states indicate the type of ramp surfacing on advance signs whereas others do not. Such variation may create uncertainty on the part of truck drivers when they are faced with using escape ramps. It is recommended that more uniform signing policies be developed.

Although there is only a limited amount of information on truck escape ramps in the technical literature, it is apparent from the results of the questionnaire that many states have conducted research on the topic. Much of this work involves selection and testing of arrester-bed aggregate and construction and maintenance policies. There is a need for better dissemination of information on studies that deal with truck escape ramps. Personnel of state highway agencies should report on the results of their research and development activities so that duplication of effort can be avoided.

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Performance of a Gravel-Bed Truck-Arrester System

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The testing of a truck-arrester system that consists of a 158-m (528-ft) long bed of 0.6-m (2-ft) deep screened gravel, backed up by an array of 88 sand-filled plastic barrels, is described. The system was constructed on NY-28 east of Utica, New York, on a steep downgrade where geometric restrictions precluded building a conventional uphill escape lane. Three trial runs with a 16 650-kg (37 000-lb) dump truck, at speeds of 34, 66, and 90 km/h (21, 41, and 56 miles/h) demonstrated the ability of the gravel bed to stop runaway vehicles. The decelerations experienced in these tests were similar to those experienced in panic stops on dry pavement.

Truck escape lanes are constructed so that runaway trucks descending long, steep grades can stop safely. These lanes, which sometimes use uphill ramps to decelerate trucks, may also contain loose sand or gravel to increase deceleration by imparting drag forces to the wheels of the vehicle (1). A device with steel nets and cables was once designed for an installation in Puerto Rico but was apparently never constructed.

A long history of runaway trucks led to the construction of an escape lane on the downslope of what is locally known as Vickerman Hill on NY-28 near the village of Mohawk, New York, 16 km (10 miles) east of Utica, under a New York State Department of Transportation (NYSDOT) contract. Selection of a design for this escape lane was complicated by site geometry. The village is located in a valley, and NY-28 descends on a long downgrade. Just south of the village limits, at the site of the escape lane, the downgrade is 10 percent. Because the highway is in a sidehill cut with the downhill lane on the fill side, an uphill ramp would require placement of excessively high fill. Thus, another design approach was necessary. A steel-net system was considered, but the idea was abandoned because of potential maintenance difficulty and a lack of data on the performance of such a system.

The design finally selected consists of two stages: a gravel arrester bed and an array of sand-filled plastic drums (see Figure 1). The 158-m (528-ft) long gravel bed—5.4 m (18 ft) wide at the entry point and tapering to 3.6 m (12 ft) near the end—consists of screened, rounded pea gravel (see Figure 2). The depth of the gravel increases from 0 to 0.6 m (0-2 ft) in the first 15

Figure 1. Plan and profile of arrester system (not to scale).

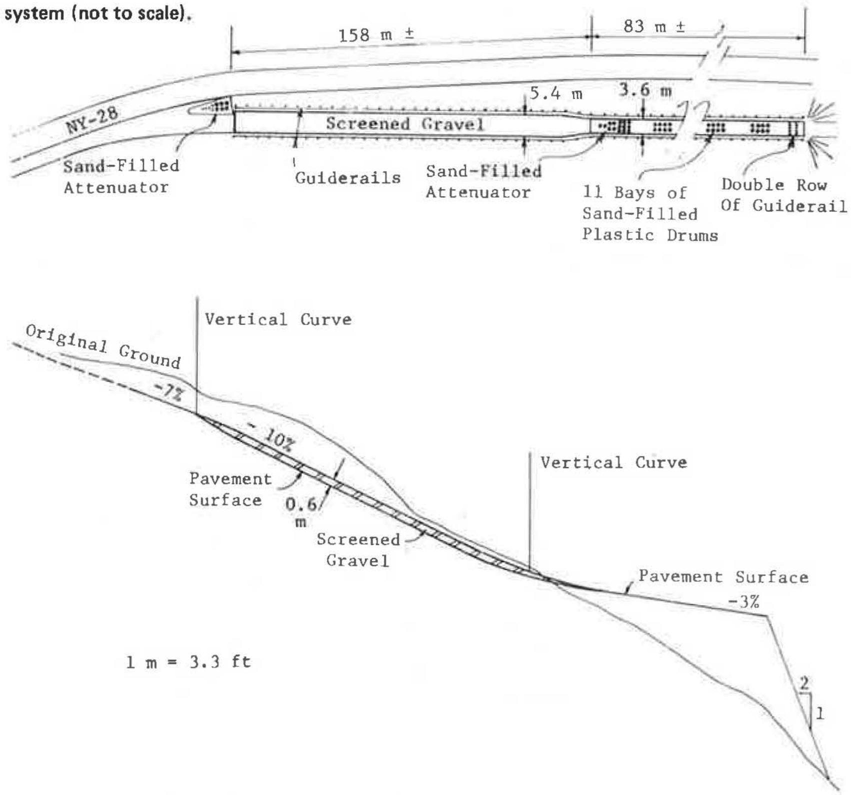

Figure 4. Approach view of arrester system showing impact attenuator to left of entrance.

m (50 ft), and the 0.6-m depth is maintained throughout most of the length, tapering back to 0 m at the other end. The approach pavement, composed of asphalt concrete, continues beneath the gravel for the entire length of the bed. The gradation of this material, sampled at 15-m (50-ft) intervals along the bed, is as follows (1 mm = 0.039 in):

	Percentage Passing		
Sample No.	25.4-mm Sieve	12.7-mm Sieve	6.3-mm Sieve
1	100.0	97.5	3.9
2	100.0	98.7	3.4
3	100.0	99.4	11.6
4	100.0	99.5	9.9
5	100.0	98.2	1.8
6	100.0	99.2	2.0
7	100.0	99.4	1.0
8	100.0	99.0	1.2
9	100.0	98.5	1.3
10	100.0	98.5	1.2

Earlier research (2, 3) had verified the concept of stopping heavy trucks by using gravel beds and indicated that a deceleration of about 0.3 *g* would be developed by this material. Trucks entering at the design speed of 128 km/h (80 miles/h) would thus exit from the 158-m (528-ft) long gravel bed at about 72 km/h (45 miles/h). Although the ramp is intended for a maximum truck weight of 36 000 kg (80 000 lb), no weight factor was considered because these earlier studies showed the deceleration rate caused by the loose gravel to be relatively independent of vehicle weight.

The second stage consists of 88 sand-filled plastic drums arranged in 11 consecutive bays (each 4 barrels long and 2 abreast), which is intended to stop large trucks that have continued through the gravel bed. These barrels are placed on 46-cm (18-in) high corrugated-metal-pipe pedestals to match their centers of mass with those of large trucks. Heavy-post corrugated-beam guiderail is installed in two separate rows at the end of the barrels to stop any vehicles that might penetrate the two stages (see Figure 3).

An installation of heavy guiderail extends the entire length of both stages to contain vehicles within the gravel bed, provide protection against jackknifing, and ensure that both rows of sand barrels are struck simultaneously. Heavy steel posts 3.6 m (12 ft) long (W6x8.5) were driven 2.1 m (7 ft) into the ground at 0.95-m (3.125-ft) centers. Three rows of 10-gage corrugated steel beams were bolted to the posts to a height of 1.5 m (5 ft).

Conventional impact attenuators designed for automobiles and light trucks are used at two locations. The first protects motorists in passenger vehicles from the guiderail ends at the entrance to the installation (see Figure 4), and the second, placed just beyond the gravel bed, ensures that any automobiles or light trucks that run through the gravel will be stopped before they strike the raised barrels.

Extensive signing is used along the route to alert drivers to the device. To minimize the chances of brake

Figure 2. Screened gravel used in arrester bed.

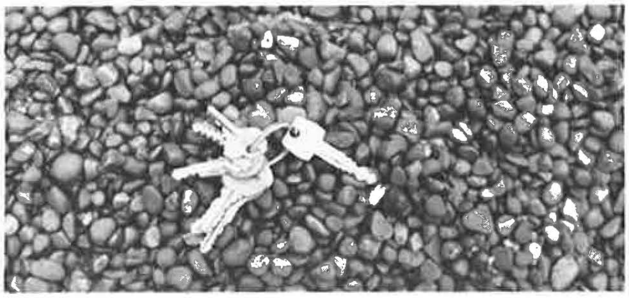

Figure 3. View of arrester system in escape lane showing heavy-post guiderail and sand barrels.

failure and ensure that the transmission is in low gear, trucks are required to stop at a specially constructed turnout before descending the grade.

TEST PROCEDURES

Because truck escape lanes are rarely encountered in New York State, and because of the unique design of this installation, three full-scale tests were conducted to demonstrate its function to potential users and to obtain data to refine future designs. Local officials and representatives of the news media were present to witness the third, highest-speed test.

A two-axle, 3.8-m^3 (5-yd^3) dump truck with dual rear wheels was loaded with sand to a test weight of 16 650 kg (37 000 lb) and driven into the arrester bed at speeds of 34, 66, and 90 km/h (21, 41, and 56 miles/h). The truck was a 1968 International Fleetstar, model 2110, with a 427-cm (168-in) wheelbase, 11.00-22 size tires, and a 213-cm (84-in) track width.

Because the performance of sand-barrel attenuators had been established, no attempt was made to test the system at speeds high enough to go completely through the arrester bed and strike the barrels. The benefits of such high-speed impacts would not justify the potential high cost of damage to the vehicle and the sand barrels or the risk of personal injury to the driver.

Several steps were taken to ensure the driver's safety: A shoulder harness and seat belt were installed, and padding was added to the interior of the vehicle in several places. All unnecessary control knobs, levers, and other protrusions were removed from the cab, and the dump body was welded to the frame to prevent movement in case of a very fast stop or rollover. Finally, the driver wore a safety helmet during each test.

The three tests were conducted during late December 1977 and early January 1978. Subfreezing temperatures and the presence of snow and ice from winter storms had resulted in a frozen crust of undetermined depth on the gravel bed before the first tests. Deicing chemicals were applied to the bed one week before the first two tests, which left the gravel thawed but wet for the three runs.

A radar unit located behind the first group of sand barrels measured the speed of the truck as it entered the arrester system. Penetration into the arrester bed was measured after each test. The principal data sources were two high-speed 16-mm movie cameras, one mounted in the vehicle's path behind the first group of sand barrels and another mounted 45 m (150 ft) normal to the vehicle's path 6 m (20 ft) upstream from the gravel bed. References for time-displacement data were targets mounted on the truck roof, range poles placed at 1.5-m (5-ft) intervals along the ramp, and a time reference of $^1/_{120}$ s printed on the film by a lamp inside each camera. Film speed varied through each run as the cameras built up speed. Using 30 m (100 ft) of film at speeds between 800 and 1000 frames/s, the cameras filmed for about 5 s. The film of each run was projected on a screen, and a time-distance chart was developed. Corrections for angular displacement of the cameras were applied. Because resolution of details was difficult from the film, distance could not be measured precisely over small time periods (50 ms). In addition, the timing light malfunctioned on the 90-km/h (56-mile/h) run, so only an approximate time-distance chart could be developed by matching the film speed to the two previous runs. For the two slower runs, speed and position were determined from the chart at 0.5-s intervals, but in both cases film ran out before the truck stopped. Average deceleration during the final portion of the run was thus computed from the measured stopping distance and velocity when the film ran out, as measured from the chart.

The time reference computed for the 90-km/h (56-mile/h) run was somewhat inconsistent. This is attributed to slower performance of the cameras in cold weather at the time of the test. A regression curve was fitted to the time-distance data, but its accuracy appears questionable. Thus, decelerations for this run were computed from the measured stopping distance.

DISCUSSION OF RESULTS

Run 1

At a speed of 34 km/h (21 miles/h), the truck entered the gravel bed with the transmission in neutral and the clutch engaged. Brakes were not applied during the run, and the truck was free wheeling. It followed a straight path with no observed yaw, pitch, or roll. The driver provided no steering other than a firm grip on the steering wheel and reported complete control. The penetration of the truck into the gravel bed, which was measured between the beginning of the gravel bed and the front bumper of the truck when stopped, was 24 m (81 ft). Computed average deceleration for this stopping distance was 0.18 *g*. Vehicle position, speed, and deceleration data at 0.5-s intervals were as follows:

Time (s)	Accumulated Distance (m)	Velocity (km/h)	Avg Acceleration (*g*)
0.00	0	34	–
0.50	4.5	38	+0.3
1.00	10	42	+0.2

Figure 5. Truck tires embedded in gravel after first test run.

Figure 6. Final position of truck after run at 90 km/h (56 miles/h).

Time (s)	Accumulated Distance (m)	Velocity (km/h)	Avg Acceleration (*g*)
1.50	16	34	-0.5
2.00	20	21	-0.7
2.45	22	18	-0.3
3.62	24	0	-0.4

Each average acceleration value was computed over the preceding time interval. At the 2.45-s point, film ran out; subsequent data were calculated from the measured stopping distance.

The largest recorded deceleration—0.7 *g*—occurred during the time interval of 1.50-2.00 s. The film indicated a slight acceleration as the truck first entered the gravel. Deceleration did not begin until about 1 s after the truck entered the arrester bed, in this case 10 m (34 ft) into the gravel. A front-end loader pulled the truck out of the gravel after the test. At first, the tow vehicle was unable to move the truck because the wheels were partially buried in the gravel (see Figure 5). But, after the gravel was raked smooth around the truck wheels, the truck was pulled from the bed by the front-end loader, the truck assisting under its own power. The test vehicle was undamaged by the test and by subsequent removal from the bed.

Run 2

At a speed of 66 km/h (41 miles/h), the truck again entered the bed with transmission in neutral, clutch engaged, and no brakes applied. The truck again ran straight without any steering control other than the driver's firm hold on the steering wheel. Stopping distance between the beginning of the gravel and the front bumper was 53 m (177 ft), resulting in a computed average deceleration of 0.32 *g*. Vehicle position, speed, and deceleration data were as follows:

Time (s)	Accumulated Distance (m)	Velocity (km/h)	Avg Acceleration (*g*)
0.00	0	66	–
0.50	9	67	0.0
1.00	18	67	0.0
1.50	27	59	-0.4
2.00	35	53	-0.4
2.20	38	40	-0.6
4.55	53	0	-0.6

Again, each average acceleration value was computed over the preceding time interval. Film ran out at 2.20 s, and subsequent data were calculated from the measured stopping distance.

As in the 34-km/h (21-mile/h) run, deceleration did not begin until the truck was about 1 s, or 18 m (61 ft), into the gravel. Beyond that point, a more or less uniform deceleration of 0.4-0.6 *g* was experienced until the vehicle stopped. The truck tires were embedded about 30 cm (12 in) deep and were shoveled clear before the truck was pulled from the gravel bed by the front-end loader. Some gravel that had lodged in the truck brake drums was removed before the final test; otherwise, the truck was again undamaged.

Run 3

In the 90-km/h (56-mile/h) test, the truck entered the arrester bed with the transmission in neutral, the clutch engaged, and using no brakes. As the truck approached the gravel bed, a pedestrian ran in front of the vehicle, causing the driver to alter his course slightly. Consequently, the truck entered the gravel bed at a slight angle to the centerline. This was the only one of the three tests in which steering input was required to control the truck. As it traversed the gravel bed, a cyclical pitching motion and some yaw developed. Although the driver reported that considerable effort was required, he was able to control the truck without contacting the side barriers. The pitching motion was apparently initiated by the buildup and subsequent vaulting of gravel in front of each wheel. The final position of the truck is shown in Figure 6.

Because a reliable time reference could not be established for this run, as explained earlier, only average deceleration over the entire length is reported: 0.35 *g* over the 90-m (300-ft) run. Although examination of these time-distance data does not permit precise determination of speed and acceleration for 0.5-s intervals, this run appears to be similar to the other two in both respects. Again, deceleration did not begin until the truck was some distance into the gravel, and the maximum decelerations over 0.5-s intervals appear to be similar to those experienced in the first two runs. After this third test, the truck was again pulled out of the arrester bed by the front-end loader and found to be undamaged.

DISCUSSION OF RESULTS

Analysis of the data films, observations of the test runs, and the driver's reports all indicate that this truck-arrester system can safely stop heavily loaded vehicles traveling at highway speeds. The average decelerations measured in these tests over the entire stopping distances are similar to those reported by Jehu and Laker (2) but, because the truck did not begin to decelerate until it was some distance into the arrester bed, average decelerations over 0.5-s intervals were two to three times the overall average. All decelerations were well below the level likely to cause bodily injury, but the controlling factor for deceleration in this design was the prevention of load shift or fifth-wheel failure, for which no established criteria could be found. The maximum deceleration observed over a 0.5-s interval—0.7 *g*—is similar to that produced by hard braking on dry pavement. Therefore, it is concluded that the decelerations experienced in entering this arrester bed are no more critical than those experienced in a panic stop on a dry pavement.

Control of the vehicle presented no problem during the lower-speed runs, and with some difficulty the driver was able to control the vehicle on the 90-km/h (56-mile/h) run. The reaction of single-unit vehicles at higher speeds could be expected to be somewhat more severe, but the side barriers are designed to prevent excessive yaw motion and keep the vehicle within the arrester bed. Because of the very flat angle at which any contact with the barrier could result, the possibilities of severe damage to the vehicle or injury to the driver seem remote. Because no tests were conducted on articulated vehicles, it is not possible to predict the performance of the arrester bed in stopping them. However, since the gravel would apply drag forces on the trailer wheels as well as the tractor and because the side barriers are designed to prevent jackknifing, this design appears to be capable of safely stopping articulated vehicles. This is confirmed by results achieved with gravel-bed arresters elsewhere.

Based on the yaw motion experienced at 90 km/h (56 miles/h), a narrower width for the installation might be helpful in preventing excessive yaw in higher-speed runs or jackknifing of articulated vehicles. This could be accomplished by quickly narrowing the distance between the side barriers after the entrance to the chute.

Some difficulty was experienced in removing the truck from the arrester beds. With very heavy vehicles, removal could be extremely difficult, especially if a vehicle cannot assist under its own power. Tow anchors should thus be provided upstream from the entrance to the arrester bed to permit a heavy-duty wrecker to winch out vehicles trapped in the gravel.

Maintenance requirements after impact are minimal for the gravel arrester bed. The gravel was simply raked smooth by hand after the truck was removed. It took only a few minutes to ready the bed for the next run. No gravel was thrown outside the arrester bed on any of the runs. Freezing of the gravel in cold weather does present a problem. Although no tests were run for verification, it seems likely that the retarding forces developed by the gravel would be greatly reduced if the gravel were frozen. Thus, it would appear to be advisable to use deicing chemicals to maintain the gravel in an unfrozen state.

CONCLUSIONS

Based on the three test runs reported here, the following conclusions appear to be warranted:

1. The gravel arrester bed safely stopped the 16 650-kg (37 000-lb) vehicle at speeds up to 90 km/h (56 miles/h).
2. Average deceleration over 0.5-s intervals and the overall average decelerations experienced in the test runs were no greater than would be experienced in a panic stop on a dry pavement.
3. The arrester bed appears to be capable of stopping single-unit trucks at higher speeds, although contact with the side barriers might occur. Based on these tests and other results reported elsewhere, it appears that articulated vehicles would also be safely stopped by this design.
4. Substantial yaw was observed at 90 km/h (56 miles/h). Narrowing the chute width from 5.4 m (18 ft) might be helpful in preventing exessive yaw and jackknifing.
5. A suitably located tow anchor is probably necessary to remove very heavy vehicles from the gravel bed.
6. Post-impact maintenance requirements for the gravel bed are minimal.
7. Application of deicing chemicals appears to be necessary to prevent freezing of the gravel bed in winter.

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