If use of a common right-of-way is planned, it may be desirable at some locations to have grade separations for the LRT line but not for the rail freight trackage. This solution is attractive if the rail freight track is used relatively infrequently and the cost of the grade separation would be substantially increased by including it. A more elaborate example of this type of design would have the rail transit route built on an elevated structure over a non-grade-separated railroad right-of-way, as was done in portions of the San Francisco rapid transit system.

The use of railroad rights-of-way for LRT routes will often require crossings of remaining railroad trackage. In designing rapid rail systems, it has usually been thought desirable to have grade separation for all such crossings. For LRT operation, crossings of railroad lines at grade are acceptable in many situations.

The design of signal protection for a crossing depends on the degree of central control that is required on both the LRT line and the railroad. The most common crossing has no signal control on the railroad and automatic block signals without central control on the LRT line. In this situation, a key-operated time-delay interlocking is sufficient protection. Normally the interlocking is cleared for the LRT route and is activated manually by a railroad crewman. A time-delay circuit prevents the signals from clearing for the railroad line until a sufficient time has passed after the LRT signals indicate STOP so that any car that has already passed the signals will clear the crossing. A short track circuit is provided on the railroad line to restore the interlocking to its normal state after the railroad train has cleared the circuit.

A somewhat more sophisticated version of this type of crossing protection is provided by the automatic interlocking, which is controlled by approach track circuits on each line. This type of interlocking has the circuit logic of the two systems interconnected so that the crossing is cleared for the vehicle or train that arrives first at the approach section. This type of protection can be used for branch lines and secondary main lines where a mandatory stop for railroad movements over a crossing is undesirable. It is also suited to railroad operation in automatic block signal territory.

CONCLUSIONS

Railroad rights-of-way have been used for transit purposes in several cities, e.g., Boston and Edmonton. HRT lines have been built on railroad rights-of-way in Boston, Chicago, Cleveland, New York, Philadelphia, San Francisco, and Washington. A hybrid system that has characteristics of both LRT and HRT also exists in Chicago.

The use of railroad rights-of-way for LRT has differed significantly from their use for HRT because both rail-highway and LRT-railroad grade crossings are acceptable. Thus, substantial reductions in construction costs are possible. Railroad rights-of-way usually provide horizontal and vertical alignment characteristics that exceed the requirements for both LRT and HRT systems. In using railroad rights-of-way, the less restrictive alignment requirements of LRT are an advantage only in transition sections.

Joint use of trackage does not present any difficult design problems, but it does present some operational problems that are inherent in mixing LRT and railroad freight service, as well as several institutional problems. These make joint use unfeasible except where positive operational separation can be provided without degrading passenger service. Such situations exist only for low-volume switching activities.

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The Design of Light-Rail Track in Pavement

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Many existing light-rail transit (LRT) networks and parts of some new ones require the construction of track in pavement. Sometimes this track is intended for joint use with street traffic or buses; in other places paved track is used in pedestrian areas or on medians. This paper describes the types of LRT track used in pavement in North America and Europe and suggests that the standards now in use in the United States may be in need of revision. There has been very little construction of LRT track in pavement in North America in the last 40 years. What little has been built has followed the traditional standards of the industry, which date from the earliest streetcar days, and has generally used girder rail, ties, and ballast set in concrete pavement. By contrast, most European LRT systems have adopted a basically different type of track for use in pavement. It is built without conventional ties and is mechanically separated from the street pavement structure. Such track is quieter and may also be less costly; it appears to warrant serious consideration for new U.S. installations.

There has been very little construction of light-rail transit (LRT) track in street pavement in North America in the last 40 years. What little has been built, for realignment or rerailing, has been constructed to standards first developed in the earliest days of streetcars; these standards are straightforward and have stood the test of time. During the recent bleak period of transit history, there was little need for better designs and no resources available to research them. Now that several existing LRT systems in North America are engaged in refurbishing their physical plants and new systems are under design, it is appropriate to pay some attention to the progress that has been made in the search for a track design that offers potentially lower costs and environmental benefits in countries in which LRT has been the beneficiary of continuing development.

NORTH AMERICAN PAVED-TRACK DESIGN PRACTICE

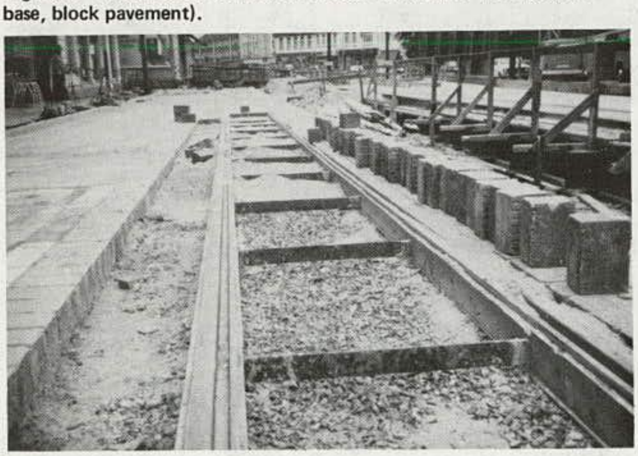
The most common form of LRT track in pavement used in North America consists of girder rails spiked directly to wooden ties that rest on ballast as is done in conventional railroad construction. The track is then paved by covering it with concrete up to pavement level (Figure 1). In some designs, an asphalt concrete surface is used instead of a full concrete section. Sometimes girder rails are bolted directly to a concrete base slab without the use of wooden ties. Here too, the track is paved by covering it with concrete up to the railhead. Occasionally, the rails are set directly into the paving slab.

The distinguishing characteristic of all of these forms of track is that the rails are rigidly set in the pavement. This rigid type of track has long been used successfully throughout North America and in many other countries. It has a long life and suffers few problems of settlement or misalignment, provided that it is built on a firm foundation. However, because the rails are rigidly encased in the pavement, vibrations are readily transmitted from the rails to the surrounding street pavement; this amplifies the noise of rolling wheels.

The need for wooden ties in paved track is also far from clear, and the practice may be a holdover from the days when street pavement was intermittent or nonexistent. Ties increase the depth of the track section and often decay long before the rails are worn out. The resilience afforded by a tie-and-ballast rail support appears to be in conflict with the ridigity of rails cast in concrete. The usual practice of placing ties at the spacing required for railroads ignores the fact that LRT axle loads are generally less than one third those of conventional railroad axle loads. Finally, changing or resurfacing the rails requires breaking out and removing the concrete pavement, as well as disturbing the underlying ties.

Figure 1. Construction of rigid track in San Francisco in 1975 (ballast, ties, concrete pavement).

Figure 2. Construction of resilient track in Heissen in 1975 (ballast base, block pavement).

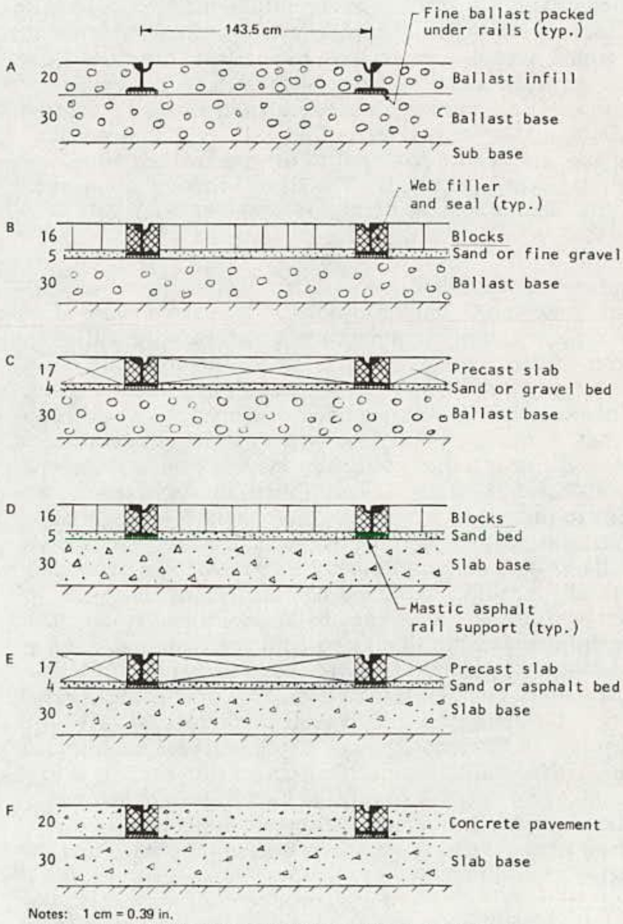


EUROPEAN PAVED-TRACK DESIGN PRACTICE

By contrast, many European LRT systems have adopted a form of resilient track for use in pavement; it is distinguished by the lack of conventional ties and by the mechanical insulation of the rails from the pavement by means of flexible joints beside and beneath the rails (Figure 2). Resilient track represents a compromise between the need for rigidity, which is necessary for a stable and long-lasting pavement, and the need for track flexibility to cut down on vibration and noise.

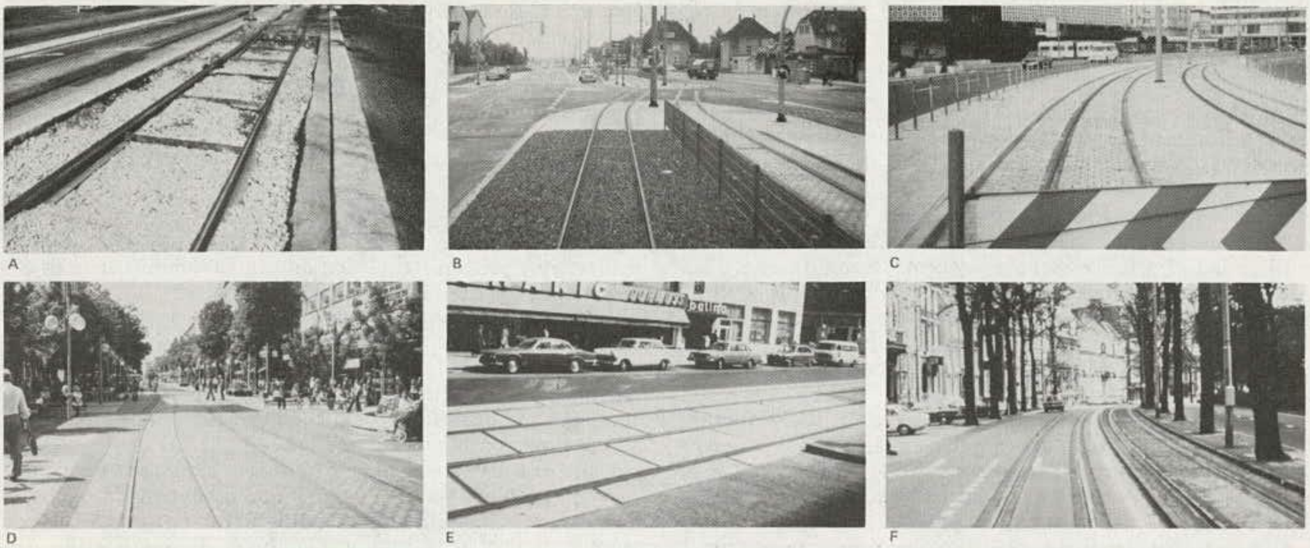
The great variety of resilient track designs used in Europe reflects the experience and preferences of the individual track engineers, funding priorities, and the continuing evolution of design theories and construction techniques. The research for this paper entailed reviewing more than 50 different track standards, most of them for resilient track. Although there are so many designs, there are only two basic types of resilient track, distinguished by the method used to support the rails: ballast-based track and slab-based track. Several permutations of track base and paving methods are used; the most

Figure 3. Types of resilient track.



Notes: 1 cm = 0.39 in.
A = full-depth ballast; B = ballast base, block pavement; C = ballast base, precast slab pavement; D = slab base, block pavement; E = slab base, precast slab pavement; F = slab base, concrete pavement.

Figure 4. Examples of types of resilient track in use.



Note: A = full-depth ballast with asphalt overlay (Gothenburg); B = transition from full-depth ballast to slab-based track with block paving (Braunschweig); C = slab-based track with block paving (Braunschweig); D = ballast-based, block-paved track in LRT pedestrian mall (Mannheim); E = precast slabs on slab base (Vienna); and F = Hannover track in center lane (Amsterdam).

common are illustrated diagrammatically in Figure 3 and in photographs in Figure 4.

Ballast-Based Track

The ballast-based track group offers the least costly approach to paved-track construction. At one time many systems even dispensed with the ballast; the rails were laid directly on the street-pavement base material. However, the higher axle loads of light-rail vehicles (LRVs) and tighter pavement specifications necessary for modern traffic have led to the general adoption of better quality material. The three most common ways in which ballast-based track is constructed are described below.

1. Full-depth ballast: In this design, the track ballast comes up to the railhead. This is necessary to keep the track in alignment and to prevent the rails from shifting laterally under thermal or dynamic stresses. Since this type of track is not actually paved, it can only be used on sections of trackway, such as on street medians or midblock in pedestrian streets where a paved finish is not required. Several line extensions constructed in Braunschweig in recent years have been built to this track standard. One variation uses a sand or gravel base under the rails and fills the track to the railhead with earth; this permits grass to be grown around the rails. It should be noted that ballast-surfaced track tends to accumulate dirt and trash, or the ballast may get displaced onto adjacent roadways; it is therefore not suitable for many urban applications. Where hard rock ballast is used with girder rail, ballast in the flangeway may result in damage to LRV wheels. In Gothenburg, full-depth ballast track is used with graded ballast (macadam) and a thin asphalt overlay of 3 to 5 cm (1.2 to 2 in) to avoid these problems. Where the track is grassed, train adhesion will be reduced whenever grass cuttings get on the rails, and the design should therefore recognize potentially reduced performance. On systems that use multiaxle cars, the lead trucks perform a rail-cleaning function, and performance may be expected to deteriorate less.

2. Block paving: The space between the ballast base and the pavement is paved with blocks made of precast concrete, industrial slag, or stone. Web fillers of cast-in-place concrete or clay tile are used to fill the web cavities (between the base and head of the rail), and the joints between the blocks and between the rails and the blocks are sealed with mastic asphalt. This is the most widely used form of paved track in Europe; it is discussed in more detail later.

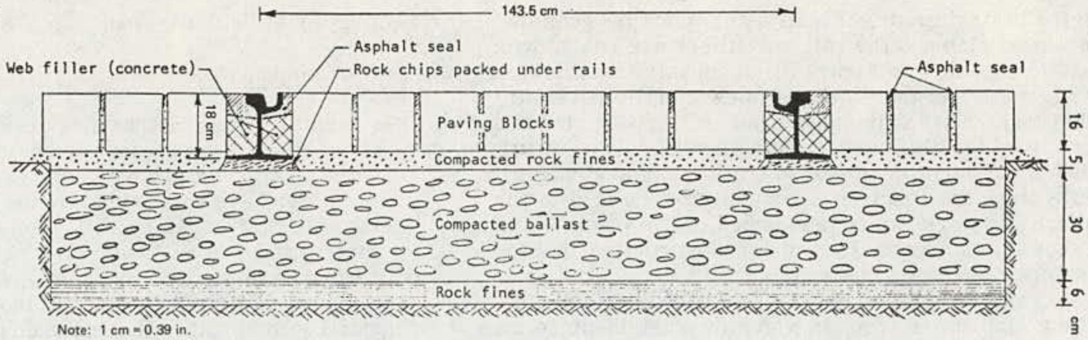
3. Precast slab pavement: This track form uses large precast concrete slabs as paving elements. The slabs are manufactured off site and are placed in position by cranes. In some designs, an asphalt concrete overlay is used over the precast concrete slabs to provide a wearing surface for traffic. Again, web fillers are used against the rails, and mastic asphalt is used to seal the joints in the pavement and between the rails and the pavement. This track form appears to have been in use experimentally for several years, but it has not been widely adopted, apparently because it is sensitive to any settlement and is therefore more suited to track on a slab base.

Slab-Based Track

Slab-based track uses a concrete slab to support the rails and can be paved in a variety of ways. To separate the rails from the slab supporting them, a mastic asphalt cushion, usually 3 to 4 cm (1.2 to 1.6 in) thick, is poured beneath the rails after they have been set to alignment and level. This technique provides for the accurate alignment of the track without the need to cast the base slab to close tolerances. Several types of slab-based track are in use; they are distinguished mainly by the method used to complete the pavement, as in the following examples.

1. Paving blocks: Web fillers are placed against the rails, and the pavement is completed with precast concrete, stone, or industrial slag blocks bedded in sand or weak concrete. The joints between the blocks and between the blocks and the railheads are sealed with mastic asphalt. This form of track is used in special loca-

Figure 5. Cross section of track with ballast base and block pavement.



Note: 1 cm = 0.39 in.

Figure 6. Construction of ballast-based, block-paved track.

Note: A = preparation of base and assembly, welding, and alignment of track; B = placement of web fillers (hollow clay tile) and sand bed for blocks; and C = placement of blocks and cleaning and sealing of pavement.

tions and is relatively uncommon, since it is both slightly more costly than other methods and may require some maintenance.

2. Precast pavement: In this design, the pavement is completed with precast concrete slab elements. These may be bedded on a layer of sand or asphalt, and they may extend the full depth or be covered with an asphalt concrete overlay. Several cities have experiemented with this type of track in recent years, and it appears to have potential for further development.

3. Concrete pavement: After the web fillers have been laid, the pavement is completed with a cast-in-place concrete slab. In some designs, an asphalt concrete overlay is used. The space between the rails and the slab is sealed with mastic asphalt. This track form is widely used and appears to be a preferred design where subbase conditions are poor and rubber-tired traffic is heavy.

SELECTION OF TRACK TYPE

The selection of track type for European LRT systems appears to reflect primarily the experience and preferences of the track engineers responsible. The most prevalent track type uses a ballast base and block pavement (Figure 5). This type is the least costly to construct, can be readily opened up for repair, and is apparently used wherever foundation conditions permit. It is used both on the major systems that have large heavy cars, such as Rhein-Ruhr, Frankfurt, and Hannover, and on the systems that operate equipment with lighter axle loads.

The construction of this type of track is straightforward (Figure 6). A track trench is excavated approximately 2.6 m (8 ft 6 in) wide and 60 m (2 ft) deep. The depth required depends on the condition of the street subbase. Where subbase conditions are good, less ballast is required beneath the rails. The ballast base is placed to within about 20 cm (8 in) of the finished pavement level, and on this base the track structure of rails and tie bars is assembled and welded. The finished track structure is then lined and leveled, and the space beneath the rails is packed with rock chips.

The next stage is to place the web fillers (which normally consist of concrete cast in place) against the rail. Finally the area between and outside the rails is filled with coarse sand or rock fines as bedding for the paving blocks. The paving blocks are especially manufactured in four basic sizes for track paving. The blocks are hand placed, a task that is greatly speeded by the use of only four standard block sizes, and then compacted to grade with a mechanical block tamper. The final task is to seal all joints with mastic asphalt to protect against water and to provide some flexibility in the pavement. Figure 7 shows the paving schedule for a typical section of standard-gauge double track paved by this method; it illustrates the regular and simple block-placement sequence.

A fairly common alternative form of track is the slab-based track with a concrete pavement (Figure 8). This type of track is approximately 20 percent more costly to construct and is accordingly used only where necessary. It is used when foundation conditions are not quite satisfactory or where maintenance is difficult, such as in a major traffic lane, because (a) it is less likely to settle and (b) it can better resist traffic damage. Its method of construction calls for the excavation of a track trench approximately 2.6 m (8.5 ft) wide and 60 cm (24 in) deep, in the bottom of which the slab base approximately 25 to 30 cm (10 to 12 in) thick is poured. On this base, the track structure consisting of rails and tie bars is assembled and welded and then aligned by using folding wedges beneath the rails to achieve accurate adjustment. Hot asphalt filler is then poured beneath the rails to fill the space between the underside of the rails and the base slab. The web fillers, consisting of either cast-in-place concrete, blocks, or hollow clay tile, are then placed in position, after which the concrete pavement slab is completed to final grade. Finally, the joints between the pavement slab and the rail web fillers are sealed with mastic asphalt. In Figure 8, an asphalt concrete overlay is used, but the sequence is essentially the same. This form of track is considered long lasting, but it suffers from the disadvantage of being difficult to repair when adjustment is needed to the line or level of the rails since the concrete pavement must be broken out before any work can be performed on the track. Figure 9 shows a slab-base track under construction, but for the block-paved variant.

In recent years, several cities have experimented with a slab-based track in which the cast-in-place concrete pavement is replaced by precast concrete pavement units (Figure 10). These units are factory made; they are brought to the site and placed in position by crane. The paving units are bedded either in gravel or in an accurately leveled asphalt layer. As for the other track forms, the final stage consists of sealing all the joints in the track structure with mastic asphalt.

The underlying design concept for each of these three track types, and indeed for almost all of the types used in Europe, is the separation of the track rails from the rest of the pavement structure through the use of some kind of nonrigid material and the provision of continuous support to the rails. One of the reasons that blocks are often preferred is that they tolerate vibration and minor settlement without damage. If settlement occurs under a slab pavement, the pavement will crack, and projecting edges will develop.

Track Components

The varieties of resilient track discussed in this paper are assembled from a range of basically standard components. The rails are normally 18-cm (7-in) girder rails, which have approximately the same depth as the standard U.S. 7-in girder rail. However, the European or metric rail has an 18-cm (7-in) base, while the U.S. rail has a base of 15.25 cm (6 in). Extra rail-base width helps to distribute the load from the rail to its supporting material. There are no data on the use of U.S. rail with all types of resilient track, since all European track is constructed with metric rail and no resilient track has been constructed in the United States. However, since the cost of rail is based on weight, the cost of the U.S. or metric sections is virtually identical, and it is probably unimportant to resolve this issue. None of the standards reviewed used T-rail in pavement. T-rail is, of course, widely used in open track for LRT.

Rail welding is widely used in new LRT track construction. Where track goes from paved to open track (ties, ballast, and no pavement), a tapered expansion joint is sometimes installed.

The tie bars consist of 10 by 80-mm (0.4 by 3.2-in) bar steel bolted to the rail webs (the larger dimension is the vertical). They are spaced at intervals of 1.5 m (5 ft) in Hannover to 2.02 m (6.6 ft) in the Hague.

Figure 7. Paving plan and materials schedule for standard-gauge double track with 2.8-m (9.2-ft) track centers.

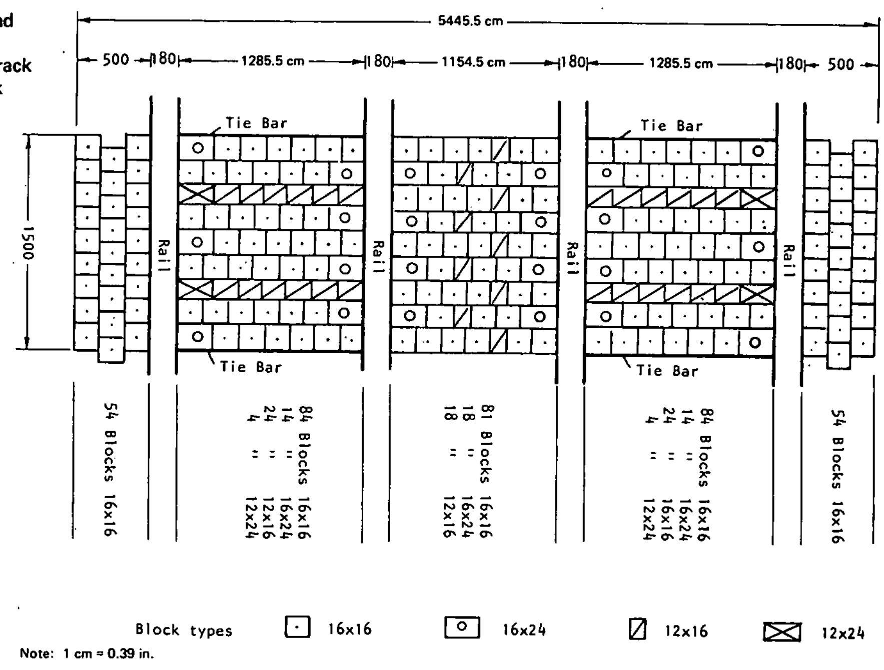


Figure 8. Cross section of track with slab base and concrete pavement.

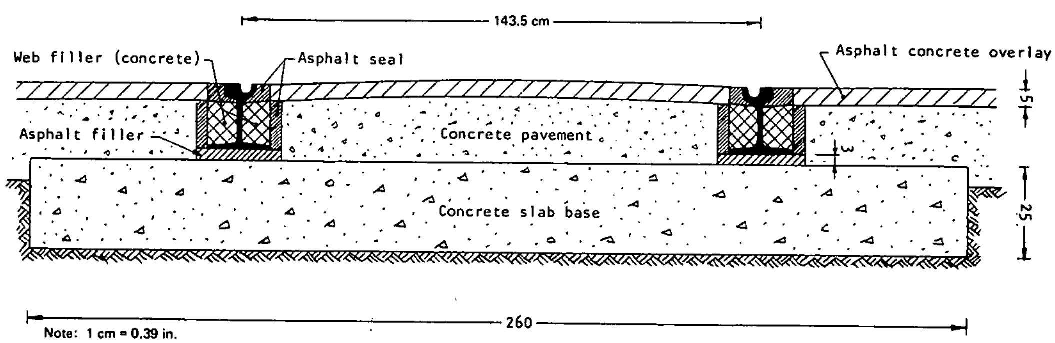
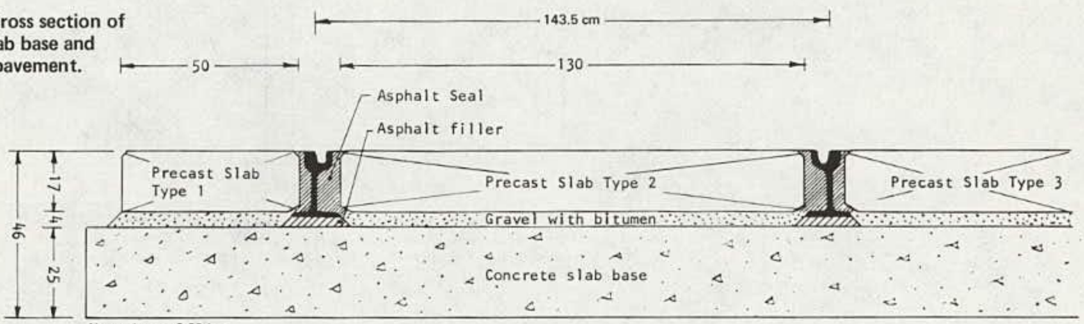


Figure 9. Construction of slab-based-block paved track.

Note: A = construction of slab and placement and welding of rails; B = installation of tie bars and lining and leveling of track (note pins that hold track in line and folding wedges that support the rails); and C = pouring of mastic asphalt under rails and placing of sand bed for paving blocks.

Figure 10. Cross section of track with slab base and precast slab pavement.



Note: 1 cm = 0.39 in.

The preferred material for paving blocks is slag from copper smelters, which has a distinctive black color and high friction qualities. Other materials are often used, including other slags, concrete, and stone blocks. If the track is part of a landscaped area, such as in a pedestrian mall, patterns of blocks of different colors may be used. The use of colored blocks to denote the LRT clearance lines in such areas is a particularly practical technique.

For the most part, the types of resilient track used on tangent sections are also used on curves and for special work. On some systems, short-radius curves are constructed using rigid track, which is encased in concrete, but this practice is not very common; it leads to increased noise levels, as is discussed below.

COMPARISON WITH U.S. PRACTICE

There is little direct comparative data concerning U.S. and European track standards. This is due in part to the lack of activity in this field in the United States and in part to the European tendency to place less emphasis on studies and data accumulation and to rely more on experience. Nevertheless, sufficient material is available to permit certain of the more significant indicators to be compared.

Cost

Enough European cost data are available to permit comparative costs to be developed for the different types of resilient track. As part of a recent study (1), comparative cost estimates were developed for track construction to typical U.S. standards and for resilient track of the ballast-based, block-paved type. The estimated costs of various forms of resilient track, referenced to the cost of U.S. rigid track (ties, ballast, and concrete pavement) are shown below. Note that these costs include base material, ties and rails, and pavement to 60 cm (24 in) outside the rails.

Track Type	Indexed Cost
Rigid track, with wood ties and concrete pavement	100
Resilient track	
Ballast base and block pavement	95
Slab base and concrete pavement	114
Slab base and block pavement	124

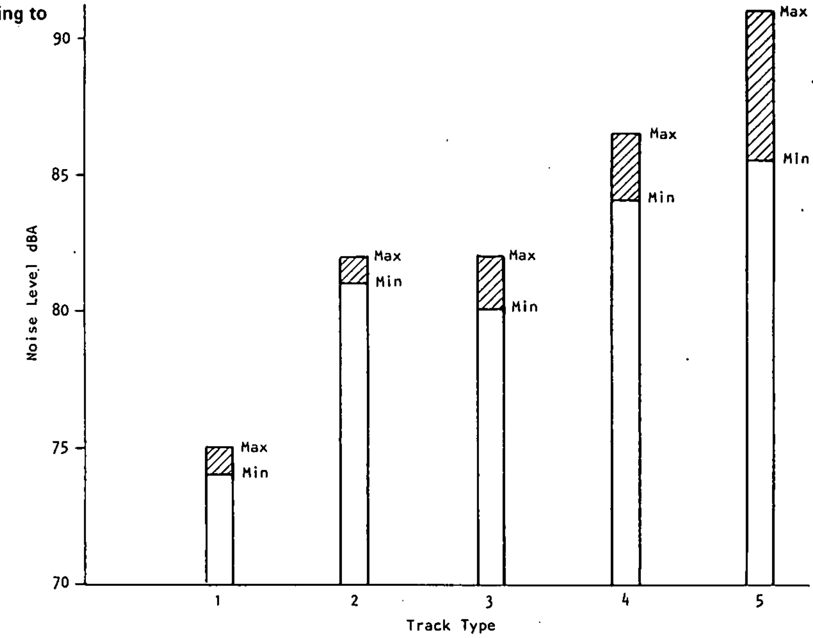
Noise

A major advantage of resilient track is its potential for reducing LRT noise. In 1974, a series of tests was carried out in the Hague to compare sections of the rigid and resilient track used on that system (2). The cars tested were modern Presidents' Conference Committee (PCC) cars, one of them equipped with Bochum wheels, which are commonly used on European LRT systems, and the other equipped with SAAB wheels, which are similar to the superresilient wheels used on U.S. PCC cars. The rigid track tested consisted of girder rail encased in concrete with an asphalt concrete overlay. The resilient track consisted of slab-based track with a cast-in-place concrete pavement and an asphalt concrete overlay. This type of track is widely used in the Netherlands, where it is called Hannover track. Ballast-based track consisting of a sandy track base with earth infill was also tested.

Almost identical tests were performed in San Francisco in 1971 (3) on rigid track only. These tests also used PCC cars, one with Bochum wheels and the other with superresilient PCC wheels. Figure 11 illustrates the data from these two tests; the tests were run at 40 km/h (25 mph), and the noise levels were measured 7.5 m (25 ft) from the track centerline. In both the Dutch and San Francisco tests, the Bochum wheel was found to be slightly noisier than the PCC wheel, except when the tests were performed on curves, where the Bochum wheel proved to be considerably quieter.

In 1973, noise tests were performed on the tracks of the Helsinki LRT system (4). These tests used a variety of vehicles, ranging from modern articulated cars to two-

Figure 11. Comparison of LRV noise level according to track type.



Notes: Track type 1 = sand base, earth infill; 2 = open track (wood ties, no infill); 3 = slab base, concrete pavement (Hannover track); 4 = rigid track (the Hague); and 5 = rigid track (San Francisco). The range of values reflects the difference in car wheels, test sites (for 5 only), and condition of test cars.

axle cars that were more than 50 years old, on both rigid and resilient track. At the test speed of 40 km/h (25 mph), it was found that the sections of resilient track were approximately 5 dB(A) quieter than sections of rigid track, which seems generally consistent with the findings of the more detailed Dutch tests.

Maintenance

The maintenance of both the track and pavement within 60 cm (24 in) of the rails is generally the responsibility of the transit agency. The life span and maintenance costs for both track and pavement are thus relevant factors. While rail life in excess of 40 years may be achieved, at certain locations (such as passenger stops and curves) rails wear out considerably faster. A significant advantage of track paved with blocks or precast slabs is that the paving material can be removed without the use of an air compressor (and hence less noise); the paving materials can also be reused. Where ballast-based track is used, the track is ready for instant use when it is completed, and it requires no time for concrete to set.

Even if the full rail life of 40 years is achieved, the settlement of the street subbase may require attention to the pavement before the rails are worn out. In such instances, the track and pavement can be readily opened up and repaired without disrupting service, and the paving materials can be reused. By contrast, if wooden ties are used, any significant disturbance of the track often results in the need to replace wooden ties.

Urban Design Treatments

Future applications of LRT are likely to place increasing emphasis on such features as LRT pedestrian malls, which are now widely used in Europe. Resilient track is environmentally well suited to such applications and also offers the opportunity to develop designs that are visually appropriate to such situations. For instance, the paving of the track zone with rounded cobbles in a flush-paved pedestrian zone provides an excellent and unobtrusive reminder to pedestrians not to wander onto the tracks outside the designated crosswalk areas.

CONCLUSIONS

There is a basic difference between paved-track construction practice in North America and in Europe. A variety of track standards are used in Europe. The manufactured components (rails, tie bars, and so on) are generally standardized, but the experience and preferences of the track engineer appear to play a significant role in selecting track design standards.

Consideration should be given to testing some of the more relevant European designs in the United States to determine whether they have any advantages over our present practice and are suitable for U.S. conditions. Because of the lead time required, such tests should be initiated without delay in order that the conclusions may be applied before major investment decisions in this field are made.

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