Final Report

DEVELOPMENT OF A STEEL PIPE VEHICLE IMPACT ATTENUATION SYSTEM

by

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INTRODUCTION

The Federal Highway Administration has encouraged the installation of energy absorbing barriers in front of gores of highway off-ramps that contain fixed objects such as large signposts or bridge rail end posts. To be technically effective, the energy absorbing barrier should, under high impact velocity, reduce the impact severity for the occupants of an errant vehicle to a survivable level. To be cost effective, the first cost and the maintenance costs should be low. In addition, the on-site repair time should be minimal because of the dangers to which the adjacent traffic and maintenance personnel are subjected while field repairs are in progress.

The State of Connecticut has, in the majority of applications, installed sand filled plastic barrel energy absorbing barriers (Fitch Inertial Barriers). These sand filled plastic barrel systems typically contain 9-17 modules, extend 18-24 feet, and provide a very effective means of dissipating the energy associated with a high speed vehicular collision.

There are, however, some drawbacks connected with the sand/barrel energy absorbing systems. In some instances these installations encroach into the desired clear area along travel lanes. At other locations, tight clearances have prevented the use of the sand/barrel system. The sand/barrel system under impact spreads over a large area. The debris and the resulting cleanup operations are serious hazards to traffic. Finally, the installation and maintenance costs of the sand/barrel system are high.

An impact attenuation device using sections of steel pipes as energy absorbing components is developed herein. The proposed unit is both technically and cost effective, and does not exhibit the above mentioned unfavorable characteristics of the sand/barrel system.

ENERGY ABSORPTION CHARACTERISTICS OF STEEL PIPES

The collapsing mode for a typical steel pipe in the proposed energy absorbing system is associated with the formation of four plastic hinges $90°$ removed from one another. Applying the theorem of virtual work and equating the internal and external work done yields

$$2 P_c \left(\frac{R\alpha}{2}\right) = 4 M_o \alpha \qquad (1)$$

where

P_c = small deflection static collapse load

R = radius of pipe

α = virtual angle change

M_o = yield moment

It follows that the collapse load is

$$P_c = \frac{4 M_o}{R} \qquad (2)$$

But the yield moment at plastic collapse may be written as

$$M_o = \frac{\sigma_o Wt^2}{4} \qquad (3)$$

where

σ_o = static yield stress

W = depth of pipe

t = thickness of pipe

which leads to

$$P_c = \frac{\sigma_o Wt^2}{R} \qquad (4)$$

Based on the stress-strain characteristics of typical steel pipes developed elsewhere [1,2,3], the static yield stress, σ_o, has been found to have a value of approximately 39,000 psi. Furthermore, it is shown in [1,2,3] that the collapsing force increases to approximately 2 P_c at complete collapse of the pipe, and the energy absorbed in the pipe is

$$\text{Energy Absorbed} = 133.38\ Wt^2 \tag{5}$$

Equation (5) is valid only under static loading conditions. Structural steel is a rate sensitive material, however, and its properties can change by as much as 100% depending on the strain rates during the deformation process. Much experimental and analytical research has been conducted in this area [4-9]. For the range of strains and strain rates to be encountered in this application, Perrone [1] suggests an overall rate sensitivity factor of 1.6. Taking W = 34 inches because of vertical stability requirements [2,3] and using a rate sensitivity factor of 1.6 yields the dynamic energy absorbed per pipe in the form

$$\text{Dynamic Energy Absorbed} = 604.66t^2 \quad [\text{ft-kips}] \tag{6}$$

In Eq. (6), t should be expressed in units of inches. It is interesting to note that the energy absorption capacity of a pipe section is independent of the diameter of the pipe.

The dynamic energy absorption capacities in ft-kips of steel pipes of various thicknesses are presented in Table 1.

TABLE 1

Dynamic Energy Absorption Capacities of Steel Pipes in ft-kips

t (inches)	NUMBER OF PIPES										
	1	2	3	4	5	6	7	8	9	10	11
0.266	43	86	128	171	214	257	300	342	385	428	471
0.375	85	170	255	340	425	510					
0.500	151	302	454								
0.625	236	472									
0.750	340										

Pipe Depth = 34 inches

DECELERATION REQUIREMENTS

The energy absorbing system must absorb energy in such a controlled way as to satisfy the Federal Highway Administration's guidelines on decelerations and deceleration rates, which are [10]:

1. Permissible average vehicle deceleration $\leq$ 12 g's.
2. Permissible deceleration onset rate $\leq$ 500 g's per second.

It is possible to calculate the minimum required length of the energy absorbing unit needed to stop a speeding vehicle, as a function of velocity, in order not to exceed 12 g's average deceleration. From dynamics, one can write

$$V_c^2 = 2as \tag{7}$$

in which

V_c = automobile speed before impact

a = average vehicle deceleration

s = required length of energy absorbing unit

Substituting V_c = 55 mph and a = 12 g's into Eq. (7) yields a minimum required length for the energy absorbing unit of 8.46 ft.

VEHICULAR IMPACT CONDITIONS

An effective impact attenuation system will function satisfactorily under impact with either a light (2250 lb) or heavy (4500 lb) vehicle [10]. The primary concern under impact with a light automobile is with the deceleration to which the automobile will be subjected. In the case of a collision with a heavy vehicle, the primary concern is with the energy absorption capacity of the attenuation system.

Assume that a 2250 lb automobile traveling at 55 mph impacts the energy absorbing unit. The kinetic energy which must be dissipated is

$$\text{Energy} = \frac{1}{2}\,(\text{mass})(\text{velocity})^2 = 228.5 \text{ ft-kips}$$

Maximum deceleration limitations require that this 228.5 ft-kips be dissipated in such a way that the automobile be brought to a stop in a distance $\geq$ 8.46 ft. The impact attenuation system should therefore collapse at least 8.46 ft before 228.5 ft-kips of energy is dissipated.

Consider next the 4500 lb automobile traveling at 55 mph impacting the system. The kinetic energy to be dissipated is doubled to 457 ft-kips. The impact attenuation system must, therefore, possess the following requirements:

1. It must deform $\geq$ 8.46 ft before dissipating 228.5 ft-kips of energy.
2. It must have an energy dissipation capacity of $\geq$ 457 ft-kips.

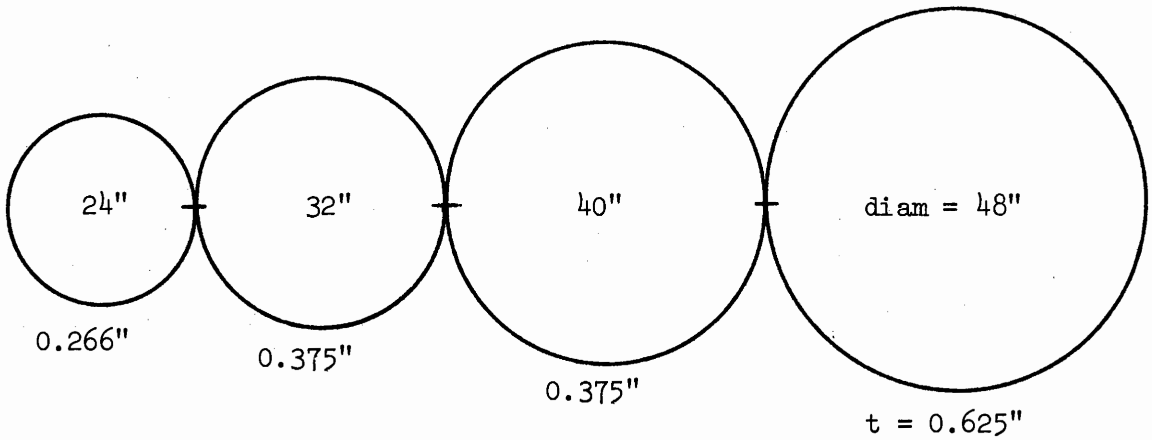
IMPACT ATTENUATION SYSTEM CONFIGURATIONS

An entire spectrum of impact attenuation systems satisfying the deceleration and energy dissipation requirements mentioned above can be designed using Table 1. It is not feasible to present every possible configuration in this report. Instead, typical designs which meet the requirements of specific practical situations and illustrate the advantages of the steel pipe vehicle impact attenuation system will be presented.

Example #1

Consider the following situation: an old, two-lane bridge spanning a river has an off-ramp on the right hand side of the roadway. The gore area contains a bridge rail end post. Tight clearance conditions will safely permit an impact attenuation system of only 12 feet in length. This requirement rules out the use of a sand filled plastic barrel system since, to be fully effective under high speed impact with a heavy vehicle, such a system should be $\geq$ 18 feet long. Let's further restrict the impact attenuation system's dimensions by restricting its width at the back to 4 feet and at the front (impacting point) to only 2 feet. The following polymodular design satisfies all the requirements of this situation:

DESIGN #1



Energy Absorption Capacity = 449 ft-kips

The system's length is 12 feet. Its width varies linearly from 4 feet at the back pipe to 2 feet at the front one. The forty-eight inch diameter pipe has a wall thickness of 0.625 inches, the 32 and 40 inch diameter pipes have wall thicknesses of 0.375 inches, and the 24 inch diameter pipe is given a wall thickness of 0.266 inches. (This is called 1/4 inch thick pipe, but it has been my experience that the average thickness for this size is 0.266 inches.) Referring to Table 1, the dynamic energy absorption capacity of this system is found to be 449 ft-kips, which essentially satisfies the 457 ft-kips energy dissipation requirement under a high speed, heavy automobile impact (55 mph, 4500 lbs). A small amount of the total energy to be dissipated will of course be used up in deforming the front end of the impacting automobile.

Next, the deceleration requirements for the high speed, light automobile (55 mph, 2250 lbs) collision should be checked. Total collapse of the first three pipes is associated with 213 ft-kips of dissipated energy and a collapsed length of 8 feet. A partial collapse of the 4 foot diameter pipe will supply the additional 15.5 ft-kips of energy and 0.46 feet of distance required.

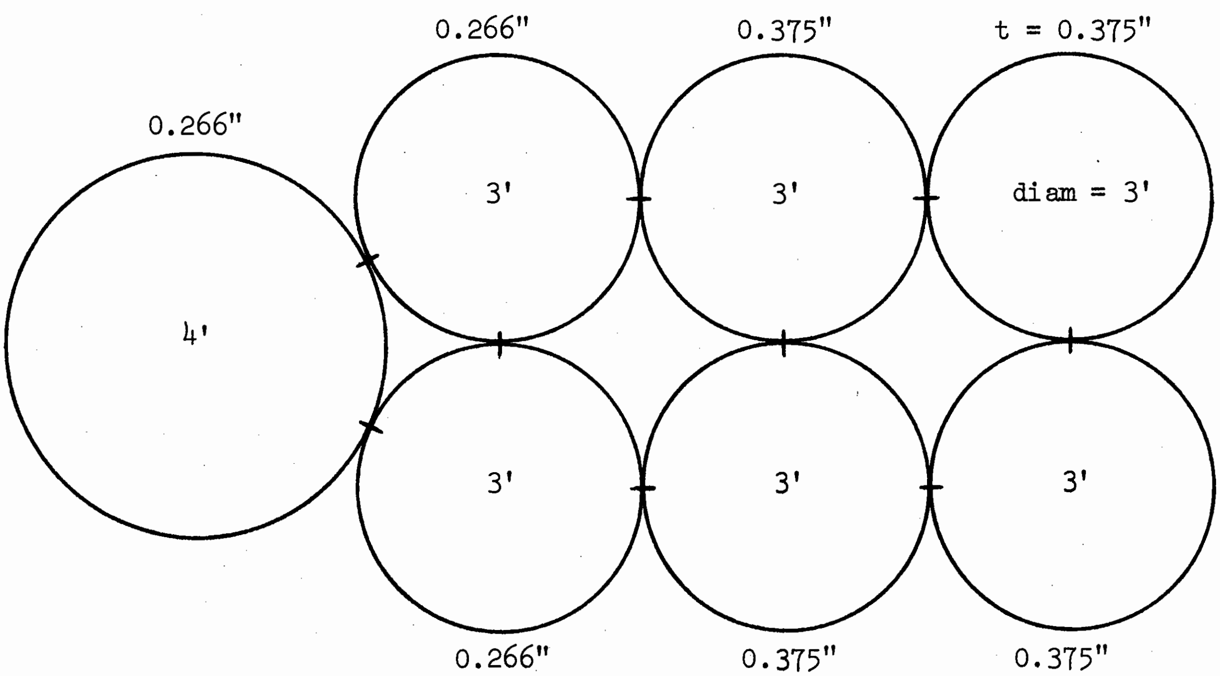
Example #2

Requirements:

1. Maximum length of impact attenuation system = 13 feet
2. Maximum width of system = 6 feet

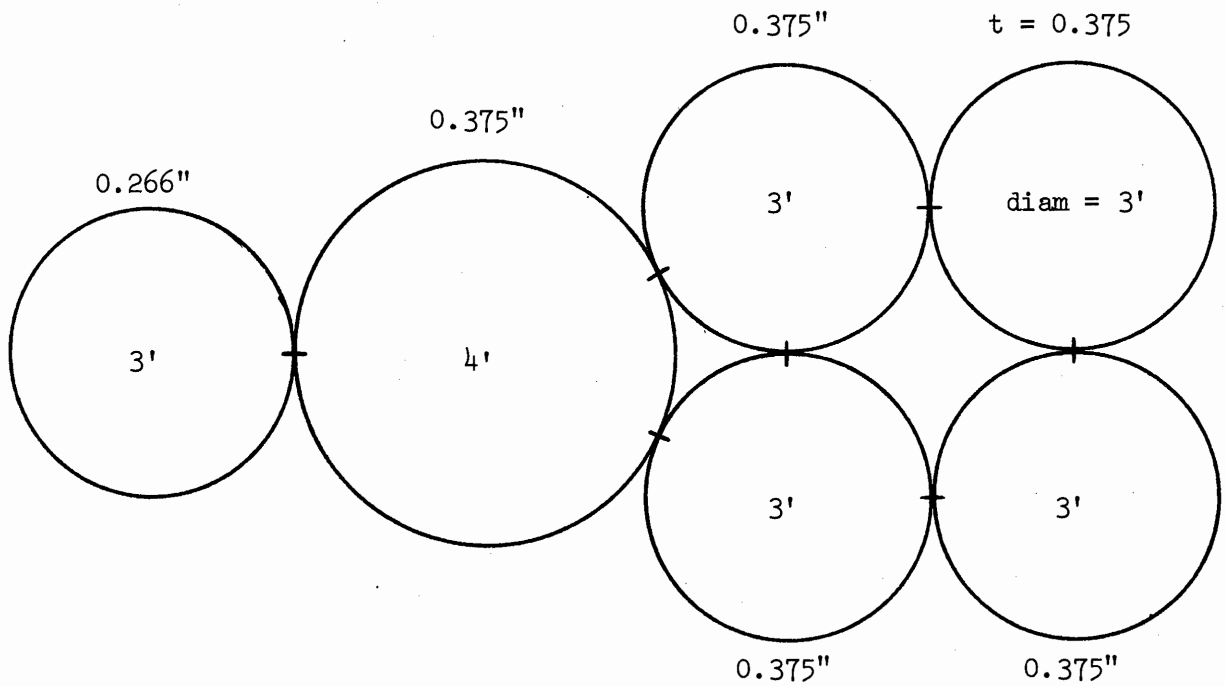
The following three polymodular designs satisfy both the above size requirements and the deceleration and energy capacity specifications:

DESIGN #2



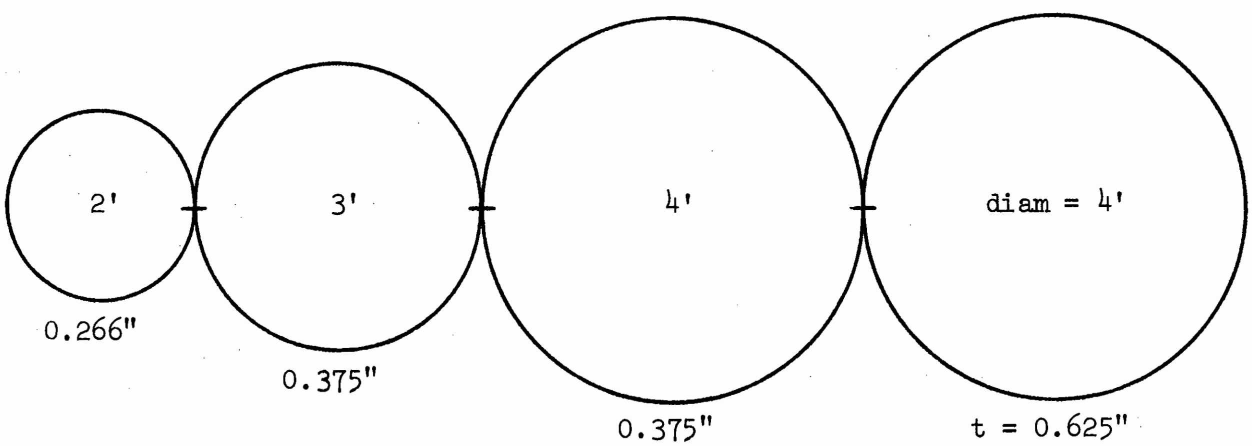
Energy Absorption Capacity = 468 ft-kips

DESIGN #3



Energy Absorption Capacity = 468 ft-kips

DESIGN #4



Energy Absorption Capacity = 449 ft-kips

It should be emphasized that the decelerations to which the automobile will be subjected will decrease when the length of the impact attenuation system of a given energy absorption capacity is increased. The system should be as long as possible without encroaching into the desired clear areas along travel lanes. And since the energy absorption capacity of a pipe is not a function of its diameter, the length of a given impact attenuation system can be increased without changing its energy absorption capacity by simply increasing the diameters of the pipes in the system. For example, designs #1 and #4 possess the same energy absorption capacities, but design #4 is one foot longer than design #1.

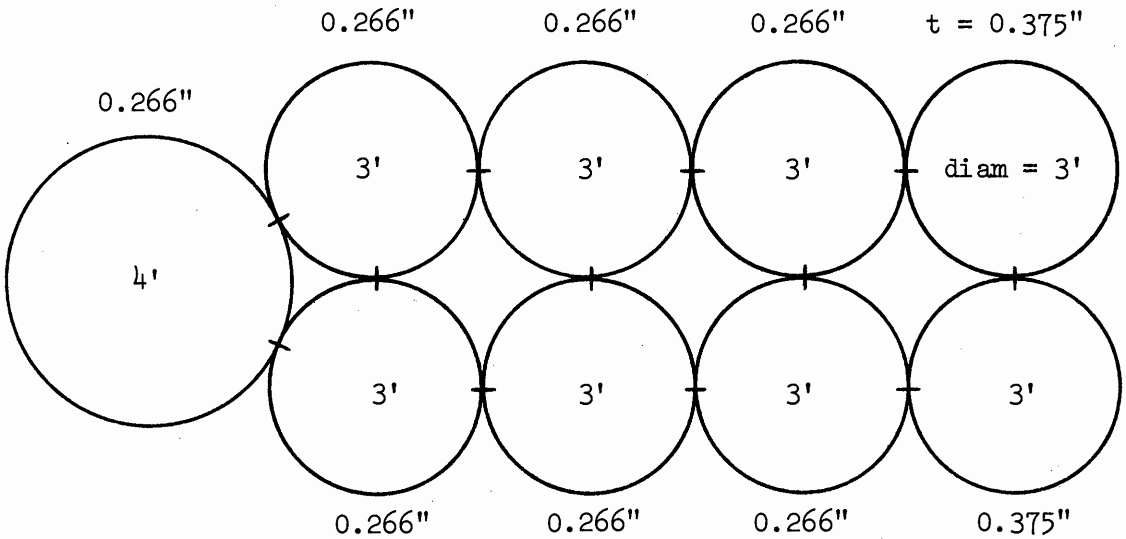
Example #3

Requirements:

1. Desired length of impact attenuation system = 16-21 feet.
2. Maximum width of system = 6 feet.

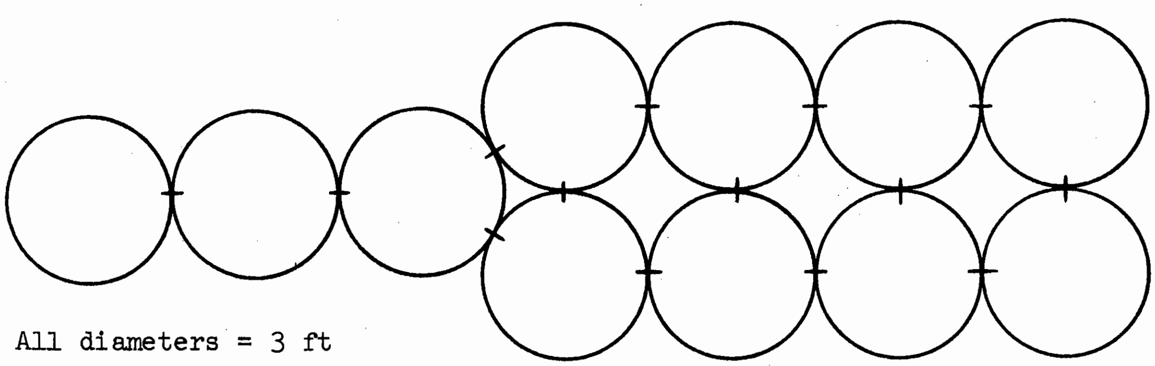
Because of debris and resulting cleanup hazards associated with the sand/barrel system after an impact, and in view of the high installation and maintenance costs associated with that system, it is decided to use a steel pipe design. Designs #5 and #6 shown below satisfy all the requirements for this situation.

DESIGN #5



Energy Absorption Capacity = 470 ft-kips

DESIGN #6



All diameters = 3 ft

All thicknesses = 0.266 in.

Energy Absorption Capacity = 471 ft-kips

CONNECTIONS AND END CONDITIONS

The 34 inch pipes in the impact attenuation system are bolted together as shown in the design configuration sketches. High strength 1 inch diameter bolts with washers having an inside diameter of 1-1/16 inches and an outside diameter of 2-1/2 inches should be used. Two bolts are required when connecting two pipes together. These bolts should be located 4 inches from the top and bottom of the pipes.

The rear of the impact attenuation system should, if possible, be secured to the fixed object it is fronting. The connection details will vary from site to site. However, the rear pipe (or pipes in the case of a two row configuration) should be bolted top and bottom to the fixed object or its extension. If this type of tie-in with the fixed object is not feasible, then the back of rear pipe (or pipes) should be secured to an embedded end post.

CONCLUSIONS AND RECOMMENDATIONS

A steel pipe vehicle impact attenuation system is developed in this report. The proposed system can be used effectively in tight clearance situations where length restrictions (allowable unit length < 18 feet) render the sand/barrel system ineffective under impact with a heavy vehicle at high speed.

The steel pipe vehicle impact attenuation system is inexpensive to build and install. The steel pipe sections are available at a cost range of $75 - $250 per pipe depending on the diameter and wall thickness of the pipe.

In the event of a collision with the steel pipe unit, the cleanup operation will be minimal and repair costs low. After a low speed impact the steel pipes can be jacked back to their original shape and reused. The low overall cost of the steel pipe vehicle impact attenuation system makes it very competitive with other systems presently being employed even when tight clearances are not a problem.

It is recommended that:

1. Scaled down models of the important configurations of the steel pipe vehicle impact attenuation system be tested experimentally to verify their expected stability and load carrying behavior.

2. Subject to the successful completion of the requirements of recommentation #1, a full scale crash testing program be conducted to evaluate the performance of the steel pipe vehicle impact attenuation system under various impact conditions.

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