

**ACI 343.1R-12**

# **Guide for the Analysis and Design of Reinforced and Prestressed Concrete Guideway Structures**

Reported by Joint ACI-ASCE Committee 343



**American Concrete Institute®**  
*Advancing concrete knowledge*



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## **Guide for the Analysis and Design of Reinforced and Prestressed Concrete Guideway Structures**

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# Guide for the Analysis and Design of Reinforced and Prestressed Concrete Guideway Structures

Reported by Joint ACI-ASCE Committee 343

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*This guide presents a procedure for the design and analysis of reinforced and prestressed concrete guideway structures for public transit, and design guidance for elevated transit guideways. The engineer is referred to the appropriate highway and railway bridge design codes for items not covered in this document.*

*Limit state philosophy is applied to develop design criteria. A reliability approach is used in defining load combinations and deriving load and resistance factors. Different target reliability indexes (4.0 for design strength, 2.5 for serviceability design for cracking, and 2.0 for serviceability design for fatigue) and a service life of 75 years were used as the basis for safety analysis. A 75-year service life is consistent with the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications.*

**Keywords:** cracking; deformation; fatigue; guideway structures; precast concrete; prestressed concrete; prestressing loads; reinforced concrete; vibration.

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The recommendations in this guide provide public agencies, consultants, and other interested personnel with comprehensive criteria for the design and analysis of concrete guideways for public transit systems. They differ from those given for bridge design and analysis in ACI 343R, American Association of State Highway and Transportation Officials (AASHTO) bridge specifications (AASHTO 2002, 2009, 2011, 2012), and the American Railway Engineering and Maintenance-of-Way Association (AREMA) *Manual of Railway Engineering* (AREMA 2012). This document provides guidance related chiefly to the design of guideway superstructures. For the design of substructure units, the reader is referred to other references such as AASHTO LRFD Bridge Design Specifications (AASHTO 2012).

**1.2—Scope**

Design criteria specifically recognize the unique features of concrete transit guideways—namely, guideway/vehicle interaction, rail/structure interaction, special fatigue requirements, and aesthetic requirements in urban areas. Criteria are based on current state-of-the-art practice for moderate-speed (up to 100 mph [160 km/h]) vehicles. Application of

these criteria for advanced technologies other than those discussed in this guide requires an independent assessment.

AASHTO LRFD Bridge Design Specifications (AASHTO 2012) and ACI 343R are referenced for specific items not covered in these recommendations, including materials, construction considerations, and segmental construction.

**CHAPTER 2—NOTATION AND DEFINITIONS****2.1—Notation**

- $A$  = exposed area of pier perpendicular to the direction of stream flow, ft<sup>2</sup> (m<sup>2</sup>)
- $A_{cp}$  = area enclosed by the outer boundary of cross section, in.<sup>2</sup> (mm<sup>2</sup>)
- $A_l$  = area of longitudinal reinforcement in a member, in.<sup>2</sup> (mm<sup>2</sup>)
- $A_o$  = lever arm area enclosed by the centerline of the shear flow, in.<sup>2</sup> (mm<sup>2</sup>)
- $A_{oh}$  = area enclosed by the centerline of the outermost closed transverse torsion reinforcement, in.<sup>2</sup> (mm<sup>2</sup>)
- $A_r$  = cross-sectional area of a rail, in.<sup>2</sup> (mm<sup>2</sup>)
- $A'_s$  = area of compression reinforcement, in.<sup>2</sup> (mm<sup>2</sup>)
- $A_t$  = area of one leg of a closed stirrup resisting torsion, in.<sup>2</sup> (mm<sup>2</sup>)
- $A_v$  = area of shear reinforcement, or area of shear reinforcement perpendicular to main reinforcement for deep beams, in.<sup>2</sup> (mm<sup>2</sup>)
- $a$  = center-to-center distance of shorter dimension of closed rectangular stirrup, in. (mm)
- $B$  = buoyancy
- $BR$  = broken rail forces
- $b$  = center-to-center distance of longer dimension of closed rectangular stirrup, in. (mm)
- $C_D$  = flowing water drag coefficient
- $C_d$  = horizontal wind drag coefficient
- $CE$  = centrifugal force, lb (N)
- $C_e$  = wind exposure coefficient
- $C_g$  = wind gust effect coefficient
- $COLFH$  = horizontal collision load, lb (N)
- $COLFV$  = vertical collision load, lb (N)
- $CR$  = forces due to creep in concrete, lb (N)
- $CT$  = collision load, lb (N)
- $c$  = clear concrete cover, in. (mm)
- $DC$  = dead load, lb (N)
- $DR$  = transit vehicle mishap load, due to vehicle derailment, lb (N)
- $DW$  = dead load of wearing surfaces and utilities, lb (N)
- $d$  = distance from extreme compressive fiber to centroid of longitudinal tension reinforcement, in. (mm)
- $d_v$  = distance from centroid of tensile steel to centroid of concrete struts, in. (mm)
- $E_c$  = modulus of elasticity of concrete, psi (MPa)
- $E_{ci}$  = modulus of elasticity of concrete at transfer of prestress, psi (MPa)
- $E_r$  = modulus of elasticity of rail steel, psi (MPa)
- $E_s$  = modulus of elasticity of reinforcement, psi (MPa)
- $EH$  = loads due to weight and pressure of soil, water, soil, or other material, lb (N)

|                                                                                                                                            |                                                                                                                                                                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $EI$ = flexural stiffness of compression members, lb-in. <sup>2</sup> (kN-mm <sup>2</sup> )                                                | $jd$ = distance between tensile and compression forces at a section based on an elastic analysis, in. (mm)                                                                      |
| $EL$ = accumulated locked-in force effects resulting from construction process, including secondary forces from post-tension               | $l$ = span length, ft (m)                                                                                                                                                       |
| $EQ$ = earthquake force, lb (N)                                                                                                            | $L$ = live load during construction, lb (N); wave length, ft (m)                                                                                                                |
| $ER$ = external restrained force, lb (N)                                                                                                   | $LF_e$ = emergency longitudinal braking force, lb (N)                                                                                                                           |
| $F_h$ = horizontal design drag load due to wind, psi (Pa)                                                                                  | $LF_n$ = normal longitudinal braking force, lb (N)                                                                                                                              |
| $F_R$ = radial force per unit length due to curvature of continuously welded rail, k/in. (Pa/mm)                                           | $LF$ = longitudinal force, lb (N)                                                                                                                                               |
| $F_r$ = axial force in the continuously welded rail, kip (kN)                                                                              | $LL$ = vertical standard vehicle load, lb (N)                                                                                                                                   |
| $F_{sj}$ = jacking force in a post-tensioning tendon, kip (kN)                                                                             | $LR$ = load on safety railing, lb (N)                                                                                                                                           |
| $F_v$ = vertical design drag load due to wind, psi (Pa)                                                                                    | $LS$ = live load surcharge, lb (N)                                                                                                                                              |
| $f_1$ = first mode flexural (natural) frequency, Hz                                                                                        | $M$ = mass per unit length of guideway, lb/in.-s <sup>2</sup> /in. (kg/m)                                                                                                       |
| $f_c$ = extreme fiber compressive stress in concrete at service loads, psi (MPa)                                                           | $M_a$ = maximum moment in member due to service loads at stage for which deflection is being computed, in.-lb (N-mm)                                                            |
| $f'_c$ = specified compressive strength of concrete, psi (MPa)                                                                             | $M_{cr}$ = cracking moment, in.-lb. (N-mm)                                                                                                                                      |
| $f'_{ci}$ = specified compressive strength of concrete at time of initial prestress, psi (MPa)                                             | $P$ = live load on service walkway, lb (N)                                                                                                                                      |
| $f_r$ = cracking strength of concrete, psi (MPa)                                                                                           | $P_D$ = dynamic wind pressure, lb/ft <sup>2</sup> (MPa)                                                                                                                         |
| $f_{cri}$ = cracking stress of concrete at time of initial prestress, psi (MPa)                                                            | $PL$ = pedestrian live load, lb (N)                                                                                                                                             |
| $f_f$ = stress range in straight flexural reinforcing steel, ksi (MPa)                                                                     | $PS$ = secondary force effects due to prestressing                                                                                                                              |
| $f_{min}$ = algebraic minimum stress, tension positive, compression negative, ksi (MPa)                                                    | $p_{cp}$ = periphery of outer boundary of the member, in. (mm)                                                                                                                  |
| $f_{pbt}$ = stress in prestressing steel immediately prior to transfer, psi (MPa)                                                          | $q_y$ = shear flow at yield, lb/in. (N/mm)                                                                                                                                      |
| $f_{pe}$ = effective stress in prestressing steel after losses, psi (MPa)                                                                  | $r/h$ = ratio of base radius to height of transverse deformations of reinforcing bars; when actual value is unknown, use 0.3                                                    |
| $f_{pu}$ = specified tensile strength of prestressing steel, psi (MPa)                                                                     | $R$ = radius of curvature, ft (m)                                                                                                                                               |
| $f_{py}$ = specified yield strength of prestressing steel, psi (MPa)                                                                       | $RS$ = rail-structure interaction, lb (N)                                                                                                                                       |
| $f_{rr}$ = axial stress in the continuously welded rail, ksi (MPa)                                                                         | $S$ = service load combinations                                                                                                                                                 |
| $f_s$ = calculated tensile stress in reinforcement at service loads, psi (MPa)                                                             | $SE$ = differential settlement effects                                                                                                                                          |
| $f_{sr}$ = stress range in shear reinforcement or in welded reinforcing bars, ksi (MPa)                                                    | $SH$ = forces due to shrinkage in concrete, lb (N)                                                                                                                              |
| $f_{st}$ = change in stress in torsion reinforcement due to fatigue loadings, ksi (MPa)                                                    | $s$ = spacing of reinforcement to resist bursting, shear, or pitch of spiral reinforcement, center- to-center spacing of longitudinal shear, or torsion reinforcement, in. (mm) |
| $f_{sv}$ = change in stress in shear reinforcement due to fatigue loadings, ksi (MPa)                                                      | $s_l$ = spacing for longitudinal reinforcement, in. (mm)                                                                                                                        |
| $f_y$ = specified yield strength of reinforcement, psi (MPa)                                                                               | $s_t$ = spacing of hoop reinforcement, in. (mm)                                                                                                                                 |
| $g$ = acceleration due to gravity = 32.2 ft/s <sup>2</sup> (9.81 m/s <sup>2</sup> )                                                        | $T_0$ = stress-free temperature of the continuously welded rail, °F (°C)                                                                                                        |
| $H$ = height from ground level to the top of the superstructure                                                                            | $T_1$ = final temperature in the continuously welded rail, °F (°C)                                                                                                              |
| $HF$ = hunting force, lb (N)                                                                                                               | $T_u$ = torsional moment, in.-lb (N-mm)                                                                                                                                         |
| $h$ = overall thickness or height of member, in. (mm)                                                                                      | $TG$ = loads due to temperature gradient in the structure exclusive of rail forces, lb (N)                                                                                      |
| $I_{cr}$ = moment of inertia of cracked section transformed to concrete, in. <sup>4</sup> (m <sup>4</sup> )                                | $TU$ = loads due to uniform temperature in the structure exclusive of rail forces, lb (N)                                                                                       |
| $I_e$ = effective moment of inertia for computation of deflections, neglecting the reinforcement, in. <sup>4</sup> (m <sup>4</sup> )       | $t$ = time, days                                                                                                                                                                |
| $I_g$ = moment of inertia of gross concrete section about the centroidal axis neglecting reinforcement, in. <sup>4</sup> (m <sup>4</sup> ) | $t_d$ = shear flow zone thickness of a member subjected to torsional forces, in. (mm)                                                                                           |
| $IC$ = ice pressure, lb (N)                                                                                                                | $U$ = ultimate load combinations                                                                                                                                                |
| $IM$ = impact factor                                                                                                                       | $V$ = speed, ft/s (m/s)                                                                                                                                                         |
| $IL_{st}$ = impact load, lb (N)                                                                                                            | $V_{cr}$ = critical speed, ft/s (m/s)                                                                                                                                           |
|                                                                                                                                            | $V_u$ = ultimate shear force, lb (N)                                                                                                                                            |
|                                                                                                                                            | $v$ = velocity of stream flow, mean hourly velocity of wind, or maximum operating speed of the vehicle, ft/s (m/s)                                                              |
|                                                                                                                                            | $WA$ = stream flow load, lb (N)                                                                                                                                                 |
|                                                                                                                                            | $WL$ = wind load on vehicle, lb (N)                                                                                                                                             |

|            |   |                                                                                                                             |
|------------|---|-----------------------------------------------------------------------------------------------------------------------------|
| $WS$       | = | wind load on structure, lb (N)                                                                                              |
| $w_c$      | = | unit weight of concrete, lb/ft <sup>3</sup> (kg/m <sup>3</sup> )                                                            |
| $w_n$      | = | natural frequency of the structure (rad/s)                                                                                  |
| $y_t$      | = | distance from the centroidal axis of cross section, neglecting the reinforcement, to the extreme fiber in tension, in. (mm) |
| $\alpha$   | = | coefficient of thermal expansion                                                                                            |
| $\Delta T$ | = | change in torsion at section due to fatigue loadings, in.-kip (N-mm)                                                        |
| $\Delta V$ | = | change in shear at section due to fatigue loading, kip (kN)                                                                 |
| $\phi$     | = | strength reduction factor                                                                                                   |
| $\gamma$   | = | mass density of water = 62.4 lb/ft <sup>3</sup> (1000 kg/m <sup>3</sup> )                                                   |
| $\lambda$  | = | multiplier for additional deflection due to long-term effects                                                               |
| $\theta$   | = | angle in degrees between the wind force and a line normal to the guideway centerline                                        |
| $\rho$     | = | density of air at sea level at 32°F (0°C) = 0.0765 lb/ft <sup>3</sup> (1.226 kg/m <sup>3</sup> )                            |
| $\xi$      | = | time-dependent factor for sustained load                                                                                    |

## 2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://terminology.concrete.org>. Definitions provided herein complement that resource.

**bogie**—wheeled frame connected via a suspension system to a railway vehicle body or underframe.

**broken rail**—fracture of a continuously welded rail.

**continuously welded rail (CWR)**—running rails that act as a continuous structural element as a result of full penetration welding of individual lengths of rail; continuously welded rails may be directly fastened to the guideway, in which case their combined load effects should be included in the design.

**flexural natural frequency**—first vertical frequency of vibration of a guideway, including all the sustained load, based on the flexural stiffness and mass distribution of the superstructure.

**linear induction motor (LIM)**—AC linear motor that works by the same general principles as other induction motors but which has been designed to directly produce motion in a straight line.

**standard vehicle**—loading, design vehicle—forces representing the wheel pattern and total weight including carriage, bogie, and passenger loads, of a railway vehicle.

## CHAPTER 3—GENERAL DESIGN CONSIDERATIONS

### 3.1—Scope

**3.1.1 General**—Transit structures frequently carry loads through urban areas. Demands for aesthetics (Fig. 3.1.1a), performance, cost, efficiency, and minimum urban disruption during construction and operation are greater than for most bridge structures.

The design of transit structures requires an understanding of transit technology, constraints and the impact to an urban

environment (Fig. 3.1.1b), the operation of the transit system, the system suppliers, and the structural options available.

A guideway becomes a permanent feature of the urban scene. Materials and features, therefore, should be efficiently used and built into the guideway to produce a structure that will support an operating transit system and fit the environment.

This guide provides an overview of key issues to be considered in guideway design. It is intended to suggest minimum materials, workmanship, technical features, design, and construction for producing a guideway that performs satisfactorily. Serviceability and strength considerations are also given. It includes analysis and design guidelines to meet serviceability and strength limit states. Sound engineering judgment should be used in implementing these recommendations.

**3.1.2 Guideway structures**—A guideway structure should support a transit vehicle, guide it through the alignment, and restrain stray vehicles. Guidance of transit vehicles includes the ability to switch vehicles between guideways. A guideway should also generally provide emergency evacua-



Fig. 3.1.1a—Example of a transit structure that blends with the environment (courtesy of MGM Mirage, Inc.).



Fig. 3.1.1b—Example of a transit structure in an urban setting (courtesy of PCA).



Fig. 3.1.2—Repetition of span lengths and column details (courtesy of PCA).



Fig. 3.1.3a—Vehicle style (courtesy of Jacksonville Transportation Authority).

tion, support wayside power distribution services, and house automatic train controls.

Within a modern transit guideway, there is a high degree of repeatability (Fig. 3.1.2) and nearly an equal mixture of tangent and curved alignments. Guideways often consist of post-tensioned concrete members. Post-tensioning may provide principal reinforcement for simple-span structures and continuity reinforcement for continuous structures. Bonded post-tensioned tendons are recommended for all primary load-carrying guideway applications, and their use is assumed in this guide. Unbonded tendons, however, may be used where approved, especially for strengthening or expanding existing structures.

**3.1.3 Vehicles**—Transit vehicles have a wide variety of physical configurations, propulsion, and suspension systems. The most common transit vehicles are steel-wheeled vehicles running on steel rails, powered by conventional guidance systems. Transit vehicles also include rubber-tired vehicles and vehicles with more advanced suspension or guidance systems, such as air-cushioned or magnetically levitated



Fig. 3.1.3b—Vehicle style (courtesy of Clarian Health).



Fig. 3.1.3c—Vehicle style (courtesy of Hitachi Corporation).

vehicles. Transit vehicles may be configured as individual units or combined into trains. Their styles vary as shown in Fig. 3.1.3a through 3.1.3d.

## 3.2—Structural considerations

**3.2.1 General**—Transit systems are constructed in four types of right-of-way (ROW): exclusive; shared-use rail corridor; shared-use highway corridor; and urban arterial.

Constraints of ROW affect the type of structural system that can be employed for an individual transit operation. Constraints resulting from a particular ROW might include limited construction access; restricted working hours; limits on environmental factors such as noise, dust, foundation, and structure placement; and availability of skilled labor and equipment. Various guideway locations within the ROW are shown in Fig. 3.2.1a through 3.2.1c.

**3.2.2 Concrete girder types**—Categorized by construction methods, three types of concrete girders are used for transit superstructures: precast, cast-in-place, and composite.

**3.2.2.1 Precast girder construction**—When site conditions are suitable, entire beam elements can be prefabricated and transported to the site. Box girder sections are frequently used for their torsional stiffness, especially in urban areas.



Fig. 3.1.3d—Vehicle style (courtesy of PCA).



Fig. 3.2.1a—Shared ROW (courtesy of PCA).



Fig. 3.2.1b—Side of ROW (courtesy of Las Vegas Monorail Company).

curves. Some transit systems with long-radius horizontal curves have used double-T beams for the structure.

Continuous structures are frequently used. Precast beams are made continuous by developing continuity at the supports. A continuous structure has less depth and increased structural redundancy than a simple-span structure. Rail systems using continuously welded rail are typically limited



Fig. 3.2.1c—ROW at median location (courtesy of PCA).



Fig. 3.2.2.1a—Precast box girders for sharp curvature (courtesy of PCA). Continuity has been provided through curved alignment.

to simple-span or two-span continuous structures to accommodate thermal movements between the rails and structure. Longer lengths of continuous construction are used more readily in systems with rubber-tired vehicles. Examples of girder types and continuity may be seen in Fig. 3.2.2.1a through 3.2.2.1d.

Segmental construction techniques may be used for major structures, such as river crossings or where schedules or access to the site favors delivery of segmental units. The use of segmental construction is discussed in ACI 343R.

**3.2.2.2 Cast-in-place structures**—Cast-in-place construction is used when site limitations preclude delivery of large precast elements or the guideway structure has a complex geometry, like being located on sharp curves. Cast-in-place construction has not been used extensively in modern transit structures unless warranted by the specific project situation.

**3.2.2.3 Composite structures**—Transit structures can be constructed in a similar manner to highway bridges, using precast concrete or steel girders with a cast-in-place composite concrete deck. Composite construction is especially common for special structures such as switches, turnouts, and long spans where the weight of an individual precast element limits its shipping to the site. The bridge



Fig. 3.2.2.1b—Precast concrete girders (courtesy of MGM Mirage, Inc.). Example of simple span construction.



Fig. 3.2.2.1d—Precast box girder on tangent (courtesy of PCA). May be simple span or continuous over multiple spans. May be span-by-span or balanced cantilever construction.



Fig. 3.2.2.1c—Precast box girder on curve (courtesy of PCA). Balanced cantilever construction provides continuity over the pier.



Fig. 3.3.2a—Walkway between rails (courtesy of Jacksonville Transportation Authority).

provides a working surface that allows accurate placement of transit hardware on the cast-in-place deck.

### 3.3—Functional considerations

**3.3.1 General**—The structural functions are to support present and future transit applications, satisfy serviceability requirements, and provide for passenger safety. The transit structure may also be designed to support other loads such as automotive or pedestrian traffic. However, mixed-use applications are not included in the loading requirements of Chapters 4 and 5.

**3.3.2 Safety considerations**—Considerations for a transit structure should include transit technology, human safety, and external safety in accordance with the requirements of the National Fire Protection Association document NFPA 130 (NFPA 2003).

Transit technology considerations include both normal and extreme longitudinal, lateral, and vertical vehicle loads. Passing clearances for normal and disabled vehicles, vehicle

speeds, environmental factors, transit operations, collision conditions, and vehicle retention should also be considered. The geometric envelope of a disabled vehicle is a function for the suspension system, support system, and vehicle design. This information must be provided by the system supplier.

Human safety addresses emergency evacuation and access, structural maintenance, and fire control. Transit operations require facilities for evacuating passengers from stalled or disabled vehicles and access for emergency personnel. In most cases, emergency evacuation is accomplished by a walkway that may be adjacent to the guideway or incorporated into its structure. Figure 3.3.2a and 3.3.2b show walkways provided between the guideway rails.

The exact details of the emergency access and evacuation methods on the guideway should be resolved among the transit operator, transit vehicle supplier, and engineer. NFPA 130 (NFPA 2003) gives detailed requirements for safety provisions on fixed guideway transit systems.

External safety considerations include safety precautions during construction, prevention of local street traffic collision with the transit structure, and avoidance of naviga-



Fig. 3.3.2b—Walkways between rails (courtesy of Las Vegas Monorail Co.).



Fig. 3.3.5—Bearings should be designed for easy replacement (courtesy of PCA).

tional hazards when transit structures pass over navigable waterways.

**3.3.3 Lighting**—The requirements for transit structure lighting should be followed in accordance with provisions of the authority having jurisdiction. Provisions may require lighting for emergency use only, for properties adjacent to the guideway structure, or that lighting be eliminated altogether.

**3.3.4 Drainage**—To prevent accumulation of water within the track area, transit structures should be designed so that surface runoff is drained to the edge or center of the superstructure, where the water can be carried longitudinally.

Longitudinal drainage of transit structures is usually accomplished by providing a longitudinal slope to the structure; with a minimum slope of 0.5 percent preferred. Scuppers or inlets of a size and number that are designed and detailed to drain the structure should be provided. Downspouts, where required, should be of a rigid, corrosion-resistant material preferable a minimum of 6 in. (150 mm) but not less than 4 in. (100 mm) in diameter. Downspouts should be provided with cleanouts. Details of the downspout and its deck inlet and outlet should prevent water discharge against any portion of the structure and erosion at ground level. Slopes should be arranged so that runoff drains away from stations. Longitudinal grades to ensure drainage should be planned with the natural topography of the site to avoid an unusual structural appearance.

Architectural treatment of exposed downspouts is important to the aesthetic appearance of the facility. When treatment becomes complicated, the use of internal or embedded downspouts is preferred. For internal or external downspouts, prevention of ice accumulation in cold-weather climates should be considered. This may require localized heating of the drain area and downspout. All overhanging portions of the concrete deck should have a drip bead or notch.

**3.3.5 Expansion joints and bearings**—Expansion joints should be provided at span ends, allowing beam ends to accommodate movements from volumetric changes within the structure. These movements come from several primary sources: temperature change, concrete shrinkage, creep effects from prestressing, and post-tensioning shortening. Joints should be designed to reduce noise transmission and prevent moisture from seeping to the bearings.

Adequate detailing should be provided to facilitate maintenance of bearings and their replacement if or when needed during the life of the structure. Figure 3.3.5 shows bearings between the box girder and the bent cap that are clearly visible. Access for jacking the structure for bearing replacement is enhanced.

When using aprons or finger plates, they should be designed to span the joint and prevent debris accumulation on the bearing seats.

**3.3.6 Durability**—To satisfy a design life of 75 years or more, details affecting durability of the structure—materials selection, structural detailing, and construction quality control—should be given adequate consideration.

Materials selection includes concrete and its mixture proportion, allowing for a low water-cementitious material ratio ( $w/cm$ ) and air entrainment in areas subject to freezing-and-thawing action. Epoxy-coated reinforcement and concrete sealers may be beneficial if:

- a) Chloride use is anticipated as part of the winter snow-clearing operations
- b) The guideway may be exposed to salt spray from a coastal environment
- c) Adjacent highways are treated with deicing chemicals

In structural detailing, reinforcement or noncorrosive reinforcement placement and methods to prevent deleterious conditions from occurring should be considered. Reinforcement should be distributed in the section to control crack

distribution and size (ACI SP-66 [ACI Committee 315 2004]). The cover should provide adequate protection to the reinforcement and follow a nationally recognized code (ACI 318 or AASHTO LRFD Bridge Design Specifications [AASHTO 2012]) or specific project requirements.

Incidental and accidental loadings should be accounted for and adequate reinforcement provided to intersect potential cracks. Stray electrical currents, which could precipitate galvanic corrosion, should be accounted for in electrical hardware and equipment design and their grounding.

Construction quality control is essential to ensure that design intent and durability considerations are properly implemented. Construction inspectors should be qualified, experienced, and certified as ACI Concrete Special Inspectors. Quality control should follow a pre-established formal plan with inspections performed as specified in the contract documents. ACI 311.4R provides guidance for establishing formal plans.

To satisfy a 75-year service life, regular inspection and maintenance programs should be instituted to ensure the integrity of structural components. Programs may include periodic placement of coatings, sealers, or chemical neutralizers. Adequate lighting may be necessary where natural light may be insufficient, such as inside box girder structures.

### 3.4—Economic considerations

The economy of a concrete guideway is measured by the annual maintenance cost and capitalized cost for its service life. The design process should include provisions to minimizing operations and maintenance cost. Consideration, therefore, should be given to the service life cost of the guideway structure. The owners should establish guidelines for a cost analysis. Economy is considered by comparative studies of reinforced, prestressed, and partially prestressed concrete construction. Trade-offs should be considered for using higher-grade materials in sensitive areas during the initial construction, against the impact of system disruption at a later date if the transit system must be upgraded. For example, higher-quality aggregates may be selected for the traction surface where local aggregates have a tendency to polish with continuous wear. The argument in support for higher-grade materials is especially important because guideway traffic cannot be rerouted during service disruptions.

### 3.5—Urban impact

**3.5.1 General**—The guideway affects an urban environment in three general areas: visually, physically, and through access of public safety equipment. Figure 3.5.1 shows the integration of the guideway within the other transportation corridors in the vicinity.

Visual impact includes guideway appearance from the surrounding area and the appearance of the surrounding area from the guideway. Physical impact includes placement of columns and beams and the dissipation of noise, vibration, and electromagnetic radiation. Electromagnetic radiation is usually a specific design consideration of the vehicle supplier. Public safety requires provisions for fire, police,



Fig. 3.5.1—Urban impact (courtesy of PCA).

emergency service access, and the emergency evacuation of passengers. Access to the guideway requires stairs, walkways, and platforms. How they are configured, attached, and where they are located will affect the visual reception by the public.

**3.5.2 Physical appearance**—A guideway constructed in any built-up environment should meet high standards of aesthetics for physical appearance. The size and configuration of guideway elements should ensure compatibility with its surroundings. Whereas the range of sizes and shapes is unlimited in the selection of guideway components, the following should be considered:

- a) View disruption
- b) Shade and shelter created by the guideway
- c) Blockage of pedestrian walkways
- d) Blockage of streets and the effect on traffic and parking
- e) Impairment of sight distances for traffic
- f) Guideway size as it relates to adjacent structures
- g) Construction in an urban environment
- h) Methods of delivery for prefabricated components and cast-in-place construction
- i) Interaction with roadway and transit vehicles
- j) Visual continuity

Figure 3.5.2a shows the location of guideway columns to avoid disruption of pedestrian traffic, vehicular traffic on local streets, and traffic sight distances.

Figure 3.5.2b demonstrates how smooth curves for both structure and vehicle allow the system to blend into its suburban surroundings.

Detailing considerations should include:

- a) Surface finish
- b) Color
- c) Joint detailing
- d) Provision to alleviate damage from water dripping from the structure
- e) Control and dissipation of surface water runoff
- f) Differences in texture and color between cast-in-place and precast elements

**3.5.3 Sightlines**—In guideway design, the view of the surrounding area from the transit system should be consid



Fig. 3.5.2a—Design decisions to fit guideway around existing features (courtesy of Las Vegas Monorail Co.).



Fig. 3.5.2b—Clean lines and smooth finishes (courtesy of Clarian Health).

ered. The engineer should recognize that patrons riding on the transit system will have a different view than pedestrians at street level; the guideway placement and sightlines should reflect sensitivity to intrusion on private properties and adjacent buildings. In some cases, the use of noise barriers and dust screens should be considered.

Figure 3.5.3 provides an example of clean sightlines as the guideway span straddles the projected lines of the water channel beyond.

Views of the guideway from a higher vantage point are important for a positive impression of the transit system on potential patrons. The interior should present a clean, orderly appearance to transit patrons and adjacent observers.

**3.5.4 Noise suppression**—A transit system will add to the ambient background noise. Specifications for new construction generally require that the wayside noise 50 ft (15 m) from the guideway not exceed a range of 65 to 76 dBA. This noise is generated from on-board vehicle equipment, such as propulsion and air-conditioning units, and from vehicle/track interaction, especially when jointed rail is used.

Normally, it is the vehicle engineer's responsibility to control noise emanating from the vehicle. Parapets and other



Fig. 3.5.3—Example of the importance of sightlines (courtesy of Clarian Health).

hardware on the guideway structure should be designed to meet general or specific noise-suppression criteria. Determination of these criteria is made on a case-by-case basis, frequently in conjunction with the vehicle supplier. ASCE 21 provides additional information regarding acceptable exterior noise levels emanating from the system.

**3.5.5 Vibration**—Transit vehicles on a guideway generate vibrations that may be transmitted to adjacent structures. For most rubber-tired transit systems, this ground-borne vibration is negligible. In many rail transit systems, especially those systems with jointed rails, the noise and vibration can be highly perceptible. In these situations, vibration isolation of the structure is necessary. ASCE 21 contains additional information regarding system-induced vibrations.

**3.5.6 Emergency services access**—A key concern in an urban area is the accessibility by fire or other emergency equipment to buildings adjacent to a guideway. Within the confined right-of-way (ROW) of an urban street, space limitations make this a particularly sensitive concern. In most cases, a clearance of approximately 15 ft (5 m) between the face of a structure and a guideway provides adequate access. Access over the top of a guideway may not represent a safe option.

## 3.6—Transit operations

**3.6.1 General**—Once a transit system is opened for service, the public depends on its availability and reliability. Shutdowns to permit maintenance, operation, or expansion of the system can affect the availability and reliability. These concerns often lead to long-term economic, operational, and planning analyses of the transit system design and construction.

In most transit operations, a shutdown period between 1:00 and 5:00 a.m. can be tolerated; slightly longer shutdowns may be possible in certain locations and on holidays. It is during shutdown that routine maintenance work is performed.

Many transit systems also perform maintenance during normal operating hours. This practice tends to compromise work productivity, guideway access rules, and a safe working space. Transit operators should provide the engi-