

ANALYSIS AND DESIGN OF REINFORCED AND PRESTRESSED-CONCRETE GUIDEWAY STRUCTURES

Reported by ACI Committee 358

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These recommendations, prepared by Committee 358, present a procedure for the design and analysis of reinforced and prestressed-concrete guideway structures for public transit. The document is specifically prepared to provide design guidance for elevated transit guideways. For items not covered in this document the engineer is referred to the appropriate highway and railway bridge design codes.

Limit states philosophy has been applied to develop the design criteria. A reliability approach was used in deriving load and resistance factors and in defining load combinations. A target reliability index of 4.0 and a service life of 75 years were taken as the basis for safety analysis. The reliability index is higher than the value generally used for highway bridges, in order to provide a lower probability of failure due to the higher consequences of failure of a guideway structure in a public transit system. The 75 year service life is comparable with that adopted by AASHTO for their updated highway bridge design specifications.

KEYWORDS: Box beams; concrete construction; cracking (fracturing); deformation; fatigue (materials); guideways; loads (forces); monorail systems; partial prestressing; precast concrete; prestressed concrete; prestress loss; rapid transit systems; reinforced concrete; serviceability; shear properties; structural analysis; structural design; T-beams; torsion; vibration.

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CHAPTER 1 - SCOPE, DEFINITIONS AND NOTATIONS**1.1- Scope**

These recommendations are intended to 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 in ACI 343R, AASHTO bridge specifications, and the AREA manual of standard practice.

The design criteria specifically recognize the unique features of concrete transit guideways, namely, guideway/vehicle interaction, rail/structure interaction, special fatigue requirements, and esthetic requirements in urban areas. The criteria are based on current state-of-the-art practice for moderate-speed [up to 100 mph (160 km/h)] vehicles. The application of these criteria for advanced technologies other than those discussed in this report, require an independent assessment.

ACI 343R is referenced for specific items not covered in these recommendations. These references include materials, construction considerations, and segmental construction.

1.2-Definitions

The following terms are defined for general use in this document. For a comprehensive list of terms generally used in the design and analysis of concrete structures, the reader is referred to Chapter 2 of ACI 318 and to ACI 116R. The terminology used in this document conforms with these references.

Broken rail - The fracture of a continuously welded rail.

Concrete, specified compressive strength of f'_c -

Compressive strength of concrete used in design and evaluated in accordance with Chapter 5 of ACI 318 is expressed in pounds per square inch (psi) [Megapascals (MPa)]; wherever this quantity is under a radical sign, the square root of the numerical value only is intended and the resultant is in pounds per square inch (psi).

Concrete-A mixture of portland cement or any other hydraulic cement, fine aggregate, coarse aggregate, and water, with or without admixtures.

Continuously welded rail - 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 must be included in the design.

Dead load -The dead weight supported by a member, as defined in [Chapter 3](#), without load factors.

Design load-All applicable loads and forces and their load effects such as, moments and shears used to proportion members; for design according to [Chapter 5](#), design load refers to load without load factors; for design according to [Chapter 6](#), design load refers to loads multiplied by appropriate load factors, as given in [Chapter 4](#).

Flexural natural frequency- The first vertical frequency of vibration of an unloaded guideway, based on the flexural stiffness and mass distribution of the superstructure.

Live load-The specified live load, without load factors.

Load factor-A factor by which the service load is multiplied to obtain the design load.

Service load-The specified live and dead loads, without load factors.

Standard vehicle-The maximum weight of the vehicle used for design; the standard vehicle weight should allow for the maximum number of seated and standing passengers and should allow for any projected vehicle weight increases if larger vehicles or trains are contemplated for future use.

1.3 - Notation

a = center-to-center distance of shorter dimension of closed rectangular stirrups, in. (mm). [Section 5.5.3](#)

a_1 = side dimension of a square post-tensioning anchor, or lesser dimension of a rectangular post-tensioning anchor, or side dimension of a square equivalent in area to a circular post-tensioning anchor, in. (mm). [Section 5.8.2.1](#)

a_2 = minimum distance between the center-lines

- of anchors, or twice the distance from the centerline of the anchor to the nearest edge of concrete, whichever is less, in. (mm). [Section 5.8.2.1](#)
- A = effective tension area of concrete surrounding the main tension reinforcing bars and having the same centroid as that reinforcement, divided by the number of bars, in.² (mm²); when the main reinforcement consists of several bar sizes, the number of bars should be computed as the total steel area divided by the area of the largest bar used. [Section 5.8.1](#)
- A = exposed area of a pier perpendicular to the direction of stream flow, ft² (m²). [Section 3.3.4](#)
- A_{bs} = area of nonprestressed reinforcement located perpendicular to a potential bursting crack, in.² (mm²). [Section 5.8.2.1](#)
- A_{oh} = Area enclosed by the centerline of closed transverse torsion reinforcement, in.² (mm²). [Section 5.5.3](#)
- A_r = Cross-sectional area of a rail, in.² (mm²).
- A_s' = Area of compression reinforcement, in.² (mm²).
- A_t = Area of one leg of a closed stirrup resisting torsion within a distance, in.² (mm²).
- A_v = Area of shear reinforcement within a distance, or area of shear reinforcement perpendicular to main reinforcement within a distance for deep beams, in.² (mm²).
- b = Width of compressive face of member, in. (mm).
- = Center-to-center distance of longer dimension of closed rectangular stirrup, in. (mm). [Section 5.5.3](#)
- b_b = Width of concrete in the plane of a potential bursting crack, in. (mm). [Section 5.8.2](#)
- BR = Broken rail forces.
- C_d = Horizontal wind drag coefficient.
- C_D = Flowing water drag coefficient.
- C_e = Wind exposure coefficient.
- C_g = Wind gust effect coefficient.
- CF = Centrifugal force, kip (kN).
- CL = Collision load, kip (kN).
- CR = Forces due to creep in concrete, kip (kN).
- d = Distance from extreme compressive fiber to centroid of tension reinforcement, in. (mm).
- d_c = Thickness of concrete cover measured from the extreme tensile fiber to the center of the bar located closest thereto, in. (mm).
- D = Dead load.
- DR = Transit vehicle mishap load, due to vehicle derailment, kip (kN).
- e = Base of Napierian logarithms.
- E_c = Modulus of elasticity of concrete, psi (Pa).
- [Section 5.6.3](#)
- E_{ci} = Modulus of elasticity of concrete at transfer of stress, psi (MPa).
- E_s = Modulus of elasticity of reinforcement, psi (MPa).
- EI = Flexural stiffness of compression members, k-in² (kN-mm²).
- EQ = Earthquake force.
- E_r = Modulus of elasticity of rail, psi (MPa).
- f_{bs} = Bursting stress behind a post-tensioning anchor, ksi (MPa).
- f_c = Extreme fiber compressive stress in concrete at service loads, psi (MPa).
- f_c' = Specified compressive strength of concrete at 28 days, psi (MPa).
- f_{ci}' = Compressive strength of concrete at time of initial prestress, psi (MPa).
- f_{cr} = Cracking stress of concrete, psi (MPa).
- f_{cni} = Cracking stress of concrete at the time of initial prestress, psi (MPa).
- $\sqrt{f_c'}$ = Square root of specified compressive strength of concrete, psi (MPa).
- f_{fr} = Stress range in straight flexural reinforcing steel, ksi (MPa).
- f_m = Algebraic minimum stress level, tension positive, compression negative, ksi (MPa).
- f_{pu} = Ultimate strength of prestressing steel, psi (MPa).
- f_{py} = Specified yield strength of prestressing tendons, psi (MPa).
- f_r = Axial stress in the continuously welded rail, ksi (MPa). [Section 3.4.3](#)
- f_s = Tensile stress in reinforcement at service loads, psi (MPa).
- f_{sr} = Stress range in shear reinforcement or in welded reinforcing bars, ksi (MPa).
- f_{st} = Change in stress in torsion reinforcing due to fatigue loadings, ksi (MPa).
- f_{sv} = Change in stress in shear reinforcing due to fatigue loadings, ksi (MPa).
- f_y = Specified yield stress, or design yield stress of non-prestressed reinforcement, psi (MPa).
- f_1 = Flexural (natural) frequency, Hz.
- F_{bs} = Total bursting force behind a post-tensioning anchor, kip (kN).
- F_h = Horizontal design pressure due to wind, psi (Pa).
- F_r = Axial force in the continuously welded rail, kip (kN).
- F_{sj} = Jacking force in a post-tensioning tendon, kip (kN).
- F_v = Vertical design pressure due to wind, psi (Pa).
- F_R = Radial force per unit length due to curvature of continuously welded rail, k/in (Pa/mm).

- g = Acceleration due to gravity = 32.2 ft/sec² (9.807 m/sec²).
 h = Overall thickness of member, in. (mm).
 h_f = Compression flange thickness of I-and T-sections, in. (mm).
 H = Ambient relative humidity. [Section 3.4.4](#)
 H = Height from ground level to the top of the superstructure. [Section 3.3.2](#)
 HF = Hunting force.
 I = Impact factor.
 ICE = Ice pressure.
 I_{cr} = Moment of inertia of cracked section transformed to concrete, in.⁴ (m⁴).
 I_e = Effective moment of inertia for computation of deflections, neglecting the reinforcement, in.⁴ (m⁴). [Chapter 5](#)
 I_g = Moment of inertia of the gross concrete section about its centroidal axis neglecting reinforcement, in.⁴ (m⁴).
 jd = Distance between tensile and compression forces at a section based on an elastic analysis, in. (mm).
 k_r = Average creep ratio.
 k_t = k , as a function of time t .
 k_v = A function of r_v for creep and shrinkage strains.
 ℓ = Span length, ft (m).
 L = Live load.
 LF = Longitudinal force.
 LF_e = Emergency longitudinal braking force.
 LF_n = Normal longitudinal braking force.
 M = Mass per unit length, lb/in.-se&in. (kg/m).
 M_a = Maximum moment in member at stage for which deflection is being computed, lb-in. (N-mm).
 M_{cr} = Cracking moment, lb-m (N-mm).
 PS^{cr} = Forces and effects due to prestressing.
 q = Dynamic wind pressure, psf (MPa). [Chapter 3](#).
 r_v = Volume-to-surface-area ratio, (volume per unit length of a concrete section divided by the area in contact with freely moving air), in. (mm).
 r/h = Ratio of base radius to height of transverse deformations of reinforcing bars; when actual value is not known, use 0.3.
 R = Radius of curvature, ft (m). [Chapter 3](#)
 s = Shear or torsion reinforcement spacing in a direction parallel to the longitudinal reinforcement, in. (mm).
 s = Spacing of reinforcement, in. (mm), [Section 5.8.2](#)
 S = Service load combinations. Chapters 4 and 5.
 SF = Stream flow load, lb (N). [Chapter 3](#).
 SH = Forces due to shrinkage in concrete.
 t = Time, days.
 T = Loads due to temperature or thermal gradient in the structure exclusive of rail forces. [Chapter 4](#).
 T = Time-dependent factor for sustained load. [Section 5.7.2](#)
 ΔT = Change in torsion at section due to fatigue loadings. [Section 5.5.3](#)
 T_0 = Stress-free temperature of rail.
 T_1 = Final temperature in the continuously welded rail.
 U = Ultimate load combinations.
 ΔV = Change in shear at section due to fatigue loadings, kip (kN). [Section 5.5.3](#).
 V = Velocity of water, wind, or vehicle, ft/sec (m/sec). [Chapter 3](#).
 VCF = Vehicle crossing frequency, Hz. [Section 3.3.1](#).
 w = Unit weight of concrete, lb/ft³ (kg/m³).
 W = Wind load. [Chapter 3](#).
 WL = Wind load on live load. [Chapters 3 and 4](#).
 WS = Wind load on structure. [Chapters 3 and 4](#).
 x_m = Location of maximum bursting stress, measured from the loaded face of the end block, in. (mm).
 y_t = Distance from the centroidal axis of cross section, neglecting the reinforcement, to the extreme fiber in tension, in. (mm).
 z = A quantity limiting distribution of flexural reinforcement.
 α = Coefficient of thermal expansion. [Chapter 3](#).
 γ = Mass density of water, lb/ft³ (kg/m³).
 ϵ_i = Initial elastic strain.
 ϵ_{cr} = Concrete creep strain at time t .
 ϵ_{sh} = Concrete shrinkage strain at time t .
 ϵ_{shu} = Concrete shrinkage strain at $t = \infty$.
 θ = Angle in degrees between the wind force and a line normal to the guideway centerline.
 λ = Multiplier for additional long-time deflection as defined in [Section 5.7.2](#).
 ρ = Density of air in [Section 3.3.2](#)
 ρ_{bs} = Ratio of nonprestressed reinforcement located perpendicular to a potential bursting crack in [Section 5.8.2](#).
 ρ' = Compression reinforcement ratio = A_s'/bd .
 ϕ = Strength reduction factor.
 ψ = A parameter used to evaluate end block stresses. [Section 5.8.2.1](#).

1.4- SI Equivalents

The equations contained in the following chapters are all written in the U.S. inch-pound system of measurements. In most cases, the equivalent SI (metric) equation is also given; however, some equations do not have definitive SI

equivalents. The reader is referred to ACI 318M for a consistent metric or SI presentation. In either case, the engineer must verify that the units are consistent in a particular equation.

1.5-Abbreviations

The following abbreviations are used in this report:

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AREA	American Railway Engineering Association
ASTM	American Society for Testing and Materials
AWS	American Welding Society
CRSI	Concrete Reinforcing Steel Institute
FRA	Federal Railway Administration, U.S. Department of Transportation

CHAPTER 2 - GENERAL DESIGN CONSIDERATIONS

2.1- Scope

2.1.1- General

Transit structures carry frequent loads through urban areas. Demands for esthetics, 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 impacts in an urban environment, the operation of the transit system and the structural options available.

The guideway becomes a permanent feature of the urban scene. Therefore, materials and features should be efficiently utilized and built into the guideway to produce a structure which will support an operating transit system as well as fit the environment.

These guidelines provide an overview of the key issues to be considered in guideway design. They are intended to be a minimum set of requirements for materials, workmanship, technical features, design, and construction which will produce a guideway that will perform satisfactorily. Serviceability and strength considerations are given in this report. Sound engineering judgment must be used in implementing these recommendations.

2.1.2 - Guideway Structures

The guideway structure must support the transit vehicle, guide it through the alignment and restrain stray vehicles. Guidance of transit vehicles

includes the ability to switch vehicles between guideways. The guideway must generally satisfy additional requirements, such as providing emergency evacuation, supporting wayside power distribution services and housing automatic train control cables.

Within a modern transit guideway, there is a high degree of repeatability and nearly an equal mix of tangent and curved alignment. 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 applications and their use is assumed in this report. However, unbonded tendons may be used where approved, especially for strengthening or expanding existing structures.

2.13-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 vehicles. Transit vehicles may be configured as individual units or combined into trains.

2.2- Structural Considerations

2.2.1-General

Transit systems are constructed in four types of right-of-way: exclusive, shared-use rail corridor, shared-use highway corridor, and urban arterial. The constraints of the right-of-way affect the type of structural system which can be deployed for a particular transit operation. Constraints resulting from the type of right-of-way may 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.

Three types of concrete girders are used for transit superstructures. Namely, precast, cast-in-place, and composite girders. The types of guideway employed by various transit systems are listed in the Committee 358 State-of-the-Art Report on Concrete Guideways.^{2,1}

2.2.2-Precast Girder Construction

When site conditions are suitable, entire beam elements are prefabricated and transported to the site. Frequently, box girder sections are used for their torsional stiffness, especially for short-radius curves. Some transit systems having long-radius

horizontal curves have used double-tee 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 than a simple-span structure and increased structural redundancy. Rail systems using continuously welded rail are typically limited to simple-span or two-span continuous structures to accommodate thermal movements between the rails and the structure. Longer lengths of continuous construction are used more readily in systems with rubber tired vehicles.

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

2.2.3 - Cast-in-place Structures

Cast-in-place construction is used when site limitations preclude delivery of large precast elements. Cast-in-place construction has not been used extensively in modern transit structures.

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

2.3- Functional Considerations

2.3.1- General

The functions of the structure are to support present and future transit applications, satisfy serviceability requirements, and provide for safety of passengers. The transit structure may also be designed to support other loads, such as automotive or pedestrian traffic. Mixed use applications are not included in the loading requirements of [Chapters 3 and 4](#).

2.3.2 - Safety Considerations

Considerations for a transit structure must include transit technology, human safety and external safety, in accordance with the requirements of NFPA 130, "Fixed Guideway Transit Systems."^{2,3}

Transit technology considerations include both normal and extreme longitudinal, lateral, and vertical loads of the vehicle, as well as passing clearances for normal and disabled vehicles,

vehicle speeds, environmental factors, transit operations, collision conditions, and vehicle retention.

Human safety addresses emergency evacuation and access, structural maintenance, fire control and other related subjects. Transit operations require facilities for evacuating passengers from stalled or disabled vehicles. These facilities should also enable emergency personnel to access such vehicles. In most cases, emergency evacuation is accomplished by a walkway, which may be adjacent to the guideway or incorporated into the guideway structure. The exact details of the emergency access and evacuation methods on the guideway should be resolved among the transit operator, the transit vehicle supplier, and the engineer. The National Fire Protection Association (NFPA) Code, Particularly NFPA - 130, 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 navigational hazards when transit structures pass over navigable waterways.

2.3.3-Lighting

The requirements for lighting of transit structures should be in accordance with the provisions of the authority having jurisdiction. Such provisions may require that lighting be provided for emergency use only, or for properties adjacent to the guideway structure, or, alternatively, be deleted altogether.

2.3.4-Drainage

To prevent accumulation of water within the track area, transit structures should be designed so that surface runoff is drained to either the edge or the center of the superstructure, whereupon the water is carried longitudinally.

Longitudinal drainage of transit structures is usually accomplished by providing a longitudinal slope to the structure; a minimum slope of 0.5 percent is preferred. Scuppers or inlets, of a size and number that adequately drain the structure should be provided. Downspouts, where required, should be of a rigid, corrosion-resistant material not less than 4 in. (100 mm) and preferably 6 in. (150 mm) in the least dimension; they should be provided with cleanouts. The details of the downspout and its deck inlet and outlet should be such as to prevent the discharge of water against any portion of the structure and should prevent erosion at ground level. Slopes should be arranged so that run-off drains away from stations. Longitudinal grades to assure drainage should be

coordinated with the natural topography of the site to avoid an unusual appearance of the structure.

Architectural treatment of exposed downspouts is important. When such treatment becomes complicated, the use of internal or embedded downspouts, becomes preferable. For internal or external downspouts, consideration must be given to the prevention of ice accumulation in cold-weather climates. This may require localized heating of the drain area and the downspout itself. All overhanging portions of the concrete deck should be provided with a drip bead or notch.

2.3.5 -Expansion Joints and Bearings

Expansion joints should be provided at span ends; this allows the beam ends to accommodate movements due to volumetric changes in the structure. Joints should be designed to reduce noise transmission and to prevent moisture from seeping to the bearings. Adequate detailing should be provided to facilitate maintenance of bearings and their replacement, when needed, during the life of the structure.

Aprons or finger plates, when used, should be designed to span the joint and to prevent the accumulation of debris on the bearing seats. When a waterproof membrane is used, the detail should be such that penetration of water into the expansion joint and the bearing seat is prevented.

2.3.6 - Durability

In order to satisfy the design life of 75 years or more, details affecting the durability of the structure should be given adequate consideration; these should include materials selection, structural detailing, and construction quality control.

Materials selection includes the ingredients of concrete and its mix design, allowing for a low water-cement ratio and air entrainment in areas subject to freeze-thaw action. Epoxy-coated reinforcement and chloride-inhibitor sealers may be beneficial if chloride use is anticipated as part of the winter snow-clearing operations or if the guideway may be exposed to chloride-laden spray from a coastal environment or to adjacent highways treated with deicing chemicals.

In structural detailing, both the reinforcement placement and methods to prevent deleterious conditions from occurring should be considered. Reinforcement should be distributed in the section so as to control crack distribution and size. The cover should provide adequate protection to the reinforcement.

Incidental and accidental loadings should be accounted for and adequate reinforcement should be provided to intersect potential cracks. Stray currents, which could precipitate galvanic corro-

sion, should be accounted for in the design of electrical hardware and appurtenances and their grounding.

Construction quality control is essential to ensure that the design intent and the durability considerations are properly implemented. Such quality-control should follow a pre-established formal plan with inspections performed as specified in the contract documents.

To satisfy a 75-year service life, regular inspection and maintenance programs to ensure integrity of structural components should be instituted. These programs may include periodic placement of coatings, sealers or chemical neutralizers.

2.4 - Economic Considerations

The economy of a concrete guideway is measured by the annual maintenance cost and capitalized cost for its service life. It is particularly important that the design process give consideration to the cost of operations and maintenance and minimize them. Therefore, consideration must be given to the full service life cost of the guideway structure. The owners should provide direction for the establishment of cost analyses. Economy is considered by comparative studies of reinforced, prestressed, and partially prestressed-concrete construction. Trade-offs should be considered for using higher grade materials for 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.

2.5 - Urban Impact

2.5.1 - General

The guideway affects an urban environment in three general areas: visual impact, physical impact, and access of public safety equipment. Visual impact includes both the appearance of the guideway from surrounding area and the appearance of the surrounding area from the guideway. Physical impacts include 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 provision for fire, police, and emergency service access and emergency evacuation of passengers.

2.5.2 -Physical Appearance

A guideway constructed in any built-up environment should meet high standards of esthetics for physical appearance. The size and configuration of the guideway elements should be

sure compatibility with its surroundings. While 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 ways
- d. Blockage of streets and the effect on traffic and parking
- e. Impairment of sight distances for traffic below
- f. Guideway mass as it relates to adjacent structures
- g. Construction in an urban environment
- h. Methods of delivery of prefabricated components and cast-in-place construction
- i. Interaction with roadway and transit vehicles
- j. Visual continuity

Attention to final detailing is important. Items to be considered 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

2.5.3 -Sightliness

In the design of a guideway the view of the surroundings from the transit system itself should be considered. The engineer should be aware that patrons riding on the transit system will have a view of the surroundings which is quite different from that seen by pedestrians at street level. As such, the guideway placement and sightliness should reflect a sensitivity to intrusion on private properties and adjacent buildings. In some cases, the use of noise barriers and dust screens should be considered.

The view of the guideway from a higher vantage point has some importance. The interior of the guideway should present a clean, orderly appearance to transit patrons and adjacent observers. Any supplemental cost associated with obtaining an acceptable view must be evaluated.

2.5.4 -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 75 dBA. This noise is generated from on-board vehicle equipment such as propulsion and air-conditioning units, as well as from

vehicle/track interaction, especially when jointed rail is used.

It is normally the responsibility of the vehicle designer to control noise emanating from the vehicle. Parapets and other 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.

2.5.5- Vibration

Transit vehicles on a guideway generate vibrations which may be transmitted to adjacent structures. For most rubber tired transit systems, this groundborne vibration is negligible. In many rail transit systems, especially those systems with jointed rails, the noise and the vibration can be highly perceptible. In these situations, vibration isolation of the structure is necessary.

2.5.6 -Emergency Services Access

A key concern in an urban area is the accessibility to buildings adjacent to a guideway by fire or other emergency equipment. Within the confined right-of-way of an urban street, space limitations make this a particularly sensitive concern. In most cases a clearance of about 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.

2.6- Transit Operations

2.6.1 - 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 of the transit system. These concerns often lead to long-term economic, operational, and planning analyses of the design and construction of the transit system.

In most transit operations, a shutdown period between the hours of 1:00 a.m. and 5:00 a.m. (0100 and 0500) can be tolerated; slightly longer shutdowns are possible in certain locations and on holidays. It is during this shutdown period that routine maintenance work is performed.

Many transit systems also perform maintenance during normal operating hours. This practice tends to compromise work productivity and guideway access rules and operations in order to provide a safe working space. The transit operators should provide the engineer with guidelines regarding capital cost objectives and their operation and maintenance plans.

2.6.2 -Special Vehicles

Transit systems frequently employ special vehicles for special tasks, such as, retrieving disabled vehicles and repairing support or steering surfaces. While the design may not be predicated on the use of special vehicles, their frequency of use, weights, and sizes must be considered in the design.

2.6.3 -Expansion of System

Expansion of a transit system can result in substantial disruption and delay to the transit operation while equipment, such as switches, are being installed. In the initial design and layout of a transit system, consideration should be given to future expansion possibilities. When expansion is contemplated within the foreseeable future after construction and the probable expansion points are known, provisions should be incorporated in the initial design and construction phases.

2.7- Structure/Vehicle Interaction

2.7.1- General

Vehicle interaction with the guideway can affect its performance as related to support, steering, power distribution and traction components of the system. It is usually considered in design through specification of serviceability requirements for the structure. In the final design stage close coordination with the vehicle supplier is imperative.

2.7.2- Ride Quality

2.7.2.1- General

Ride quality is influenced to a great degree by the quality of the guideway surface. System specifications usually present ride quality criteria as lateral, vertical and longitudinal accelerations and jerk rates (change in rate of acceleration) as measured inside the vehicle. These specifications must be translated into physical dimensions and surface qualities on the guideway and in the suspension of the vehicle. The two elements that most immediately affect transit vehicle performance are the support surface and steering surface.

2.7.2.2 - Support Surface

The support surface is basically the horizontal surface of the guideway which supports the transit vehicle against the forces of gravity. It influences the vehicle performance by the introduction of random deviations from a theoretically perfect alignment. These deviations are input to the vehicle suspension system. The influence of the support surface on the vehicle is a function of the type of the suspension system, the support medium (e.g., steel wheels or rubber tire), and the speed of the vehicle.

There are three general components of sup-

port surfaces which must be considered. Namely, local roughness, misalignment, and camber. Local roughness is the amount of distortion on the surface from a theoretically true surface. In most transit applications, the criterion of a 1/8-inch (3 mm) maximum deviation from a 10 ft. (3 m) straightedge, as given in ACI 117, is used.

With steel rails, a Federal Railway Administration (FRA) Class 6^{2.2} tolerance is acceptable. The FRA provision include provisions for longitudinal and transverse (roll) tolerances. These tolerances are consistent with operating speeds of up to 50 mph (80 km/h). Above these speeds, stricter tolerance requirements have to be applied.

Vertical misalignment most often occurs when adjacent beam ends meet at a column or other connection. There are two types of misalignment which must be considered. The first, is a physical displacement of adjacent surfaces. This occurs when one beam is installed slightly lower or higher than the adjacent beam. These types of misalignment should be limited to 1/16 in. (1.5 mm) as specified by ACI 117.

The second type of vertical misalignment occurs when there is angular displacement between beams. Such an angular displacement may result from excessive deflection, sag, or camber. Excessive camber or sag creates a discontinuity which imparts a noticeable input to the vehicle suspension system.

In the design and construction of the beams the effects of service load deflection, initial camber and long-time deflections should be considered. There is no clear definition on the amount of angular discontinuity that can be tolerated at a beam joint. However, designs which tend to minimize angular discontinuity generally provide a superior ride. Continuous guideways are particularly beneficial in controlling such misalignment.

Camber or sag in the beam can also affect ride quality. Consistent upward camber in structures with similar span lengths can create a harmonic vibration in the vehicle resulting in a dynamic amplification, especially in continuous structures. When there are no specific deflection or camber criteria cited for a project, the designer should account for these dynamic effects by analytical or simulation techniques. The deflection compatibility requirements between structural elements and station platform edges should be accounted for.

2.7.2.3- Steering Surface

The steering surface provides a horizontal input to the vehicle. The steering surfaces may be either the running rails for a flanged steel-wheel-rail system or the concrete or steel vertical surfaces that are integrated into the guideway struc-

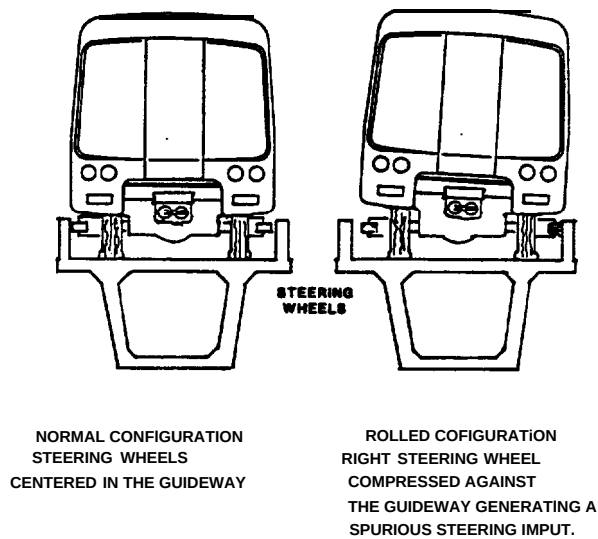


Fig. 2.7.2.3- Interaction between support and steering

ture, for a rubber tired system. The condition of the steering surface is particularly important since few vehicles have sophisticated lateral suspension systems. In most existing guideways, the tolerance of a 1/8 in. (3 mm) deviation from a 10 ft. (3 m) straightedge, specified by ACI-117, corrected for horizontal curvature, has proven to be adequate for rubber tired vehicles operating at 35 mph (56

km/h) or less. In steel-rail systems, an FRA Class 6^{2.2} rail tolerance has generally proven to be satisfactory for speeds up to 70 mph (112 km/h). Other tolerance limits are given in Table 2.7.2.3.

There is a particular interaction between the steering surface and the support surface, which is technology dependent and requires specific consideration by the engineer. This interaction results from a coupling effect which occurs when a vehicle rolls on the primary suspension system, causing the steering mechanism to move up and down (Fig. 2.7.2.3). The degree of this up and down movement is dependent on the steering mechanism which is typically an integral part of the vehicle truck (bogie) system, and the stiffness of the primary suspension which is also within the truck assembly.

Depending upon the relationship between the support and the steering surfaces, and the support and guidance mechanisms of the vehicle (primary, in the case of rubber tired system) a couple can be created between the two, which causes a spurious steering input into the vehicle. There are no general specifications for this condition. The engineer should be aware that this condition can exist and, if there is a significant distance separating the horizontal and vertical contact surfaces, additional tolerance requirements for the finished surfaces have to be imposed. This is in order to reduce the considerable steering input, which can cause over or under steering, which leads to an accelerated wear of components and degraded ride comfort.

Table 2.7.2.3 Track Construction Tolerances

Type and Class of Track	Variations in		Track Alignment Deviation			
	Gage	Cross-level & Sup.	Total		Middle Ordinate 62' (19 m) Cord	
			H	V	H	V
Direct Fixation and Ballasted Main Line	1/8 (3)	1/8 (3)	1/4 (6)	1/4 (6)	1/8 (3)	1/8 (3)
Ballasted Yard and Secondary Lines	+1/4, -1/8 (+6, -3)	1/4 (6)	1/2 (12)	1 (24)	1/8 (3)	1/4 (6)

Notes: -Tolerances are all positive, unless otherwise indicated.

-Dimensions are in inches (mm)

-H=Horizontal. V=Vertical, Sup.=Superelevation

-Total Deviation is measured between the theoretical and the actual alignments at any point along the track.

-Variations from theoretical gage, cross level and superelevation are not to exceed 1/8 in. (3 mm) per 15' -6 (4.7 m) of track.

-The total Deviation in platform areas should be zero towards the platform and 1/4 in (6 mm) away from the platform.

2.7.3 -Traction Surfaces

Transit vehicles derive their traction from the physical contact of the wheels with the concrete or running rail or through an electromagnetic force. In those systems where traction occurs through physical contact with the guideway, specific attention must be given to the traction surface.

In automated transit, the traction between the wheel and the reaction surface is essential to ensure a consistent acceleration and a safe stopping distance between vehicles. It is also important for automatic control functions. The engineer should determine the minimum traction required for the specific technology being employed. If the traction surface is concrete, appropriate aggregates should be provided in the mix design to maintain minimum traction for the working life of the structure.

Operation in freezing rain or snow may also affect traction on the guideway. The engineer should determine the degree of traction maintenance required under all operating conditions. If full maintenance is required, then the engineer should examine methods to mitigate the effects of snow or freezing rain. These mitigating effects may include heating the guideway, enclosing the guideway, or both.

If deicing chemicals are contemplated, proper material selection and protection must be considered. Corrosion protection may require consideration of additional concrete cover, sealants, epoxy-coated reinforcing steel, and special concrete mixes.

2.7.4 -Electrical Power Distribution

There are two components to electrical power distribution: the wayside transmission of power to the vehicle and the primary power distribution to the guideway. The wayside power distribution to the vehicle is normally done through power rails or through an overhead catenary. Provision must be made on the guideway for the mounting of support equipment for the installation of this wayside power.

For systems using steel running rails, where the running rail is used for return current, provisions must also be made to control any stray electrical currents which may cause corrosion in the guideway reinforcement or generate other stray currents in adjacent structures or utilities.

The primary power distribution network associated with a guideway may require several substations along the transit route. Power must be transmitted to the power rails on the guideway structure at various intervals. This is usually done through conduits mounted on or embedded in the guideway structure.

Internal conduits are an acceptable means of

transmitting power; they may be used to route power from the substation to the guideway. However, access to internal conduits is difficult to detail and construct. Sufficient space must be provided within the column-beam connection and within the beam section for the conduit turns; space must also be provided for safe electrical connections. Exterior conduits can detract from the guideway appearance and can cause increased maintenance requirements.

2.7.5 - Special Equipment

A guideway normally carries several pieces of special transit equipment. This equipment may consist of switches, signaling, command and control wiring, or supplemental traction and power devices. The specialty transit supplier should provide the engineer with explicit specifications of special equipments and their spatial restrictions. For example, the placement of signaling cables within a certain distance of the wayside power rails or reinforcing steel may be restricted.

The transit supplier should also provide the engineer with the forces and fatigue requirements of any special equipment so that proper connections to the structure can be designed and installed. An example of connection requirements would be linear induction motor reaction rail attachments.

When no system supplier has been selected, the engineer must provide for the anticipated services and equipment. In this instance, a survey of the needs of potential suppliers for the specific application may be required prior to design.

2.8- Geometries

2.8.1 - General

The geometric alignment of the transit line can have a substantial impact on the cost of the system. Standardization of the guideway components can lead to cost savings. During the planning and design stages of the transit system, the benefits of standardizing the structural elements, in terms of ease and time of construction and maintenance, should be examined and the effective options implemented.

2.8.2 -Standardization

Straight guideway can be produced at a lower cost than curved guideway. Geometric alignments and column locations that yield a large number of straight beams tend to be cost-effective. Physical constraints at the ground influence column locations. However, when choices are available, the placement of columns to generate straight beams, as opposed to those with a slight horizontal or vertical curvature, will usually prove to be more