HIGHWAY SIGN SUPPORT STRUCTURES

VOLUME 3

A FEASIBILITY STUDY OF IMPACT ATTENUATION OR PROTECTIVE DEVICES FOR FIXED HIGHWAY OBSTACLES

Final Report
of
Project HPR-2(104), Contract No. CPR-11-3550
Highway Sign Support Research

Area II - Protective Devices

Texas Transportation Institute
Texas A&M University
College Station, Texas

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FORWORD

The information contained herein was developed on Research Project HPR-2(104), entitled "Highway Sign Support Research," which was a pooled fund research project sponsored jointly by the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads, and the following highway departments: Alabama, California, Illinois, Kansas, Louisiana, Minnesota, Mississippi, Nebraska, North Dakota, Oklahoma, South Dakota, Tennessee, Texas, and the District of Columbia.

The result of this Research Project have been reported in three separate volumes, each concerning itself with the specific area of investigation as follows:

VOLUME 1	BREAK-AWAY ROADSIDE SIGN SUPPORT STRUCTURES
VOLUME 2	WIND LOADS ON ROADSIDE SIGNS
VOLUME 3	FEASIBILITY STUDY OF IMPACT ATTENUATION OR PROTECTIVE DEVICES FOR FIXED HIGHWAY OBSTACLES

Each volume is complete within itself, presenting the objectives, work done, conclusions, and recommendations.

The Contract Manager of this project was R. F. Baker of the Office of Research and Development, Bureau of Public Roads. A Policy Committee composed of engineers from the various participating highway departments and the Bureau of Public Roads was established to represent the participating agencies to (1) insure that the contractor would be responsive to the desires of the cooperating highway agencies, (2) provide a means for keeping all parties informed of progress and action on the subject, and

(3) provide adequate liaison between the technical personnel on the project and those of the technical staff of the Bureau of Public Roads and the participating agencies to insure the success of the work and its early acceptance.

This Policy Committee was composed of the following members and alternates.

Chairman: T. S. Huff

Vice Chairman: J. E. Wilson

Secretary: M. D. Shelby (ex officio)

STATE	MEMBER	ALTERNATE
Alabama	J. F. Tribble	F. L. Holman
California	J. E. Wilson	J. L. Beaton
Illinois	J. E. Burke	V. E. Staff
Kansas	R. L. Anderson	J. D. McNeal
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Oklahoma	B. C. Hartronft	
South Dakota	P. A. Hoffman	R. S. O'Neill
Tennessee	L. E. Hinds	H. M. Brooks
Texas	T. S. Huff	R. L. Lewis
District of Columbia	F. W. Ellerman	
Bureau of Public Roads	A. Taragin	C. F. Scheffey

In addition, a Technical Subcommittee was established to provide continuous and critical review of the progress of the work. This committee was selected by the Policy Committee and was composed of engineers with special technical competence and ability to contribute to the success of the project and implementation of its findings. The members of the Technical Subcommittee were as follows:

Chairman: T. S. Huff

Secretary: M. D. Shelby (ex officio)

STATE	MEMBER
California	J. L. Beaton
Kansas	R. L. Anderson
Louisiana	W. T. Taylor, Jr.
Tennessee	L. E. Hinds
Texas	T. S. Huff

The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the Bureau of Public Roads.

ACKNOWLEDGEMENTS

This project was conducted by the Texas Transportation Institute, C. J. Keese, Director, through the Texas A&M Research Foundation, Fred J. Benson, Vice President. The work was accomplished through combined efforts of the Structural Research Department, T. J. Hirsch, Head, and the Highway Design and Traffic Department, Charles Pinnell, Head.

The organization of the research team in responsible charge for accomplishing the objectives of the research was under the Co-Directorship of R. M. Olson (Structures) and Neilon J. Rowan (Highway Design and Traffic). The three specific research efforts were under the supervision of three research area supervisors as follows:

Area I	Sign Support Structures Thomas C. Edwards, Supervisor
Area II	Protective Devices Peter D. Weiner, Supervisor
Area III	Reduction of Wind Loads Hayes E. Ross, Jr., Supervisor

In addition to the research area supervisors, a support group under the supervision of Thomas Williams and James Mahle provided purchasing, procurement, fabrication, and test installation services.

James Bradley supervised the photographic coverage of all crash tests and assisted Rowan and Olson in the preparation of the 16 mm sound movie summarizing the results of the Break-Away Roadside Sign Research.

Mrs. Diantha Langley was in charge of data reduction and processing from the high speed movie film records and oscillogram records from all crash tests. Mrs. Langley also made significant contributions in preparing this final report by documenting crash tests with selected photographs and tabulated data.

Electronic instrumentation, including transducers, recordings, and other devices was accomplished by A. M. Gaddis, Gerald Clark, James Byram, and Monroe White.

The typing and preparation of the manuscript for this report was accomplished by Mrs. Ruth DeShaw and Mrs. Sylvia Velasco.

M. D. Shelby, Research Engineer of TTI, was Secretary (ex officio) of both the Project Policy Committee and Technical Subcommittee and worked tirelessly in coordinating the efforts of the researchers in response to the requirements of the sponsoring agencies.

Charles F. Scheffey, Chief of Structures and Applied Mechanics Division, Office of Research and Development, BPR, is due particular acknowledgement for the many hours spent in counseling the researchers concerning the technical aspects of this research. His advice and counsel based on many years of experience were invaluable to the researchers.

The suggestions and encouragement of A. C. Taylor, Regional Engineer, Bureau of Public Roads, were a continuing source of inspiration which are sincerely and gratefully acknowledged.

Last, but not least, the significant contributions of Leon Hawkins, Texas Highway Department Engineer, are acknowledged. Mr. Hawkins deserves credit for developing the original concept and design of the break-away base for use on cantilever type roadside signs. From the beginning and throughout this project, Mr. Hawkins has worked closely with the

researchers of TTI offering his technical and practical advice concerning the development and implementation of the break-away design concept. He supervised the preparation and revision of standards for design and installation of the many break-away signs now installed along Texas highways. He has worked tirelessly in collecting information concerning the behavior and performance of sign installations in Texas.

A distinguishing characteristic of this research study has been the activities of the Project Policy Committee, whose interest in the primary objective of eliminating roadside hazards, and whose examination of the detailed information developed in this investigation, has proven invaluable to the research staff. It is believed that the liaison between the practicing engineers and the researchers during this investigation has resulted in a clearer understanding of the nature of the hazard and its elimination through a cooperative research effort. It is apparent that the elapsed time between research investigation and field application has been substantially reduced by the continuing deliberations of the Project Policy Committee.

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CHAPTER 1

INTRODUCTION

Fatalities or disabling injuries have been sustained by passengers in a vehicle colliding with fixed objects at high speeds, even though the passengers were fully restrained by seat belts, due to a magnitude and rate of onset of deceleration which are beyond human tolerance. The hazard of certain fixed objects along the roadway, such as roadside signs and luminaire poles can be eliminated by employing the "break-away" design concept. Attempts have been made to protect other fixed obstacles such as bridge piers, wing walls, abutments, supports of large overhead sign bridges, certain utility poles, etc., by employing guardrails. Such guardrail installations have not been entirely successful because guardrails at present are not specifically designed as impact absorbing devices. They have been designed principally to restrain and redirect vehicles, i.e., traffic separation barriers on freeways and vehicle retainers on the shoulders of roadways with steep backslopes, etc.

To protect motorists from certain fixed obstacles mentioned previously, an energy absorbing impact attenuation barrier or device is needed to bring out-of-control speeding vehicles to a controlled stop. The objective of this study was to investigate the feasibility of impact attenuation or protective devices for fixed highway obstacles. The factors considered were human tolerance for deceleration levels, vehicle characteristics, available energy absorbing materials, and fundamental theory of engineering mechanics.

CHAPTER 2

LITERATURE SURVEY

This literature survey has been subdivided into three sections: the first deals with human tolerance limits of deceleration and onset of deceleration or "jerk"; the second considers vehicle characteristics; and the third presents information concerning the absorption characteristics of various materials which might be incorporated into an impact attenuation system.

2.1 Human Tolerance Limits

There has been an extensive amount of work done in this area. A list of references is included at the end of the literature survey.

Beaumier discusses safety improvements under consideration by the automobile industry such as a swinging bumper, extra energy absorbing material and padding. Beaumier says: "Safety will 'cost' the auto industry an estimated $500 million dollars in 1966, about $27.78 per car."[1]

In a report on seat belt installations, Sharp makes the following statement: "The deceleration forces experienced by a crew member of a B-58 ejecting at supersonic speeds are comparable with, or more severe than, a typical head-on automobile crash. Forces of approximately 30 g's are involved yet crewmen survive with little or no injury. The secret is the controlled environment with an adequate restraint system."[2]

Investigations by Stapp into human exposure to linear deceleration were conducted following World War II. These studies employed a rocket propelled slide which was occupied by Stapp and two other healthy young men. In his conclusions, he states, "Linear deceleration of 30 g's lasting for .11 seconds can be tolerated by human subjects in the backward facing position. The mild degrees of injury and discomfort noted indicate that higher values of deceleration can be survived by humans in this position if the body is uniformly supported."[3]

In a later paper, Stapp discusses military experience with lap-belt-shoulder harnesses and notes that with a "full harness" human subject tests were conducted up to 46 g's.[4]

Lininger and others conducted more than 50 crash tests at public gatherings which created interest in seat belts. Lininger personally participated in the crashes. He writes: "In these demonstrations we approached the 25-30 g level and at no time did I experience any tendency to submarine under the lap-belt chest-strap combination."[5] Lininger also reports on the development of a portable swing seat for making comparative tests in controlling sudden stops with or without seat belts.

Haynes, writing on design aspects of automobile safety reports that ". . . during an average impact, the deceleration level falls from a value of well over 100 g's at the bumper to about 30 g's in the area of the front seat compartment . . ."[6]

A summary of literature by Eiband contains the statement: "The voluntary-human-tolerance boundary shows that subjects have endured maximum uniform accelerations of 45 g's for 0.044 seconds with no injurious or debilitating (weakening) effects . . ."[7]

According to Pesman and Eiband, "A human being can tolerate decelerative loads of 45 g's perpendicular to the spine, and 20 g's of compressive load parallel to the spine if adequately supported."[8]

The Texas Transportation Institute Staff has discussed tolerance limits with other researchers and it is apparent that an established criterion does not exist. However, general agreement exists on the following requirements:

1. The body must be restrained.
2. The method for determination of g values must be stated.
3. The location of accelerometers or other devices must be stated.
4. Peak g values and time of occurrence are related.

2.2 Vehicle Characteristics

The following selected references are representative of findings reported in current literature concerning vehicle characteristics; such as angle of approach, percentage of single vehicle accidents, and vehicle attenuation capabilities.

Hutchinson and Kennedy say " . . . it is doubtful that a vehicle could encroach upon the median at an angle greater than about 25° unless it was traveling at a slow speed, was involved in a relatively severe collision, or was involved in initial movements resulting in running off the pavement to the right."[9] Review of their research on 266 encroachments on Interstate 74 shows that 90% of the encroachments were at angles less than 20° and 96% were less than 30°; and for 284 encroachments on Interstate 25, 90% were below 20° and 95% below 30°.[10]

The Warnock Hersey Company, Ltd. of Montreal conducted 13 crash tests on guardrails in which the angle of impact was 21^{o} and the vehicle speed varied from 25 to 60 mph. This research was initiated because from September, 1959 to November, 1962, a total of 33 vehicles had broken through the safety barriers on Metropolitan Boulevard in Montreal resulting in six deaths. Data taken from the report show a maximum lateral deceleration of 6.5 g's, a maximum longitudinal deceleration of 14.3 g's and a rebound of from seven to 36 feet.[11]

Huelke and Gikas, of the University of Michigan, state that during the period from November 1, 1961 to November 1, 1965, they observed 139 accidents with 177 deaths of which 54 had hit fixed objects within 18 feet of the roadway. They contend that we will always have accidents; therefore, we must improve the vehicle design for crash attenuation or clear the highway of obstacles.[12]

In their study of median barriers, Beaton and Field tested 15 types of median barriers, including flexible, semi-rigid and rigid barriers. The tests were made using various weight vehicles with different approach angles and velocities. Based on the department's past experience, "The 60 mph speed and the 30^{o} angle of approach combination was selected as representative of the more severe type of oblique accident with a median barrier."[13]

Moskowitz and Shaefer state that for the period from 1956 through 1958 on all types of full freeway fatal accidents in California, 43% were single vehicle accidents.[14]

Crosby, doing work on cross median accidents in New Jersey says: Single vehicle accident deaths on the 131 mile New Jersey Turnpike from

1952 through 1958 amounted to 33 persons. This was 20.9% of all fatalities.[15]

Stonex concludes: "The single car accidents contribute nearly 42% of highway traffic accident fatalities or an average currently of nearly 16,000 deaths," and, further ". . . seven billion dollars are wasted annually in traffic accidents."[16] Johnson, writing on fatal accidents on highways, reports that single vehicles hitting fixed objects account for 31% of the freeway fatal accidents in California.[17]

Fredericks, discussing data from crash tests by the Ford Motor Company, states: "For the full range of velocities tested, the deceleration level in the passenger compartment always has been less than half that observed at the front of the frame."[18]

Severy and Mathewson further state, ". . . crumpling may reduce the deceleration forces acting on the part of the car near the driver to less than 1/10 the force at the bumper. But, to take advantage of this force attenuation, the driver must be 'tied' to the car."[19]

Additional work by Severy on fixed barrier collisions shows that their experiments with impact speeds of 28 and 35 mph, ". . . the collision event for the car is essentially complete by 80 milliseconds . . . ."[20]

Ford engineers say, ". . . a vehicle involved in a serious front end collision generally collapses in this order: bumper, fender sheet metal, hood, then radiator, into which the fan and water pump are pushed. Next frame members may begin to buckle; and in some cases, the floor pan may bend. It's all over in one tenth of a second."[21]

Stonex makes the statement: "It is clear to the investigators in this area that the ultimate solution cannot lie in packaging the passenger. Even at moderate road speeds the energies are too high to be absorbed in the time available by any packaging system which is apt to be accepted and used by drivers and passengers universally."[22]

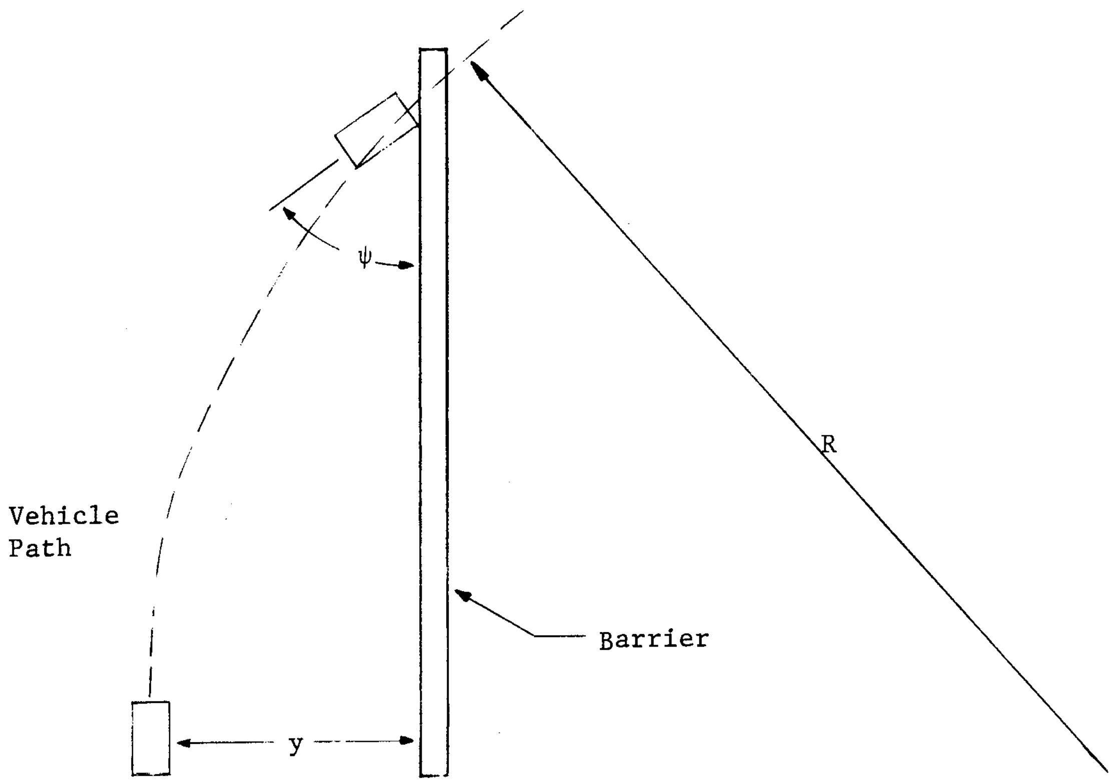
Stonex[23] states that Hutchinson, in reporting on 91 cases in a study of median encroachments on divided highways, found that only 10% of the vehicles leave the pavement at angles greater than 15°.

Johnson, on investigating freeway accidents for the California Division of Highways, found that 25% of all freeway accidents (fatal and non-fatal) were caused by collisions with fixed objects.[24]

Kassel, Tamburri and others of the California Division of Highways, wrote on guardrail installation criteria showing that in 1963 and 1964 there were 2402 accidents and 155 fatalities by single vehicle collisions with fixed objects on 1100 miles of freeway in California. They also show that of the 155 fatalities, 51 were caused by collisions with abutments and piers.[25]

Investigators in New York conducted studies and full-scale dynamic tests of Highway Barriers, and present an equation to predict the angle of impact of a vehicle and a fixed barrier. This equation is shown in Figure 1. In discussing the equation they note that large initial lateral displacements are necessary to produce angles of impact above 30°, and that variation of the coefficient of friction has a significant effect on impact angle. They state

> "For example, an increase of effective friction coefficient from 0.60 to 0.85 increases the maximum impact angle from 22 degrees to 16 degrees for a



$$\psi = \frac{1}{V}\sqrt{2gy(\mu + \phi)\left[1 + \frac{V^2\Theta}{5730g\,(\mu + \phi)}\right]}$$

where

ψ = maximum impact angle

g = pull of gravity

ϕ = super elevation

μ = coefficient of friction

V = velocity of vehicle

Θ = angle of road curvature

y = lateral displacement

R = minimum turning radius

FIGURE 1

speed of 60 mph (88 ft./sec.) and an initial lateral displacement of 30 feet. Vehicle velocity has a major effect on impact angle, causing a decrease from 30 degrees at 30 mph to 15 degrees at 60 mph for 10 feet of initial lateral displacement and an effective friction coefficient of 0.85. Road curvature has only minor effect on impact angle for small lateral displacements, but significant effects at initial lateral displacements of 20 to 30 feet."[26]

Review of current literature indicates general agreement on the following requirements for establishing interim vehicle characteristics:

1. The angle of approach cannot be definitely determined for all vehicle-driver actions; therefore, a rational value must be established. The equation of the New York investigators can be applied; an upper limit might be established based on a percentage of expected encroachments.
2. The number of single vehicle accidents is sufficient to require lateral clearances of 20 feet or more for fixed objects.
3. The nature of the fixed object must be considered (e.g., sign support, bridge bent, retaining wall, etc.).
4. Vehicle attenuation characteristics must be supplemented by fixed object attenuation systems.

2.3 Absorption Materials or Devices

The mechanical properties of certain common materials such as aluminum and steel are readily available; however, hardly any mechanical information is available for materials such as plastic and foam. The following will give a brief review of these other materials.

A honeycomb structure can be made from many types of materials, some of which are kraft paper, foams, aluminum, balsa wood, reinforced plastic, cotton, stainless steel and titanium. The cost of the honeycomb ranges from 25 cents per cubic foot for the paper honeycomb to as high as 10,000 dollars per cubic foot for the titanium honeycomb.

The crush strength of honeycomb can vary from 5 to 2000 pounds per square inch of surface, and its density can vary from 1 to 15 pounds per cubic foot. Because of these variable properties, almost any kind of system can be designed depending on the weight of a vehicle, stopping distance and deceleration required.[27,28,29] Curves illustrating force as a function of displacement, or honeycomb deformation are available which show that the material is an elastic-plastic material and that the elastic range is very small.[30] Dunlop writes that tests on honeycomb show that the initial crushing strength is approximately twice the final crushing force, but precrushing reduces this initial peak.[31]

Platus et al, on work done on impact absorption say that "Considerable research has been conducted on methods and devices for landing impact. Most of these studies, with the exception of those concerned with retrorockets, have dealt with devices which absorb energy by totally or partially destroying themselves upon impact. These devices include (1) fragmenting tubes, (2) crushable materials, (3) deformable structures and (4) gas bags and gas-filled collapsible shells."[32]

Discussing a new concept for energy absorption, they state that "A cyclic strain energy impact device absorbs energy by converting unidirectional motion into cyclic deformation of a working material.

The device consists of three basic parts: (1) load transmitter, (2) cycling mechanism, and (3) working elements."[33] An example of this type of a device is the "torus" shown in Figure 2. Platus employs a unit energy term, called the specific energy absorption (S.E.A.); comparison by Esgar[34] of different high energy absorption mechanisms, shows that for

Balsa Wood	S.E.A. = 24,000 ft-lbs/lb
Metal Honeycomb	S.E.A. - 12,000 ft-lbs/lb

For a frangible tube, McGhee[35] gives the value 31,000 ft-lbs/lb; and Platus, for a titanium metal which was cycled in a plastic strain sufficient to produce failure in 100 cycles, says "The total S.E.A. at failure is approximately 350,000 ft-lb/lb."[36]

Work done by Deleys and McHenry at Cornell Aeronautical Laboratory on guardrails shows that a 6" X 8" wooden post embedded 40" to 43" in sand is capable of absorbing approximately 15,500 ft-lbs of energy with a maximum impact force of 4800 lbs.[37]

Beaton and Field found from tests on median barriers that the 9 gage chain link fabric on 2 1/4 inch by 4.1 lbs/ft steel H posts spaced 8 feet apart was the best balanced median system, since it provided sufficient resistance to decelerate the vehicle and produced tolerable deceleration rates on the vehicle occupants. They obtained results for the 36 inch high chain link barrier,[38] as shown in Table I.

Skelton, working on hedge barriers, says that "Hedges of multiflora roses were proved to be effective barriers for stopping passenger automobiles, provided the width was sufficient to prevent the vehicle from passing through the hedge. For a vehicle to be stopped within the

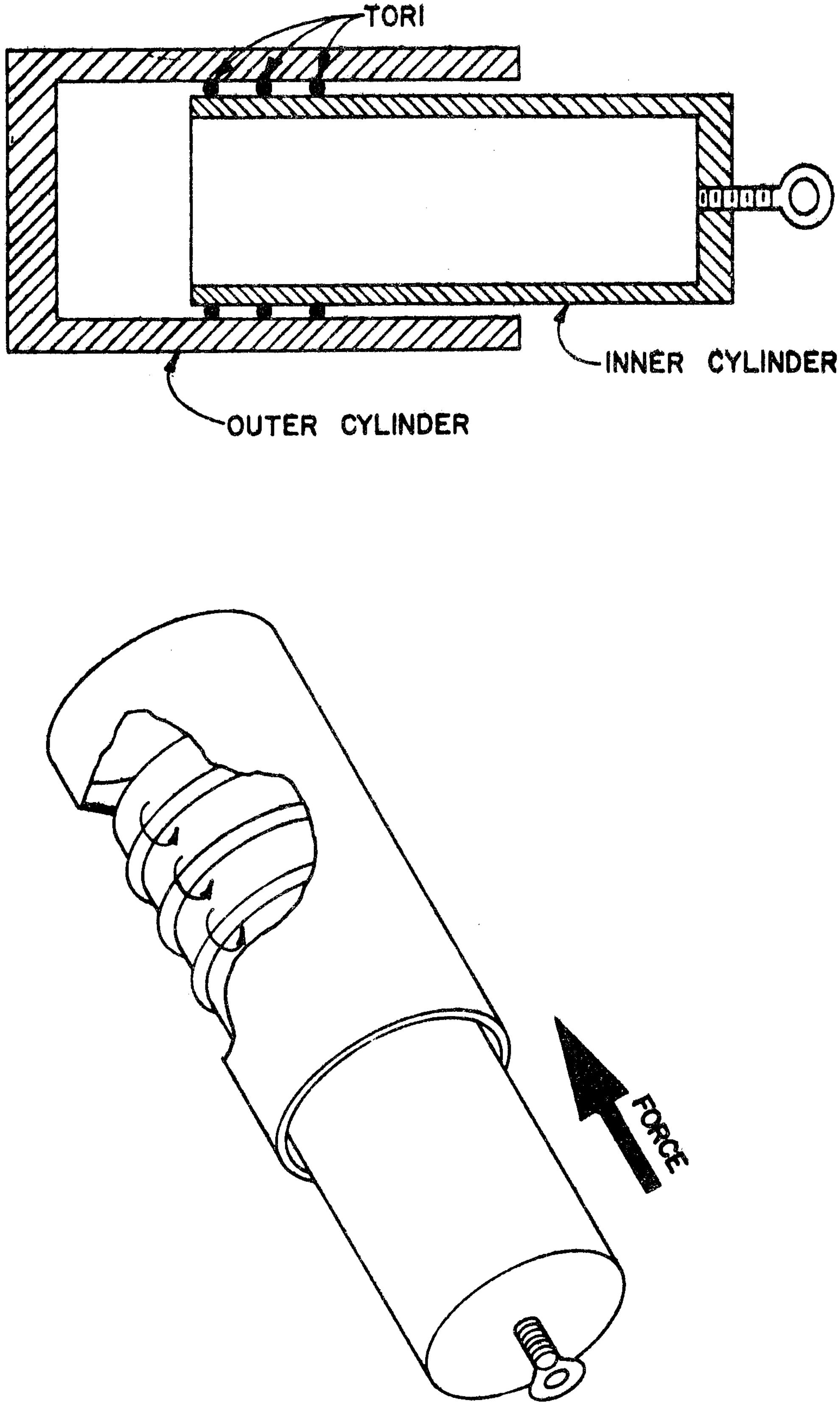


FIG. 2 TORUS IMPACT DEVICE

TABLE 1

TEST NO.	VEHICLE WEIGHT	VEHICLE VELOCITY	APPROACH ANGLE	NO. POSTS DAMAGED	FENCE DISPLACEMENT	LENGTH OF DAMAGE
14	4000 lbs.	61 mph	31^{o}	11	8' - 6"	80'
19	3700 lbs.	41 mph	15^{o}	4	3' - 4"	35'
21	3850 lbs.	60 mph	31^{o}	12	8'	56'
23	17500 lbs.	42 mph	34^{o}	23	12'	90'

hedge at speeds not to exceed 50 mph, without the use of brakes, the minimum required effective length of hedge on the path of travel was 75 feet."[39]

Clark, working with air bag restraining systems, found in testing a swing impact sled with a human subject and an air bag restraint, that the "sled experienced about 50 g's whereas the man experienced 7 g's."[40]

New York State has done a considerable amount of work on energy absorption characteristics of different types of posts embedded in sand and glacial till. The posts were embedded to a depth of 39 inches having 27 inches above the ground. These were then impacted by an instrumented truck with a bumper height of 21 inches. Some of the properties obtained from their plotted curves [41] are contained in Table II.

Tests run by Shield and Carington on impact cushioning, show properties for Quartermaster 108C and 100C foamed plastic; [42] typical properties are listed in Table III.

Hirsch and Edwards, working with pile cushioning materials, have arrived at the following coefficient of restitution values: [43]

Material	Coefficient of Restitution
Oak	0.50
Fir Plywood	0.43
Pine Plywood	0.27
Gum	0.20

Since the coefficient of restitution is a measure of the energy absorption characteristics of a material, the above table shows the relative merits of the various woods.

TABLE 2

TYPE POST AND IMPACT DIRECTION	MAXIMUM FORCE LBS.	MAXIMUM DEFLECTION INS.	ENERGY ABSORBED IN.-LBS.	SOIL
→ ∿ 6" 4"	4000	28	100,000	Sand
→ S	4100	30	110,000	Sand
→ ∿	5500	27	81,000	Till
→ S	5000	25	90,000	Till
→ 3 5 Hollow Aluminum	7000	18	63,000	Conc.
→ 5 3	5000	22	55,000	Conc.
→ Cedar	5300	43	200,000	Sand
→ Cedar	6200	8	48,000	Till
→ Cedar	5800	47	200,000	Sand
→ Cedar	7500	5	30,000	Till
→ I 3I5.7	4300	25	78,000	Sand
→ I 3I5.7	4500	22	30,000	Till

TABLE 3

MATERIAL	DENSITY LBS/FT^3	% STRAIN	STRESS LBS/FT^2	MASS LBS.	VELOCITY FPS.
108C	4	40%	7,500	295	50
(2'x2'x6")	4.25	40%	8,000	295	50
	5	40%	10,000	295	58
	6	40%	16,000	295	71
	6.87	40%	17,500	295	75
100C	4	40%	7,000	190	47
(2'x2'x3")	4.25	40%	7,000	190	44
	6.00	40%	7,000	190	63.5
	6.25	40%	7,000	190	50

2.4 Discussion

It has been estimated that 49,000 deaths occurred in 1965. Wise states: "Approximately 4,000,000 people were injured in 1965 in automobile accidents."[44] The resulting property losses aggregate more than 10 billion dollars annually. Single car accidents are the proximate cause of about 42% of the deaths.[22]

This study investigates feasible systems to reduce the number of casualties which result from fixed object collisions with abutments, overhead bridge supports, and piers which cannot be eliminated from the roadway. Stonex suggests that the "...relative hazard at the immediate edge of the road is very high, and it decreases rapidly as the distance from the edge of the pavement increases."[45] It appears that 95% of the accidents occur within 20 feet of the edge of the roadway.

Stapp[3], Lininger[5], Eiband[7] and others indicate that a human being is capable of surviving a crash with a deceleration of 25 g's with little or no injury if adequately restrained in a vehicle. Therefore, in order to save lives, a system must be designed which is capable of absorbing the kinetic energy of a vehicle weighing 1500 to 4000 pounds, traveling at velocities to 100 feet per second, and which will produce a deceleration of 25 g's or less.

CHAPTER 3

THEORETICAL CONSIDERATIONS

3.1 Energy, Forces, Deceleration Rates, and Stopping Distances

The change in kinetic energy of the vehicle can be expressed by

$$\Delta KE = \int_{V_1}^{V_2} Mv \; dv \tag{1}$$

Since the mass of the vehicle is constant, the magnitude of the kinetic energy of the vehicle for a particular velocity may be expressed:

$$KE = 1/2 \; M \; V^2 \tag{2}$$

where M = vehicle mass

V = vehicle velocity

Table IV on the following page shows the kinetic energy for various vehicles traveling at 40, 80 and 100 fps. A plot of vehicle kinetic energy is shown in Figure 3.

Since the work necessary to stop the vehicle must be equal to the initial kinetic energy of the vehicle as shown by

$WORK = \Delta KE$

$$\int_0^d Fds = \int_{V_1}^{0} Mv \; dv \tag{3}$$

or $F_{avg} \; d = 1/2 \; MV^2$

TABLE 4

VEHICLE KINETIC ENERGY

VEHICLE WEIGHT	VEHICLE MASS (slugs)	VEHICLE VELOCITY (fps.)	KINETIC ENERGY (ft.-lbs.)
1500	46.6	40	37,500
		80	114,500
		100	179,000
2000	62.2	40	49,800
		80	199,000
		100	310,000
2500	77.7	40	62,500
		80	214,000
		100	334,500
3000	93.3	40	74,600
		80	299,000
		100	476,000
3500	109.	40	87,200
		80	348,000
		100	544,000
4000	124.4	40	99,600
		80	398,000
		100	622,000

FIG. 3

KINETIC ENERGY VERSUS VEHICLE WEIGHT FOR VARIOUS VEHICLE VELOCITIES

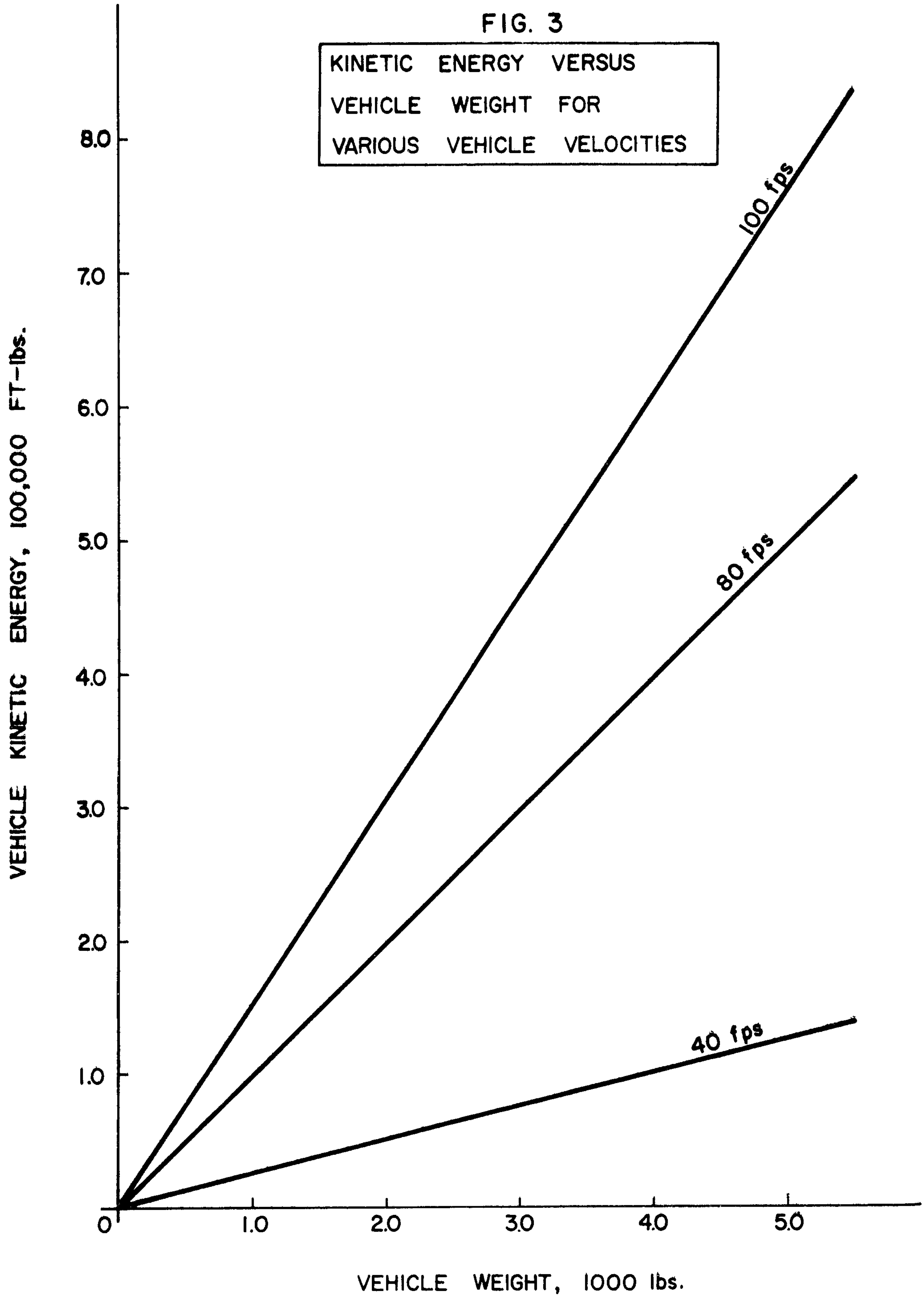


Figure 4 shows this stopping distance d as a function of the average force imposed on the vehicle and the kinetic energy of the vehicle.

However, the deceleration of the vehicle is a function of the mass of the vehicle and the applied force or from the equation for force, mass and acceleration:

$$a = \frac{F_{avg}}{W} g \tag{4}$$

A plot of this relationship is shown in Figure 5; by entering this plot, or by using Equation (4), the maximum average stopping forces are found to be 37,500 and 100,000 pounds for the 1500 and 4500 pound vehicle respectively. It can readily be seen from these values that the system used must be variable, otherwise some vehicles will have either very high deceleration rates if the 100,000 pound force is used, or excessive stopping distances if the 37,500 pound system is used.

The deceleration of the vehicle can be expressed by

$$a = \frac{dv}{dt} \tag{5}$$

or multiplying both sides of the equation by ds, we get

$$a\ ds = \frac{dv\ ds}{dt}$$

however,

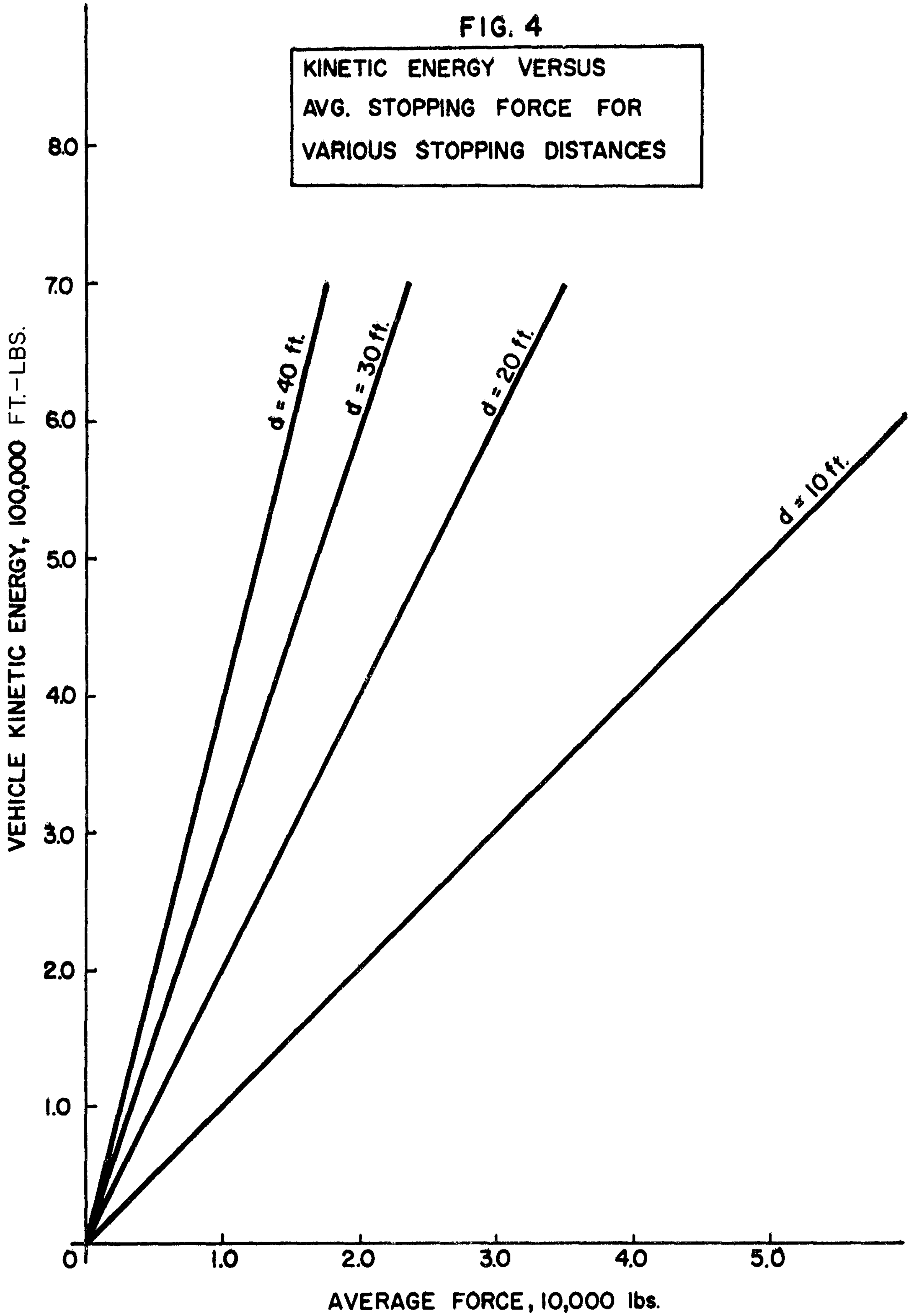
$$v = \frac{ds}{dt}$$

which becomes

$$\int_{o}^{d} a\ ds = \int_{V_1}^{V_2} v\ d\ v \tag{6}$$

after putting in the limits.

FIG. 4



KINETIC ENERGY VERSUS AVG. STOPPING FORCE FOR VARIOUS STOPPING DISTANCES
VEHICLE KINETIC ENERGY, 100,000 FT.-LBS.
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1.0
2.0
3.0
4.0
5.0
AVERAGE FORCE, 10,000 lbs.
d = 40 ft.
d = 30 ft.
d = 20 ft.
d = 10 ft.

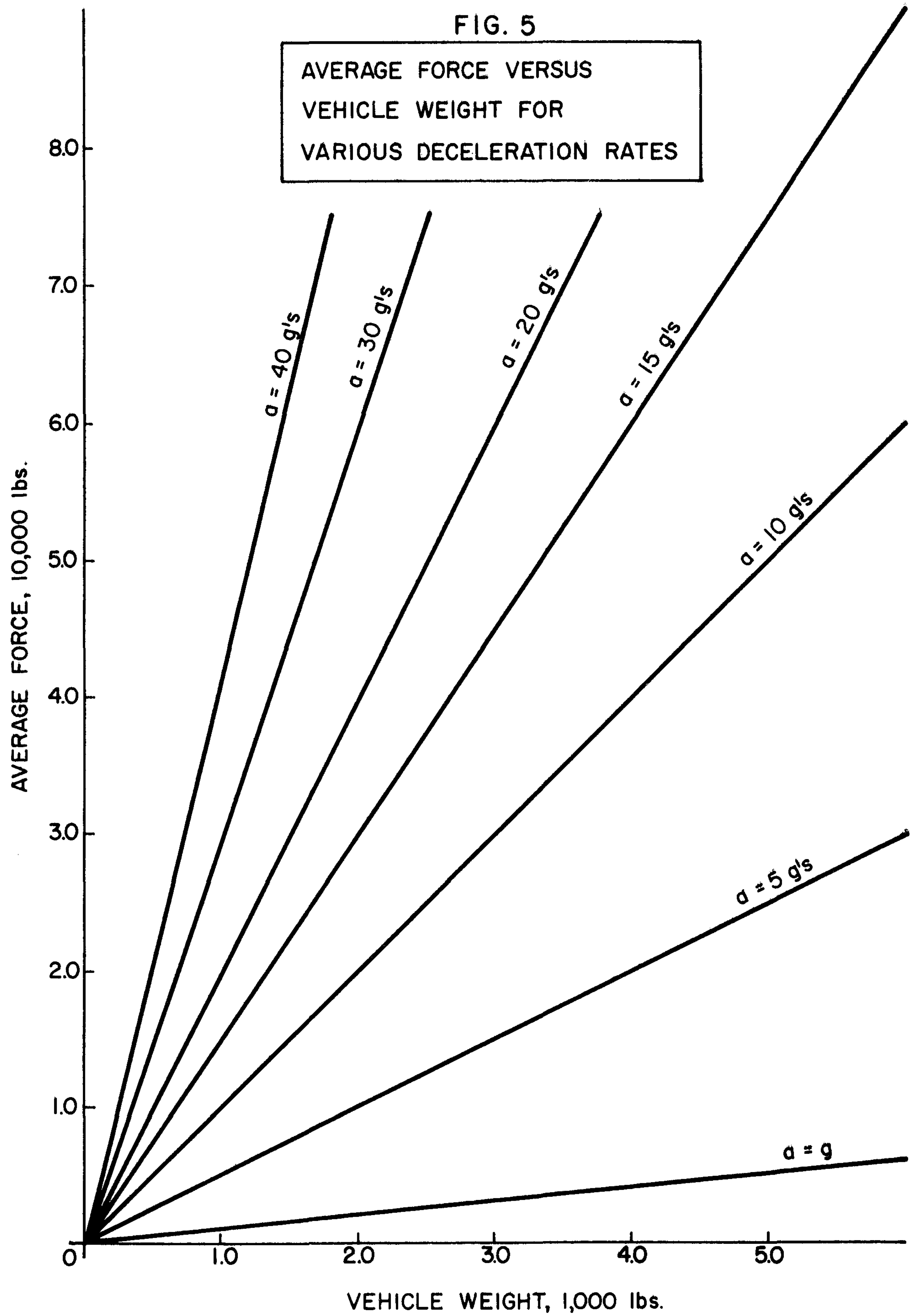


FIG. 5
AVERAGE FORCE VERSUS VEHICLE WEIGHT FOR VARIOUS DECELERATION RATES
AVERAGE FORCE, 10,000 lbs.
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1.0
2.0
3.0
4.0
5.0
VEHICLE WEIGHT, 1,000 lbs.
a = 40 g's
a = 30 g's
a = 20 g's
a = 15 g's
a = 10 g's
a = 5 g's
a = g

Integration of (6) and the substitution of limits yields the following expression for displacement when the acceleration is not a function of displacement

$$d = \frac{v_2^2 - v_1^2}{2a} \qquad (7)$$

or letting $v_2 = 0$

the stopping distance would be

$$d = \frac{v_1^2}{a} \qquad (8)$$

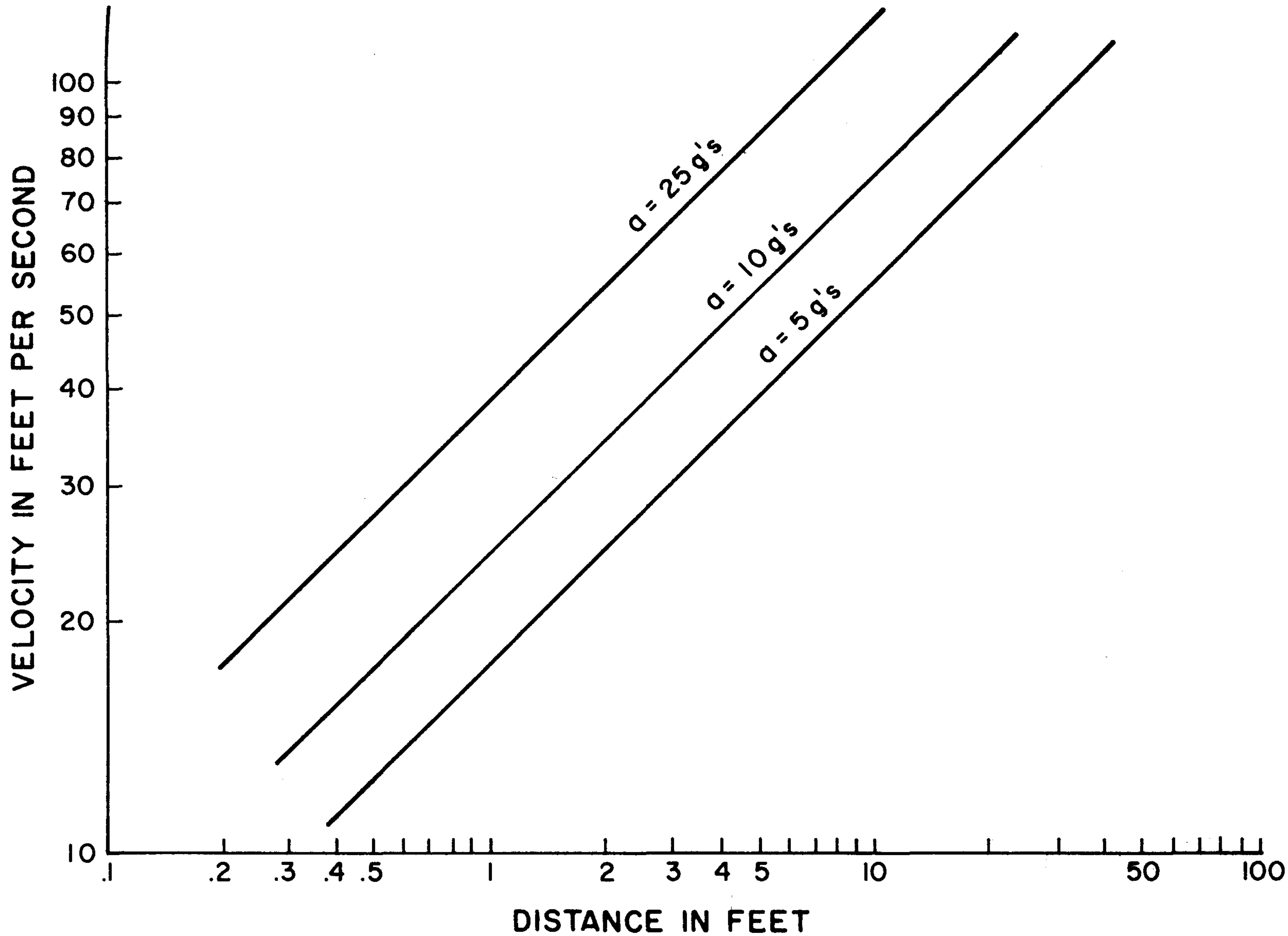
A plot of the stopping distance required for various vehicle velocities and deceleration rates is shown in Figure 6.

3.2 Idealized Protective Systems

An idealized system is presented in Figure 7 and a linear force-deformation curve for the vehicle is illustrated in Figure 8. It is recognized that such an idealization does not represent the actual behavior of a vehicle subjected to a collision incident. A more sophisticated description of a vehicle system based on empirical results is not available; therefore, this simple system is proposed as a first approximation.

The work done in Figure 8 is considered to represent the energy absorbed by the deformation of the vehicle upon impact with the attenuation system.

Assume that a vehicle having a weight, W, is traveling at a velocity V_1 and can be represented by the mass and linear spring shown, the dimension, d, is taken as the crushing of the vehicle. A fixed object having an impact attenuation system consisting of three discrete elements of lengths L_1, L_2 and L_3, for which three arbitrary coordinate systems are established, the



VELOCITY VERSUS STOPPING DISTANCE
FOR VARIOUS DECELERATION RATES
FIGURE 6

displacements of which are taken as X_1, X_2 and X_3.

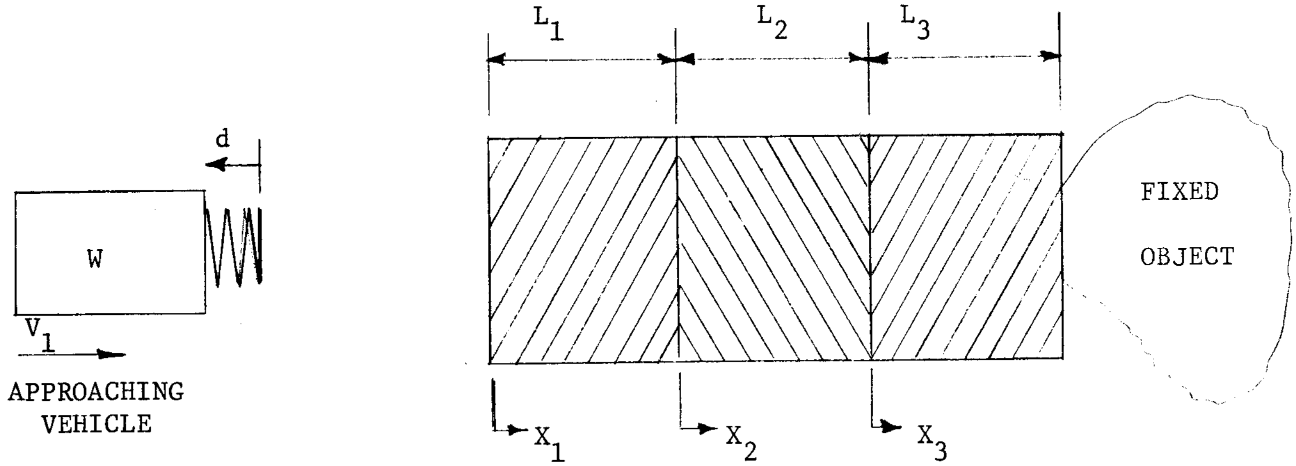


FIGURE 7

The idealized linear force-deformation of the vehicle may be represented as follows:

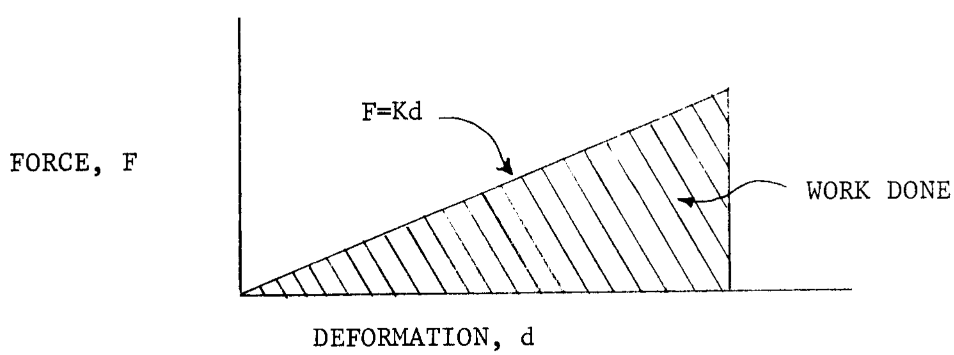


FIGURE 8

Each element of the impact attenuation system acts as an independent plastic section, and the work is represented by the idealized force-deformation curve shown in Figure 9:

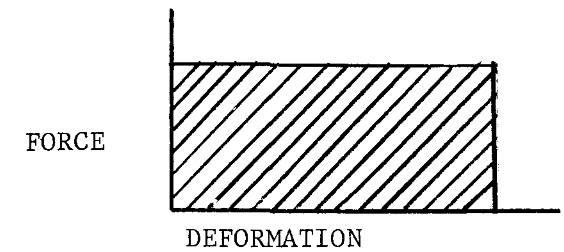


FIGURE 9

Assuming the force on each element to be proportional to: (1) the frontal surface area of the element, and (2) the crush strength of the element. Then, taking

$A_1, A_2, A_3, - - A_n$ = Frontal surface area (ft^2)

$L_1, L_2, L_3, - - L_n$ = Element depth (ft)

$x_1, x_2, x_3, - - x_n$ = Element penetration (ft)

$C_1, C_2, C_3, - - C_n$ = Element crush strength (lbs/ft^2)

K = Vehicle spring constant (lbs/ft)

W = Vehicle weight (lbs)

V = Vehicle velocity (ft/sec)

d = Vehicle deformation (ft)

By employing the well known relationship of work and energy:

Work = change in kinetic energy

The work done by the deformation of the vehicle is

$$\text{Work (vehicle)} = \frac{F\,d}{2} \quad (9)$$

but, since $F = K\ d_1$, the work $= \frac{K\ (d^2)}{2}$ (10)

The work done by the plastic attenuation element is shown in Figure 10.

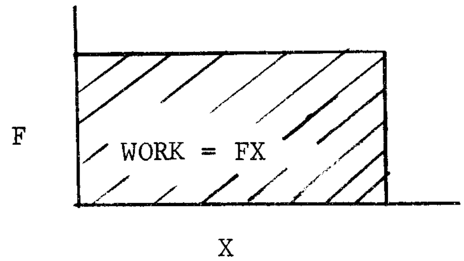


FIGURE 10

But, this constant crushing force is a function of the surface area, A, of the element and the crush strength, C, of the element, or

$$F_n = C_n\ A_n \tag{11}$$

which must also be equal to the force on the vehicle, or

$$F = A_n\ C_n = K\ d \tag{12}$$

using these relationships, the energy absorbed in the first element is:

$$\frac{-F\ d}{2} \quad -F\ x_1 \quad = 1/2\ \frac{W}{G} \quad (V_2^{\ 2} - V_1^{\ 2}) \tag{13}$$

or

$$\frac{-C_1 A_1 d}{2} \quad -C_1\ A_1\ x_1 \quad = 1/2\ \frac{W}{G}\ (V_2^{\ 2} - V_1^{\ 2})$$

but

$$d = \frac{C_1\ A_1}{K} \quad \text{(Car deformation)} \tag{14}$$

then

$$-\frac{(C_1 A_1)^2}{2\ K} \quad - C_1\ A_1\ x_1 = 1/2\ \frac{W}{G}\ (V_2^{\ 2} - V_1^{\ 2}) \tag{15}$$

If we set $V_2 = 0$ and solve for x_1

$$x_1 = 1/2 \left[\frac{W V_1^2}{C_1 A_1 g} - \frac{C_1 A_1}{K} \right] \quad (16)$$

and if $x_1 \leq L_1$ the vehicle is stopped in this element and the vehicle deceleration is given by

$$a = \frac{C_1 A_1}{W} g \quad (17)$$

and the vehicle deformation by (14)

$$d = \frac{C_1 A_1}{K}$$

If, however, $x_1 > L_1$, the vehicle is not stopped in the initial element, and the second element must be considered as follows.

From work and energy:

$$- \frac{(C_2 A_2)^2}{2K} - C_1 A_1 L_1 - C_2 A_2 x_2 = \frac{W}{2g} (V_2^2 - V_1^2) \quad (18)$$

If we set $V_2 = 0$ and solve for x_2, the penetration into Element 2

$$x_2 = 1/2 \left[\frac{W^2 V_1^2}{C_2 A_2 g} - 2 \frac{C_1 A_1 L_1}{C_2 A_2} - \frac{C_2 A_2}{K} \right] \quad (19)$$

If $x_2 \leq L_2$, the vehicle is stopped in Element 2 and

$$a = \frac{C_2 A_2}{W} g \quad (20)$$

and

$$d = \frac{C_2 A_2}{K} \quad (21)$$

If, however, $x_2 > L_2$, the vehicle is not stopped by the first two elements and the third element must be considered as follows

$$- \frac{(C_3\ A_3)^2}{2\ K} - C_1A_1L_1 - C_2A_2L_2 - C_3A_3x_3 = \frac{W}{2g}\ (V_2{}^2 - V_1{}^2) \quad (22)$$

Setting $V_2 = 0$

$$x_3 = 1/2 \left[\frac{W\ V_1{}^2}{C_3A_3g} - 2\ \frac{C_1A_1L_1}{C_3\ A_3} - 2\ \frac{C_2A_2L_2}{C_3\ A_3} - \frac{C_3\ A_3}{K} \right] \quad (23)$$

and if $x_3 \leq L_3$ the vehicle is stopped in Element 3 and

$$a = \frac{C_3\ A_3}{W}\ g \quad (24)$$

and

$$d = \frac{C_3\ A_3}{K} \quad (25)$$

If, however, $x_3 > L_3$, the vehicle hits the object or another element is needed.

For example, let the following conditions apply:

$A_1 = A_2 = A_3 = 10\ ft^2$

$L_1 = L_2 = L_3 = 6\ ft$

$V_1 = 100\ ft/sec$

W = 1500, 3000, 4000, 6000 lbs

C_1 = 25 lbs/in^2, 3600 lbs/ft^2

C_2 = 50 lbs/in^2, 7200 lbs/ft^2

C_3 = 75 lbs/in^2, 10,800 lbs/ft^2

K = 30,000 lbs/ft

then, for the 1500 pound vehicle.

Checking the penetration in Element 1 using (16)

$$x_1 = 1/2\left[\frac{(1500)\ (10000)}{(3600)\ (10)\ (32.2)} - \frac{(3600)\ (10)}{30000}\right] = 1/2\ \left[12.9 - 1.2\right]$$

$x_1 = 5.85$ ft $< L_1$ therefore stops in Element 1 and the peak deceleration is (17)

$$a = \frac{(3600)\ (10)}{1500}\ g = 24\ g\text{'s}$$

and the vehicle deformation (14)

$$d = \frac{(3600)\ (10)}{30000} = 1.2\ \text{ft}$$

Now then, checking the 3000 pound vehicle. Checking Element 2 using equation (19)

$$x_2 = 1/2\ \left[\frac{(3000)\ (10000)}{(7200)\ (10)\ (32.2)} - 2\ \frac{(3600)\ (10)\ (6)}{(7200)\ (10)} - \frac{(7200)\ (10)}{30000}\right]$$

$$x_2 = 1/2\ \left[12.9 - 6 - 2.4\right]$$

$x_2 = 2.25$ ft $< L_2$ therefore stops in Element 2 and the peak deceleration is from (20)

$$a = \frac{(7200)\ (10)}{3000}\ g = 24\ g\text{'s}$$

and the deformation of the vehicle from (21)

$$d = \frac{(7200)\ (10)}{30000} = 2.4\ \text{ft}$$

Now then, using the 4000 pound car and checking Element 2 using (19)

$$x_2 = 1/2\ \left[\frac{(4000)\ (10000)}{(7200)\ (10)\ (32.2)} - 2\ \frac{(3600)\ (10)\ (6)}{(7200)\ (10)} - \frac{(7200)\ (10)}{30000}\right]$$

$$x_2 = 1/2 \left[17.2 - 8.4\right]$$

$x_2 = 4.4$ ft $< L_2 = 6'$ therefore stopped in Element 2, and the deceleration is

$$a = \frac{(7200)\ (10)}{4000}\ g = 18\ g's$$

and the deformation of the vehicle

$$d = \frac{(7200)\ (10)}{30000} = 2.4 \text{ ft.}$$

If the vehicle had weighed 6000 pounds, then it would have penetrated Element 3 and

$$x_3 = 1/2 \left[\frac{(6000)\ (10000)}{(10800)\ (10)\ (32.2)} - 2\,\frac{(3600)\ (10)\ (6)}{(10800)\ (10)} - 2\,\frac{(7200)\ (10)\ (6)}{(10800)\ (10)} - \frac{(10800)\ (10)}{30000}\right]$$

$$x_3 = 1/2 \left[17.3 - 4 - 8 - 3.6\right]$$

$x_3 = 0.9$ ft $< L_3 = 6'$ therefore, stopped in Section 3, and the deceleration is

$$a = \frac{(10800)\ (10)}{6000}\ g = 18\ g's$$

and the deformation of the vehicle

$$d = \frac{(10800)\ (10)}{30000} = 3.6 \text{ ft}$$

All of the above deceleration rates are below the human tolerances for survival as reported in the literature survey; and therefore, a belted person should be able to survive the example collision.

There are several materials that are readily available with the necessary properties; these include paper and aluminum honeycomb, and polyurethane foam.

An alternate system for vehicle attenuation would be the use of posts made of wood, steel, plastic, aluminum or other material where the post would fracture or bend over in the ground. Work done by the Cornell Aeronautical Laboratory on guardrails [46] shows that a 6" x 8" wooden post embedded 40" to 43" in sand is capable of absorbing approximately 15500 ft-lbs of energy with a maximum impact force of 4800 lbs. A system consisting of a multiple post barrier is shown in Figure 11.

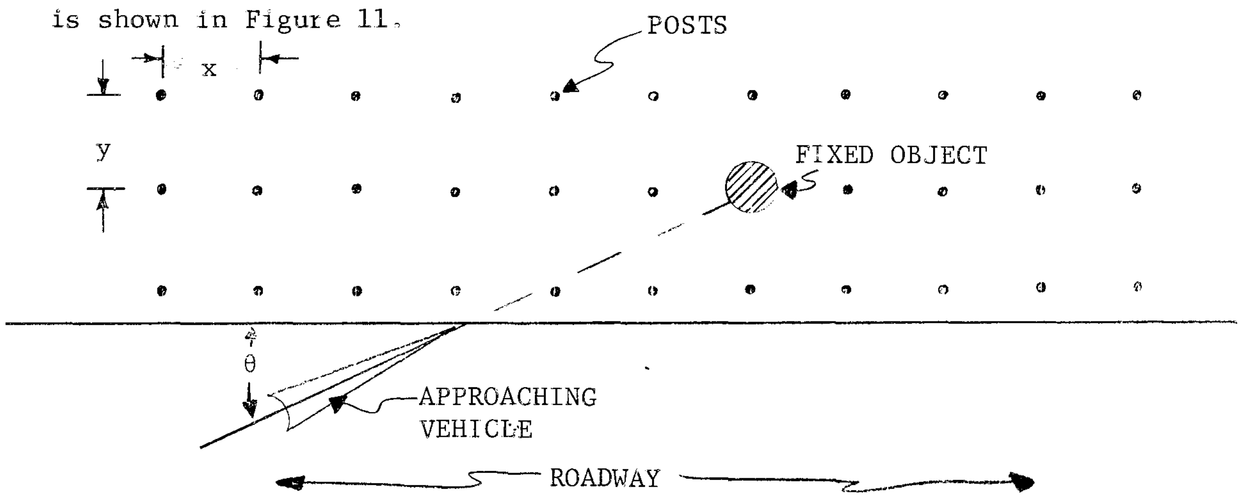


FIGURE 11

Assuming that the vehicle remains on a straight trajectory and that it clears out a six foot path, Table V shows what weight vehicle can be stopped at various angles (θ) of approach and various velocities (V) for different post spacing. By letting the spacing in the x and y directions be the same, we get the following results for central impact (C),

TABLE 5

θ Degrees	V (fps)	x&y (ft.)	Weight (lbs.)		
			C	L	R
5	100	2	4700	1700	3480
5	100	3	2190	1200	1700
5	88	2	6100	2200	4500
5	88	3	2830	1550	2200
5	73.4	2	8700	3140	6450
5	73.4	3	4050	2220	3150
10	100	2	2800	1000	5200
10	100	3	1600	695	2100
10	88	2	3600	1300	6200
10	88	3	2060	900	2700
10	73.4	2	5200	1840	9600
10	73.4	3	2950	1290	3860
15	100	2	2500	695	3200
15	100	3	1100	500	2000
15	88	2	3220	900	4160
15	88	3	1400	650	2600
15	73.4	2	4610	1280	5900
15	73.4	3	2000	925	3700

left side of vehicle (L), right side of vehicle (R), and 2 and 3 foot spacings (see Table V).

The table shows that when posts alone are used, the ordinary car can be stopped with the 2 foot post spacing, when travelling at a velocity up to 50 mph for direct central impact, and for right side impact up to angles of approach of 15°. However, if the left side of the car is to be impacted, some other means of protection is necessary. This other means could be a thin metal or other type of guardrail which could direct the vehicle from the fixed object, or could deform and pull down additional posts thus absorbing the post energy and the energy due to the deformation of the protective device.

This type of system could be made up of a series of posts (Figure 12) with a thin gage metal or cables attached to the posts. The metal or cables would act like a tension member, so that when the vehicle impacts the system, it would stretch and pull down additional posts, thus absorbing energy.

The primary purpose of the tension member is not to stop the vehicle before it hits the post, but to redirect it. Therefore, the amount of energy that must be absorbed in the y direction must be obtained. Using the following conditions:

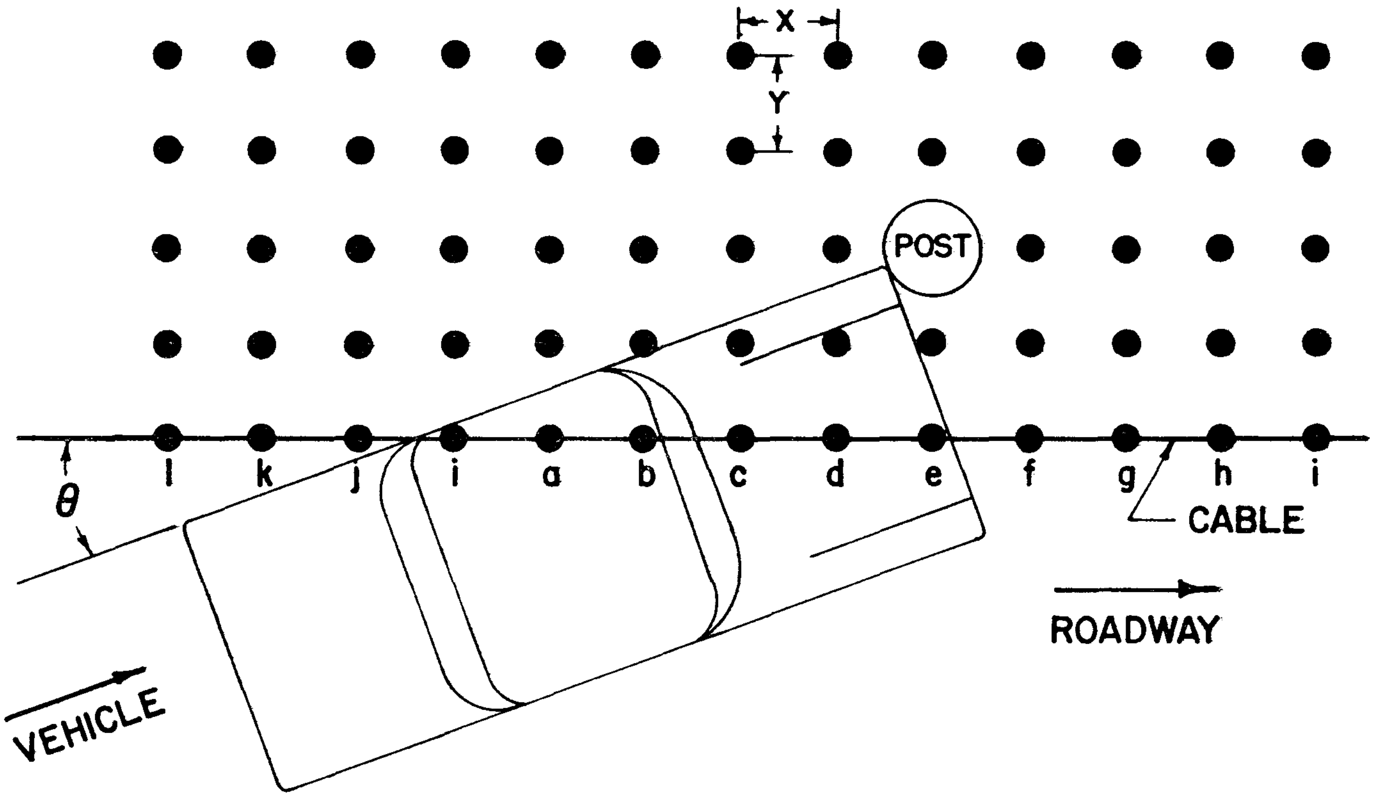
vehicle weight = 4000 lbs

vehicle velocity = 100 fps

angle of approach = 20°

The kinetic energy in the y direction would be

$$K.E._y = 1/2 \frac{(4000)}{(32.2)} (100 \sin 20°)^2 = \frac{(4000)}{(64.4)} (1170)$$



POSTS WITH CABLE OR THIN METAL
TENSION MEMBER

FIGURE 12

$$K\,E\,y = 72{,}600 \text{ ft-lbs}$$

Taking into consideration that each post is capable of absorbing 15,500 ft-lbs of energy and that the post starts moving at approximately 5000 pounds.

Let us examine the failure of the posts, i. e., the number and the sequence in which they will fail if the tension member remains intact and pulls down posts, thus absorbing the energy of the vehicle.

Using the following diagram:

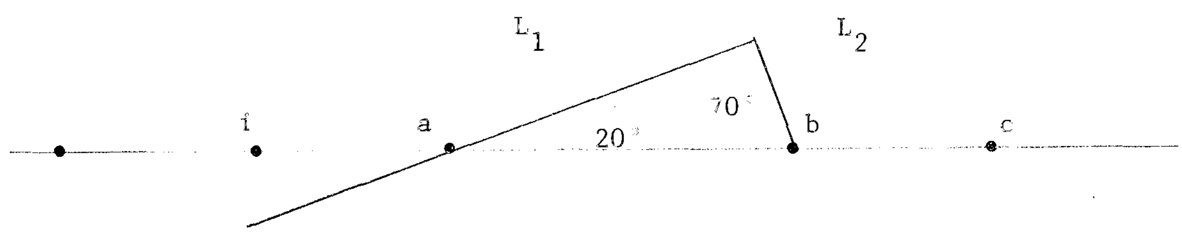


FIGURE 13

and assuming that the vehicle could stretch the cable or thin metal as shown; let us determine if post a or b have failed.

$$L_1 = (2) \cos 20° = 1.88 \text{ ft}$$

$$L_2 = (2) \sin 20° = 0.685 \text{ ft.}$$

If the elongation of the tension member must be .565 ft, and letting the cable or thin metal have a cross sectional area of 1 in^2, the resulting tension in the member is using the relationship

$$S = E\ \varepsilon$$

or

$$F = E\,A\left(\frac{\Delta L}{L}\right)$$

and using a steel member for which $E = 30 \times 10^6$ psi

then

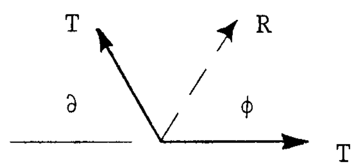
$$F = \frac{(30 \times 10^6)\ (1)\ (.565)}{2}$$

$$F = 846{,}000 \text{ lbs.}$$

This is the force that the cable would have if deflected as shown in Figure 13.

Now, determining the tensile force needed for a post to fail for the given position.

Using the following free body:



FREE BODY OF POST

FIGURE 14

and knowing that the post fails whenever the resultant exceeds 5000 pounds:

taking $\quad \Sigma \overset{+}{\vec{F}}x = T - T\cos\partial = 5000\cos\phi$

$$Rf_x = T - T\cos\partial$$

then $\quad T\,(1-\cos\partial) = 5000\cos\phi$

$$\Sigma \overset{+}{\uparrow}Fy = T\sin\partial = 5000\sin\phi$$

if $\partial = 70°$

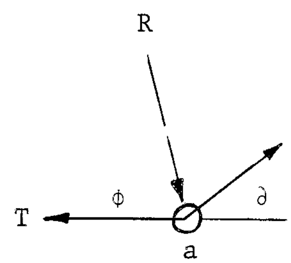
$$\tan \phi + \frac{\sin 65°}{1-\cos 65°}$$

$$\phi = 57.5°$$

and $$T = \frac{5000 \sin 57.5°}{\sin 65°}$$

$$T = 4650 \text{ lbs for the post } \underline{\text{b to fail}}.$$

Now determining the force it takes to fail post a, using the following free body:



FREE BODY OF POST

FIGURE 15

where $$\Sigma F_x = T \cos \partial + R \cos \phi - T = 0$$

$$T(1 - \cos \partial) = R \cos \phi$$

$$T = \frac{R \cos \phi}{1 - \cos \partial}$$

$$\Sigma F_y = T \sin \partial - R \sin \phi = 0$$

$$T = \frac{R \sin \phi}{\sin \partial}$$

and $\phi = \tan^{-1} \dfrac{\sin \partial}{1-\cos \partial}$

But since R = 5000 lbs, the force needed in the tension member to fail post a is, using $\partial = 20°$

$$\phi = \tan^{-1} \frac{\sin 20°}{1-\cos 20°}$$

$$\phi = \tan^{-1} \frac{.342}{[1-.94]}$$

$$\phi = 89°$$

$$T = \frac{(5000)\ (\sin 89°)}{\sin 20°}$$

$$T = 14{,}620 \text{ lbs}$$

It follows that for angles greater than 20° the force required would be less and that these posts would fail first.

Using the following penetrations, let us determine if the posts are still breaking and thus absorbing energy.

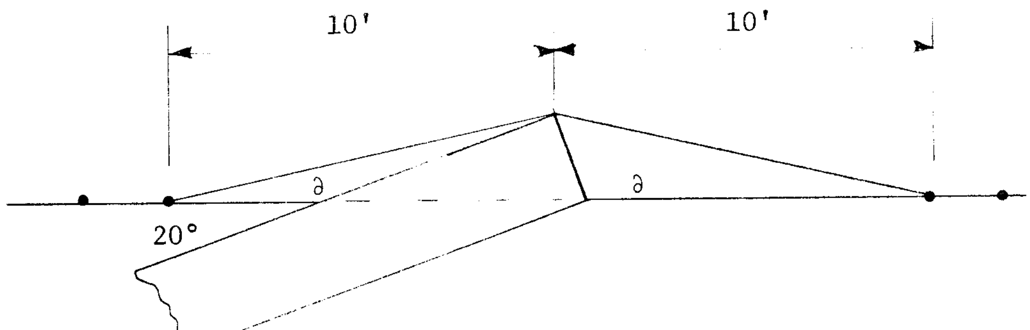


FIGURE 16

where $\tan \partial = 1/10$

$$\partial = 5.78°$$

and $\phi = 90°$

then $T = \frac{5000}{\sin 5.78} = 50{,}000$ lbs

Now, checking to see if a tensile force of 50,000 lbs is possible for this penetration, the final length of the tension member must be determined first and it would be equal to:

$$L_f = 2[(10)^2 + (1)^2]^{1/2}$$

$$= 2\ (10.0498)$$

$$= 20.0996 \text{ ft}$$

or $\Delta L = .0996$ ft

and the resulting force is

$$F = \frac{(30 \times 10^6)\ (1)\ (.0996)}{20} = 149{,}500 \text{ lbs}$$

which is greater than 50,000 lbs, therefore, the posts would still be failing.

With only one foot of penetration when using 2 foot post spacing, at least 10 posts have either failed or deflected, absorbing 155,000 ft-lbs of energy. This is in excess of the initial vehicle energy in the y direction, preventing the vehicle from penetrating any deeper and thus causing it to be redirected from the post.

This analysis shows that with the tension member attached to the posts, a great deal of additional energy can be absorbed, which must be done in the cases where the vehicle's impact is very close to the rigid object.

Still another system that has merit is one in which the impact surface is connected by cables to a fluid damping device to absorb the energy of impact, Figure 17. This would be a reusable system whereas the previous systems would not be reusable.

The drag force is proportional to the square of the velocity, plate area, fluid density and viscosity, as shown by the following equation:[47]

$$DRAG = C_D A \frac{V^2}{2} \rho$$

Using a drag coefficient of 1.2, the drag force for various surface area plates and velocities can be obtained. A curve illustrating the drag forces obtained in water is shown in Figure 18.

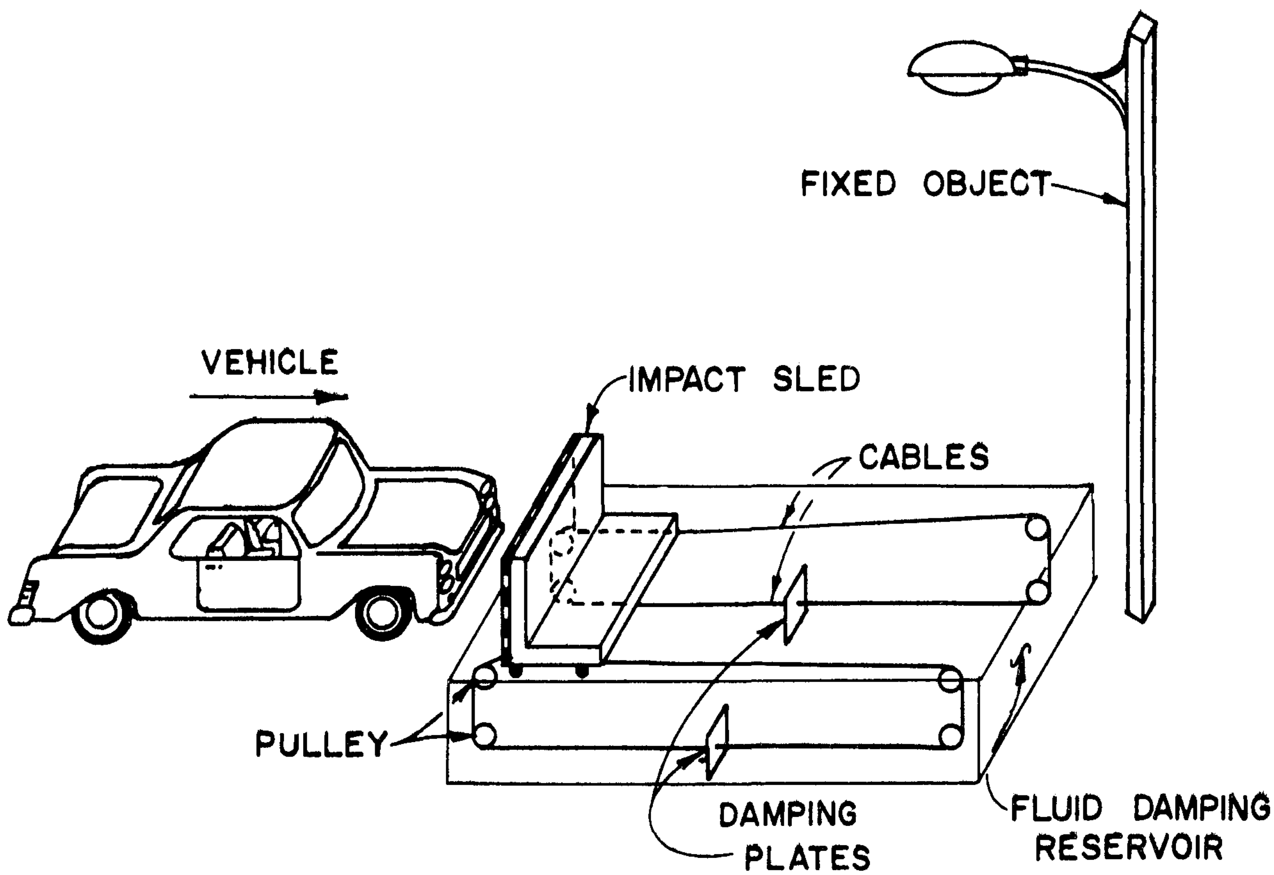

FIXED OBJECT
VEHICLE
IMPACT SLED
CABLES
PULLEY
DAMPING PLATES
FLUID DAMPING RESERVOIR

FIG. 17

DRAG FORCE VERSUS VELOCITY FOR A FLAT PLATE BEING PULLED THROUGH STILL WATER FOR VARIOUS SURFACE AREAS

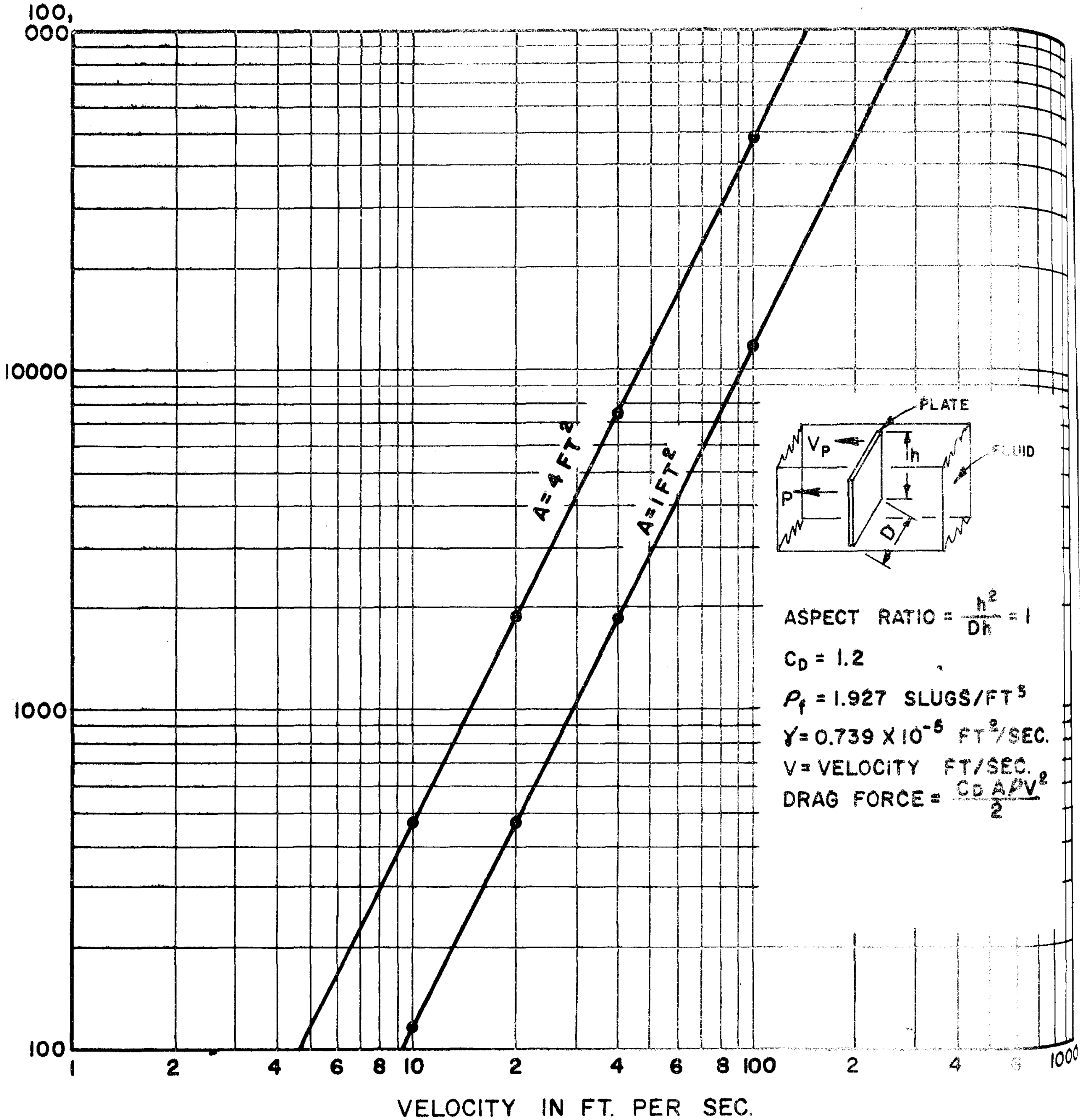


FIG. 18

CHAPTER 4

PROPOSED IMPACT ATTENUATION SYSTEMS

A series of impact attenuation systems using a deformable section, or a deformable section in conjunction with a series of posts, are shown in Figures 19 through 27. These systems employ various densities of polyurethane foam in the deformable section. The polyurethane foam is used rather than honeycomb which has been mentioned previously in this report in that the honeycomb has unidirectional properties and the foam is multi-directional. These are foamed in place on a concrete slab which is enclosed by a series of posts covered on the exterior by a thin gage metal band extending to ground level. The concrete and metal banding serve as the form for the polyurethane support required for the foaming process. The concrete also serves as a support for the vehicle when it impacts the system and should not need to be replaced after impact. The metal band has the additional benefit of distributing the load of the vehicle upon impact over the polyurethane foam, resulting in more uniform crushing, as well as protecting the foamed material from vandalism, minor collisions, and weathering. The mastic employed over the top of the foamed surface is to prevent the deterioration of the exposed top surface of the foam.

Systems 1, 2 and 3, which are to be used on a narrow 9'-6" median, are shown in Figures 19, 20 and 21. Their impact properties are shown in Tables 6, 7 and 8, respectively, the cost being shown in Table 14.

System 2 employs two different densities of foam, the 2#/ft.^{3} and 4#/ft.^{3}, and is capable of stopping a 4000 pound vehicle going 60 miles per hour at an impact angle of 30^o. This system's initial cost should be approximately \$2500 and its replacement cost should not exceed \$1500.

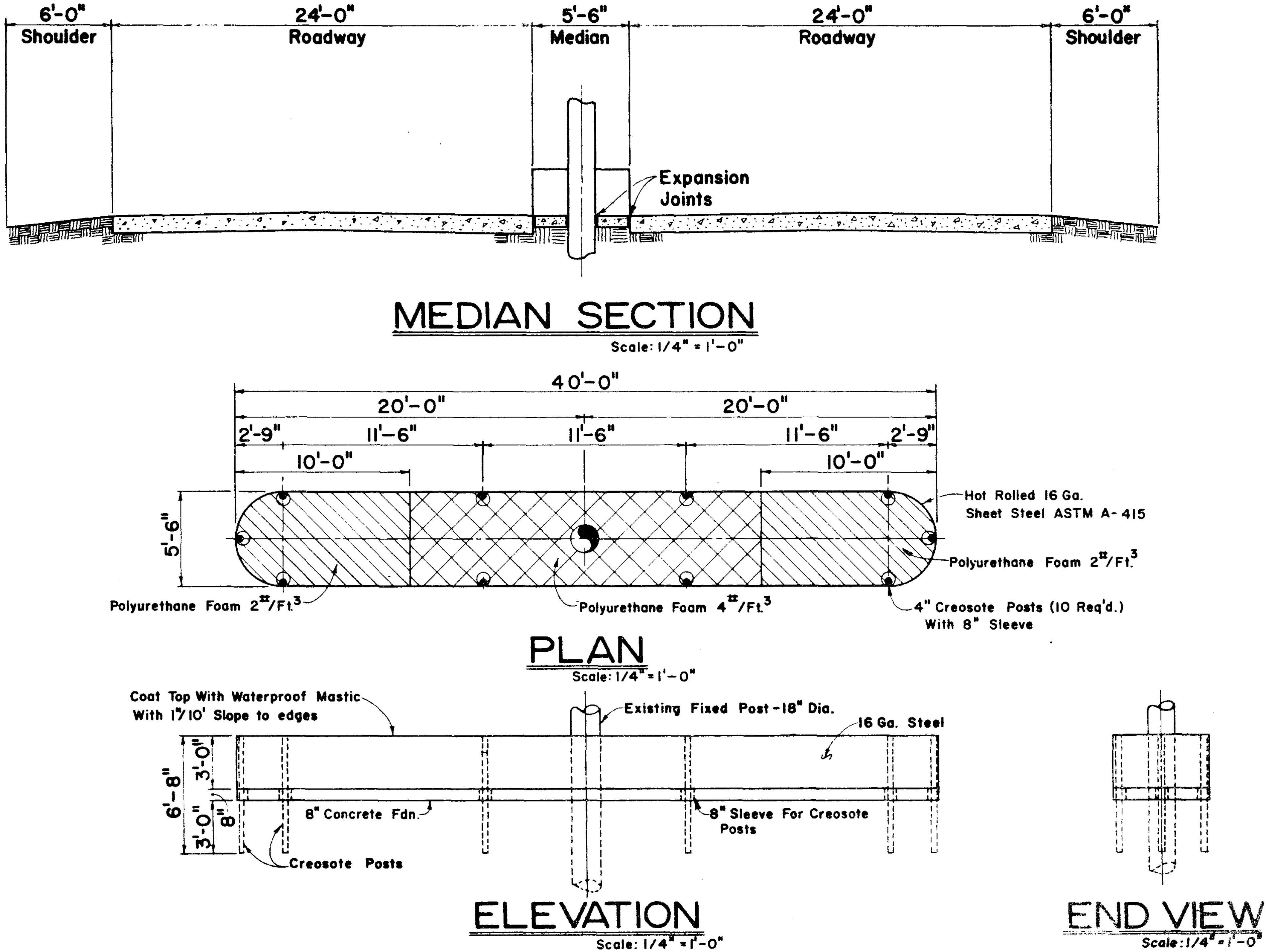
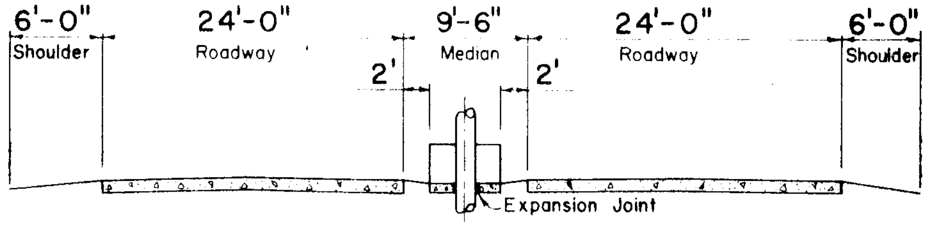
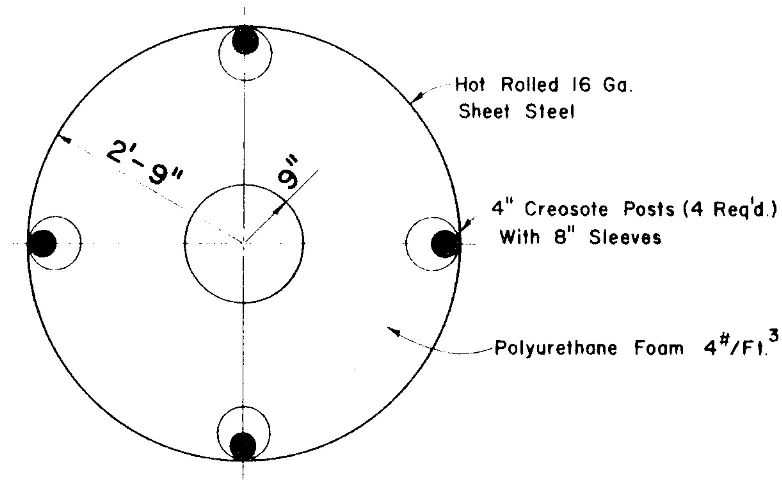


Figure 19 SYSTEM 1



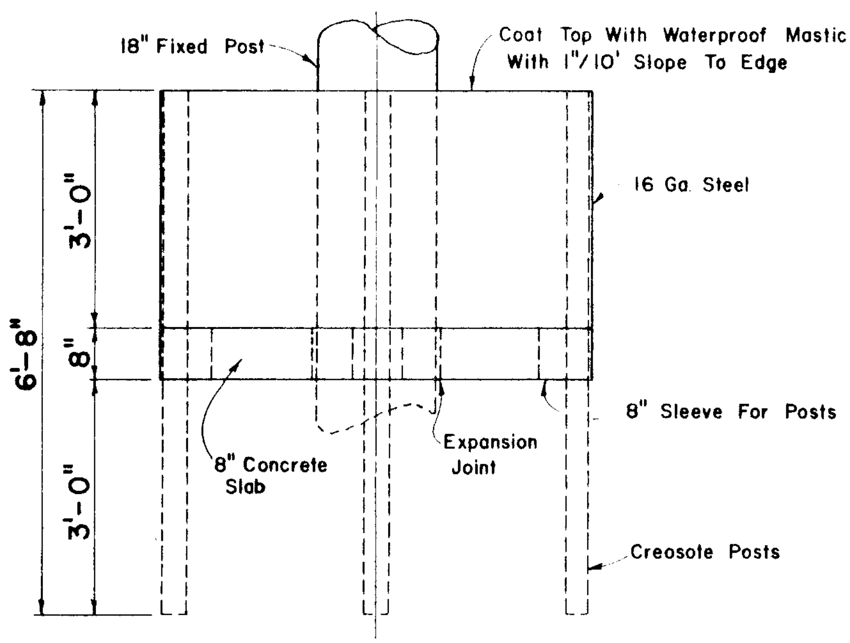
MEDIAN SECTION

Scale: 1/8" = 1'-0"



PLAN

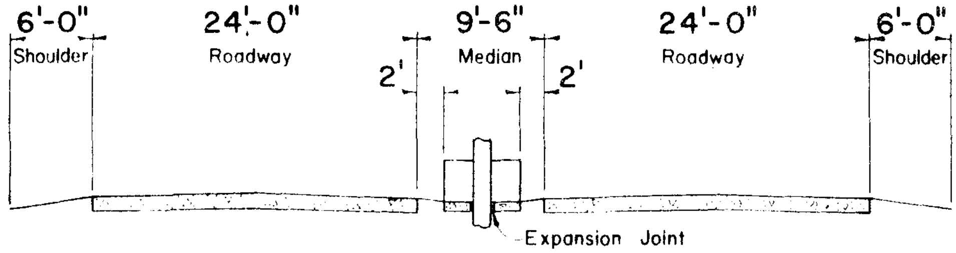
Scale: 3/4" = 1'-0"



ELEVATION

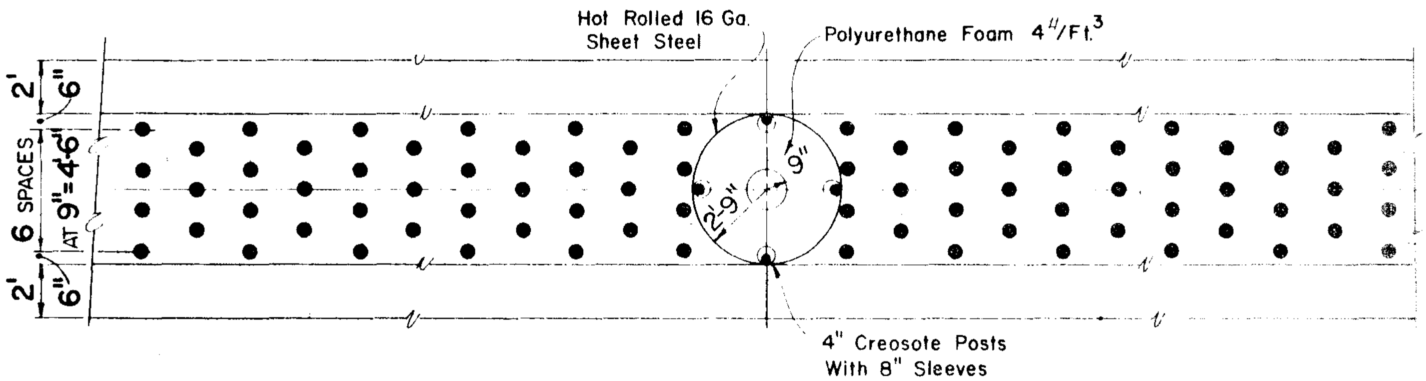
Scale: 3/4" = 1'-0"

Figure 20
SYSTEM 2



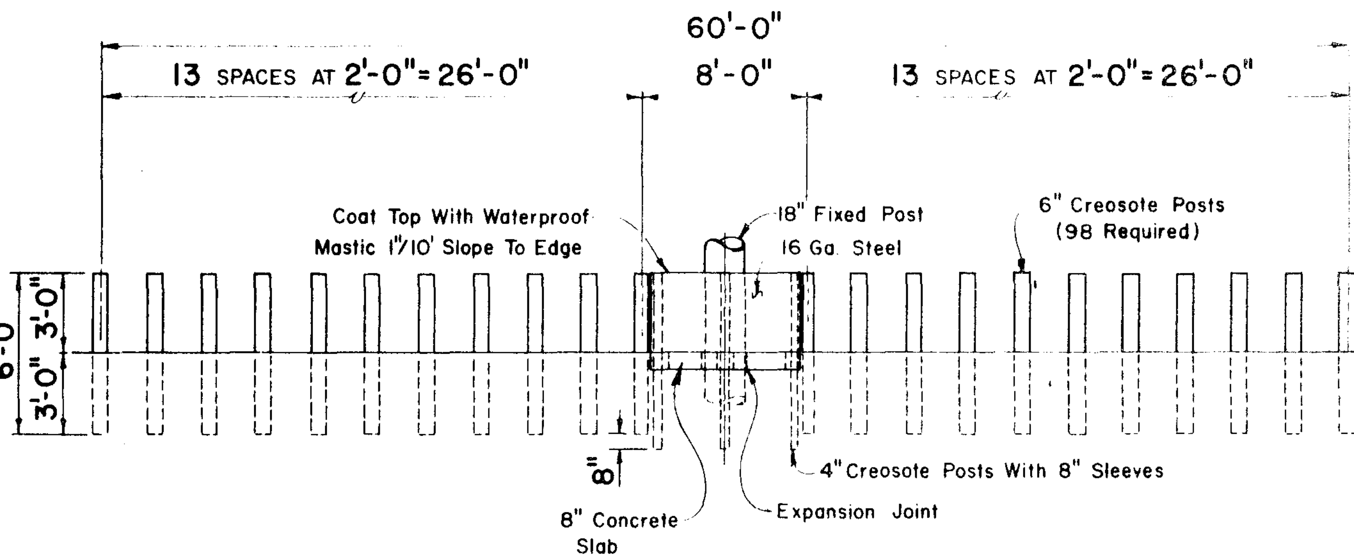
MEDIAN SECTION

Scale: 1/8" = 1'-0"



PLAN

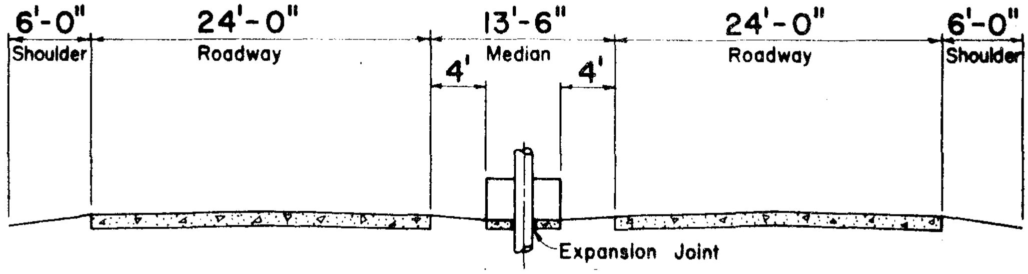
Scale: 1/4" = 1'-0"



ELEVATION

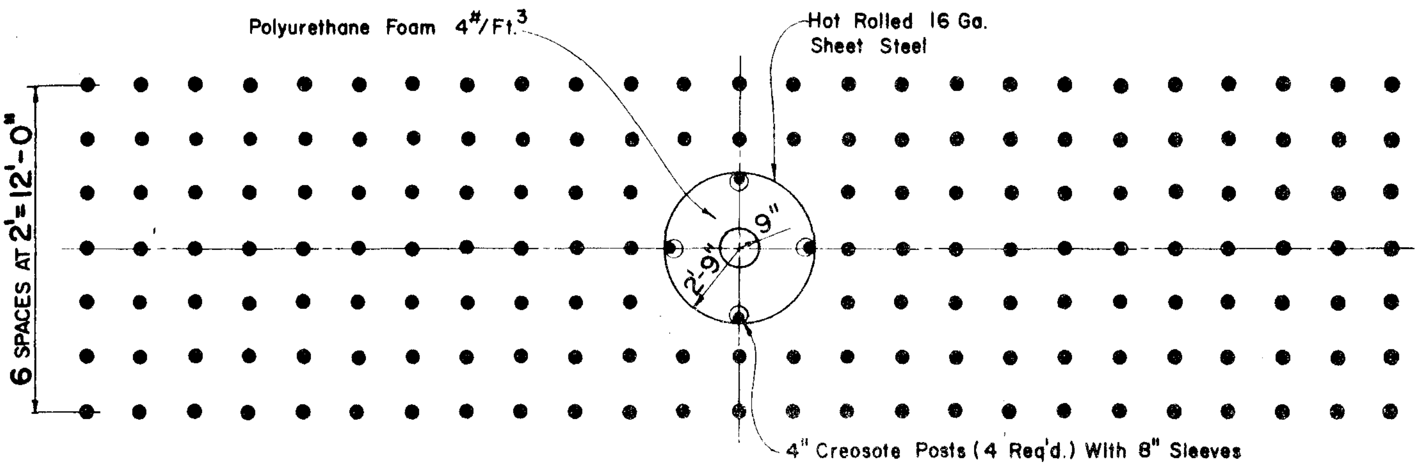
Scale: 1/4" = 1'-0"

Figure 21
SYSTEM 3



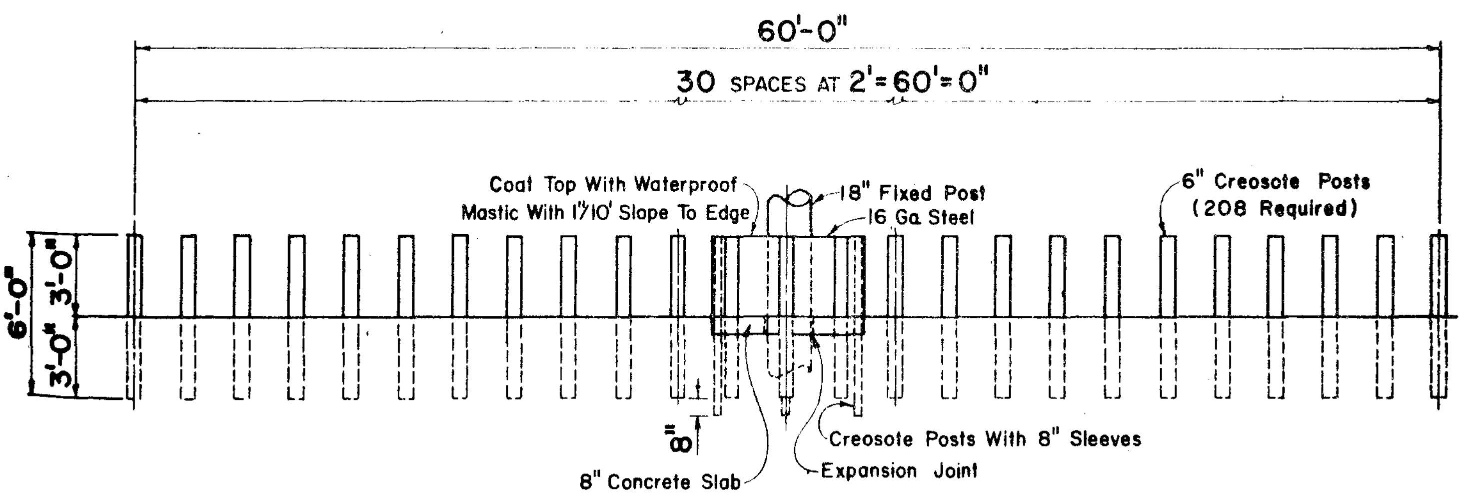
MEDIAN SECTION

Scale: 1/8" = 1'-0"



PLAN

Scale: 1/4" = 1'-0"

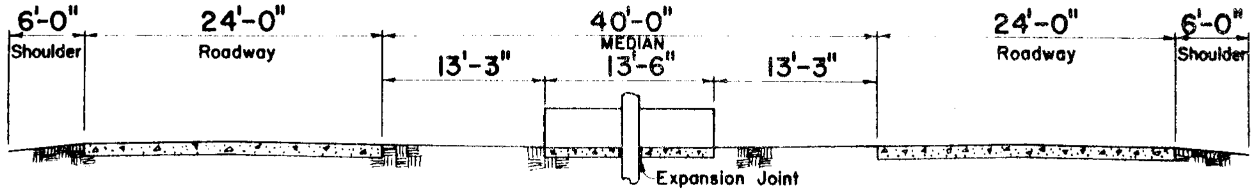


ELEVATION

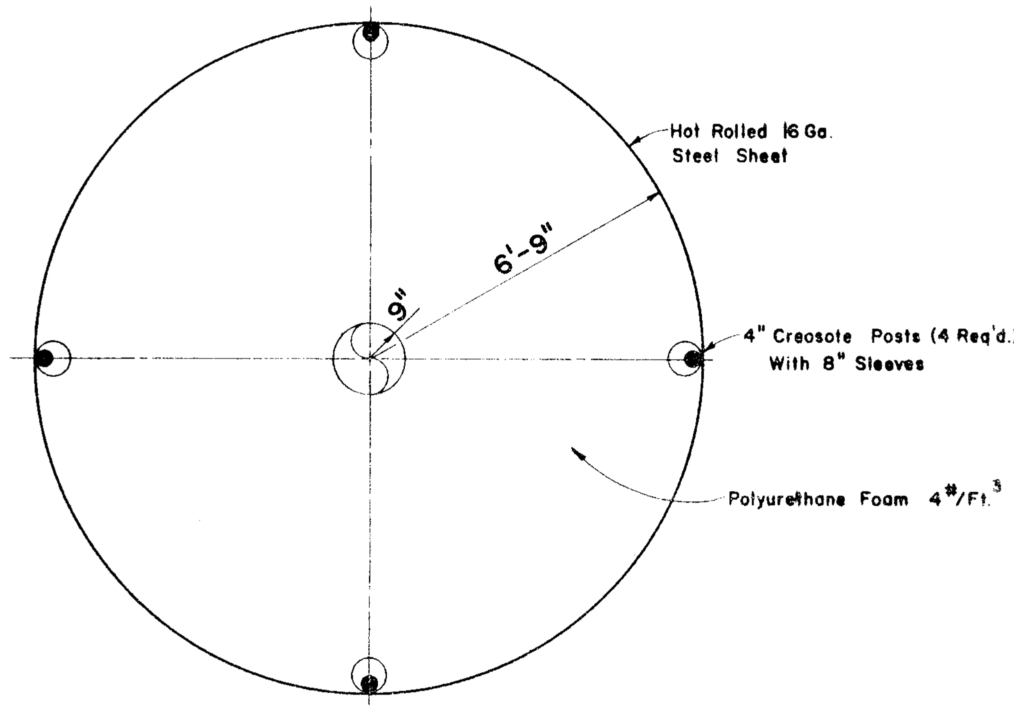
Scale: 1/4" = 1'-0"

Figure 22

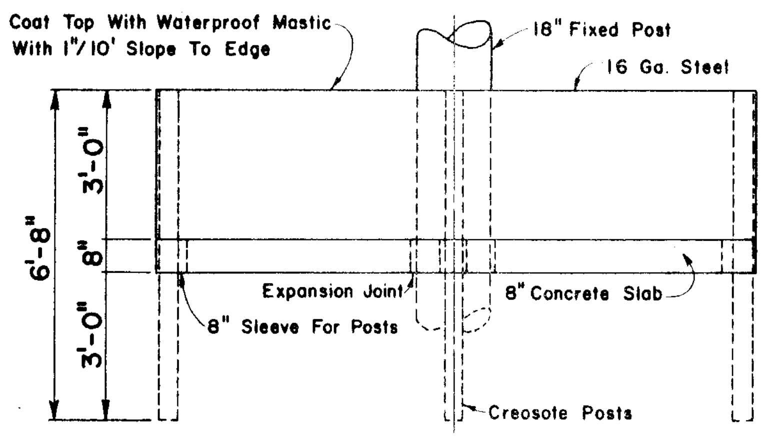
SYSTEM 4



MEDIAN SECTION
Scale: 1/8" = 1'-0"

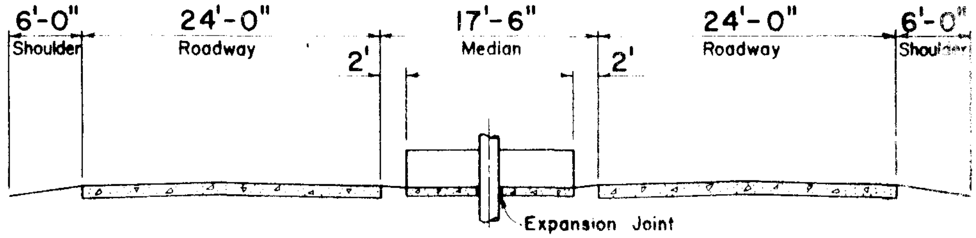


PLAN
Scale: 1/2" = 1'-0"



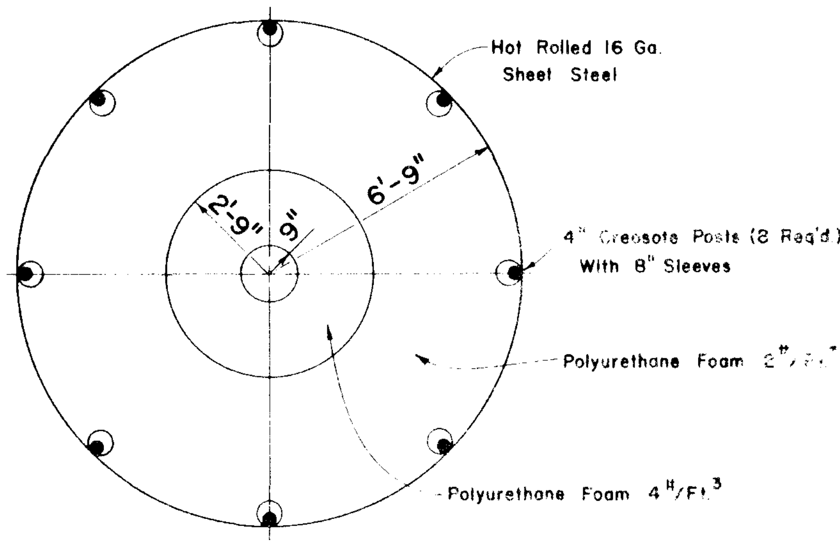
ELEVATION
Scale: 1/2" = 1'-0"

Figure 23
SYSTEM 5



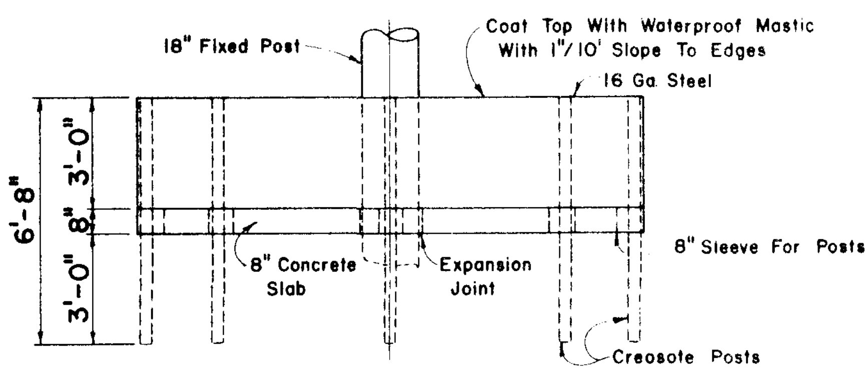
MEDIAN SECTION

Scale: 1/8" = 1'-0"



PLAN

Scale: 3/8" = 1'-0"



ELEVATION

Scale: 3/8" = 1'-0"

Figure 24
SYSTEM 6

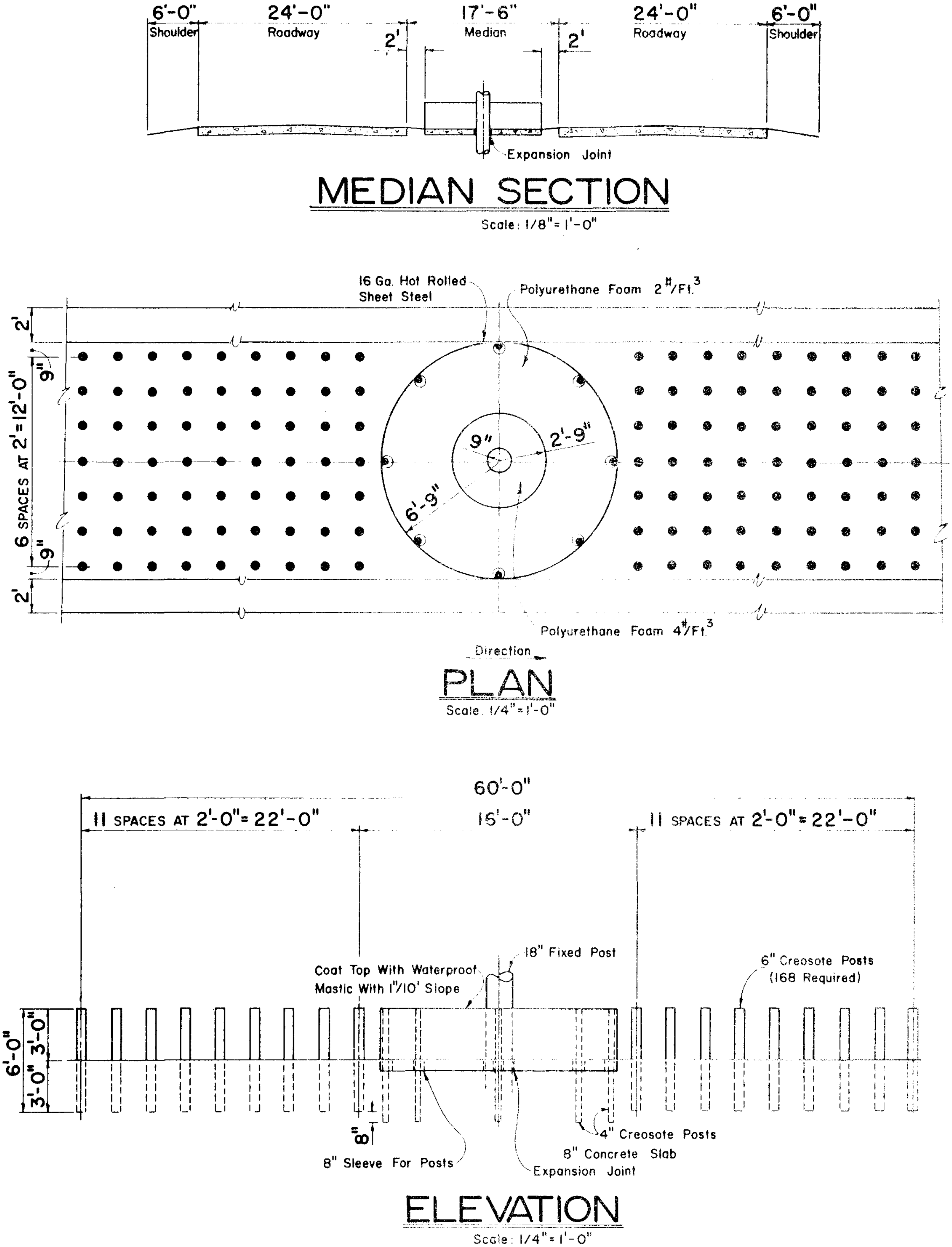
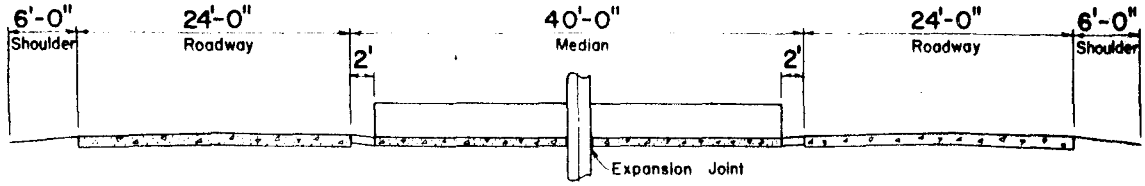
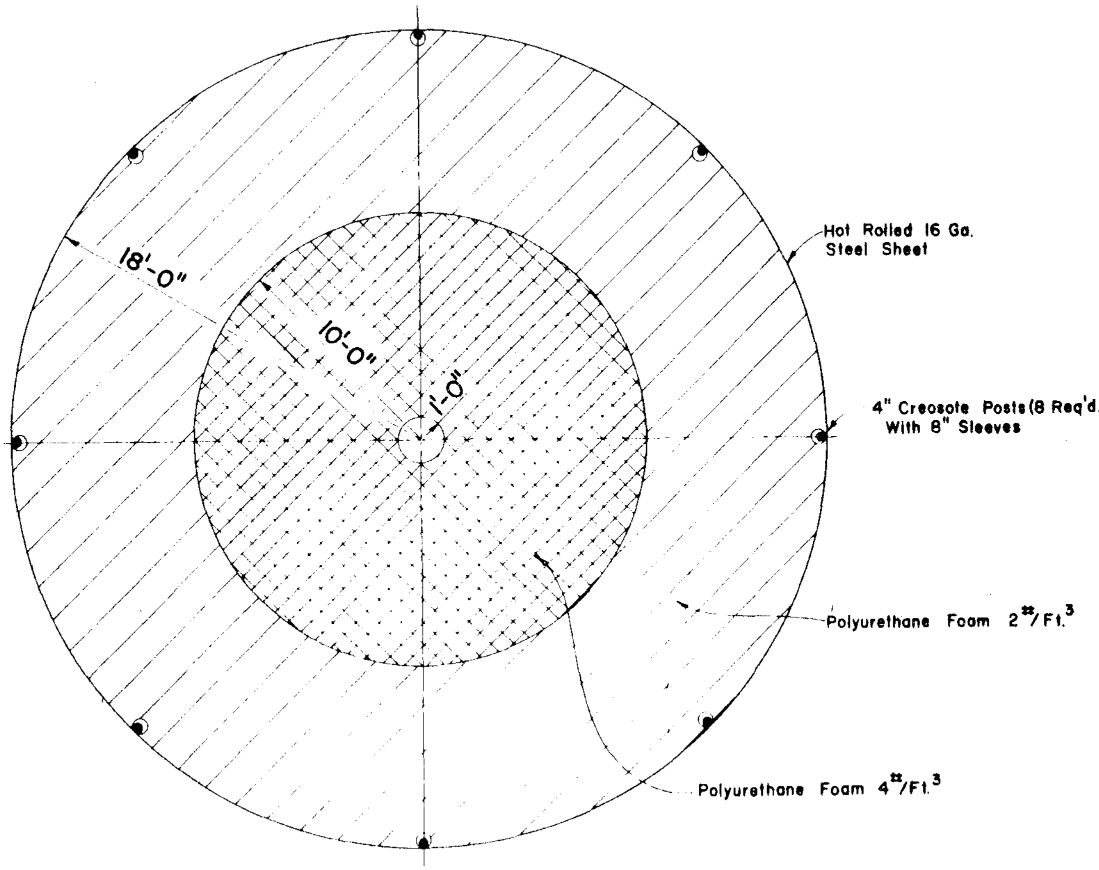


Figure 25
SYSTEM 7



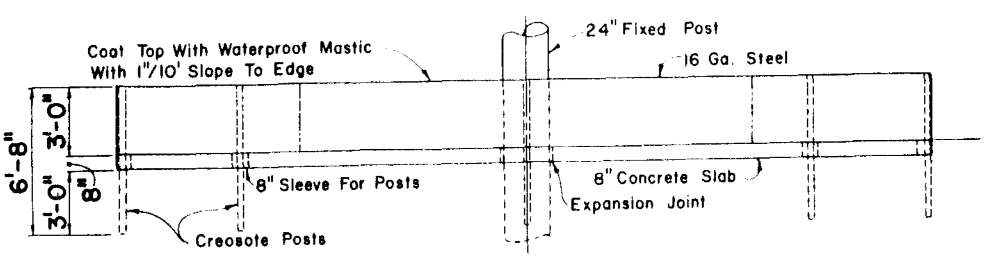
MEDIAN SECTION

Scale: 1/8" = 1'-0"



PLAN

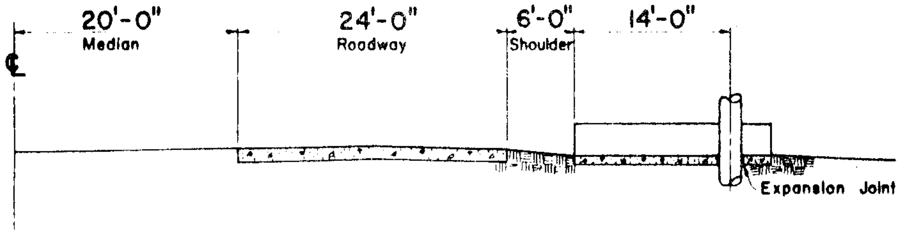
Scale: 1/4" = 1'-0"



ELEVATION

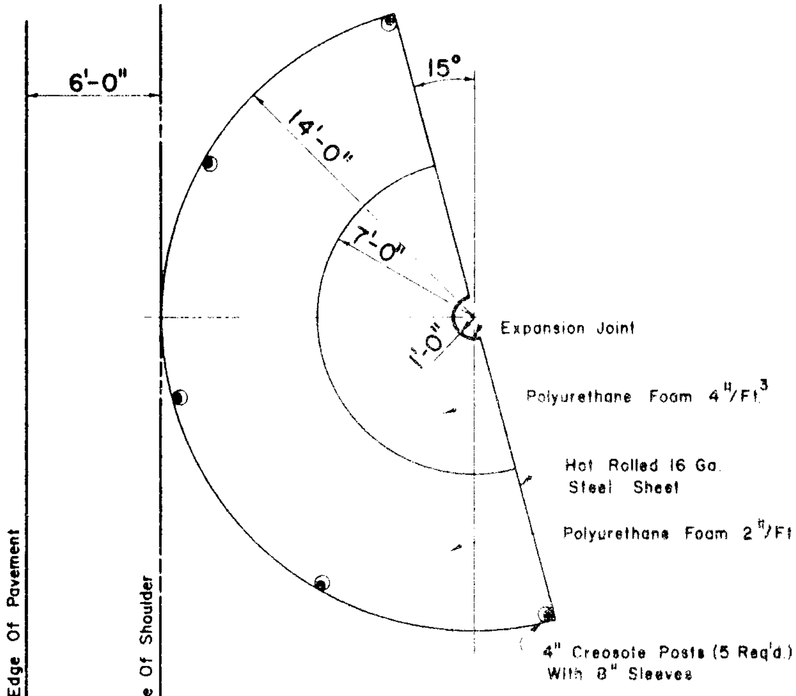
Scale: 1/4" = 1'-0"

Figure 26
SYSTEM 8



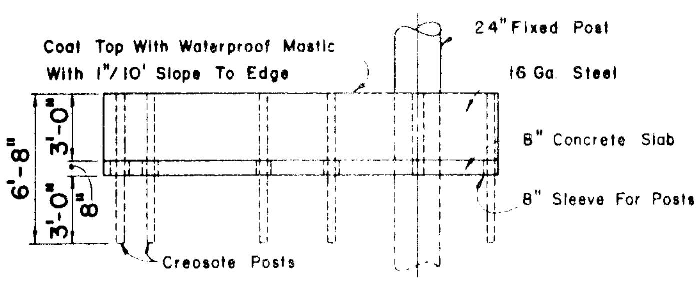
MEDIAN HALF-SECTION

Scale: 1/8" = 1'-0"



PLAN

Scale: 1/4" = 1'-0"



ELEVATION

Scale: 1/4" = 1'-0"

Figure 27
SYSTEM 9

TABLE 6

SYSTEM 1

WEIGHT (lbs.)	VELOCITY (ft./sec.)	ANGLE OF APPROACH (degrees)	REQUIRED STOPPING DISTANCE (ft.)	AVAILABLE STOPPING DISTANCE (ft.)	PEAK DECELERATION (g's)
5000	80	30°	4.5	4.25	(hits post)
5000	73.3	30°	3.48	4.25	17.3
5000	66	30°	2.50	4.25	17.3
4000	88	30°	4.1	4.25	21.6
4000	66	30°	1.68	4.25	21.6
3500	100	30°	4.81	4.25	(hits post)
3500	88	30°	3.42	4.25	24.7
3000	100	30°	3.41	4.25	28.8
3000	66	30°	0.90	4.25	28.8
5000	100	20°	7.5	7.25	(hits post)
5000	88	20°	5.5	7.25	17.3
5000	66	20°	2.5	7.25	17.3
4000	100	20°	5.11	7.25	21.6
4000	88	20°	4.10	7.25	21.6
4000	66	20°	1.68	7.25	21.6
3500	100	20°	4.81	7.25	24.7
3500	88	20°	3.42	7.25	24.7
3000	100	20°	3.41	7.25	28.8
3000	88	20°	2.7	7.25	28.8

TABLE 6 (continued)

WEIGHT (lbs.)	VELOCITY (ft./sec.)	ANGLE OF APPROACH (degrees)	REQUIRED STOPPING DISTANCE (ft.)	AVAILABLE STOPPING DISTANCE (ft.)	PEAK DECELERATION (g's)
5000	100	10°	10.36	15.0	17.3
4000	100	10°	8.6	15.0	21.6
3000	100	10°	6.7	15.0	28.8
2500	100	10°	5.9	15.0	34.6
2000	88	10°	4.8	15.0	21.6
5000	100	0°	12.6	19.25	17.3
4000	100	0°	10	19.25	10.8
3000	100	0°	7.6	19.25	14.4
2000	100	0°	6.5	19.25	21.6

TABLE 7

SYSTEM 2

WEIGHT (lbs.)	VELOCITY (ft./sec.)	REQUIRED STOPPING DISTANCE (ft.)	AVAILABLE STOPPING DISTANCE (ft.)	PEAK DECELERATION (g's)
5000	62	2	2	17.3
4000	69	2	2	21.6
3000	80	2	2	28.8
2000	98	2	2	43.2

TABLE 8

WEIGHT (lbs.)	VELOCITY (ft./sec.)	NUMBER OF GUARD POSTS REQUIRED	SYSTEM 3 9.5 FT. MEDIAN NUMBER OF GUARD POSTS ENCOUNTERED						SYSTEM 4 17.5 FT. MEDIAN NUMBER OF GUARD POSTS ENCOUNTERED					
			2 feet spacing			3 feet spacing			2 feet spacing			3 feet spacing		
			Angle θ			Angle θ			Angle θ			Angle θ		
			10°	20°	30°	10°	20°	30°	10°	20°	30°	10°	20°	30°
5000	100	28	30	13	6	18	10	4	60	33	20	23	16	10
	88	13	30	13	6	18	10	4	60	33	20	23	16	10
	66	3	30	13	6	18	10	4	60	33	20	23	16	10
4000	100	21	30	13	6	18	10	4	60	33	20	23	16	10
	88	7	30	13	6	18	10	4	60	33	20	23	16	10
	66	0	30	13	6	18	10	4	60	33	20	23	16	10
3000	100	12	30	13	6	18	10	4	60	33	20	23	16	10
	88	1	30	13	6	18	10	4	60	33	20	23	16	10
2000	100	1	30	13	6	18	10	4	60	33	20	23	16	10
	88	0	30	13	6	18	10	4	60	33	20	23	16	10

TABLE 9

SYSTEM 5

WEIGHT (lbs.)	VELOCITY (ft./sec.)	REQUIRED STOPPING DISTANCE (ft.)	AVAILABLE STOPPING DISTANCE (ft.)	PEAK DECELERATION (g's)
5000	100	7.5	6.0	(hits post)
5000	88	5.5	6.0	17.3
5000	66	2.5	6.0	17.3
4000	100	5.1	6.0	21.6
4000	88	4.1	6.0	21.6
4000	66	1.7	6.0	21.6
3000	100	3.4	6.0	28.8
3000	88	2.7	6.0	28.8
3000	66	0.9	6.0	28.8
2000	100	2.1	6.0	43.2
2000	88	1.3	6.0	43.2
2000	66	0.1	6.0	43.2

TABLE 10

SYSTEM 6

WEIGHT (lbs.)	VELOCITY (ft./sec.)	REQUIRED STOPPING DISTANCE (ft.)	AVAILABLE STOPPING DISTANCE (ft.)	PEAK DECELERATION (g's)
5000	100	9.6	6.0	(hits post)
	88	7.5	6.0	(hits post)
	66	4.5	6.0	17.3
4000	100	7.8	6.0	(hits post)
	88	6.2	6.0	(hits post)
	66	4.0	6.0	10.8
3000	100	6.0	6.0	28.8
	88	4.8	6.0	28.8
	66	2.9	6.0	14.4
2000	100	4.2	6.0	43.2
	88	4.0	6.0	21.6
	66	1.7	6.0	21.6

TABLE 11

SYSTEM 7

WEIGHT (lbs.)	VELOCITY (ft./sec.)	NUMBER OF POSTS REQUIRED	NO. OF POSTS ENCOUNTERED					
			2 feet spacing			3 feet spacing		
			θ			θ		
			10°	20°	30°	10°	20°	30°
5000	100	17	35	26	13	19	13	6
	88	9	35	26	13	19	13	6
	66	0	35	26	13	19	13	6
4000	100	10	35	26	13	19	13	6
	88	1	35	26	13	19	13	6
	66	0	35	26	13	19	13	6
3000	100	1	35	26	13	19	13	6
	88	0	35	26	13	19	13	6

TABLE 12

SYSTEM 8

WEIGHT (lbs.)	VELOCITY (ft./sec.)	REQUIRED STOPPING DISTANCE (ft.)	AVAILABLE STOPPING DISTANCE (ft.)	PEAK DECELERATION (g's)
5000	100	11.6	17.0	17.3
	88	9.5	17.0	17.3
	66	7.1	17.0	8.7
4000	100	9.8	17.0	21.6
	88	8.2	17.0	21.6
	66	5.6	17.0	10.8
3000	100	8.0	17.0	14.4
	88	7.6	17.0	14.4
	66	4.0	17.0	14.4
2000	100	6.5	17.0	21.6
	88	4.8	17.0	21.6
	66	2.4	17.0	21.6

TABLE 13

SYSTEM 9

WEIGHT (lbs.)	VELOCITY (ft./sec.)	REQUIRED STOPPING DISTANCE (ft.)	AVAILABLE STOPPING DISTANCE (ft.)	PEAK DECELERATION (g's)
5000	100	11.0	13.0	17.3
	88	9.0	13.0	17.3
	66	7.0	13.0	8.7
4000	100	9.3	13.0	21.6
	88	7.7	13.0	21.6
	66	5.6	13.0	10.8
3000	100	7.5	13.0	28.8
	88	7.0	13.0	14.4
	66	4.0	13.0	14.4
2000	100	6.5	13.0	21.6
	88	4.8	13.0	21.6
	66	2.4	13.0	21.6

TABLE 14

SYSTEM	COST ($)
1	2500
2	500
3a	1000
3b	800
4a	1500
4b	1100
5	1400
6	1000
7a	2300
7b	1700
8	7400
9	3400

System 2 employs a ring of $4\#/ft.^3$ polyurethane foam and is capable of stopping a 4000 pound vehicle going 47 miles per hour. This system should cost approximately \$500 for its initial installation.

System 3 is a combination of System 2 and a series of posts embedded in sand. This system, when using a 2 foot post spacing, should stop a vehicle weighing 4000 pounds going 60 miles per hour at an angle of 30^o and when using a 3 foot post spacing, should stop a 4000 pound vehicle going 60 miles per hour at an angle of 20^o. The systems will cost approximately \$1000 and \$300 respectively.

Systems 4, 5, 6 and 7 (Figs. 22, 23, 24, and 25) can all be employed in a 17'-6" median.

System 4 is a combination of System 3 and a field of posts embedded in sand and is capable of stopping when using 2 foot spacing, a 4000 pound vehicle going 63 miles per hour at an angle of 30^o (Table 8), and when using 3 foot spacing, going 60 miles per hour at an angle of approach of 30^o. These systems should cost about \$1500 and \$1100 respectively and the replacement costs should not exceed \$800 and \$600.

System 5 which employs a ring of $4\#/ft.^3$ polyurethane foam is capable of stopping a 4000 pound vehicle going at 70 miles per hour and costs about \$1400. The replacement cost should not exceed \$1000.

System 6 (Fig. 24) employs both a ring of $4\#/ft.^3$ and $2\#/ft.^3$ foam and is capable of stopping a 4000 pound vehicle going 45 miles per hour (Table 10). This system would have an initial cost of about \$1000 and a replacement cost of about \$600.

System 7 (Fig. 25) is a combination of System 6 and a field of posts. It is capable of stopping a vehicle weighing 4000 pounds and going 70 miles per hour at an approach angle of 30^o when using a 2 foot post spacing.

When using the 3 foot post spacing, it will stop a 4000 pound vehicle traveling in excess of 60 miles per hour at an approach angle of 30^{o}. These systems would cost \$2300 and \$1700, respectively, and the replacement cost would be \$1200 and \$900.

System 8 (Fig. 26) is to be used in a 40 foot median and employs a ring of $2\#/ft.^3$ and $4\#/ft.^3$ polyurethane foam. This system, which would cost \$7400 initially, is capable of stopping a 5000 pound vehicle traveling in excess of 70 miles per hour. The replacement cost would be \$2500.

System 9 (Fig. 27) is to be used on the side of the road and is a half section employing both $2\#/ft.^3$ and $4\#/ft.^3$ foam. This system is capable of stopping a 5000 pound vehicle traveling in excess of 70 miles per hour and would cost approximately \$3400 to install. Its replacement cost would be approximately \$3000.

It is believed that impact attenuation systems are feasible and should be considered for use on our nation's highways.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. It is apparent, from the references cited previously, that a human being is capable of withstanding deceleration rates in excess of 25 g's lasting for 0.1 seconds with onset rates in excess of 500 g's per second without injurious or disabling effects provided that the person is properly restrained.
2. A sizeable reduction in the number of deaths caused by single car accidents can be realized by the use of attenuation systems that will decelerate an impacting vehicle with a deceleration rate that is less than 25 g's and with an onset rate of less than 500 g's per second.
3. The systems as outlined in the report are capable of meeting the deceleration requirements necessary for the prevention of this unnecessary loss of life, maiming and property damage.
4. The necessary construction materials required for the fabrication of these systems are presently available from industry.
5. A feasible system for use around fixed objects, such as interior bents, bridge abutments and overhead supports, located in areas where a limited amount of vehicle stopping distance is available, can be obtained by using the concept illustrated by Figure 7. This system employs a series of plastic acting impact elements for the absorption of the vehicle kinetic energy upon impact.
6. A system that employs a field of posts in conjunction with a cable

or guardrail system as illustrated in Figure 12, appears to be feasible for use where a large amount of stopping distance is available.

Recommendations

In an attempt to reduce the injuries, fatalities and loss of property caused by the single vehicle accidents, the following recommendations are made:

1. A program should be inaugurated for the determination of mechanical properties of the various available energy absorbing materials (foam, honeycomb, plastics, etc.) that can be used in the construction of impact attenuation systems. The material properties should be determined under loadings which are both static and dynamic. These tests would enable the determination of the energy absorbing capabilities of the various materials.
2. The fabrication techniques necessary for the construction of the various impact attenuation systems should be studied.
3. Material and fabrication cost studies should be made; this should include material durability, maintenance and replacement requirements so that the most economical system will result.
4. Full-scale crash tests of selected systems and materials should be made to evaluate the impact behavior of the various systems under actual collision conditions.
5. From the analysis of the various attenuation systems and preliminary laboratory tests on polyurethane foam, it is recommended that systems similar to those shown in Figures 19 through 27 be considered for field testing and application.

The expected impact properties of the respective systems for various vehicle parameters are shown in Tables 6 through 13. The approximate fabrication and material costs for these systems are shown in Table 14.

The material (polyurethane foam) is presently available from the Polytron Company in Brookpark, Ohio, and costs less than one dollar a pound. It can be foamed in place with a density of only 2 pounds a cubic foot. According to test data its crush strength with this density would be approximately 25 psi.

Another material that looks promising is foamed sulfur. This material which can also be foamed in place with controlled densities and strength, has a much lower cost per pound than polyurethane foam.

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