THE DESIGN OF VEHICLE ARRESTER BEDS

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ABSTRACT

An investigation was carried out to develop selection criteria for fill material for a vehicle arrester bed. Three trial beds were constructed. Tests were carried out using a car, a rigid truck and a large articulated vehicle. Entry speeds over a range of 11 km/h to 63 km/h were used. The results of the trials indicated that the average deceleration rate is dependent upon entry speed and is at a maximum for entry speeds of approximately 50 km/h and decreases for increases in entry speed above the figure. This fact is significant because some earlier published results suggest that the average deceleration rate remains constant after the maximum value is reached. Tests with the single axle rigid truck were carried out in both a laden and unladen condition. The results indicated that vehicle mass has little effect on deceleration rate whereas axle and tyre configuration did. The large articulated vehicle which had tandem axles on both the prime mover and the trailer had a lower deceleration rate than the single axle rigid truck. For effective performance in an arrester bed, the fill material should consist of uncrushed gravel, which is essentially single sized with a nominal size of five to ten millimetres. The individual particles should be round and smooth such that there is a low angle of internal friction. A simple slump angle test was developed as a measure of this last property.

INTRODUCTION

1. The problem of runaway trucks with brake failures on long steep grades is well known. The use of an arrester bed of soft earth or loose gravel to provide a safe means of stopping out-of-control vehicles has been reported by Bade (1968), Laker (1971), Shatlock (1976), Allison, Hahn and Bryden (1978) and Versteeg (1978).

2. In 1977 the Main Roads Department, Western Australia (MRD WA) commenced an investigation into the design of vehicle arrester beds. A trial bed was constructed and filled with crushed granite. However, observation of the material under the action of construction traffic indicated that it would not provide the necessary rolling resistance for the effective arrest of an out-of-control vehicle. Construction vehicles were able to move over the material with little appreciable penetration.

3. As a result of the poor performance of the crushed granite, the MRD WA concentrated its investigation on the determination of properties likely to lead to satisfactory performance of a material in an arrester bed. This investigation included full scale vehicle tests in two trial arrester beds to determine the deceleration rate of an unbraked vehicle entering the bed. The materials tested in the two test beds were both screened laterite pea gravels. Both were from the

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same source but produced by different screening processes. The nominal size of the gravel was seven millimetres.

4. From consideration of the results of the MRD WA trials and those others reported in the literature, it was concluded that the principal factors affecting the rate of deceleration of a vehicle in an arrester bed are as follows:

(a) Vehicle entry velocity.
(b) Material properties.
(c) Vehicle type.
(d) Arrester bed geometry.

In general, average deceleration rate is low for low entry velocities, increases with increasing entry velocity until a maximum is reached, then decreases as entry velocity continues to increase. The significance of this relationship to arrester bed design and an explanation as to the causes are discussed in this paper. The material properties likely to lead to a high deceleration rate (i.e. the desirable properties) are round, smooth particles and single sizedness. The ideal size has not yet been determined but is probably about five to ten millimetres nominal size. Though there is insufficient evidence from field tests for a definite conclusion to be reached, it is probable from theoretical considerations that a low particle density is desirable. The vehicle factor having the most significant effect on deceleration rate is axle configuration. For a given vehicle type, vehicle mass has a minor effect on deceleration rate. Arrester bed geometry, particularly slope, depth of material and surface shape, can also have an effect on deceleration rate. As part of this investigation a test, to assess the suitability of a material as fill in an arrester bed, was developed.

5. In addition to a knowledge of deceleration rate in an arrester bed, it is necessary in preparing a design to make an assessment of probable entry velocity of an out-of-control vehicle. As part of this investigation, a method was developed for estimating the velocity of a vehicle rolling downhill, without braking and out of gear.

The results of most of these tests were presented as a relationship between 'mean deceleration rate' and entry velocity. The mean deceleration in each case being calculated from the measured stopping distance using eqn (1).

\[ \alpha = \frac{V^2}{2Lg} \]  

where \( \alpha \) = mean deceleration (g)
\( V \) = entry velocity (m/s)
\( L \) = stopping distance (m)
\( g \) = acceleration due to gravity (9.81 m/s²)

The results of tests reported in the literature plus those reported here (MRD WA) showed that the general form of the relationship between deceleration rate and entry velocity is as shown in Fig 1.

6. Vehicle deceleration in beds of natural gravel, artificial gravel and sand have been reported for trials conducted by the Road Research Laboratory (TRRL), now the Transport and Road Research Laboratory, the Royal Aircraft Establishment (RAE), the Department of Main Roads, New South Wales (DMR), the New York State Department of Transportation (NYSDOT) and the Oregon State Highway Division (OSH). The RAE tests involved the use of a road vehicle, various aircraft and scaled model tests. Tests reported by the others related to road vehicles only.

7. Barnes (1971) in reporting the results of tests at the RAE suggested an explanation of the general form as follows:

When the wheel is moving slowly forward, the motion is resisted by the soil frictional and cohesive forces, but the act of disturbing the soil ahead of the wheel may decrease or increase the forces from their undisturbed values by causing compaction or dilation of the soil structure. Drag also arises due to the heaping up of soil ahead of the wheel in the form of a wave. As the speed increases impingement of the soil on the wheel and tyre create a dynamic pressure which might further modify the local state of compaction and hence the shear resistance. Whether shear resistance increases or decreases probably depends upon the undisturbed state of compaction. The pressure acting on the tyre gives rise to lift and drag forces on the wheel which in turn have the effect of increasing soil bearing strength and reducing sinkage. Although the dynamic drag force continues to increase with increasing speed a stage is reached when sinkage is reduced to such an extent that the net drag force is also reduced. Under these conditions it is
probable that the inertia forces are dominant although the speed at which this is likely to occur is not known. It is however likely that the planing condition occurs at a speed less than that calculated from consideration of the equality of tyre and dynamic soil pressures.

8. The effect of tyres planing on the arrester bed surface at high entry velocity has fairly serious implications in terms of design. The velocity of runaway vehicles is likely to put them past the peak of the curve shown at Fig 1. Most test results with road vehicles have been conducted with entry velocities less than this value. Test results reported by Bade (1968) using aircraft extended to 150 km/h and model tests to 180 km/h (scaled velocity). The effect of reduced rolling resistance due to planing is most pronounced at these higher velocities.

9. The general form of the mean deceleration/entry velocity curve was common in many tests by others. However, the actual decelerations measured varied considerably with both vehicle and material type. While the desirable material properties for a gravel arrester bed have been defined in the descriptive terms as 'small stones with a high degree of roundness' (Laker 1966), no reliable method of predicting deceleration rate based on simple laboratory tests is available from published research work. For this reason the MRD WA decided to undertake full scale tests in trial arrester beds using what was considered to be the 'best' locally available materials.

### TABLE I

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>MESH SCREENED LATERITE</th>
<th>HARP SCREENED LATERITE</th>
<th>CRUSHED GRANITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS Sieve Size</td>
<td>% Passing by Mass</td>
<td>% Passing by Mass</td>
<td>% Passing by Mass</td>
</tr>
<tr>
<td>13.20</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9.50</td>
<td>96</td>
<td>99</td>
<td>78</td>
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<tr>
<td>6.70</td>
<td>69</td>
<td>83</td>
<td>18</td>
</tr>
<tr>
<td>4.75</td>
<td>23</td>
<td>49</td>
<td>9</td>
</tr>
<tr>
<td>2.36</td>
<td>5.1</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>1.18</td>
<td>1.6</td>
<td>2.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Friction Angle</td>
<td>43°</td>
<td>41°</td>
<td>44°</td>
</tr>
<tr>
<td>Slump Angle*</td>
<td>31°</td>
<td>32°</td>
<td>38°</td>
</tr>
<tr>
<td>Unit Mass (Loose)</td>
<td>1.99 t/m³</td>
<td>1.97 t/m³</td>
<td>-</td>
</tr>
<tr>
<td>Saturated Surface Density of Coarse Particles</td>
<td>3.34 t/m³</td>
<td>3.33 t/m³</td>
<td>-</td>
</tr>
</tbody>
</table>

* The test method for slump angle is described in paragraph 35.
11. The arrester beds were filled with screened laterite pea gravel. Two types of screened laterite were produced from the one source material using two methods: a mesh screen and a harp screen. The mesh screen was of the common type consisting of woven wire. The harp screen consisted of parallel wires only, stretched taut across a frame.

![Image of mesh and harp screens]

\[ \text{Mesh Screen} \quad \text{Harp Screen} \]

The material was a nominal seven millimetres in size. The actual particle size distribution is shown in Table I. By visual inspection the material had a high degree of roundness. However, the measured angle of internal friction was high (approximately 42°). The material is shown in Fig 3.

12. Three vehicles were used in the trials, a Holden sedan, a two axle Toyota rigid truck and a five axle Mack semi-trailer. The rigid truck was tested in both a laden and unladen condition. Details of the vehicles are shown in Table II. Vehicle mass in each case was determined on a weighbridge and included the driver.

13. The tests were carried out by driving the vehicle up to the test beds and disengaging gear at the point of entry. The vehicles were allowed to run freely without braking to simulate the 'out-of-control' situation in a real arrester bed. The drivers were restrained in their seats by seat belts. The drivers had no difficulty in controlling their vehicles in the beds. There were no problems of 'jack-knifing' with the articulated vehicle. Following the completion of each test run the test bed was smoothed over using rakes and shovels.

14. The tests were carried out with the gravel in a dry state initially and then under wet conditions. A water truck was used to wet the gravel.

15. The exact speed of entry was measured by radar. At low speeds up to about 55 km/h the vehicle was decelerated sufficiently to stop within the bed. When the vehicle had stopped, its stopping distance was measured and the mean deceleration rate calculated using eqn (1). Stopping distance was measured from the start of the arrester bed to the front axle of the vehicle.

![Image of test materials]

\[ \text{Fig. 3 - Test materials} \]

**Table II**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>DESIGNATION</th>
<th>AXLE CONFIGURATION*</th>
<th>GROSS MASS (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Vehicle, Holden Sedan</td>
<td>P1</td>
<td>S S</td>
<td>1.37</td>
</tr>
<tr>
<td>Rigid Truck, Toyota - Unladen</td>
<td>R5</td>
<td>S D</td>
<td>5.47</td>
</tr>
<tr>
<td>Rigid Truck, Toyota - Laden</td>
<td>R10</td>
<td>S D</td>
<td>10.25</td>
</tr>
<tr>
<td>Articulated Truck, Mack - Laden</td>
<td>A35</td>
<td>S DD DD</td>
<td>34.81</td>
</tr>
<tr>
<td></td>
<td>A36</td>
<td>S DD DD</td>
<td>35.65</td>
</tr>
</tbody>
</table>

* S indicates single tyre and D indicates dual tyres.
16. At high entry speeds the vehicles travelled right through the beds so a stopping distance could not be measured directly. Video recordings were taken of the tests and from these recordings an estimate of the exit velocity was possible. For these tests the average deceleration rate was calculated for the velocity change range only using eqn (2).

\[ \alpha = \frac{v^2 - u^2}{2Lg} \]  

(2)

where \( \alpha \) = mean deceleration (g)  
\( V \) = entry velocity (m/s)  
\( U \) = exit velocity (m/s)  
\( L \) = length of bed (m)  
\( g \) = acceleration due to gravity (9.81 m/s^2)

17. This procedure may have slightly underestimated the average deceleration rate which would have occurred if sufficient bed length had been available. Results published by Bade (1968) (for aircraft) and Laker (1966) (for road vehicles) indicated that the instantaneous deceleration rate was low when the vehicle first entered the arrester bed and increased during the initial stage of travel through the bed. Laker’s (1966) results indicate that after a time of about 0.5 seconds the deceleration rate was roughly constant. If this occurred during the MRD WA trials, then the average deceleration rate calculated for vehicles which passed through the bed was probably slightly less than the true average rate to a stopped condition.

18. The results are presented in graphical form with average vehicle deceleration (\( \alpha \)) as a function of entry velocity (\( V \)) at Figs 4 to 7 inclusive.
DISCUSSION OF RESULTS

19. The average deceleration rate of a vehicle in an arrester bed is affected by a number of factors including entry velocity, bed depth, surface shape of the bed, material properties and vehicle characteristics. All of these factors are interrelated and with the limited number of tests carried out, the effect of each factor could not be isolated absolutely. However, by combining the results of this study with those by TRRL, RAE, DMR, NYS DOT and OSHD, some general trends become apparent.

20. Most of the MRD WA results followed the general form discussed in paragraph six and shown at Fig 1. That is, the average deceleration rate was significantly affected by entry velocity. At low velocities, the average deceleration rate increased with increasing entry velocity, while at higher entry velocities, the average deceleration rate decreased with increasing entry velocity. A maximum average deceleration rate was observed from most vehicles in the MRD WA study with an entry velocity of approximately 50 km/h. The average deceleration rate decreased for increases in entry velocity once this peak was reached.

21. A similar result was reported by Laker (1968) for angular gravel where the peak average deceleration rate corresponded to an entry velocity of about 50 km/h. However, Laker’s (1966) results with rounded gravel, which were all at fairly low speed, do not show a peak. It is possible that the speed to cause planing with the particular gravel tested had not been reached.

22. There is evidence in Shattock’s (1976) results for sand, of a peak in average deceleration corresponding to an entry velocity of 60 km/h. The authors suggest an alternative interpretation of his results which is shown at Fig 8.

23. The results reported by Bade (1968) for trials with aircraft, indicated that the entry velocity corresponding to maximum average deceleration rate varied with aircraft type but typically was at 70 km/h to 110 km/h.

24. The length of the MRD WA trial pits was not sufficient to permit trials much in excess of 60 km/h. However, confirmation that the decrease in average deceleration rate continues at higher entry velocities with road vehicles is available from the OSHD trials reported by Versteeg (1979) which included a number of runs with entry velocities in the 80 to 90 km/h range. Using Versteeg’s (1979) results as a guide, it would appear that the average deceleration rate for road vehicles with a high entry velocity (100 to 120 km/h) is likely to be about 80% of the rate at 50 km/h.

25. By comparing the results with road vehicles previously cited with those from aircraft reported by Bade (1968), it is apparent that the ‘peakedness’ of average deceleration rate as shown in Fig 1, is not as sharp with road vehicles as it is for aircraft. This is possibly related to tyre configuration and/or load which is discussed more extensively in the following paragraphs.

EFFECT OF VEHICLE CHARACTERISTICS

26. The MRD WA tests on dry mesh screened gravel showed little difference in results for a passenger vehicle (Pl) and a rigid truck (R5 and R10) with a single rear axle. This is a similar result to that reported by Shattock (1976) in the DMR tests where a station sedan and a truck with a single rear axle were used.

27. Changes in loading of the rigid truck in the MRD WA tests had little effect on the observed average deceleration rate. This is somewhat in contrast with results reported by Versteeg (1979) for the OSHD trials where significantly higher deceleration rates were recorded for a loaded two axle truck compared to an unloaded truck.

28. A far more significant effect than vehicle load was found in the MRD WA trials, to be axle configuration. The five axle semi-trailer, which incorporated two sets of tandem axles, was found to have a much lower average deceleration rate. Similar results occurred in the OSHD trials where a vehicle incorporating tandem axle groups was used. This finding appears reasonable. While decelerating in the gravel bed, the rear axle in each tandem group was moving in the ‘wake’ of the front axle of the group and little heaping up of the material in front of these tyres occurred. The dust thrown up by the moving vehicle precluded confirming this hypothesis from the photographs or video records of the tests.

29. Tyre configuration may also explain, at least partially, why Bade (1968) achieved much higher deceleration rates with aircraft than have generally been reported by others with road vehicles. The aircraft tested had tyres in a tricycle configuration so that every tyre was running into ‘fresh’ arresting material rather than in the wake or rut from a preceding wheel.
EFFECT OF MATERIAL PROPERTIES

30. The two materials tested by MRD WA had similar properties and were produced from the same source material. The differences in properties were so small, that definite conclusions of the effect of grading and angle of internal friction could not be made on the basis of these trials alone. To provide a wider basis of comparison, the results need to be compared to those achieved in the RAE, TRRL, DMR, NYSDOT and OSHD trials.

31. Laker (1966) reported that in the TRRL trials 'rounded stones are better than angular stones'. Barnes (1971) in reporting the RAE trials indicated that material with a low angle of internal friction gave higher deceleration. The poor performance of the crushed rock gravel in the first trial arrester bed in Western Australia supports this finding. The report by Versteeg (1978) on the OSHD trials refers to the material used as a 'pea gravel', thus reinforcing the recommended use of a material with a low angle of internal friction.

32. To achieve a high deceleration rate it is necessary that vehicle tyres sink into the arrester bed material. The desirable material properties are therefore likely to be those associated with low strength. In this respect a single sized material is likely to give the best results.

33. Just what this size should be is still somewhat of a vexed question. Both Laker (1966) in reporting the TRRL trials and Bade (1968) in reporting the RAE trials, concluded that a smaller material gave higher deceleration rates. Laker (1966) was comparing 10 mm nominal size material to 38 mm nominal size, while Bade (1968) was comparing 10 mm nominal size material to 19 mm nominal size. Shattock (1976) achieved reasonable results using a dune sand, though there is evidence that once this material was compacted, its effectiveness was reduced. MRD WA experience of road construction in the Perth area, where dune sand is the predominant subgrade type, indicates that sand is unlikely to be satisfactory as an arresting material unless it is kept in a loose condition and there is regular maintenance to prevent the establishment of vegetation. The available data is not sufficient to indicate what the optimum size material is, but it is probably about 5 to 10 mm with a larger size to be favoured in climates where freezing may occur to ensure good drainage.

34. The desirability of having a material with low shear strength to permit tyre penetration has already been stated. However, the magnitude and rate of shear which occurs when a high speed vehicle ploughs through an arrester bed, are at least an order of magnitude different to those occurring in a conventional laboratory shear box test. The behaviour of a material in an arrester bed is in some respects more analogous to fluid rather than to a solid. Fig 9 shows the material 'spraying' out from the tyres as a high speed vehicle moves through the bed. The analogy to fluid behaviour with respect to planing has already been stated.

35. While the strain rates occurring in actual field use cannot conveniently be reproduced in the laboratory, it is possible to come closer than the shear box test. With this objective, a test was developed to measure the internal friction under large shear strain conditions. A concrete slump cone of dimensions specified in Australian Standard 1012 (1976) was used. With the slump cone in the inverted position (large diameter to the top) and sitting on a level base, the cone was loosely filled with the sample material. The slump cone was then raised vertically at a rate of 10 mm/s. The radius of the cone of material was then measured in four positions and the 'slump angle' (φ) calculated using eqn (3).

\[ \phi = \arctan \left( \frac{5.25 \times 10^6}{R^2} \right) \]

where R is the average base radius in millimetres.

The results on dry material from the two trial arrester beds at Chidlow and on the crushed granite which was known to perform poorly in the first trial arrester bed are shown in Table I.

36. The effect of wetting of the arrester bed material on deceleration rate was investigated in the MRD WA trials at Chidlow. For both the mesh screened and the harp screened material there was a small reduction in deceleration rate due to wetting. Laker (1966) reported that 'tests were made under both wet and dry conditions' in the TRRL trials. However, no distinction was made in the presentation of results and it can only be assumed that the effect was negligible. Moisture content is most likely to be significant only in regions where freezing can occur.
37. If the hypothesis of planing at high speeds is valid, then material density is likely to have a significant effect on deceleration rates. From dynamic considerations, planing should occur at lower velocities with dense materials. Low density is therefore likely to lead to higher average deceleration rates. This is supported by results reported by Jehu and Laker (1969) of high average deceleration rates with an artificial lightweight aggregate.

EFFECT OF ARRESTER BED GEOMETRY

38. The tests by TRRL, RAE, DMR and MRD WA were all in level test beds. The OSOH tests reported by Versteeg (1978) were on a bed with a descending grade of 5.6%. The NYS DOT trials reported by Allison et al. (1978) were in an arrester bed with a down grade of 10%. The authors have been unable to locate any literature reporting results where all factors, (material, vehicle, geometry), except slope were constant. However, it appears reasonable from a force vector analysis that a longitudinal slope (θ) in an arrester bed will increase (or decrease) the deceleration by an amount g sin θ. This assumption is probably reasonably valid when θ is small but would obviously breakdown as θ approached the angle of repose of the material. In selecting a site for an arrester bed, an uphill grade is preferable in order to minimise the length of bed required.

39. The effect of depth of soft material was not investigated in the MRD WA trials. A uniform depth of 0.5 m was used throughout. In the RAE trials reported by Bade (1969) various depths were investigated and it was concluded that:

Increases in gravel depth are shown to give an increase in mean deceleration though they are not in proportion to the depth increase.

Obviously there is some upper limit beyond which any increase in depth is of negligible benefit. There is not sufficient evidence available as yet to accurately define this but it is probably somewhere between 0.5 m and 1.0 m.

40. All trials in the MRD WA arrester beds were carried out with the surface in a smooth, flat condition. The use of transverse berms or mounds was investigated in the OSOH trials and reported by Versteeg (1979). The use of berms or mounds to absorb energy caused the vehicle to bounce, a loss of control and vehicle damage.

41. Windrows of gravel have been used successfully on haul roads by a number of mining companies in Australia to stop out-of-control vehicles. The windrows have a triangular cross-section and the longitudinal axis is parallel to the direction of travel of vehicles. The cross-section width of the windrows is kept narrow so that the tyres remain on hard ground. The mining vehicles straddle the windrow such that the windrow is engaged by the vehicle bumper and the underside body work. A fairly detailed description of dimensions to be used for mining vehicles is given by Eck (1980) in his very comprehensive report on truck escape ramps.

42. Before applying such a concept to an arrester bed, it is necessary to remember that a mining company is dealing with a limited range of vehicles whose characteristics in terms of wheel track and ground clearance is known. Such vehicles, because of the work they are required to do, are fairly 'rugged'. An arrester bed on a public road must, however, be able to cater for a range of vehicles from a compact sedan to a large articulated truck. A windrow which is high enough for the latter type of vehicle may well cause dangerously high deceleration rates or even cause a roll-over for a small, low clearance car.

43. A particular problem may also occur with articulated vehicles where the windrow method is used. A windrow will apply a retarding force to the prime mover and none to the trailer, thus increasing the possibility of 'jack-knifing'. That this does not occur in a flat arrester bed, where retarding force is applied to the trailer tyres as well as the prime mover, has already been established.
ACCELERATION OF VEHICLES ON GRADE

44. The determination of the stopping distance of a vehicle in an arrester bed requires an estimate to be made of the entry velocity. The acceleration of a vehicle rolling down a grade, out of gear and without braking may be derived from Newton's second law of motion:

\[ F = ma \]  \hspace{1cm} (4)

where

- \( F \) = force (N)
- \( m \) = mass (kg)
- \( a \) = acceleration (m/s²)

Substituting the forces of gravity, internal friction and wind drag and rearranging, eqn (4) may be rewritten as:

\[ a = g \sin \theta - \frac{F_r}{m} - \frac{C_d \rho A v^2}{2m} \]  \hspace{1cm} (5)

where

- \( a \) = acceleration (m/s²)
- \( g \) = acceleration due to gravity (9.81 m/s²)
- \( \theta \) = slope of the grade
- \( F_r \) = internal friction and rolling resistance (N)
- \( m \) = mass of the vehicle (kg)
- \( C_d \) = drag coefficient
- \( \rho \) = density of air (kg/m³)
- \( A \) = frontal area of vehicle (m²)
- \( v \) = velocity of the vehicle relative to the air*

45. This can be rewritten as a differential equation with the solution given in eqn (6). The derivation of this solution is presented in Appendix A.

\[ v = \left( \frac{C_2}{C_1} \left(1 - e^{-2C_1 s}\right) + u^2 e^{-2C_1 s} \right) \]  \hspace{1cm} (6)

where

- \( C_1 = C_d \rho A/2m \)
- \( C_2 = g \sin \theta - F_r/m \)
- \( s \) = distance travelled (m)
- \( u \) = initial velocity (m/s)
- \( e \) = the base of natural logarithm (2.718)

46. By substituting typical values of mass, frontal area drag coefficient and internal friction (from Steeds 1960) for road vehicles, it is readily apparent that the vehicle likely to have the highest entry velocity is the large semi-trailer with tandem or triaxle groups. As this is the vehicle with the lowest average deceleration rate in an arrester bed, it is obviously the critical vehicle for selection of arrester bed length.

CONCLUSIONS

47. In this paper the results of an investigation into the design of arrester beds has been described. The investigation included the construction of trial arrester beds into which a range of vehicles were driven at speeds of up to about 65 km/h. By combining the results achieved in these trials with those reported for trials conducted by the RAE, TRRL, DMRB, NYSDOT and OSHP, a number of general conclusions can be reached about the factors which affect the average deceleration rate of a vehicle in an arrester bed.

(a) Average deceleration rate is significantly affected by entry velocity. For low entry velocities it increases with increasing entry velocity until a peak is reached at about km/h and thereafter for higher entry velocities it decreases. As entry velocities for out-of-control vehicles may be as high as 100 to 120 km/h, it is recommended on the basis of results reported by Versteeg (1979), that a value equal to 80% of the peak value be used for design purposes.

(b) Vehicle loading or gross vehicle mass in itself is not a major variable affecting average deceleration rate. However, vehicle mass is an important factor affecting acceleration of a vehicle on a grade and a fully laden vehicle is likely to have a higher entry velocity than an unladen one. Axle configuration has a significant effect on deceleration rate, and vehicles which include multiple axle groups such as tandem axles and triaxles are likely to have lower average deceleration rate in an arrester bed.

(c) Arrester bed fill material should consist of smooth, round, uncrushed gravel which is essentially single sized. The optimum size has not been established but is probably about 5 to 10 mm nominal size. From theoretical considerations at least, low density is also likely to be a desirable property. A suggested material specification is provided at Appendix B. This specification should be regarded as preliminary only and may need to be revised in the light of further experience and testing.

(d) A method of assessing the internal friction of materials under conditions of high shear strain was developed based on the use of a concrete slump cone. The use of this test by others to cover a broader range of materials is required to establish a correlation between this factor and average deceleration rate.

(e) The actual average deceleration rate will be influenced by the arrester bed slope and an adjustment should be made to the rate achieved in a level bed when applying the results to the design of a sloping bed.

* It is assumed for design purposes that wind velocity is zero and v is therefore vehicle velocity.
(f) It is possible to achieve increased deceleration rates by the incorporation of mounds in the arrester bed or by constructing a longitudinal windrow so that the material comes in contact with the front bumper and underbody of the vehicle entering it. The possibility of this causing a loss of vehicle stability in the case of a small vehicle or 'jack-knifing' in the case of a semi-trailer, cannot be ignored and the use of such methods on arrester beds for public use is not recommended.

48. As part of this study an equation was developed for predicting the likely velocity of a vehicle rolling out of gear and unbraked down a steep grade. By substituting typical vehicle parameters for various road vehicle types into this equation, it is apparent that the large semi-trailer type vehicle with multiple axle groups is likely to have the highest entry velocity into an arrester bed. This type of vehicle is also likely to have the lowest average deceleration rate and is therefore the critical design vehicle for the determination of arrester bed length.

APPENDIX A : SOLUTION OF EQUATION FOR ACCELERATION OF VEHICLES ON GRADE

49. The equation for acceleration of a vehicle on a grade has been presented at paragraph 44.

\[ a = g \sin \theta - \frac{F_r}{m} - \frac{C_{dp}A v^2}{2m} \]  

(7)

This can be rewritten as a differential equation:

\[ \frac{dv}{ds} = C_2 - C_1v^2 \]  

(8)

where \( C_1 = \frac{C_{dp}A}{2m} \)

\[ C_2 = g(\sin \theta - F_r/mg) \]

Eqn (8) can be rewritten as:

\[ \frac{dv}{ds} = C_1v^2 - C_2 = 0 \]  

(9)

where \( s = \) distance (m)

By dividing through by \( v \), eqn (9) is reduced to a standard Bernoulli equation (Kreyzig 1965) with the solution:

\[ v^2 = C_2 \left( 1 - e^{-2C_1s} \right) + \frac{u^2}{C_1} e^{-2C_1s} \]  

(10)

with boundary conditions:

\[ s = 0 \]

\[ v = u \]

where \( u = \) initial velocity (m/s)

APPENDIX B : SUGGESTED SPECIFICATION OF GRAVEL FOR ARRESTER BEDS

50. The material shall be clean, uncrushed, hard, durable, natural gravel, consisting primarily of smooth, round particles.

Particle Size Distribution

<table>
<thead>
<tr>
<th>Test Method AS 1141.11 - 1980:</th>
<th>Percentage by Mass Passing Each Sieve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australian Standard Sieve Size (mm)</td>
<td>13.20</td>
</tr>
<tr>
<td></td>
<td>9.50</td>
</tr>
<tr>
<td></td>
<td>6.70</td>
</tr>
<tr>
<td></td>
<td>4.75</td>
</tr>
<tr>
<td></td>
<td>1.18</td>
</tr>
</tbody>
</table>

Particle Toughness

<table>
<thead>
<tr>
<th>Test Method WA 223.1:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing - not greater than 5%</td>
</tr>
<tr>
<td>Cracking - not greater than 5%</td>
</tr>
</tbody>
</table>

Slump Angle

<table>
<thead>
<tr>
<th>Test Method - as described at paragraph 35:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump angle - not greater than 30°</td>
</tr>
</tbody>
</table>

Bulk Density (Saturated Surface Dry)

<table>
<thead>
<tr>
<th>Test Method AS 1141.6 - 1974:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (SSD) - not greater than 3.4 t/m³</td>
</tr>
</tbody>
</table>

REFERENCES


——— (1979). 'Personal communication'.