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A REVIEW OF

TRUCK ESCAPE RAMPS

for

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EVALUATION OF ARRESTER BED PERFORMANCE

by

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TRUCK ESCAPE RAMPS

INTRODUCTION

Truck escape ramps, for the purposes of this review, are designed by highway engineers to safely slow down and stop a runaway vehicle. The typical runaway vehicle may be a loaded tractor trailer unit speeding down a long hill with overheated brakes and no way to stop under its own power. The vehicle ultimately reaches a velocity where curves can no longer be negotiated and crashes - into an embankment, a ravine, or another vehicle.

Truck escape ramps have been used in this country for over 30 years. There are currently over 65 escape ramps in use throughout the United States today. Of the three types (gravity ramps, sandpiles, gravel beds) of escape ramps, the gravel bed is the most predominant design used today. The aggregate used in the gravel bed has been referred to as "pea" gravel, which has many connotations, depending on the agency or part of the country one is in.

DESIGN

The design of escape ramps has evolved from a trial and error process. At the present time, there are no nationally accepted design standards for truck escape ramps. Several states have departmental policies and/or guidelines for designing escape ramps in their jurisdictional boundaries. There are numerous articles and publications on the subject; however, many lack the supporting documentation necessary to justify an overall design methodology for universal use. An article by Ballard (1) summarizes the characteristics of truck escape ramps and points out that most designs are based on empirical methods, which may not be conducive to developing the best design for a given escape ramp need.

The AASHTO publication <u>A Policy on Geometric Design of Highways and Streets</u>, 1984, contains this statement under the heading **Emergency Escape Ramps**, "...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..." This publication is used as a standard by many agencies for lack of anything more definitive.

The geometric design is fairly straightforward and predicated on safely moving a runaway vehicle from a highway to an escape ramp. However, there are a lot of questions to be answered in regard to the arrester bed, the portion of the escape ramp which stops the runaway vehicle. Specifically, what length should the bed be and what aggregate will produce the drag force coefficient used in determining the bed length.

The effectiveness of arrester beds in stopping runaway vehicles results from the interaction between vehicle motion and gravel movements. The forces acting on the vehicles can be divided into several components: air drag force, grade force, and drag force between gravels and the vehicle. Of the three forces, the drag force between gravels and the vehicle is the least-known or understood component.

Traditionally, the drag force has been called rolling resistance; however, this is really a misnomer. Drag force is generated through two mechanisms: 1) momentum that is imparted from the truck to the gravels and 2) the shear energy generated when the gravels are moved. At this time, there is no simple analytical formula to determine the drag force coefficient; however, research is underway at the Pennsylvania Transportation Institute (PTI) which may lead to such a formula.

A definitive arrester bed material and configuration has not, at this time, been fully determined. Research being conducted by PTI should provide invaluable insight to this critical area. The following examples cite the need for more quantifiable information:

1. The depth of gravel needed in an arrester bed has not been established with any certainty. (2) [CALTRANS design guide, Oct 1986]

2. Using the results of this study to determine design lengths for other arrester beds should be done with caution. The F-values [drag force] are site-specific, particularly because they depend upon the size and gradation of the gravel used in the arrester bed. (3) [Oregon DOT, Jan 1986]

3. Although it is believed that the gradation of gravels may affect the drag force, no specific study has been done to reveal the relationship between the two. (4) [PTI report, May 1983]

4. Additional needed research has been identified in the areas of: ...bed configuration and rolling resistance, material effectiveness over time, maximum and minimum size aggregate for arrester, ... (5) [ITE Journal, Feb 1982]

5. Details of gravel gradation and physical qualities for successful operation are beyond the scope of this paper. (6) [FHWA Region 9, Feb 1981]

6. Additional research is needed on arrester beds to quantify what is necessary to stop high speed runaway trucks. ...Field testing is needed so that designers can confidently predict minimum values of rolling resistance for various configurations of arrester beds. (7) [ITE Journal, May 1979]

There remains many questions to be answered in regard to acceptable aggregate gradation and recommended bed depths for the aggregate selected for a specific arrester bed. A review of some state's experience with truck escape ramp testing will further reinforce the lack of quantifiable information in the area of arrester bed design.

HISTORICAL EXPERIENCE

Drag force has been estimated by many researchers on a site specific basis. Almost every report which documents escape ramp testing has a different drag force coefficient. Many factors such as aggregate gradation, shape, texture, specific gravity, depth of bed, axle load, tire configuration, and speed effect the drag force coefficient.

Field testing done in Oregon by the Department of Transportation (3) at Siskiyou Summit Arrester Bed in 1977 had the following drag force values: 25-28 mph, 0.296-0.418; 38-42 mph, 0.279-0.356; 50-55 mph, 0.273-0.356. 38 entries were conducted in the 18 inch pea gravel (100% passing 3/4", 0-15% passing 1/2", and 0-5% passing the 1/4" screens) arrester bed. Three test vehicles were used: a five cubic yard Ford dump truck, a five cubic yard Dodge dump truck, and an International tractor and flat bed trailer (5 axles). There were two load conditions for each truck, empty and loaded. The data shows the drag force is decreasing as the entry speed increases.

A New York State study (8) [Allison et al., 1978] showed a deceleration of 0.18 g for a 21-mph entry speed, 0.32 g for a 41-mph speed, and 0.35 g for a 56-mph speed. The three entries into the 24 inch gravel (100% passing 1", 98.8% passing 1/2", and 3.7% passing the 1/4" screens) arrester bed were made by a loaded five cubic yard dump truck. This data shows the drag force increasing as the speed increases.

A Utah study (9) [Baldwin, 1975] was conducted with a 4700 lb. vehicle at speeds of 20, 25, and 35 miles per hour into selected loose gravel. The plotted data indicated that favorable results could be predicted. Based on the test results, an arrester bed was constructed with 12 inches of pea gravel (100% passing 1" screen and retained on 1/4" screen).

New Jersey (10) [Indahl et. al., 1976] did extensive testing to develop a configuration of gravel that would stop an out-of-control automobile within one hundred feet. A 3800 lb. automobile was used on gravel beds of various configurations and depths. It was concluded that a bed with a uniform height of 1.5 ft. best accommodated a 55-mph impact.

England was possibly the first country to field test gravel beds to determine rolling resistance. Laker (11) [1966] calculated a deceleration rate of 0.45g. for angular gravels in a 12 inch arrester bed tested with automobiles at 30 mph . Jehu and Laker (12) [1969] tested heavy vehicles and concluded that at a given entry speed, the mean values of deceleration were dependent upon the size and shape of the gravel, but not so much upon the vehicle type or entry speed. Values at 30 mph for a 24 inch bed of 3/8"-3/16" lightweight aggregate material (Lytag) were 0.58g.; for a 18 inch bed of 3/8"-1/4" rounded gravel, 0.6g.; and 0.45g. for a 3/8"-1/4" angular gravel. Additional full scale tests with automobiles and heavy trucks was performed by Laker (13) [1971] on Lytag to study the side-entry into arrester beds. A deceleration value of 0.5g. was found to satisfactorily stop end-on entries at 72 kl/hr without the use of brakes.

Shattock (14) [1976] in Australia conducted field testing on arrester beds of dune sand. He found partly crushed river gravel to be too flaky and angular to use. He reported a deceleration of 0.39 for dune sand. A station wagon and a single-unit truck were used in his test.

There are several articles which document entries into truck escape ramps from a performance standpoint. The articles were written to address the safety aspect of the ramps by citing actual entries by on-the-road truck drivers. Although the articles are important to document actual in-service performance, they offer little quantifiable data from which definitive conclusions can be reached. However, they are none-the-less invaluable from an empirical standpoint.

The Colorado Department of Transportation was contacted (15) to learn of their latest research efforts. A study was recently completed addressing the freezing over of the arrester bed in the high elevations. Nine arrester beds were evaluated during the winter months to determine freezing characteristics of the bed material. Drag force was not addressed. The following gradation was recommended for arrester beds in cold climates: 100% passing 2", 25% passing 1", 10% passing 3/4", 5 % passing 1/2", and 0-5% passing 3/8" screens.

The California Department of Transportation (CALTRANS) was contacted (16) to determine their latest research efforts in escape ramp technology. CALTRANS has not done any formal research with truck escape ramps. They have twice submitted research proposals to NCHRP to address design technology and to document the latest research efforts. CALTRANS is very concerned about hazardous waste spills in their beds. They would like to have arrester beds tested (tested one year with a follow-up test 2-3 years later to determine effects over time) via a research project through NCHRP; as they do not have the funds or commitment to do their own study. Most of their design criteria has been established by observing existing truck escape ramps and design experience.

Aggregate characteristics are a major concern to CALTRANS. Southern California lacks an abundant supply of high quality well rounded river gravel; therefore, suppliers in the area have a difficult time meeting the arrester bed aggregate requirements. CALTRANS would like to see additional research in the aggregate area; specifically, how the fractured faces relate to performance.

The Pennsylvania Department of Transportation has a current research project (No. 83-26) under contract to the Pennsylvania Transportation Institute addressing truck escape ramp design methodology. A final report (PTI 8617) is due soon. Fifty-three full scale tests were conducted on three existing escape ramps and two test beds. Depth of bed and aggregate characteristics were two criteria addressed. The following section will document in more detail this ongoing research.

CURRENT RESEARCH

The most extensive research to date in the escape ramp area is being conducted by PTI in Pennsylvania. The project started in 1983 with an extensive literature review (4) which documented not only the need for further research, but the lack of quantifiable data from which an optimum design procedure could be developed.

Full scale testing was conducted from 1984 to 1986. In addition to the in-situ testing, a full laboratory analysis of each aggregate in the arrester beds was conducted. There were five aggregates utilized, with top sizes ranging from 1-1/2 inches to 3/8 inches, including a crushed gravel. The following tests were performed to characterize the aggregates: gradation, specific gravity, particle angularity and sphericity, durability, and shearing resistance.

Two truck configurations were used in the field testing. An International Fleetstar dump truck and a GMC single-axle tractor with a flatbed trailer. The trucks were tested in a loaded and unloaded condition. Entry speeds ranged from 29.4 mph to 53.7 mph for the dump truck and 40.3 mph to 60.2 mph for the tractor trailer. Bed depths ranged from 15 inches to eight (8) feet.

The following information was extracted from the PTI DRAFT Final Report 83-26 dated December 1986, entitled, <u>A FIELD AND LABORATORY STUDY TO ESTABLISH TRUCK ESCAPE RAMP DESIGN METHODOLOGY</u>, by J.C. Wambold and M.C. Wang.

> Depth of bed and particle characteristics definitely play an important part in determining a drag force. The average deceleration in river gravel was 30 to 35 percent larger than that in crushed gravel. The mean deceleration increased with the increased depth of the river gravel; however, it reached a maximum between 30 and 36 inches at which point it leveled off at 0.5g.
>
> The testing also identified a "porpoising" effect. After entering the bed, the truck would sink into the gravel, to a certain depth and then pop back up,

riding almost on top of the gravel, before sinking in once again. This would account for some of the variability in drag factors encountered in previous testing at the different speeds. In gravel with a depth greater than 30 inches, porpoising was at a minimum or nonexistent if the bed was properly fluffed so there were no compacted areas. This phenomena was more noticeable in short wheel bases.

Additionally, a planing effect was established beginning at speeds of 40 to 45 mph. In order to compensate for the planing effect, a third order velocity equation is necessary to accurately determine the arrester bed length.

Loading the trucks did not have a significant effect on the stopping distance in the crushed gravel tests. This is probably because the increase in momentum is compensated for equally by the increase in the drag force caused by deeper penetration into the gravel. Loaded and unloaded conditions were also compared in the river gravel, and it was found that unloaded trucks planed more easily than loaded trucks.

The results of the study should be in final print soon. In addition to a written report, an IBM-PC computer program is being developed by PTI to allow for the interactive design of an arrester bed using river gravel, with or without mounds, and with or without barrels. The program will prompt for input.

CONCLUSIONS AND RECOMMENDATIONS

The importance of scientific data from which to base engineering judgment can not be overemphasized. This is especially true in an area which is relatively new in regard to design criteria and long term performance.

There are still questions which need to be addressed when designing a truck escape ramp. One of the most crucial is what is the safest and yet economical aggregate which should be used in an arrester bed. What is the criteria to be used in determining the quality and expected drag force coefficient of an aggregate?

Almost all reports studied which documented a drag force coefficient qualified their results by stating that their drag force was based on the particular beds tested and should not be used as standards for other designs. There is no standard test to determine drag force coefficient nor what the depth of bed should be.

The study at PTI documents many of the concerns expressed by escape ramp experts and quantifies many of the attributes required for the design of escape ramps. The extensive laboratory testing in conjunction with the field testing provides a framework which may prove invaluable in analyzing potential aggregate sources for arrester bed material. Even though the testing was specific to the aggregates in the Pennsylvania area, the methodology used can be the basis for determining aggregate characteristics elsewhere in the country.

The aggregate specifications and depth of arrester bed specified in the Arizona Department of Transportation's **TRUCK ESCAPE RAMP POLICY** (17) are consistent with the documented literature and should provide a safe design by current practice. However, the drag force coefficient is still unknown for the aggregates to be used. Arizona has no method to estimate or determine what value should be used for a particular aggregate source. The cost of the arrester bed aggregate may be the single highest expense for the construction of Arizona's truck escape ramps; therefore, research should be performed to determine what the actual drag force is for the aggregate being used.

Field testing of existing truck escape ramps and a complete characterization of the arrester bed aggregates will provide the necessary information from which a drag force can be calculated. Additionally, with the data from the PTI study, it may be possible to adjust the aggregate specification limits to find a more economical aggregate while still maintaining a high drag force coefficient in order to keep the length of the ramp as short as safely possible.

The only way to determine the drag force is through testing. In the past, almost all testing had been performed in the field. Now, with the information gathered in the PTI study, we may be able to correlate laboratory testing to actual field conditions. This should be done in Arizona. The potential benefits are cost savings in arrester bed aggregates, whether it be a specification change which may be more easily attainable by local suppliers or a reduction in the arrester bed length due to a more realistic drag force value.

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1. Ballard, Andre J., "Current State of Truck Escape-Ramp Technology," Transportation Research Record, No. 923, 1983, pp. 35-42.

2. Tye, Edward J., Design Guide for Truck Escape Ramps, Traffic Bulletin No. 24, Division of Traffic Engineering, California Department of Transportation, Sacremento, California, October 1986.

3. Hardy, Thomas A., Hamilton, Allison, and Beecroft, Gordon, Siskiyou Summit Negative Grade Arrester Bed For Runaway Trucks, Experimental Feature Project OR 77-02, Research Section, Oregon Department of Transportation, Salem, Oregon, January 1986.

4. Wambold, J.C., Yeh, E.C., Henry, J.J., and Wang, M.C., Truck Escape Ramp Design Methodology: Literature Review, Phase I Report, Pennsylvania Transportation Institute, Pennsylvania State University, University Park, Pennsylvania, May 1983.

5. Institute of Transportation Engineers Technical Committee 5B-1, "Truck Escape Ramps: Proposed Recommended Practice," ITE Journal, Vol. 52, No. 2, February 1982, pp. 16-17.

6. Newton, James M., Roadside Truck Arrester Beds, Federal Highway Administration, Region 9, San Francisco, California, February 1981.

7. Williams, Earl C., and Horne, C. Franklin, "Runaway Truck Ramps Are Saving Lives and Reducing Damage," ITE Journal, Vol. 49, No. 5, May 1979, pp. 38-41.

8. Allison, Joseph R., Hahn, Kenneth C., and Bryden, James E., "Performance of a Gravel-Bed Truck-Arrester System," Transportation Research Record, No. 736, 1979, pp. 43-47.

9. Baldwin, Glenn S., Truck Escape Lane, Materials and Test Division, Utah State Department of Transportation, Salt Lake City, Utah, September 1975.

10. Indahl, George W., Quinn, John J., and Afferton, Kenneth C., Vehicle Entrapment, New Jersey Department of Transportation, Trenton, New Jersey, June 1976.

11. Laker, I. B., Vehicle Deceleration in Beds of Loose Gravel, Lab. Report 19, Road Research Laboratory, U.K., 1966.

12. Jehu, V. J., and Laker, I. B., Vehicle Decelerations In Beds of Natural and Artificial Gravels, Road Research Laboratory, U.K., 1969.

13. Laker, I. B., Tests to Determine the Design of Roadside Soft Arrester Beds, Road Research Laboratory, RRL Report No. 376, U.K., 1971.

14. Shattock, J. W., "Deceleration Bed Tests of Dune Sand," Australian Road Research Board Proceedings, Vol. 8, Session 22, August 1976, pp. 10-15.

15. Derakhshandeh, M., Colorado Department of Highways, Denver, Colorado, Telephone Communique, December 1987.

16. Tye, Edward J., Division of Taffic Engineering, California Department of Transportation, Sacremento, California, Telephone Communique, December 1987 and October 1986.

17. Traffic Engineering Section, <u>Truck Escape Ramp Policy</u>, Arizona Department of Transportation, Phoenix, Arizona, January 1987.

ANNOTATED BIBLIOGRAPHY:

(1) Allison, J.R., Kenneth, C.H., and James, E.B., "Performance of a Gravel-Bed Truck Arrester System," Transportation Research Record No. 736, Transportation Research Board, Washington, D.C., 1979.

This article documents various aspects of the design, construction and testing of a truck-arrester system on the downslope on NY-29, known as Vickerman Hill, near Mohawk, New York. A precise description of construction and specifications is included. Documentation regarding gravel size, plan and profile of the bed location are attached. Also included are test procedures, discussion of results and conclusions of the tests

(2) Baldwin, G.S., Truck Escape Lane, Materials and Test Division, Utah State Division of Transportation, Salt Lake City, Utah, Sept., 1975.

The report documents the escape ramp on I-80 , Parley's Canyon, Utah and gives site location and all relevant information concerning construction of the ramp. Included is one account of actual ramp use by an out-of-control truck. A mathematical model of the estimated decelerating effects of Parley's Canyon truck escape is presented along with some deceleration value.

(3) Ballard, A.J., "Current State of Truck Escape Ramp Technology,", Transportation Research Record No. 923, Transportation Research Board, Washington, D.C.,1983.

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.

(4) Brown, R.G., "Report on Arrester Bed Tests Carried Out by the New South Wales Department of Main in March, 1982," Australian Road Research Board Proc., Vol.12, No.7, 1984.

The design of arrester beds, also known as deceleration beds, is dependent on an accurate estimation of the deceleration of a vehicle entering the bed at speeds up to 160 km/h. This paper describes field testing undertaken in March, 1982 of two arrester beds constructed on a level disused airstrip. These beds, one made with dune sand and the other with 10 mm rounded river gravel, were tested at entry speeds ranging from 60 km/h to 94 km/h by loaded and unloaded rigid body and articulated vehicles. Deceleration in an arrester bed was found to be dependent on vehicle type, vehicle load, entry velocity, bed material and bed depth. The deceleration characteristics derived from the tests were then used to devise formulae for estimating the required length of a sand or gravel arrester bed.

(5) Carrier, R.E., Pachuta, J.A., Runaway Trucks in Pennsylvania, Report No. SAE 811262, Society of Automotive Engineers, 1981.

This paper addresses efforts to develop runaway truck countermeasure programs and facilities. A summary of Pennsylvania's truck accident experience and a brief analysis of the driver-roadway-vehicle interaction is given. This program is described as it is being implemented in one highway district which has severe grade problems. A specific example of a runaway truck escape facility is described in detail. A full scale trial using a loaded tandem dump truck is described. Additionally, the field performance of an actual runaway truck facility is given.

(6) Derakhshandeh, M., Truck Escape Ramp Aggregate, Final Report,Report No. CDOH-DTP-R-84-4, Colorado Department of Highways, Denver, Colorado, Feb., 1985.

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.

(7) Eck, R.W., "State Practice And Experience in the Use and Location Of Truck Escape Facilities," Transportation Research Record No. 736, Transportation Research Board, 1979.

One phase of a study undertaken to develop warrants for the use and location of truck escape ramps is described. A questionnaire submitted by mail to state highway agencies sought information on (a) the type and number of escape facilities constructed, (b) variables considered in determining the need for escape ramps, (c) factors that affect ramp location, and (d) operational experience with escape ramps. The study results indicated that, although most ramps are located on four-lane divided and two-lane highways, they can also be found on three-lane routes, in medians, and at the end of freeway off-ramps. Only two states indicated that a rational techniques made use of accident rates. Other important factors in determining the need for escape ramps included length and percentage of grade, percentage of trucks, and conditions at the bottom of grades. Topography was cited as the primary factor in ramp location. Examples of satisfactory and unsatisfactory ramp location are described.

(8) Erickson, R.C., Jr., A Field Test Of a Grade Severity Rating System, Colorado Department of Highways,Traffic Engineering Branch, Denver, Colorado, April, 1985.

A national research project has shown that truck brake temperature on grades is a major problem causing runaway trucks. Control of overheating of truck brakes can be achieved through correct speed. A truck brake heating model lead to development of a Grade Severity Rating (GSR) System to be used with a Weight Specific Speed (WSS) sign. The Colorado Department of Highways has cooperated with an FHWA contractor to test the GSR system and the WSS sign. Interim results of test have been inconclusive as to the reduction of speed of heavy trucks. The WSS sign should be extended for three years to permit additional study of the effectiveness of the signs. Before and after accident data will be submitted to FHWA to indicate the effect of these signs on driver response.

(9) Hardy, T.A., Hamilton, A., and Beecroft, G., Siskiyou Summit Negative Grade Arrester Bed For Runaway Trucks, Final Report, Experimental Feature Project OR 77-02, Oregon State Highway Division, Salem, Oregon.

This report documents the design, construction and on-site testing of a negative grade runaway truck escape ramp on I-5 near Oregon- California Border. Based on this study, it was concluded that design length should be done carefully. The performance of this negative grade escape ramp has been defined satisfactory. Several recommendations have been made for aiding in the design of a negative grade arrester bed.

(10) Hayden, R.L., Mt. Vernon Canyon Runaway Truck Escape Ramp, Final Report, No.FHWA-CO-RD-83-03, Colorado Department of Highways, Denver, Colorado, Dec., 1982.

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.

(11) Hunter, W., Crowe, N.C., Jr., Cole , David G., An Examination Of Runaway Truck Escape Ramps, Report No. HS-023 754, University of North Carolina, Hwy. Safety Research, 1978.

The effectiveness of the design of two runaway truck escape ramps along a section of highway in North Carolina has been and continues to be evaluated using photographic surveillance and accident data from investigation reports of ramp usage. Brake failures on large trucks descending steep grades in the mountains of North Carolina have annually accounted for a large amount of fatalities, injuries, and property damage. On 1 Feb 1974, the North Carolina Div. of Highways opened a runaway truck escape ramp on a 5-mile, 6% to 8% grade section of U.S. 70 between Ridgecrest and Old Fort, N.C. After the opening of this escape ramp, it was found that the ramp was used so frequently that an additional back-up ramp was constructed just downhill from the first ramp and made operational on 15 Dec 1975. The ramps are constructed of sand and are approximately 350 ft in length, rising in elevation from 0-10 ft above the roadway in order to present the truck with a level (0 percent grade) runway. The runway is approximately 30-ft wide at the mouth and widens to approximately 45 ft at the far end. The surface has been shaped into irregular surface mounds approximately 3 ft high on 15-ft centers. The accident study has shown the escape ramps to be highly effective. In all cases except one, the runaway vehicles were stopped, the sole exception involving an entry speed of 80 mph. Most ramp impacts produce only property damage. The recently undertaken photographic surveillance study of actual truck involvements, using two movie cameras with wide angle lenses, will aid engineers in determining the most effective design characteristics for future escape ramps (length, ramp grade, materials (e.g. pea gravel vs. sand), and the behavior of trucks with varying heights and weights at differing entry speeds). Initial and maintenance costs of the ramps are low; this combined with the overall low injury experience and low property damage to the vehicles make the project highly cost-beneficial.

(12) Indahl, George W., Quinn, John J., and Afferton, Kenneth C., Vehicle Entrapment, New Jersey Department of Transportation, Trenton, New Jersey, June 1976.

The New Jersey Department of Transportation conducted a study to develop a configuration of gravel that would act as a vehicle arrester, 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 arrester bed configurations were tested using a local 3/8 in. (1cm) washed pea gravel. Overall, the pile bed with a uniform height of 1 1/2-ft (.46-m) piles resulted in the best design to accommodate a 55-mph (88.5-km/h) impact. The performance of other bed configurations was less acceptable, 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.

(13) Institute of Transportation Engineers Technical Committee 5B-1, "Truck Escape Ramps: Proposed Recommended Practice," ITE Journal, Vol.52, No.2, Feb., 1982., PP.16-17.

This briefly describes a full report by the ITE Technical Committee on the history of truck escape ramps, circumstances concerning their location, design, Maintenance and costs and the need for on-going research. It also lists the conclusions of the report on the feasibility of certain types of escape ramps

(14) Jehu, V.J., Laker, I.B., Vehicle Decelerations In Beds Of Natural And Artificial Gravels, Road Research Laboratory, U.K., 1969.

Deceleration measurements of vehicles running into beds of loose gravel were extended to include heavy vehicles and to cover private cars at speeds up to 61 mph. Characteristics of arrester beds are examined. Their most promising use appears to be as escape routes from long down-gradients for vehicles which experience brake failure.

(15) Jenkins, J.C., Beecroft, G.W., Quinn, W.J., Evaluation of Truck Escape Ramp Characteristics, Oregon Department of Transportation, Salem, Oregon.

Typically, truck escape ramps have been designed to combine the energy absorbing characteristics of a pea gravel roadbed with an ascending grade to stop trucks that have lost their brakes on long downgrades. Frequently, terrain is such that it is not feasible to obtain an upgrade to assist in decelerating the vehicle. The escape ramp associated with this study has a 5.5 mile downgrade from the Siskiyou summit in Southern Oregon. The escape ramp is the same as that of the roadway, minus 5.5%. The objective is to determine the stopping characteristics of trucks in the 18" deep bed of3/4" to 1/2" gravel. Tests will be made with different trucks, loaded and unloaded, at

speeds of 25,40, and 55 miles per hour. Low transverse gravel mounds will also be evaluated for their capability in absorbing the energy of runaway trucks.

(16) Johnson, W.A., DiMarco, R.J., Allen, R.W., The Development And Evaluation Of a Prototype Grade Severity Rating System, Report No: FHWA-RD-81-185, Federal Highway Administration Office of Research and Development, Washington D.C., March, 1982.

This report summarizes a study to evaluate techniques for reducing the incidence and severity of truck downgrade accidents. It includes a description of an improved version of a grade severity rating model, and detailed instructions for using it to determine a recommended maximum grade descent speed for each of several truck weight ranges on any given grade. These maximum recommended speeds could be posted on a weight-specific speed (WSS) sign at the beginning of a grade. This would enable truck drivers to descend the grade in a safe manner without guesswork in selecting a speed. Additional driver simulator and field tests of the weight-specific speed signs format will be carried out to determine the most effective WSS sign. Other tasks that were carried out on this study and reported herein are to develop a means for determining the cost-effectiveness of alternative techniques, to evaluate the cost-effectiveness of alternative techniques, and to determine criteria for deployment of the techniques. Full-scale field tests as well as a simulation in a fixed-base truck simulator were used in carrying out these tasks. Examples of the techniques considered included several types of signing, a grade severity rating system, and truck escape ramps.

(17) Laker, I.B., Tests to Determine the Design of Roadside Soft Arrester Beds, Road Research Laboratory, RRL Report No. 376, U.K., 1971.

Full-scale tests have shown that soft arrester beds should be suitable for stopping vehicles which lose their brakes on long down-gradients. The deceleration of private cars and heavy vehicles was measured after end-on entry at high speeds into a long bed of lightweight aggregate material (lytag). With end-on entry all the vehicles were stopped satisfactorily from 72 km/h without the use of brakes at a deceleration value of about 0.5g. In the case of the dual-track bed a 300 mm high curb was required along the far side to ensure that the vehicles were contained within it for typical side-entry angles of 5 - 10 degrees to the length of the bed. In the case of the single track bed, a 300 mm high curb surmounted by a hydraulic crash barrier was found to be necessary. This arrangement decelerated vehicles at about 0.3g on level ground corresponding to about 0.2g on a down hill gradient of 1 in 10.

(18) Laker, I.B., Vehicle Deceleration in Beds of Loose Gravel, Lab. Report 19, Road Research Laboratory, U.K., 1966.

This report describes tests to measure vehicle deceleration when they were driven into beds of gravel of different depths and types at different speeds. Several conclusions were made regarding size of gravels and depth of gravel bed.

(19) Overend, R.B.,"Truck Escape Ramps:Exits To Safety," Traffic Safety, Vol.79, No.8, 1979.

The design of truck escape ramps is addressed, with reference to the construction of ramps in Colorado, Oregon, Idaho, Washington, Utah, New Mexico, Texas, California, Virginia, West Virginia, Pennsylvania, North Carolina and Tennessee. Highway departments in many parts of the country are building ramps at key locations

where truck drivers have been killed in run-off-the-road crashes. Most ramps follow a similar design pattern. Signs on a downgrade alert drivers of trucks with failing brakes to a strip of loose gravel or sand which allows tires to sink in and thereby slow the vehicle. To further slow the truck, ramps are built on an upgrade, except in some areas where terrain necessitates that ramps go downhill. Ramps range in length from 250 to 1,200 feet. Costs of installing ramps vary from $8,000 for a 250-foot ramp in Pennsylvania to $245,000 for a 1,200-foot ramp in Oregon. Terrain is a major factor in construction costs. A survey by "Traffic Safety" magazine of 17 states and one Canadian province, indicates that 12 states have escape ramps and find them to be worth the cost. Procedures followed by various states in the design and construction of ramps are described.

(20) Pigman, J.G., Agent, K.R., <u>Evaluation of Truck Escape Ramps</u>, Report No.UKTRP-85-3 University of Kentucky Transportation Research Program, Lexington, Kentucky. Jan., 1985.

Out-of-control vehicles on steep grades have the potential for and frequently do result in severe accidents. There are two truck escape ramps in Kentucky, and both were constructed as a result of severe accidents and the potential for additional accidents. One escape ramp is on the Hyden Spur (KY 118) in Leslie County. Because of geometric conditions of the highway and topographic constraints, an arrester-type escape ramp was designed with pea gravel as the arrester material. The beginning of the ramp is a 386-foot paved section on an 8-percent downgrade; followed by a gravel bed 520 feet long on a 4-percent downgrade. This ramp was opened for use in 1980, and it has been used four times in emergency situations. The other escape ramp is on KY 11 leading into Beattyville in Lee County and is a combination gravity and arrester design. The ramp includes a 400-foot paved approach, followed by a 700-foot arrester bed over a 1.5-percent downgrade and then a 210-foot arrester bed over a 14-percent upgrade. There has been only one reported emergency usage of this ramp since it opened in 1980. Overall, the escape ramps have proven to be operating properly and appear to be performing as they were designed. Of the five cases where the ramps were used by out-of- control vehicles, no one has been injured and there has been very little damage to the vehicles involved.

(21) "Roadside Bunkers to Trap Runaway Trucks", <u>Public Works</u>, Vol.103, No.7, July, 1972.

In mountainous and hilly parts of California many towns located at the base of highways traversing these grades are endangered by trucks whose brakes have failed. The problem was given of the materials and research laboratory of the division of highways, which in turn requested a computerized search of the files of the highway research information service, sponsored by the Highway Research Board in Washington, d.c. This search revealed that three engineers at the Road Research Laboratory in England had conducted research on the problem and published a report that indicated satisfactory results from construction of beds of pea-size gravel in the medians of long downhill grades. By turning his wheels into the beds, the driver of a runaway vehicle might hope to be a slowed to safe speed by the energy-absorbing inertia of the carefully selected loose material. The division of highways is now constructing three "arrester beds" on a two-mile grade outside La Canada, near Los Angeles. Signs at the top of the grade will encourage drivers of brakeless vehicles to enter the median. If the project is successful, the method will be extended to other areas where state highways traverse steep hills.

(22) Rooney, F.D., Speeds and Capacities on Grades, Climbing Lanes, Passing Lanes, and Runaway Trucks, California Department of Transportation, Division of Transportation Operations, Sacramento, California, May 1985.

This report provides guidelines for determining capacities for upgrades along proposed highways and tests the factors to be taken into account when determining whether climbing lanes, passing lanes and truck escape ramps should be constructed. Because the steepness of an upgrade can affect their average speeds, thee passenger car equivalencies of trucks will vary widely (e.g., 2 on level ground several on a typical significant grade). Therefore, the upgrade should be taken into account when determining the capacity of a given stretch of highway. There are no absolute criteria for where climbing lanes and passing lanes should be constructed. Factors include the environment, typical trip distances, corridor design continuity, present and probable future traffic volumes and volume to capacity ratios, present and probable future truck and recreational vehicle volumes, number of vehicles delayed by slow vehicles, congestion, costs and benefit to cost ratios including vehicle operating costs, delay and safety. If the maximum safe downgrade speeds for trucks along a new or realigned highway would be near or less than either 55 mph or the speeds at which the curves can be safely driven, a study should be done regarding whether one or more truck escape ramps should be constructed. Factors include total traffic volumes, truck volumes, especially of three, four and five-axle trucks, the number of lanes downgrade, whether there would be so many curves that most runaway trucks would run off of the road prior to one or more truck escape ramps and whether there would be a safe area such as a tangent freeway for runaway trucks to decelerate beyond the downgrade provided that the trucks did not run off of the road or hit other vehicles. Posted speed limits for trucks may possibly reduce accidents but are usually not a factor regarding whether one or more truck escape ramps should be constructed along new or realigned highways.

(23) Schultz, M., "How We'll Run Killer Trucks Off The Roads," Popular Mechanics, Vol.152,No.3, 1979.

Fatalities in U.S. truck-related accidents increased consistently from 3483 in 1975 to 5120 in 1978. In 1978, the 191,837 new registrations of heavy trucks hit an all-time high, up 23% from 1977. On-the-spot investigations by the National Transportation Safety Board (NTSB) have found that many accidents result from mechanically deficient trucks and/or irresponsible operation. Of the 29,936 accidents in 1977 involving heavy trucks regulated by the Interstate Commerce Commission, 1650 involved trucks with mechanical defects; contributing to the remainder were truck or light-vehicle driver negligence, drinking, fatigue, and highway conditions. In one spot safety check in Pennsylvania in 1978, 382 out of 711 trucks were found in a hazardous condition. Since brake defects are the major culprit, NTSB urges construction of runaway "escape ramps" to avert brake-loss accidents on steep grades. The new Federal Motor Vehicle Safety Standard (FMVSS) 130 (revision of FMVSS 121) sets requirements in such areas as better resistance of truck brakes to heat buildup, a reasonable 60 mph stopping distance, and backup braking. Other National Hwy. Traffic Safety Administration proposals to reduce heavy-truck accidents include self-adjusting brakes for new trucks, better policing to get illegal/unsafe drivers off the road, stricter operating hours, speed-governing devices, installing tachographs, and underride barrier standards. The industry's self-regulation efforts are no substitute for the removal from the highway of incompetent and unsafe drivers, through government and industry cooperation. Some defensive driving tips for the motorist include keeping to the right lane, dropping speed and pulling close to shoulder on two-lane highways when a truck wants to pass, using lights to help trucks pass, being

aware of potential runaways, and checking traffic before crossing signalized intersections.

(24) Shattock, J. W., "Deceleration Bed Tests of Dune Sand," Australian Road Research Board Proceedings, Vol. 8, Session 22, august 1976, pp 10-15.

Sites for conventional safety ramps are difficult to obtain in the Wollongong Area of New South Wales, Australia. The Road Research Laboratory (presently Transport and Road Research Laboratory) in the United Kingdom has tested deceleration beds of gravel and artificial aggregate, but similar materials are not available near Wollongong. This paper describes the field testing of a deceleration bed of dune sand on a level site using a station sedan and a single-unit truck with a gross weight of 10 tonnes. Entry speeds ranging from 20 km/h to 85 km/h were covered, and the deceleration obtained was of the same order as that achieved by the gravel and artificial aggregate beds in the RRL tests. Stopping distance was found to be similar for both test vehicles and dependent on entry speed.

(25) Stanley, A.F., Calculator Program for Selecting the Locations, Grades and Lengths of Gravel Bed Truck Escape Ramps, Idaho Department of Transportation, Division of Highways, Boise, Idaho.

The project objective is to develop an easy-to-use program for programmable desk calculators, to be used as a design aid for gravel bed escape ramps. An energy balance approach is used to estimate the speed of a coasting truck on pavement or in loose gravel. Some field verification of program results is included in the project. The Program is available upon request.

(26) Stein, A.C., Johnson, W.A., "Effective Signing to Reduce Truck Downgrade Runaways" American Association for Auto Medicine Conf Proc., 1984, PP 77-89.

This paper discusses two aspects of the runaway problem. First, it presents a brief discussion of escape ramps. Ramps have been a traditional means of containing a runaway truck, and have proven successful in this endeavor. The second, and major portion of the paper discusses the development of a grade severity rating system which is used to create roadside signs to tell drivers the appropriate descent speeds based on gross truck weight. This methodology represents a major step forward in highway safety as it tells the driver WHAT TO DO, rather than presenting information which requires further evaluation.

(27) Trueblood, M.S., Design and Construction of a Truck Arrester Bed Research Facility, Pennsylvania State University, Department of Mechanical Engineering, University Park, Pennsylvania , Aug., 1984.

During the summer of 1984, an Arrester Bed Research Facility was constructed adjacent to the Pavement Durability Research Facility of the Pennsylvania Transportation Institute. The Arrester Bed Research Facility is to be used for experimentation in the mechanism of stopping runaway vehicles with escape ramps. The results of the study will be empirically-substantiated criteria for the design of highway escape ramps. This report is the first segment of a paper which will include descriptions of (1) construction of the arrester bed, (2) experiments performed, (3) analysis and presentation of results, and (4) recommended design criteria. Specific items covered in this first report are (1) background information, (2) design description, (3) construction phase elements, and (4) work sampling studies and productivity reports.

(28) Tye, EJ, Design Guide for Truck Escape Ramps, Traffic Bulletin, Division of Traffic Engineering, Caltrans, No.24, Oct., 1986.

(29) Walker, G., Better Brakes For Mountain Mining Trucks--A Progress Report, Report No. SAE-77066, University of Calgary, Calgary, Alberta, Canada, 1977.

A new Code of Practice for the brake performance of off-highway vehicles was established in Alberta (Canada) in 1976. Vehicles loaded to gross vehicle weight must be capable of stopping with mechanical brakes five times in quick succession on a grade of 10% from a speed of 26 mph. Comparative trials (powered drag tests, loaded downhill stopping tests) have been conducted of various brake systems on rear-dump trucks (heavy mine vehicles), and some combinations capable of meeting the Code have been established. The Code is a practicable attainable minimum standard of braking performance requirements that should do much to improve the safety of personnel in loaded downhaul operations. Continuing areas of interest and concern in heavy mine-haul truck braking include the effects of high dynamic loading during downhill operation on single front tires, front-axle components, and steering mechanisms; the practice on some of the large electric-wheel trucks of driving the metal friction disc of the rear-wheel disc brakes at the wheel motor armature speed; and provision of means to reduce the front-wheel braking effect ("slippery road valve"). A number of concepts have been explored for runaway-truck emergency brakes and best results have been obtained in model tests with the "slipper flap" system, in which flat material hanging below the truck box is released in an emergency, falls under the rear wheels, and skids along the ground. This would be suitable for installation on existing older trucks.

(30) Wambold, J.C., Wang, M.C., A Field And Laboratory Study To Establish Truck Escape Ramp Design, DRAFT Final Report, The Pennsylvania Transportation Institute, Pennsylvania State University, University, Park, Pennsylvania, December 1986.

This study was undertaken to study the energy absorbing characteristics of the gravel in the gravel arrester bed and to develop better design criteria at Pennsylvania Transportation Institute at The Pennsylvania State University. Full scale testing of gravel arrester bed was conducted. This report summarizes the data taken, the methods used for data reduction and analysis, conclusions based on these tests and recommendations for arrester beds. Test ramps were constructed, one with river gravel and the other with angular crushed gravels. It was found that rounded river gravels produced more deceleration than the more angular crushed gravel. Loading the truck did not have any significant effect on the stopping distance in the crushed gravel. Finally, mounds and crashed barrels filled with stone were tested and evaluated. Based on the test results, a model was developed for use in arrester bed design.

(31) Wambold, J.C., Yeh, E.C., Henry, J.J., Wang, M.C., Truck Escape Ramp Design Methodology: Literature Review. Phase-1 Report, Pennsylvania Transportation Institute, Pennsylvania State University, University Park, Pennsylvania, May, 1983.

Runaway heavy vehicles on long, steep down grades, if not properly stopped, can cause loss of life and huge amounts of property damage. This report is a summary of a literature review of truck escape ramp design, particularly the arrester bed filled with gravel. The review encompassed four aspects: current design methodology, field and laboratory tests, performance history, and initial cost and

maintenance. Recommendations and conclusions are given, and an annotated bibliography is appended.

(32) Williams, E.C., Jr., Skinner, H.B., Young, J.N., "Emergency Escape Ramps for Runaway Heavy Vehicles," Public Roads, Vol.42, No.4, March, 1979.

This article summarizes the findings of the State-of-the-Practice Report on truck escape lanes which was developed by the Tennessee Department of Transportation for the Federal Highway Administration's Implementation Division. It also includes an example of the development of a truck escape ramp in the Siskiyou Mountains of southern Oregon.

(33) Williams, E.C., Horne, C.F., "Runaway Truck Ramps are Saving Lives and Reducing Damage," ITE Journal, Vol.49, No.5, 1979.

The basic EERRHV (Emergency Escape Ramps for Runaway Heavy Vehicles) types used in the U.S. today are described (gravity ramp, arrester bed, and combination of the two). Positive points of the gravity ramp include: no need for special equipment to remove truck from ramp, minimal routine maintenance, and no impairment by adverse weather. This type of ramp is usually expensive because it must be long enough to dissipate the forward energy of the truck. The arrester bed does not need to be nearly as long as a gravity ramp, and the initial cost is lower. The surface does not require a special treatment, and it is easier to locate near the problem area. Once the vehicle is stopped, it will not roll back, and very little damage is done to the vehicle, although it sometimes takes two wreckers to pull out a tractor-trailer. The ramp surface must be redressed after use, and snow and freezing rain may cause minimal problems. An arrester bed should be wide enough to accommodate more than one vehicle. It is emphasized that no one type or style of runaway ramp is feasible in all situations; each location and physical condition must be considered individually. The success of an EERRHV involves informing the motoring public of ramp function and purpose, and installing signs to inform the driver of ramp location. It is concluded that the use of runaway truck ramps and brake check areas, along with truckers' awareness of the potential dangers of runaway vehicles, may well be the most cost-effective and rational alternatives for minimizing steep grade hazards. Research is needed to obtain certain critical ramp performance data. There are at present no formal design or construction criteria for guidance in planning these essential safety features.

(34) Williams, E.C., Jr., Emergency Escape Ramps For Runaway Heavy Vehicles, Report No.FHWA-TS-79-201, Tennessee Department of Transportation , Nashville, Tennessee, March, 1978.

This report presents a state-of-the practice synopsis of EERRHV technology, findings of a current questionnaire survey, and an overview of existing ramp facilities in regard to design, construction, and practical operational techniques. Several existing emergency escape lanes are described, listing many of the benefits and shortcomings of each.

(35) Young, J., ,"Field Testing a Truck Escape Ramp ;Descending Truck Escape Ramp as an Alternative for Runaway Truck Problems," Highway Focus, Vol.11, NO.3, Sept., 1979.

In an attempt to provide an insight into the use of a descending truck escape ramp as an alternative for runway truck problems, this report describes the

development of the Siskiyou truck escape ramp, testing procedures used to evaluate the ramp's effectiveness, preliminary results, findings and recommendations. Information is also presented on the material requirements of the gravel bed and instances of actual use of the escape ramp. Construction details and maintenance are described. If the need for a truck escape ramp is established, the ascending ramp should be the one considered for application. However, if the terrain prohibits the use of an ascending ramp, consideration should be given to the descending truck ramp comprised of gravel arrester bed as possible alternative. Where freezing temperatures or the potential for arrester bed contamination by fine soils exists, the ascending bed design should be retained wherever possible.