ABSTRACT
Various types of concrete slab track are in service in Japan, Europe and North America. In Japan, where slab track has been used for thirty years, recent slab track construction costs are 30% to 50% higher than for standard ballasted track. However, in Japan the maintenance costs for slab track are one-fourth of those for ballasted track. This paper describes the current types of slab track in use and in research and development in North America, Japan, and Europe. Where data is available, performance of existing installations of slab track is discussed. Much of the research and development currently is in Japan and Europe where slab track is important for the support of high-speed trains on heavily traveled lines.
This paper also includes design recommendations for addressing soils investigation, concrete slab, direct fixation fasteners and noise. Construction methods, tolerances and life cycle costs are discussed. The paper also discusses the benefits from slab track including increased durability, much-improved vertical and horizontal alignment stability, improved ride quality, and reduced track maintenance and associated downtime. Future efforts to expand the use of slab track in North America are recommended in the paper.

INTRODUCTION
Axle loads on freight railroads were 30,000 pounds in 1880, 50,000 pounds in 1906 and are 80,000 pounds today (1). In addition to increasing axle loads, traffic is increasing at the rate of 20 million train miles per year and it is expected that high-speed passenger trains will share track with freight trains. Reports of a scarcity of good ballast in some regions of the country are becoming more frequent.
Because of the increasing maintenance of way cost on heavy haul freight routes due to increasing load and the future need to maintain accurate rail alignment for high-speed rail, the railroad industry is looking for a stronger track structure than the ballasted track now used.

The term “slab track” is used to describe non-ballasted track structures that may have combinations of concrete slab, ties and road pavement used where strength and durability are required. Slab track is commonly used for light rail transit systems and will be used for corridors where high-speed passenger trains share track with freight trains.

Slab track use has increased greatly since 1899 when the Southern Railroad built a concrete slab under existing track in order to stabilize a section of track on poor soil. Widely accepted for use on light rail transit systems in the United States and Canada, slab track is used extensively on corridors where light rail shares the slab track pavement with automobiles, trucks and/or buses.

It is also used on light and heavy rail transit systems in tunnels and on aerial structures through direct fixation of the rail to the concrete structure. In addition, slab track sections are in service on the Canadian Pacific Railway, the Long Island Railroad and in the Eurotunnel under the English Channel.

This paper provides a summary of several types of slab track used today and discusses slab track design and construction methods. The paper also contains some recommendations for research. Comments by the reader are welcome by the authors.

**SLAB TRACK USE**

As a way of describing alternate methods of construction, the following are examples of slab track installations that will likely be used for future track structures.

**Canadian Pacific Railway**

The CPR constructed a test section near Rogers Pass in British Columbia. The 930-ft test slab track section at Albert Canyon was built during late 1984 using the patented PACT-TRACK system developed in the United Kingdom (2). The track test section was built to investigate and simulate the use of the PACT-TRACK for the 9.8-mile single-track section in the McDonald Tunnel. Since the test was successful, the railroad built the slab track in the McDonald Tunnel. Both the test and tunnel sections are performing well. Traffic on the line is over 60 MGT per year.

The PACT-TRACK for the Canadian Pacific Railway has a 22.9 cm (9 in) thick concrete slab that is 2.43 m (7.97 ft) wide. Concrete was placed using a customized slipform paving machine, which rides on two 136 RE rails, which
Concrete is fed into the front of the paving machine using a conveyer system. After the concrete has cured, the continuously welded rail is laid on a continuous ¼ to ½ in. thick rubber compound pad and clipped to inserts embedded in the slab. Details of the PACT TRACK system are shown in Figure 1.

**Japanese National Railroad**

Slab track is used extensively on high-speed rail in Japan. The high-speed rail needs a very accurate rail alignment to maintain passenger comfort. The Japanese National Railways (JNR) began use of slab track over 30 years ago on the Shinkansen and narrow gauge lines and it is used on over 2,400 km (3). The slab track has provided excellent performance by maintaining track geometry and reducing maintenance of track cost. Criteria for use of slab track by the JNR are as follows:

- Slab track construction cost should not be greater than 30% more than the cost of ballasted track.
- Slab track should be structurally sound and have resilience equivalent to that of ballasted track.
- The speed of construction should be reasonable.
- Slab track should allow for adjustments in the vertical and lateral directions to account for deformations of the subgrade.

Although, most of the slab track was initially used for tunnels and bridges, slab track was also tried on soil roadbed during the mid-1970s. A current version of slab track for at-grade application, referred to as the reinforced concrete roadbed system (RCRS), is shown in Figure 2 (4). Since 1990, the RCRS system has undergone experimental testing and monitoring and has been used on the Hokuriku Shinkansen line from Takasaki to Nagano, which opened to service in October 1997. The slab track consists of precast concrete slabs 5 m long and a layer cement asphalt mortar (CAM) beneath the concrete of a viaduct or in a tunnel, short concrete posts (400 mm in diameter and 200 mm high) are provided at intervals of 5 m. The track slabs are made of precast reinforced concrete or prestressed concrete. The track slab for the Shinkansen is 2340 mm (92 in) wide, 4930 mm (16.2 ft) long, and 160 (6.3 in) to 200 mm (7.87 in) thick and weighs 5 tons. Recent modifications to slab track include use of vibration reducing grooved slab mat under the track slab.

The cost of the RCRS type slab track is higher than that of ballasted track by 18% in cuts and by 24% in fill sections. It is expected that because of low track maintenance, the extra costs will be recovered in about 12 years of operation. It is also expected that the workforce required to maintain the slab track will be 30% lower than that...
required to maintain ballasted track. The Japanese standard for at-grade slab track settlement is that final settlement less estimated settlement should be less than or equal to 30 mm (1.18 in).

The Shinkansen slab tracks carry 10 to 15 million gross tons per year (MGT) as of 1990. The overall condition of the slab track is good except for minor cracking due to alkali-silica reaction (ASR), CAM layers, and some warping of slab in tunnels. Overall, slab track maintenance is found to be much less than ballasted track on the Shinkansen lines, ranging from about 0.18 to about 0.33 of the maintenance cost required for ballasted track. The average construction cost of slab track is 1.3 times that of ballasted track. The difference in construction costs will be recovered in 8 to 12 years.

**Long Island Railroad**

The LIRR Massapequa Station Slab Track Project was constructed just east of the Massapequa Station and consists of 1.13 miles of two parallel, continuously reinforced concrete (CRC) slab tracks on an embankment section with continuously welded rail and direct fixation fasteners. The project was constructed during the late 1970s and opened for traffic in December 1980 (5). The bottom up construction method and details of the slab track sections are shown in Figure 3. The concrete slab is 10 ft-6 in wide and 12 in thick and uses 0.9% of continuous reinforcement divided into two layers. The concrete slab was constructed using bottom up methods and side forms on a subbase of 6 in thick asphalt concrete. Rail attachment is provided by Pandrol e clips at 30 in spacing.

The twenty year old slab track carries 12 MGT per year made up of commuter passenger trains and freight trains and is now in excellent condition except for some broken bolts. The Long Island Railroad also used slab track at the West Side Storage Yard and the Richmond Hill Yard because it is difficult to release track for maintenance in these yards.

**Eurotunnel**

Slab track is used in the Eurotunnel under the English Channel where axle loads are 25 US tons and the annual tonnage is expected to be 264 MGT with a maximum passenger train speed of 125 mph. The slab track is called Low Vibration Track (LVT) and was developed by the Sonneville International Corporation. The LVT consists of two independent tie blocks encased in rubber boots and then partially embedded in a concrete slab as shown in Figure 4. Each block tie is 200 mm (4 in) high under the rail pad and 675 mm (2.21 ft) long and rests on a microcellular pad to provide a resilient track structure and dampen vibrations. The LVT has been thoroughly tested in laboratories and uses a “top-down” construction method. The top-down method consists of temporarily
suspension of the preassembled rails and two tie blocks above a concrete slab. The lower portion (136 mm or 5.35 in) of each tie block is encased in a rubber boot to isolate the tie from the concrete slab and to allow the tie block to move up and down without wear on the concrete slab. After the rail and tie blocks are accurately positioned for line and grade, concrete is placed under and around the tie blocks, partially embedding the tie blocks in the concrete. Sonneville, Pandrol and Vossloh fasteners are used to attach the rails to the tie blocks. This system allows the rails and tie blocks to be removed and replaced easily if necessary.

The LVT system has also been used for MARTA, BART, Tri-Met, MTA (Los Angeles), Metrolink (St. Louis) and DART (Dallas) transit systems in the United States, and in numerous other countries.

The Netherlands

The Embedded Rail System (ERS) has been used since the 1970s in the Netherlands. This system uses a compound called Corkelast (a cork/polyurethane mixture) to provide continuous support for rails installed in troughs in concrete slabs. The system, shown in Figure 5, is used extensively for light rail in Europe and has been used on bridges. In the ERS the rail is temporarily suspended in a trough in the concrete slab and then the elastic material is placed around the rail and allowed to harden. The ERS system is widely used by light rail transit systems where the top of the slab also serves as pavement for vehicle traffic. Recently, a 3-km (1.86 mi) length of the ERS concrete slab track placed on grade was built in the south of the Netherlands. The structure consists of a continuously reinforced concrete slab resting on a cement-stabilized base, which was placed over a sand subbase. The use of the ERS system for the HSL-Zuid high-speed line from Amsterdam to the Belgian border is now being considered.

In several light rail transit projects in the US and Canada, cementitious material is used in place of the polyurethane material to support the rail. When cementitious material is used, the rail is encased in a rubber boot.

The Edilon block track, also developed in the Netherlands, is mainly used for bridges and tunnels. The Edilon system has been used for over 100 km (62 mi) on railways and the light rail transits system in the Netherlands and over 100-km (62 mi) of the Madrid metro system.

Deck Track is a recent innovation developed for use with embedded rail. A schematic of the Deck Track is shown in Figure 6. A 200-m (656 ft) test section of the track was constructed during the spring of 1999 near Rotterdam and was opened to traffic during July 1999. The track is used by many heavy freight trains every day. Although it is too early to judge the performance of the track, the constructability of the track has been demonstrated, apparently at a reasonable cost.
German Railroads

Slab track use has been undergoing development in Germany for many years. In 1996, the German Railway began operating a test track in Karlsruhe consisting of seven new types of ballastless track (10). Approximately 340 km of slab tracks has been constructed throughout the German Railway network.

One of the best-known German designs is the Rheda compact design, which uses a top down method of construction. In the Rheda system, full-length concrete ties are cast into a continuously reinforced concrete slab formed with curbs at the sides of the slab. The Rheda system was developed during the 1970s and is shown in Figure 7. During construction of the RHEDA system, preassembled track consisting of rail and ties, are assembled on the base concrete slab. After the rail is positioned to line and grade, concrete is placed below and around the ties, partially embedding the ties. The slab track has to be constructed over load-bearing frost-protected subgrade and the groundwater should be greater than 1.5 m below the slab.

About 147 km (91.3 mi) of slab track will be constructed along the new 219 km (136 mi) Cologne-Rhine/Main high-speed line. The justifiable cost factor for the slab track in Germany is considered to be 1.4 of that of ballasted track. It is expected that higher initial cost will be offset by future maintenance costs savings and by greater availability of the tracks due to less downtime for track maintenance.

DESIGN OF SLAB TRACK

The design of slab track addresses many of the same items as does the design of ballasted track and includes, geotechnical, track modulus, rail stress, rail attachment, and concrete slab design.

Good geotechnical investigation, analysis and design is very important to the success of any track structure. One geotechnical engineer for a Class I railroad estimated that 90% of the subgrade on existing track provides adequate support for the track structure. When designing for slab track, it is essential to identify the 10% of the subgrade having poor soils and to design appropriate remediation measures. Remediation for poor soils can include removal and replacement, improvement with soil cement or other methods. Poor drainage situations also need to be identified and corrected during the design phase of a track project. One of the most common track problems, subgrade pumping, is the result of a combination of poor soil, high pressures and inadequate drainage all acting together. Also, frost susceptible soils have to be addressed. The object of geotechnical design is to have a subgrade that provides continuous uniform support of the track structure. AREMA (11) recommends as a guideline that the subgrade bearing pressure not exceed 20 psi (3,000 psf.)
Track modulus is a measure of overall track stiffness and track stability. It is an indicator of the load required to produce a unit deflection in the rail. The track modulus, \( u \), can be determined using the beam on elastic foundation analysis from the following equation (12):

\[
u = \frac{k^{4/3}}{(64EI)^{1/3}}
\]

where: 
- \( k \) = track stiffness (load required to produce unit deflection)
- \( E \) = modulus of elasticity of the rail
- \( I \) = movement of inertia of the rail

In the U.S., track modulus is determined in units of lb/in./in. and values of track modulus may range from as low as 1,000 lb/in./in. for ballasted track in very poor condition to about 4,000 to 6,000 lb/in./in. for ballasted track in very good condition. The use of concrete ties instead of wood ties, continuously welded rail instead of jointed rail, increased ballast depth, use of heavier rail, and use of slab track will result in higher track modulus. The track modulus for slab track systems is probably between 7,000 to 8,000 lb/in/in.

Track structures with higher track modulus result in better ride quality, lower rail deflections, lower subgrade pressures, reduced rail wear and reduced rail stresses. It should be noted that a certain amount of resilience is required in all track structures with perhaps a modulus of 10,000 lb/in/in being the upper limit of acceptable track. However, conventional ballasted track normally provides too much rather than too little resilience (12) and the resilience tends to be non-uniform as a result of non-uniform track degradation under traffic. Too much resilience results in poor ride quality and excessive rail wear.

As with ballasted track systems, track engineers need to consider the dynamic response of the slab track including noise and vibration considerations.

During 1999, AREMA included slab track in the Manual for Railway Engineering (13). The design considerations for slab track are included in Part 27 of the manual and are based primarily on the experience gained on the Long Island Railroad slab track project. The concrete slab type addressed is the continuously reinforced concrete (CRC) slab supported on a stabilized subbase and compacted subgrade.

Typical rail sections are designated by AREMA. These range from about 115RE for transit tracks to 136RE for heavier freight applications. Continuously welded rail (CWR) is commonly used for heavy freight, transit and intercity passenger railroads. Rail bending stress is limited to 25,000 psi for CWR and rail deflection for heavy haul freight is limited to 25 in.
Tie-pads are required for slab track where the rails rest directly on a concrete surface except in the case of LVT where the pad is at the bottom of the tie. Dual rubber pads, with a 50 to 60 Shore A durometer on the bottom and 75 to 85 Shore A durometer reinforced rubber pad on top or equivalent pads are typically used.

The subbase (or base) under the slab allows a more uniform distribution of wheel load stresses, dissipates these stresses, and provides frost protection. The subbase also provides a platform for construction of the slab. The subbase must be designed along with the slab track. Depending on loading, the subbase can be either large aggregate, soil cement or other type of stabilized material.

A schematic of a CRC slab track system is shown in Figure 8. It should be noted that the concrete slab develops a transverse-cracking pattern within a few days after concrete placement due to volume changes in the concrete. Additional cracking may develop after the first winter. Thereafter, crack development decreases. Cracks are held tight by the longitudinal reinforcement. Desirable crack spacing in CRC slab (based on pavement related experience) is 3 to 5 ft. This spacing is achieved by using longitudinal reinforcement of 0.7 to 0.8 square inches per foot and depends on concrete strength and other factors. It is desirable to have a uniform crack spacing pattern and to minimize both the closely spaced (less than 2 ft) as well as the widely spaced (more than 6 ft) cracking. A uniform subbase support, uniform concrete quality, favorable ambient placement and adequate curing will result in high concrete slab quality.

Use of a finite element model is recommended for design of slab track. The model includes the rail as a discrete elastic beam resting on a slab, which rests on a spring foundation. The slab dimensions are modeled realistically as are the wheel loads (single or multiple axles). The output consists of rail and slab stresses and deflections, fastener loading and compression, and subbase/subgrade bearing pressures. Customized software or general-purpose commercial software is available.

Procedures exist to determine crack spacing and cracks within a CRC slab on grade (14). These procedures developed for highway concrete pavements can be readily applied to CRC track slab. Procedures are also available to determine the minimum amount of longitudinal reinforcement for CRC slabs (15).

Concrete used for slab track construction is no different than that used for interstate highway pavement construction. The AREMA manual has minimum requirements for concrete used in slab track.
Transitions between slab track and structures are typically achieved using multiple expansion joints near the slab end and use of a sleeper slab under the slab track for 25 to 50 ft distance at the slab end. The AREMA manual has a typical detail for termination of a slab track adjacent to a bridge.

Transition from slab track to ballasted track can be achieved using a sleeper slab under the slab track, which is extended below the ballasted track for a distance of at least 20 feet. Transitions between slab track on cut-and-fill subgrade may be achieved by stabilizing the fill material using soil cement or by having a thicker subbase in the fill area for a distance of 20 to 30 ft. The AREMA manual provides details for assuring continuity of the slab track over bridge decks and in tunnels. The Japanese have performed full-scale tests of structure approach slabs on soils. For bridge decks, friction-reducing treatments (bituminous layer or polyethylene sheets) are used between the bridge deck concrete and the track slab.

**DIRECT FIXATION FASTENERS**

Except for ERS, slab track systems require use of a fastener that directly attaches the rail to the concrete slab. Direct fixation fasteners maintain gage and alignment, control longitudinal rail movement, provide resilience, provide electrical insulation, reduce vibration, noise and rail stresses, and prevent abrasion of the concrete under the rail.

The fastener assembly typically consists of one or two steel plates, elastomeric (rubber) pads, inserts, elastic clips, and insulators. Inserts installed in cored holes or cast into the concrete allow the fastener to be attached to the concrete slab or tie. Elastic clips fitted with electrical insulation material hold the base of the rail to the fastener and the elastic pads provide the desired track resiliency. The elastic clips exert sufficient force on the rail base to restrain longitudinal movement of the rail. Specific requirements for fasteners are included in the AREMA test specification ([11](#)).

Some of the more widely used fastener systems for transit, commuter, freight or high-speed applications include: Pandrol Systems ([16](#)), Sonneville System, ([6](#)) Stedef System ([17](#)), L.B. Foster System ([18](#))

**TRACK NOISE**

For speeds up to about 300 km/h (186 mi/hr) rolling noise is predominant. Rolling noise is initiated at the wheel rail contact area because of surface irregularities, and the noise is then propagated by the wheel and the rail. Other noise sources include wheel/rail squeal on curves, aerodynamic noise, impact noise at joints and traction power noise. To mitigate rolling noise, which can be as high as 20dB(A), regular application of rail grinding, rail lubrication, track
alignment maintenance, resilient rail pads and proper wheel design (19) are necessary. Concrete slab track and rail pads dampen some noise frequencies but may reflect other frequencies and this should be addressed in the design and maintenance of slab track.

CONSTRUCTION
For track projects of substantial length, slip-form paving is probably the most economical method of construction. Several slip-form pavers are available that can readily place narrow width track slabs (width of 8 ft to 12 ft). Close to urban centers, local suppliers can supply ready-mix concrete while in remote areas, portable batch plants can be used effectively. Materials, cement, aggregate and water, can be delivered in railroad cars to the portable batch plant.

Construction tolerances are a critical issue for slab track construction and become smaller with greater train speed. Vertical tolerances at the slab surface are required to minimize the need to use shims or to grind at fastener locations. The AREMA Manual recommends a vertical tolerance of +0 in. and -¼ in. for the finished concrete surface. However, it is recommended that vertical tolerances for slab construction be: subgrade ±1.20 in, subbase ±0.40 in, slab ±0.20 in, and drilled holes ±0.20 in. in any direction.

FRA Track Safety Standards Part 213 contains limits for track deviations from gage, uniform profile and alignment for nine classes of track based on speed. The class 9 (200 mph maximum) track deviation limits are as follows: gage: 4 ft-8 ¼ in to 4 ft-9 ¼ in with a maximum of ½ in in change in 31 ft; track surface: ½ in per 31 ft chord, ¾ in per 62 ft chord, and 1 ¼ in per 124 ft chord; alignment ½ in per 31 ft chord, ½ in per 62 ft chord and ¾ in per 124 ft chord.

The tolerance limits established for track on the high speed (167 mph) Shinkansen rail lines are as follows (3): track gage +1 mm, -2 mm; cross-level ±1 mm; longitudinal level ±2 mm per 10 meters, alignment ±2 mm per 10 meters.

LIFE CYCLE COST CONSIDERATIONS
Non-uniform ballasted track degradation results in higher rate of rail wear, rail defects, and poor ride quality. Maintenance of track (MOT) activities include tamping and adding ballast every 15 MGT, surfacing and alignment, subgrade improvement, tie replacement at an average rate of 60 to 100 ties per mile per year and rail replacement after 3 to 5 years on heavy haul lines. Rail grinding is also done on routine basis to mitigate noise and vibration irrespective of track type. For heavy haul lines, MOT is a major cost item and can lead to significant revenue loss due to track down time or longer re-routing of trains. The cost of re-routing trains on 60 MGT track is estimated at
$252,000 (20). This includes fuel, track maintenance, and operation costs and is based on one week of track closure and a re-route distance of 120 to 125 miles. It is reported that equivalent annual costs for ballasted track maintenance (MOT) range from $20,000 to $50,000 per mile.

In North America, the cost of slab track construction on a large scale is expected to be very favorable because of the availability of slab construction equipment and expertise. For the simpler cast-in-place construction, it is possible that the slab track costs can be kept to within 1.2 to 1.3 times the cost of ballasted track. Such a cost differential can be recovered within 5 to 10 years.

Other benefits to be considered when evaluating life cycle costs include: fewer rail failures due to buckling and high stresses, less downtime from maintenance in congested areas such as passenger stations, improved lateral and longitudinal restraint for the rail, and better ride quality. Improved track structure integrity allows spanning over utilities and isolated incidence of weak soil. Also, the continuous slab track exerts lower pressure on the subgrade compared to ballasted track.

RESEARCH AND DEVELOPMENT

The Federal Railroad Administration (FRA) recently awarded a contract to develop specific criteria for upgrading existing railroad routes to accommodate mixed traffic of high speed trains (125, 150, and 200 mph maximum speeds) and conventional freight trains (with axle loads up to 39 tons). FRA wants a track that is affordable, practical, durable, and capable of being maintained at modest cost. PCA intends to develop a design guide for the use of slab track and to confirm the design methods with field tests.

CONCLUSION

Conventional ballasted track systems have served the railroad industry well over the last 150 years. Ballasted track is expected to also serve the needs of the industry in the future years. The several types of slab track systems discussed in this report will be important solutions to construct the improved track structures demanded by increasing freight tonnage and the use of high-speed passenger service. Because slab track strength and durability are unsurpassed by other track structures, it will continue to be used for light rail transit on rights of way shared with bus, truck and automobile traffic.
Credits

This paper is based on a soon-to-be published paper by Shiraz D. Tayabji of Construction Technology Laboratories.

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Figure 1 – The PACT TRACK System (2)
Figure 2 – Japanese Type RCRS Slab Track on Grade (4)

Figure 3 – The Long Island Railroad Slab Track (5)
Figure 4– Sonneville Track used in the Eurotunnel (6)
Figure 5 – Embedded Rail Slab Track System (8)
Figure 6 – Deck Track System (9)
Figure 7 – The Rheda Slab Track System (10)
Figure 8 – Schematic of a Typical CRC Slab Track (13)