

VEHICLE ENTRAPMENT

GEORGE W. INDAHL

JOHN J. QUINN

KENNETH C. AFFERTON



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New Jersey Department of Transportation
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16. Abstract The New Jersey Department of Transportation has conducted a study to develop a configuration of gravel that would act as a vehicle arrestor, stopping and entrapping out-of-control automobiles within a hundred feet, with minimized resultant injury to the occupants and minimal damage to the vehicle. Eight gravel arrestor bed configurations were tested using a local 3/8" (1 cm) washed pea gravel. Overall, the pile bed of uniform height of 1-1/2 foot (.46 m) high piles resulted in the best design to accommodate a 55 mph (88.5 km/h) impact. The performance of the other bed configurations tested were less acceptable than the 1-1/2 foot pile bed due to either increased vehicle damage with correspondingly higher deceleration forces or increased required stopping distances at the same speed. Also presented in this report are details on the design of the test track, vehicle control and guidance systems, and the construction, maintenance and restoration of the various gravel bed configurations after impact.					
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ABSTRACT

This report details the results of a study to develop a configuration of gravel that would act as a vehicle arrestor, stopping and entrapping out-of-control automobiles within a hundred feet, with minimized resultant injury to the occupants and minimal damage to the vehicle. Details are presented on the design of the test track, vehicle control and guidance systems, and the construction, maintenance and restoration of the various gravel bed configurations after impact.

Eight gravel arrestor bed configurations were tested using a local 3/8" (1 cm) washed pea gravel:

1. Level Beds

a. Tapered Transition - gradually increasing depth starting out at zero depth at the beginning of the bed, increasing to one foot (.3 m) in depth at 45 feet (13.7 m) into the bed and remaining uniform at this depth for the remainder of the bed.

b. Uniform Depth - a one foot (.3 m) uniform depth of gravel with the top of the bed being at ground level.

c. Tapered Bed - constructed on top of the uniform depth bed with the height of the gravel above ground level being zero at the beginning of the bed and increased at a rate of 1 foot (.3 m) per 100 feet (30.5 m) in bed length.

2. Pile Beds

a. Uniform Height - a series of transverse piles of uniform

height, each pile in the form of a windrow perpendicular to the direction of travel; beds of three different pile heights (1 foot (.3 m), 1 1/2 foot (.46 m), 2 foot (.6 m) were tested.

b. Tapered Pile - the first 25 feet (7.6 m) of the bed with 1 foot (.3 m) high piles, the middle 24 feet (7.3 m) with 1 1/2 foot (.46 m) high piles and the last 100 feet (30.5 m) with 2 foot (.6 m) high piles.

c. 1 1/2 Foot (.46 m) Uniform Height Pile - at 25° angle - 1 1/2 foot (.46 m) high pile bed oriented at an angle of 25° as measured from the head-on direction.

Of all the bed configurations tested, the pile bed of uniform height of 1 1/2 foot (.46 m) high piles resulted in the best design to accommodate a 55 mph (88.5 km/h) impact. This was determined after analyzing the resultant stopping distance, average vehicle deceleration and vehicle damage data for all the beds tested.

Although the 2 foot (.6 m) high pile bed stopped the test vehicle in a shorter distance than the bed with 1 1/2 foot (.46 m) high piles, damage to the vehicle was somewhat severe and the peak deceleration forces were exceptionally higher.

The level bed configurations (tapered transition, uniform depth and tapered) required approximately 50% to 200% more stopping distance at the same speed than the 1 1/2 foot (.46 m) high pile bed.

CONCLUSIONS

Of the eight gravel bed configurations tested, the 1-1/2 foot (.46 m) pile bed was most effective. Study results indicate that this design is capable of stopping a standard size automobile impacting the bed at 55 mph (88.5 km/h) within a distance of 100 feet (30.5 m). The occupants of the vehicle should undergo a peak deceleration of approximately 4 g's and an average deceleration of approximately 1 g during impact. These forces are well within an acceptable range and would not in themselves inflict injury to restrained occupants (lap belt). Although New Jersey's program was limited to one type and size of vehicle, a comparison with the earlier investigations of gravel arrestors by Great Britain's Road Research Laboratory^(2,3) seem to imply that this study's deceleration and vehicle penetration values may be valid for a wide range of vehicle sizes. However, it must be recognized that the applicability of these values to other size vehicles has not been established in the present study.

An installation of any gravel type arrestor would be a relatively simple operation requiring the use of only a motor grader to level the installation site, dump trucks to haul the gravel to the site, and a front end loader to place the material. After an impact, a front end loader would be required to restore and shape the gravel bed. Little, if any, replacement gravel should be needed.

Under moderate impact (vehicle speeds less than 40 mph (64.4 km/h)) damage should be minimal, in most cases, allowing the vehicles to be driven away under its own power after being towed out of the bed area.

It must be noted that any of the gravel arrestors tested would require a relatively large installation space as compared with impact attenuators such as the Fitch Inertial Barrier.

RECOMMENDATIONS

It is recommended that the use of the 1-1/2 foot (.46 m) foot transverse pile gravel configuration be considered for locations where space is available and potentially hazardous conditions could be alleviated. It should be noted that all stopping distance values reported in this study are absolute values. For design purposes an appropriate safety factor should be included when determining the length of bed required for a particular location. It is believed that, at a minimum, the bed length should be 25 feet (7.6 m) greater than the specific stopping distance established in this research. This will provide for at least a three standard error of the estimate tolerance on the predicted stopping distance.

Several additional factors must be considered when attempting to apply the findings of this research:

First, only one vehicle weight class was tested in the study. The implied performance of the proposed configuration as an entrapment system for heavier vehicles requires verification through full-scale testing of representative vehicle types. Without that verification the authors caution against use of the recommended configuration as an entrapment mechanism where the heavier vehicles are to be encountered.

Second, since the testing program was conducted on a level roadway, care must be taken in using study results for design of vehicle "run-off" areas at the bottom of steep grades.

Finally, dry, relatively warm winters through the field test phase of the study precluded the investigation of a frozen bed condition.

Care should be taken to insure that ample drainage is provided in any installation in order to minimize the possibility of "trapped" water freezing in the bed area.

Gravel for use in the bed should meet NJDOT grading requirements for Number 8 size coarse aggregate. It must further meet the quality requirements for washed gravel coarse aggregate as specified in Article 8.5.6 of the New Jersey Department of Transportation standard specifications.

If and when installations are made, the pile configurations should be observed and restored as necessary. Any hits should be recorded at the time and costs involved in maintaining the beds be noted for comparison with the impact attenuation devices currently in use.

Since the performance of the other configurations tested in this study were less acceptable, their use as arrestor beds is not recommended.

I. INTRODUCTION

A. Specific Aim:

The objective of this project was to develop a configuration of gravel that would act as an arrestor, stopping vehicles within one hundred feet (30.5 m) and entrapping outside of the driving lanes an out-of-control vehicle with minimized resultant injury to the occupants and damage to the vehicle.

The following design criteria were used as the basis for developing the gravel bed design:

1) Stopping Distance

Vehicle should be stopped within a 100 foot (30.5 m) distance, which at the inception of the project was thought to be the maximum area available for installation of an arrestor without extensive site alterations, at 55 mph, which was designated as the design speed.

2) Average Vehicle Deceleration

An upper limit for average vehicle deceleration of 12 g's "while preventing actual impacting or penetration of the roadside hazard" was established based on a report from the FHWA on highway barriers (Reference 1). This limitation is also suggested by Calspan. Table 1 is a listing of their recommended limits under varying occupant restraints.

3) Vehicle Damage

The resultant damage to an impacting vehicle should be minimal and there should be no penetration into the vehicle's occupant compartment. The system ideally should allow the vehicle to be driven away under its own power after being towed out of the bed area.

TABLE 1
 TENTATIVE TOLERABLE DECELERATION LIMITS
 SUGGESTED BY CORNELL AERONAUTICAL LABORATORY
 (CALSPAN, 1969)

Occupant Restraint	Maximum Deceleration (g's)		
	Lateral	Longitudinal	Total
Unrestrained	3	5	6
Lap Belt	5	10	12
Lap Belt & Shoulder Harness	15	25	25

B. Significance of Work

The severity of "out-of-control" vehicle accidents could be reduced through the use of a properly designed gravel, energy-absorbing arrestor. Low resultant occupant injury and the potential for low installation and maintenance costs, with high stopping ability should permit wide usage.

C. Immediate Applications

The gravel bed type of arrestor would have immediate applications at New Jersey's numerous circles, divided roadways and gore areas, illustrations of which are given in Appendix A-1.

Gravel beds could be installed in the center of the numerous circles throughout the state with minor site alterations such as replacing the existing 8" vertical curb with a mountable type curb. If a driver, upon entering the circle's roadway, lost control of his vehicle and went straight into the center island, the gravel bed would stop him, preventing him from exiting the island into the path of oncoming traffic.

Certain sections of state divided roadways without a center barrier have grass median zones which are not wide enough for drivers to regain control. Therefore, it is possible that a speeding out-of-control vehicle could cross this grass-median and collide with oncoming traffic before the driver realized that the vehicle is out-of-control and try to correct the vehicle's motion and stop it. In

other areas a drainage ditch is in the center of the sloped grass median. A speeding vehicle, not reacting in time, could possibly be demolished upon impacting the ditch. A gravel bed, 25' (7.6 m) - 50' (15.2 m) wide located in the center of the grass median, could be used in both cases to stop an out-of-control vehicle. Since the gravel bed would be very porous, the bed might additionally be able to act as a drainage ditch.

Two other areas for potential application of the gravel bed arrestor are "turnoffs" and "forks". When approaching a fork or a turnoff ramp the vehicle may not go in either direction, but continue straight into the gore. In another situation, the vehicle may enter the turnoff or fork at too high a rate of speed and leave the roadway. A gravel bed in the gore and the curve areas would entrap a runaway vehicle before it travels too far.

Another possible application for this type of arrestor would be at a "runoff" area at the bottom of a steep grade. A truck which has experienced brake failure on a down grade would be directed by proper signing to a "runoff" area constructed of gravel, where the vehicle would be gradually slowed to a stop.

The exact locations for installation and the details of design of gravel bed arrestors would have to be determined after reviewing the accident reports (locate areas of high accident rates) and space available for installation (modification of basic layout).

D. Advantages and Disadvantages of Various Types of Arrestors

The following is a review of the advantages and disadvantages of alternate means of stopping an errant vehicle: fixed steel beam

guiderail, wide median strip, concrete barrier, and gravel bed.

Fixed steel-beam guiderail:

Advantages:

- (1) Minimal mounting space is required, usually only three feet or less.
- (2) Will reduce the chance of a head-on collision.

Disadvantages:

- (1) Depending upon speed and angle of impact, possible severe injury to occupants and damage to vehicle upon impact.
- (2) Vehicle could plow through or vault the guiderail into the path of oncoming traffic or into the obstruction.
- (3) Vehicle could be redirected upon impact back into the stream-of-traffic it just left, still in an out-of-control condition.
- (4) Vehicle impacting the guiderail risks being hit by another vehicle if it blocks a traffic lane.

Wide median strips:

Advantages:

- (1) Appearance is pleasing.
- (2) Usually no maintenance required after use by an out-of-control vehicle.
- (3) Located off-roadway.
- (4) Indestructible.
- (5) Minimal restoration costs after an impact.

Disadvantages:

- (1) Width is usually insufficient for driver to recover control of car and stop before hitting center drainage ditch or oncoming traffic. Therefore, offers no protection if driver does not regain control of vehicle.
- (2) Additional right-of-way may have to be purchased due to the relatively large installation space required.

Concrete Barrier:

Advantages:

- (1) Minimal mounting space is required, usually only three feet or less.
- (2) Will reduce considerably the chance of a head-on collision.
- (3) If struck at a slight angle (less than 10°) there will be minimal resultant vehicle damage and the vehicle will be deflected back to its original line of travel, the driver being able to regain control of the vehicle.

Disadvantages:

- (1) Depending upon speed and angle of impact, possible severe injury to occupants and damage to vehicle upon impact.
- (2) Vehicle could be redirected upon impact, back into the stream-of-traffic it just left, still in an out-of-control condition.
- (3) Vehicle impacting the concrete barrier risks being hit by another vehicle if it blocks a traffic lane.

Travel Bed:

Advantages:

- (1) Vehicle can impact bed at almost any angle and be slowed down

without severe resultant vehicle damage, as established by Great Britain's tests and later confirmed by New Jersey's testing.

- (2) Vehicle would be entrapped off roadway, reducing possible resultant traffic congestion and the chance of "entrapped" vehicle being hit by another vehicle.
- (3) Minimal chance of vehicle leaving the roadway and being redirected back into the path of oncoming traffic.
- (4) Stopping ability independent of driver control.
- (5) Minimal restoration costs after impact.
- (6) Practically indestructible.

Disadvantages:

- (1) Due to the relatively large installation space required (probably 25' (7.6 m) - 50' (15.2 m) wide) additional right-of-way may have to be purchased.
- (2) Can be applied only to few existing highways, but any future ones, if designed for them.

E. Background

The decision was made to test and develop a usable design of the gravel type arrestor after reviewing the promising results of the Road Research Laboratory in Great Britain.

In 1966 and 1969 the Road Research Laboratory conducted full scale tests on gravel arrestor barriers (2,3). The test vehicles varied from a small passenger car to a 20 ton fire truck and the arrestor bed material varied from 1 1/2 (3.8 cm) inches crushed

stone to 3/8 (1 cm) inches lightweight aggregate. A total of nine different combinations of material type bed depths and aggregate gradation was tested.

These tests brought out the important fact that the stopping distances were related to the bed characteristics and initial vehicle impacting velocity and seemed to be independent of the size or weight of the impacting vehicles. It is assumed that this would hold true for test beds evaluated in New Jersey's study.

II. STUDY DESIGN

A. General:

The development and subsequent evaluation of gravel bed arrestors, in this research effort, required four years to complete. The project was divided into two phases, theoretical analysis and field testing. The theoretical phase involved a literature search, analysis of results of dynamic field tests, and development of a mathematical model of the vehicle's motion.

The field testing phase involved impacting full-size "obsolete" vehicles at various speeds into different gravel bed configurations, documenting the impact forces with an accelerometer-recorder system and recording the vehicle behavior with both a high speed 16 mm camera and a video tape system. The vehicles used in the tests were 1966 Plymouth Fury, 4 door Sedans, with a weight of approximately 3800 pounds (1700 kg mass) including instrumentation. Pertinent dimensions of the vehicles are given in Appendix A-2.

Various gravel configurations were tested on both level bed and transverse pile types. Figures 1a - 1f are sketches of each of the beds tested. All configurations were constructed with a 3/8" (1 cm) washed pea gravel. This material was chosen for it was felt from the inception of the study to be the most widely available material that would perform adequately. Specifications for and a sample gradation of the gravel are given in Appendix A-3. Initial tests were conducted in the "head on" condition with oblique entry tests at 25° performed on the most promising configuration (1 1/2 foot (.46 m) high pile configuration). The oblique entry tests were achieved by

Figure 1

BED CONFIGURATION

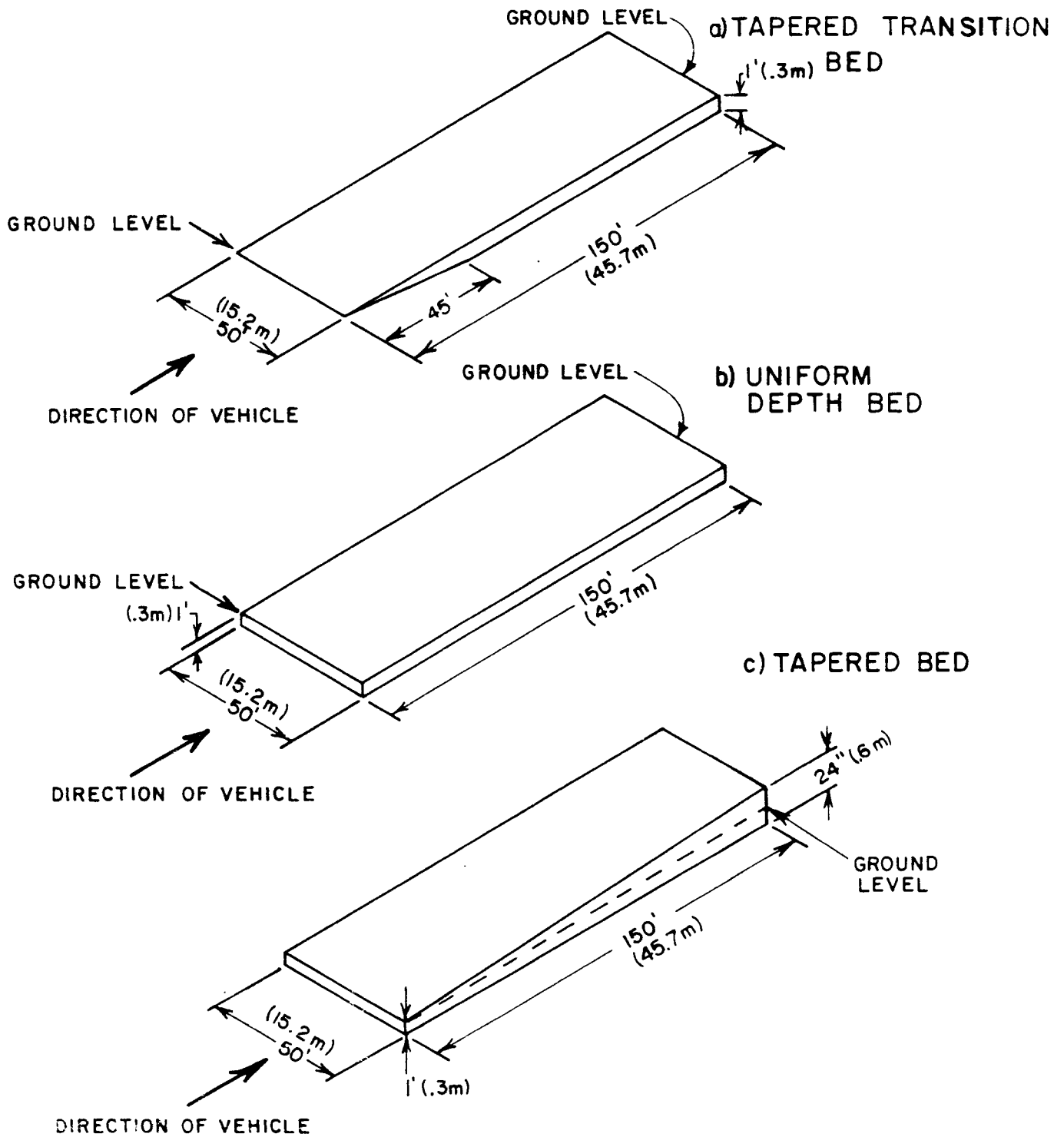
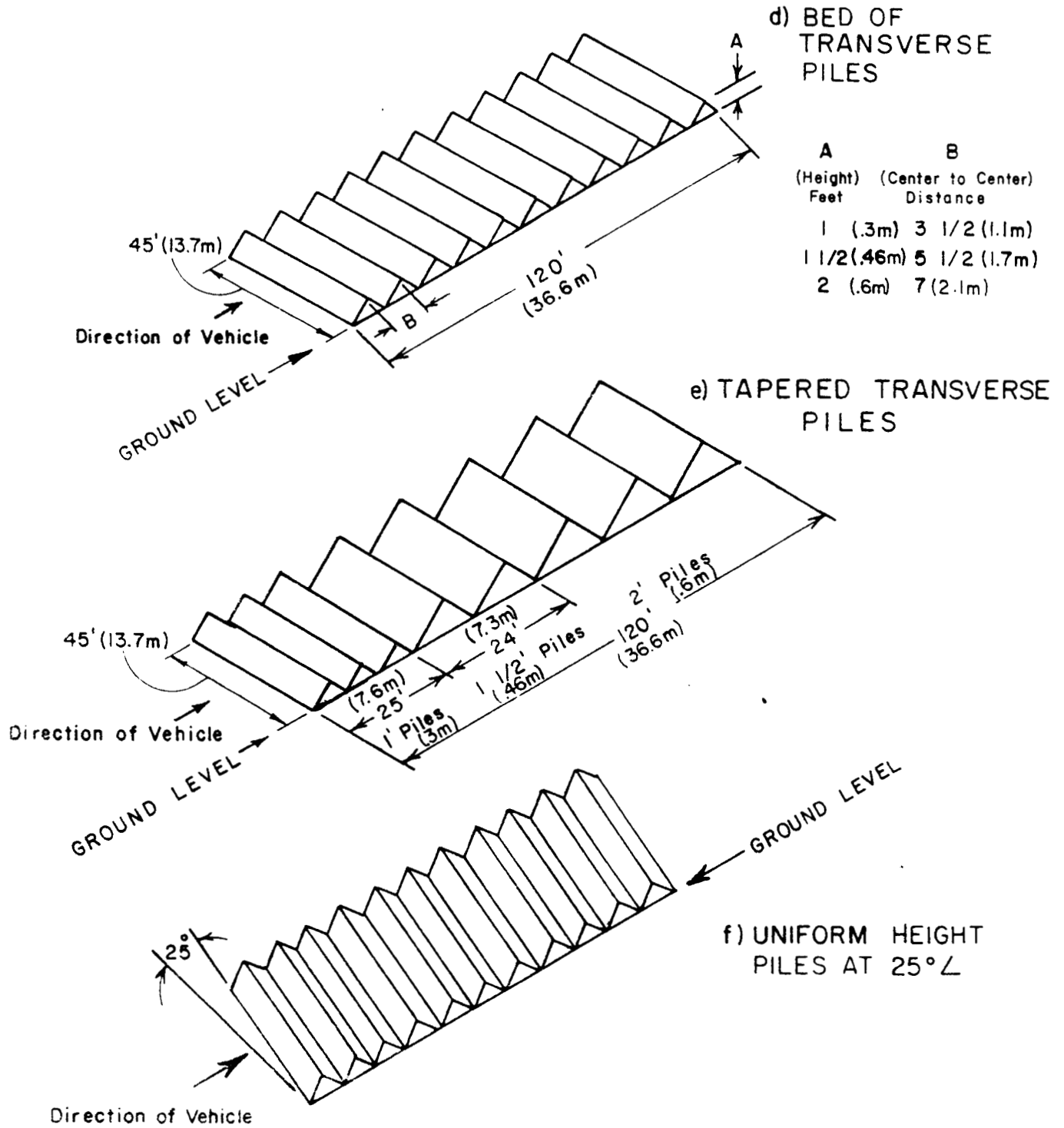


Figure 1 (cont.) BED CONFIGURATION



rotating the axes of the piles since the approach road and guidance systems were in fixed positions relative to the bed. A detailed discussion of the test location, vehicle control system, test documentation, construction and restoration of the gravel beds, and testing procedure is given in Appendix A-7.

B. Data Collection:

Before the test vehicle was removed from the bed, the vehicle's path on the gravel bed was measured and this information along with other items such as vehicle speed (which was obtained from the setting of the vehicle mounted speed control device), bed configuration, etc., was recorded on a data sheet (Appendix A-4).

Also, the strip chart giving accelerometer output for each test was removed from the vehicle mounted recorder to be stored for data reduction at a later date. Then after a series of tests were conducted, the raw data was transferred from the strip chart (deceleration vs. time) to computer code sheets for use in the computer analysis programs.

C. Data Analysis:

To preclude the necessity of conducting hundreds of tests, a mathematical performance model for each gravel bed configuration tested was developed. A computer program performed a first order regression analysis on the sample data, resulting in equations to predict the vehicle stopping distance and the average deceleration values for a range of vehicle speeds for each bed configuration.

The regression analysis was limited to first order because with the high resultant correlation coefficients, a higher order analysis was not felt to be needed.

Table 2 is a list of the stopping distance equations obtained for each of the bed types (slope and intercept) with the correlation coefficient (how good the equation fit was to the experimental data). Also included in this table is the standard error of the estimate which is an indicator of the tolerance band of the estimated stopping distance values.

The mathematical model of the vehicle behavior proved to be extremely useful. A set of performance characteristics could be obtained after conducting only a few tests and not a whole series, thus eliminating a considerable amount of testing that would have been necessary otherwise.

Once the stopping distance equation was obtained, a table listing the estimated stopping distances at various vehicle speeds was generated making it possible to predict the required stopping distance and resultant average deceleration value at a particular speed without actually having to conduct a test at that speed. Table 3 is a listing of the estimated stopping distances for each bed tested. It must be emphasized that these values were obtained from a regression analysis performed on a limited number of tests. In order to use these estimated distances in designing installations, three standard errors of the estimate must be added to the length to be 99.9 percent confident that the vehicle will halt within the bed confines.

TABLE 2
 STOPPING DISTANCE EQUATION
 BASED ON REGRESSION ANALYSIS
 OF THE DATA

Stopping Distance = Intercept + (Slope x M.P.H.)

<u>Test Bed</u>	<u>Intercept</u>	<u>Slope</u>	<u>Correlation Coefficient</u>	<u>Standard Error of Estimate</u>
Tapered Transition	-90.0	7.0	.988	8.7
Uniform Depth*	9.0	2.6	.737	29.0
Tapered	-39.9	5.18	.819	10.6
1 Ft. Pile	-41.0	3.70	**	**
1 1/2 Ft. Pile	-18.1	2.12	.972	7.7
2 Ft. Pile	-39.6	2.44	.976	5.0
Tapered Pile	-29.0	2.77	.916	12.6
1 1/2 Ft. Pile 25° angle	-13.2	1.85	1.000	.4

* Based on all initial data but excludes data from rerun tests. If rerun tests are included the values would change to:

Intercept: 68.5

Slope: 1.08

Correlation Coefficient: .313

** Insufficient data to calculate.

TABLE 3

ESTIMATED STOPPING DISTANCE (ft.)

WITH VARYING ENTRY SPEEDS

BASED ON REGRESSION ANALYSIS

<u>MPII</u>	<u>Tapered Transition</u>	<u>Uniform Depth</u>	<u>Tapered</u>	<u>1 Ft. Pile</u>	<u>1 1/2 Ft. Pile</u>	<u>2 Ft. Pile</u>	<u>Tapered Pile</u>	<u>1 1/2 Ft. Pile at 25° Angle</u>
20	50.0	61.9	63.7	33.0	24.3	9.2	26.4	23.8
25	85.0	75.1	<u>89.7</u>	51.5	34.9	21.4	40.3	33.1
30	120.0	88.3	115.6	<u>70.0</u>	45.5	33.6	54.1	42.3
35	<u>155.0*</u>	101.5	141.5	88.5	56.1	45.8	68.0	51.6
40	190.0	114.8	167.4	107.0	66.7	<u>58.0</u>	<u>81.8</u>	<u>60.8</u>
45	225.0	<u>128.0</u>	193.3	125.5	77.3	70.2	95.7	70.0
50	260.0	141.2	219.2	144.0	<u>87.9</u>	82.4	109.5	79.3
55	295.0	154.4	245.2	162.5	98.5	94.6	123.4	88.6
60	330.0	167.6	271.1	181.0	109.1	106.8	137.2	97.8

*Data below this point was estimated by extrapolation, no tests conducted at these speeds

The vehicle's behavior was microscopically analyzed as it impacted the gravel (as opposed to the macroscopic analysis of stopping distance data). A computer program was written, for use with the Department's main computer, that would accept the deceleration vs. time data points obtained from the strip chart recorder for integration (to obtain velocity and distance travelled) plotting and curve generation. In this way, each test run could be studied to determine if any possible situations occurred as the vehicle was travelling through the bed that could be hazardous to the occupants of the vehicle, such as an exceptionally high peak deceleration value or a long time duration at a certain deceleration level, which would have been masked when considering only the overall or average values.

III. TEST RESULTS AND DISCUSSION

A. General Discussion:

The following discussion of the performance of the eight bed configurations tested will be based on a design speed of 55 mph (88.5 km/h) and each will be compared with the 1 1/2 foot (.46 m) high pile bed configuration. The raw data for each bed configuration tested is presented in Appendicies A-5 and A-6.

The 1 1/2 foot (.46 m) bed was chosen as the best design after analyzing the resultant stopping distance and average vehicle deceleration (both obtained from the regression analysis) for all the beds tested.

B. Discussion of Each Bed Type:

1. Tapered Transition (Figure 1a):

The first bed type tested was the tapered transition bed. Before the testing phase began, it was theorized that a bed of this design would be needed. It was not known at that time what would happen when the front wheels of the speeding test vehicle came in contact with the gravel bed. Consideration was given to the possibility that the vehicle might abruptly change direction and veer off out of control, especially if the test vehicle did not impact the bed squarely but at a slight angle. It was felt that a bed of this design would enable the test vehicle to gradually come into contact with the full depth of the bed rather than have an abrupt change in support condition.

As preliminary testing got underway, the cause for concern did not materialize. As the test vehicle impacted the test bed, the

anticipated reactions did not occur. The vehicle rode the top of the gravel bed with little change in direction or loss of velocity and did not sink appreciably. There were four tests conducted on this configuration at speeds ranging from 20 to 35 mph (32.2 to 56.3 km/h). The target value for stopping distance at 55 mph (88.5 km/h), which was 100 feet (30.5 m), was exceeded during the 30 mph (48.3 km/h) test.

The average deceleration value predicted for this bed at the 55 mph (88.5 km/h) design speed was the lowest of all bed configurations, 0.34 g. However, these low g forces were estimated with a correspondingly large stopping distance of 295 ft. (89.9 m). This is approximately 3 times the distance predicted for the 1 1/2 foot (.46 m) pile bed with the same vehicle entrance speed.

Based on the results of these tests, it was decided that the next bed for testing would be below ground level and at a uniform depth of one foot (.3 m).

2. Uniform Depth (Figure 1b):

The reasoning behind the selection of this configuration was that for a vehicle to stop within a shorter distance, the vehicle had to sink into the gravel bed sooner and this may be achieved by eliminating the transition zone.

The results of the first test conducted on this bed was as anticipated. The vehicle sank into the gravel after travelling only a few feet on the bed. However, the stopping distances were longer than had been expected although an improvement over the tapered transition configuration in the 30 - 40 (48.3 - 64.4 km/h) mph range was achieved. Repeated testing led to scattered results with low

linear correlation.

The results of the 11 tests performed at speeds ranging from 20 to 45 mph (32.2 to 72.4 km/h) showed no repeatability. This was probably caused by a number of factors. In order for this bed to perform effectively, the vehicle has to sink into the gravel. If anything prevents the vehicle from sinking into the bed, it rides on top with little loss of velocity. In several of the repeat runs this type of performance occurred at various points within the bed. The main cause was felt to be a gradual compaction of the gravel. The gravel may have settled under its own weight over the time span of the tests which covered several weeks. Fines in the form of sand could have gotten into the voids of the washed 3/8" (1 cm) pea gravel. The test site was located in a sandy area with little vegetation to stop the wind from blowing the fine sand over and into the gravel bed. Also, surface runoff from rain could have carried the fine particles into the bed. In addition, repeated impact with the test vehicle and the necessity for a front end loader to travel on the bed in both pulling out the entrapped vehicle and then restoring the bed could have caused further compaction.

Considering the results of all the tests performed, this bed would require, even in its least compact state, approximately 60% greater stopping distance than the 1 1/2 foot (.46 m) pile bed. As can be seen in Table A-5, the upper stopping distance limit was exceeded during the rerun of the 20 mph (32.2 km/h) test.

Based on these reasons, it was decided that another bed design was necessary. Repeatability was considered essential to performance

reliability.

3. Tapered Bed (Figure 1c):

The next bed design tested was the tapered bed. This bed was constructed on top of the existing uniform depth bed. The idea behind this configuration was that the vehicle would have an increasing depth of gravel into which it could penetrate as it progressed through the bed.

As was the case with the tests on the uniform depth configuration, the test vehicle did not sink into the gravel as was anticipated but rode on top of the bed most of the way. This probably occurred for the same reasons stated for the uniform depth bed.

The result of the 7 tests conducted on this bed at 20 - 25 mph (32.2 - 40.2 km/h) was that the stopping distance for two of the tests run at 25 mph (40.2 km/h) came very close to exceeding the 100 foot (30.5 m) limit.

4. Pile Beds:

Since the vehicle didn't consistently sink into the gravel bed with the initial patterns, a new above-ground design was determined to be necessary. It was decided that a series of windrows or piles constructed above ground would have better stopping potential. Stopping the vehicle with this new design would not be dependent upon the vehicle sinking into the gravel, but could be accomplished by the vehicle impacting successive elevated piles as it progressed into the bed.

The design that was finally chosen consisted of a series of transverse piles in the form of a windrow perpendicular to the direction of travel of the test vehicle. For the testing, the layout was about

45 feet (13.7 m) wide and 120 feet (36.6 m) long (Figure 1d - 1f).

Four different configurations of this design were tested. Three configurations of uniform height piles were tested (1 foot (.3 m), 1 1/2 foot (.46 m) and 2 foot (.6 m) plus a tapered pile bed where the bed consisted of groups of piles of uniformly increasing heights (from 1 foot to 2 foot (.3 m to .6 m). In all, 20 tests were run on the various pile beds at speeds ranging from 20 to 50 mph (32.2 to 80.5 km/h).

a. 1 foot piles (Figure 1d):

The first pile configuration tested was the 1 foot piles. Although the test vehicle was stopped in a shorter distance than the beds previously tested (tapered transition, uniform depth and tapered) and with minimal damage, the projected stopping distance at the higher design speed (55 mph (88.5 km/h) would be greater than the maximum desirable stopping distance (100 feet (30.5 m).

A distance of 163 feet (49.7 m) would be required to stop a vehicle at 55 mph (88.5 km/h) entry speed with a resultant average deceleration of .62 g. This stopping distance is 65% further than that required by the 1 1/2 foot (.46 m) pile configuration.

b. 2 foot (.6 m) piles (Figure 1d):

The height of the piles was increased to 2 feet (.6 m). This bed stopped the test vehicle in the shortest distance of all the beds tested (a predicted 95 feet (29 m) for a 55 mph (88.5 km/h) entrance speed which was 96% of the 1 1/2 foot (.46 m) pile's stopping distance). However, damage to the test vehicle was severe. The radiator was

punctured and there was front bumper and sheet metal damage. The higher the impact speed the greater the damage to the test vehicle. At the higher speeds, the vehicle was lifted upward upon impacting the first 2 foot (.6 m) high pile and then actually vaulted over a number of piles before crashing back down. The average deceleration predicted for this bed at the 55 mph (88.5 km/h) design speed is 1.07 g's. This is slightly higher than the value for the 1 1/2 foot (.46 m) piles.

c. Tapered Pile (Figure 1e):

The tapered pile was tried next. With this set up, the first 25 feet (7.6 m) of the bed was constructed of 1 foot (.3 m) high piles, the middle 24 feet (7.3 m) of 1 1/2 foot (.46 m) high piles and the last 100 feet (30.5 m) of 2 foot (.6 m) high piles. The idea behind this configuration was that the vehicle's speed would gradually reduce as it impacted higher piles. Thus, vehicle damage and deceleration forces should be kept at a minimum. This bed produced stopping distances about halfway between the 1 foot (.3 m) and the 2 foot (.6 m) pile beds. Results indicated that 123 feet (37.5 m) was needed to stop a vehicle at the design speed which is 25% greater than required for the 1 1/2 foot (.46 m) pile bed. The average predicted deceleration value is .82 g's.

While this configuration seemed to be better than the 1 (.3 m) and 2 foot (.6 m) pile beds, it was felt that it would be difficult to construct and maintain due to the changing height.

d. 1 1/2 foot (.46 m) piles (Figure 1d):

The final configuration tested was the 1 1/2 foot (.46 m) high

piles as a compromise between the 1 foot (.3 m) and 2 foot (.6 m) piles.

With this arrestor, the resultant vehicle damage was minimal with only a small increase in the stopping distance required for the 2 foot (.6 m) piles. The performance results indicated that a vehicle at 55 mph (88.5 km/h) would stop within the original design stopping distance limit of 100 feet (30.5 m). Ninety-nine (30.2 m) feet was predicted as being required to stop the test vehicle, the second lowest of all the bed configurations tested. The average deceleration value of 1.03 g's is well within the allowable limits.

e. 1 1/2 foot (.46 m) pile at 25° angle (Figure 1f):

The favorable results obtained when impacting the 1 1/2 foot (.46 m) pile beds indicated that this bed should receive further consideration. The question arose as to how the vehicle would behave if it entered the bed at other than head on.

It was anticipated before the tests were conducted that the test vehicle, upon impacting this bed, might veer off parallel to the windrows and exit off to the side in the middle of the bed.

As the tests got under way, the cause for concern did not materialize. When the vehicle impacted the windrows, it continued to proceed in a straight line, as was the case with the regular 1 1/2 foot (.46 m) high pile bed. In fact, this configuration stopped the vehicle in a distance 10 percent shorter than the regular 1 1/2 foot (.46 m) piles. Eighty-nine feet (27.1 m) was predicted as being required for a 55 mph (88.5 km/h) impact speed with an average

deceleration of 1.14 g's, a little higher than was predicted for the 1 1/2 foot (.46 m) piles.

C. Test Conditions:

1. Activation of Brakes:

In addition to the tests discussed in this report which were conducted in the unbraked mode, a number of tests were run on the level, tapered and 2 foot (.6 m) pile configurations with the brakes applied prior to the vehicle entering the bed. However, the response time of the braking system was such that it precluded the brakes being applied at the same point for each test.

The point of application of the vehicle's brakes varied from test to test, masking the actual results of the combined stopping effect of the application of the vehicle's brakes and impacting the gravel. Therefore, it was decided to exclude these tests from the report. In general, however, a marked decrease in stopping distance was observed when braked tests were compared with unbraked tests at the same speed.

2. Weather Conditions:

For the most part, the tests were conducted during the spring-fall months on clear days with the temperature above freezing. Few, if any, tests were conducted in the rain due to operation of the radio control unit.

However, it is assumed that the results obtained during impact in a rain storm would not differ greatly from those obtained in this study, provided the bed was located in a well drained area and was not

under water.

It was planned to conduct a few tests during midwinter on a frozen bed to investigate any possible adverse effects. However, the test bed location did not remain below freezing long enough to obtain this condition. It is estimated that this condition should also have minor effects on a bed stopping quality if the bed was situated in a well-drained area.

D. Comparison with Tests of Road Research Laboratory in Great Britain:

In an effort to evaluate the relative performance of New Jersey's tests, a comparison was made with the results of the Road Research Laboratory of Great Britain,^(2,3) which was the only other agency to conduct full scale impact tests on this type of arrestor.

Of all their combinations, the bed of 3/8" (1 cm) lightweight aggregate 2 foot (.6 m) uniform depth stopped the test vehicles within the shortest distance. Table 4 lists the estimated stopping distances based on a regression analysis performed on the raw data presented for this bed. The stopping distance of the 2 foot (.6 m) uniform depth bed at 55 mph (88.5 km/h) was approximately 15% greater than that for New Jersey's 1 1/2 foot (.46 m) pile configuration and 30% shorter than that for New Jersey's uniform depth configuration.

The 3/8" (1 cm) lightweight aggregate seems to be a more efficient arrestor material than New Jersey local 3/8 inch (1 cm) pea gravel. A probable reason for the 30% shorter stopping distance on a similar bed configuration is that the lightweight aggregate allowed the

impacting vehicle to sink into the bed sooner and/or deeper than on the 3/8" (1 cm) gravel.

However, the lightweight material is not available in New Jersey at this time.

TABLE 4
 ESTIMATED STOPPING DISTANCE FOR
 3/8" LIGHTWEIGHT AGGREGATE 2 FOOT UNIFORM DEPTH BED
 ROAD RESEARCH LABORATORY

Vehicle Speed (mph)	Stopping Distance (ft.)
20	28
25	40
30	52
35	64
40	76
45	88
50	100
55	112
60	124

Eq. for Lightweight Aggregate

$$D_s = -20.0 + 2.4 V_{\text{MPH}}$$

IV. COST ANALYSIS

Another area that should be included in the final analysis of the merits of each of the bed configurations tested is the cost for the material that would be required to construct a bed capable of stopping a vehicle at 55 mph (88.5 km/h).

Table 5 lists the quantity of gravel required and the related material costs for each of the bed types to stop an out-of-control vehicle at 55 mph (88.5 km/h). These figures are based on the stopping distances obtained from the regression analysis and do not include any labor,* equipment, or right of way costs involved with the installation of the gravel bed.

As can be seen in Table 5, the 1 1/2 foot (.46 m) bed had the lowest material cost of all the other types.

The three level bed types (tapered transition, uniform depth, and tapered) had higher material costs than all the other types tested.

*While exact labor and equipment costs were not obtained for the pile or the level bed type of arrestor, it is felt that the costs for each would balance out. Although the labor costs for the installation procedure for the pile beds would be higher than for the level bed type, it would be offset by reduced site preparation requirement.

TABLE 5
 QUANTITY AND COST OF GRAVEL REQUIRED
 TO STOP A VEHICLE AT 55 MPH

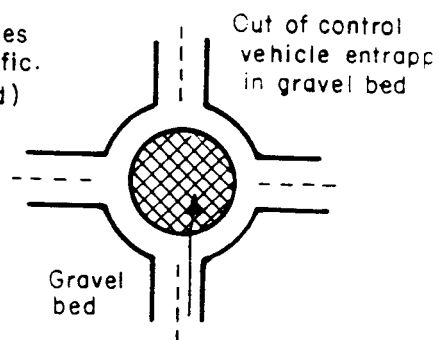
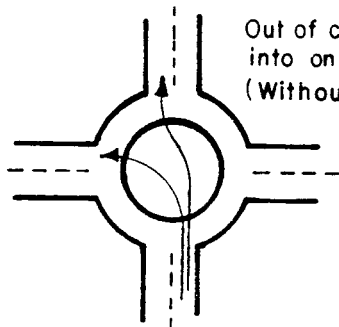
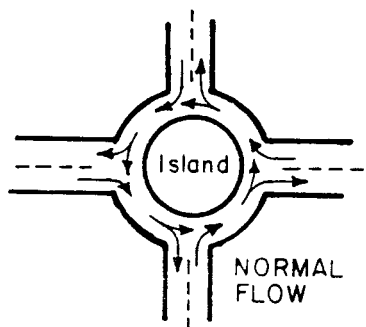
<u>Bed Configuration</u>	<u>Quantity (tons)</u>	<u>Material Cost (\$)</u> <u>(\$8.75/ton)</u>
Tapered Transition	756.9	6,622.88
Uniform Depth	427.8	3,743.25
Tapered	340.3	2,977.63
1 ft. Pile	226.4	1,981.00
1 1/2 ft. Pile	206.2	1,804.25
2 ft. Pile	263.9	2,309.13
Tapered	290.3	2,540.13

APPENDICES

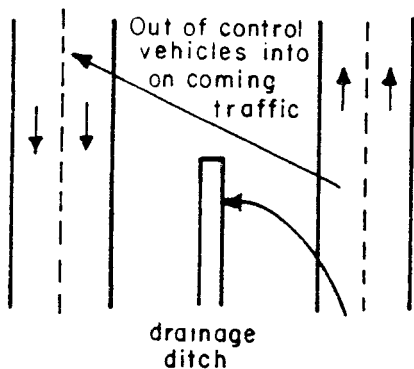
- A-1 Application of Gravel Bed Arrestors
- A-2 Test Vehicle Characteristics
- A-3 Sample Gravel Gradation and Specification
- A-4 Sample Data Sheet
- A-5 Test Data - Stopping Distance
- A-6 Test Data - Average Deceleration
- A-7 Field Test Method of Procedure

APPLICATION OF GRAVEL BED ARRESTORS

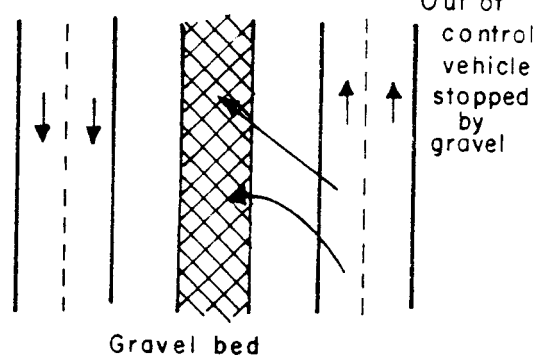
CIRCLE



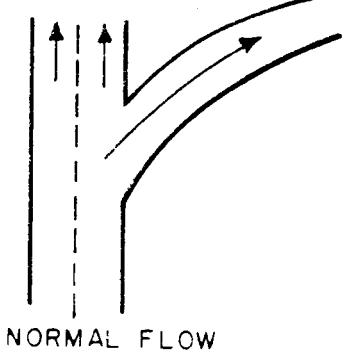
WIDE MEDIAN



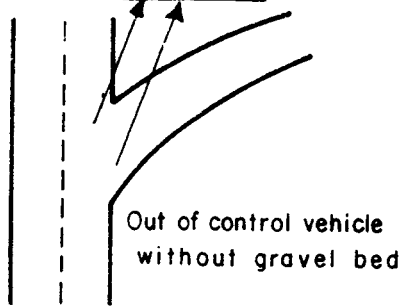
NORMAL FLOW



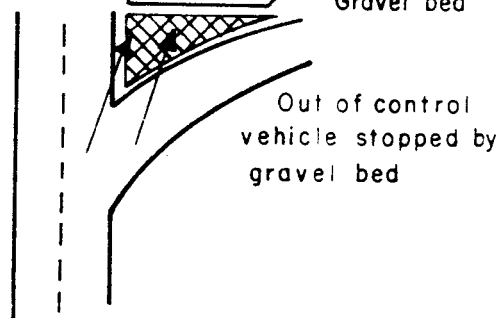
conc. abut.



conc. abut.



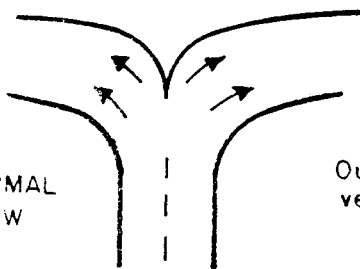
conc. abut.



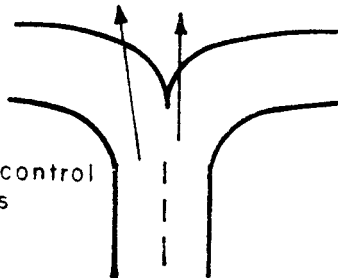
TURN OFF RAMP

FORK

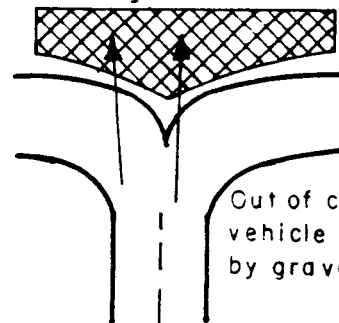
NORMAL FLOW



Out of control vehicles



gravel bed



APPENDIX A-2
TEST VEHICLE CHARACTERISTICS

Weight	3800 lbs.	(1724 kg mass)
Overall length	210"	(5.33 m)
Overall width	79"	(2 m)
Wheel Base	119"	(3 m)
Ground clearance	4 1/2"	(11.4 cm)
Tire Size	7.75 X 14	
Turning Circle	47 ft.	(14.3 m)

APPENDIX A-3

SAMPLE GRAVEL GRADATION & SPECIFICATIONS

Sieve Size	Percent Passing	Specifications
1/2	100	100
3/8	98	85 - 100
No. 4	21	10 - 30
No. 8	3	0 - 10
No. 16	2	0 - 5

Bulk Density: 96 lbs/ft³

APPENDIX A-4

SAMPLE DATA SHEET

IMPACT TESTS

VEHICLE ENTRAPMENT PROJECT

#7701

Test No. 92

Braking Action None

Date 12-10-73

Measured Distance traveled on Bed

Shape of Bed 1-1/2 ft. (46m) Piles

84 ft. (25.6m)

Vehicle Entry Speed 50 MPH (80.5 km/h)

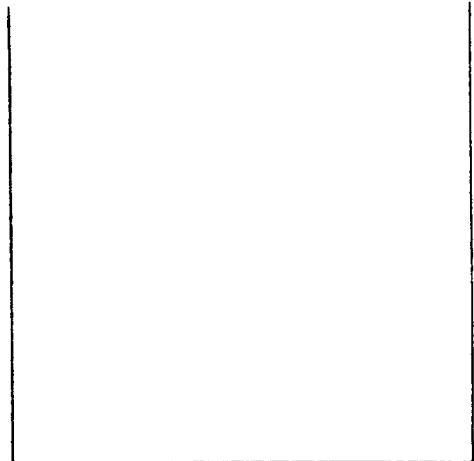
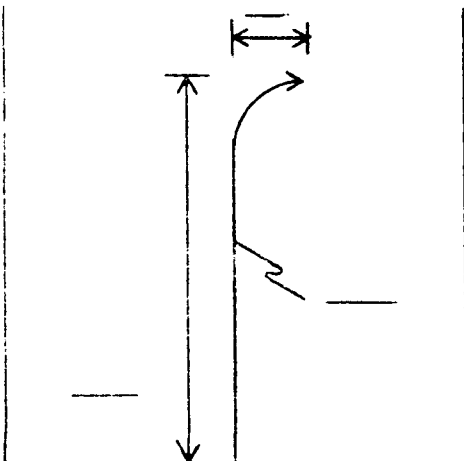
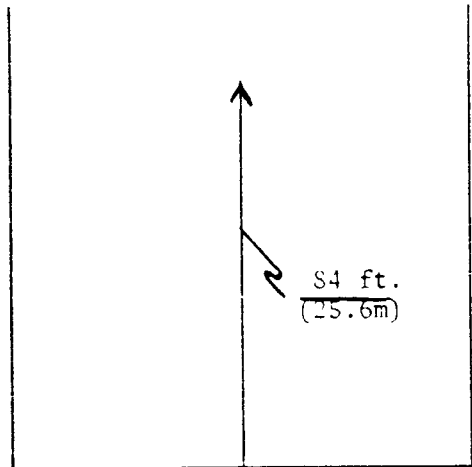
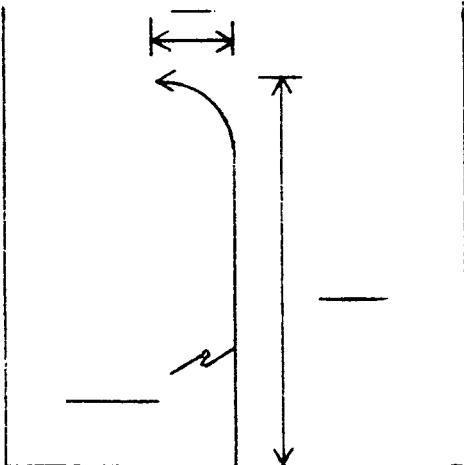
Average G's 1.00

Steering Control Cable

Peak G's 3.46

Comments:

Vehicle Motion



APPENDIX A-5

TEST DATA

STOPPING DISTANCE (ft.)

<u>MPH</u>	<u>Tapered Transition</u>	<u>Uniform Depth</u>	<u>Tapered</u>	<u>1 Ft. Pile</u>	<u>1 1/2 Ft. Pile</u>	<u>2 Ft. Pile</u>	<u>Tapered Pile</u>	<u>1 1/2 Ft. Pile at 25° Angle</u>
20	45	41 106* 121*	58 56* 68* 73*	33	15 33	11	26 26	24
25	95	93 96* 133*	74 98* 97*			21		
30	115	68 110*		70	45	34	47	42
35	155	75				39	86	
40		113			70	63	72	61
45		137						
50					86			

*Retests made approximately four weeks after initial test.

APPENDIX A-6

TEST DATA

AVERAGE DECELERATION (G's)

<u>MPH</u>	<u>Tapered Transition</u>	<u>Uniform Depth</u>	<u>Tapered</u>	<u>1 Ft. Pile</u>	<u>1 1/2 Ft. Pile</u>	<u>2 Ft. Pile</u>	<u>Tapered Pile</u>	<u>1 1/2 Ft. Pile at 25° Angle</u>
20	.30	.33 .13 .11	.23 .24 .20 .18	.41	.89 .41	1.22	.51 .51	.56
25	.22	.23 .22 .16	.28 .21 .22			1.00		
30	.26	.44 .28		.43	.67	.89	.64	.72
35	.27	.55				1.05	.48	
40		.47			.76	.85	.74	.88
45		.50						
50					.97			

APPENDIX A-7

FIELD TEST METHOD OF PROCEDURE

A. Test Location:

All the tests were conducted in an isolated part of Bennett Sand and Gravel Company Quarry, Brielle, New Jersey. Location of the test facility is shown in Figure A-1.

The Department's Bureau of Maintenance supplied the necessary manpower and equipment to complete the construction of the test bed area and approach roads at the test site. Except for the gravel used as the crash barrier, the material used to build the approach road and bring the slopes up to grade came from areas adjacent to the test site.

B. Vehicle Control:

Only a few preliminary low speed tests in the gravel beds were conducted with an actual driver. To minimize the potential for injury, all the other tests used remote (radio) control and a cable guidance system to operate the test vehicle.

1. Remote Control Unit

A six channel radio control unit manufactured by Kraft Systems, Inc. of California was used. Figures A-2 and A-3 are sketches of the transmitter and receiver components respectively. The receiver's servo-mechanisms were linked to various types of toggle switches. These switches electrically controlled the vehicle mounted speed control device, the braking unit, the brake hold device, the ignition, the recorder and the recorder's event marker.

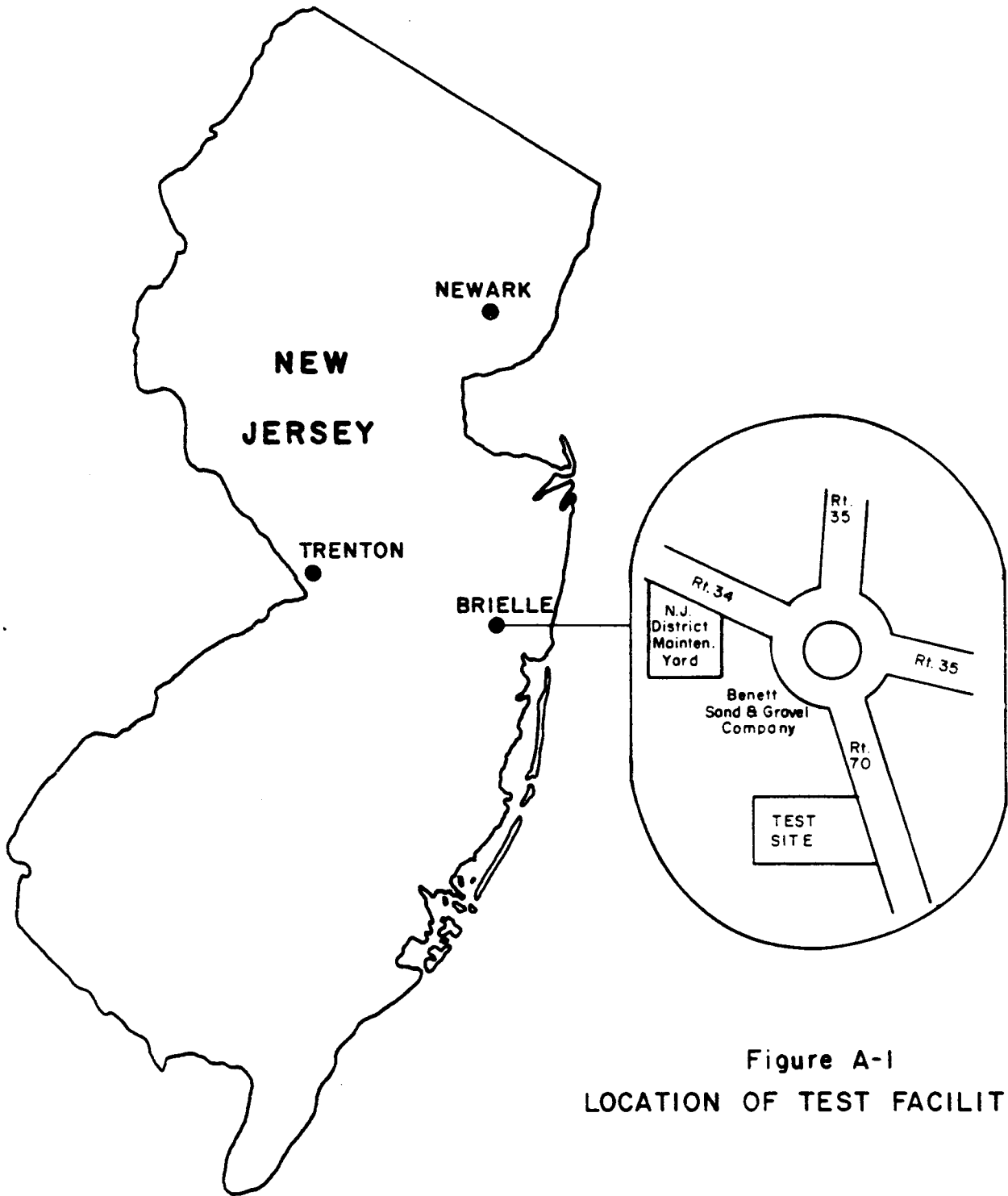
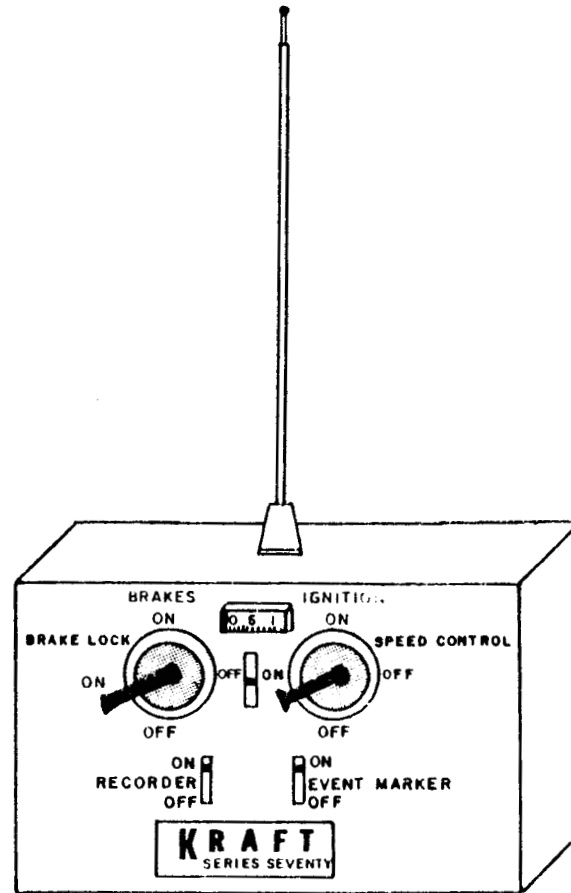


Figure A-1
LOCATION OF TEST FACILITY



RADIO CONTROL TRANSMITTER

Figure A-2

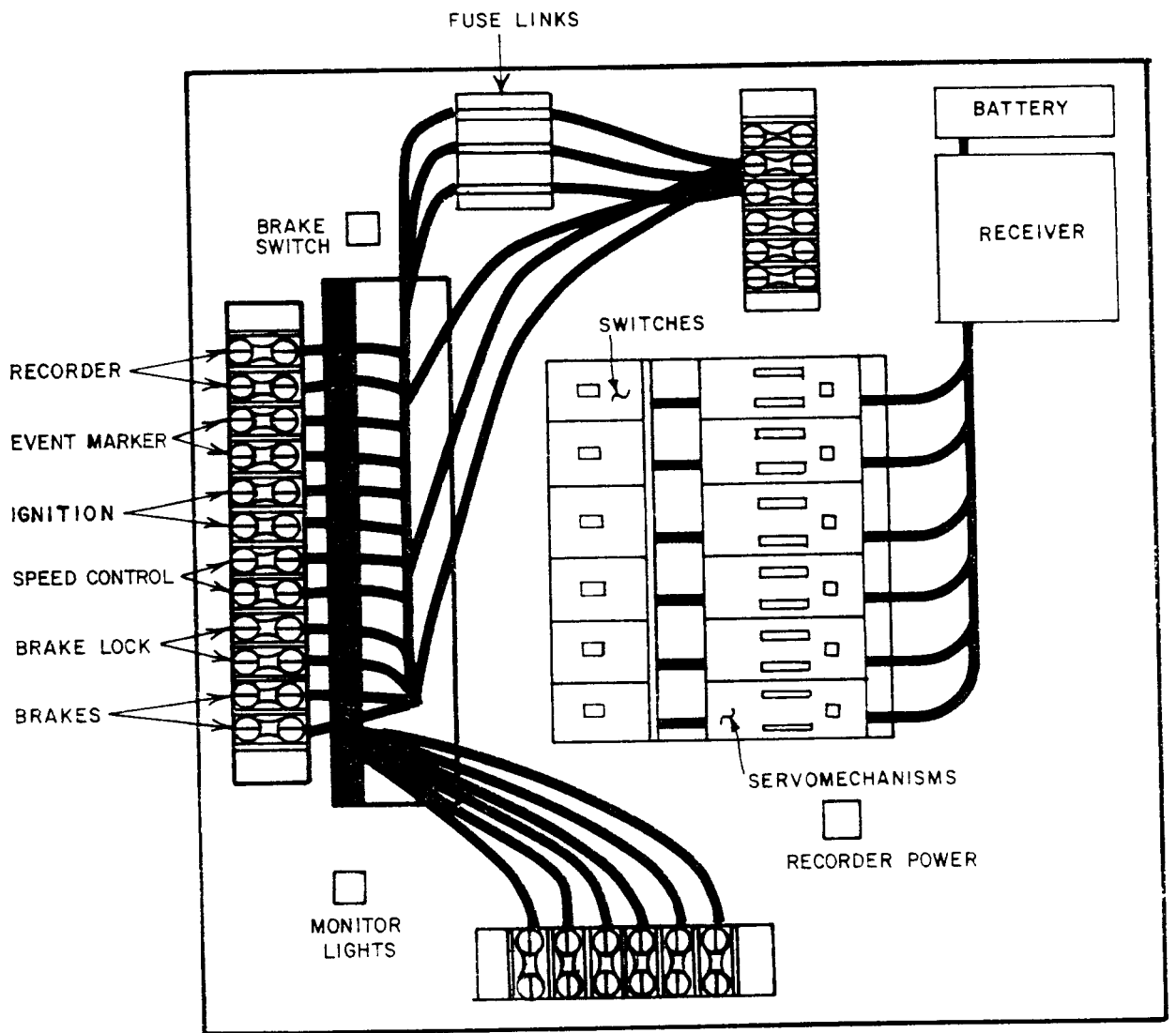


Figure A-3
 RADIO CONTROL RECEIVER

Once activated, the speed control device would adjust the throttle to accelerate the test vehicle up to the desired speed and then hold it steady after that speed was obtained.

The braking unit used was a 12 volt screw jack that bolted to the vehicle's brake pedal. The motion of this brake unit was controlled by means of micro switches so that the jack would uniformly apply the brakes to a predetermined setting and then hold the brakes there. This unit was used to not only conduct tests with the vehicle's brakes applied in the test bed area, but also to stop the vehicle before the bed area in case of any system malfunction.

The brake lock device was a solenoid placed in the vehicle's brake line. Once the brakes were applied, this unit would lock the brakes preventing the vehicle from moving, thus enabling the vehicle's transmission to be placed in drive and the speed control unit engaged.

A switch was placed in the ignition system so that the ignition could be cut off just before the vehicle impacted the test bed. This reduced the threat of fire in case of gas tank rupture or gas line leakage. To conserve recorder chart paper, the recorder chart drive mechanism was not activated until the vehicle was close to the bed area (usually at the breakaway posts).

The recorder event marker could introduce a blip on the chart paper. This was intended to identify an unusual occurrence for later reference.

2. Cable Guidance System

To control the direction of the test vehicle, a cable guidance system consisting of 1,000 (305 m) feet of aircraft type cable,

anchorage points, cable supports and connectors was used. There were two anchorage points, one at each end of the approach road about 1,000 (305 m) feet apart, consisting of a three foot (.9 m) cube of concrete sunk about a half of a foot (.15 m) below ground level. The cable supports consisted of a two piece I-beam unit. One I-beam was encased in each concrete anchor point flush with the ground. The second I-beam, bolted to the first, had the cable attached to it. This allowed the above surface I-beam to be replaced when damaged. A number of brackets connected the vehicle's left front wheel to the cable.

A break-away post was located a few feet before the anchor post nearest the test bed. As the vehicle impacted the breakaway post, the two brackets (one connected to the car, the other to the cable) would separate, thus allowing the vehicle to freewheel into the test bed.

Figure A-4 is an assembly sketch of the cable-vehicle brackets (part of cable guidance system) and Figure A-5 is an overhead sketch of the overall layout of the test site with a vehicle connected to the guidance system.

C. Documentation:

1. Recorder-Accelerometer System

A two channel analog recorder manufactured by Technirite-Gulton of Rhode Island produced a strip chart of the output of two accelerometers. A timer put blips on the edge of the paper every second as a reference point and the chart speed was kept constant at 125 mm/sec. Thus, the chart trace indicated deceleration vs. time.

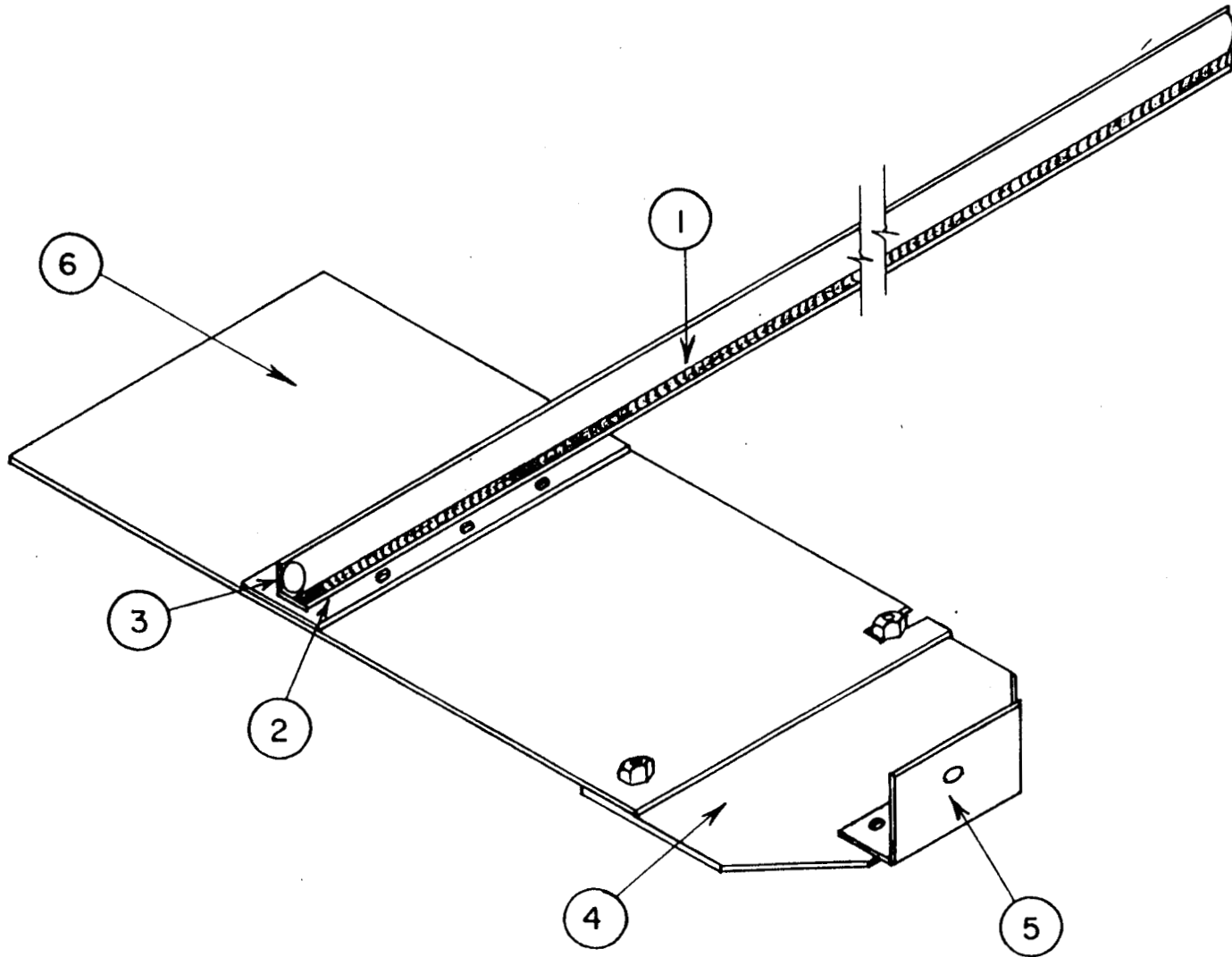
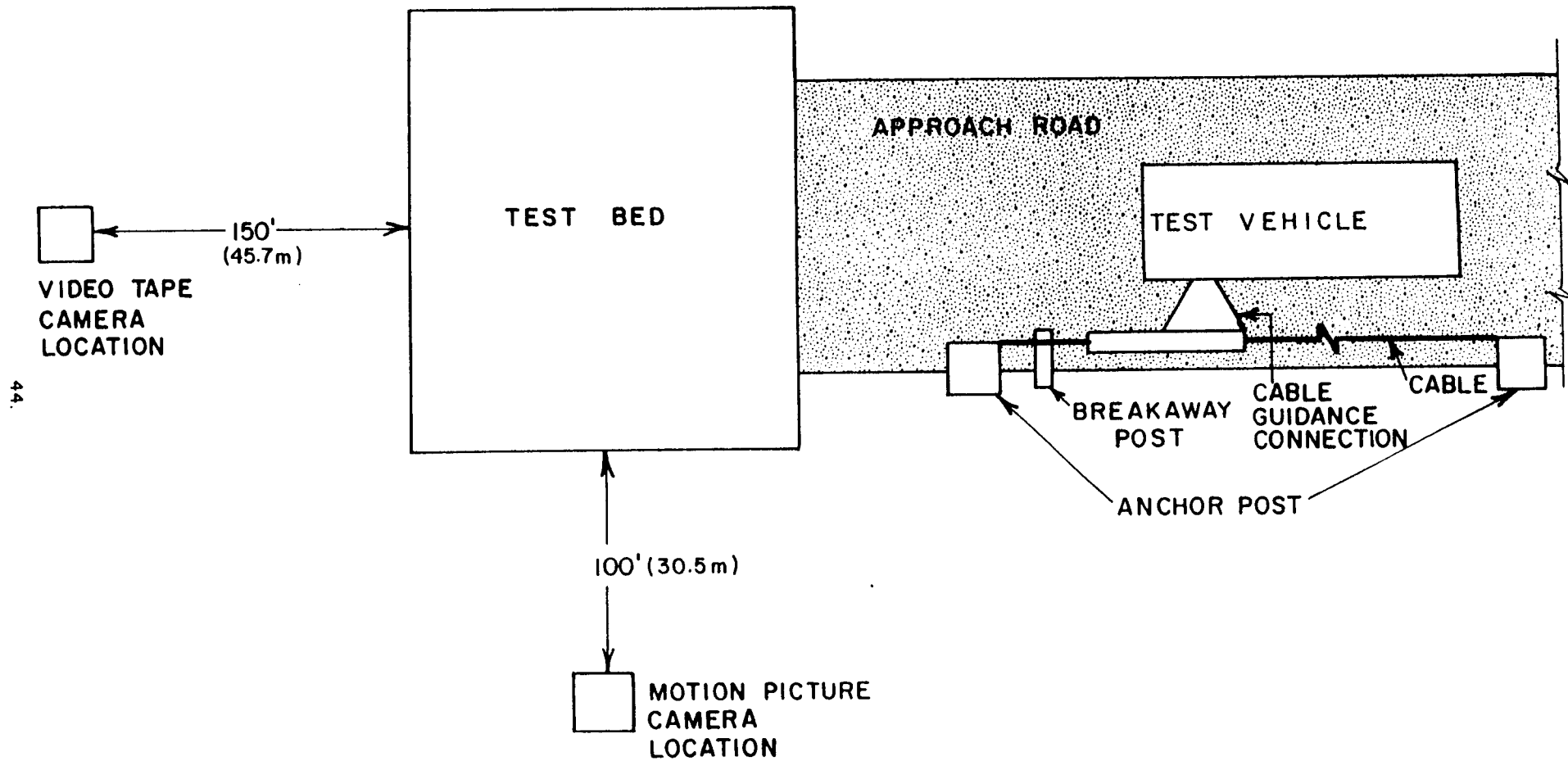


Figure A-4
CABLE GUIDANCE ASSEMBLY



44.

OVERALL LAYOUT OF TEST SITE

Figure A-5

The two accelerometers were a $\pm 2 \frac{1}{2}$ and a ± 10 g unit. For the lower deceleration tests, the $2 \frac{1}{2}$ g unit was mounted in the direction of motion. For the higher deceleration tests, the 10 g unit was mounted in the direction of motion. In either case, the other accelerometer would be oriented along the second most critical axis, which was the direction perpendicular to travel (Y or Z axis). Either the side deceleration forces in the horizontal plane (Y direction) for the level bed tests or the vertical deceleration for the pile beds (Z direction) was measured.

However, due to operational difficulties, no usable data could be extracted from this system. The chart traces were not accurate traces of the input from the accelerometers.

2. Photography

The basic piece of equipment used for photographic documentation of the tests was a 16 mm Bolex motion picture camera. The unit was tripod mounted, positioned approximately 100 feet (30.5 m) away from the middle of the bed, and operated at 64 frames per second.

Filming the motion of the test vehicle was started when the vehicle was at the breakaway post and continued until the vehicle either came to a rest or exited the bed area. In order to obtain enough detail of the test vehicle, the lens was adjusted so that the vehicle took up most of the frame. Also, a technician moved the camera (tracked) to keep the vehicle in view.

The lens used was a zoom lens, capable of going from 18 mm to 86 mm. Also, an automatic electric eye was used to adjust the lens openings for the changing light available.

The Model F Nikon, a 35 mm still frame camera was used to record the before and after conditions of the tests and the installation of the instrumentation.

A video tape system was used from time to time for documentation - a back up for the Bolex system. It was also used when two or three shots of the same event from different locations was desired.

When conducting the oblique tests, the Bolex and two video tape cameras were employed. The Bolex was mounted parallel to the piles. One of the video tape cameras was perpendicular to the pile configuration whereas the other was parallel to the direction of travel on the far side (or back end) of the bed. Location of cameras for the various tests are shown in Figure A-5.

D. Construction of the beds:

A diagram which illustrates the various gravel bed configurations, whose construction is described below, is shown in Figure 1.

With the below ground level beds (tapered transition and uniform depth) only a few stakes were needed to outline the perimeter of the bed. A bulldozer was used to excavate the bed area. After the bulldozer brought the bed to rough finish a motor grader was used to bring the bed to final grade. The gravel was then trucked in and dumped on the bed area. A grader or a front end loader would then spread out the gravel and level it off.

To construct the tapered bed, stakes were needed along both sides of the bed so that the proper grade was maintained. As was the case with the other beds, the gravel was dumped on the bed area and leveled out with a grader.

Construction of the pile configuration was very simple as compared to the below ground level beds. A bulldozer and heavy duty grader were not required to excavate the bed area as this type of bed is built on ground level. Only a light duty grader is needed to level the area where this type of configuration would be installed.

Stakes were placed marking off the center of each row of gravel, one on each side of the bed. The gravel was trucked to the site and dumped in a pile near the bed. The front end loader would obtain a bucket full of gravel and move to the first stake. A technician would guide the loader to the first stake, positioning it so that the gravel would fall on the center line of the stakes. To obtain the proper height, the technician would check the height with a long stake with the height marked on it. When the gravel was at the proper height, he would signal the operator to stop dumping material and move to the next pile. The spacing of piles was such that the piles just made contact at their bases.

E. Restoration of Bed:

To remove a vehicle from the gravel bed a tow truck was needed as an entrapped vehicle would not leave the bed under its own power. Attempts to drive out of the bed resulted in the vehicle sinking deeper into the gravel. A front end loader was also needed to restore the bed to its original condition. Unless the gravel was scattered far by the impacting vehicle, no replacement gravel was normally required.

F. Testing Procedure:

Prior to testing, the vehicle guidance system had to be set up. The first step was to apply tension to the cable. A technician would attach a tension gauge to one end of the cable, have a dump truck pull the cable until the proper tension was reached (approximately 4000 lbs (1800 kg), then set the tensioning chucks which had previously been slid on the cable and have the truck back up, releasing tension of the free end of the cable. The cable now had the proper tension between supports.

Next, the vehicle was connected to the cable. After the brackets were connected, the technician would drive the vehicle down the approach road to see how the vehicle would track. It was usually necessary for the technician to adjust the brackets about two times before the vehicle would track properly.

The technician would then turn the recorder power on, check its calibration and make sure the system was balanced, apply the brakes, set the brake lock, release regular brakes, start up the vehicle, put the transmission in drive, set the speed control, set all switches on the R/C receiver board to operate position and get out of test vehicle. He would then board a chase vehicle on the passenger side, with the antenna of the radio control unit sticking out of the door window.

He would release the brake lock switch by means of the radio control unit and follow the test vehicle down the approach road in the chase vehicle. As the test vehicle hit the breakaway post separating the breakaway coupling and was freewheeling into the test bed area,

the ignition switch was turned off and the recorder chart drive motor turned on. After the vehicle came to a rest, the chart drive was turned off.

A cameraman to the left of the test bed would start to track (pan) the test vehicle just as it impacted the breakaway posts and continue to film until the vehicle came to a rest.

A tow truck would then attach a chain to the vehicle to tow it out of the bed.

When tests were concluded on one bed configuration, the loader or grader would be used to pile the gravel up and then to construct the next configuration to be tested after the bed area was surveyed and grade stakes marked.

REFERENCES

1. Tamanini, F. J. and J. G. Viner, "Structural Systems in Support of Highway Safety," FIWA, 1969.
2. Laker, I. B., "Vehicle Deceleration in Beds of Loose Gravel," Road Research Laboratory Report No. 19, 1966.
3. Jahu, V. J. et al, "Vehicle Deceleration in Beds of Natural and Artificial Gravels," Road Research Laboratory Report No. LR 264, 1969