DTD Applied Research and Innovation Branch

Where Ideas Become Reality

Report No. CDOT-2008-1
Final Report

Evaluation of Truck Arrester Beds in Colorado

William (Skip) Outcalt

January 2008

COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

Technical Report Documentation Page

1. Report No. CDOT-2008-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of Truck Arrester Beds in Colorado		5. Report Date January 2008
		6. Performing Organization Code
7. Author(s) William (Skip) Outcalt		8. Performing Organization Report No. CDOT-2008-1
9. Performing Organization Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222		13. Type of Report and Period Covered
		14. Sponsoring Agency Code 92.09
15. Supplementary Notes Prepared in cooperation with the US Department of Transportation, Federal Highway Administration		

16. Abstract

In 2006, CDOT initiated development of a specification for aggregates used in truck arrester beds. First, it was necessary to know what was currently in the arrester beds throughout the state. Each bed needed to be evaluated for safety, performance, and maintenance needs. This study evaluated the condition of 13 arrester beds throughout Colorado. Based on the performance of those arrester beds and the evaluation of materials recommended by other agencies, a specification for truck ramp aggregate was written and approved.

Implementation:

Section 703.11, Truck Escape Ramp Aggregate, was added to the CDOT Standard Specifications for Road and Bridge Construction.

17. Keywords: truck escape ramps, aggregates	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) None	20. Security Classif. (of this page) None	21. No. of Pages 46	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Evaluation of Truck Arrester Beds in Colorado

by

William (Skip) Outcalt, E/PS Tech III

Report No. CDOT-2008-1

Colorado Department of Transportation

Research Branch

Sponsored by

Colorado Department of Transportation

In Cooperation with the

U. S. Department of Transportation

Federal Highway Administration

January 2008

Colorado Department of Transportation

4201 E. Arkansas Avenue

Denver, CO 80222

ACKNOWLEDGEMENTS

Thanks to study panel members Allen, Marcee; Paul DeJulio, Mike DeLong, Dan Falls, Glen Frieler, Mike Gallegos, Don Miller, Eric Prieve, Rich Sarchet, Bill Schiebel, Dave Weld and Ken Wissel.

Special thanks to Maintenance Sections 3, 5, 6, and 7 for their invaluable help in collecting samples.

EXECUTIVE SUMMARY

The Colorado Department of Transportation needed a Standard Specification to describe the aggregates for use in truck escape ramps. All thirteen of Colorado's existing escape ramps were sampled and the aggregates analyzed for size and shape. The results of the analysis were combined with information from other agencies and used to write Section 703.11, Truck Escape Ramp Aggregate, which was approved and added to the Standard Specifications on October 25, 2007. The specification describes the shape, gradation, and wear characteristics of material acceptable for use in truck escape ramp arrester beds in Colorado.

IMPLEMENTATION STATEMENT

Section 703.11, Truck Escape Ramp Aggregate, was approved and added to the Standard Specifications on October 25, 2007. The specification describes the shape, gradation, and wear characteristics of material acceptable for use in truck escape ramp arrester beds in Colorado.

TABLE OF CONTENTS

BACKGROUND..1
LITERATURE SEARCH SUMMATION...1
TRUCK ESCAPE RAMP EVALUATIONS..5
STANDARD SPECIFICATION 9
RECOMMENDATIONS 10
REFERENCES...11
APPENDIX A GRAPHS OF THE SAMPLE AGGREGATE GRADATIONS.. A-1
APPENDIX B LITERATURE SEARCH DOCUMENT LIST............................B-1

LIST OF FIGURES

1. Gradations charts………..…………………………………………..…………5
2. Lower Straight Creek arrester bed……..……………………………………...6
3. Truck tracks in the arrester bed….……………………………………..…...6
4. Polluted pea gravel at Mt. Vernon Canyon………………………………..…..7

LIST OF TABLES

1. Colorado’s Truck Escape Ramps September 2006……..…………………..8

BACKGROUND

As of 2006 the Colorado Department of Transportation (CDOT) did not have a standard specification for aggregates used in the arrester beds of runaway truck escape ramps (TERs). This study determined the size and shape of the aggregate in the arrester beds throughout the state and evaluated each bed for contamination with fine material. In conjunction with the aggregate evaluations, each escape ramp was evaluated for safety, performance, and maintenance needs. Previous studies noted problems with infiltration of fine particles, which can hold water and freeze in cold weather, reducing the ramp's ability to control runaway trucks. The results of this study were used to develop Section 703.11 Truck Escape Ramp Aggregate for CDOT's Standard Specifications for Road and Bridge Construction.

CDOT first built gravel arrester beds in runaway truck escape ramps in the early 1980's. Since then approximately 20 arrester beds have been built. Little or no research has been done since 1985 as to the safety, performance and maintenance needs of these beds. During 2006 CDOT Maintenance workers became concerned with the distance trucks were traveling into the Lower Straight Creek escape ramp on I-70 west of the Eisenhower-Johnson Memorial tunnels. The arrester bed in the escape ramp had become polluted with fine material and information was needed as to what would be the best way to fix the problem.

The objective of this study was to develop design standards for evaluation of the condition of current ramps and for use in future construction. It recommends materials and maintenance procedures and schedules to maintain truck escape ramp arrester beds in optimal condition.

The study was done in several parts:

A literature search found information in 14 documents addressing arrester bed aggregate size and gradation, depth, width and length and various design and maintenance issues.

Research personnel collected samples from each of Colorado's 13 escape ramps. Two samples were taken at each of three locations evenly spaced along the length of the arrester beds. The top sample was collected after removing about 6" from the surface of the bed. The bottom sample was taken approximately 18 inches below the surface of the arrester bed. The CDOT central lab analyzed the aggregate samples for size, shape and gradation.

LITERATURE SEARCH SUMMATION

The Transportation Research Information Service (TRIS) system literature search, done in July of 2006, found 14 reports, dating as far back as 1982, written by various agencies in the U.S. and Canada. There is a great deal of information relating to design and maintenance of truck escape ramps. However, the information concerning aggregate size and gradation is limited

Some of the important information relating to aggregate used in truck escape ramps is listed here:

Arrester beds should be constructed with a minimum aggregate depth of 36 inches, with 42 inches recommended. To assist in decelerating the vehicle smoothly, the depth of the bed should taper from three inches at the point of entry to full depth in the initial 100 to 200 feet. (1)

A width of 26 feet is set as a minimum, with 30 to 40 feet being desirable. (2)

If an arrester bed is used, the material should be clean, not easily compacted, rounded and of one size with a high coefficient of friction. Pea gravel is sited as the most commonly used material. (2)

The aggregate depth should be a minimum of 36 inches, tapering from 3 inches at entry to maximum depth within 100 to 200 feet. (2).

Fine materials are sited as one of the principal contaminants of arrester beds. Contamination can come from four main sources;

1. Existing ground: Paving the bottom and sides of the arrester bed basin can control ground contamination.

2. Surface: Contamination brought by the surface can be minimized by an adequate drainage system, providing good roadway drainage as well as arrester bed drainage.

3. Vehicles: Contamination caused by vehicles entering the arrester bed is difficult to control, as it is usually unpreventable.

4. The gravel itself: The aggregate itself is the final contaminant, as over time it will weather and breakdown. For this reason, the aggregate will need to be replaced and/or reprocessed periodically. Using high quality gravel can minimize contamination from the aggregate. (2)

To minimize the need to remove and replace or wash the gravel, the policy states that it is desirable that the arrested bed be of sufficient depth to allow normal contamination, but still maintain the ability to retard and stop an out-of-control vehicle. Arrester beds shall gradually increase from an initial depth of six inches to a maximum depth of 48 inches in the first 150 feet. The surface of the arrester bed aggregate should be as smooth as possible with no humps or hollows (2).

Arrester bed ramps vary in detail depending on the material used. The material can range from sand to 1½ inch aggregate. The grade of the arrester bed will also influence length, with ascending ramps providing greater stopping ability. (2)

Experience has shown that trucks will sink at least 12 inches into the arrester bed material. Additional experience has also shown that the lower 12 inches of material will typically become so contaminated and compacted that it will virtually act like cement treated base. For these reasons, the Bulletin recommends a minimum depth of material to be 36 inches, with 30 inches being an absolute minimum. The depth of the aggregate should taper from six inches at the beginning of the bed to maximum depth within 100 feet. This allows for gradual deceleration and reduces the risk of load shift. (2)

The surfacing material used in the arrester bed should be clean, not easily compacted, and have a high coefficient of rolling resistance. (1)

Arrester beds should be constructed with a minimum aggregate depth of 0.6 m. (1)

Contamination of the bed material can reduce the effectiveness of the arrester bed by creating a hard surface layer up to 300 mm thick at the bottom of the bed. Therefore, an aggregate depth up to 1000 mm is recommended. (1)

A positive means of draining the arrester bed should be provided to help protect the bed from freezing and avoid contamination of the arrester bed material. (1)

The entrance to the ramp must be designed so that a vehicle traveling at a high rate of speed can enter safely. (1)

More recent tests of arrester bed performance show that larger gravel sizes and deeper beds produce higher rolling resistance,…(3)

Smooth, rounded, uncrushed gravel of approximately a single size is the most effective arrester bed material. The best size appears to be near 0.5 in. .The river gravel graded to AASHTO Gradation 57 was found to be the best of those materials tested. (3)

Smooth, rounded, uncrushed gravel of approximately a single size is the most effective arrester bed material. The best size appears to be near 0.5 in. (3)

Visual inspection in the winter revealed that large aggregate with low contamination levels developed only a thin frozen crust at the surface. In contrast, smaller aggregate with high contamination was frozen solid to the full bed depth. (3)

Rounded gravel, rather than crushed aggregate, is required. Uniform grading with an approximate size range of 0.5 to 0.7 in. provides the greatest rolling resistance and thus permits the shortest ramp lengths. (3)

Maintenance must include re-grading after each use and periodic "fluffing." (3)

The effectiveness of arrester beds is related to the long term performance of the aggregate used. Roundness is important, but so are hardness and durability. Resistance to abrasion and crushing are essential to minimizing the contamination by fines and resultant bed consolidation. (3)

There are three main types of arrester beds: gravity ramp, sand piles, and gravel beds. Of these three types, gravel beds have been shown to be safer and more efficient. The field performance of gravel arrester beds depends greatly on two aggregate properties, namely inter-particle friction and free drainage. The ideal condition is an inter-particle friction low enough for tires to sink into the aggregate, yet sufficiently high to stop the vehicle within a desired distance. The aggregate must be free-draining to prevent the accumulation of excess water in the arrester bed and minimize the effects of freezing. (4)

To possess both low inter-particle friction and high permeability, the aggregate must have rounded particles with uniform gradation. A natural aggregate that can satisfy this requirement is pea gravel; for this reason, pea gravel has been used often in the construction of arrester beds (4)

Page 6: “Based on the results of this study, it can be concluded that aggregate gradation and inter-particle friction are not sufficient to determine performance in the arrester bed. Factors such as particle angularity and sphericity also greatly influence aggregate performance. Moreover, for long-term performance, particle durability is a dominant factor. Therefore, testing of aggregate for use in the arrester bed should involve determinations of not only gradation and inter-particle friction, but also angularity number, sphericity and durability. (4)

The Pennsylvania Transportation Institute (PTI) constructed two 300-ft-long test ramps, one filled with rounded river-bed gravel and the other with more angular crushed gravel. Using a dump truck and a single-axle tractor with a flatbed trailer, tests were performed measuring entry speed, stopping distance, accelerometer data, cross-section measurements of the ruts left by the truck tires, and distance vs. time data. The river gravel exhibited greater tire penetration, greater volume of stones displaced and greater deceleration forces than the crushed gravel. (5)

Freezing of aggregate during the winter months is closely related to the aggregate contamination problem. (6)

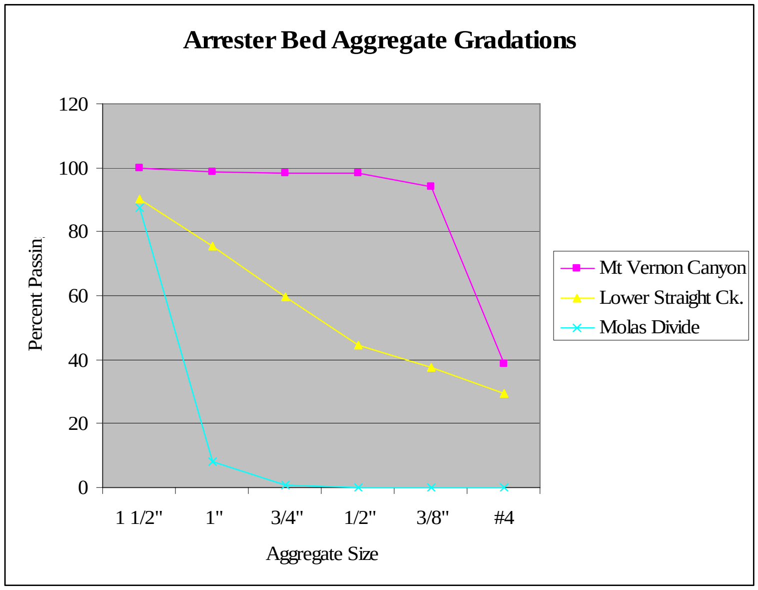
The Oregon Department of Transportation has conducted a comprehensive study on aggregate gradation and its performance in truck escape ramps. The study involved a comparison between 3/4 to 1/4 inch material and 3/8 inch to No. 10 pea gravel. It was concluded that the penetration of wheel loads would be very similar for both materials when each was clean and dry. But, the larger sized material was preferable with regard to freezing or contamination. To compare the freezing characteristics of two materials, they filled cylinder molds with the gravels, saturated them with water, allowed them to drain for five minutes, and then put them in a freezer. After freezing, the cylinders were removed from the molds and quickly tested for unconfined compressive strengths. The coarser, free draining material failed at around 70 PSI and the finer material failed at around 120 PSI. The better drainage of the coarse material provided a definite advantage; but, there were no direct relationships between these tests and the actual field conditions. (6)

Visual inspections of all aggregate during the cold winter months indicated that the stiffness of the aggregate in various ramps was primarily dependent on the aggregate gradation. Larger aggregate with low degrees of contamination only developed a thin frozen crust on the surface of the arrester beds. Smaller aggregate with high degrees of contamination were frozen solid to full depth of the arrester beds, and it was impossible to penetrate through the frozen aggregate with a shovel. (6)

Appendix B contains a list of the documents found. Each document was searched for four key words: sand, aggregate, gravel, and gradation. Brief summaries of the information located in the key word search are included in the appendix. Much of this information is repeated in two or more of the reports.

TRUCK ESCAPE RAMP EVALUATIONS

During August of 2006 Research personnel collected samples of the aggregates in the arrester beds in all 13 of the TERs in Colorado. Table two shows the locations of the ramps and the traffic data for the highway. Three locations evenly spaced along the length of the beds were selected. At each location two samples were taken. For the upper sample, the top six inches of the bed aggregate was scraped away and a sample collected (approximately 50#) by hand. A loader was used to remove about 18 inches of the surface aggregate, and then the second sample bag was filled by hand. Some of the beds were found to be only about 18 inches deep, so the lower sample was taken near the bottom of the bed, but with care to not go into the native soil.



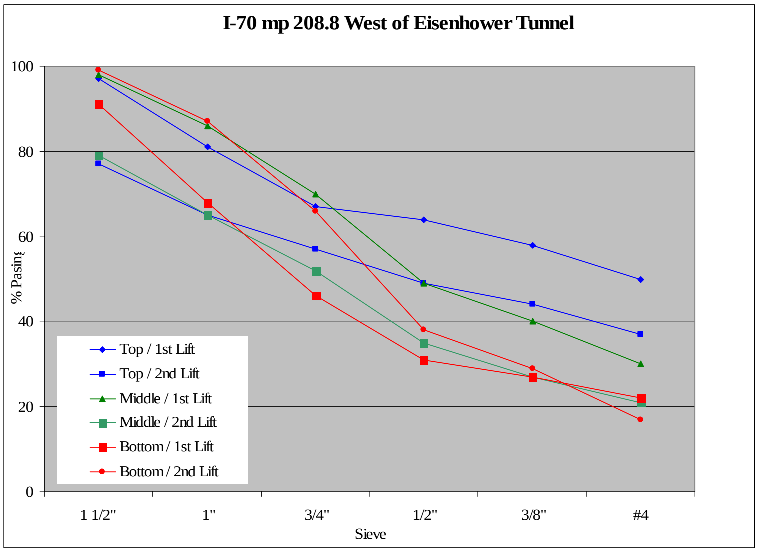


Figure 1. Top - Average gradations at Mt. Vernon Canyon, Lower Straight Creek and Molas Divide. Bottom -All samples Lower Straight Creek.

The average maximum size of aggregate in the ramps varied from of about 2 inches down to about 3/8 inch. The Molas Divide ramp on US-550 had 100% passing 2 inch and only 1% passing ¾ inch; Mt Vernon Canyon, on I-70, had 94% passing 3/8 inch and 39 % passing #4. Gradations of each of the arrester beds are graphed in Appendix B.

During the sample collection the Research personnel visually assessed the condition of each of the ramps. Simply walking the length of an arrester bed gives good insight into what the aggregate gradation will probably be. The two ramps mentioned above represent the extremes of size of aggregate, but both are quite difficult to walk in and perform well at stopping runaway trucks.

Figure 2. The Lower Straight Creek arrester bed near the entrance. The references are 1" squares.

Figure 3. The last truck to use the ramp barely made tire tracks.

The Lower Straight Creek Ramp on I-70, the lower of two ramps on the westbound descent from the Eisenhower/Johnson Memorial tunnels to Dillon, was in the worst condition by far. The graphs in **Figure 1**, above, show the average gradations for the Mt. Vernon Canyon, Molas Divide and Lower Straight Creek TERs. The sample from Lower Straight Creek is very evenly graded, as can be seen in the bottom graph. The material compacted in the aggregate bed very much like road-base gravel, and was performing very poorly as an escape ramp (**Figures 1 & 2)**.

The Lower Straight Creek Ramp is about 1000 feet long and steep, but trucks were going deep into the ramp. In fact, more than one had gone completely past the end of the ramp. Walking in the lower half of the arrester bed on this ramp was like walking on a hard, gravel road, and the upper half was only slightly better. **Figures 2 & 3** show that the arrester bed was heavily polluted with fine material and solidly compacted. The heavy loader used in the sampling sank into the bed less than two inches.

The aggregate of the arrester bed in this escape ramp is placed directly on the native soil with no barrier, either on the bottom or the sides, between the bed and the native soil. Fine material appeared to come from both the side hill above and from below the bed due to the mixing action of trucks using the ramp and of grooming activities.

Records of the use of Colorado's TERs exist, but their completeness is questionable. The records that are available for 2001 through 2004 indicate that the Lower Straight Creek ramp was used nearly 10 times more than the other 12 ramps in the state combined.

Of thirteen ramps sampled, all but three were built with the arrester bed directly on the native soil. The ramps on US-6 west of Loveland Pass and on US-50 on the west side of Monarch Pass are built on a concrete base with concrete barriers on both sides. I-70 at Mt. Vernon Canyon has an asphalt base with concrete barrier along the right side.

The concrete in the US-6 and US-50 ramps protects the arrester beds from the intrusion of fine material from the surrounding soil; especially from below.

Figure 4. Mt. Vernon Canyon's 1/2" pea gravel arrester bed is heavily polluted by fine material. A quantity of 1" aggregate was added to the bed at some time.

The mixing action of runaway trucks and of grooming operations may be the main cause of pollution from below the arrester beds

The Mt. Vernon Canyon escape ramp is directly adjacent to the highway with its left side open to I-70 along its entire length; it follows the curvature and grade of the highway. This is the only downhill ramp in Colorado – Slick Rock, on SH-141 is nearly level and the others all are uphill. The arrester bed at Mt. Vernon Canyon is pea gravel over an asphalt base. The bed contains a considerable amount of fine material, probably traction sand carried off the adjacent highway by water and snow plowing operations. In cold weather this arrester bed requires frequent scarifying because it tends to freeze.

Table 1. Colorado's Truck Escape Ramps September 2006

Hwy	MP	Location	AADT	% Trucks	Ramp Use
US-6	219.0 WB	W/o Loveland Pass	1,200	20.0	
US-40	142.1 WB	W/o Rabbit Ears Pass	3,600	10.8	
US-50	194.0 WB	W/o Monarch Pass	2,300	20.0	
US-50	204.0 EB	E/o Monarch Pass	2,300	20.0	
I-70	182.0 WB	W/o Vail Pass	19,900	13.0	
I-70	185.5 WB	W/o Vail Pass	19,900	13.0	
I-70	208.8 WB	W/o Eisenhower Tunnel	28,800	9.7	
I-70	211.9 WB	W/o Eisenhower Tunnel	28,800	9.7	
I-70	256.7 EB	Mt. Vernon Canyon	67,400	6.4	
SH-141	18.5 NB	S/o Slick Rock	540	31.5	
US-160	160.8 WB	W/o Wolf Creek Pass	2,500	11.6	
US-160	162.5 WB	W/o Wolf Creek Pass	2,500	11.6	
US-550	52.5 WB	S/o Molas Divide	2,000	11.0	

STANDARD SPECIFICATION

Thanks to the work done on this study, Section 703 of the CDOT Standard Specifications was revised as follows.

Sample Project Special Provision: 703tera

10-25-07

REVISION OF SECTION 703

TRUCK ESCAPE RAMP AGGREGATE

Section 703 of the Standard Specifications is hereby revised for this project as follows:

Add subsection 703.11 as follows:

703.11 Truck Escape Ramp Aggregate. Truck escape ramp aggregate shall consist of washed, free draining, uncrushed natural gravel.

The truck escape ramp aggregate shall have less than 50 percent flat and elongated particles by mass when tested in accordance with ASTM D 4791 using an opening ratio of 2:1.

The truck escape ramp aggregate shall have a minimum of 20 percent rounded particles by mass. A rounded particle has no fractured faces. The truck escape ramp aggregate shall have a maximum of 10 percent of the particles by mass with 3 or more fractured faces. Fractured faces will be tested in accordance with CP-45. The minimum sample size for CP-45 shall be 1000 g.

The truck escape ramp aggregate shall have a percentage of wear less than 50 percent when tested in accordance with AASHTO T96.

The truck escape ramp aggregate shall meet the following gradation requirements:

Sieve Size	Mass Percent Passing Square Mesh Sieves
50mm (2 inch)	100
19mm (3/4 inch)	0-10

RECOMMENDATIONS

Based on the information gathered from the literature search and Colorado's experience with Truck Escape Ramps, the following are recommended:

1. Aggregate under consideration for use in an arrester bed should be tested for hardness and durability in addition to roundness and size. In an enclosed arrester bed most of the fine material will come from fractured aggregate caused by runaway trucks and the equipment used by maintenance personnel for grooming the bed after use.

2. To head off problems caused by fine material pollution, a regular sampling program for each arrester bed should be implemented, with its frequency set by the frequency of use of the ramp and the condition of the arrester bed.

3. For each use of a ramp, the penetration distance should be recorded. When the average penetration distance begins to increase, plans should be made to rehabilitate the arrester bed through one of the following: 1. Addition of new, properly graded aggregate on top of the existing bed, 2. Removal, screening and replacing of the existing aggregate, or 3. Bed replacement.

4. For high usage TERs, particularly at locations like I-70 at Lower Straight Creek, consideration should be given to updating to a concrete contained arrester bed with an appropriate drainage system.

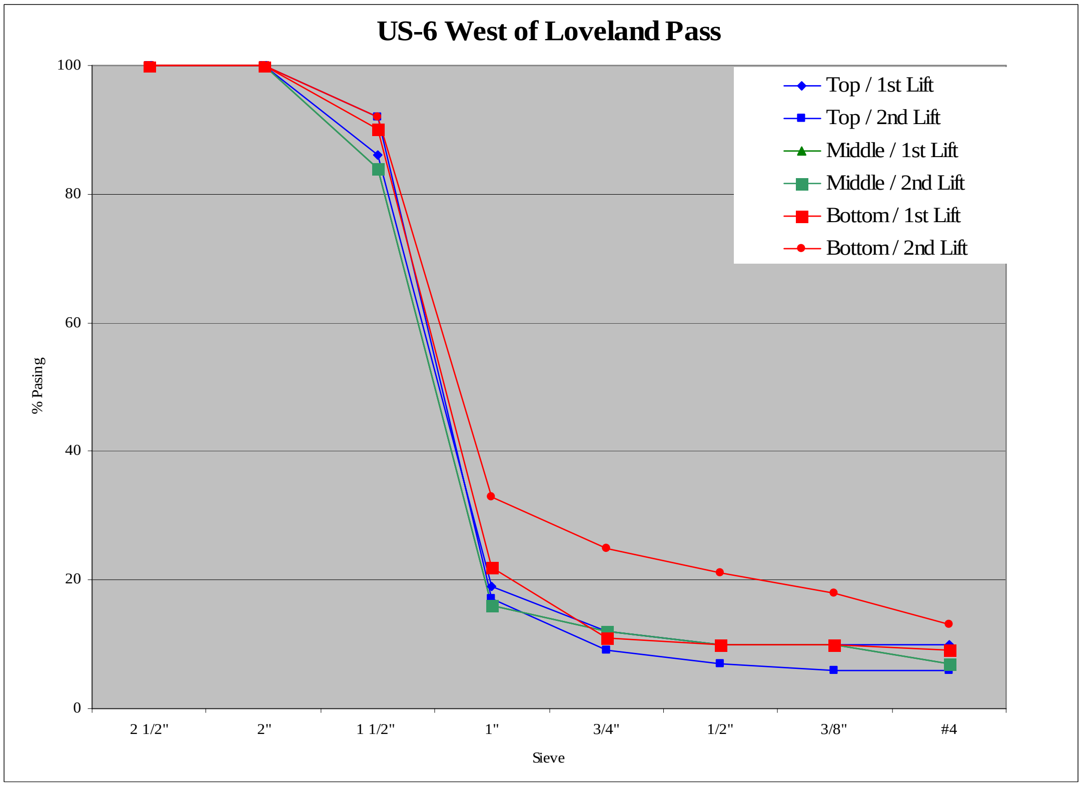
5. Escape ramp arrester beds should be a minimum of 26 feet wide. For high usage ramps like Lower Straight Creek, 30 to 40 feet is preferred, to reduce the risk of collisions when the ramp is used by more than one truck at a time.

REFERENCES

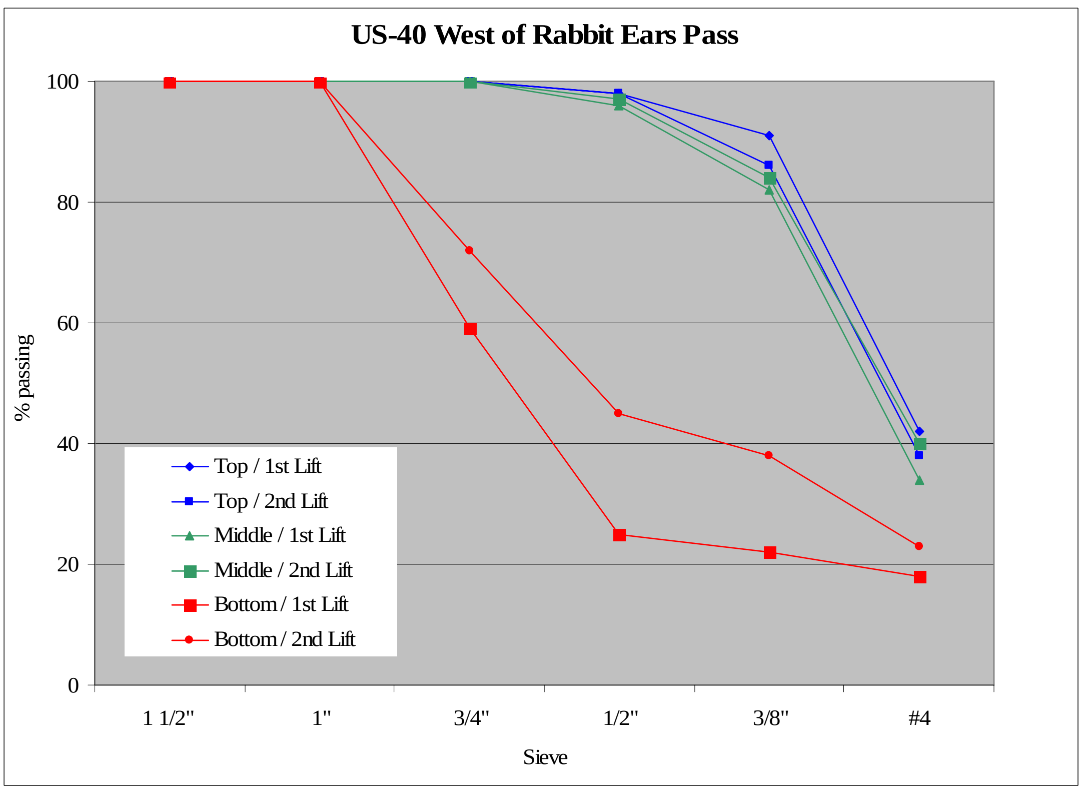
1. A Policy on Geometric Design of Highways and Streets. AASHTO (The Green Book)
2. Truck Escape Ramp Study – Final Report Prepared by HDR Engineering for Arizona DOT, November, 2003 **http://tpd.az.gov/pps/study/truck_escape_ramp.pdf**
3. Witheford, DK, Truck Escape Ramps. In NCHRP Synthesis of Highway Practice, Issue 178 Transportation Research Board 05/00/1992
4. Wang, MC , Aggregate Testing for Construction of Arrester Beds, in Transportation Research Record Issue 1250. Transportation Research Board 1989
5. Wambold, J. C.; Rivera-Ortiz, L. A., Wang, M. C. Truck Escape Ramp Design Methodology, Volume 2: Final Report. Pennsylvania Transportation Institute. 10/00/1988
6. Derakhshandeh, M., Truck Escape Ramp Aggregate. Final Report. CDOT 02/00/1985

APPENDIX A

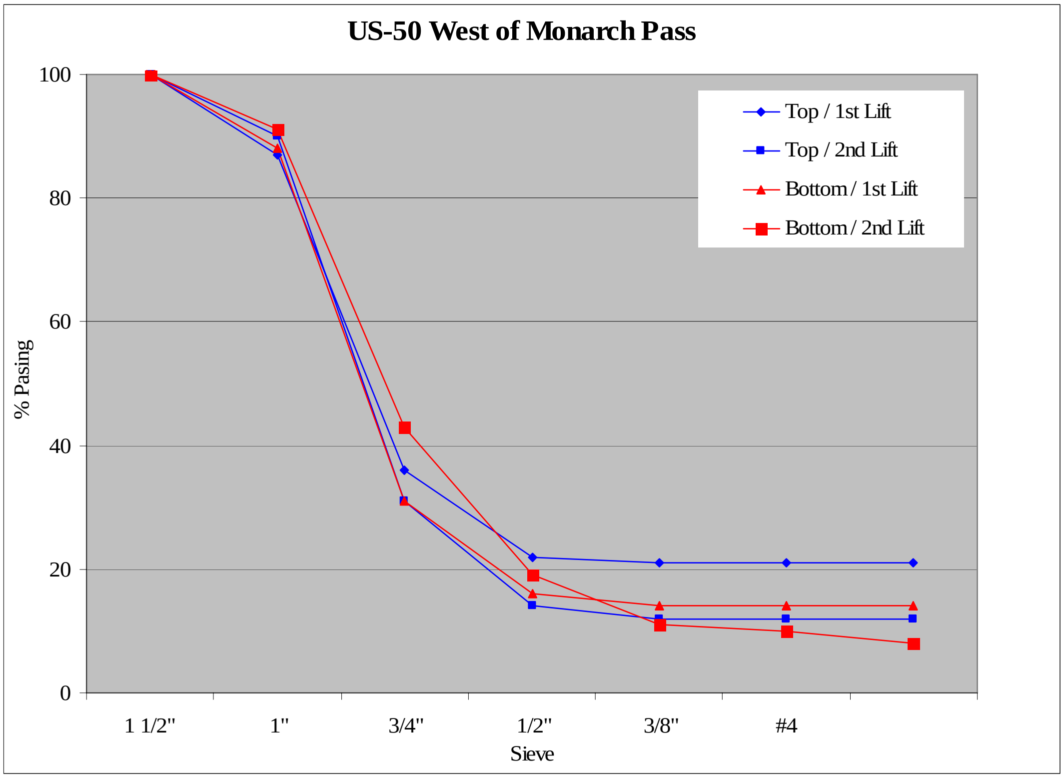
Graphs of the sample aggregate gradations from the TER arrester beds.

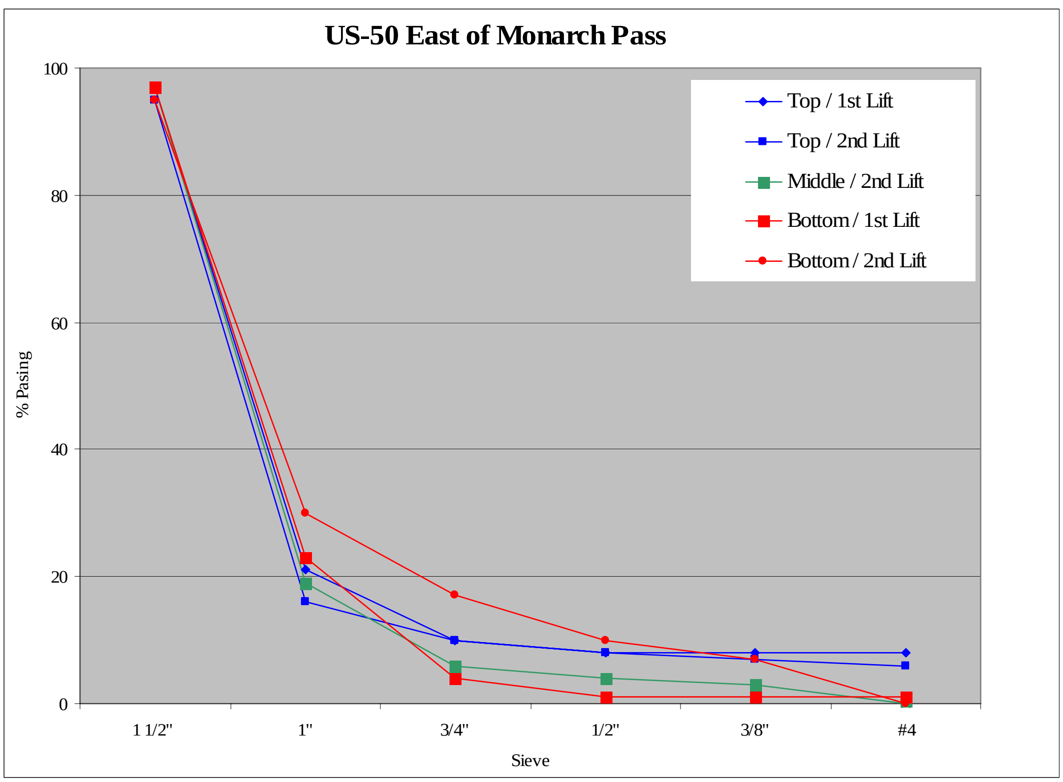


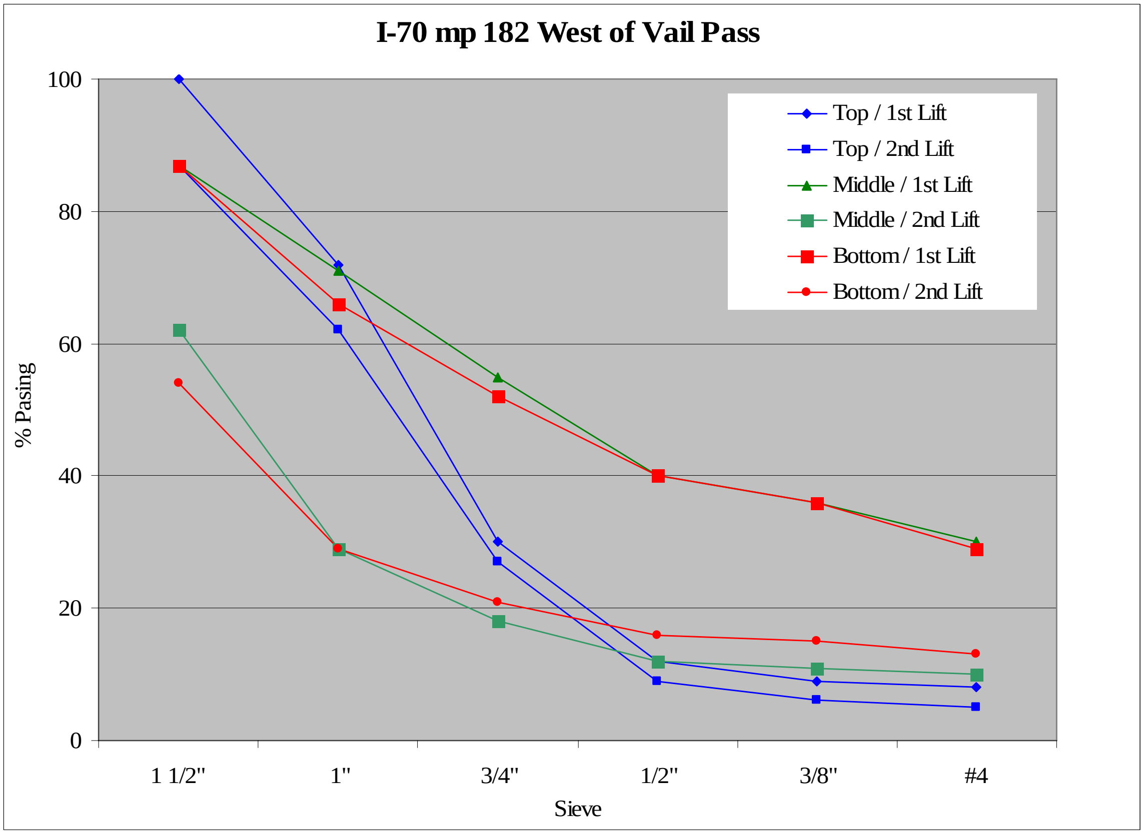
US-6 West of Loveland Pass
100
80
60
40
20
0
% Pasing
2 1/2"
2"
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift

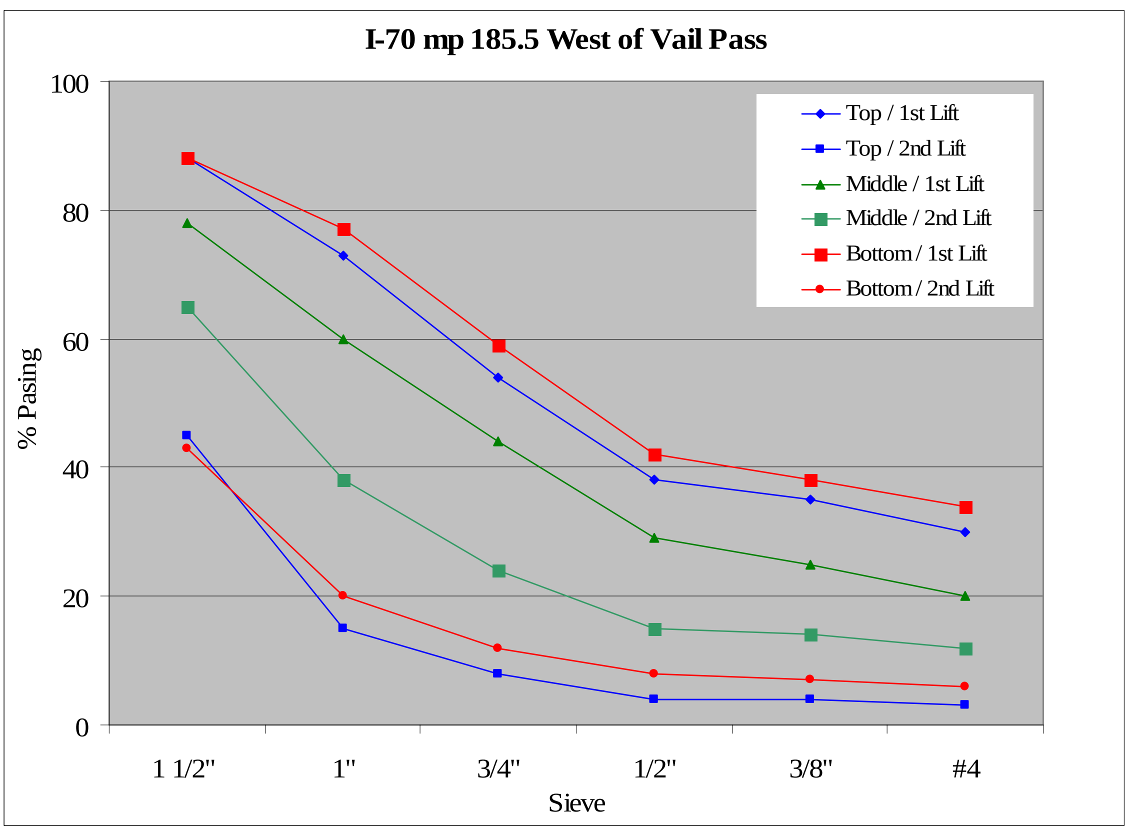


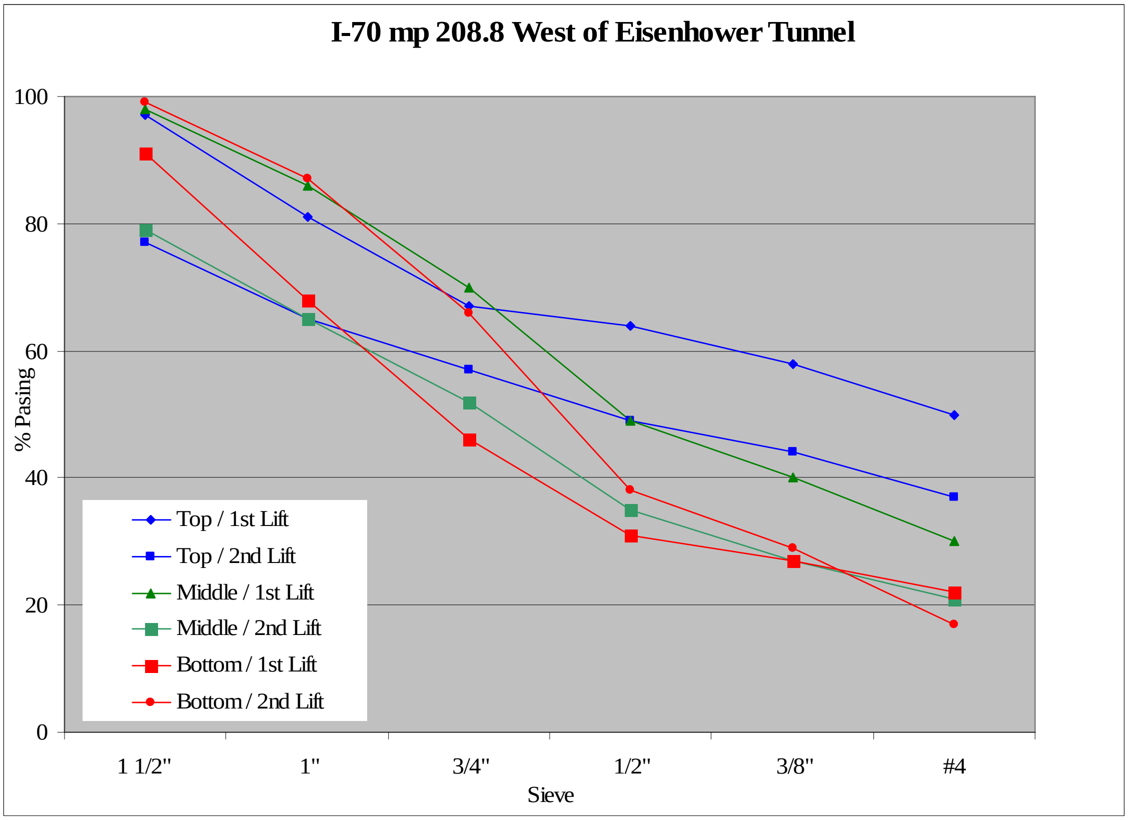
US-40 West of Rabbit Ears Pass
100
80
60
40
20
0
% passing
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift

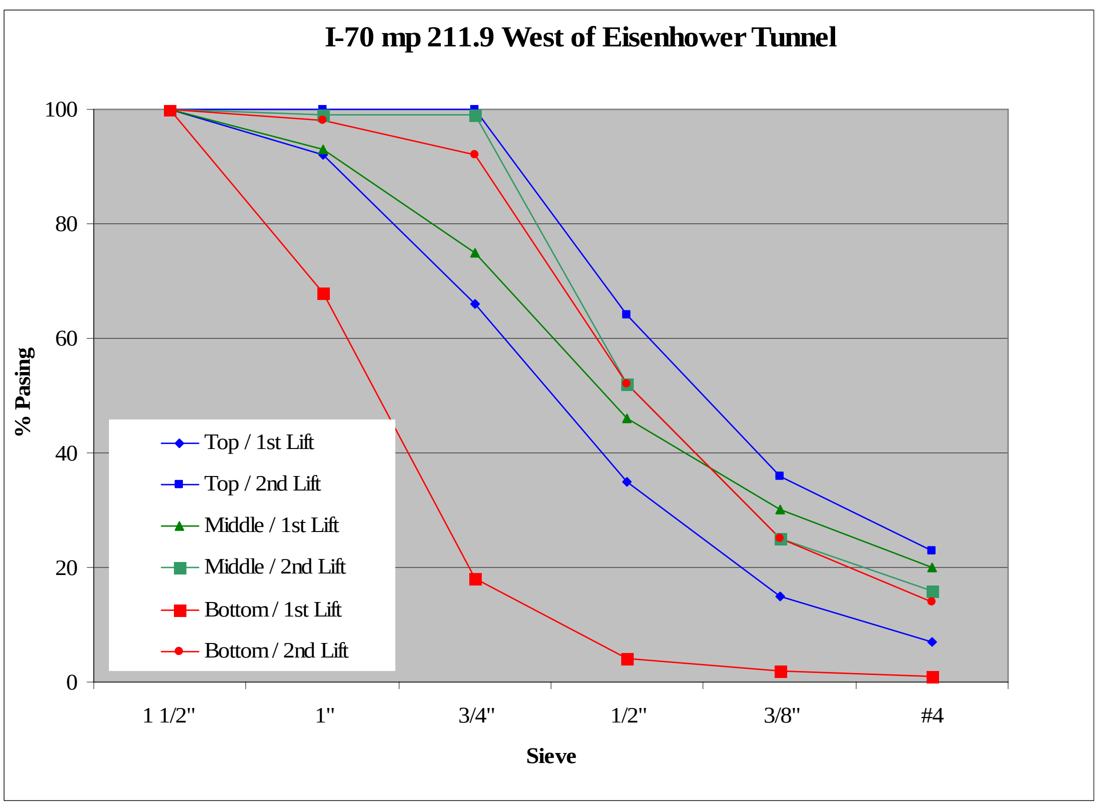

US-50 West of Monarch Pass
100
80
60
40
20
0
% Pasing
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve
Top / 1st Lift
Top / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift

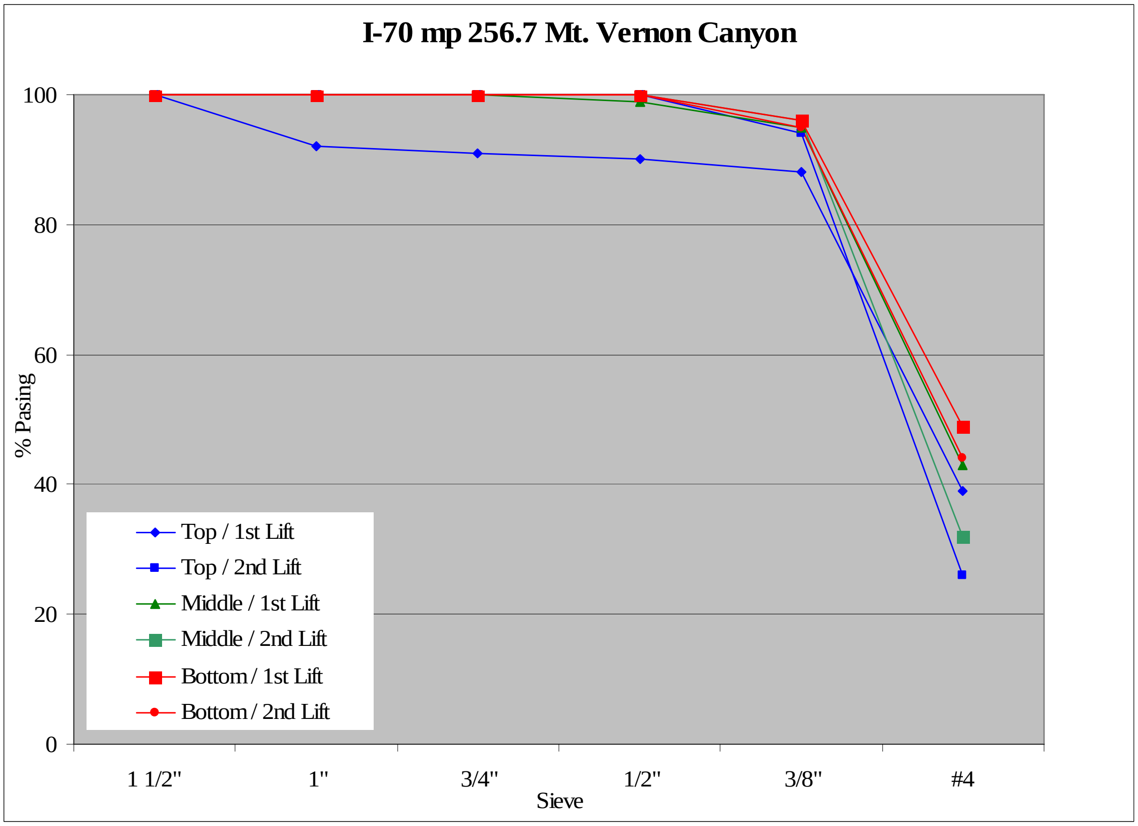

US-50 East of Monarch Pass
100
80
60
40
20
0
% Pasing
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve
Top / 1st Lift
Top / 2nd Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift

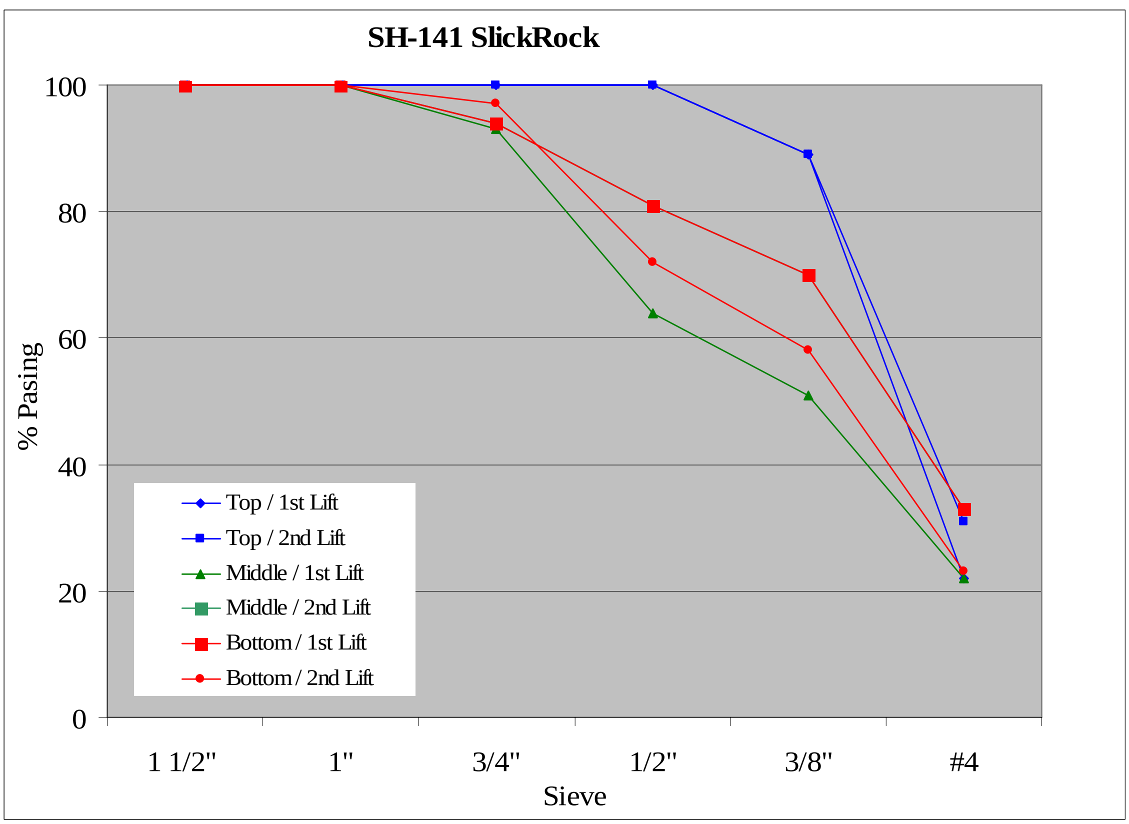

I-70 mp 182 West of Vail Pass
% Pasing
Sieve
1 1/2"
1"
3/4"
1/2"
3/8"
#4
0
20
40
60
80
100
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift

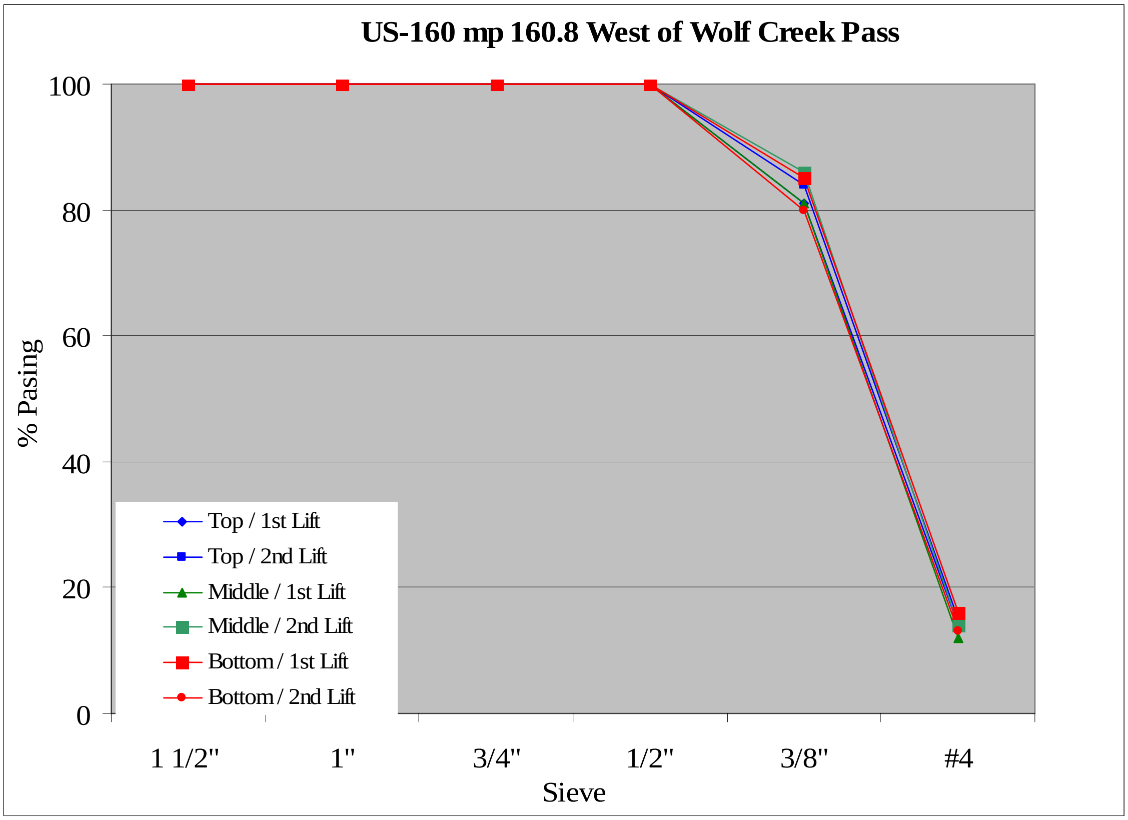

I-70 mp 185.5 West of Vail Pass
% Pasing
Sieve
1 1/2"
1"
3/4"
1/2"
3/8"
#4
0
20
40
60
80
100
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift

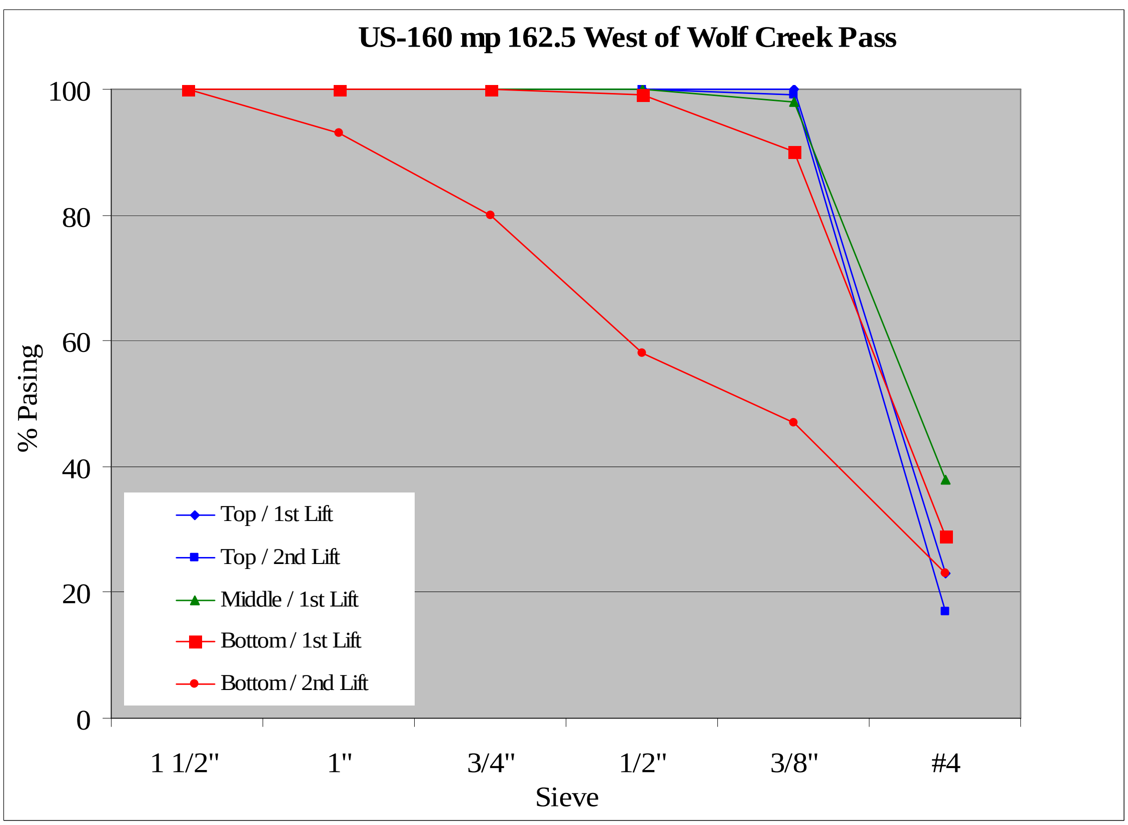

I-70 mp 208.8 West of Eisenhower Tunnel
100
80
60
40
20
0
% Pasing
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve

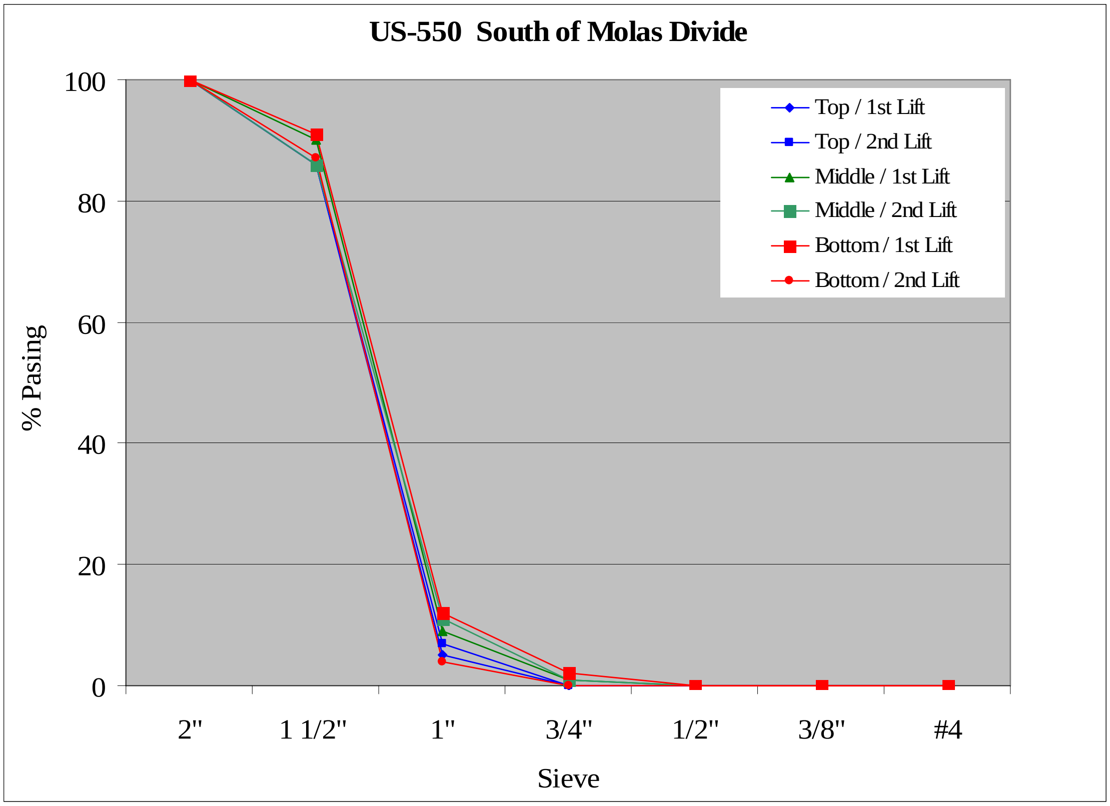

I-70 mp 211.9 West of Eisenhower Tunnel
100
80
60
40
20
0
% Pasing
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve


I-70 mp 256.7 Mt. Vernon Canyon
100
80
60
40
20
0
% Pasing
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve


SH-141 SlickRock
100
80
60
40
20
0
% Pasing
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve


US-160 mp 160.8 West of Wolf Creek Pass
100
80
60
40
20
0
% Pasing
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve


US-160 mp 162.5 West of Wolf Creek Pass
100
80
60
40
20
0
% Pasing
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Bottom / 1st Lift
Bottom / 2nd Lift
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve



US-550 South of Molas Divide
100
80
60
40
20
0
% Pasing
Top / 1st Lift
Top / 2nd Lift
Middle / 1st Lift
Middle / 2nd Lift
Bottom / 1st Lift
Bottom / 2nd Lift
2"
1 1/2"
1"
3/4"
1/2"
3/8"
#4
Sieve

APPENDIX B

Literature search document list with abstracts and summary of pertinant information.

This is the list of documents found by a TRIS search on Truck Escape Ramps done in July of 2006. It includes abstracts where available.

Each document was searched for four key words: sand, aggregate, gravel, and gradation. The information found was then copied this study and referenced by page in the original document. The information begins below the TRIS abstract for each report.

In all of the documents there is a great deal of information relating to design and maintenance of truck escape ramps. Much of the information is repeated in several of the reports, and they often cite each other as sources of information.

Links (in blue) are included to the documents where available.

1. Truck Escape Ramp Study   Arizona DOT, 2003

http://tpd.az.gov/pps/study/truck_escape_ramp.pdf

This study is concerned mainly with the design and construction of TERs in Arizona. It deals mainly with geometry of the highway and of the ramps.

Excerpts from the report:

Page 3-35: “The Green Book states the following considerations for the design and construction of an effective TER:

….4. Arrester beds should be constructed with a minimum aggregate depth of 36 inches, with 42 inches recommended. To assist in decelerating the vehicle smoothly, the depth of the bed should taper from three inches at the point of entry to full depth in the initial 100 to 200 feet.

Page 3-6: “The Green Book states that the principal determinations as to the need for a TER should be the safety of the other traffic on the roadway, the operator of the out-of-control vehicle, and the residents along and at the bottom of the grade. To determine the distance required to bring an out-of-control vehicle to a stop with consideration given to the rolling resistance and gradient resistance, the following equation is recommended:

$L = V_2 / [30(R \quad . \; G)]$

where: L = distance to stop (length of arrester bed), feet

V = entering velocity, mph

G = percent grade divided by 100; and

R = rolling resistance expressed as equivalent percent gradient divided

by 100 (See **Table 3.2.1**).

Table 3.2.1
Rolling Resistance Based on Material Type

Surfacing Material	Rolling Resistance (lb/1000ob GVW)	Equivalent Grade (percent)[1]
Portland cement concrete	10	1.0
Asphalt concrete	12	1.2
Gravel, compacted	15	1.5
Earth, sandy, loose	37	3.7
Crushed aggregate, loose	50	5.0
Gravel, loose	100	10.0
Sand	150	15.0
Pea gravel	250	25.0

[1]Rolling Resistance expressed as equivalent gradient.

Page 3-7: The agencies note that the length of the ramp should be calculated taking into account velocity, percent grade and rolling resistance. A width of 26 feet is set as a minimum, with 30 to 40 feet being desirable. If an arrester bed is used, the material should be clean, not easily compacted, rounded and of one size with a high coefficient of friction. Pea gravel is sited as the most commonly used material. The aggregate depth should be a minimum of 36 inches, tapering from 3 inches at entry to maximum depth within 100 to 200 feet. Signage is referred to in detail as a necessary means of early warning to allow proper use of the TER.

Page 3-17: "The primary theory behind the gravel arrester bed is that the vehicle will sink into the gravel, slowly bringing the out-of-control vehicle to a safe stop. To do this, the material must have a low bearing capacity and not be easily compacted; characteristics usually found in single-sized, well-rounded stream gravel. The aggregate used in the arrester bed shall be in compliance with ADOT Materials Specifications as shown in Table 3.2.2 below. Fine materials are sited as one of the principal contaminants of arrester beds. Contamination can come from four main sources; existing ground, surface, vehicles and the gravel itself. Paving the bottom and sides of the arrester bed basin can control ground contamination. Contamination brought by the surface can be minimized by an adequate drainage system, providing good roadway drainage as well as arrester bed drainage. Contamination caused by vehicles entering the arrester bed is difficult to control, as they are usually unpreventable. And using high quality gravel can minimize contamination from the aggregate itself. To minimize the need to remove and replace or wash the gravel, the policy states that it is desirable that the arrested bed be of sufficient depth to allow normal contamination, but still maintain the ability to retard and stop an out-of-control vehicle. Arrester beds shall gradually increase from an initial depth of six inches to a maximum depth of 48 inches in the first 150 feet. The surface of the arrester bed aggregate should be as smooth as possible with no humps or hollows (See **Table 3.2.2**).

Table 3.2.2
Materials Specification (ADOT)

Specification for Arrester Bed Aggregate		
Description:	The work shall include furnishing and placing arrester bed aggregate.	
Materials:	Aggregate for the arrester bed and secondary retarder material shall be clean, uncrushed, inert stone or gravel composed of naturally rounded screened particles free from lumps or balls of clay, calcareous or clay coating, caliche, synthetic materials, organic matter or other deleterious substances.	
The arrester bed and secondary retarder aggregate shall conform to the following requirements:		
	The gravel shall be washed.	
	Gradation – (ARIZ. 201b, Section 12(3))	
	Sieve Size	1 **Percent Passing**
	1 inch	100
	½ inch	0 – 5.0
	No. 200	0 – 2.0
	Abrasion – (AASHTO T 96) 500 Rev., Maximum 35%	
	Bulk Specific Gravity – (ARIZ 211b) Range 2.30 to 2.85	
	Water Absorption – (ARIZ 211b) 4% Maximum	
	Fractured Faces – (ARIZ 212) 10% Maximum	
	Flakiness Index (ARIZ 233b*) 7% Maximum	
*ARIZ 233b shall be modified as follows:		
1. Paragraph 2 (c) add 1" sieve.		
2. Table I: is revised to read:		

	Table I	
	Sieve Size	
Passing	**Retained**	**Weight, G**
1 inch	¾ inch	1,200
¾ inch	½ inch	1,000
½ inch	⅜ inch	700
⅜ inch	¼ inch	300
¼ inch	No. 4	200
No. 4	No. 8	100

3. Table II: is revised to read:

	Table II	
	Size of Material	
Passing	**Retained**	**Slot Width, G**
1 inch	¾ inch	0.525
¾ inch	½ inch	0.375
½ inch	⅜ inch	0.263
⅜ inch	¼ inch	0.184
¼ inch	No. 4	0.131
No. 4	No. 8	0.084

Page 3-30: "Arrester bed ramps vary in detail depending on the material used. The material can range from sand to 1½ inch aggregate. The grade of the arrester bed will also influence length, with ascending ramps providing greater stopping ability.

Page 3-32: Fine materials are one of the principal contaminants of arrester beds. There are four main sources: ground, surface, vehicles and the gravel itself. Paving the sides and bottom of the arrester bed with either asphalt concrete, Portland cement concrete or a geotextile fabric, can reduce contamination from the ground. Providing a positive means of drainage surrounding the ramp, directing all roadway run-off from entering the arrester bed, can reduce surface contamination. Vehicles entering the ramp can contaminate the aggregate with fluids or load material. A positive means of draining the arrester bed and maintenance following each use will reduce these contaminants. The aggregate itself is the final contaminant, as over time it will weather and breakdown. For this reason, the aggregate will need to be replaced and/or reprocessed periodically.

Experience has shown that trucks will sink at least 12 inches into the arrester bed material. Additional experience has also shown that the lower 12 inches of material will typically become so contaminated and compacted that it will virtually act like cement treated base. For these reasons, the Bulletin recommends a minimum depth of material to be 36 inches, with 30 inches being an absolute minimum. The depth of the aggregate should taper from six inches at the beginning of the bed to maximum depth within 100 feet. This allows for gradual deceleration and reduces the risk of load shift.

Page 3-50 " Synthesis 178 (TRIS no. 3, below) found that the preferred design for TERs is the arrester bed. The arresting aggregate should be rounded gravel no less than 36 inches in depth. Uniform grading with an approximate size of 0.5 to 0.7 inches provides the greatest rolling resistance, producing shorter length ramps.

2 Excerpt from 1994 AASHTO Green Book

http://www.webs1.uidaho.edu/niatt_labmanual/Chapters/geometricdesign/professionalpractice/DescendingGrades.htm

The entire excerpt is below:

Descending Grades The following excerpt was taken from the 1994 edition of AASHTO's *A Policy on Geometric Design of Highways and Streets* (pp. 268-276) (**1994 AASHTO Green Book).**

Where long descending grades exist or where topographic controls require such grades on new alignment, the design and construction of an emergency escape ramp at an appropriate location is desirable for the purpose of slowing and stopping an out-of-control vehicle away from the main traffic stream. An out-of-control vehicle generally is the result of an operator losing control of the vehicle because of loss of brakes either through overheating or mechanical failure, or failure to downshift at the appropriate time.

Specific guidelines for the design of escape ramps are lacking at this time. However, considerable experience with ramps constructed on existing highways has led to the design and installation of effective ramps that are saving lives and reducing property damage. Reports and studies of the existing ramps indicate that their operational characteristics are providing acceptable deceleration rates and affording good driver control of the vehicle on the ramp.

Escape ramps generally may be built at any feasible location where the main road alignment is tangent. They should be built in advance of main line curvature that cannot be negotiated safely by an out-of-control vehicle and in advance of populated areas. Escape ramps should exit to the right of the main line. On divided multilane highways, where a left exit may appear to be the only feasible location, difficulties may be expected by the refusal of vehicles in the left lane to yield to out-of-control vehicles attempting to shift lanes.

Speeds in excess of 130 to 140 km/h will rarely, if ever, be attained. Therefore, an escape ramp should be designed for a minimum entering speed of 130 km/h, a 140 km/h design speed being preferred. Several formulas and software programs have been developed to determine the runaway speed at any point on the grade. These methods can be used to establish a design speed for specific grades and horizontal alignments. The design and construction of effective escape ramps involve a number of considerations as follows:

To safely stop an out-of-control vehicle, the length of the ramp must be sufficient to dissipate the kinetic energy of the moving vehicle.

The alignment of the escape ramp should be tangent or of very flat curvature to relieve the driver of undue vehicle control problems.

The width of the ramp should be adequate to accommodate more than one vehicle because it is not uncommon for two or more vehicles to have need of the escape ramp within a short time

The surfacing material used in the arrester bed should be clean, not easily compacted, and have a high coefficient of rolling resistance

Arrester beds should be constructed with a minimum aggregate depth of 0.6 m.

Contamination of the bed material can reduce the effectiveness of the arrester bed by creating a hard surface layer up to 300 mm thick at the bottom of the bed. Therefore, an aggregate depth up to 1000 mm is recommended.

A positive means of draining the arrester bed should be provided to help protect the bed from freezing and avoid contamination of the arrester bed material. . . .

The entrance to the ramp must be designed so that a vehicle traveling at a high rate of speed can enter safely. . . .

Access to the ramp must be made obvious by exit signing to allow the operator of an out-of-control vehicle time to react, so as to preclude the possibility of missing the ramp. . .

A service road located adjacent to the arrester bed is needed so the wrecker and maintenance vehicles can use it without becoming trapped in the bedding material

Wrecker anchors, usually located adjacent to the arrester bed at 50 to 100 m intervals, are needed to secure the tow truck when removing a vehicle from the arrester bed.

3 TRUCK ESCAPE RAMPS

Author(s): Witheford, DK

Publication Date: 05/00/1992 (Available from CDOT Library)

Abstract: This synthesis will be of interest to highway design engineers, maintenance personnel, safety and enforcement officials, traffic engineers, and others responsible for the safe operation of large trucks on highways. Information is provided on the critical aspects of site location, design criteria, and maintenance procedures, and their relationship to truck escape ramp performance. The safety of truck drivers, other road users, and occupants of roadside properties is often imperiled by the combination of heavy trucks and steep downgrades on highways. Frequently, gearing down, applying the brakes, and using the retarding power of the engine are not sufficient to control the truck, and serious crashes can result. Many states have constructed truck escape ramps to safely remove runaway trucks from the traffic stream. This report of the Transportation Research Board provides information on the location, design, construction materials, geometrics, and construction costs of truck escape ramps. Operational considerations, such as descriptions of advance warning signs, traffic control devices at the ramp, and vehicle removal procedures are described. Information on frequency and type of usage, maintenance of the ramps, and driver-related issues is also included.

From the publication:

Page 12: **“**More recent tests of arrester bed performance show that larger gravel sizes and deeper beds produce higher rolling resistance, and that a third order equation can be used to predict the needed ramp lengths. As adopted in the Pennsylvania Highway Design Manual (24), the model is as follows:

$$L = AV + BV + CV2+ DV3$$

where L equals stopping distance or bed length (ft), V equals entry velocity (mph), and A,B,C, and D are constants derived in the research. Their values reflect the rolling resistance of material described as a rounded, uncrushed river gravel in the 0.25 to 1.5-in. range and a mean size in the 0.5 to 0.7-in. range (AASHTO Gradation 57). Appendix B provides a tabulation of calculated bed lengths related to entry speed and ramp grade.

TABLE 4
VALUES OF "R" FOR
DIFFERENT MATERIALS (9)

Surfacing Material	"R" Value
Portland cement concrete	0.010
Asphalt concrete	0.012
Gravel compacted	0.015
Earth, sandy, loose	0.037
Crushed aggregate, loose	0.050
Gravel, loose	0.100
Sand	0.150
Pea gravel	0.250

Page 13: "AASHTO (9) says that a "last chance" device should be considered when an overrun could have serious consequences, recommending a mound of arrester bed material between 2 and 5 ft high and with a 1.5:1 side slope.

Furthermore, at the end of a hard-surfaced gravity ramp, a gravel bed or attenuator array may sufficiently immobilize a brakeless runaway vehicle to keep it from rolling backward. Where barrels are used, it is recommended that they be filled with the same material used in the bed, rather than with sand, which could contaminate the bed and reduce rolling resistance. As with mounds, barrel end treatments should only be employed where conditions do not permit full ramp lengths.

Page 15: "Smooth, rounded, uncrushed gravel of approximately a single size is the most effective arrester bed material. The best size appears to be near 0.5 in. .The river gravel graded to AASHTO Gradation 57 was found to be the best of those materials tested.

Page 15: "Requirements for materials in TERs are described by AASHTO (*A Policy on Geometric Design of Highways and Streets,* American Association of State Highway and Transportation Officials, Washington, D.C. (1990) pp. 272-280.) as follows:

The surfacing material used in the arrester bed should be clean, not easily compacted, and have a high coefficient of rolling resistance. When aggregate is used, it should be rounded, predominantly single size, and as free from fines as possible. The use of large predominantly single-size aggregate will minimize the problems due to moisture retention and freezing as well as minimizing required maintenance, which must be performed by scarifying when the material compacts Pea gravel is representative of the material used most frequently, although loose gravel and sand are also used. A gradation with a top size of 1.5 in. has been used with success in several states.

Page 15: *Truck Escape Ramp Design Methodology* (TRIS no 4, below), gives these conclusions from extensive field testing of materials: . Smooth, rounded, uncrushed gravel of approximately a single size is the most effective arrester bed material. The best size appears to be near 0.5 in. .The river gravel graded to AASHTO Gradation 57 was found to be the best of those materials tested.

Page 16:

TABLE 5
EXAMPLES OF GRADATIONS REPORTED FOR ARRESTER BED GRAVELS

	PERCENT PASSING								
SIZE OR	STATE								
SIEVE NO.	AR	CA	CO	MD	NV	NM	OR	TN	VT
2"			100						
1-1/2"		100							
1"		90-100	25		100		100		
3/4"		0-10	10		90	100	90-100	100	100
5/8"									90-100
1/2"			5		25-50	97-100	0-10		
3/8"	90-100		0-5	90-100	0-20				
#4		0-2		0		0-5		8	0-5
#8								4	
#10							0-2		

Page 26: “The report further states that visual inspection in the winter revealed that large aggregate with low contamination levels developed only a thin frozen crust at the surface. In contrast, smaller aggregate with high contamination was frozen solid to the full bed depth.

Page 32: “The nature or values of some ramp elements appear to be settled. Among these are the following: .

The arrester bed is the preferred technique for truck escape ramps. Rounded gravel, rather than crushed aggregate, is required in at least a 36 in. bed. Uniform grading with an approximate size range of 0.5 to 0.7 in. provides the greatest rolling resistance and thus permits the shortest ramp .lengths.

Mounds and barrels should be used only where needed ramp length cannot be provided. Vehicles should be slowed to 25 .mph or less before reaching impact with them.

Beds should be straight, at a minimal angle to the roadway, and begin at a lateral distance sufficient to keep gravel from spraying back on the main roadway.

Regulatory signing must be adequate to discourage "casual .use" of ramps and stopping by other than runaway vehicles.

Vehicle removal must be facilitated by provision of service lanes and anchor blocks.

Maintenance must include re-grading after each use and periodic "fluffing."

Provisions to avoid contamination of the bed are essential.

Page 33: “Tests of Aggregate Suitability. The effectiveness of arrester beds is related to the long term performance of the aggregate used. Roundness is important, but so are hardness and durability. Resistance to abrasion and crushing are essential to minimizing the contamination by fines and resultant bed consolidation. Better methods are needed to measure and evaluate the suitability of materials for arrester bed use.

Page 47: ADAPTED FROM DESIGN GUIDELINES FOR IMPROVEMENT OF TRUCK ESCAPE RAMPS COLORADO DEPARTMENT OF HIGHWAYS (27)

A.l AGGREGATE DESIGN

Theoretically, if clean, well-graded round pea gravel is placed in a truck escape ramp, the aggregate will have the potential to develop a thin frozen crust on the surface of the arrester bed during the winter months. Trucks break through this thin crust on the coarse material, but would not do so for fine-grained materials. The phenomenon was also observed for Colorado's truck escape ramps. Therefore, in cold mountains, the gradations of the aggregate should be as close as possible to the one presented in Figure 3.13 [not included here]. In addition, the round aggregate is preferred over angular aggregate for the increase of rolling resistance in the arrester bed.

Page 47: “A.2 VARIOUS METHODS TO PREVENT AGGREGATE CONTAMINATION

The major reason for contamination of the aggregate is lack of a proper drainage system for run-off water due to rain or snow melting. Observations of Colorado truck escape ramps reveal that the contaminated run-off water from top and sides of the ramps is the prime source for contamination of the arrester bed aggregate.

4 FIELD STUDY TO ESTABLISH TRUCK ESCAPE RAMP DESIGN METHODOLOGY

Author(s): Wambold, JC

Publication Date: 00/00/1989 *(Available from CDOT Library)*

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

From the Report:

Excerpt from AASHTO Standard Specification for Sizes of Aggregate for Road and Bridge Construction

Table 1 – Standard Sizes of Processed Aggregate

Amounts Finer Than Each Laboratory Sieve (Square Openings), Mass, Percent								
Size No.	*Nominal Size; Sq. Openings*	*37.5 mm (1-1/2")*	*25.0 mm (1")*	*19.0mm (3/4")*	*12.5 mm (1/2")*	*9.5 mm (3/8")*	*4.75 mm (No.4) 0.187"*	*2.36mm (No. 8) 0.093"*
5	25.0 to12.5mm (1" to ½")	100	90 to 100	20 to 55	0 to 10	0 to 5	---------	---------
56	25.0 to 9.5mm (1" to 3/8")	100	90 to100	40 to 85	10 to 40	0 to 15	0 to 5	---------
57	25.0 to 4.75mm (1" to No. 4)	100	95 to 100	-----------	25 to 60	---------	0 to 10	0 to 5
67	19.0 to 4.75mm (3/4" to No. 4)	100	-----------	90 to 100	-----------	20 to 55	0 to 10	0 to 5

5 AGGREGATE TESTING FOR CONSTRUCTION OF ARRESTER BEDS

Author(s): Wang, MC

Publication Date: 00/00/1989 *(Available from CDOT Library)*

Abstract: This paper presents methods of testing aggregate for use in arrester beds. Also presented are test results of five aggregates and the performance of the aggregates in the arrester beds. The test aggregates were obtained from five existing arrester beds throughout Pennsylvania. They were Pennsylvania State University (PSU) river pea gravel, PSU crushed aggregate, Pleasant Gap gravel, Green Tree gravel, and Freeport gravel. Tests performed in the laboratory included gradation, specific gravity, Los Angeles abrasion, and freeze-thaw. In addition, particle angularity, sphericity, and shearing resistance were determined. The field performance of the test aggregates except Green Tree gravel was evaluated in terms of mean average truck deceleration in the bed. The available data show that PSU crushed aggregate performs most poorly of the four. The other three perform nearly equally well, although Pleasant Gap gravel has a static internal friction angle considerably lower than PSU river pea gravel. These results indicate that aggregate performance depends not only on interparticle friction but also on other properties such as particle angularity and sphericity. For long-term performance, particle durability is also an important factor. Thus, testing of aggregate for use in the arrester

bed should involve determination of gradation, interparticle friction, angularity, sphericity, and durability.

From the Report:

AGGREGATE TESTING FOR CONSTRUCTION OF ARRESTER BEDS

"This paper presents methods of testing aggregate for use in arrester beds. Also presented are test results of five aggregates and the performance of the aggregates in the arrester beds. The test aggregates were obtained from five existing arrester beds throughout Pennsylvania."

Page 1: "There are three main types of arrester beds: gravity ramp, sand piles, and gravel beds. Of these three types, gravel beds have been shown to be safer and more efficient. The field performance of gravel arrester beds depends greatly on two aggregate properties, namely interparticle friction and free drainage. The ideal condition is an interparticle friction low enough for tires to sink into the aggregate yet sufficiently high to stop the vehicle within a desired distance. This condition must be maintained throughout the entire service life of the arrester bed without being influenced by freezing and other possible adverse factors. The effect of freezing can be minimized by preventing the accumulation of excess water in the arrester bed. Therefore, the aggregate must be free-draining.

To possess both low interparticle friction and high permeability, the aggregate must have rounded particles with uniform gradation. A natural aggregate that can satisfy this requirement is pea gravel; for this reason, pea gravel has been used most often in the construction of arrester beds.

Page 6: "Based on the results of this study, it can be concluded that aggregate gradation and interparticle friction are not sufficient to determine performance in the arrester bed. Factors such

as particle angularity and sphericity also greatly influence aggregate performance. Moreover, for long-term performance, particle durability is a dominant factor. Therefore, testing of aggregate for use in the arrester bed should involve determinations of not only gradation and interparticle friction but also angularity number, sphericity, and durability.

6. TRUCK ESCAPE RAMP DESIGN METHODOLOGY, VOLUME 1: EXECUTIVE SUMMARY

Author(s): Wambold, JC

Publication Date: 10/00/1988 (This report is not available, but the information may be contained in TRIS 4 (by the same author).

Abstract: One of the best and most frequently used mechanisms for stopping runaway trucks is the truck escape ramp, in particular, the gravel arrester bed. To learn more about the energy-absorbing characteristics of the stone and to develop better design criteria, the Pennsylvania Transportation Institute (PTI) conducted full-scale testing of gravel arrester beds. This report presents a summary of the data taken, the methods used for data reduction and analysis, and

conclusions based on these tests, and recommendations for gravel arrester bed design are given in chapter 8 of Volume 2. For this study, PTI constructed two 300-ft-long test ramps, one filled with rounded river-bed gravel and the other with more angular crushed gravel. Tests were performed using a dump truck and a single-axle tractor with a flatbed trailer. The data taken included entry speed, stopping distance, accelerometer data, cross-section measurements of the ruts left by the truck tires, and distance vs. time data. The river gravel exhibited greater tire penetration and volume of stones displaced along with greater deceleration forces than the crushed gravel. Existing arrester beds at the Punxsutawney, Pleasant Gap, and Freeport sites were also studied and represented the standards of excellence, showing an average deceleration of 0.516 g. However, test results show that 36 inches give similar decelerations. Finally, mounds and crash barrels filled with stone were tested and evaluated. Based on test results, a model was developed for use in arrester bed design.

7 TRUCK ESCAPE RAMP DESIGN METHODOLOGY, VOLUME 2: FINAL REPORT

Author(s): Wambold, JC; Rivera-Ortiz, LA; Wang, MC

Publication Date: 10/00/1988 (This report is not available, but the information may be contained in TRIS 4 (by the same author).

Abstract: One of the best and most frequently used mechanisms for stopping runaway trucks is the truck escape ramp, in particular, the gravel arrester bed. To learn more about the energy-absorbing characteristics of the stone and to develop better design criteria, the Pennsylvania Transportation Institute (PTI) conducted full-scale testing of gravel arrester beds. This report presents a summary of the data taken, the methods used for data reduction and analysis, and conclusions based on these tests, and recommendations for gravel arrester bed design are given in chapter 8 of Volume 2. For this study, PTI constructed two 300-ft-long test ramps, one filled with rounded river-bed gravel and the other with more angular crushed gravel. Tests were performed using a dump truck and a single-axle tractor with a flatbed trailer. The data taken included entry speed, stopping distance, accelerometer data, cross-section measurements of the ruts left by the truck tires, and distance vs. time data. The river gravel exhibited greater tire penetration and volume of stones displaced along with greater deceleration forces than the crushed gravel. Existing arrester beds at the Punxsutawney, Pleasant Gap, and Freeport sites were also studied and represented the standards of excellence, showing an average deceleration of 0.516 g. However, test results show that 36 inches give similar decelerations. Finally, mounds and crash barrels filled with stone were tested and evaluated. Based on test results, a model was developed for use in arrester bed design.

8. Title: TRUCK ESCAPE RAMP AGGREGATE. FINAL REPORT

Author(s): Derakhshandeh, M

Publication Date: 02/00/1985 *(Available from CDOT Library)*

Abstract: Performance of aggregate in various truck escape ramps in Colorado was monitored over a 2 year period. Samples were obtained and their distributions were determined. Freezing of aggregate during the winter months is closely related to the aggregate contamination problem. Discussion of the aggregate distributions and means to prevent their contamination in the arrester beds is provided. The results of this study should provide satisfactory guidelines for selecting the most appropriate aggregate type for the arrester beds of the truck escape ramps located in cold mountains.

Page 8: "Perhaps, the Oregon Department of Transportation has conducted a more comprehensive study on the aggregate gradation and performance in truck escape ramps than any other state. The study involved a comparison between 3/4 to 1/4 inch material and 3/8 inch to No. 10 pea gravel. It was concluded that the penetration of wheel loads would be very similar for both materials when each was clean and dry. But, the larger sized material was preferable with regard to freezing or contamination. To compare the freezing characteristics of two materials, they filled cylinder molds with the gravels, saturated them with water, allowed them to drain for five minutes, and then put them in a freezer. After freezing, the cylinders were removed from the molds and quickly tested for unconfined compressive strengths. The coarser, free draining material failed at around 70 PSI and the finer material failed at around 120 PSI. The better drainage of the coarse material provided a definite advantage; but, there were no direct relationships between these tests and the actual field conditions.

Page 22: "Contamination due to run-off water from the adjacent mountains seemed to be the single most important reason for aggregate freezing during the cold winter months. During the extreme cold weather conditions, the aggregate in the arrester beds tend to freeze. The degree of aggregate freezing is primarily dependent on the following factors: (1) Amount of fine material (contamination), (2) Temperature, and (3) Moisture. Visual inspections of all aggregate during the cold winter months indicated that the stiffness of the aggregate in various ramps was primarily dependent on the aggregate gradation. Larger aggregate with low degrees of contamination only developed a thin frozen crust on the surface of the arrester beds. On the contrary, the smaller aggregate with high degrees of contamination were frozen solid in full depth of the arrester beds and it was impossible to penetrate through the frozen aggregate by means of a shovel. A good example of such aggregate freezing was observed in the upper Wolf Creek truck escape ramp. Figure 3.8 shows a chunk of frozen aggregate sample obtained from this ramp during an extreme cold weather condition. In this picture the ice and the fine material have completely filled the voids between the larger aggregate. It was extremely hard to dig into the full depth (18" - 24") of the arrester bed and it was obvious that the weight of a runaway vehicle would not provide enough penetration force for the wheels to sink into such hard material. All ramps with contaminated minus one inch aggregate showed similar behavior in extreme cold weather conditions.

Page 35: Based on the literature review and the test results obtained during this research study, the following aggregate gradation is suggested for the ramps prone to freezing:

sieve Size	% Passing by Weight
2"	100
1"	25

3/4"	10
1/2"	5
3/8"	0-5

Page 41: “A.3 Aggregate Specification Recently Used by Colorado Aggregate specifications for the most recent truck escape ramp located on Monarch Pass, Colorado:

Material for Aggregate Base Course (Special) shall be composed of washed, free draining, uncrushed gravel of uniform shape and size.

The gradation requirements are as follows:

Passing 2" Sieve	100%
Passing 1'1/2" Sieve -	90 -.100%
Passing 1" Sieve -	0 - 10%
Passing No. 4 Sieve -	0 - 2%

Delete Subsection 304.04 and replace with the following:

304.04 Placing

The aggregate shall be placed dry, loose, and shall be raked smooth to the line, grades and typical cross section shown on the plans or established.

Delete Subsection 304.05 and replace with the following:

304.05 Mixing

Mixing will only be required to assure uniform grading of the aggregate as directed by the Engineer.

Delete Subsection - 304.06.

9. Title: CURRENT STATE OF TRUCK ESCAPE-RAMP TECHNOLOGY

Publication Date: 1983 *(Available from CDOT Library)*

Abstract: Drivers who lose control of their heavy vehicles on long, steep downgrades have an alternative to riding out the hill when a truck escape ramp is on the grade. There are six basic types of escape ramps in the United States. Only recently has there been an appreciable increase in the advancement of truck escape-ramp technology. Many of these advancements were developed by state transportation agencies and are documented individually in the various states' reports. The purpose of this paper is to provide a pool of information on the characteristics of the many truck escape ramps that are found in the numerous literature sources throughout the United States.

No information was found in the above study that was not mentioned in one or more of the other studies listed.

10. MT. VERNON CANYON RUNAWAY TRUCK ESCAPE RAMP

Author(s): Hayden, RL

Publication Date: 12/00/1982 *(Available from CDOT Library)*

Abstract: A gravel arrester bed type Runaway Truck Escape Ramp was built on a 5.2% downgrade along I-70 in Mt. Vernon Canyon, Colorado. The ramp was completed in July 1979 and to date it has stopped fifty-three runaway or potentially runaway trucks. Only two trucks sustained damage and there were no injuries or fatalities in the escape ramp. During the same period at this location there were eighteen accidents involving runaway trucks that did not use the escape ramp, resulting in seven fatalities and twenty-four injuries. A closed circuit TV surveillance system was included as part of the project, and twenty-three trucks were recorded on video tape as they used the escape ramp. Analysis of the tape indicated the rolling resistance to a truck in the gravel decreased as the speed increased. Further research is needed to verify and expand this finding for design purposes. Research is also needed to develop the methodology to predict the maximum probable entry speed of a runaway truck. Research is currently underway to predict the deterioration or contamination rate of the aggregate materials used in arrester beds.

No information was found in the above study that was not mentioned in one or more of the other studies listed.

11. HEAVY VEHICLE ESCAPE RAMPS--A REVIEW OF CURRENT KNOWLEDGE. FINAL REPORT

Author(s): Ballard, AJ; Kimball, CE, Jr

Publication Date: 04/00/1982

Abstract: The objectives of this study are to: (1) review current truck escape ramp literature; (2) document all acceptable designs; (3) determine any and all shortcomings in the current method of arresting heavy vehicles and recommend specific research needs to eliminate these deficiencies; and (4) develop a framework of information, criteria, and specifications concerning truck escape ramps such that national design standards may later be developed. Pertinent literature from all available sources, e.g., professional meeting proceedings, state transportation agencies' design plans and research studies, was gathered and critiqued for acceptable and poor design aspects. These design aspects are manifested in six types of truck escape ramps: sandpile, gravity ramp, ascending grade arrester bed, horizontal grade arrester bed, descending grade arrester bed, and roadside arrester bed. Each of the truck escape ramp types has some design elements, e.g., length, width, depth, signing, etc., for which there are still many unanswered questions. Thus, there are several topics suggested for future research. In addition, interim guidelines are provided for the design of truck escape ramps.

12. Excerpt from Washington State DOT Design Manual (see page 4)

http://www.wsdot.wa.gov/EESC/Design/DesignManual/desEnglish/1010-E.pdf

1010.08 Emergency Escape Ramps ***(1) General*** Consider an emergency escape ramp whenever long, steep down grades are encountered. In this situation, the possibility exists of a truck losing its brakes and going out of control at a high speed. Consult local maintenance personnel and check traffic accident records to determine if an escape ramp is justified.

(2) Design (a) ***Type.*** Escape ramps include the following types:

• Gravity escape ramps are ascending grade ramps paralleling the traveled way. They are commonly built on old roadways. Their long length and steep grade can present the driver with control problems, not only in stopping, but with rollback after stopping. Gravity escape ramps are the least desirable design. • Sand pile escape ramps are piles of loose, dry sand dumped at the ramp site, usually not more than 400 feet in length. The deceleration is usually high and the sand can be affected by weather conditions; therefore, they are less desirable than arrester beds. However, where space is limited they may be suitable.

• Arrester beds are parallel ramps filled with smooth, free draining gravel. They stop the out-of-control vehicle by increasing the rolling resistance. Arrester beds are commonly built on an up grade to add the benefit of gravity to the rolling resistance. However, successful arrester beds have been built on a level or descending grade. • *The Dragnet Vehicle Arresting Barrier.* (See Chapter 710 for additional information.) (b) ***Location.*** The location of an escape ramp will vary depending on terrain, length of grade, and roadway geometrics. The best locations include in advance of a critical curve, near the bottom of a grade, or before a stop. It is desirable that the ramp leave the roadway on a tangent at least 3 miles from the beginning of the down grade.

Design Manual Auxiliary Lanes May 2006 Page 1010-5 (c) ***Length.*** Lengths will vary depending on speed, grade, and type of design used. The minimum length is 200 feet. Calculate the stopping length using the following equation: L =

V2

0.3(R±G)

Where:

L = stopping distance (ft)

V = entering speed (mph)

R = rolling resistance (see Figure 1010-1)

G = grade of the escape ramp (%)

Speeds of out-of-control trucks rarely exceed 90 mph; therefore, an entering speed of 90 mph is preferred. Other entry speeds may be used when justification and the method used to determine the speed are documented. **Material R**

Roadway 1

Loose crushed aggregate 5

Loose noncrushed gravel 10

Sand 15

Pea gravel 25

Rolling Resistance (R) ***Figure 1010-1***

(d) ***Width.*** The width of each escape ramp will vary depending on the needs of the individual situation. It is desirable for the ramp to be wide enough to accommodate more than one vehicle. The desirable width of an escape ramp to accommodate two out-of-control vehicles is 40 feet and the minimum width is 26 feet. (e) The following items are additional considerations in the design of emergency escape ramps:

• If possible, at or near the summit, provide a pull off brake check area. Also, include informative signing about the upcoming escape ramp in this area.

• A free-draining, smooth, non-crushed gravel is preferred for an arrester bed. To assist in smooth deceleration of the vehicle, taper the depth of the bed from 3 inches at the entry to a full depth of 18 to 30 in inches in not less than 100 feet.

• Mark and sign in advance of the ramp. Discourage normal traffic from using or parking in the ramp. Sign escape ramps in accordance with the guidance contained in the MUTCD for runaway truck ramps.

• Provide drainage adequate to prevent the bed from freezing or compacting.

• Consider including an impact attenuator at the end of the ramp if space is limited.

• A surfaced service road adjacent to the arrester bed is needed for wreckers and maintenance vehicles to remove vehicles and make repairs to the arrester bed. Anchors are desirable at 300-foot intervals to secure the wrecker when removing vehicles from the bed.

A typical example of an arrester bed is shown in Figure 1010-8.

Include justification, all calculations, and any other design considerations in the documentation of an emergency escape ramp documentation.

13. Excerpt from Geometric Design Guide for Canadian Roads, 1999

Type of material:

To achieve a high deceleration rate it is necessary that vehicle tyres sink into the bed material. Rounded uncrushed gravel and single size cubic aggregate or similar artificial lightweight aggregate has performed satisfactorily in tests and should be used in preference to angular gravel (i.e. crushed rock) or sand, which tend to restrict wheel penetration and compact with time and usage.

Arrestor bed material should be free draining and adequate drainage should be provided so that in freezing or saturated conditions it still retains its function of wheel penetration, thereby bringing vehicles to a standstill. A suitable specification for the bed material is given below as a guide. This may need to be modified to allow locally available suitable materials to be used, in the light of further experience and testing. Typical specification for arrestor bed material The material should be clean, uncrushed, hard durable natural gravel consisting primarily of smooth round particles. Alternatively, an appropriate artificial lightweight aggregate may be used.

The following particle size distribution is suitable:

BS Sieve Size	Percentage by mass passing
10 mm	100%
5 mm	0%

14. Colorado Procedure 33 for Suitability of Aggregates
http://www.dot.state.co.us/DesignSupport/Field%20Materials%20Manual/2004/CP%2033-04.pdf

Colorado Procedure 33-95

Standard Method of Test for

Determining the Percent of Elongated and Flat

Particles in Natural Gravel Used in Truck Escape Ramps

1. SCOPE

1.1 This procedure describes the method for determining the suitability of aggregates for use in truck escape ramps. The escape ramp aggregate shall be uncrushed natural gravel.

1.2 Acceptable aggregate is defined as having 12% or less elongated and flat particles. Elongated and flat particles have a maximum dimension more than twice the minimum dimension.

2. APPARATUS

2.1 Balance or Scale - Balance of sufficient capacity and sensitive to 0.1 grams or 0.02 percent of the principal sample weight, whichever is greater.

2.2 Sieves - Series of sieves of the proper size necessary to determine compliance with the specifications for the material being tested. Sieves shall have square openings and shall conform to the requirements of AASHTO M 92 for wire cloth sieves.

2.3 Sample Splitter - Splitter, the minimum width of the individual chutes of which shall be approximately 50% larger than the largest particles in the sample to be split.

3. PROCEDURE

3.1 Select a sample in accordance with CP 30.

3.2 Perform a sieve analysis in accordance with CP 31. Record the portion retained on each sieve as Factor A [lbs (kg)].

3.3 By a splitting procedure, obtain a representative portion in the amounts listed in Table 33-1. Record as Factor B.

NOTE: If less than 5% of the total sample is retained on any sieve, it need not be included in the test.

TABLE 33-1

Sieve Size		Retained
1 in.	(25.0 mm)	1500 g
3/4 in.	(19.0 mm)	1000 g
1/2 in.	(12.5 mm)	500 g
3/8 in.	(9.5 mm)	300 g
No. 4		100 g

3.4 Spread the selected portion from a sieve on a well lighted flat surface, and visually separate the particles having a maximum dimension greater than twice the minimum dimension. When the separation is completed, weigh the elongated and flat particles and record as Factor C.

3.5 Repeat the above procedure on each portion representing an individual size Factor.

4. CALCULATIONS

4.1 Determine the weight (mass) of elongated and flat particles in the initial gradation portions as follows:

$$D = A \times \frac{C}{B}$$

Where:

D = Weight (mass) of elongated and flat particles in initial gradation on any one sieve,

A = Weight (mass) of initial gradation on the sieve,

C = Weight (mass) of elongated and flat particles in the total sample,

B = Weight (mass) of total sample.

The referenced Factors A, B, and C from Section 3.2, 3.3, and 3.4 respectively.

Example:

Sieve Size		
1/2 in.	$5.8 \times \dfrac{37}{500}$	$= 0.4$
3/8 in.	$4.1 \times \dfrac{27}{300}$	$= 0.4$
Totals	$\overline{9.9}$	$\overline{0.8}$

4.2

4.2 Calculate the percent elongated and flat particles as follows and report to the nearest percent:

$$\%\ \text{elongated and flat particles} = \frac{\text{Total } D}{\text{Total } A} \times 100$$

Example:

$$\frac{0.8}{9.9} = 8\%$$