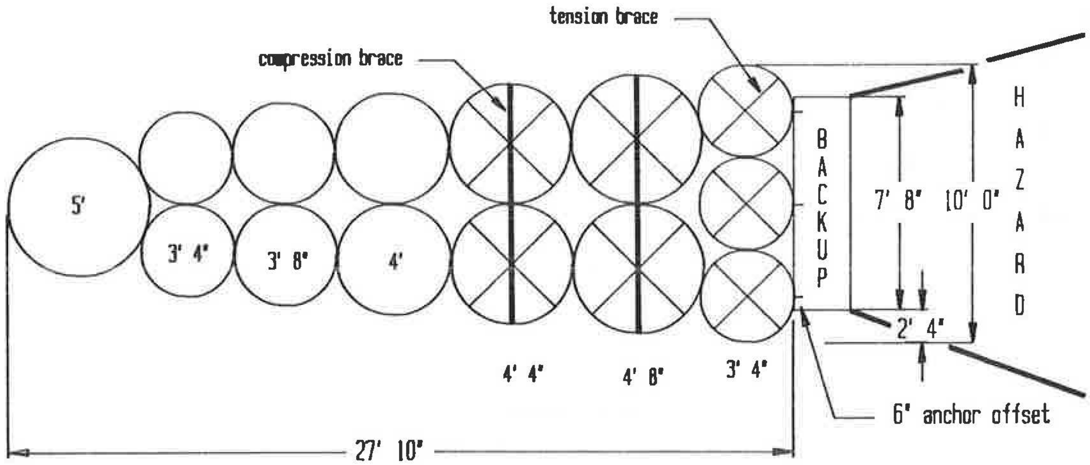

FIGURE 8 Example CIAS Design.

TABLE 4 RESULTS OF THE 10-FT-WIDE CIAS EXAMPLE RUN

DESIGN SPEED 60 mph WIDTH 10.00 ft LENGTH 27.91 ft	ROW 1	2	3	4	5	6	7	
CIAS Description								
Diameter (in)	60	40	44	48	52	56	40	
Thickness (in)	0.1644 Gage 8	0.1250 1/8	0.1250 1/8	0.1943 Gage 6	0.2500 1/4	0.3125 5/16	0.2500 1/4	
4500-lb Car Simulation								
Energy (kip-ft)	541.12	520.12	495.84	471.56	407.89	305.76	149.01	0.00
Velocity (ft/s)	88.00	82.51	77.28	72.26	63.04	50.51	32.29	0.00
Time (sec)	0.0000	0.059	0.100	0.149	0.209	0.285	0.398	0.609
Delta-V (ft/s)	5.49	5.23	5.02	9.22	12.52	18.23	32.29	
Deceleration (g's)	2.91	3.98	3.18	4.84	5.10	5.02	4.74	
OCCUPANT IMPACT VELOCITY = 23.89 ft/s occurs in Row 4								
1800-lb CAR SIMULATION								
Energy (kip-ft)	216.45	195.45	171.17	146.88	83.22	0.00		
Velocity (ft/s)	88.00	75.29	64.53	55.10	37.02	0.00		
Time (sec)	0.0000	0.061	0.109	0.170	0.257	0.458		
Delta-V (ft/s)	12.71	10.75	9.43	18.08	37.02			
Deceleration (g's)	6.45	7.00	4.78	6.46	5.73			
OCCUPANT IMPACT VELOCITY = 29.04 ft/s occurs in Row 3								

bles that of the original CIAS. In the simulation of the 1,800-lb car, the slope is significantly less severe than that for the test with the Honda.

CONCLUSIONS

The development of the Connecticut Attenuator Design System (CADS) has been described in this paper. The CADS generalizes the design of the Connecticut Impact Attenuation System (CIAS) so it can be optimally located in a wide variety of site configurations. CADS employs the guidelines of *NCHRP Report 230* to ensure that performance requirements relating to occupant risk are met. The individual cylindrical wall thicknesses are determined so that the occupant impact velocities and ridedown accelerations are minimized, subject to the dual constraints of system length and the required energy dissipation capacity. This computer-based design system allows the nonexpert to design site-specific versions of the CIAS.

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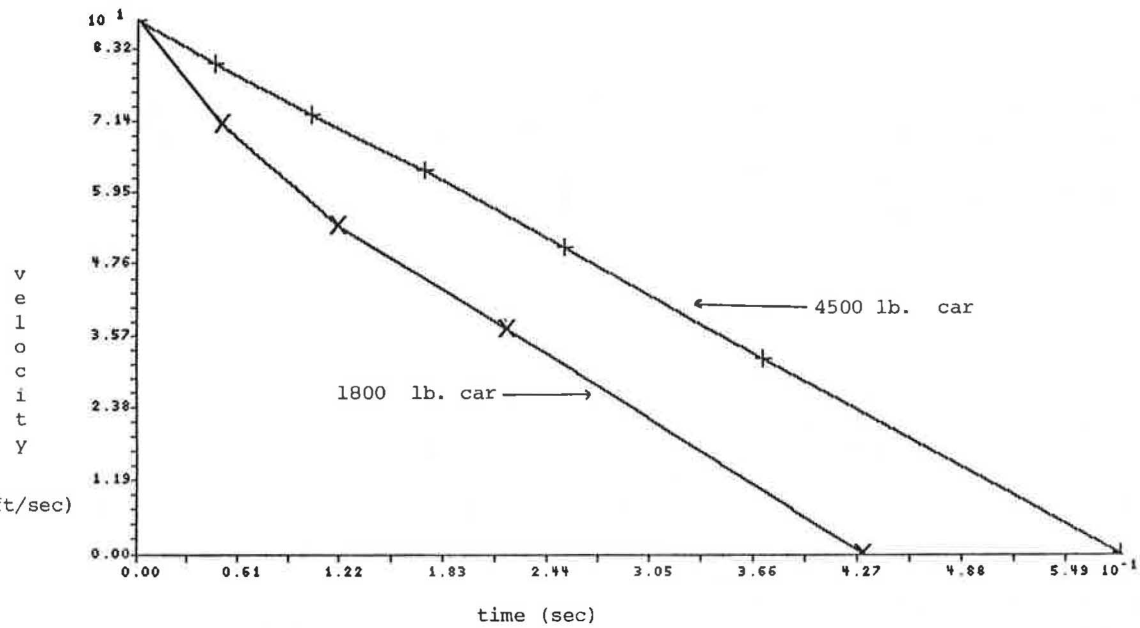

FIGURE 9 Velocity vs. time plots of light and heavy car simulations from the example design.

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