University of HUDDERSFIELD

Institute of Railway Research

On behalf of

LIGHT RAIL Safety and Standards Board

LRSSB - Light Rail Technical Note – LRTN 1.0 Review of Sand Drag Retardation at Tram Termini – Phase 1

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Executive Summary

The terminus design of tramway systems include requirements to safely halt a tram that may have overrun the normal limit of operation. Buffer stops are a traditional solution, but they have some disadvantages in a tramway environment. It is possible to entirely avoid terminating tracks in public areas by using loop tracks instead of dead-ends, but this requires more complex track layouts and additional space.

In recent years, UK light-rail system installations and extensions have increasingly used forms of sand drag or 'arrestor bed' at the end of terminal tracks in public areas. There are numerous variants of how this concept is implemented in practice, which have been grouped into five basic concepts. In principle, sand drags can provide energy absorption, moderate retardation rates, a smooth surface for pedestrians, and avoid a trapping risk.

Guidance for the design of such retardation devices for light-rail is limited and there is a lack of information contained in standards. LRSSB identified a need for further research to collate the relevant information to support future designs and provide assurance that these designs are fit for purpose. To support this research the University of Huddersfield Institute of Railway Research is conducting a two-phase study into the use of sand drags and arrestor beds. This report presents the findings of Phase 1, a review of literature and existing practice in the UK.

Sand drags are no longer preferred as the sole means of terminal over-run protection on Network Rail or London Underground. However, there is historical data on their performance in tests and incidents, and standards or guidance defining their design and maintenance. The IRR have not identified any formal design calculations for sand drags or arrestor beds on light-rail systems, nor any test results or evidence of their effectiveness in practice.

It is important to define the scenario that the over-run protection is designed to cope with. Industry consensus is a laden tram at 15 km/h approach speed with the brakes released and the driver incapacitated. There could be a risk assessment element based on local conditions similar to that required by RSSB for mainline terminals.

For arrestor bed designs that require the wheels to break through a hard surface layer, there is a design dilemma between the arresting requirements and the requirements to support pedestrian and perhaps light vehicular traffic. If the design is optimised for arresting, then the surface may soon become cracked and uneven, presenting a tripping hazard and requiring frequent maintenance. If the design is optimised

for lower maintenance, then the tram wheels may not break through the surface and the arrestor will be ineffective. There is also a risk that the reality of the installation may not reflect the design intent.

The IRR also has concerns that existing light-rail arrestor bed installations may be too short to stop a tram at speeds much over 5 km/h. Based on historical British Rail design guidelines and test results, a sand drag length of 15 m to 30 m would be necessary to arrest a typical tram at 15 km/h, much more than the ≈5 m installation length typically seen on UK light-rail systems.

The key recommendations for further work in Phase 2 are as follows:

- Define the scenario which the over-run protection is designed to protect.
- Provide guidance on the arresting concept of a sand drag or arrestor bed.
- Gain more evidence of the performance of sand drags and arrestor beds, including:
    - Acquire and review the historic London Underground report on sand drag tests.
    - Review any light-rail terminal over-run incidents involving sand drags or arrestor beds and determine the effectiveness of the over-run protection.
    - Review the design principles used by consultants in developing existing designs of light-rail arrestors, particularly the AECOM design of flush surfaced arrestor bed.
    - Analyse relevant test results and modelling in other related fields (civil engineering, agriculture, earthmoving, other transport modes) to determine trends which can be applied to extrapolate the test results and experience of railway sand drags and arrestor beds.
    - Where there is presently insufficient evidence to validate calculation methods, consider quasi-static laboratory testing of various surface coverings (concrete, tarmac, resin-bonded aggregate) and thicknesses on a sand or gravel substrate to determine the likelihood of a typical tram wheel breaking through the surface.
    - Where there is presently insufficient evidence to validate calculation methods, consider full-scale instrumented tests on LRSSB's test track to demonstrate real-life performance when a tram is run into one or more types of sand drag or arrestor bed.
- Investigate the suitability of the aviation industry EMAS retarding material for light-rail.
- Define a method for calculating sand drag performance.
- Draft an LRSSB guidance document.

Contents

1. Introduction

The terminus design of tramway systems include requirements to safely halt a tram that may have overrun the normal limit of operation. Buffer stops are a traditional solution, but they have some disadvantages in a tramway environment:

- Retardation rates may be inappropriate for relatively lightweight trams, causing damage to the vehicles and/or injury to passengers during the sudden deceleration;
- Simple designs offer no energy absorption capability;
- Improved designs with better energy absorption and lower retardation rates can require a lot of space, and may block circulating areas or present a tripping hazard to pedestrians;
- In street or pedestrian environments, there are risks of pedestrians being trapped and crushed between the tram and the buffer stop in the event of an over-run.

A fatal accident in Barcelona in January 2019 illustrated the need for terminal over-run protection, and the potential dangers of a tram carbody colliding with a solid object – shown in Figure 1.

Figure 1: Tram crash in Barcelona, January 2019, showing the fatal consequences of a relatively low speed front-end collision with a traction pole

It is possible to entirely avoid terminating tracks in public areas, for example by using loop tracks instead of dead-ends. Blackpool is an example of a UK system which did not have terminating tracks outside of depot areas until the new extension to Blackpool North station was built. The concept is widely used in Europe where many trams are single-ended and never change direction. However, this requires more complex track layouts and additional space.

In recent years, UK light-rail system installations and extensions have increasingly used some form of sand drag or arrestor bed at the end of terminal tracks in public areas. Beyond the normal stopping point is an area of sand, gravel or earth, contained within a defined boundary. When the tram's wheels over-run into this, they are retarded by the sand. There are numerous variants of how this concept is implemented in practice.

In principle, sand drags can provide energy absorption, moderate retardation rates, a smooth surface for pedestrians, and avoid a trapping risk. However, guidance for the design of such retardation devices for light-rail applications is limited and there is a lack of information contained in standards. LRSSB identified that further research was required to collate the relevant information to support future designs and provide assurance that these designs are fit for purpose.

To support this work, the University of Huddersfield Institute of Railway Research is conducting a two-phase study into the use of sand drags and arrestor beds. Other forms of arrestor such as friction buffer stops and large planters are not explicitly covered, but may have some aspects in common and are referred to where appropriate.

The first phase described in this report consists of a literature review, gathering information from standards, guidance documents and designs to identify gaps in existing knowledge. Further work needed to support a future LRSSB guidance document is identified, and this will be conducted during the second phase.

2. Review of Standards and Previous Work

2.1. Overview

In the UK, sand drags are used on Network Rail, London Underground, and some light-rail systems. Alternative terminology includes 'sand hump', 'train arrestor', 'arrestor bed', or 'safety siding' [22]. Several different concepts of sand drag are used, and these will be described and illustrated in detail in this section, with a summary in Section 3. Selected examples from abroad have also been considered.

Other transport modes such as highways and airports also use types of sand drag or arrestor bed, and these are examined briefly where there are relevant lessons to learn for the light-rail application.

2.2. Network Rail Applications

2.2.1. Standards and Practices

Early (1950s) editions of the Permanent Way Institution's reference book 'British Railway Track' [1] refer to sand drags in a section on 'catch roads' where sidings join running lines. Their purpose is to ensure that any vehicle on the siding running away or over-running the siding signal is diverted from the main line. Several types of catch road are listed, the relevant one is:

> *(4) Catch Road with stops. These form a dead end siding, which should be long enough to accommodate a vehicle clear of the fouling point between the catch road and the siding. Occasionally buffer stops are used at the end of such catch roads, but the most satisfactory arrangement is to have a mound of sand or similar material at the end of the catch road, as with this there is less shock to a vehicle running away into the catch road.*
> *A development of this is known as a 'sand drag'. In this, boards are fixed to the sleepers clear of the chairs, by brackets, one each side of the rail, so they are parallel to the rails, and project an inch or two above the rail level, like the sides of a box around each rail. The space between each pair of boards is filled with sand, beach or similar material, so that the rails are just covered. A vehicle running over this is quickly brought to rest, especially if the sand drag is arranged to be on a rising gradient. The length of a sand drag is determined by local conditions, a usual length being 40 ft.*

Considering the date of the reference and the application, it is likely that such sand drags were primarily intended for stopping individual short-wheelbase wagons with a mass of around 20 tonnes and moving at slow speeds. Sand drags are not mentioned in other chapters of the 1956 edition, and do not feature at all in the 1993 edition [2] of this book. Their use as over-run protection at terminal platforms is not considered.

Figure 2 shows an example of a boarded sand drag at Marsden on the Trans-Pennine Line. This is unusually long: over 50 m, and also has a conventional buffer stop at the end.

Figure 2: Sand drag with boarded troughs around each rail, at Marsden.

Network Rail's internal documents also include NR/L2/TRK/2049/MOD05 section E.5.1 'Suggested form of Sand Drags' [55]. Three types of sand drag are defined, as well as an 'interlaced retarder'. In contrast to the boarded sand drags described above, the 'suggested form' is a mounded sand drag across the full width of the track, and higher than the retaining boards, as shown in Figure 3.

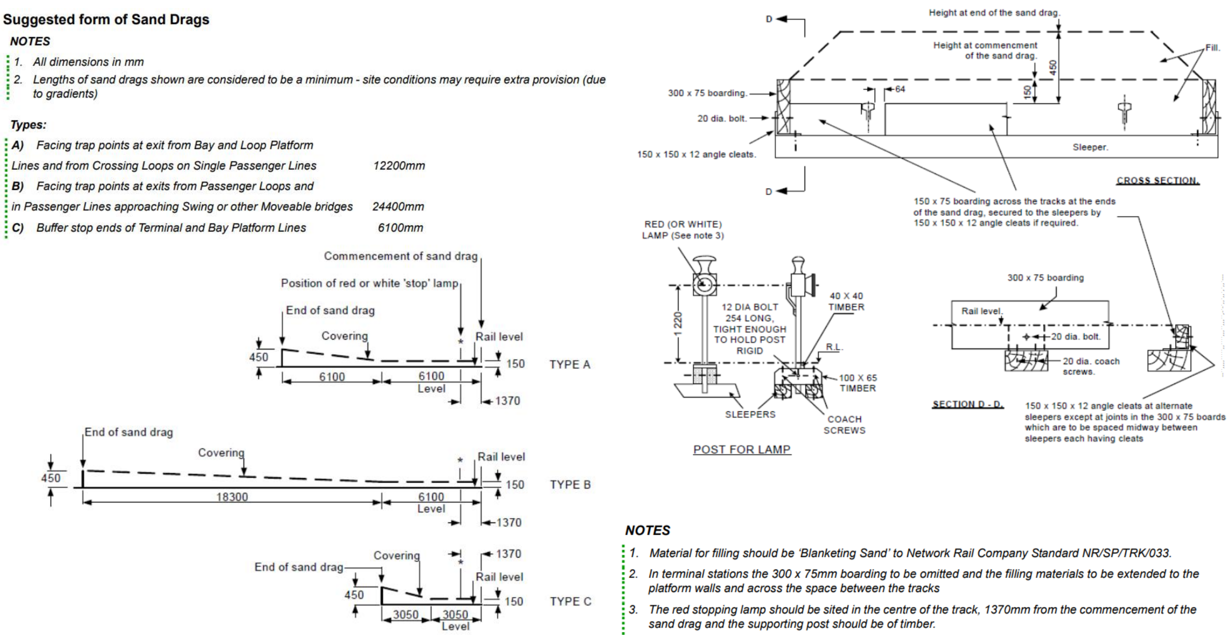

Figure 3: Extracts from NR/L2/TRK/2049/MOD05 'Suggested form of Sand Drags' [54]

Note that this does define a sand drag design for terminal platforms (type C), but implies that it is to be used in conjunction with a buffer stop rather than as the sole retardation device. Where the sand drag is the only form of retardation, a minimum length of 12.2 m is required. Similar designs are included in the Ministry of Defence railway standards [63] with a minimum length of 6.5 m.

Network Rail's internal standard for manual inspection and maintenance of permanent way [4] refers to numerous modules, including NR/L2/TRK/001/mod18 for buffer stops [5]. This also contains inspection requirements for sand drags, as follows:

> *7 Sand drags*
> *Inspect to confirm that:*
> *a) sand is to the top of the retaining boards;*
> *b) the sand has a soft top surface layer (not a hardened crust).*

Again, this suggests that the sand must be loosened and levelled to be effective. There is also a requirement for operational risk assessments for all buffer stops and arresting devices at stations, to determine whether they are adequate for the location concerned.

Some RSSB standards and guidance also address buffer stops and arresting devices. The currently applicable standard is RIS-7016-INS [6]. For new constructions, this standard requires energy absorbing buffer stops to be installed at terminal or bay platforms. For existing terminal or bay platforms, buffer stops must be installed and a risk assessment must be carried out to indicate whether the design of the buffer stop is adequate for the local conditions. End impact walls are also required where reasonably practicable and where they would reduce the risk of a train overrun causing harm to people and damage to critical structures. Outside of stations, RIS-7016-INS provides some guidance for buffer stops in depots and sidings but there are no mandatory requirements.

Previously, the buffer stop requirements were included in GC/RT5033 [7]. This did include mandatory requirements to provide 'buffer stops or arresting devices' for new construction of freight lines and sidings, and factors to consider in the selection of an appropriate device. In this context, 'arresting devices' includes sand drags, but there are no specific requirements relating to sand drags and they are not mentioned other than in the definitions section.

2.2.2. Performance

British Rail (BR) issued a series of 'Permanent Way Notes' in 1964 which included graphs to determine the length of sand drags required as a function of train speed and weight [58]; similar data for friction buffer stops was also produced [59]. The key equation for sand drags was defined as follows:

Length (feet) = 0.7 × Speed (mph) × √Weight (tons)

In plotting the results of this equation, train weights of between 50 tons and 1000 tons were considered by BR, with speeds up to 60mph. It may be that the simple equation was intended to be most accurate at higher train weights/speeds.

In preparation for testing of the APT in 1975, BR Research required some form of train arrestor at the ends of the test track [3]. The specification was very demanding as it was to retard 142 tonnes travelling at speeds of 193km/h. Several types of arresting systems were investigated, including a sand drag. Although the sand drag was found to be unsuitable for this application, the test results are useful in illustrating its performance:

> *1.1 Sand Drag*
> *Sand is contained within a structure running along each side of each rail and levelled off about 50 mm above rail head. The retardation of a vehicle rolling into the sand is caused by the compression of the sand between the wheel tread and the rail head.*
> *Tests were carried out by loose shunting a 20 tonne brake van into a sand drag at various speeds and measuring the retardation distance.*
> *At 16 km/h the distance varied between 15 and 21 m. For 32 km/h the distance increased to 42 to 48 m. Whilst at 48 km/h the distance increased considerably to 91 m. Between each run the highly compacted sand was loosened and re-levelled.*
> *Extra sand, to a depth of 100 mm above rail head, was added and at 24 km/h a stopping distance of 26 m was achieved. A 40 km/h test produced a distance of 41 m but the vehicles had run for 24 m derailed in a virtually straight line. This was caused by the greater depth of compressed sand causing the flanges to be clear of the rail head.*
> *These tests showed that a sand drag would be of no value for the required application.*

These results have been plotted and compared to the 1964 design values, as shown in Figure 4. The tests featured a 20 tonne vehicle so the theoretical stopping distances have been calculated for this as shown in the solid black line. The diamond markers are the test results, which indicate that the stopping distance was typically twice that determined from the design calculation.

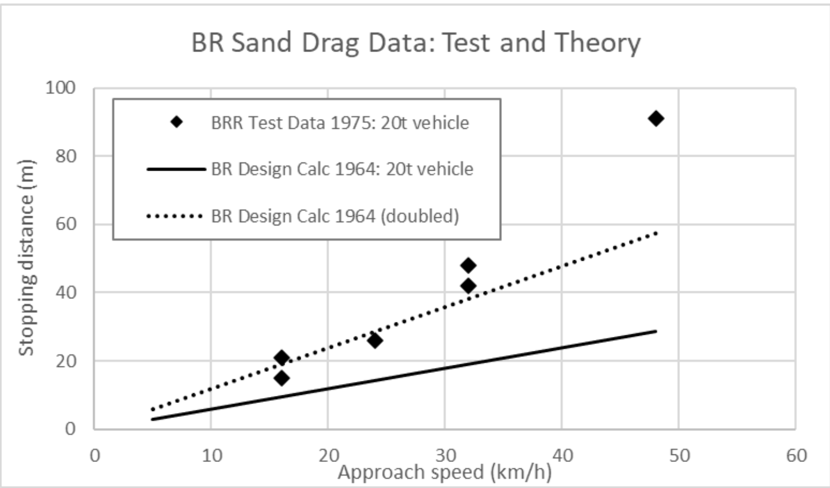

Figure 4: British Rail sand drag performance – theory and test

These tests were carried out at speeds and axleloads appropriate to the light-rail over-run scenario. At 16 km/h, the typical sand drag length of 40 ft (12.2m) mentioned in [1] and [55] would be insufficient to stop the tested 20t vehicle; for a heavier vehicle an even longer sand drag would be needed.

The test report [3] also notes that the compacted sand was loosened and levelled between tests, implying that this is necessary for the sand drag to be effective. This suggests that, once compacted by the leading wheelset, the drag on subsequent wheelsets would be reduced.

Another interesting observation is that in the final test, the wheels climbed on top of the sand and derailed. This indicates that sand, when contained, can be capable of supporting a railway wheel. Assuming that railway wheels will dig into the sand may not always be correct. In this case there was a load of 5 tonnes per wheel, which is comparable to typical wheel loads for a laden tram.

Several historic accident reports provide information on the performance of sand drags for terminal protection. The accident at Sheerness-on-Sea in 1971 [56] featured a sand drag broadly in accordance with type C in Figure 3, but formed with pea gravel rather than sand. The driver of an approaching train lost consciousness as the train approached the station at a speed of around 10mph with the brakes released. At about the same time that the train entered the sand drag, the electro-pneumatic brakes were applied (probably by the vigilance device). The sand drag had only a small influence in slowing the train, with the stopping distance comparable to the effect of the brakes alone. The train comprised 10 EMU coaches totalling 364 tons, which crashed into the buffers and over-rode them with the leading coach destroying the station concourse. A similar incident occurred at Dorchester West in 1974 [57]; again the sand drag was entered at low speed (<15 mph) with the brakes on, but the loco and leading carriage went through and beyond the 9 m long sand drag.

An online forum discussion [8] gives examples of some locations of sand drags on Network Rail and London Underground, and their usage. Another forum discussion [15] on the use of sand drags on former GWR routes includes some personal experiences from a time-served railway operator. Although this is anecdotal it is consistent with the findings of the BR Research tests [3]:

> *In my experience short sand drags were useless at stopping anything as big as a loco although they might have slowed it down a bit (to do any good I get the impression that the GWR preferred sand drags to be well over 100 yards long!).*

2.2.3. International Comparison

It is interesting to compare with Indian Railways practice which is similar in concept [27][28]. According to drawing RDSO/T-347, the sand drag is 30 m long on a rising gradient, with both the sand and the gradient contributing to the arresting effect. As shown in Figure 5, the sand fills a trough to a nominal height of 65mm above rail. Beyond the end of the rails, a rising earth bank continues for a further 30 m, giving a total retarding distance of 60 m. This is substantially longer than the Network Rail designs, but more in accordance with the stopping distances found in the BR Research tests [3].

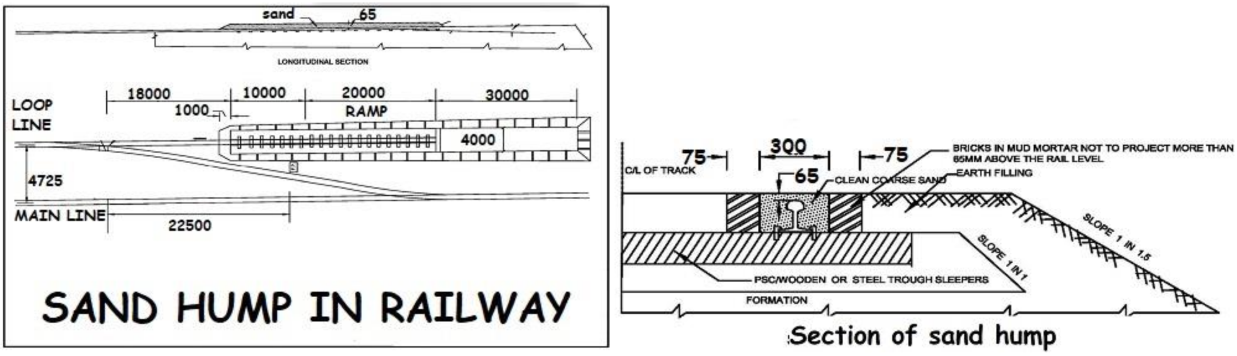

Figure 5: Indian Railways specifications for sand drags based on drawing RDSO/T-347 [27][28]

In Japan, the conventional railways use gravel rather than sand in their arrestor beds [30]. The USA and Canadian railroads do not use sand drags or arrestor beds for terminal protection [51].

2.2.4. Summary

In summary, on the GB main line it is mandatory to use buffers in station terminal and bay platforms. Sand drags may be a permitted as an alternative in depots and sidings in some circumstances but they do not appear to be the preferred option. The normal type consists of a shallow trough of sand surrounding each rail individually, but for new installations a mounded form across the full width of the track is recommended. There is practical and anecdotal evidence that they are only suitable for arresting relatively short, light vehicles at slow speeds, unless the sand drag is many tens of metres long. Similar designs are also used on some main lines abroad.

2.3. London Underground Applications

2.3.1. Standards and Practices

London Underground (LU) uses sand drags in numerous locations. These are generally of the mounded type and are used on the approach to a fixed bufferstop, as shown in Figure 6. Therefore, the sand drag does not provide the sole over-run protection but is intended to provide a more gradual deceleration than a solid buffer.

Figure 6: London Underground Mounded Sand Drag

LU provided some detailed dimensioned drawings of typical sand drags installed in the 1990s [34][35] which show a mound of sand 610 mm high across the width of the track, contained between vertical concrete slabs mounted at the sleeper ends. The normal sand drag length is approximately 10-12 m. This is broadly consistent with Network Rail's suggested design in [55] but LU requires a deeper pile of sand.

A document on 'Terminal Protection' [12] gives some historical context about the installation of sand drags on LU. One of the earliest installations is described thus:

> *The development of terminal protection can probably be said to have started as a result of two end wall tunnel collisions by empty trains in the siding at Tooting Broadway, the first on 7 October 1960. In this the motorman was injured, but there was no loss of life. Probably for this reason, no accident report was generated. This produced a knee-jerk reaction from London Transport and with effect from 6 November 1960, a "sand drag" was installed at the end of the siding. This did absolutely nothing to prevent a second accident at the same location on 4 May 1971, but on this occasion the motorman lost his life.*

There was a similar incident at Edgware in 1946 where a 20 ft long sand drag was insufficient to stop a train at 15 mph, and it hit the end wall at 5-7 mph [13].

After several further terminal collisions including the very severe incident at Moorgate in 1975 [13] (where a sand drag was again ineffective), LU made a number of improvements to their terminal protection, primarily signalling or train control to ensure that approach speeds are low [12]. LU experience was that sand drags usually activated the tripcock which would make an emergency brake application, but fixed train stops and approach speed control were also fitted post-Moorgate as recommended in the accident report [12][13][14].

LU standard S1170 [11] sets requirements for the inspection and maintenance of train arrestors including sand drags. Some specifications for sand drag components are given in S1170, but these are limited to material requirements for sand, concrete and fastenings and do not relate to the specification or design of the size or performance of the sand drag (in principle these are in S1169, but only applicable to other types of train arrestor).

S1170 requires that sand drags are subject to a specific detailed inspection and preventative maintenance at intervals of not more than two years; this must also be done 'post-engagement' (i.e. when a train has run into the sand drag). Additionally, there are more frequent basic visual inspections of the sand profile and condition described in standard S1158 [10]. S1170 clause 3.3.5 describes the maintenance requirements for the sand drag itself:

> *3.3.5 Routine maintenance of drag arrestors - sand*
> *3.3.5.1 The designed sand profile shall be maintained at all times.*
> *3.3.5.2 Clean sand shall be used.*
> *3.3.5.3 The sand shall be kept free from foreign materials such as sleepers and other track components.*
> *3.3.5.4 The surface of the sand shall be kept loose.*
> *3.3.5.5 Concrete components and their metal connecting brackets, used for containment of the sand, shall be replaced if damaged or corroded.*

Sand drags are no longer used for new installations on LU, and TfL are planning a programme to remove existing sand drags from the network owing to the maintenance requirements [36]. Nevertheless, many sand drags presently remain on LU.

2.3.2. Performance

Following the Moorgate incident, LU also carried out a series of tests on various designs of sand drags and developed a train arrestor design where the train collides with a 'crash dolly' (effectively a sliding buffer stop) and this is pushed into a deep trough of gravel. These were found to be much more effective than the simple sand drag and are still used in some terminal locations: two examples are illustrated in [12].

The results of these tests still exist in paper format in the TfL historic archives, and we are in discussion with the TfL archivists to arrange to view them. There is a considerable lead time to retrieve the documents from deep storage and arrange an appointment to study them in the reading room so this data will be considered in Phase 2 of the work.

TfL standard S1169 [33] defines the performance and design for all types of train arrestors. Now, friction arrestors are required at terminal stations, though other types of arrestor can be permitted subject to risk assessment and mitigations in the approach speed of trains. S1169 defines safety considerations for train arrestors, and principles for the calculation of the required energy absorption and retardation rates [33] – these will be considered in more detail in Section 4.

2.3.3. International Comparison

Similar sand drags are used on other metro systems worldwide. Figure 7 shows an example on Montreal Metro [22].

Figure 7: Sand Drag on Montreal Metro, similar to those on London Underground but deeper across the full width of the track

2.3.4. Summary

In summary, sand drags are widely used on LU, but not on passenger terminal tracks, and there are plans to eliminate them entirely. The normal type consists of a high mound across the track, and there are inspection and maintenance requirements specified for this. They are accompanied by other means of terminal protection such as approach speed limits, automatic train stops and bufferstops. It is recognised that sand drags have limited effectiveness at stopping a train but may assist in a controlled deceleration.

2.4. Light-Rail Applications

2.4.1. Standards and Practices

An official guidance document on tramway requirements has been issued by several organisations over the years, including HMRI, ORR [17], UKTram [16], and it is now managed by LRSSB under the title 'Tramway Principles and Guidance' [18]. The requirements relating to terminating tracks (below) have remained largely unchanged since the 2006 edition although paragraph 5.51 is a more recent addition.

Terminating Tracks

5.49 Where tram tracks terminate, arrangements should be made for any potential tram that overrun the normal limit of operations to be brought to a halt or contained safely. The arrangements may include (not exclusively):

- *sand drags,*
- *soft macadam surfacing over the rails, or*

• energy-absorbing architectural features such as large planters, etc

5.50 The selection of the arrangements for a location should be on the basis of tram kinetic energy, the risks arising from an overrun, and suitability for the surrounding environment. The means chosen should discourage pedestrians from lingering in an overrun area.

5.51 Without proper consideration of energy absorption rates the provision of buffer stops could increase risk.

The Blackpool system avoids terminating tracks in public areas by using loops at locations where trams reverse direction – the exception being the new extension to Blackpool North Station which has buffer stops.

2.4.2. Usage in the British Isles

An online forum discussion thread on tram terminal protection [19] states that all terminal locations on Tyne & Wear Metro, Docklands Light Railway and Sheffield Supertram have full buffer stops, as do all locations on Nottingham Express Transit except for Phoenix Park (which has solid end walls). Although an informal source, this information is corroborated by an email from LRSSB [20] indicating that the only LRSSB members with experience of (or interest in) sand drags were Manchester Metrolink, Edinburgh Tram and West Midlands Metro. These systems use buffers in some places but some form of sand drags in others. Known locations of sand drags or arrestor beds in the British Isles include:

<u>West Midlands</u>

- Wolverhampton St Georges (old design)
- Wolverhampton Railway Station (new design and installation)
- Also proposed for other locations as part of future network expansion

<u>Manchester</u>

- Eccles
- East Didsbury (two tracks)
- Sheffield Street (Piccadilly) turnback
- Ashton (two tracks)
- Rochdale Town Centre (two tracks)
- Trafford Centre (two tracks)

<u>Edinburgh</u>

No sand drags are actually installed. There were plans to use them at Newhaven and Airport termini and a concept design was produced [45]. However, after review of the nearby structures at Airport it was decided that this was inappropriate for the location. There was further debate about the overrun protection provided at Newhaven [21] but eventually the design was changed to provide large planters. These are substantial concrete open-topped boxes, filled with aggregate and soil and planted for aesthetic purposes. They rest on the ground and effectively act as a friction buffer – an impacting tram pushes the weight of the planter across the ground with the weight of the planter providing retarding friction at its base.

Dublin

Dublin's LUAS is not formally within LRSSB's remit at present, but is a UKTram member and it is useful to include the system in this review because it has sand drags at the following terminals:

- Tallaght (two tracks)
- Saggart (two tracks)
- Broombridge (two tracks)
- Bride's Glen (two tracks)
- St Stephen's Green turnback

2.4.3. Review of Types of Sand Drags

There is considerable variation in the forms of the sand drags at these locations, no doubt due to local conditions and design evolution over time.

A minority of light-rail locations use a design where the rails continue into the sand drag, as they would on the main-line or metro sand drags discussed previously. In discussion with engineers at Dublin's LUAS [64] their view was that the rails provide a significant guidance and support function, controlling the path of the over-running tram and minimising the risk of rollover or jack-knifing during the deceleration.

The LUAS termini at Tallaght, Saggart, Broombridge and St Stephen's Green have an arrangement where the rails pitch downwards to give an increasing depth of sand. The earlier installations have a surface 100 mm above the approach rail height with a wooden kerb, but the more recent ones are flush. In all cases the surface is coated with resin-bound aggregate as shown in Figure 8. The similar but slightly larger installation at Tallaght is illustrated in Figure 9.

Where fitted, the low wooden kerb would be below the carbody itself, but may engage with the tram's obstacle deflector. If so, this would be the first impact. If the kerb is not destroyed by an obstacle deflector impact, then the wheels would strike it.

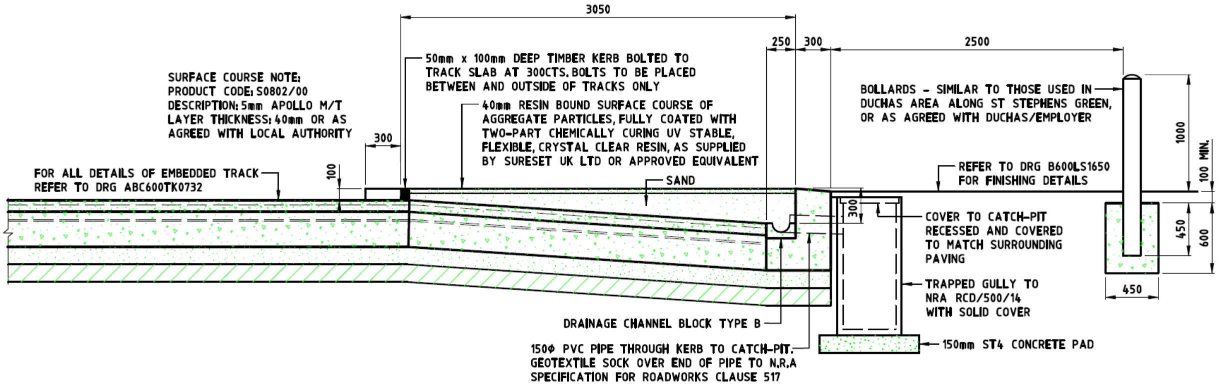

Figure 8: Longitudinal cross-section of the concept used at several of Dublin's LUAS termini (note that dimensions vary by location and not all have the wooden kerb)

In the UK, only Eccles on Manchester Metrolink has a similar installation. Here the rails remain horizontal and the surface of the sand drag slopes upwards. 'MOT Type 1' mixed-grade aggregate is used as the arresting medium; this has a good load-bearing performance and may not be ideal as an arrestor. At Eccles the surface is coated with a thin layer of asphalt as shown in Figure 9 and Figure 10, and there is no kerb.

Figure 9: Terminal tracks at Tallaght (left) and Eccles (right)

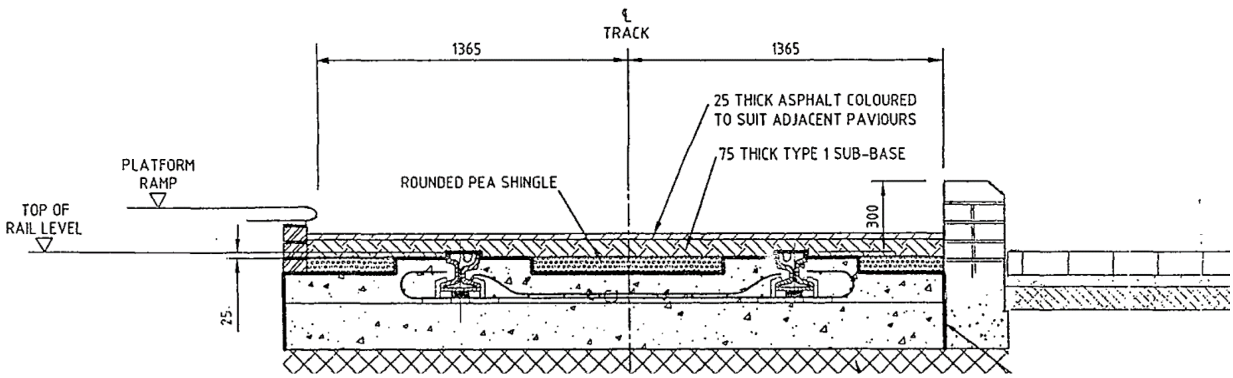

Figure 10: Transverse cross-section of the concept used at Eccles

LUAS Bride's Glen terminus has more in common with Eccles, but the loose material in the sand drag is unsurfaced as shown in Figure 11, and is mounded up to a greater height over a longer distance. The rails continue horizontally under the mound. This location has greater consequences of an over-run than other LUAS termini because the trams run on an elevated overpass rather than at ground level.

Figure 11: Terminal tracks at Bride's Glen, Dublin LUAS

The remaining light-rail examples are all positioned beyond the end of the rails. Manchester Trafford Centre and Wolverhampton St Georges both have a planted 'catch pit' of soft-surfaced earth beyond the end of the rails to retard an over-running vehicle. The aesthetic treatment is different as shown in Figure 12, with St Georges having a slate-chipping surface planted with miniature conifers, while Trafford Centre has a grassy bank with embedded plastic mesh. Functionally, St Georges also differs by having a raised kerb so that the initial impact would be between the tram's obstacle deflector and the kerb. Note that the kerb facing the rails (not visible in Figure 12) is lower than on the other three sides.

Figure 12: Catch pit arrestor beds at Wolverhampton (left) and Trafford Centre (right)

The design cross-section for Trafford Centre is shown in Figure 13 but the as-built differs in several key respects – the kerbstone is set almost flush with rail level, the sloping bank is much longer (≈8 m) and the surface is a lightweight plastic mesh with grass growing through it, rather than true ‘grasscrete’. These changes may improve its effectiveness as an arrestor.

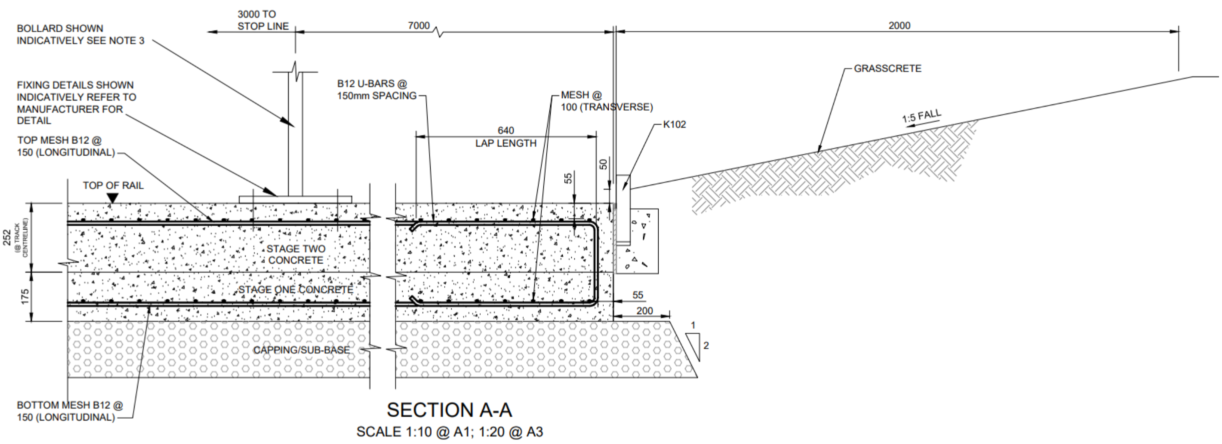

Figure 13: Longitudinal cross-section of Trafford Centre catch pit

Another design was proposed for use on the Edinburgh system, as illustrated in Figure 14 [45]. The rails end prior to a raised kerb 300 mm above rail level. This is the height of the tram’s structural floor plate, and it was envisaged that the initial impact would be with the front end of the tram carbody to displace the coping and disrupt the paving slabs. The tram wheels would then ride up onto the paving slabs, and break through them into the soft granular aggregate fill beneath. The drawing shows Class 6N fill, which is quarried crushed rock (limestone/granite) containing a well graded mixture of particles ranging from 0 mm to 80 mm in size and has a good load-bearing capacity.

The length of the pit was planned to be 6 m, and the expectation was that the wheels and then the nose of the tram body would dig into the fill material providing rapid deceleration. The design was abandoned before any detailed calculations or modelling were undertaken. One wonders whether the load-bearing capacity of the paved fill would have been low enough for the tram to break through. Also, the initial impact and the change in level would tend to make the leading segment of the tram pitch upwards, reducing the likelihood of the nose digging into the fill.

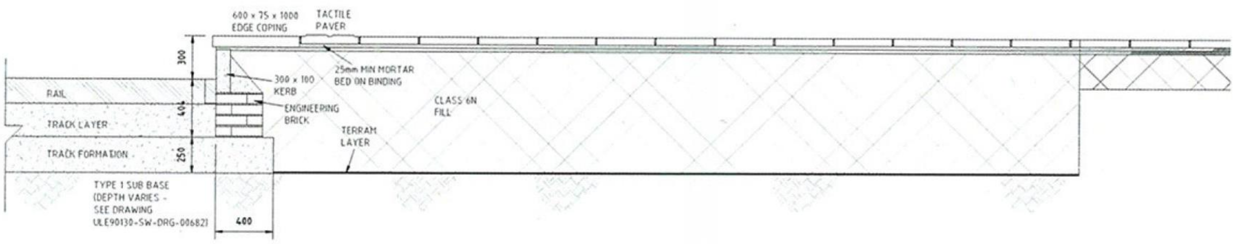

Figure 14: Concept longitudinal cross-section for Edinburgh catch pit arrestor

One of the main goals of using a sand drag retarder rather than a buffer stop is to avoid high collision forces being applied to the end of the carbody. The Edinburgh concept is distinctly different as a collision with the end of the carbody was part of the design intention. The detail design was never completed, and none have been installed; it is possible that the design would have evolved further.

The other Manchester locations have a common design which may be described as a flush surfaced arrestor bed. These are used at East Didsbury, Ashton-under-Lyne, Rochdale Town Centre, and the Sheffield Street (Piccadilly) turnback. These also have a 'catch pit' beyond the end of the rails with the top flush with rail level. This is filled with pea gravel and then surfaced with a 75 mm layer of unreinforced concrete. A cross-section of the design is shown in Figure 15; the arrestor bed is the 5 m long section towards the right-hand side. The surface is intended to give way under the weight of a tram, dropping the wheels into the pea gravel to decelerate it.

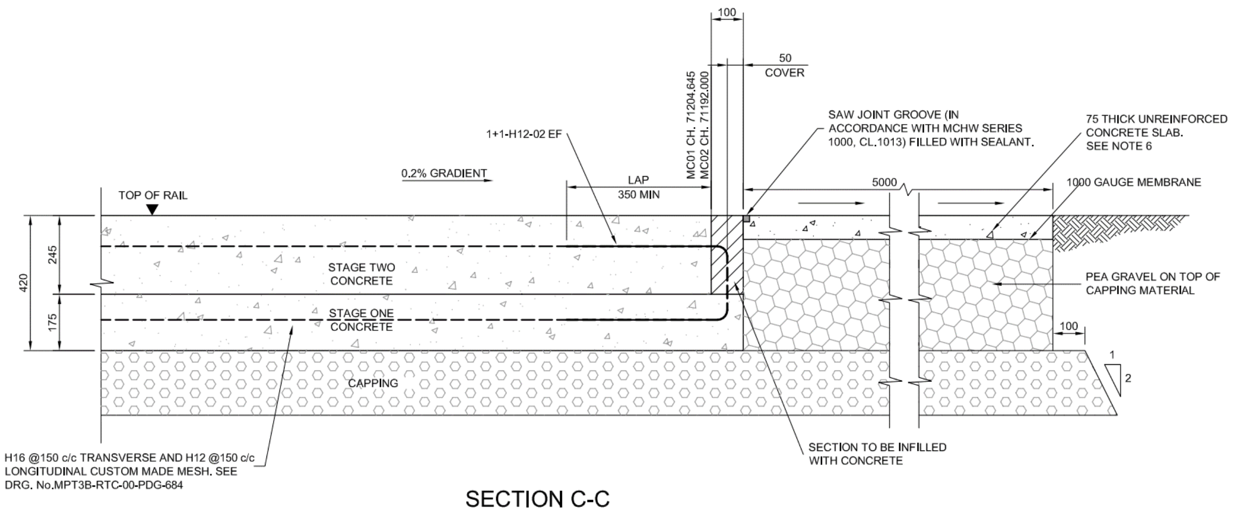

Figure 15: Longitudinal cross-section of Rochdale flush surfaced arrestor bed

Practical evidence suggests this doesn't always work, as demonstrated by an over-run incident at Sheffield Street during summer 2022, which was caused by driver error [19][60]. A recent visit to this location by the author of this report observed that the leading bogie of a tram had rolled over the arrestor bed on its flange tips without breaking through the surface (despite the very high localised pressure at the flange tip contacts). The arrestor bed did not do its job, and the tram was only brought to a standstill after colliding with a bollard demarking a pedestrian crossing. Figure 16 shows the site in April 2023.

The drawings for the arrestor bed at Sheffield Street show a significant difference to the other similar locations: the membrane on the top of the pea gravel is not shown. If the concrete was poured directly onto the pea gravel bed, it is postulated that the finer constituents of the concrete may have penetrated the pea gravel and created a concrete slab that was significantly thicker than intended. This cannot be confirmed until the slab is broken out and renewed – an important step to determine the reason why the wheels did not break through the surface of the arrestor bed.

Figure 16: 'Two nice parallel lines and a wonky bollard' [19] Evidence of the Sheffield Street over-run: the flush surfaced arrestor bed (grey rectangle) did not function as intended.

As an aside, note that the front of the tram considerably overhangs the leading wheelset, and even if the wheels had been brought to a stand within the arrestor bed the tram may still have struck the bollard. Figure 17 shows the similar installation at Rochdale, and one wonders whether the traction pole might be at risk in the event of an over-run – even the prospect of a Barcelona-type incident.

The arrestor beds at East Didsbury appear to be of similar construction, but in this more rural location they are bounded by wooden shuttering rather than set into a hard surface. One slab remains in good condition despite the surrounding vegetation. However, the other is unofficially used as a short-cut pedestrian route to the tram stop platform, and this slab is breaking up as shown in Figure 18. This illustrates the design dilemma of an arrestor bed with a frangible surface – if it is weak enough to break under the weight of a tram, will it be strong enough to maintain integrity in normal usage?

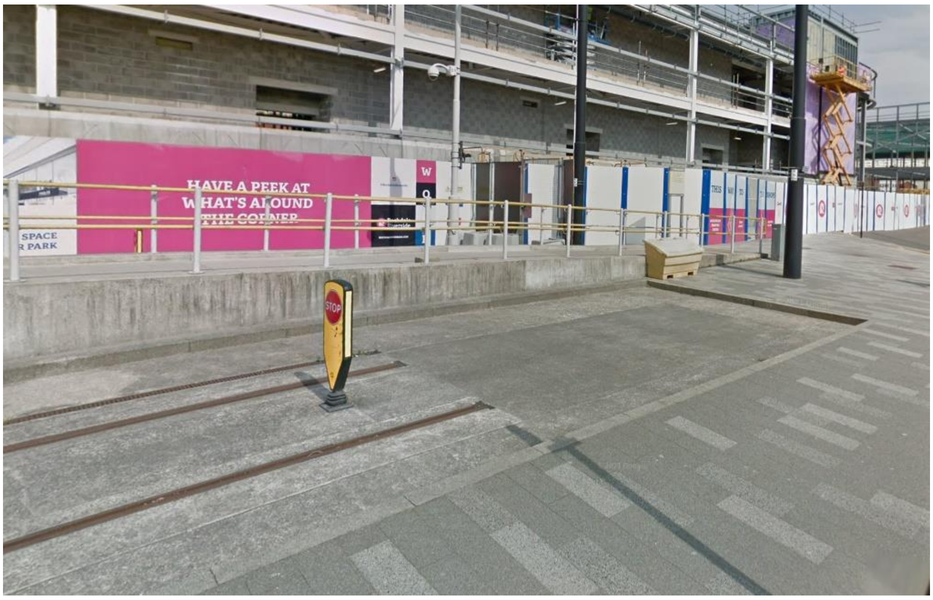

Figure 17: Flush surfaced arrestor bed at Rochdale Town Centre

Figure 18: Flush surfaced arrestor bed at East Didsbury, breaking up under pedestrian traffic

The flush surfaced arrestor bed design proposed for Wolverhampton Station is very similar: a cross-section drawing is shown in Figure 19. We understand that AECOM was responsible for both the Manchester and Wolverhampton designs. In this case, there is a bed of pea gravel 310mm deep, topped with a membrane and 75 mm thickness of unreinforced concrete. The bed is 5 m long, as with the Manchester installations.

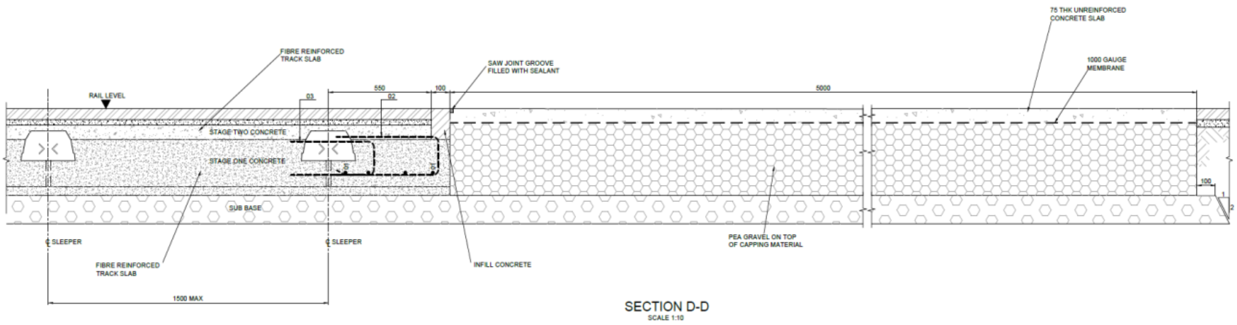

Figure 19: Longitudinal cross-section of flush surfaced arrestor bed design for Wolverhampton Station

However, the Wolverhampton design has been revised to include a further arresting feature beyond – an unsurfaced pea gravel bed 7.5 m long. This gives a total arresting length of 12.5 m. Additionally, there is a tram turnback/stabling position between the tram stop and the end of the tracks, giving an extra 35 m stopping distance before the arrestor bed as shown in Figure 20.

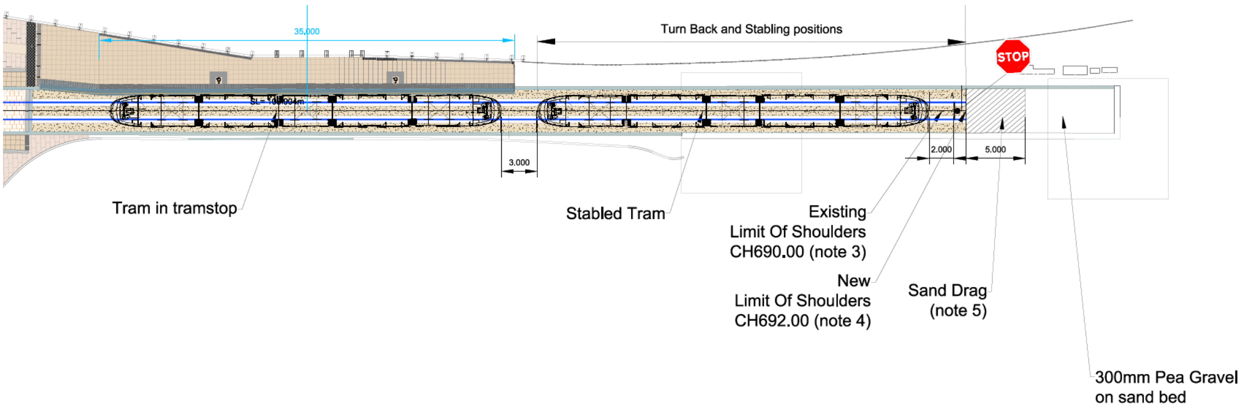

Figure 20: Plan view of terminal tram stop at Wolverhampton Station

2.4.4. International Comparison

Within the scope of this review it is not practical to fully investigate international practice. Many of the larger tramway systems in Europe have single-ended trams and return loops, so terminal tracks are rare. Also, many European tramway networks have been established for over a century, so there may be limited opportunities for redesign of terminal over-run protection. The Barcelona incident (Figure 1) was an example of a location without terminal over-run protection (other than the traction pole).

The modern tramway in Valenciennes, France uses a small wheel retarder on one rail of each track at its three terminal stops, as shown in Figure 21. This appears similar in principle to a 'skate retarder' [61] with two sprung plates that apply friction to the flangeback and outer face of the wheel passing between them. At Vieux-Condé Le Boulon and Famars/Université, this is followed by a small bollard and then at least

10 m of grassed level ground acting as a catch pit. However, at Denain Espace Villars there is a major road beyond, and a substantial fixed buffer stop has been installed on the commonly used turnback line.

Figure 21: Termini at Valenciennes - upper: Denain Espace Villars; lower: Famars/Université

2.5. Other Transport Modes

2.5.1. Highways

On major roads in mountainous regions, emergency escape ramps are often provided to slow down vehicles whose brakes have failed. These are also known as runaway truck ramps, runaway truck lanes, escape lanes, or truck arrestor beds. They often combine an upward incline with a loose gravel bed.

The tyre/road interface has a much larger surface area and operates at lower pressures than rail/wheel contact. Therefore, highway arrestor beds are engineered on a larger scale than railway sand drags. Rounded gravel with a fairly consistent size is used: the size chosen can vary from 5-10 mm [41] to 20-50 mm [43] but 15-25 mm seems generally considered the optimum [44]. They are typically

100-300 m long [43]. The bed depth normally increases in a ≈30 m long taper to ≈1.0 m in the main part of the drag [43]. The wheels of heavy goods vehicles are expected to sink ≈0.3 m into the surface [43] but smaller vehicles may sink less than 0.1 m [44].

Experience shows that if the gravel has a mix of particle sizes, angular particles, or when the gravel becomes clogged with fines, the arrestor bed becomes ineffective [43]. This is because it becomes capable of supporting the wheels without giving way, and therefore the drag is minimal. To remain effective, steps must be taken to minimise contamination and provide effective drainage [43], and highway gravel drags need to be maintained through scarifying, levelling and cleaning [32].

Design standards for highways in Asia [62] include an equation for the required arrestor bed length, which includes a factor dependent on the aggregate used:

Length of arrester bed $L = v^2 /(254(i + Di)$ *where:*

v	*Speed of errant vehicle (km/h) – typically 130km/h*
i	*Gradient (e.g. 0.05 for 5%, +ve for uphill gradient)*
Di	*Rolling resistance of arrester bed materials*
	(0.25 for pea gravel, 0.15 for sand, 0.1 for loose gravel, 0.05 for loose crushed aggregates)

Tests indicate that if a vehicle follows in the tracks of a previous one, the stopping distance is extended by 15-20% [32]. Similarly, vehicles with more axles are less effectively arrested because the trailing wheels are following in the tracks of the leading ones [41]. While drag was found to generally increase with speed, some tests indicated that the drag at the highest speeds can be lower than at moderate speeds [43]. The mass of the vehicle can have surprisingly little effect on the stopping distance because heavier vehicles either have more wheels providing drag or dig in further [44].

Highway arrestor beds are usually engineered on a rising gradient to provide additional retardation, and to provide some benefit even if the gravel condition is not optimal.

An alternative design for highway arrestors is the ‘mound’ or ‘sand pile’ typically between 0.6 m and 1.5 m high. This is no longer a preferred solution because it provides a more abrupt deceleration and can induce the engaging vehicle to pitch, yaw or jack-knife [29]. Sometimes they are used at the far end of gravel arrestor beds as a ‘last chance’ device [43].

The design of highway arrestor beds seems to be largely empirical, based on some testing and considerable experience of their use in practice. Highway design manuals sometimes give equations to calculate the stopping length based on the entry speed, gradient and rolling resistance [43]. Their geographical positioning may be designed more analytically in accordance with local topology [42].

2.5.2. Aviation

Within the last 30 years, the aviation industry has developed and implemented a new form of arrestor bed to reduce the consequences of a runway excursion (over-run) on landing. This is known as an 'Engineered Materials Arrestor System' (EMAS) [31][39], and is intended to stop an aircraft overrun with no human injury and minimal aircraft damage. The size of the EMAS bed depends on the aircraft types and local factors, but the active part of the EMAS is typically ≈100 m long and this is sufficient to halt an aircraft massing ≈50 tonnes and travelling at ≈70 knots (130km/h) [40].

After early experiments with phenolic foam materials [37], two types of EMAS have been developed and approved for use. The more common version comprises precast concrete blocks with a cellular structure [37]. Each lightweight block is secured to the EMAS base with hot asphalt and the seams between blocks are then taped at their upper surface to prevent water penetration. The depth of the EMAS bed gradually increases with increasing distance from the runway, typically from around 0.25 m up to 0.75 m. A more recent development uses a foamed silica bed contained within a high-strength plastic mesh system anchored to the pavement. The foamed silica is poured into lanes bounded by the mesh and covered with a poured cement layer and treated with a top-coat of sealant. [38].

Both these materials crush under the weight of an aircraft in a reliable and predictable way [37] as shown in Figure 22. The aircraft is slowed by the loss of energy required to crush the EMAS material.

Figure 22: EMAS system showing the blocks crushed locally under the aircraft wheels [31]

Several hundred installations have been made [38], primarily at airports in the USA where there is insufficient space for a full-length 1000ft runway safety area at the end of the runway. EMAS systems are primarily intended for medium to large aircraft (tens or hundreds of tonnes) and are ineffective for smaller aircraft lighter than 5700 kg [37].

The arresting performance of the EMAS system appears to be around ten times better than the sand drag tested by BR [3]:

- EMAS: 50 tonne aircraft at 130 km/h (33 MJ kinetic energy) stops in 100 m
- Sand Drag: 20 tonne brake van at 48 km/h (2 MJ kinetic energy) stops in 91 m

The EMAS has a flush surface and is designed to take the weight of normal road vehicles, but the higher pressure of aircraft wheels is sufficient to crush it. It appears that this material could be appropriate for light-rail applications in flush-surfaced arrestor beds. Further investigation of the physical and economic suitability of the material would be worthwhile.

3. Summary of Types of Sand Drag / Arrestor Bed

The literature review discussed in the previous section identified several types of arrestor bed or sand drag, with different applications in various transport modes; these are summarised here. We have used the term 'sand drag' for types where the rails continue into the sand, and the term 'arrestor bed' for those where the rails stop before the arrestor. Note that arrestor types involving fixed or moving buffer stops are not detailed in this section. Also, the Edinburgh concept design is not included as this was never progressed.

3.1. Boarded Trough Sand Drag

Description:	Sand is contained in individual troughs around each rail, to a height of ≈50 mm above rail. The drag comes entirely from interaction with the wheels, and it is intended that these remain guided and supported by the rails. Often the sand drag is installed on a rising gradient to provide additional retardation.
Typical Length:	12 – 100 m
Applications:	Used by Network Rail and some other main-line railway networks for over-run protection on sidings without buffer stops. Not used for terminal station protection.
Performance:	Some performance test data is available, as are BR design calculations.
Comparable to:	Nothing comparable in other transport modes.

3.2. Mounded Sand Drag

Description:	Sand is formed in a mound across the full width of the track, typically to a height of around 0.5 m. The drag comes from the train 'bulldozing' the mound of sand, with a secondary contribution from the wheels. It is intended that the wheels remain guided and supported by the rails.
Typical Length:	≈ 10 m
Applications:	Used by LU and some other metro systems for over-run protection in turnbacks and sidings. Used in conjunction with signalling-based approach speed limitation, and with fixed buffer stops or end walls. Sand drags are no longer permitted for terminal station protection on LU, who intend to phase them out in other locations too owing to their ongoing maintenance requirements. Network Rail also provides guidance on the dimensions and construction of this type of sand drag, but they are not a preferred option for new installations. Bride's Glen on Dublin's LUAS is of this type.
Performance:	Performance test data currently available is limited to evidence of their ineffectiveness in several main-line and metro incidents. Tests were carried out by LU and the test report exists in the TfL archives.

Comparable to:	Where space is limited, some highway arrestor beds have sand mounds, but these are not a preferred solution.

3.3. Surfaced Sand Drag

Description:	Sand is formed across the full width of the track, with the depth increasing gradually along the length of the drag, either by the rails being angled down or the surface being angled up. The surface is covered with a thin layer of tarmac or resin-bonded aggregate. There may be a low kerb (≈100 mm) at the start of the drag. The drag comes predominantly from the wheels, but the tram's obstacle deflector may also be involved.
Typical Length:	≈ 5 m
Applications:	This type is used on Dublin's LUAS at Tallaght, Saggart and Broombridge, also at Eccles on Manchester Metrolink.
Performance:	We are not aware of any performance data.
Comparable to:	Nothing comparable in other transport modes.

3.4. Catch Pit Arrestor Bed

Description:	An area of loose material is placed beyond the rail ends, slightly higher than rail level or with an upward slope. This is distinct from the three previous types because the rails stop before the arrestor bed starts, and therefore cannot be expected to support or guide the vehicle. Therefore, the wheels may dig in further, potentially providing more drag. For aesthetic reasons and to discourage pedestrians from remaining in the area, the arrestor bed may be provided with a soft surface covering (slate chippings, plastic mesh) and may be planted.
Typical Length:	≈ 5 m
Applications:	This type is used at Trafford Centre on Manchester Metrolink and Wolverhampton St Georges on West Midlands Metro. The design for Wolverhampton Station has a combination of a flush surfaced arrestor bed followed by a catch pit arrestor bed filled with pea gravel.
Performance:	We are not aware of any performance data.
Comparable to:	This type is most closely equivalent to the gravel arrestor beds normally used on highways, but the light-rail examples are very much shorter and with more variable aggregate. Highway experience is that rounded aggregate of consistent size provides the best performance.

3.5. Flush Surfaced Arrestor Bed

Description:	A pit is placed beyond the rail ends, filled with pea gravel and surfaced with a frangible layer of concrete that is flush with rail level and the surrounding surface. Again, the rails stop before the arrestor bed starts, and therefore cannot be expected to support or guide the vehicle. In theory, the wheels will break through the surface layer and dig into the pea gravel to provide drag. The arrestor bed area is often available for pedestrian use without obvious deterrent.
Typical Length:	≈ 5 m

Applications:	This type is used on Manchester Metrolink at several terminals including: East Didsbury, Rochdale Town Centre, Ashton-Under-Lyne, and Sheffield Street turnback. The design for Wolverhampton Station has a combination of a flush surfaced arrestor bed followed by a catch pit arrestor bed filled with pea gravel.
Performance:	An over-run at Sheffield Street failed to break through the surface and the tram eventually collided with a bollard. It is postulated that the concrete slab is stronger or thicker than intended. We are not aware of any performance data for flush surfaced arrestor beds operating correctly.
Comparable to:	This type is most closely equivalent to the EMAS system used in the aviation industry. However, it appears that the crushing performance of the design may not be so well optimised.

4. Retardation Requirements

4.1. Overview

The design of any terminal over-run retarder should consider the energy to be dissipated, the operating conditions, the acceptable retardation rates, and the physical environment where it is installed. Many of these considerations are the same for all types of buffer stops, sand drags, arrestor beds and large planters. They are considered in more detail here.

4.2. Vehicle Mass

In an over-run situation, the most severe consequences are likely to occur with a laden vehicle, as there are more passengers involved and the over-run distance and/or decelerating forces will be greater. LU's train arrestor standard S1169 [33] normally requires the arrested vehicle mass to be determined in crush laden condition, although lighter loads can be justified based on the peak passenger numbers using the site (with a safety factor applied).

An arrestor designed to decelerate a laden vehicle should stop a tare vehicle more quickly, with greater deceleration and jerk rates. S1169 therefore requires the arrestor design to consider the likely range of vehicle masses to ensure that the deceleration rates are tolerable for all realistic conditions.

The modern light-rail vehicles presently in service in the UK typically have a tare mass in the range 35t to 45t, and a laden mass between 50t and 65t. Exceptions to this are the Rotherham tram-train vehicles which are about 20t heavier. Manchester's trams often operate in pairs, totalling around 80t tare, 110t laden.

The mass of vehicle to be decelerated by an over-run retarder therefore varies a great deal between systems and in designing retardation devices this should be defined based on local conditions rather than specified in standards. For illustrative calculations, 60t would be a reasonable median laden value to consider.

There is less variation in tram axleloads because the heavier trams have more axles. Tare axleloads are typically between 6t and 7t, laden between 8t and 10t. The axleload is significant for arrestor designs which rely on the wheels breaking through a hard surface layer.

4.3. Vehicle Geometry

The geometry of the vehicle design can also be relevant for arrestor design.

Considering arrestor designs which act primarily on the wheels, the front of the tram may be several metres beyond the arrestor before the first wheelset enters it and the drag starts to take effect. One would hope that the tram would have stopped before the third wheelset enters the drag. The stopping distance is therefore influenced by the relative positions of the tram front and the leading two wheelsets.

For arrestor designs which interface with the front of the tram body or the obstacle deflector (including mounded sand drags and catch pit designs with raised kerbs), the arrestor design should consider the height above rail where they can interface with a robust part of the vehicle structure.

The tram's articulation design may also influence its interactions with an arrestor. The likelihood of carbody pitching or jack-knifing will be influenced by the length of the carbody segments and the nature of the linkages between them. If the front of a vehicle pitches upwards when it meets the arrestor, then it is not realistic to rely on its nose digging into a sand pit to provide additional drag.

4.4. Approach Speeds and Conditions

The approach speed of the tram is crucial for defining the required arrestor performance, as the energy dissipation needed is proportional to the square of the speed.

Network Rail provides approach speed control to buffer stops at the end of passenger platforms, through the use of TPWS. These are fitted approximately 65 m from the buffer stops and will trigger a brake application at speeds greater than 10 mph (16 km/h) [47]. RSSB requirements for buffer stops in terminal platforms state that the determined impact speed shall not be less than 10 km/h [6].

LU requires the arrestor impact speed to be agreed with the Signalling Engineer as appropriate for the site [33]. The LU standard S1169 gives examples with impact speeds of 20 km/h and 24 km/h. It also notes the following:

> *In optimising the balance between retardation and distance, retardation rates shall take priority. Where the available slide length is less than that assessed as necessary for a likely impact speed, further measures to limit approach speeds shall be taken.*
> *In determining the retardation force imposed by the arrestor, account shall be taken of whether or not the train's braking system is likely to be in operation during impact.*

For tramway arrestor design, there is a need to define the approach speed and whether or not the brakes will be applied.

Modern trams have very effective service, hazard and emergency brakes which can stop a tram in a short distance if required. If the tram driver is alert and performing their duties competently, and the tram's braking systems are in working order, then an external arrestor device should never be necessary. Trams are also fitted with driver vigilance devices which should ensure that drivers remain alert, and in theory the braking systems should be fail safe.

Nevertheless, situations do occur where tram drivers do not perform their duties correctly, and the automatic safety systems do not intervene promptly. It is in these circumstances that an external arrestor device may be called into use. It is necessary to define realistic scenarios to consider, particularly the tram speed and whether its brakes are applied. Any gradients at or near the terminal should also be considered.

From discussion with Colin Kerr at Edinburgh Trams [53], the scenario being protected is last-minute inattention by the tram driver on approach to the terminal stop. In this scenario the maximum approach speed is 15km/h, with no brakes applied.

Michael Doughty of Keolis Amey Metrolink also considers that the scenario is an incapacitated tram driver, and the brakes released. In Manchester, there is a 10 mph (16 km/h) speed restriction at terminal platforms, so this would be considered a realistic maximum approach speed for an arrestor.

Engineers at Dublin's LUAS considered that their sand drags were suitable for approach speeds of 5 km/h to 10 km/h but would expect the tram to over-run the drag at higher speeds [64].

In a discussion with Tony Stanley of West Midlands Metro, Kouessan Kangni of Metro Alliance and David Keay [54], the consensus was that 15 km/h was a reasonable approach speed for terminal stops. Again, the scenario being protected is last-minute inattention by the tram driver on approach to the terminal stop. It was noted that the driver's vigilance device on WMM activates after 15 seconds, and there can be a 4 second delay before the brakes are then applied: at 15 km/h the tram could travel nearly 80 m in 19 s.

In practice, this period of inattention would be measured not from the normal stopping point, but from the point at which the driver ought to start braking from the stop. Another issue is how far the end of track is beyond the normal stopping point: if there is a stabling point between the platform and the arrestor bed then the credible approach speed for the arrestor bed is much less. David Keay had calculated that for the Wolverhampton example, the vigilance device would have activated the brakes as the tram passed the stop board, and that the speed would have reduced to 5 km/h by the start of the arrestor bed [54].

RSSB guidance [6] on terminal tracks prefers that they should be straight on approach to the buffer stop, so that the longest vehicle likely to use the track will approach the arrestor perpendicular to it. LU S1169

[33] recognises that installing arrestors on curved track represents an increased risk, although it does not prohibit their use on curves. When interacting with an arrestor, there would be a greater risk of tram jack-knifing or derailment if the tram approached on curved track. When designing an arrestor it would be reasonable to assume a straight approach and to require this for new installations. Almost all reviewed installations are straight – the exception being Bride's Glen on LUAS.

4.5. Retardation Rates

There is an optimum range of retardation rate for a train arrestor. If the vehicle is decelerated too slowly, it will cover a long distance before it stops, increasing the risk of secondary collisions and requiring more space in the terminal area. However, if the retardation is too rapid, the effect of deceleration and jerk will cause injuries to passengers in the vehicle and may cause structural damage to the vehicle itself.

RSSB requirements for terminal platform arrestors limit the normal average retardation rate to 1.47 m/s^2 [6]. Where site constraints make it unavoidable, lightweight trains may be subjected to average retardation rates up to 2.45 m/s^2.

LU standard S1169 [33] requires that friction train arrestors (the preferred type) should be designed to achieve a desirable retardation rate ≤1.47 m/s^2. At locations where different types/weights of train operate, an absolute maximum retardation rate of 2.45 m/s^2 is permitted. These deceleration rates are consistent with the RSSB limits. There are also requirements for the maximum force applied to the train, to minimise vehicle damage.

From discussion with Colin Kerr at Edinburgh Trams, the acceleration and jerk rates appropriate for an emergency brake application are a good benchmark when considering retardation rates for train arrestors.

The now-superseded ORR guidance document [17] gave specific requirements on the retardation and jerk rates for tram brake systems, and these will have been used for the design of many trams currently in service:

- Service brake: average retardation ≈1.3 m/s^2 , jerk <0.8 m/s^3.
- Hazard brake: average retardation ≥2.5 m/s^2, instantaneous maximum 3 to 4 m/s^2, jerk <1.0 m/s^3.

The more recent equivalent LRSSB guidance [18] refers to BS EN 13452 [46] for braking rates. This data suggests that the average deceleration rate limits specified by RSSB and LU are also appropriate for light-rail applications. The optimum deceleration should therefore be in the range 1.47 to 2.45 m/s^2. A tram travelling initially at 15 km/h and decelerated at 2.0 m/s² would take 4.3 m to stop. This distance is comparable with the length of the arrestor beds used on UK light-rail systems.

Because light-rail sand drags tend to be short, they act on the wheels of the leading bogie, whereas most trams have 3 or 4 bogies which would normally contribute to the braking rate. Trying to decelerate the entire vehicle at 2.0 m/s² by applying all the drag force to the leading bogie could significantly over-stress the bogie/body interface. To avoid vehicle damage, a lower deceleration rate might be preferable, although this would require a longer distance to stop. A tram travelling initially at 15 km/h and decelerated at 1.0 m/s² would take 8.6 m to stop, which is longer than most arrestor beds.

4.6. Energy Absorption

Considering a typical laden tram with a mass of 60t and a speed of 15 km/h, its kinetic energy is 0.5 MJ: all this must be dissipated to bring it to a stop. To decelerate it at 2.0 m/s², the required drag force would be 120 kN.

This force can be compared to the total vertical load on the wheels of the tram's leading bogie (≈200 kN) and one might consider whether the bogie might ride up more easily than digging in to a sand drag.

A required drag force of 120 kN can also be compared to the total drag forces for a 2-axle 20t vehicle in a boarded sand drag (based on BR Research measurements [3]) which were in the range 10 kN to 20 kN. With just 20 kN drag force the stopping distance from 15 km/h would be 26 m.

This suggests that a 120 kN drag force and a 5 m stopping distance from 15 km/h is unrealistic for a sand drag and may also damage the body/bogie interface. A combination of longer sand drags and lower approach speeds would provide a more realistic performance requirement.

Methods of calculating drag force performance are considered in Section 5.

5. Performance of Sand Drags and Arrestor Beds

5.1. Overview

To date the IRR has not identified formal, detailed calculations of the drag force or deceleration rate provided by sand drags or arrestor beds in a railway environment. Some evidence of their performance is provided by design advice [58], test results [3] and incident reports or investigations [12][13].

As seen in Section 2, maintenance requirements for sand drags in railway applications consistently require the sand to be maintained clean, loose and to the required profile, and it is recognised that the grade of aggregate and consistency of particle size is important in the effectiveness of a sand drag. However, no evidence has been found from railway applications of the quantitative effects of these issues.

Test and modelling data from analogous situations may provide a useful indicator of trends, although the absolute figures will not be applicable. Relevant analogies include arrestor beds in other transport modes, drag forces from earthmoving and agricultural implement research, and the bearing capacity of sand in civil engineering applications.

This section considers the five categories of sand drag or arrestor bed identified in Section 3, and the approaches that might be used to determine the drag forces and deceleration rates that they could achieve. Carrying out those calculations and/or other tests or modelling would form part of Phase 2 of this project.

5.2. Boarded Trough Sand Drag

This type of sand drag only retards the wheels in the sand drag, and the effect on the leading wheelset will be greater than on subsequent wheels because the sand the latter encounter will already be compacted. One must also consider also the end overhang of the tram, before the leading wheels reach the arrestor bed.

BR equation to determine the length of sand drag required as a function of train speed and weight [58] was as follows:

$$\text{Length (feet)} = 0.7 \times \text{Speed (mph)} \times \sqrt{\text{Weight (tons)}}$$

Considering a typical 60-ton (60t) tram travelling at 9.4mph (15km/h), the required sand drag length would be 50 feet (15 m). For a Manchester double tram of 100t at 10 mph, the required sand drag length would be 70 feet (21 m). These are both significantly longer than the typical 5 m length used for light-rail sand drags.

However, test data from BR Research [3] provides a practical indication of the effectiveness of this type of sand drag and the influence of speed and sand depth. The tests indicated that the performance was significantly worse than estimated in the design guidelines [58], giving even longer stopping distances.

The test results could be used as the basis for calculations of drag force; initial assessment is that the drag of the sand alone is only about 10% of the desirable maximum for a tram arrestor bed (see Section 4.6).

On Network Rail, boarded trough sand drags are often installed on a rising gradient, and this should also improve their performance. This could be included in the calculation if it was a realistic scenario in a light-rail environment.

If the tram has its brakes on, then the performance of a boarded trough sand drag may be significantly improved – the sanded rails should improve wheel/rail friction and magnetic track brakes have some rails to work with.

5.3. Mounded Sand Drag

The Moorgate accident report [13] included a simple analysis of the retardation provided by a mound-type sand drag. The assumption made in that analysis was that the train effectively 'bulldozed' the sand above rail level, and the retardation was derived from accelerating the mass of sand to the same speed as the train. This is plausible but neglects any friction effects so it may have under-estimated the retardation. Nevertheless, the conclusion remains valid that the 37ft (11m) sand drag was entirely ineffective at stopping a heavy train travelling at moderate speed. Analysis of main-line accidents such as that at Sheerness-on-Sea [56] also indicated that the presence of a sand drag made little difference to the stopping distance of an over-running train.

The mounded sand drag interacts with both the front of the vehicle and its wheels. The drag on the wheels can be assessed in the same way as the boarded trough sand drag considered above.

One method of calculating the drag force applied to the front of the vehicle would be to consider the bulldozing analogy. Several research papers have tested or modelled the drag on a bulldozer as a function of speed, soil type, depth and width of the blade [48][49][50].

By combining these methods, it should be possible to estimate the drag force of a mounded sand drag, as a function of its shape and size. This could then be partially validated by comparison with the known performance in incidents. Results from the old London Underground tests mentioned in [12] could be very valuable if they can be obtained.

5.4. Surfaced Sand Drag

If the vehicle wheels break through the surface layer, this becomes similar to the mounded sand drag. Whether the wheels are likely to break through is discussed in more detail in Section 5.6.

Some surfaced sand drags also have a low kerb which may collide with the tram's obstacle deflector. This interaction may depend more on the detail design of the tram than the infrastructure.

Some surfaced sand drags have a downward gradient on the rails which could also be accounted for in the calculations.

5.5. Catch Pit Arrestor Bed

This is similar to the mounded sand drag, with the important difference that the rails end before the catch pit commences. Also, most catch pits use rounded pea gravel rather than sand, which will reduce the bearing capacity. This means that the wheels have the potential to dig in further, and to bring other parts of the tram into contact with the arrestor bed. If this can be accounted for, the methodology used for a mounded sand drag calculation can form the basis for the catch pit arrestor bed.

When a railway wheel runs over sand or gravel, to what extent will it sink in and drag effectively? The load-bearing capacity of aggregate is strongly influenced by whether it is compacted or not, how it is contained, the range of particle sizes, and by its moisture content (think of walking on a beach). The BR Research sand drag tests [3] included one condition where the wheels climbed onto the sand and the vehicle derailed, which demonstrates that sand can be capable of supporting a railway wheel, at least in a dynamic situation.

BS8004 [23] defines the design load bearing capacity for various foundation materials, and this data is also readily accessible online, for example [24]. 300 kPa is given as a typical design capacity for the bearing capacity of compacted sand; 600 kPa may be used for dense sand/gravel. For loose sand the design load capacity can be as low as 100 kPa. These design loads contain a factor of safety and the actual load-bearing capacity may be higher. However, physical tests of the bearing capacity of sand [25] suggest that 300 kPa is a realistic value when the pressure is applied to the surface of the sand. Higher values can be achieved if the foundation is embedded or the sand is contained, as in a flush surfaced arrestor bed.

Considering a typical tram with an 8t axleload, carried on two wheels 0.1 m wide and with a length of 0.2 m in contact with the sand. This would give a contact pressure ≈ 2,000 kPa, well in excess of the load capacity of sand so statically we would normally expect the wheel to sink in – the dynamic interaction would be more complex.

In existing UK light-rail applications, catch pit arrestor beds may be filled with a variety of soils or aggregates and may be surfaced with materials as diverse as plastic mesh, decorative chippings, grass, or shrubs. The over-run arresting capability will surely be influenced by these variations, but the IRR has not yet seen any design calculations to determine their effectiveness.

Assuming that the arrestor bed surface covering fails to support the wheels and they dig in, then a railway wheel in a sand drag is broadly analogous to an agricultural disc harrow being dragged through soil. Tests have been carried out to determine the drag force of a harrow as a function of speed, tillage depth (TD) and soil moisture content (SMC) [26]. Results have been selected from that work considering the tillage depth applicable to a railway wheel in a sand drag and are shown in Figure 23.

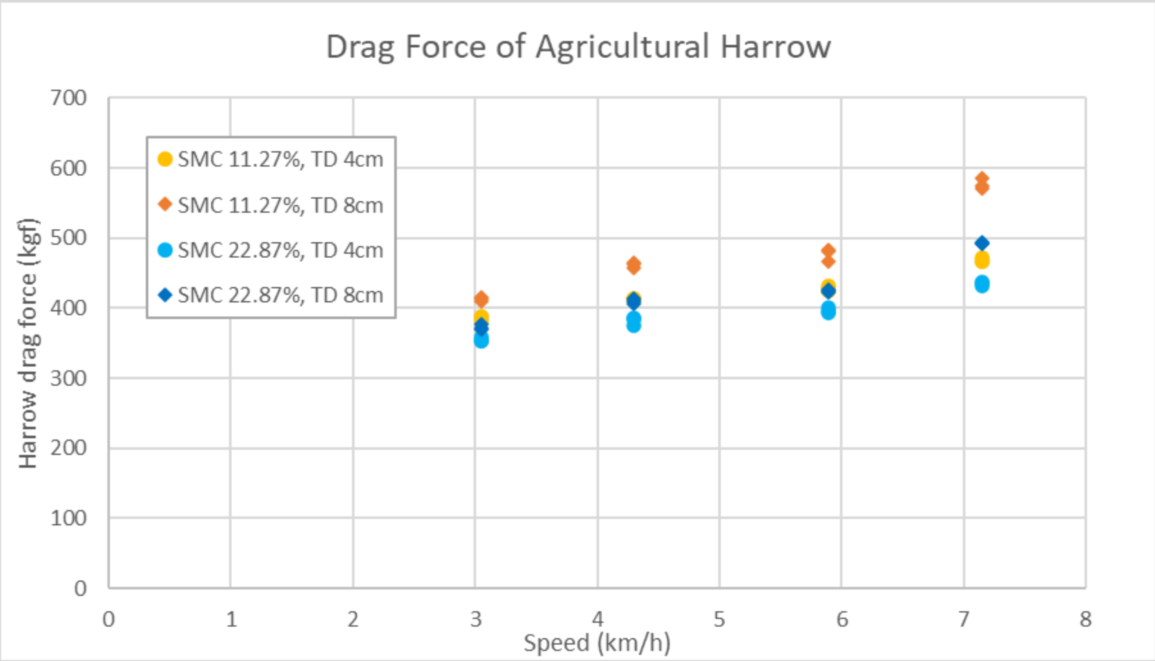

Figure 23: Drag force for Agricultural Harrow: Influence of Speed and Depth

These results indicate that the drag force increased with speed, but for the range of speeds tested the increase was relatively small: a 134% increase in speed gave only a 29% increase in drag. The drag force also increased with depth, but doubling the depth gave only an 11% increase in drag.

This suggests that the wheels themselves may not cause much more drag when they dig in, but they would bring other parts of the tram into contact with the sand in the ‘bulldozer’ mode. The mounded sand drag calculation method could be adapted to represent this effect. Further analysis of Highway arrestor bed data may be able to provide some validation data for such a model.

If the tram has its brakes on, this may have little influence on the performance of the catch pit arrestor bed itself. In particular, track brakes do not work in the absence of magnetic rails. However, brakes on the rear bogies of the tram still on the rails will make a useful contribution to the deceleration rate.

5.6. Flush Surfaced Arrestor Bed

Considering the experience of Sheffield Street (Figure 16) a key issue for the flush surfaced arrestor bed is whether the tram's wheels break through the surface or not. If not, then the arrestor bed is entirely ineffective, and the tram will continue to roll across the flush surface until something else brings it to a halt. If the wheels do break through the surface, then the drag can be estimated using a similar method to the catch pit arrestor bed.

In the previous section, we considered a typical tram with an 8t axleload, carried on two wheels 0.1 m wide and with a length of 0.2m in contact with the sand. This would give a contact pressure ≈ 2,000 kPa, well in excess of the load capacity of sand or pea gravel so we would normally expect the wheel to sink in. But if we assume a surface layer distributes the load over a larger area of 0.3 m x 0.4 m, the mean contact pressure ≈ 333 kPa. This is quite plausible to be carried by compacted sand.

In the Sheffield Street case, the tram ran over the arrestor bed on its flange tips. In this case, the contact area was only 0.01 m wide and perhaps 0.2 m long, giving a contact pressure ≈ 20,000 kPa. Concrete with a compressive strength of 28,000 kPa is commonly used in commercial structures so this is plausible if the surface layer is well supported.

Therefore, a key consideration in any calculations for the flush surfaced arrestor bed is a realistic calculation of the bearing capacity of the surface. It may be possible to use or adapt standard civil engineering methods for this, although care must be taken to account for any implicit factors of safety. The installation must also be carefully specified and monitored to ensure that it is not built stronger than the design intent.

The EMAS design used in the aviation industry might offer a much more consistent and predictable performance in a flush surfaced arrestor bed. Commercial aircraft use pneumatic rubber tyres which operate at about ten times the pressure of road vehicle tyres. The applied loads are quite comparable with light-rail applications, as is the mass of the vehicle to be decelerated. Although wheel/rail contact patches in normal service are much smaller than aircraft tyres, the area of contact between a derailed wheel and the ground may be similar to the aircraft. A typical commercial aircraft tyre pressure of 200 psi ≈1,400 kPa which is similar to the ≈2,000 kPa pressure estimated for a tram wheel in contact with sand calculated in Section 5.5. Based on published information for a variety of aircraft [40] it may be possible to infer a deceleration performance curve for a typical tram on EMAS.

Retardation solutions for aircraft may therefore be worthy of further investigation: it is possible that the EMAS material would be directly suitable for flush-surfaced arrestor beds in light-rail applications.

6. Gap Analysis

The key gaps in existing knowledge have been identified as follows:

- A defined scenario which the arrestor is designed to protect (vehicle load condition, approach speed, brakes on/off, optimum deceleration rate etc.) – either a standard set of parameters or a calculation method based on local conditions.
- Guidance on whether there should there be an impact with the obstacle deflector and/or the carbody, or just the wheels.
- Guidance on surface coverings and how to ensure the wheels break through the surface.
- Guidance on whether the rails should continue into the sand drag or stop before the arrestor bed.
- Guidance on the optimum aggregates to use in the sand drag or arrestor bed, and the appropriate depth of bed.
- Defined method for calculating the provided arresting performance (based on arrestor type, length etc) based on the suggestions in section 5 or any other design information or test data we can find.
- Testing to determine the performance of those cases where there is presently insufficient evidence of their behaviour to validate calculation methods – this could include both surface break-through and drag forces achieved.

7. Maintenance Requirements

7.1. Sand Drags: Boarded Trough and Mounded Types

The effectiveness of these types of sand drags relies on the sand being loose, clean, uncompacted and shaped to the required profile. This is recognised by the maintenance requirements in mainline and LU standards, which require regular inspection and maintenance. The grade and consistency of the sand used is also closely defined.

The presence of the sand and retaining boards also impedes access to the underlying track for inspection, and may hide the deteriorating condition of sleepers, fastenings and rails. TfL are planning a programme to remove existing sand drags from the LU network owing to the inspection and maintenance demands.

If a vehicle engages with the sand drag, then it should be relatively simple to restore it to use by re-grading the sand with a manual rake or miniature excavator.

7.2. Catch Pit Arrestor Beds

In existing UK light-rail applications, these may be filled with a variety of soils or aggregates and may be surfaced with materials as diverse as paving slabs, plastic mesh, decorative chippings, grass or shrubs. The maintenance requirements are likely to be more associated with landscape gardening than maintaining the effectiveness of the arresting capability. For those surfaced with paving, see also the comments in Section 7.3.

If a vehicle engages with the catch pit, it would need re-landscaping.

7.3. Surfaced Sand Drags and Flush Surfaced Arrestor Beds

In principle, these may not require any maintenance unless they are engaged by a tram. However, there is a design dilemma between the arresting requirements (soft, loose sand/gravel with a thin, weak surface layer) and the requirements to support pedestrian and light vehicular traffic (a well-compacted mixed aggregate with a more robust surface layer). If the design is optimised for arresting, then the surface may soon become cracked and uneven, presenting a tripping hazard and requiring frequent maintenance. If the design is optimised for lower maintenance, then the tram wheels may not break through the surface and the arrestor will be ineffective.

If a vehicle engages with the arrestor bed, the sand/gravel pit will need to be levelled and the surface replaced.

8. Conclusions

The usage of sand drags and arrestor beds on UK railways and tramways has been investigated, along with a limited review of international practice and other transport modes. Main line and heavy metro practice is to have the rails continuing through the sand drag, and Dublin's LUAS also uses this approach. Elsewhere, tramway practice often has the rails ending before the arrestor bed. There is great variety in the concept and detail design of sand drags and arrestor beds, but they can be grouped into five types, as follows:

- Boarded Trough Sand Drag
- Mounded Sand Drag
- Surfaced Sand Drag
- Catch Pit Arrestor Bed
- Flush Surfaced Arrestor Bed

Sand drags are no longer used as the sole means of terminal over-run protection on Network Rail or London Underground. However, there is historical data on their performance in tests and incidents, and standards or guidance defining their design and maintenance.

Sand drags or arrestor beds are becoming a preferred form of terminal over-run protection on light-rail systems in the British Isles. The IRR have not identified any formal design calculations for these, nor any test results or evidence of their effectiveness in practice. However, calculation and modelling methods have been suggested based on experience from comparable scenarios in other fields of transport, agriculture, and civil engineering. These will require further development and validation in Phase 2 of the work, as noted in the recommendations.

It will be very important to define the scenario that the over-run protection is designed to cope with. This includes factors such as approach speed, brakes on/off, vehicle weight, approach gradients. Additionally, the designed arrestor performance must consider acceleration and jerk rates, forces applied to the vehicle and various local conditions. These factors are not unique to sand drags and arrestor beds but also apply to all types of buffers, heavy planters etc. Recommendations are made for the general principles to be considered in defining the over-run scenario but these need to be refined.

The IRR has concerns that existing arrestor bed designs that require the wheels to break through a hard surface layer may not function as intended. There is a design dilemma between the arresting requirements (soft, loose sand/gravel with a thin, weak surface layer) and the requirements to support pedestrian and perhaps light vehicular traffic (a well-compacted mixed aggregate with a more robust surface layer). If the design is optimised for arresting, then the surface may soon become cracked and uneven, presenting a tripping hazard and requiring frequent maintenance. If the design is optimised for lower maintenance, then the tram wheels may not break through the surface and the arrestor will be ineffective. There is also a risk that the reality of the installation may not reflect the design intent. The commercial aviation industry uses a similar over-run arrestor principle with well-defined and proven performance, and this may also be effective in the light-rail application as the wheel loads and vehicle mass are comparable.

The IRR also has concerns that existing light-rail arrestor bed installations may be too short to stop a tram at speeds much over 5 km/h. The general consensus of light-rail engineers consulted was that the design approach speed should be 15 km/h. Based on historical BR design guidelines and test results, a sand drag length of 15 m to 30 m would be necessary to arrest a typical tram at this speed, much more than the ≈5 m installation length on UK light-rail systems. Testing is needed to establish the actual performance of the types of arrestor beds used on light-rail systems. Arrestor beds may need to be longer, or approach overspeed control may be required.

9. Recommendations, including Scope of Future Work

LRSSB should consider the following activities to support future designs of terminal over-run protection, and to provide assurance that these designs are fit for purpose. The IRR would be delighted to support LRSSB in delivering these workstreams.

9.1. Define the scenario which the over-run protection is designed to protect

This is not specific to just sand drags and arrestor beds, but equally applies to friction buffer stops, large planters and other over-run protection solutions. LRSSB guidance should define a scenario which the arrestor is designed to protect, including factors such as vehicle load condition, approach speed, brakes on/off, optimum deceleration rate.

This could be a standard set of parameters, or a calculation method based on local conditions. There may be a risk assessment element similar to that required by RSSB for mainline terminals. This could be supported by analysis of the frequency of stop over-runs (not just terminal stops) and assessment of the consequences of over-runs depending on local conditions (such as the existence of a turn-back or stabling point beyond the terminal tram stop).

9.2. Guidance on the arresting concept of a sand drag or arrestor bed

Existing installations have a wide variety of concepts and detail designs. Guidance should be provided, including the following factors:

- Should there be interaction with the obstacle deflector and/or the carbody, or just the wheels/bogies? (considering also whether this is consistent with the requirements for carbody/coupler strength and obstacle deflectors in existing guidance [18]).
- Should the rails continue into a sand drag, or stop before an arrestor bed?
- Suitable aggregates to use in the sand drag or arrestor bed, and the appropriate depth or profile.
- Surface coverings which allow the wheels to break through the surface, while ensuring the surface is robust enough for normal use.

9.3. Gain more evidence of the performance of sand drags and arrestor beds

At present the only evidence of sand drag or arrestor bed performance is from a few historic tests (of a type of sand drag not used on light-rail systems) or experience from incidents (in which they did not perform satisfactorily). This is not a sound basis for design or performance calculation. Further evidence is required of sand drag and arrestor bed performance. This should include:

- Acquire and review the historic London Underground report about sand drag tests.
- Review any light-rail terminal over-run incidents involving sand drags or arrestor beds and determine the effectiveness of the over-run protection.
- Review the design principles used by consultants in developing existing designs of light-rail arrestors, particularly the AECOM design of flush surfaced arrestor bed.
- Analyse relevant test results and modelling in other related fields (civil engineering, agriculture, earthmoving, other transport modes) to determine trends which can be applied to extrapolate the test results and experience of railway sand drags and arrestor beds.
- Where there is presently insufficient evidence to validate calculation methods, consider quasi-static laboratory testing of various surface coverings (concrete, tarmac, resin-bonded aggregate) and thicknesses on a sand or gravel substrate to determine the likelihood of a typical tram wheel breaking through the surface.
- Where there is presently insufficient evidence to validate calculation methods, consider full-scale instrumented tests on LRSSB's test track to demonstrate real-life performance when a tram is run into one or more types of sand drag or arrestor bed.

9.4. Further investigate the suitability of EMAS

The aviation industry EMAS retarding material appears suitable for a light-rail flush surfaced arrestor bed and could offer better and more reliable performance that existing sand drag designs. This should be further investigated, including a quantitative assessment of crushing pressures, drag forces, stopping distances and the costs of purchase and installation.

If this work confirms its suitability, full-scale instrumented tests could be carried out on LRSSB's test track to demonstrate real-life performance when a tram is run into an EMAS arrestor bed. Government research funding (such as the FOAK scheme) could be sought to support such work.

9.5. Define a method for calculating sand drag performance

Based on the findings of the work described in Section 9.3 (and 9.4 if completed), define a method for calculating the arresting performance of a sand drag or arrestor bed, based on arrestor type, length etc.

9.6. Draft an LRSSB guidance document

Combine the findings of Tasks 9.1, 9.2 and 9.5 into a definitive guidance document for the design, installation and maintenance of future light-rail sand drags and arrestor beds.

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