

# Field Study to Establish Truck Escape Ramp Design Methodology

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One of the best and most frequently used mechanisms for stopping runaway trucks is the truck escape ramp, particularly the gravel arrester bed. To learn more about the energy-absorbing characteristics of the stone and to develop better design criteria, the Pennsylvania Transportation Institute (PTI) conducted full-scale testing of gravel arrester beds. For this study, PTI constructed two 300-ft-long test ramps, one filled with rounded river-bed gravel and the other with more angular crushed gravel. The data taken included entry speed, stopping distance, accelerometer data, cross-section measurements of the ruts left by the truck tires, and distance-versus-time data. River gravel exhibited greater deceleration forces than crushed gravel. The existing Pennsylvania Department of Transportation (PennDOT) beds at Punxsutawney, Pleasant Gap, and Freeport represented the standard of excellence, showing an average deceleration of 0.516 g. However, test results show that a 36-in-deep bed gave the same results as a bed that sloped to 8 ft deep. Finally, mounds and crash barrels filled with stone were tested and evaluated.

The goal of this research project was to understand the physical characteristics of the stopping mechanism and to provide a means for adequately designing and maintaining a gravel arrester bed.

Full-scale testing was performed at operational gravel arrester beds within the state as well as at two research gravel arrester beds located at the Pennsylvania Transportation Institute's (PTI's) Truck Escape Ramp Research Facility (1). Figure 1 shows the locations of the gravel arrester beds where the testing was conducted. At the PTI facility, both beds, each containing a different type of gravel, were designed to accommodate variations in gravel depth, vehicle entry speed, and size of mounds.

The capability of gravel to absorb energy from a rolling tire makes it a most effective and feasible material to use in runaway-truck arrester beds. Although the effectiveness of such material has been proven through its wide use, only limited fundamental understanding of the energy-absorbing mechanisms exists. With a more thorough understanding, the safety and effectiveness of ramp design can be optimized.

To gain this understanding, experiments were conducted to simulate actual arrester-bed use and to gather as much data as possible. The resulting interrelationships among the various physical properties were used to provide design standards.

The experiments involved the following input parameters: entry speed of tire, load on tire, type of tire (e.g., footprint and rolling diameter, single or dual), type of gravel, depth of gravel, contour of bed (e.g., mounds), and condition of gravel (e.g., contamination, moisture content, and temperature).

## TRUCK ESCAPE RAMP TESTS

### Data Collection

Fifty-two full-scale escape ramp tests were performed during the project (fall 1984 through fall 1987): 39 at the PTI site, including 11 in crushed gravel and 28 in river gravel; 1 at the Punxsutawney site; 3 at the Pleasant Gap site; and 9 at the Freeport site. In addition, 31 controlled full-scale tests were made: 11 using mounds, 8 using barriers (barrels), and 12 drag tests. Two PTI vehicles (a dump truck and a tractor-trailer) were used for all but the last test, for which a rented triaxle truck was chosen because that type is often used to haul coal in Pennsylvania. Figure 2 provides an overall view of the two ramps, and Figure 3 shows a view of one of the ramps filled with river gravel. One bed was filled with type A2 crushed limestone and was 300 ft long. The second bed was filled with uncrushed, rounded river gravel (AASHTO grade 57) and was 350 ft long.

The Punxsutawney bed is 275 ft long, with an initial depth of 18 in. The depth increases gradually to a maximum of 8 ft at a distance of 100 ft from the bed entrance and remains at this depth to the end. The stone is uncrushed river gravel, AASHTO grade 57. The Pleasant Gap bed is 310 ft long. It has an initial depth of 1 ft 4 in, increases to 8 ft at a distance of 25 ft, and is 8 ft deep beyond that distance. The stone is uncrushed river gravel, AASHTO grade 5. The Freeport bed, which is 276 ft long, has an initial depth of 1 ft 4 in and increases to a depth of 6 ft at a distance of 140 ft. The stone is uncrushed river gravel, AASHTO grade 67.

### Data Summary

#### Entry Speed

This information was obtained using radar with the reading taken just before the truck entered the bed. For the first two tests, tape switches were also used. However, this method was replaced with the entry-speed timing method described below.

#### Time To Travel Each 10 ft

The truck's velocity through the bed was initially obtained from videotaped recordings of each test. The elapsed time was noted as the truck passed distance markers placed 10 ft apart. However, a more accurate method of determining the truck's velocity throughout the bed was subsequently developed. The improved method deployed microswitches at 10-



### Stopping Distance

The stopping distance was determined by measuring the distance from the front of the bed to the front axle of the truck after the truck came to rest.

### Tire-Rut Cross Section

Cross-sectional area measurements were taken for one of the two tire ruts left by the truck. Measurements were made every 10 ft and included the top width, bottom width, middle depth, and the heights of the ridges that formed along the ruts.

### Final Depth

The final depth of penetration was determined by observing how deep the front tires had sunk into the gravel at the end of the test.

### Accelerometer Data

An accelerometer was mounted inside the truck to measure the horizontal deceleration of the truck during the test. The analog signal was recorded on cassette tape for further anal-

ESCAPE RAMP TEST						
DATE _____		TEST NO. _____				
TIME _____		LOCATION _____				
WEATHER CONDITIONS _____						
TRUCK		GRAVEL				
TYPE _____		TYPE _____				
MASS _____		DEPTH _____				
LOADED? _____		MOUNDS? _____				
FRONTAL AREA _____		WETNESS _____				
TIRE DIA. _____		GRADE OF SLOPE _____				
TIRE WIDTH _____		SIZE _____				
NO. OF TIRES _____		GRADATION _____				
OTHER _____		OTHER _____				
ENTRY SPEED _____						
STOPPING DISTANCE _____						
STOPPING TIME _____						
DEPTH OF PENETRATION _____						
NOTES:						

ESCAPE RAMP TEST						TEST NO. _____
DISTANCE (ft.)	VOLUME OF STONES DISPLACED			TRUCK TO MARKER (ft.)		
	DEPTH OF PENETRATION (in.)			WIDTH (in.)		
	D <sub>1</sub>	MIDDLE	D <sub>2</sub>	TOP	BOTTOM	
10						
20						
30						
40						
50						
60						
70						
80						
90						
100						
110						
120						
130						
140						
150						
160						
170						
180						
190						
200						
210						
220						
240						
260						
280						
300						

LOCATION OF CAMERA		CROSS SECTION OF TIRE TRACK
FROM FRONT OF BED	DISTANCE _____	
FROM CAMERA TO MARKERS	_____	

FIGURE 4 Data sheets used for escape ramp tests.

ysis. After the time to travel each 10 ft was recorded, accelerometer data were used as backup.

### Videotape of Test

All tests were recorded on videotape by two cameras, one located along the side of the bed and one at the end. Large distance markers were placed every 10 ft along the bed. In addition, all tests conducted in 1986 (including full-scale, barrel, and mound tests) used a spin physics high-speed video system.

### Distance From Markers to Tire Rut, Camera to Markers, and Camera to Front of Bed

These distances were used to account for parallax (caused by the camera angle) when the distance-versus-time data were determined from the videotapes.

Other data analyzed in the tests include truck characteristics, gravel characteristics, and weather conditions. Reduced copies of the data sheets are shown in Figure 4.

### Data Reduction and Analysis

Distance-versus-time data were used to calculate velocity versus time, velocity versus distance, and acceleration versus time. For each test, the average deceleration of the truck was found and plotted versus the entry speed. The cross-sectional measurements yielded plots of depth of penetration versus

distance, along with the average depth and approximate volume of stones displaced for each test (approximate because the original side wall gives way). Also, curves of stopping distance versus entry speed were plotted for each bed. The following data reduction methods were used:

- Distance versus time,
- Velocity and deceleration versus time,
- Average deceleration and stopping time,
- Velocity versus distance,
- Change in velocity versus velocity,
- Depth and volume data,
- Accelerometer data, and
- Stopping distance versus entry speed.

Table 1 provides a summary of the 1986 test results. Test results from 1984, 1985, and 1986 are available from PTI (1). A summary of the average decelerations (negative accelerations) for the various types of tests is shown in Table 2. The average deceleration in river gravel was 30 to 35 percent greater than that in crushed gravel. The loaded tests in crushed gravel showed an 11-percent greater deceleration than the unloaded tests; however, the standard deviation was 13 percent for loaded and 14 percent for unloaded. A similar effect was also found in the river gravel for both truck types. The mean deceleration increased with the increased depth of the river gravel; however, it reached a maximum between 30 and 36 in, at which point it leveled off approximately 0.5 g. The crushed gravel did not change with depth and remained nearly constant at an average of 0.275 g. The distance the truck traveled before losing 10 percent of its entry speed was used as a measure of how much planing occurred in each bed, and

TABLE 1 ESCAPE RAMP TEST SUMMARY FOR 1986

Test	Date	Gravel		Truck		Entry Speed (mi/h)	Stopping Distance (ft)	Average Decel. (g)	Total Volume (ft <sup>3</sup> )	Avg. Depth (in)	Final Depth (in)
		Type	Depth (in)	Type	GVW (lb)						
86-1	6/10/86	river	36	Dump	32,700	41.6	119.0	.59	264.0	5.70	12.5
86-2	6/10/86	river	36	Dump	32,700	45.6	149.0	.48	340.0	5.31	13.0
86-3	6/10/86	river	36	Dump	32,700	41.9	151.0	.48	299.0	5.50	11.0
86-4	6/12/86	river	36	Dump	14,300	39.6	131.0	.45	168.0	3.64	9.0
86-5	6/12/86	river	36	Dump	14,300	46.8	173.0	.50	245.0	4.02	11.0
86-6	7/7/86	river	36	TT	40,950	51.3	219.0	.39	608.6	5.00	9.5
86-7	7/8/86	river	36	TT	40,950	42.1	176.0	.32	356.0	4.74	5.5
86-8	7/8/86	river	36	TT	20,900	40.3	150.0	.37	253.4	4.08	8.5
86-9	7/23/86	river	36	TT	20,900	47.7	243.0	.29	417.3	4.16	7.0
86-10	7/23/86	river	36	TT	20,900	42.8	207.5	.44	330.2	4.13	7.5
86-11	7/23/86	river	36	TT	40,950	42.6	213.0	.34	486.2	5.5	8.0
86-12	8/12/86	river	36	Triaxle	54,000	41.0	152.0	.39	440.3	6.42	10.5

TABLE 2 AVERAGE DECELERATION DATA

Test Type		Average Deceleration	Standard Deviation
Crushed Aggregate - 18 inches		.275	.036
Crushed Aggregate	loaded	.288	.036
Crushed Aggregate	unloaded	.265	.038
River Gravel - 36 inches			
Dump Truck	loaded & unloaded	.52	.05
	loaded	.535	.047
	unloaded	.475	.025
Tractor Trailer	loaded & unloaded	.358	.049
	loaded	.35	.029
	unloaded	.367	.061
Field Tests			
Dump Truck	loaded & unloaded	.499	.035
	loaded	.525	.026
	unloaded	.474	.022
Tractor Trailer	loaded & unloaded	.413	.074
	loaded	.393	.021
	unloaded	.463	.058
River Gravel	18 inches	.35	.007
	22 inches	.40	.045
	30 inches	.49	.061
	36 inches	.52	.050

these results are shown in Table 3. A comparison of the unloaded and loaded tests shows that less planing occurred when the truck was loaded and that more planing occurred at higher entry speeds, starting at around 40 to 45 mph. Figure 5 shows tests at two similar speeds (tests 1 and 4, 1986). This figure also shows that the initial slope is flat, which indicates planing. The shapes of all velocity-versus-distance curves are similar, suggesting a similar curve fit.

#### REGRESSIONS OF FIELD TESTS

Beginning with the early tests, it was found that the stopping distance as a function of entry speed gave consistent results for a given depth of gravel or a particular gravel type. There are some differences for a tractor trailer versus a dump truck or a loaded truck versus an unloaded one. These small differences, shown below, are insignificant. Because the total set contains too many values to include in this paper, examples are given. The entire set is available from PTI (1).

#### Dump Truck Tests

By design, more tests were run with the dump truck than with any other type of vehicle, and it was used as the baseline vehicle. Figure 6 gives the loaded/unloaded stopping distance data as a function of entry speed for the PTI tests (using 36 in of gravel) combined with the Freeport tests. The only noteworthy difference in the data is that, for the loaded dump truck, there is slightly more data scatter; however, there are also more data points, collected over a much longer period of time.

#### Tractor-Trailer Tests

Similar results were obtained for the tractor-trailer tests. Figure 7 gives the results for the combined Freeport, Pleasant Gap, and 36-in-depth PTI tests for unloaded, loaded, and loaded/unloaded testing. There was considerably more scatter of these data than for the dump truck.

TABLE 3 PLANING DATA

Test*	Entry Speed (mi/h)	-10% Speed Location (ft)	Percentage of Total Distance	Test*	Entry Speed (mi/h)	-10% Speed Location (ft)	Percentage of Total Distance
84-1	37.9	62	40	(86-3)	41.9	36	24
84-2	35.8	62	36	86-4	39.6	54	41
84-3	29.4	42	33	86-5	46.8	13	8
(84-4)	46.4	60	23	(86-6)	51.3	51	24
(84-5)	36.8	48	27	(86-7)	42.1	33	19
(84-6)	53.6	49	61	86-8	40.3	38	25
(84-8)	41.7	53	32	86-9	47.7	95	39
(84-9)	28.8	53	27	86-10	42.8	22	11
(85-3)	46.2	24	9	(86-11)	42.6	19	9
(85-4)	35.2	45	28	(86-12)	41.0	35	23
(85-5)	43.5	63	21	(Punx)	39.3	43	43

\*Numbers in parentheses are tests with load.

\*From first 10 ft of barrel.

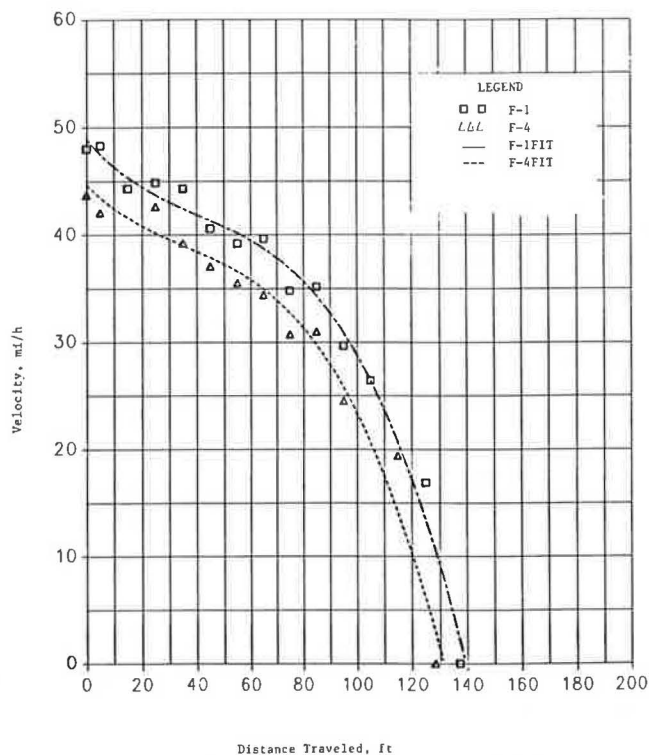
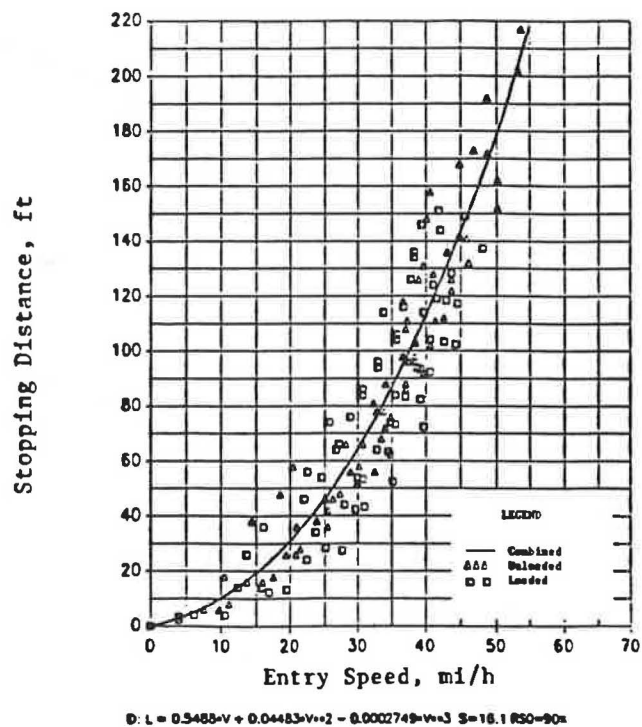


FIGURE 5 Similar test results for the Freeport bed tests.



$$D: L = 0.5485 \cdot V + 0.04483 \cdot V^2 - 0.0002749 \cdot V^3 \quad S = 16.1 \text{ (RSD} = 90\%$$

FIGURE 6 Freeport and PTI river gravel arrester beds, combined loaded and unloaded dump truck.



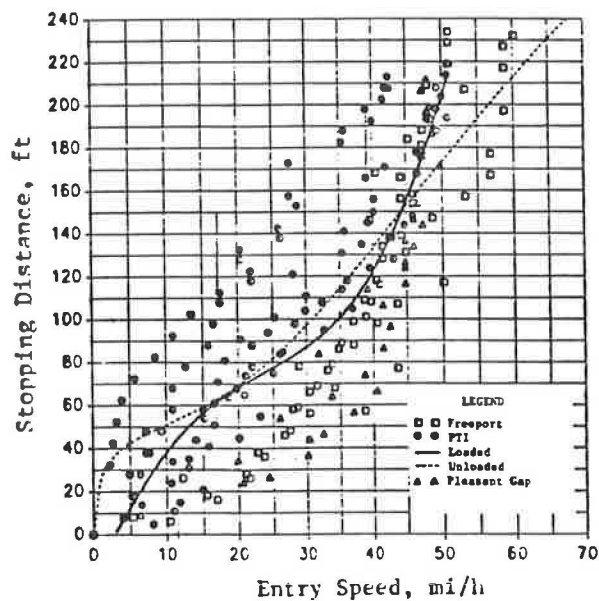


FIGURE 7 Loaded/unloaded tractor-trailer results at all locations.

### Average Decelerations

Figure 8 shows the results for the two trucks (tractor-trailer and dump truck) and the difference between crushed limestone and river gravel. As in previous tests, these results show a decrease in effectiveness with the tractor-trailer in comparison with the dump truck (i.e., effectiveness is dependent on the vehicle axle configuration). There was a decrease from a mean of 0.58 g for the dump truck to 0.39 g for the tractor-trailer in river gravel and from 0.30 to 0.24 g in limestone (factors of 2.49 and 1.25, respectively). Similarly, the figure shows a decrease in effectiveness for the angular gravel from a mean of 0.54 to 0.30 g, or a factor of approximately 1.8. The figure also shows the dependence on entry speed, as did Cocks (2) and Laker (3), but the peak at 40 to 45 mph agrees better with Laker's work. Cocks indicated a peak at 3 mph; however, his test only went to 40 mph, the beds were much shorter, and the vehicles exited at higher speeds.

### Comparison With FHWA Design Guidelines

FHWA's interim guidelines (4) for the design of emergency escape ramps give the following equation:

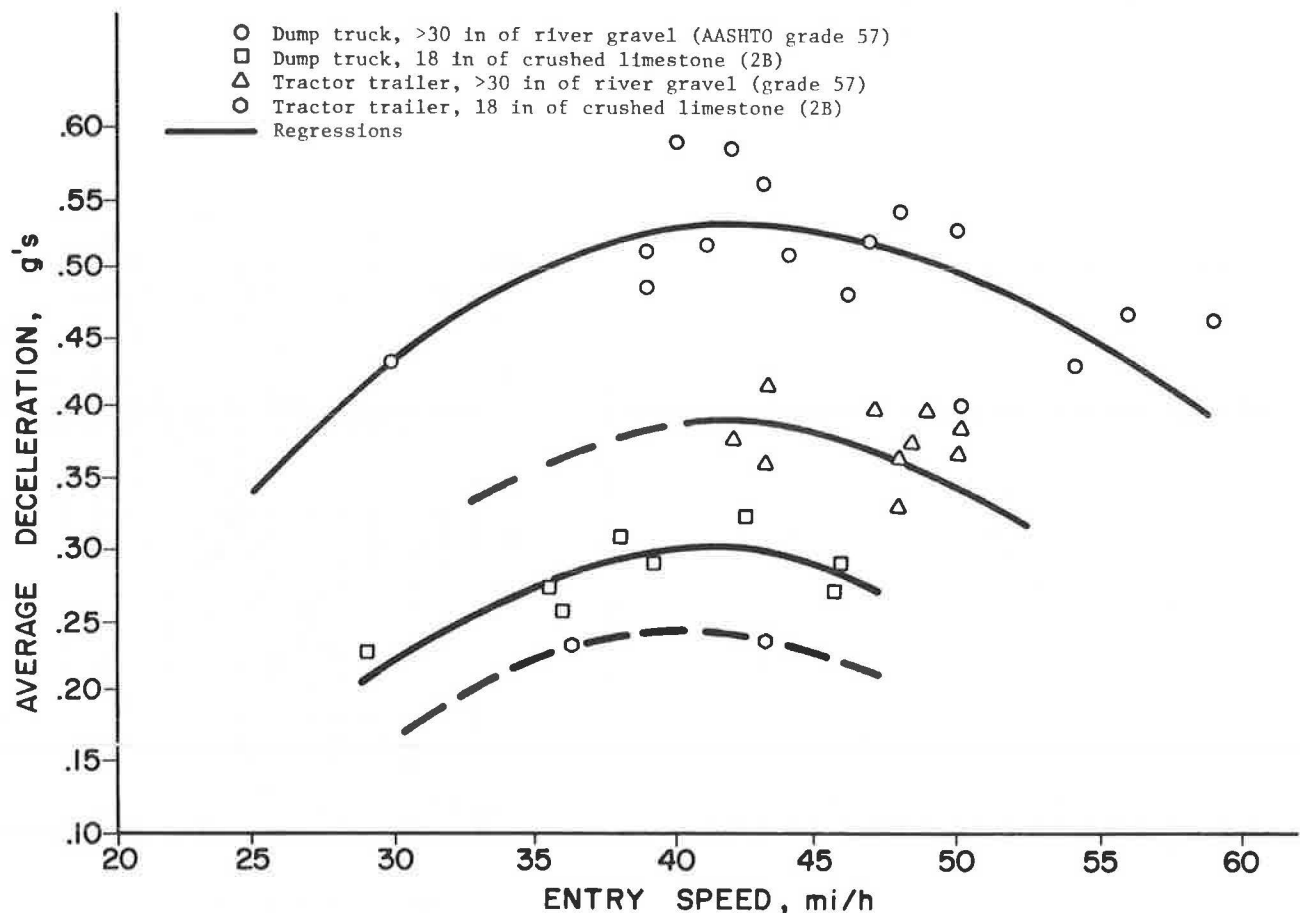


FIGURE 8 Average deceleration vs. speed in river gravel and in crushed limestone, using a dump truck and a tractor-trailer.

$$L = \frac{V^2}{30(R \pm G)} \quad (1)$$

where

$L$  = distance to stop (i.e., length of arrester bed),  
 $V$  = entering velocity (mph),  
 $G$  = percent grade divided by 100, and  
 $R$  = rolling resistance expressed as equivalent percent gradient divided by 100.

This equation fails to account for planing and is invalid when there is inelastic impact with another mass. However, it was assumed to be fairly accurate except under higher speeds, where planing occurs.

Figure 9 compares the FHWA equation for various drag factors with that of actual test data. The FHWA equation is close to the test data up to 30 mph; above that speed, the equation underpredicts the length required. Regressions show that, at higher speeds, a third order of velocity ( $V^3$ ) is required in addition to the second-order term ( $V^2$ ). The regression for the tractor-trailer tests on a flatbed is

$$L = .6V + .021V^2 + .00092V^3 \quad (2)$$

as opposed to  $L = .066V^2$  for the FHWA equations.

## BARRIERS, MOUNDS, AND DRAG TESTS

During the course of the project, 11 tests were conducted to determine the effectiveness of mounds of river gravel. Simi-

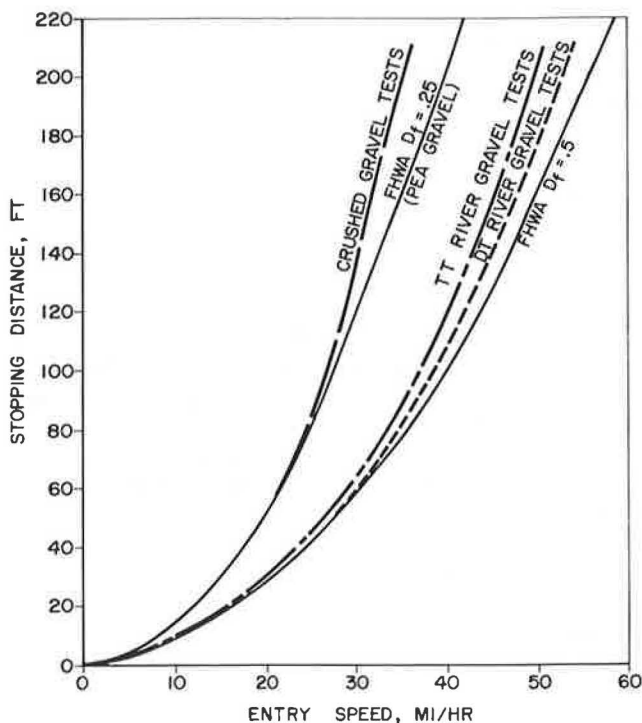


FIGURE 9 Comparison of FHWA equations for various  $R$  values vs. tests for arrester beds.

larly, eight tests were conducted into barrels filled with sand or gravel to determine if gravel can be used in place of sand so the beds would not be contaminated when struck. The last series of tests involved running a single tire through four different gravels at various speeds and loads to determine the drag for each case.

During the project, tests were made to evaluate methods of extracting trucks from the beds, and, at the end, a simple apparatus was developed to fluff the beds. These tests and the fluffing apparatus are discussed below. More details are contained in the PTI report.

## Mound Tests

During the project, 11 mound tests were conducted using two mound shapes, referred to as half- and full-sized mounds. Half-sized mounds are gravel piles 5 ft long by 1 ft high; full-sized mounds are 10 ft long by 2 ft high. The complete set of test results is given in Table 4. The tests showed that about 50 percent of the speed reduction was obtained in the first foot of travel. They also showed that mounds should not be placed nearer than 100 ft into the bed because a truck that is riding on top of the bed (planing) will ride up over the mound, giving high vertical acceleration.

## Inertial Barrier (Barrel) Tests

Eight sets of crash barrel tests were conducted to compare sand-filled and gravel-filled barrels and to test the effectiveness of gravel-filled barrels. Figure 10 is a still photo from the standard video side position of a test with 13 barrels. For each test, the time to travel each 6 in was measured, and the velocity and accelerations were calculated for each 12 in of travel. Table 5 summarizes the test results, giving the speed change for 1-, 3-, 6-, and 9-ft intervals. For all tests, a 50-percent reduction in speed was obtained after the first foot of travel and a 66-percent reduction after the first 3 ft. Several tests with a single and three barrels showed the same velocity changes for either sand- or gravel-filled barrels, as reported in the PTI study.

## Extraction Methods

Throughout the three seasons of testing, various methods of extraction were tried. In the river gravel, it was always necessary to use a tow truck for extraction. A fully loaded truck

TABLE 4 AVERAGE LOSS IN SPEED FOR MOUND TESTS

Speed $V$ (mph)	Half Mounds		Full Mounds	
	$\Delta S$	$\Delta S/V$	$\Delta S$	$\Delta S/V$
10-15	2.62	.22	8.45	.64
15-20	3.68	.20	—	—
20-25	—	—	12.1	.47
25-30	—	—	7.83	.36
Average	—	.21	—	.45





FIGURE 10 Test at 20 mph into 13 barrels filled with river gravel.

TABLE 5 LOSS IN SPEED FOUND IN BARREL TESTS

Number of Barrels	Speed <sup>a</sup>	Speed Loss (mph)			
		1 ft into Bed	3 ft into Bed	6 ft into Bed	9 ft into Bed
1	10	5	6		
3	20	9	13	15.5	
10	20	10	14	15.5	16.5
20	15	7.5	10	15	
20	25	12.5	18	21	25

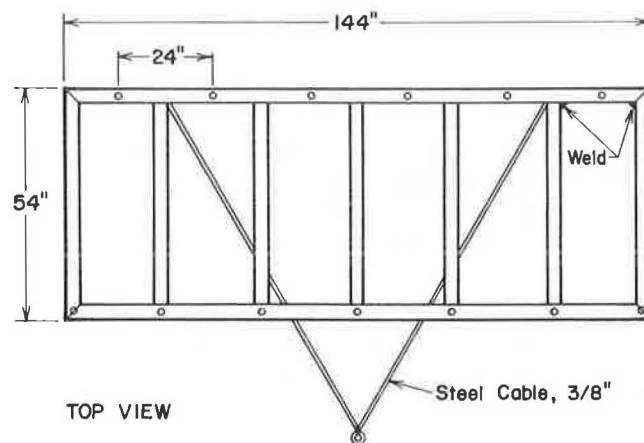
<sup>a</sup>These speeds were computed over the last 6 in before contact with the barrels.

of 80,000 lb requires 40,000 lb of pulling force for extraction from the arrester bed because the river gravel produces an effective drag resistance of around 0.5.

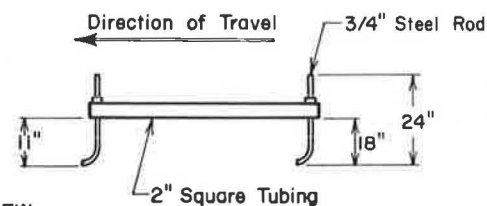
To eliminate the need to pull half the weight of the truck, many possible solutions were investigated that considerably reduced the pulling load. For example, if the truck is pulled up onto some support so that its weight is distributed, the effort required is greatly reduced. Airfield expanded metal, fencing, conveyor belts, sheet metal, and 2 by 6 boards were tried. Basically, if the material has too much flex (fencing and sheet metal), it was found to be ineffective. The 2 by 6 boards worked as well or better than any material tested.

### Gravel Fluffer

To preserve the similarity of the testing conditions, the gravel bed was fluffed periodically between tests. A mechanical device was constructed for this purpose, consisting of a sled with prongs that extended down into the gravel bed (see Figure 11). The gravel fluffer was found to be extremely simple in design and very effective for fluffing the bed. It was weighted with around 200 lb and towed with a cable attached to a dump truck.



TOP VIEW



SIDE VIEW

FIGURE 11 Layout of gravel fluffer design.

### Winter Maintenance

During the two winter seasons of the project, no bed maintenance was required unless an icy crust of 1 in formed. In such a case, the fluffer can be used, possibly with a de-icing treatment. If more than 1 in of crust forms, both de-icing and fluffing are needed. Snow alone did not adversely affect the beds.

### CONCLUSIONS

In general, the following conclusions were determined from this study:

- Smooth, rounded, uncrushed gravel of approximately a single size is the most effective material for arrester beds. The best size appears to be near 0.5 in. Grade 57 river gravel was found to be the best of those materials tested.
- An appropriate crush test, such as the Los Angeles abrasion test, should be used to evaluate the durability of stones in arrester beds. Rounded river gravel produces higher decelerations than the more angular crushed gravel.
- The estimated volume of stones displaced was a good measure of the amount of momentum energy transferred to the stones.
- Maximum average decelerations in the beds of about 0.5 g were shown by the accelerometer data.
- Testing showed that a bed with at least 36 in of river gravel gives the same results as a bed as deep as 8 ft. A bed of at least 42 in is recommended.

- Porpoising was minimal in deeper beds but was still found in the Pleasant Gap tests where mounds had caused compaction. This phenomenon was more noticeable for short wheel bases.

- A well-fluffed bed gives better results than one that has been sitting for some time since compaction occurs over time. The study showed that a bed must be fluffed at least twice during a year and after each use.

- Loading the truck had no significant effect on the stopping distance.

- Moisture had a negligible influence on the effectiveness of the beds.

- A planing effect was observed on the escape ramps.

- Barrels can be filled with the same stone as that used in the bed, rather than with sand, and produce the same results for trucks.

- The use of mounds should be avoided, if possible. If mounds are used, however, they should be placed in the bed such that they will be hit by the vehicle only at speeds slower than 25 mph. Above that speed, the vehicles begin to plane and act as a launch platform.

- The results show a deceleration of around a 0.5 g max-

imum, which is no more than a hard-braking stop. If a driver's load shifts, it would have shifted for a hard-braking stop, in which case the load would not have been secured properly.

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