ENERGY ABSORPTION OF GRAVEL MOUNDS FOR TRUCK ESCAPE RAMPS

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by

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16. Abstract

Escape ramps, used to stop trucks that have had brake failures on long downhill grades, are usually constructed in terrain where an ascending grade can be utilized to assist in stopping the vehicles. An arrester bed of noncompacting gravel is typically used to assist in stopping the truck and to prevent roll-back of trucks after having stopped. In terrain where an ascending grade is not available and the length available for ramp construction is limited, other energy absorbing means are needed. Some use has been made of gravel mounds at the end of escape ramps as an emergency measure to stop vehicles not stopped by the arrester bed. Documentation of the reaction of trucks striking these gravel mounds is very limited. The purpose of this study was to evaluate the reaction of trucks impacting transverse gravel mounds.

Mounds 1 foot, 2 feet, and 2.5 feet were tested singly and in groups of three. The test vehicles were two-axle dump trucks loaded with gravel. Test speeds were generally at 25 mph and 40 mph. The higher mounds were effective in slowing the truck without driver injury but truck damage in the form of bent tie rods was common and the front axles were bent on several trucks.

Transverse gravel mounds are not recommended for truck escape ramps except in critical circumstances.

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ENERGY ABSORPTION OF GRAVEL MOUNDS FOR TRUCK ESCAPE RAMPS

INTRODUCTION

Escape lanes have been used for many years to stop trucks that have had brake failures on long downhill grades and their use is increasing. Emergency truck escape ramps have almost always been constructed in terrain where an ascending grade can be utilized to assist in stopping the trucks. In terrain where escape ramps cannot utilize ascending grades to absorb the kinetic energy of runaway vehicles, other energy absorbing means must be used. One such energy absorbing device is the use of a bed of noncompacting gravel. For short ramps, something more than a pea gravel arrester bed is needed. Infrequent use has been made of gravel mounds at the end of escape ramps as an emergency measure to stop vehicles not stopped by the arrester bed. In this use, it is anticipated the truck will be traveling at a relatively slow speed by the time it reaches the mounds. Documentation of the reaction of trucks striking these gravel mounds is very limited. The purpose of this study was to evaluate the reaction of trucks impacting transverse gravel mounds.

BACKGROUND

The Oregon State Highway Division included a truck escape ramp in an improvement contract now underway on the South Ashland Interchange-California State Line Section of Pacific Highway I-5. At this site, it is not possible to achieve an ascending grade. The truck escape ramp is designed on the same minus 5.5 percent grade as the highway. The length available for the ramp is limited, being about 1200 feet. The intent is to incorporate the energy absorbing capacity of transverse mounds to assist the pea gravel arrester bed in decelerating runaway trucks. Before constructing the mounds, it was considered necessary to determine the reaction of trucks to different shapes, sizes, and material gradations of the mounds.

Truck escape ramps utilize a deep bed of fine noncompacting gravel to assist in bringing runaway trucks to a safe stop. Values of the coefficient of rolling resistance provided by these beds are not well known. The value would vary with the gradation of the material, probably with its moisture content, and with freezing of the moisture in the bed. Also, there is a question whether the coefficient of rolling resistance remains constant or if it varies with truck speed, weight, and axle configuration. Data gathered from truck utilization of the Emigrant Hill escape ramps in Eastern Oregon and some information from other states was used to calculate coefficients of rolling resistance. The stopping distances were sometimes measured, sometimes estimated, and entry speeds were provided by the truck drivers. Under the stress of conditions confronting the drivers, the speed estimates are of questionable accuracy. The stopping distances are more reliable but they, too, lack precision. The resultant calculations yielded a wide spread in coefficients of rolling resistance, ranging from 0.17 to 0.76. When all of the values are considered, the mean value is 0.34. When the values that seemed unreasonably high were omitted, the mean of the remaining coefficients was 0.26. Using all of the values, the standard deviation was 0.15 from the mean of 0.34.

From data supplied by Tennessee where eight test runs were made under controlled conditions into a pea gravel bed 18 inches thick, the mean coefficient of rolling resistance was 0.35 with a standard deviation of 0.065. The mean value is very close to that found in Oregon. The smaller standard deviation results from the tests being conducted under controlled conditions. A single example from a Utah report provided a coefficient of rolling resistance of 0.33, very similar to the mean values found in Oregon and Tennessee.

Recognizing that the arrester bed materials may become silted and perhaps packed, a coefficient of rolling resistance of 0.2 was assumed as a reasonable "worst case" for design purposes. For the available length of escape ramp and the descending 5.5 percent grade existing at the Siskiyou site, a coefficient of 0.2 would not be enough to stop a truck that entered the ramp at 85 mph without brakes. To supplement the retarding capability of the arrester bed, the use of transverse gravel mounds was proposed. The HPR study reported here resulted from that proposal.

PROCEDURE

To conduct the tests under controlled conditions without traffic interference, permission was obtained to utilize a section of street at Camp Adair, a former military base now managed by the Oregon Department of Fish and Wildlife. The site provided roughly one-half mile of tangent on which the trucks could accelerate to the selected test speed plus providing an ample stopping distance beyond the mounds. The test road had a bituminous surfacing about 30 feet wide.

Uncrushed gravel to construct the mounds was hauled from Corvallis. Two gradations were used: 3/4-inch to 1/2-inch and 3/8-inch to #10. Also, limited tests were conducted with mounds constructed from chopped vehicle tires. Mounds were constructed at heights of 1 foot, 2 feet, and 2.5 feet. Single mounds and groups of three mounds were used in different tests. Most mounds had slopes of 1.5 to 1 both front and back and came to a peak at the top. Several tests were conducted on mounds having a 3 to 1 front slope and a 1.5 back slope. The 3/8 to #10 material had a natural slope of about 1.75 to 1. Several tests were conducted on mounds that had flat tops ranging from 5 to 8 feet in length in the direction of travel. The 23 tests that were conducted will be described more fully in the discussion of results.

The test trucks were all two-axle dump trucks loaded with gravel. They were vehicles recently retired from the maintenance fleet and were scheduled for trade-in. The trucks were driven by Maintenance Section personnel on a volunteer basis. The drivers used a well secured seat belt and wore hard hats. It was originally intended to use test speeds of 25 and 50 mph but except for one run on a 1 foot high mound, a nominal high speed of 40 mph was used. At the time of impact, the radar-measured speeds were less than 40 mph.

Truck reaction to striking the mounds was determined by recording radar and by photography. To provide a reference for the motion pictures, three stands were constructed, each 10 feet long, having rails 1.6 feet and 4.1 feet from the ground. The top rail was painted in 1 foot increments and the vertical members were painted at 0.1 foot increments. Three targets were painted on the side of the trucks at the elevation of the top rail. The targets were on the fender over the center of the front wheel, at the front of the bed, and at the back of the bed. Also, the wheel hubs were painted white with a black dot at the center. These various markings and targets were to aid in measuring the truck reactions to striking the gravel mounds. Two movie cameras were used on each run and a third high speed camera was used on a few of the runs. At least one of the cameras was always directed toward the end of a mound to record the vertical reaction of the truck as it passed through or over the mound. The second camera was sometimes used similarly for a different mound and sometimes used to get a more general view of the approaching truck and its reaction. A recording radar was located a safe distance downstream, beyond the mounds, to obtain the vehicle speed before and after passing the test mounds.

SUMMARY OF TEST RESULTS

The first tests were conducted with mounds made from 3/4-inch to 1/2-inch gravel. The first three tests were with a single one foot high mound having slopes of 1.5 to 1 coming to a peak at the top. With this mound, test speeds of 25, 34, and 43 mph were used. The truck reaction to this mound was not exceptionally harsh, however the front wheels did leave the ground at the 34 and 43 mph speeds. Prior to testing, it was hoped the truck would pass through the mounds with only minimum vertical reaction. The vertical reaction during testing was greater than anticipated. Although the trucks displaced a large amount of gravel in the wheel paths, the tires ramped over a portion of the gravel in the mound. Most of the vertical reaction was absorbed by the springs, with a much smaller movement of the truck bed. At each test speed, this one foot high mound reduced the velocity by one mile per hour as the truck passed through the mound. A summary of all of the test runs is presented in Table 1, following this section.

Two tests were conducted, at speeds of 28 and 38 mph, on a single one foot high mound having a 3 to 1 approach slope and a 1.5 to 1 back slope, coming to a peak at the top. With the 3 to 1 slope, there was a much smaller spring reaction but a much greater vertical reaction of the truck bed. At 28 mph, the front wheels left the ground, and the truck battery came out of its mount which, in turn, broke a radiator hose. It was concluded the truck reaction was less favorable with the 3 to 1 slope.

The next two runs, test numbers 6 and 7, were conducted with a series of three 1 foot high mounds spaced at 30 feet center to center. Each mound had approach and back slopes of 1.5 to 1. As with the single mound having 1.5 to 1 slopes, much of the vertical reaction at the front of the truck was taken by the springs. At an entry speed of 26 mph, the three mounds reduced the speed by 2 mph. The radar trace indicates each mound reduced the speed by about 0.5 mph. At a test speed of 35.5 mph, the exit speed was 33 mph after passing the three mounds. Although the reaction to striking the mounds was not particularly severe, neither were they very effective in slowing the vehicles.

The next group of tests was conducted with 2 foot high mounds. Test number 8 used a single mound with 1.5 to 1 approach and back slopes coming to a peak at the top. It was constructed with the same 3/4-inch to 1/2-inch gravel used in the previous tests. At a test speed of 25.5 mph both the front hub and the target on the front fender were displaced vertically over 0.5 feet. The mound slowed the vehicle by 3 mph but significant damaged was caused. The reaction broke both front shock absorber mountings, caused a radiator leak, and the steering wheel was bent by the driver.

Test number 9 used a 2 foot high mound with a 3 to 1 approach slope and a 1.5 to 1 back slope. The entry speed was 36.5 mph and the truck slowed 4 mph in passing through the mound. The reaction was violent and the driver commented he nearly lost control of the truck. The front axle was damaged to the extent the truck was out of action. Test number 10 used the same 2 foot high mound with 3 to 1 front and 1.5 to 1 back slopes. The entry speed was 26 mph and the exit speed 22.5 mph. The test was conducted without truck damage although the measured vertical reactions were more severe than the previous tests.

Test number 11 employed three 2 foot high mounds spaced at 30 feet center to center having 1.5 to 1 front and back slopes coming to a peak. The test was conducted at a nominal speed of 25 mph, however, the recording radar was inoperative.

During the preparation for these tests, interest had been expressed in utilizing rubber chips made by chopping old tire casings. A load of chopped tires having a gradation of approximately 2-inch to 1/2-inch was used to form several mounds of different shapes. Test number 12 utilized three mounds at a 30 foot spacing. Each was 2 feet high and had 1.5 to 1 front and back slopes coming to a peak. The vertical reaction of the truck was similar to that with the gravel mounds of similar shape and spacing, however no front axle damage resulted with the rubber tire chips. The three mounds produced a 5 mph reduction in speed. Test number 13 used the same three mounds as in number 12 but the test speed was 38 mph. Again, the mounds reduced the speed by 5 mph.

Test number 14 utilized the rubber chips with a 2 foot high mound having 1.5 to 1 slopes but with a 5 foot flat top in the direction of travel. The entry speed was 26 mph and the exit speed 22 mph. The truck ramped up over the mound, resulting in a nose landing which caused the load to shift forward, but there was no axle damage.

Test number 15 utilized the rubber tire chips in a mound 2.9 feet high having an 8 foot flat top with 1.5 to 1 slopes front and rear. With an entry speed of 25.5 mph, the truck slowed to 20 mph crossing the mound. The truck climbed up and through the pile and the front was airborne as it passed over the downstream end. The pitching action of the truck caused a portion of the load to be spilled. No damaged was done to the truck.

The next test, number 16, was a repeat of test number 11. It utilized three 2 foot high mounds of gravel at 30 foot spacings with 1.5 to 1 front and back slopes coming to a peak at the top. The entry speed was recorded at 23.5 mph and the exit speed 13 mph; however, the large change in speed was caused in part by a tie-rod failure which caused the right front wheel to turn outward at a sharp angle.

Test number 17 utilized a 2 foot high mound constructed of the 3/4 to 1/2 inch gravel having a 6 foot flat top in the direction of travel and 1.5 to 1 slopes front and rear. With the flat top, the truck climbed as it passed through the berm and was essentially airborne as it passed through the back of the mound. Again, the tie-rod of the truck failed and the wheels turned outward so a skidding action assisted in decelerating the truck. The entry speed was 22.5 mph and the exit speed 16 mph. If the truck had passed through the mound, rather than climbing up as it went into the mound, the extra mass provided by having a 6 foot flat top would have provided additional stopping resistance not available with a pointed mound. However, since the truck did climb as it went into the mound, the reaction was severe.

When the single-unit dump truck impacted the mounds spaced at 30 feet center to center, the spring reaction was such that the truck had already started to rise before striking the next mound. It was thought mounds spaced closer together might be more effective in decelerating a truck if the front axle reached a succeeding mound as the rear axle passed the previous mound. To test this hypothesis three mounds were placed at 14 feet center to center. Each was 2 feet high and had 1.5 to 1 slopes front and back coming to a peak. This spacing was such that the truck was pitching downward at the front end when the front axle reached the second mound and a similar situation existed as the front axle reached the third mound. Tie-rod damage was initiated at the first mound and worsened with each succeeding impact. The truck barely cleared the third berm before stopping, and while much of the deceleration can be attributed to the skidding action of the wheels after the tie-rod buckled, placing a berm at the point of maximum spring compression did increase the effectiveness of the berms. The entry speed was 24 mph and the exit speed 10 mph.

Test number 19 utilized a single mound 2.5 feet in height with 1.5 to 1 slopes coming to a peak. The mound was constructed with 3/4-inch to 1/2-inch gravel. The vertical displacement of the front target as the truck passed through the mound was 1.0 foot and for the rear target the value was 1.1 feet. Again, the tie-rod buckled making the truck inoperable. The mound slowed the vehicles by 6 mph, from 25 to 19 mph.

Starting with test number 20, a 3/8-inch to #10 pea gravel was used to construct the mounds. Tests 20 and 21 utilized three 2 foot high mounds spaced at 30 feet center to center with 1.5 to 1 slopes coming to a peak. Trucks passed through the finer gravel with less vertical movement and a greater displacement of the aggregate. In number 20, the speed was reduced from 20.5 to 8.5 mph in passing through the three mounds. The reaction was less violent than with the coarser aggregate and no vehicle damage resulted. The only variable between test 20 and 21 was the vehicle speed. Test 21 had an entry speed of 32 mph and an exit speed of 20 mph. The front axle of the truck was bent during the test, probably when the wheels came down hard on the bituminous pavement of the street. The tie-rod was not buckled in this case.

Test number 22 utilized a series of three mounds spaced at 14 feet center to center. Each mound was 2 feet high and came to a peak with 1.5 to 1 front and back slopes. The entry speed was 26 mph and the exit speed 14.5 mph. Observers thought the three closely spaced mounds stopped the truck more quickly than those spaced at 30 feet center to center; however, the in and out radar measurements indicate very little difference. Truck damage in the form of a bent tie-rod and bent front axle resulted from the test.

The final test, number 23, utilized a single mound 2 feet high with a 5 foot flat top in the direction of travel and 1.5 to 1 slopes front and rear. The mound was formed from the same 3/8-inch to #10 pea gravel used in the previous three tests. The entry speed was 25 mph and the exit speed 17 mph. The truck climbed through the mound and jumped as it reached the rear end. The tie-rod bent and gravel was thrown up the grill during the test. As with the other flat-top mounds, the vertical reaction of the truck was greater than with the peaked mounds. In this test, the target on the front fender rose 1.27 feet above its level-road position and the target on the rear of the bed rose slightly over 2 feet as the truck crossed the mound.

Table 1, following, summarizes the test conditions for each test and provides information on the vertical reaction of the truck and the entry and exit (in/out) speeds as determined by recording radar. The shape notation refers to the front and back slopes of the mounds and whether they came to a sharp peak or had a flat top in the directon of travel. The maximum vertical reactions of front and rear hubs and of front and rear targets are shown. The front target was mounted on the front fender and the rear target at the rear of the truck bed. The horizontal measurements provide the distance from the center of the mounds to the point where the maximum vertical reaction occurred. All of the vertical measurements are from an at-rest position on the pavement surface.

Following Table 1 are several photographs showing typical truck reactions to the mounds and the tie-rod damage that frequently occurred. The tie-rod failures resulted in one or both front wheels turning sharply outward which caused the truck to stop quickly from the skidding action. The pictures are referenced to the test number so details can be obtained from Table 1.

Notes from the 23 test runs indicate truck damage occurred during 11 tests. Where the truck damage could be repaired fairly easily, repairs were made and the truck was used in subsequent tests. None of the vehicles were damaged beyond repair but repairs were more difficult for those having bent axles. The axle damage is attributed to the test conditions in which the mounds were placed on an asphalt surfaced road. The cushion effect of fine gravel in an escape ramp arrester bed is expected to minimize the prevalence of bent axles.

TABLE 1. TEST CONDITONS AND SUMMARY OF TRUCK REACTION TO MOUNDS

Test No.	Mound shape, number, and spacing	Height ft.	Material	Peak, Front hub, ft.		Peak, Front target, ft.		Peak, Rear hub, ft.		Peak, Rear target, ft.		In/Out Radar MPH	Comments
				Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz		
1	1.5:1 Peak Single	1	3/4-1/2" Gravel	+0.45	0	+0.16	+4.6	+0.19	0	+0.17	+2.0	25/24	Mild reaction.
2	1.5:1 Peak Single	1	3/4-1/2" Gravel	+0.57	0	+0.17	+5.2	+0.17	+0.6	+0.23	+3.2	34/33	Front wheels left ground.
3	1.5:1 Peak Single	1	3/4-1/2" Gravel	+0.67	+0.6	+0.23	+4.6	+0.23	+0.6	+0.23	+5.2	43/42	Front wheels left ground.
4	3:1 Peak Single	1	3/4-1/2" Gravel	+0.45	0	+0.40	+5.8	+0.20	±0.6	+0.46	+0.6± 0.3	28/27	Front wheels left ground. Battery came out of mount; Broke radiator hose.
6	1.5:1 Peak 3 @ 30' c-c	1	3/4-1/2" Gravel	+0.46	0	+0.12	+4.9± 0.3	+0.17	0± 0.3	+0.23	+0.6	26/24	End pile 3; Each berm reduced speed 1/2 mph.
				+0.38	0	+0.21	+6.0	+0.15	0	+0.18	+1.4		End pile 1; 3 separate impacts - no carry-over.
7	1.5:1 Peak 3 @ 30'	1	3/4-1/2" Gravel	+0.48	0	+0.29	+7.2	+0.35	+0.3	+0.40	+4.9	35.5/33	End pile 3; 1st Target ±0.3 below bar on approach.
				+0.53	0	+0.23	+7.5± 0.1	+0.18	+0.6	+0.14	+4.0		End pile 1; Rear wheel leaves ground.

Test No.	Mound shape, number, and spacing	Height ft.	Material	Peak, Front hub, ft.		Peak, Front target, ft.		Peak, Rear hub, ft.		Peak, Rear target, ft.		In/Out Radar MPH	Comments
				Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz		
8	1.5:1 Peak Single	2	3/4-1/2" Gravel	+0.54	+0.9	+0.52	+5.5 ± 0.3	+0.35	+0.9 ± 0.3	+0.69	+1.2	25.5/ 22.5	Axle spread gravel 50' downstream. Broke both front shock mountings, radiator leak, bent steering wheel.
9	3:1 Peak Single	2	3/4-1/2" Gravel	+0.60 (est.)	+2.3	+0.63	+7.5 ± 0.3	+0.48 (est.)	+0.6	+0.60	+4.9	36.5/ 32.5	Driver nearly lost control of truck. Bent front axle or broke kingpins. Truck out of action.
10	3:1 Peak Single	2	3/4-1/2" Gravel	+1.01	+5.5	+1.15	+6.9 ± 0.6	+0.84	+4.0	+1.32	+0.6 ± 0.6	26/ 22.5	Softer than #8 and #9. No truck damage.
11	1.5:1 Peak 3 @ 30'	2	3/4-1/2" Gravel	-	-	-0.71	-5.8	-	-	-	-	25±	Data is for low point prior to impact of berm #3.
				+0.58	+5.2	+0.64	+1.2	+0.79	+1.7	+1.12	+0.86		Data for berm #3 after impact.
				+0.46	-0.6	+0.29	+3.5 ± 1.2	+0.37	-0.3	+0.60	0		Berm #1 data; Scattered gravel over test area. Tie rod and axle skims tops of piles, bent tie rod. Out of action.
12	1.5:1 Peak 3 @ 30'	2	1/2-2" Rubber Tire Chips			-0.35	-2.3					38.5/ 23.5	Data for low point prior to impact of berm #3.
				+0.37	0	0	-0.6	+0.31	+1.4	+0.32	+2.3		Berm #3, after impact.
				+0.59	0	+0.25	+1.7	+0.26	+0.6	+0.43	+0.6		Piles compress, moderate reaction. No front axle damage, berm #2 data.

Test No.	Mound shape, number, and spacing	Height ft.	Material	Peak, Front hub, ft.		Peak, Front target, ft.		Peak, Rear hub, ft.		Peak, Rear target, ft.		In/Out Radar MPH	Comments
				Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz		
13	1.5:1 Peak 3 @ 30'	2	1/2-2" Rubber Tire Chips			-0.35	-9.2					38/33	Data for low point prior to impact of berm #3.
				+0.69	+0.3 ± 0.3	-0.37	-2.3	+0.46	+0.3	+0.58	+1.44		Berm #3 after impact.
				+0.67	+0.3	+0.29	+5.2 ± 0.3	+0.38	+0.9 ± 0.3	+0.60	+2.9		Camera pan - berm #2. Truck jumps over each berm.
14	1.5:1 5' Flat top Single	2	1/2-2" Rubber Tire Chips	+0.81	+1.7	+1.06	+6.9	+0.89	+2.9	+1.35	+1.2	26/22	Camera fixed - end pile.
				+0.62	+1.7 ± 0.3	+1.01	+6.0 ± 0.9	+0.73	+4.0	+1.35	+2.0		Camera pan - nose landing, shifted load forward.
15	1.5:1 8' Flat top Single	2.9	1/2-2" Rubber Tire Chips	+2.01	+8.1	+2.28	+6.9	+1.61	+5.8	+2.24	+3.2	25.5/20	Camera fixed - end pile.
				+2.04	+7.5	+2.24	+6.9	+1.55	+4.9	+2.23	+2.9		Camera pan - truck climbed up and through pile. Leaped over downstream end, dumped part of load. No damage.
16	1.5:1 Peak 3 @ 30'	2	3/4-1/2" Gravel			-0.59	-4.6 ± 0.6					23.5/13	Data for low point, before impact - berm #3.
				+0.40	+2.3	+0.53	+2.9 ± 0.6	+0.46	+0.6	+0.48	0 ± 1.2		Berm #3 after impact.
				-	-	-	-	+0.51 (est.)	+1.2 (est.)	+0.44 (est.)	+0.9 (est.)		Camera pan Berm #2 - tie rod bent (partly damaged after second berm). Right wheel turned out after third berm resulting in tire drag frictional stoppage.

Test No.	Mound shape, number, and spacing	Height ft.	Material	Peak, Front hub, ft.		Peak, Front target, ft.		Peak, Rear hub, ft.		Peak, Rear target, ft.		In/Out Radar MPH	Comments
				Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz		
17	1.5:1 6' Flat top Single	2	3/4-1/2" Gravel	+1.29 ± 0.23	+4.0	+1.27	+4.3	+1.16	+1.4	+1.50	-0.9	22.5/16	Camera fixed - end pile. Truck climbed through berm, breaking out on backside. Tie rod bent.
18	1.5:1 Peak 3 @ 14' c-c	2	3/4-1/2" Gravel	-	-	-0.53	-1.7	-	-	-	-	24/10	Camera pan - data for low point prior to impact of berm #2.
				-	-	+0.26	+5.2	-	-	-	-		Camera pan - data for high point after impact with berm #2.
				-	-	-0.63	-1.4	-	-	-0.3	-7.5		Camera fixed - data for low point before impact with berm #3.
				-	-	+0.12	+3.5	-	-0.9 ± 0.3	+0.52	-3.5		Camera fixed - data for high point after impact with berm #3. Tie rod damage began at first berm and worsened with each succeeding impact. Truck barely cleared 3rd berm before stopping, little jump.
19	1.5:1 Peak Single	2.5	3/4-1/2" Gravel	obscured		+1.00	+5.2 ± 0.6	+0.70	+3.5	+1.09	+1.4	25/19	Camera pan.
				obscured		+1.00	+6.3 ± 0.6	+0.71	+2.0	+1.10	+0.3		Camera fixed. Tie rod bent. Climbed through pile, not much jump.

Test No.	Mound shape, number, and spacing	Height ft.	Material	Peak, Front hub, ft.		Peak, Front target, ft.		Peak, Rear hub, ft.		Peak, Rear target, ft.		In/Out Radar MPH	Comments
				Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz		
20	1.5:1 Peak 3 @ 30'	2	3/8-#10 Gravel	-	-	-0.63	-3.7	-	-	-	-	20.5/ 8.5	Camera pan - data for low point prior to impact of berm #2.
				+0.58	+4.2± 0.6	+0.99	+3.7	+0.56	+0.3± 0.3	+0.56	-2.0		Camera pan - data for high point after impact with berm #2.
				-	-	-0.69	-7.8	-	-	-	-		Camera fixed - data for low point before impact with berm #3.
				+0.52	-1.7	+0.48	-1.4	+0.46	-0.3± 0.3	+0.59	-3.7		Camera fixed - data for high point after impact with berm #3. Less violent than with coarse aggregate. No vehicle damage.
21	1.5:1 Peak 3 @ 30'	2	3/8-#10 Gravel	-	-	+0.25	-1.2	-	-	-	-	32/20	Camera fixed - data for low point before impact with berm #3.
				-	-1.2± 0.3	+0.29	+2.0	-	+2.0	+0.98	0		Camera fixed - data for high point after impact, bent axle, tie rod okay. Truck swerved left.

Test No.	Mound shape, number, and spacing	Height ft.	Material	Peak, Front hub, ft.		Peak, Front target, ft.		Peak, Rear hub, ft.		Peak, Rear target, ft.		In/Out Radar MPH	Comments
				Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz		
22	1.5:1 Peak 3 @ 14' c-c	2	3/8-#10 Gravel	-	-	-0.35	0	-	-	-	-	26/ 14.5	Camera pan - data for low point prior to impact with berm #2.
				-	-2.3	+0.14	+7.5	-	-0.6	+0.3	-0.9		Camera pan - data for high point after impact with berm #2.
				-	-	-0.37	-1.7	-	-	-	-		Camera fixed - data for low point prior to impact with berm #3.
				obscured		+0.23	+4.3	-	0± 0.6	+0.81	-2.3		Camera fixed - data for high point after impact with berm #3. Three close berms stop truck faster. Tie rod and axle bent up at spindle and shackle and exposed tie rod ends.
23	1.5:1 5' Flat top Single	2	3/8-#10 Gravel	+1.09	+1.2	+1.07	+4.6	+1.44	+2.3	+2.01	+0.9± 0.9	25/17	Camera pan - front end of pile.
				+1.09	+2.3	+1.27	+5.2	+1.55	+1.7	+2.08	0		Camera fixed - truck climbed through berm and jumped. Dodge axle higher than Ford thus giving better protection to tie rod. Tie rod still bent. Gravel thrown up grille.

Test No.2 - Single 1 ft mound. Left front wheel airborne.

Test No.6 - Three 1 ft mounds at 30 ft.

Test No.8 - Single 2 ft mound. Flying gravel obscures front wheels.

Test No.10 - 2 ft mound with 3:1 front slope. Front wheels airborne.

Test No.11 - Three 2 ft mounds. Tie rod bent.

Test No.17 - 2 ft mound with 6 ft flat top. Truck climbs through mound.

Test No.18 - Typical truck damage.

Test No.19 - Single 2.5 ft mound.

Test No.20 - Three 2 ft mounds at 30 ft.

Test No.20 - Mounds after truck passed.

Test No.22 - Three 2 ft mounds at 14 ft.

Test No.22 - Mounds after truck passed.

DISCUSSION OF TEST RESULTS

The truck reaction to the mounds was more severe than had been envisioned prior to testing. The 1 foot high mounds caused little damage to the truck although significant bouncing occurred. All of the tests were conducted without injury or threat of serious injury to the drivers. However, a driver without a firm lap belt would probably have been injured. Each 1 foot high peaked mound reduced the truck velocity by about 1 mph. A better measure perhaps is that a series of three mounds reduced the velocity by 2 mph when the entry speed was 26 mph and by 2.5 mph when the entry speed was 35.5 mph.

The truck reaction to the 2 foot and 2.5 foot high gravel mounds was quite severe. In many of the tests, the trucks were damaged to the extent they were immobilized. The 2 foot high mounds slowed the truck by roughly 3 mph each. Although they were effective in slowing the truck without driver injury, it was concluded, because of truck reaction and truck damage, that the higher mounds should not be used except in cases where the alternative hazard was severe.

The mounds made from chopped tire casings were about as effective in slowing the truck as those made with gravel but had the advantage of being less damaging to the vehicles. A disadvantage, however, was that the tire chips were spread over a wide area on impact. A practical means of retrieving the chips to reshape the mounds after use is lacking. The rubber chips may warrent evaluation in other ways, such as using them in an arrester bed in place of gravel, but they do not seem practical for use in mounds.

The idea of using the flat topped mounds was that more mass would be provided to absorb energy. Prior to testing, the effectiveness of the various mounds was estimated on the basis of a transfer of momentum from the truck to the gravel particles of the mounds. It was hypothesized that the truck would pass through the mounds and gravel would be displaced by the wheels and by the bumper or underside of the vehicle. The higher mounds and the mounds having a flat top would provide more material to be moved. Some ramping up and over the higher and longer mounds was anticipated, but not to the extent that was found during testing. The reaction to the flat-topped mounds and the high mounds was unreasonably severe for a practical application.

AGGREGATE GRADATION COMPARISONS

In the dry state that existed during testing, the finer 3/8-inch to #10 pea gravel was as effective as the coarser 3/4-inch to 1/2-inch material in slowing the truck and was less damaging to the vehicles. However, these tests were made to assist in the design of the Siskiyou Summit escape ramp where snow and freezing temperatures are prevalent. The likelihood of encountering a firm frozen crust is greater for the finer material since it is somewhat less free-draining. In a climate not subject to freezing weather, the finer material would offer a slight advantage over the 3/4-inch to 1/2-inch gravel.

Prior to conducting the field tests, laboratory tests were conducted to compare the two materials. A large box, about four feet square and two feet deep was filled with each of the materials and a Kelly ball, usually used for concrete consistency tests, was dropped from the ceiling into the box. The depth of penetration of the ball was measured. The mean penetration of the ball was slightly greater for the fine material than for the coarser gravel.

In another test, to determine the potential for freezing, concrete cylinder molds were filled with gravel and then with water. The water was subsequently allowed to drain for 5 minutes after which the cylinders were frozen at 10 F. The frozen cylinders were then tested in compression. The 3/8-inch to #10 material had a compressive strength of 121 psi and the 3/4-inch to 1/2-inch material had a strength of 83 psi. This test gives some indication of relative moisture retention of the two sizes and the relative hazard of using each in truck escape ramps which might freeze solid. Truck tire inflation pressures are usually in the 70 to 80 psi range so, under slightly less severe conditions, a truck would break through a crust of the coarser material but would probably be supported by the finer material.

CONCLUSIONS

These tests showed that transverse gravel mounds are effective in slowing a truck without brakes and in critical circumstances they would provide a useful method of stopping runaway trucks. The truck reactions were somewhat more severe than had been anticipated prior to testing but in each case the vehicles were slowed without driver injury nor serious threat of injury. All drivers used a firmly secured lap belt. There is a probablility that a driver without a lap belt would have been injured in some of the tests. Also, higher vehicle speeds would increase the hazard of striking the mounds. The 1 foot high mounds would seem reasonably safe at high speeds but the higher mounds would constitute a serious hazard.

Truck damage was quite prevalent during the tests. The most common damage was to the tie-rods and the moving pictures show that this was caused by the gravel as the truck penetrated the mounds. Other frequent damage consisted of bent axles. At the test site, the mounds were placed on asphalt paved surfaces. The axle damage probably occurred from impacting the pavement, perhaps aggravated by the effect of the bent tie-rod. An arrester bed of fine gravel would help to cushion the contact and minimize the chance of axle damage.

If the mounds were frozen, a very violent truck reaction would be anticipated. If mounds were used in areas subject to hard freezes, some provision should be made to prevent freezing of the gravel. Possible solutions could be periodic salt applications or covering the mounds with light plastic to keep the gravel dry. For mounds that are subject to freezing, the coarser 3/4 to 1/2-inch gravel would be preferable to the 3/8-inch to #10 material. In areas not subject to freezing, the finer material would be preferable because it caused less vehicle damage.

A given mound is more effective in slowing a truck than the transfer of momentum calculations would indicate. It is believed the energy absorbed by the springs, tires, and shock absorbers during the vertical reaction is the major contributor to this difference.

RECOMMENDATIONS

From the results of the Camp Adair tests it is recommended that mounds not be used except under very critical circumstances.

Mounds could be used near the ends of escape ramps where the consequence of not stopping a truck would be critically hazardous.

If mounds are used, they should be quite low, have front and back slopes of approximately 1.5 to 1, and come to a peak at the top.

Closely spaced mounds seemed more effective than those at wider spacing. A number of low, closely spaced mounds would surely be preferable to large widely spaced mounds. The Camp Adair tests used spacings of 30 feet and 14 feet. The mounds probably could have been spaced at less than 14 feet and still been as effective. A closer spacing would make it feasible, of course, to provide more mounds in a given length of ramp but might make maintenance more difficult.

If freezing weather is anticipated, salt or other antifreeze solution or plastic coverings should be provided if feasible. If it is not reasonable to prevent the mounds from freezing, coarse, free-draining materials should be used.

MOVING PICTURE FILM

A film was prepared by inserting statistical data on each test run (Test number, truck speed, height, shape, number of mounds, and camera position) ahead of the film taken during the run to provide a permanent record. The film provides a good illustration of the truck reaction to the various mounds.