Dragnet Vehicle Arresting System

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The "dragnet" vehicle arresting system consists of a net made of steel cables attached at each end to Metal Bender energy-absorbing devices. The system was subjected to six full-scale automobile crash tests to evaluate its performance in stopping a speeding vehicle over a relatively short distance with acceptable deceleration levels. The decelerations encountered were significantly lower than those produced by rigid barriers, and could have been reduced even more by the use of less restraining force on the net, resulting in longer stopping distances. Time-displacement and deceleration data (and observation of damage) from the test series, along with the predictability of system performance in specified situations, indicate that practical application of the arresting system at such locations as dead ends of roads, ferry landings, and highway medians at bridge overpasses is feasible.

•VEHICLE crash testing contributes significantly to the development of new concepts and devices to increase highway safety. However, it is also a valuable tool for determining the applicability of existing devices to highway safety problems.

One existing device that was subjected to full-scale crash testing by the Texas Transportation Institute is the "dragnet" vehicle arresting system developed by Van Zelm Associates, Inc., of Providence, Rhode Island. Six tests were conducted under a contract with the Bureau of Public Roads as part of their program on Structural Systems in Support of Highway Safety (4S Program).

The system, which consists of a steel net attached at each end to Metal Bender energy-absorbing devices, has been used on "drag strip" raceways and, in a modified form, for aircraft arrestments, but prior to this test program the dragnet system has not been widely applied to suitable locations on the public roads. This may be due to the lack of independent analysis of the system's effectiveness in such applications.

DESCRIPTION OF ARRESTING SYSTEM

This system consists of a net made of steel cables attached at each end to Metal Bender energy-absorbing devices as shown in Figures 1 and 2. The Metal Benders, which are supported on rigid steel posts, are steel boxes containing a series of rollers around which the metal tape is bent back and forth as it is pulled through the case. Each end of the net is attached to one end of the metal tape extending from a Metal Bender. The Metal Benders are designed so that a specified force will be necessary to pull the metal tape through the case. This force is relatively independent of velocity and environmental conditions and depends on the size of the tape used. By varying tape size, a number of different tape forces are available.

TEST PROGRAM

Six vehicle crash tests of the dragnet arresting system were conducted during the period from December 19, 1967, to November 21, 1968. A summary of this testing

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program is given in Table 1. Both compact and full-sized vehicles were directed into the system. Tests A through D employed Metal Benders with 25,000-lb tape loads. These tape loads were reduced to 12,500 lb for Tests E and F.

Each test was recorded using high-speed motion picture cameras. The film was analyzed to give detailed time-displacement data. Lower speed motion picture cameras were placed at selected points to provide a qualitative record of the test in progress. Still photographs of the vehicle before and after each test and photographs of various details of the arresting system were obtained.

Accelerometer transducers were attached to the frames of the vehicles to determine deceleration levels during each test. Maximum decelerations under specified filtering techniques were determined

Figure 1. Metal Bender with 25,000-lb tape attached to net.

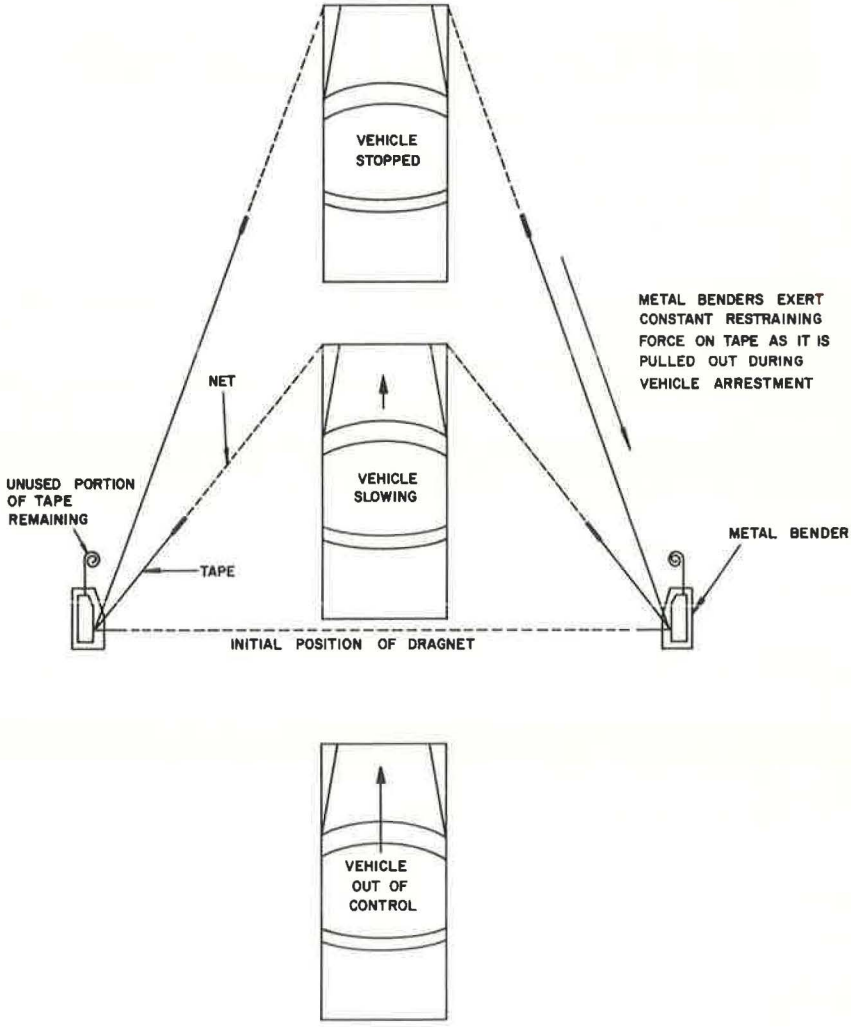

Figure 2. Idealized function of dragnet arresting system.

from these accelerometer traces, while average decelerations were calculated on the basis of initial speed and stopping distance.

An Alderson articulated anthropometric dummy weighing 161 pounds was used to simulate a human driver in each test. A seat belt securing the dummy was equipped with strain gages that permitted the measurement of seat belt force.

Test A

A Renault Dauphine weighing 1,460 pounds was directed head-on into the dragnet at a speed of 42 mph. The tape force for each Metal Bender was 25,000 lb. All components of the system performed as designed and the vehicle was stopped after penetrating 10.2 ft. Stopping distance is defined as the distance the center of gravity of the vehicle travels after the vehicle contacts the net. The Metal Bender strap pullout accounted for 63 percent of the vehicle's initial kinetic energy of 87.1 kip-ft. The remaining energy was expended in stretching the net, crushing the vehicle, and increasing the vehicle's potential energy due to raising the center of gravity. The amount expended in increasing gravitational potential energy was only about 1 kip-ft.

The damage to the front of the vehicle was severe (Fig. 3). The maximum longitudinal deceleration was 16 g. The average deceleration was 5.8 g over 0.25 second.

Test B

A 4,300-lb Mercury sedan traveling at 60 mph was directed head-on into the arresting system. The dragnet, which was equipped with 25,000-lb tape tension Metal Benders, performed as designed. The vehicle was brought to a stop in 19.4 ft and tape pullout expended 58 percent of the vehicle's energy. The front of the vehicle was pulled down to the ground, which caused some frictional energy losses. The change in potential energy due to the elevation of the center of gravity was estimated to be about 17 kip-ft, or 3.3 percent of the initial energy.

The damage to the front of the vehicle, shown in Figure 4, includes a downward bending of the front of the vehicle's frame. This was due to the net applying pressure to the lower portion of the vehicle's front end. The maximum significant deceleration was 16 g, and the average deceleration was 6.1 g.

Test C

A 1,620-lb Volkswagen traveling at 48 mph entered the arresting system at an angle of 30 deg to the perpendicular to the net. All subsequent angle tests will be defined on this basis. The vehicle was stopped in 13.8 ft, and pulled a total of 3.4 ft of tape out of

Figure 3. Vehicle and dragnet after Test A.

Figure 4. Vehicle and left Metal Bender after Test B.

Figure 5. Vehicle after Test C.

the 25,000-lb Metal Benders. This tape pullout consumed 70 percent of the vehicle's kinetic energy. The estimated energy necessary to impart a horizontal rotation, or spin, to the vehicle and to elevate its center of gravity was about 3 kip-ft. These energy levels are defined at the time during the test when the tapes stop pulling out of the benders. The average deceleration level was 5.5 g, while the maximum deceleration was about 13 g. The vehicle damage as shown in Figure 5 was moderate.

Test D

In Test D a 4,520-lb Oldsmobile sedan traveling at 54 mph impacted the net on an initial trajectory of 30 deg. The high-speed films show a maximum travel of 23.5 ft after impact. The 25,000-lb Metal Benders allowed 8.6 ft of metal tape to be pulled through, accounting for 50 percent of the initial kinetic energy. When the maximum tape pullout had occurred, the vehicle was estimated to have 36 kip-ft of rotational energy and 11 kip-ft of gravitational potential energy. The net entrapped only the lower portion of the front of the vehicle. As the front pulled down below the vehicle center of gravity, the unbalanced inertia force resulted in the vehicle's rotating about the restrained point (Fig. 6). The vehicle was completely off the ground and the rear end went over and outside of the restraining net after the tapes had stopped pulling out. When the vehicle fell back to the ground, it came very close to rolling. The average and maximum significant longitudinal decelerations were 4.1 and 8 g respectively.

Test E

Test E was similar to Test B in that a heavy car, a 3,760-lb Dodge sedan, was directed head-on into the dragnet at a velocity of 56 mph. However, in this and the following test the Metal Bender tape load was decreased to 12,500 lb and the net was raised about 4 in. off the ground to better entrap the front of the vehicles.

The vehicle was stopped in 26.3 ft and pulled out a total of 30.7 ft of tape, which is equivalent to 384 kip-ft, or 96 percent of the vehicle's kinetic energy. The vehicle had

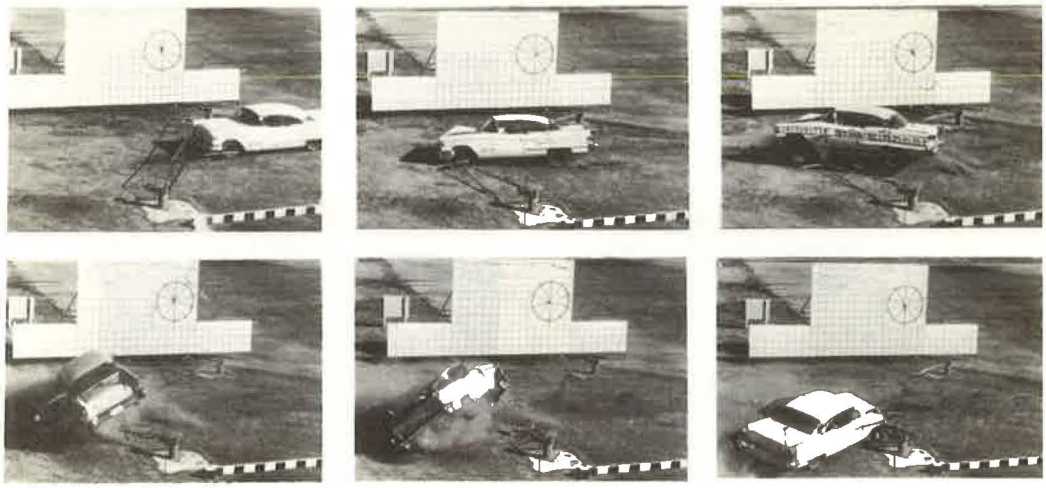

Figure 6. Sequential photographs of Test D showing behavior of net during arrestment.

no significant rotational energy at maximum penetration, but had gained about 7 kip-ft of gravitational potential energy.

The vehicle damage was minor (Fig. 7), as would be expected since the maximum deceleration was only 7.0 g, and the average deceleration was 4.0 g.

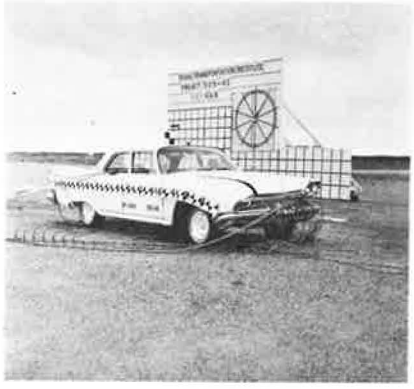

Figure 7. Vehicle after Test E.

Test F

As the final test in this series, a 3,880-lb Ford sedan traveling at 62 mph collided with the dragnet at an impact angle of 30 deg. As in the previous test, 12,500-lb Metal Bender tapes were used.

The tape on the right side was expended and pulled free of the Metal Bender before the vehicle had been brought to a stop (Fig. 8). The system performed as designed up to the point of tape pullout. The net, which was still attached to one Metal Bender, caused the vehicle to spin through an angle of about 120 deg after pulling out the right tape before coming to rest.

The total tape pullout when the right tape pulled free was 32.9 ft, which accounts for 89 percent of the kinetic energy lost up to that point. The high-speed films indicate that the vehicle had lost about 91 percent of its initial energy at this point and that the speed was down to about 17 mph.

The total tape pullout of 38.5 ft at full stop accounts for 94 percent of the vehicle's initial energy. Comparisons of actual and theoretical values are made up to the point of tape expenditure.

The deceleration levels of 5.0 g (maximum) and 2.4 g (average) are tolerable to restrained humans (1).

RESULTS

The complete test series conducted on the Van Zelm dragnet is summarized in Table 1. The vehicles used ranged in weight from 1,460 to 4,520 lb. All test vehicles impacted the dragnet at its center. Tests A, B, and E were head-on tests, while Tests C, D, and F were 30-deg angle tests. This means that the initial trajectory of the vehicle made an angle of 30 deg with a perpendicular to the original position of the dragnet.

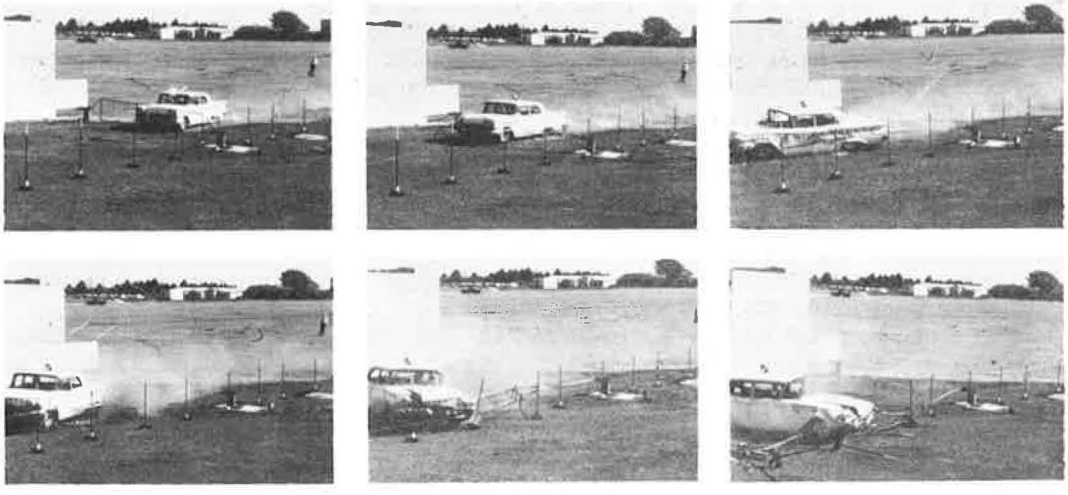

Figure 8. Sequential photographs of Test F.

TABLE 1

SUMMARY OF TEST RESULTS

Factor	Test					
	A	B	C	D	E	F
Angle of impact	Head-on	Head-on	30 deg	30 deg	Head-on	30 deg
Vehicle weight (lb)	1,460	4,300	1,620	4,520	3,760	3,880
Vehicle speed (mph)	42	60	48	54	56	62
Metal Bender tape load (kip)	25	25	25	25	12.5	12.5
Vehicle deformation (ft)	1.8	1.0	0.9	1.5	0.3	0.5
Vehicle stopping distance (ft)	10.2	19.4	13.8	23.2	26.3	29.5[a]
Total Metal Bender tape pullout (ft)	2.2	11.8	3.4	8.6	30.7	32.9[a]
Energy absorbed by Metal Bender (kip-ft)	54.8 (63 %)	296 (58 %)	86 (70 %)	214 (50 %)	384 (96 %)	411[a] (89 %)
Maximum significant deceleration (g), electromechanical curves	16	16	13	8	7	5
Average deceleration (g), film, $V^2/2gX_{max}$	5.8	6.1	5.5	4.1	4.0	2.4[a]
Duration of impact (seconds)	0.25	0.39	0.29	0.48	0.67	0.49

[a]Up to point tape expended.

Tapes producing a 25-kip pull were used in Tests A through D, while in Tests E and F this tape force was reduced to 12.5 kips.

The energy absorbed by the Metal Benders ranged from 50 percent to 70 percent of the vehicle's initial kinetic energy for the first four tests, which used the 25-kip tape loads. In Tests E and F the percent of energy absorbed by the Metal Benders ranged from 89 percent to 96 percent. There are several reasons for this difference. At the end of Metal Bender tape pullout, which corresponds approximately to zero longitudinal velocity, significant amounts of energy may remain in the form of gravitational potential energy and rotational kinetic energy. In most impacts there is some gravitational potential energy gain caused by the tendency of the net to pull the vehicle down in front and the tendency for the rear end to rise. This results in an increase in the elevation of the vehicle's center of gravity. In the case of angle tests, there may be a significant amount of horizontal rotational energy present, equal to half the product of the vehicle mass moment of inertia (about the vertical axis through the vehicle's center of gravity) times the square of the vehicle's angular velocity about this axis. Also present may be transverse rotational energy, which is defined in the same way as the horizontal rotational energy except that the mass moment of inertia and angular velocity is about the longitudinal vehicle axis. Other energy expenditures may be accounted for by the axial strain energy that goes into the cable and tapes, the vehicle deformation, and frictional losses such as contact of rigid portions of the vehicle with the ground. This last energy expenditure was prevalent in Test B. It can be concluded, at least within the range of tape forces tested, that the lower the tape force the greater the percentage of energy dissipated in the Metal Benders. If the extreme example of a tape with infinite load capacity is considered, almost all of the kinetic energy of the vehicle would be expended in vehicle deformation, rolling, etc.

A convenient way of indicating the relative desirability of dragnet arrestments is to compare the deceleration levels determined by these tests with the decelerations that would be encountered during a collision with a rigid barrier. The attenuation index is defined as the ratio of decelerations during an attenuated arrestment by dragnet, for example, with those estimated decelerations during a rigid barrier impact (2). Both maximum and average attenuation indexes (AI_{max} and AI_{avg}), which compare maximum and average deceleration levels, are given in Table 2.

Tests E and F, using 12,500-lb Metal Benders, have smaller attenuation indexes than the first four tests. This is the obvious result of cutting the stopping force in half. This reduction in stopping force significantly reduces the vehicle damage. The relatively large energy differences between tape energy and initial kinetic energy in Tests A through D are the result of large energy expenditures on vehicle deformation.

In the Appendix is a theoretical treatment that algebraically relates vehicle weight, velocity, tape force, and stopping distance. The error induced by considering the vehicle

TABLE 2

COMPARISON OF VAN ZELM DRAGNET PERFORMANCE WITH RIGID BARRIER IMPACT

Factor	Test					
	A	B	C	D	E	F
Metal Bender tape load (kip)	25	25	25	25	12.5	12.5
Vehicle weight (lb)	1,460	4,300	1,620	4,520	3,760	3,880
Vehicle velocity (mph)	42	60	48	54	56	62
Maximum deceleration (G_{max})						
Dragnet[a]	16	16	13	8	7.0	5.0
Rigid barrier[b]	37.8	54.0	43.2	48.6	50.4	55.8
Average deceleration (G_{avg})						
Dragnet[c]	5.8	6.1	5.5	4.1	4.0	2.4
Rigid barrier[d]	24.1	34.4	27.6	31.0	32.1	35.6
Attenuation index						
$AI_{max} = \frac{G_{max}\ \text{Dragnet}}{G_{max}\text{Rigid}}$	0.42	0.30	0.30	0.17	0.14	0.09
$AI_{avg} = \frac{G_{avg}\ \text{Dragnet}}{G_{avg}\ \text{Rigid}}$	0.24	0.18	0.20	0.13	0.12	0.07

[a] G_{max} Dragnet is from frame accelerometer data.

[b] G_{max} Rigid = 0.9 (vehicle velocity in mph) (2).

[c] G_{avg} Dragnet = $\frac{V^2}{2gX_{max}}$ from film data.

[d] G_{avg} Rigid = 0.574 (vehicle velocity in mph) (2).

to have no finite width is approximately compensated for by the fact that after impact the "spreaders" at the ends of the net buckle, increasing the effective length of the net. Because the main net cables loop over and under the front of the vehicles and the vehicles are deformed differently, some inaccuracy is expected, especially in arrestments with short stopping distances. It is also assumed in the calculations that the vehicle continues along its original path during arrestments, which is only a rough approximation in angled or noncentric hits.

Figure 9 is a plot of dragnet force on the vehicles against distance traveled after contact. The data used for this plot are taken from the theoretical calculations in the Appendix.

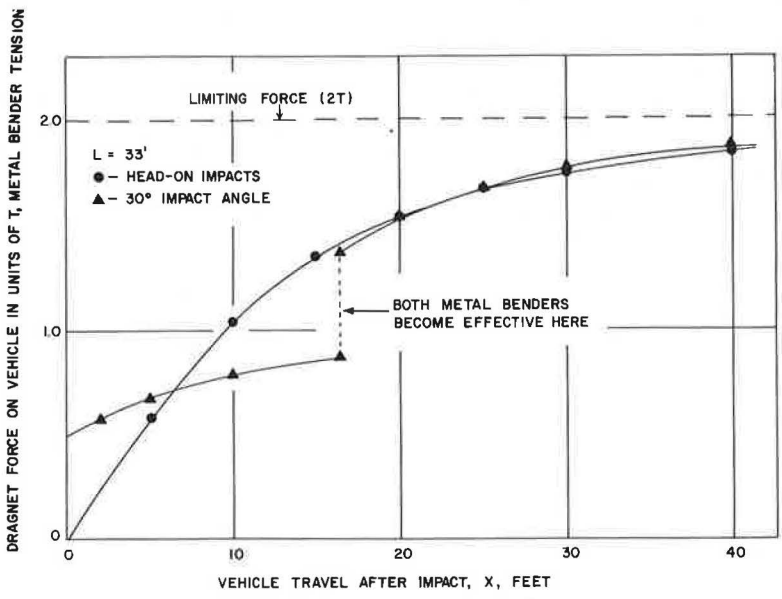

Figure 9. Theoretical stopping force-displacement curves for centric impacts.

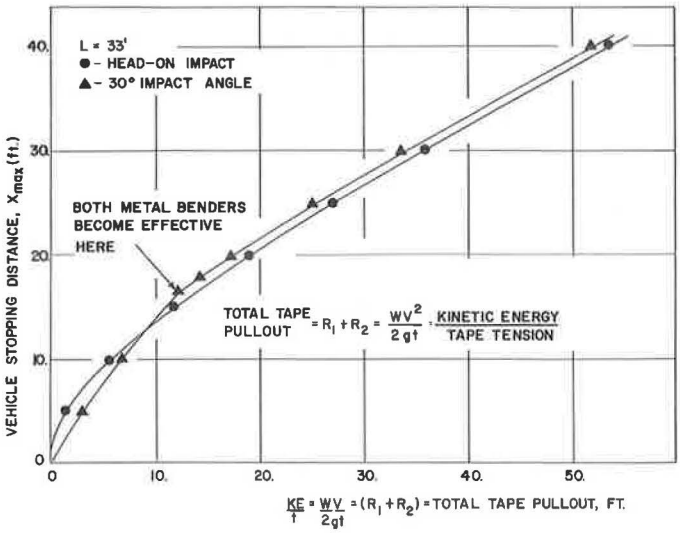

Figure 10. Stopping distance vs. total tape pullout.

From the theoretical treatment, a plot of total Metal Bender tape pullout against X_{max}, the theoretical stopping distance, was made for head-on and 30-deg angled impacts. Neglecting other energy-dissipation modes, the initial vehicle kinetic energy divided by the Metal Bender tape tension should equal the total tape pullout. By taking the initial velocity, determined from the high-speed films, and calculating initial kinetic energy, and by knowing the Metal Bender tape tensions, we can calculate the theoretical total tape pullout. Using this value and Figure 10, we can determine theoretical stopping distance. The theoretical stopping distances so determined are compared with actual stopping distances from the high-speed film data in Table 3. In this comparison, the measured stopping distance is the measured stopping distance of the vehicle's center of gravity minus the vehicle's deformation. (This is the distance traveled by the vehicle's front end after contacting the net.)

Again, the percentage difference between actual and theoretical values is greater for short stopping distances (high Metal Bender tensions). Examination of the high-speed films indicates that in Test C the combination of the low, narrow front end of the vehicle and the collapse of the end net spreaders, which occurred in every test, delays application of the main stopping force until the vehicle has traveled about 4 ft beyond initial contact. This is a considerable portion of the total stopping distance, and explains the large difference between measured and calculated stopping distance. For this vehicle's initial energy, the calculated total tape pullout is 4.9 ft. This compares favorably with the actual measured tape pullout of 3.4 ft.

TABLE 3

COMPARISON OF COMPUTED STOPPING DISTANCES WITH MEASURED STOPPING DISTANCES

Stopping Distance	Test					
	A	B	C	D	E	F[a]
$(X_{max})_M$ (ft)[b]	8.4	18.4	12.9	22.0	26.0	29.0
$(X_{max})_C$ (ft)[c]	7.8	21.0	7.6	20.2	27.7	29.5
$[(X_{max})_C - (X_{max})_M]$ (ft)	-0.6	+2.6	-5.3	-1.8	+1.7	+0.5

[a]Calculated up to point metal tape was expended.
[b]Measured stopping distance from film minus vehicle deformation.
[c]Calculated stopping distance from initial vehicle velocity and theoretical treatment in Appendix.

CONCLUSIONS

The Van Zelm dragnet vehicle arresting system performed basically as designed in all tests. The performance of the system was very good in four of the six tests. In Test D the dragnet was engaged too low on the front of the vehicle, which resulted in the vehicle's rear end vaulting the net after most of the longitudinal deceleration had occurred. In Test F the performance of the dragnet system was ideal until one of the tapes ran out. Had this tape been long enough to continue applying load until the vehicle was completely stopped, the performance probably would have been excellent. Deceleration levels were reduced to a small fraction of those that would be expected in rigid barrier impacts. Increasing design tape load results in shortening the stopping distance, increasing the deceleration level and increasing vehicle damage. For any given application of the dragnet system, the longer the allowable stopping distance, the more desirable the deceleration characteristics of the system because a smaller tape load can be used.

The height of the net was shown to be an important factor in the performance of the system. The net should be positioned so that it completely entraps the front of the entering vehicle. If it is too low, a less desirable performance may be expected, as was found in Test D. Good performance was found when the lower main cable of the net was positioned 4 in. above the ground.

No permanent damage was sustained by the dragnet system during any of these tests. All major components were reusable except for the expendable metal tapes. The system can be applied to a variety of situations by varying the Metal Bender tape tension, the tape length, and the geometry of the installation. A variety of Metal Bender tape tensions are available from Van Zelm Associates.

This series of tests has shown that reasonably accurate predictions of vehicle stopping distance and deceleration levels can be obtained using the equations developed in the Appendix.

RECOMMENDATIONS

The dragnet vehicle arresting system is an effective, practical, and economical system for safely stopping vehicles that are out of control at certain highway sites. Some obvious locations for its employment are

1. Across highway medians between double bridges,
2. At "dead ends" of highways or roads,
3. At ferry landings or drawbridges, and
4. In front of certain rigid obstacles in highway rights-of-way.

It is recommended that the height of the arresting net be increased to approximately 4 ft. The net used in these tests was 3 ft high, and in several tests (notably Test D) it failed to completely entrap the vehicle's front end. It is desirable that the upper net cable clear the top of the vehicle hood in order to more securely entrap the vehicle.

The lowest Metal Bender tension force compatible with the available stopping distance should be selected. In general, Metal Bender tension forces of 12,500 lb or less are recommended. The behavior of these dragnet systems can be predicted very well with the mathematical analysis presented in the Appendix.

REFERENCES

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Appendix

SIMPLIFIED THEORETICAL ANALYSIS

Relatively simple equations will be developed here that will aid in selecting a desirable Metal Bender tape tension force (T) and length (R_{max}) in order to stop a vehicle of given weight (W) and speed (V).

Van Zelm now has available metal tapes and Metal Benders (sometimes called "torture chambers") that provide tape tension forces (T) of 2,500 lb, 4,000 lb, 12,500 lb, 18,750 lb, and 25,000 lb. Two of the 4,000-lb Metal Benders can be stacked on top of each other to provide a tape tension force of 8,000 lb.

For these tape tension forces, we can compute the minimum required length of tape (R), the stopping distance required (X_{max}), and the maximum and average g forces on the vehicle as follows:

$$\text{Kinetic Energy of Vehicle} = \frac{WV^2}{2g}$$

Assuming all energy is absorbed by Metal Bender tape,

$$2TR_{max} = \frac{WV^2}{2g}$$

the maximum tape run-out is then

$$R_{max} = \frac{WV^2}{4Tg} \text{ and } R_{max} = R_{1_{max}} = R_{2_{max}} \tag{1}$$

since the system is symmetrical in this case. From Figure 11,

$$X = \sqrt{\left(R + \frac{L}{2}\right)^2 - \left(\frac{L}{2}\right)^2} \tag{2a}$$

$$X_{max} = \sqrt{R_{max}^2 + R_{max} L} \tag{2b}$$

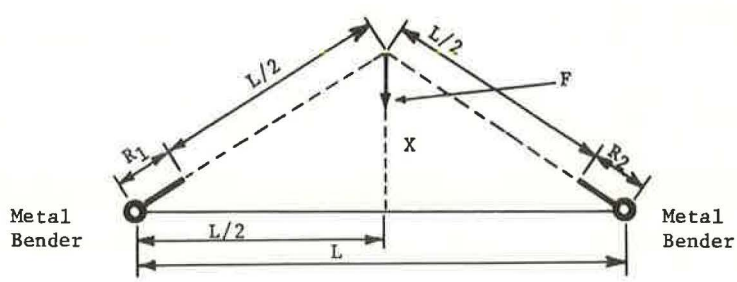

Figure 11. Diagram for analysis of Van Zelm Metal Bender dragnet system head-on centric vehicle collision. L = length of net, ft; T = Metal Bender tape tension force, lb; $R = R_1 = R_2$ = run-out of Metal Bender tape (assuming all energy is absorbed by tape), ft; X = travel distance of vehicle after engaging net, ft; X_{max} = stopping distance, ft; F = stopping force component on vehicle, lb; W = weight of vehicle, lb; V = initial velocity of vehicle, ft/sec; and g = acceleration due to gravity, 32.2 ft/sec^2.

If the stopping force component on the vehicle is

$$F = 2T\left(\frac{X}{R + \frac{L}{2}}\right) \tag{3a}$$

then the maximum vehicle stopping force for head-on collisions would be

$$F_{max} = 2T\left(\frac{X_{max}}{R_{max} + \frac{L}{2}}\right) \tag{3b}$$

The maximum G force on the vehicle is

$$G_{max} = \frac{F_{max}}{W} \tag{4}$$

The average G force on the vehicle would be

$$G_{avg} = \frac{V^2}{2gX_{max}} \tag{5}$$

From Eq. 2a,

$$R = \frac{1}{2}\sqrt{L^2 + 4X^2} - \frac{L}{2}$$

so that

$$F = 2T\left[\frac{1}{\sqrt{\left(\frac{L}{2X}\right)^2 + 1}}\right] \tag{6}$$

The analysis for angled impacts resulted in the following equation of stopping distance for 30-deg angles:

$$X_{max} = \sqrt{\left(\frac{WV^2}{4gT}\right)\left(\frac{WV^2}{4gT} + L\right)} \tag{7}$$

More details on the analysis and a design example are found in "Dragnet Vehicle Arresting System," Technical Memorandum 505-4, Texas Transportation Institute, Texas A&M University, which is available through the authors.