APTA STANDARDS DEVELOPMENT PROGRAM
GUIDELINE
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APTA Streetcar Subcommittee Work Group

Modern Streetcar Vehicle Guideline

Abstract: This document provides guidelines to support specification and procurement of modern streetcar vehicles by identifying and describing important technical and operating principles relating to their application.

Keywords: modern streetcar, light rail, low-floor vehicle

Summary: Modern light rail and streetcar vehicles are fundamentally very similar, the differences having largely to do with how they are applied. The primary difference between the two modes is the degree of integration into the urban environment and the scale of the associated infrastructure. This difference in application makes some common light rail vehicle design features unnecessary for streetcar application but may also require the use of other features that may or may not be incorporated into a typical light rail vehicle.

The Guideline includes an introduction and four chapters: Vehicle Configuration, Vehicle/Platform Interface, Vehicle/Track Interface and Power Supply. Recognizing that streetcar systems vary considerably in form and function, the document identifies and explains the underlying principles and interdependencies associated with each topic, and examines the trade-offs involved in various different design approaches. Throughout, emphasis is placed on the need to treat vehicles, infrastructure and operations as an integrated *system*.

Scope and purpose: The purpose of this Guideline is to facilitate the successful introduction of modern streetcar vehicles into North American systems by promoting understanding of the core technical and operational issues. From this understanding, agencies will be able to better navigate the process of specifying a vehicle and designing compatible infrastructure.

The document is intended to provide guidance to planners, transit agencies, local governments and others interested in developing new streetcar systems or enhancing existing streetcar systems using low-floor modern streetcar vehicles. High-floor vehicles and heritage streetcars fall outside the scope of this document, although many of the same technical and operating fundamentals also apply.

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INTRODUCTION

Although the vehicle is naturally a major focus of any streetcar operation, in reality it is only one of several key sub-systems, all of which must function together as an integrated system. Recognizing that the early phases of project design involve key infrastructure decisions that will ultimately impact the vehicle, this Introduction provides an overview of vehicle information from the perspective of the planner evaluating alignment alternatives. The four chapters that follow then look in-depth at the underlying technical and operating principles that will ultimately drive vehicle selection.

Streetcar and light rail systems (often defined collectively as "tramways" in Europe) operate in more than 400 cities throughout the world, with systems varying considerably in form and function, as well as regulatory requirements. While streetcars are often thought of in the urban circulator context here in the U.S., they can also be deployed in a "rapid streetcar" mode that speeds service by using less frequent stops and traffic separation / priority, or even as a precursor to a full light rail system. Partial inter-operation with an otherwise separate light rail system is also possible.

At present in North America, the modern streetcar can also vary a great deal from other modes in terms of the institutions involved. Given their potential value as an urban development tool, modern streetcar projects are currently being advanced by numerous different types of organizations, including some who do not have a great deal of experience with transit operations, delivering major capital projects, or which have a core function that is very different from a traditional transit authority. These include city governments, business improvement districts, non-profits and other non-traditional projects sponsors. Worldwide, project delivery methods are also changing, potentially impacting how vehicles are sourced. While this further illustrates the diversity and potential flexibility of the mode, it also highlights the importance of ensuring that streetcar systems live up to their potential in terms of their core transit functionality.

Since the advent of modern low-floor vehicle technology in 1984, more than 8,000 low-floor streetcar / light rail / tramway vehicles have been ordered, (1,400 in North America). Given the wide range of applications worldwide, vehicle requirements vary substantially, as do the opinions of different cities about the desired "look" of their vehicles. Carbuilders (of which there are a relatively limited number) have responded by developing modular product lines that permit multiple vehicle configurations and visual design elements based around standardized vehicle "platforms." Within these modular product families, customers can select from a catalog of "standard" options to tailor the vehicles to their system. These standard options typically include the number of vehicle "modules" (and thus overall length and capacity), the number and location of doors, a choice among three standard widths, varying interior appointments, vehicle end styling, and interior and exterior color schemes. By selecting options from within a standard product range, vehicle costs and delivery times can be reduced while still providing an individual identity for the vehicles in each city.

As a starting point for vehicle selection on a new system, this Guideline document explores the important technical and operating issues that will become decision points for local project development. Given the industry's use of modular vehicle "platforms", consideration is also given to identifying the dividing line between "standard" and "custom" for different vehicle characteristics. While there are many possible variations on the streetcar vehicle concept, the standard products available in the marketplace tend to fall within certain basic ranges. Rather than starting from scratch on each project, the selection process should first look at the basic ranges of vehicle configuration and performance characteristics. That said, it is also noted that legacy systems exist throughout the world which, because of the requirement for compatibility with existing vehicle fleets and infrastructure, routinely purchase vehicles that fall outside these standard ranges. Such systems tend to purchase vehicles in relatively large numbers, absorbing the extra costs associated with vehicle customization[1]. Smaller "startup" systems typically purchase vehicles in smaller quantities (<12 vehicles) where major customization is not likely to be economically feasible.

A major objective of this Guideline is to assist the planner of a new system in making decisions from a *systems* perspective, by explaining the relationship between the vehicle and other elements of the streetcar infrastructure. Although the vehicle is naturally a major focus of any streetcar operation, in reality it is only one of several key sub-systems which must all function together as an integrated system. These relationships are critical to understanding the implications of planning decisions, particularly with regard to determining where it would normally be preferable to impose requirements on the infrastructure rather than the vehicle, and vice-versa.

A streetcar system is a major investment that demands skillful planning. The process of selecting a viable alignment for a new system involves balancing the many factors related to effectively serving a corridor's transit needs, without being too costly in either initial investment and / or operating cost. Transit needs to go to places where people want to go; consequently the urban nature of streetcar alignments often demand the use of sharper curves and steeper gradients than a typical light rail system. Because of the inherent flexibility of the light rail/streetcar mode, it is *possible* to operate over extremely demanding alignments in terms of curvature and gradient. However, minimizing the use of such extremes brings numerous benefits in terms of passenger comfort, higher operating speeds, lower operating costs and the ability to purchase "standard" vehicles from multiple suppliers. The art of system design lies in the effective balancing of these often conflicting demands.

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Designers are advised to apply design minimums and maximums thoughtfully, and in the context of a *system* approach that considers the vehicles to be used and balances operational benefits with the related tradeoffs. For example, a short steep grade or sharp curve that allows an alignment to access a major source of ridership, or which might eliminate the need for an expensive infrastructure component such as a tunnel or flyover, could justify the associated trade-offs. At the other end of the spectrum, an alignment could become too flexible. If trying to please too many constituencies results in a circuitous route that offers poor connectivity to other transit services and is vulnerable to congestion, operating speeds and service reliability will suffer, potentially burdening the line with low ridership and high operating costs.

The Guideline seeks to help users understand the inherent trade-offs and take a balanced approach to design. For example; sharp horizontal curves are a trade-off with long-term costs for track and wheel maintenance as well as noise, operating speed and passenger comfort, and compatibility with standard vehicle designs. Overly broad curvature is a trade-off with space requirements / urban fit, potentially precluding certain alignment options or creating "corner clips" that could necessitate property acquisition. Steep gradients are a trade-off with vehicle cost, operating speed and maintenance costs. Overly-conservative gradient criteria may rule out

[1] The City of Toronto, Canada, North America's largest streetcar system, is in the process of replacing its entire vehicle fleet. 204 new low-floor vehicles are being built to a custom design that accommodates this legacy system's unique infrastructure, including extremes of horizontal curvature (11 m) and gradient (8 percent).

certain otherwise beneficial alignment options. Above all, whether an existing system introducing new vehicles, or a new start, a *system* approach is required; the parties responsible for vehicles and for infrastructure (especially track design) must be working in concert to produce optimum compatibility.

Table A - Recognizing the need for some level of detail on the vehicle during the early phases of project design, Table A suggests some baseline vehicle assumptions for initial planning purposes. As design progresses, all of these areas will need to be developed in greater detail, but these assumptions can be used as an initial starting point during early project development. These suggestions are given with the caveat that in all cases engineering judgment, guided by an interdisciplinary systems approach and considering project and site-specific information, should govern, not arbitrary guidelines.

Table A: Representative vehicle description for initial project development

Characteristic	Typical assumption for initial planning purposes	Guideline Section
Configuration	Double-ended, double-sided vehicle	1.6
Width	Narrow (2.4 m) or wide (2.65 m)	1.4
Length	Between 66 and 99 feet (20 and 30 m), depending on desired vehicle capacity	1.3.1
Multiple Unit (MU) capability	Typically single-unit operation for streetcar, MU for light rail	1.3
Vehicle floor height	Typically 14 inches (355 mm) at door thresholds in low floor section	2.3.3
Operating voltage / current collection	750VDC, OCS power distribution with pantograph on vehicle	4.1
Minimum turning radius	59 feet (18 m) or 66 feet (20 m) for streetcar, 82 feet (25 m) for light rail)	3.1.1
Maximum sustained grade	Varies depending on local conditions ; typical "fatal flaw" screening criteria applied to alignment alternatives are: • ≤ 6% sustained- acceptable, subject to review of duty cycle • > 6% - ≤ 9% sustained- further evaluation required, may be acceptable if all other screening criteria are met • > 9% sustained- eliminated	3.1.2
Minimum vertical clearance	Typically 14 feet (4.27 m)	4.1
Fare collection	Off-vehicle and/or on-board ticket machines (no operator intervention)	1.4.3.3

Table B examines a complete range of project design criteria for a new system and how they relate to vehicle capabilities. It prioritizes the decisions which are typically needed during the early phases of project design using a simple color code; red for most relevant during early design, followed in descending order of importance by yellow and green for decisions which will be resolved later in the design process. Ranges of "standard" vehicle capabilities are noted so that they may be used to inform screening of project alternatives, helping identify areas where it would normally be preferable to impose requirements on the infrastructure rather than the vehicle. References to the relevant sections of the Guideline are also included.

Table B: Alignment design- early planning considerations / impacts on vehicle configuration

Chart highlights range of significance during early project planning from red (1) "most important" to green (3) "less important". AA=alternatives analysis

Alignment Considerations		AA	Influence on Vehicle Selection	Guideline Section
Shared Use (crossing or shared track / R-O-W with mainline / heavy rail)	Red Flag- Major project impacts!	1	Significant regulatory hurdles, may impact vehicle design. Note: entirely different issue than light rail/streetcar interoperation or crossing (which is fairly common).	Introduction
Lane Selection	Curb lane, middle lane, median	1.5	Very important project design criteria but influence on vehicle is limited assuming double-sided vehicles are used. Also related to turning radius.	3.1.1 Turning radius and urban fit. (Fig. 30-31)
Horizontal Curvature (Turning Radius)	Look for extraordinary cases; will inform screening of alignment alternatives	1	Below 18 m, vehicles options are narrowed considerably. Turning radius is also a trade-off with space requirements, operating speed, noise, wheel and rail wear. Also impacts interoperability with LRT (where applicable).	3.1.1 Turning radius and urban fit
Gradient		2	Above 7% (typical) sustained, may narrow vehicle choices. Above 9% sustained route may be infeasible. Will also influence traction power requirements. Also a trade-off with operating speed and long-term operating / maintenance costs.	3.1.2.1 Grade abilities ("gradability")
Vertical Curvature		2	Variation between vehicles is not significant. Minimum limits are workable, but smaller radii may eliminate some alignment alternatives from consideration	3.1.2.2 Vertical curves
Horizontal Clearance		2	11' traffic lane width or better typically required. Lane width influences selection of vehicle width.	1.4.2 Lane widths / urban fit
Vertical Clearance		2	Variation between vehicles is not significant. Min / max limits are workable, but exceeding them may eliminate some alignment alternatives from consideration. Typical minimum vertical clearance is 14 feet (4.3 m).	4.2 Operating voltage & current collection
Pavement Cross-Slope		2	Track twist is a significant issue for low-floor vehicles in general; may be some further variation between different vehicles. Maximum limits are workable, but exceeding them may eliminate some alignment alternatives from consideration	3.2.3 Track twist and wheel unloading
Block Length / Urban Blending	Streetcar is typically low-impact	3	Minor or no impacts for 20m (66 ft.) - 30m (98 ft.) long streetcars. Streetcars available in different lengths, but do not approach multi-car light rail "train" lengths.	1.3.1 Vehicle length

Operational Considerations		AA	Influence on Vehicle Selection	Guideline Section
Vehicle / System Capacity	How many vehicles, and what width/length?	1	Capacity requirements drive vehicle length, width, ratio of seating to standing space, and number of vehicles required	1.3 Capacity
Stop Spacing	Define based on route	2	Accurately defining duty cycle is important in all cases. Number of stops per mile (including passenger stops and stops due to traffic control) and dwell times will impact vehicle propulsion system.	1.1. Duty cycle
Climatic Conditions	Extreme climate conditions will influence certain aspects of vehicle	2	Accurately defining duty cycle is important in all cases. Extreme climate conditions combined with in-street operation will influence certain aspects of vehicle including HVAC.	1.1. Duty cycle, 1.2.8 Street operation environmental considerations
R-O-W Type	Mixed traffic, segregated lanes, reserved R-O-W, traffic priority	3	Important project design criteria but influence on vehicle limited to vehicle capacity (length) and fleet size (faster schedule speed can reduce required fleet size).	1.3 Capacity
Acceleration / Deceleration Rates	Assume standard rates unless extraordinary case	3	Rates don't vary much between streetcar / light rail. Streetcar propulsion system may be optimized for mixed traffic (start/stop) operations. Accurately defining duty cycle is important in all cases	1.1. Duty cycle
Terminal Arrangements	Assume double-ended vehicles	3	New streetcar systems use double-ended, double-sided vehicles almost universally	1.6 Single versus double-ended vehicles
Stop Considerations		**AA**	Influence on Vehicle Selection	Guideline Section
Platform Height / Accessibility	Near-level or fully-level boarding?	1	Vehicle load-leveling function required for fully-level boarding (may narrow vehicle choices), bridgeplates required for near-level boarding.	2.3.3 Platform height and accessibility. See also Tables 1 and 2
Sharing w/ Buses?	More practical with near-level platforms instead of fully-level	1	Sharing stops with buses requires near-level boarding (lower platform), or other special measures	2.6 Streetcar and bus sharing a platform
Stop Length	Partial or full-length platforms?	2	Related to choice of vehicle length and door locations.	2.3.3 Platform length
Platform offset from track	Determined by vehicle width	2	Determined by vehicle width (either narrow 2.4 m or wide 2.65 m). Sets standard for future system expansion (and any interoperation with light rail).	2.3.1 Platform offset from track
Stop Location	Near side, far side, mid-block	3	Important operational issue, but influence on vehicle is limited	

Stop Side	Is all boarding on one side of vehicle, or are there a mix of platform locations?	3	New streetcar systems use double-ended, double-sided vehicles almost universally so they can serve a mix of right- and left-side platforms	1.6 Single versus double-ended vehicles
Fare Collection	Assume operator not involved with fare collection	3	Low-floor vehicles are designed for use with a fare collection system that does not involve the operator, maximizing benefits of multiple low-floor doorways (reducing dwell time).	1.4.3.3 Fare collection
Power Supply Considerations		**AA**	Influence on Vehicle Selection	Guideline Section
Off-Wire Capability	Detailed analysis required	1	Individual solution must be applied based on thorough analysis of local physical and operating conditions. May narrow vehicle choices and impose proprietary technology.	4.4 Off-wire capability
Ground Level Power System	Detailed analysis required	1	Individual solution must be applied based on thorough analysis of local physical and operating conditions. May narrow vehicle choices and impose proprietary technology.	4.5 Ground-level power systems
Power Collection	Assume pantograph	3	Pantograph used universally on new streetcar / LRT systems (OCS can be designed to accommodate both pantographs and trolley poles if it is desired to also have some heritage vehicle operations)	4.2 Operating voltage & current collection
Operating Voltage	Assume 750 VDC unless region already using another voltage	3	750 VDC most common for new systems, unless in a region with other rail transit that has another operating voltage. Having a common voltage within region can have important benefits.	4.2 Operating voltage & current collection
Other Considerations		**AA**	Influence on Vehicle Selection	Guideline Section
Operations & Maintenance Facility	How much space is needed for the O&M facility? How will wheel truing be performed?	2	Basic facility requirements similar for all low-floor vehicle types. Facility size / layout determined by vehicle length and number of vehicles in fleet. Plan needed for how wheel truing will be done.	1.3.1 Vehicle length, 3.2.4 Running gear maintenance
Vehicle Aesthetics	Modular vehicle families provide for custom styling	3	Common industry issue, most carbuilders offer a modular vehicle family with range of styling options.	1.0 Vehicle configuration

CHAPTER 1: VEHICLE CONFIGURATION

1.0 Introduction

Streetcar and light rail systems operate in more than 400 cities throughout the world, with systems varying considerably in form and function, as well as regulatory requirements. Consequently, vehicle requirements vary as well, as do the opinions of different cities about the desired "look" and overall aesthetics of their vehicles. In Europe, the major carbuilders have responded by developing modular product lines that permit multiple vehicle configurations and visual design elements based around standardized vehicle "platforms." Within these modular product families, customers can select from a catalog of "standard" options to tailor the vehicles to their system. These standard options typically include the number of vehicle "modules" (and thus overall length and capacity), the number and location of doors, a choice of three standard widths, varying interior appointments, vehicle end styling, and interior and exterior color schemes. By selecting options from within a standard product range, vehicle costs and delivery times are reduced, while still providing an individual identity for the vehicles in each city.

To a certain extent, this same approach has also been applied to vehicles in the U.S. market; however lower overall market volume has tended to limit the number of different "standard options" offered. At the other end of the spectrum, cities with legacy streetcar systems are often required to purchase custom vehicles in order to maintain compatibility with existing infrastructure or vehicle fleets. These systems typically order vehicles in larger quantities, absorbing the extra engineering costs associated with customization.

An overview of vehicles currently offered to the North American market can be found in the on-line Carbuilder Survey (see Appendix 1). All are multi-section, articulated, low-floor vehicles, further classified as either partial or 100 percent low floor[2]. These vehicles are all derived from designs developed in Europe and Japan. High-floor vehicles are still used on many light rail systems but are considered to be outside the scope of this document.

1.1 Duty Cycle

The initial step in determining vehicle configuration is to understand how the vehicle will be used; taking into consideration the physical characteristics of the alignment and the operating plan (collectively describing the vehicle's "duty cycle"). Because streetcars operate primarily in-street and move with traffic, their duty cycle will typically include a high percentage of slow-speed, start-and-stop operations. The vehicle's ability to meet such requirements is a function of the thermal limits of the propulsion and braking systems.

Traditionally, the key factor in assessing duty cycle is the number of stops per mile and their duration (dwell time), including passenger stops and stops due to traffic control systems. While all streetcar vehicles can be expected to meet certain minimum performance requirements and propulsion equipment can be specifically designed to be run at higher-than-normal levels for short periods, local conditions must always be carefully considered. Changing the performance characteristics of established vehicle designs is expensive; the art is in designing a viable system within the range of performance characteristics of the readily available vehicle product lines. Most importantly, throughout the design process, vehicle and infrastructure must be treated as a system, not addressed in isolation.

[2] Some single-unit vehicles with short low-floor sections have also been developed in Eastern Europe, but none are presently in use in Western Europe or North America.

GUIDANCE: DEFINING DUTY CYCLE

It is important that the agency thoroughly understands the duty cycle for both its existing / first phase and future streetcar lines, and that it clearly communicates this information in the vehicle procurement process. The duty cycle should be defined as specifically as possible, and the vehicle supplier required to confirm satisfactory operation over the entire alignment. It is especially important to identify any exceptional conditions imposed by climate, infrastructure, or operations, including conditions which might restrict vehicle dimensions or speed. A suggested duty cycle "checklist" is provided below, and this information would typically be incorporated into the system's design criteria document.

Alignment definition. Detailed descriptions of both initial operating segment (or existing system) as well as proposed future alignments. Where detailed information is not available for future alignments, basic system design standards for these alignments (e.g., maximum gradient, stops per mile, minimum curvature) should still be provided. The alignment definition should include:

- Track plan and profile, with all stop locations (passenger stops and stops due to traffic control) over all main tracks, as well as any yard and maintenance/storage facility trackage. This should include length and severity of all gradients, and horizontal and vertical curves, over all trackage.
- Operating plan, including hours of operation and frequency of service (headways), including identification of any peak periods, planned running time, dwell times at stops and estimated passenger loadings, as well as any local speed limits. Planned annual vehicle mileage should also be included.
- Traction electrification standards, including nominal, minimum and maximum line voltage, and details of any regenerative braking operations. Any requirements for off-wire capabilities must also be clearly stated.
- Track maintenance standards.
- Any requirements to interface with an existing vehicle fleet.

Climatic conditions. Providing detailed information on local climatic conditions[3] is also essential to ensure that vehicle subsystems operate satisfactorily under all expected conditions. These include yearly min/max values for temperature, humidity, precipitation, (rain, snow, ice) and winds.

1.2 Optimizing the Vehicle for the Streetcar Operating Environment

Modern light rail and streetcar vehicles are fundamentally very similar, the differences having largely to do with how they are applied. The primary difference between the two modes is the degree of integration into the urban environment and the scale of the associated infrastructure. This difference in application makes some common LRV design features unnecessary for streetcar application, but may also require the use of other features that may or may not be incorporated into a typical light rail vehicle. See also Section 3.1.1 "Turning Radius and Urban Fit."

[3] As a resource, detailed climatological design information can be found in publications such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers' "ASHRAE Handbook—Fundamentals."

GUIDANCE: OPTIMIZING THE VEHICLE FOR THE STREETCAR OPERATING ENVIRONMENT

Streetcar systems operate predominantly on in-street alignments (though not always in mixed traffic) using line-of-sight operating principles. In addition to having a vehicle that is appropriately suited for the alignment geometry and duty cycle of a particular operation, the design characteristics outlined in Subsections 1.2.1 through 1.2.8 are important to ensure that the vehicle is well matched to the streetcar operating environment.

Attention is also called to the subject of incorporating any owner-supplied/specified equipment, such as fare collection or communication and other intelligent transportation systems (ITS) equipment. It is recommended that detailed information about the requirements for integrating any owner-supplied/specified equipment be incorporated into the vehicle procurement process from the beginning instead of being treated as a change order or an after-purchase retrofit.

1.2.1 Leading-End Design

Recognizing the urban nature of light rail transit in its many forms, significant research has been conducted in the past decade on improving collision safety for both light rail vehicle occupants and for other roadway users. Important new standards for structural safety, such as ASME RT-1, include content that addresses the safety of occupants in motor vehicles that might be struck by a light rail vehicle or streetcar by addressing vehicle leading-end design.

In addition to having a leading-end design that provides the operator with unobstructed forward and side vision, the streetcar ends and sides should be free of sharp edges and continuously skirted, designed to deflect objects and people who may come into contact with the vehicle and stop them from passing underneath. Couplers, if used, should not protrude beyond the end of the carbody. The leading-end and bumper design should at a minimum comply with ASME RT-1, Section 3.2, “LRV and Streetcar Leading-End Design for Protection of Street Vehicles.”

Skirting arrangement may vary depending on alignment curvature. Operating a given vehicle at its minimum turning radius may require a modified approach to side and truck skirting in order to permit the vehicle to navigate these turns (for example, by attaching a portion of the skirting to the trucks instead of to the carbody). Skirting should also not impede normal vehicle maintenance or access to equipment, and should allow for abnormal operating conditions, such as instances in which trucks are rotated beyond their normal range as in a switch-splitting incident. Skirting should deform to suit without causing deformation of any body structure.

1.2.2 Breakdown Provisions / Failure Management

As part of their required operational and system safety plans, streetcar systems should “plan for the unplanned” by having detailed procedures for managing vehicle faults that develop “on the road.” Failure management procedures typically seek to minimize service disruption by distinguishing between different levels of faults and the resulting restrictions on continued operation, ranging from a minor fault that can be addressed after the vehicle completes its normal service day, to severe vehicle impairment requiring towing by another vehicle. It is also important to recognize that appropriate operational provisions must be included in the design of the streetcar infrastructure. These typically include cross-overs (or other turnback provisions) and storage tracks at appropriate locations.

In general, vehicles are designed with redundant systems to enable them to continue operating (with appropriate restrictions) in a degraded mode in order to minimize the need for towing. However, towing a disabled streetcar is sometimes necessary and is typically performed by a following streetcar pushing it to a location where it will not interfere with operations, and ultimately back to the appropriate facility for repairs. Failure management planning should include worst-case scenarios such as the need to first re-rail a derailed vehicle, as well as other major failure scenarios such as the need to move a vehicle with a seized axle / bearing. Recovery moves are normally made without passengers on board either vehicle.

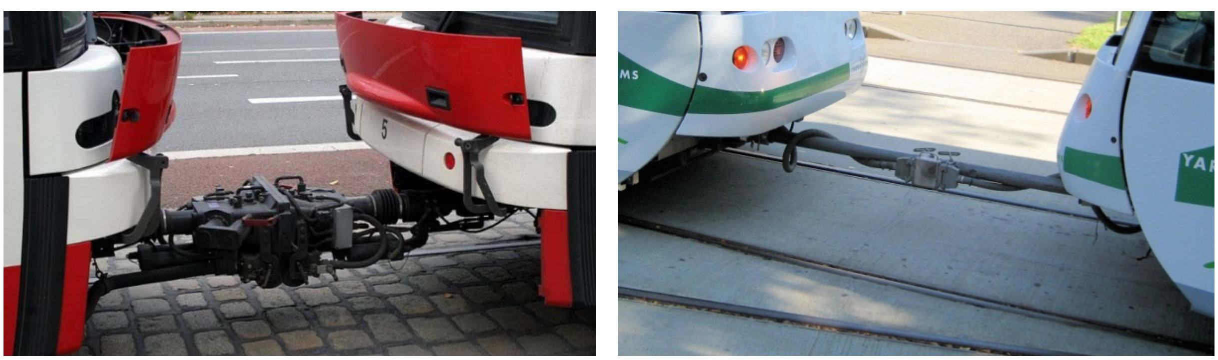
The towing procedure (whether pushing or pulling) should provide for the operator in the cab of the disabled vehicle to be in continuous communication with the operator of the recovery vehicle, and for either operator to be able to initiate an emergency stop. Safety can be further enhanced by having stoplights, turn signal indications and audible warnings linked between the two vehicles. Rubber-tired and "hi-rail" recovery vehicles are also used in some cities, equipped with appropriate tow gear/couplers. While the towing process is relatively straightforward on level, tangent, paved trackage, curves and grades can present significant challenges. For these reasons, pushing or towing with another suitable streetcar is the preferred method.

The towing procedure (whether using another streetcar or some other type of vehicle) should also include a means of controlling the brakes on the streetcar under tow if they are operable. If the brakes on the disabled streetcar cannot be operated, the brakes of the assisting vehicle should be such as to enable it to haul and to control the disabled streetcar under all conditions. The recovery procedure should limit the speed at which such moves are made.

Unless configured for multiple-unit operation, streetcars typically employ a retractable or removable tow bar provision rather than full couplers (see **Figure 1-1**). Regardless of whether a tow bar or full couplers are used, during normal operation they should not protrude beyond the carbody, and the vehicle ends should be continuously skirted. Couplers or tow bar equipment should be suitable for both pushing *and* pulling a disabled vehicle over any section of the alignment with no interference between the couplers/tow bar and car structure/skirting. A typical design criteria requirement would be that one vehicle, either empty or loaded, be capable of pushing / pulling another fully loaded disabled vehicle over any portion of the alignment without damage to any subsystems or engagement / deformation of the Crash Energy Management system components. Consideration must also be given to ease of field operation (removal of skirting, unfolding or placement of tow bar, coupling) including the necessity to couple vehicles on curves.

FIGURE 1-1

Couplers vs. Towbars



Claudia Wolf

Full couplers (retractable type, with movable carbody skirt) in Dortmund, Germany.

Portable tow bar in use between two Melbourne, Australia, trams.

1.2.3 Forward and Side Visibility

Vehicle leading-end design, including structural elements incorporated into the windshield area, should not unduly obstruct the operator's forward and side vision[4]. Mirrors or rear-view cameras should be provided to give the operator a rearward-facing view along both body sides. Mirrors may also be used to supplement the operator's view of the area immediately in front of the vehicle.

At stops: The operator should be able to clearly observe passengers boarding and alighting, to confirm before starting that no passenger has been trapped by a closed door and that all pedestrians are adequately clear of the vehicle, including the areas immediately in front of the vehicle and at both front corners.

While in motion: The operator should be able to observe traffic on either side of the streetcar, especially with regard to under- or overtaking vehicles, where the streetcar turns or otherwise crosses lanes of traffic.

Rear-vision devices should be placed so that they are easily visible to the operator from his or her normal position, without the need to unduly divert attention from the road ahead. From within the cab, the operator should be able to adjust the position or angle of any rear-view mirrors. The images presented to the operator should not be unduly affected by darkness, glare, low-angled sun or prevailing weather conditions (e.g., rain in dark conditions). Where double-ended vehicles are employed in winter climates, the viewing devices at the rear end should be protected from snow and ice buildup so that they will be fully useable after an end-change is made.

The height of the mirrors or cameras relative to pedestrians, and in particular those standing on streetcar stop platforms, should be considered carefully so as to obtain the best compromise between visibility to the streetcar operator and the risks of pedestrians standing close to the platform edge being struck by them.

1.2.4 External Lighting

The streetcar should be equipped with lighting that is in compliance with applicable local regulations and that is appropriate for all the environments in which it operates (e.g., operating both in-street in mixed traffic and off-street on unlit sections of reserved right-of-way). The vehicle's external lights are generally required to be lit at all times when the vehicle is in service, i.e. in daytime as well as nighttime.

At a minimum, streetcars are typically equipped with headlights, rear marker (tail) lights, turn signals (incorporating a "hazard" flasher function), as well as stop (brake) lights. A cab repeater function is provided to make the operator aware of the status of turn signals and headlights. In the absence of superseding local regulations, Table I "Required Motor Vehicle Lighting Equipment Other Than Headlamps" in 49 CFR 571.108 should be consulted for guidance. Doorway lighting is also provided as an aid to boarding and alighting passengers. Legacy systems that have boarding directly from street level may also use supplemental rear-facing warning/hazard lights to alert motorists that doors are open and passengers are boarding / alighting.

Headlights should be arranged so that an oncoming streetcar does not blind other road users. The centrally located (triangle arrangement) railroad headlight found on a typical U.S. light rail vehicle generally is not required for use on in-street streetcar alignments. Where the alignment may also have gated crossings, the use of the triangle lighting arrangement is recommended.

[4] The rail transit industry is working to codify requirements for cab design and visibility. Documents which specifically address the visibility issue include the German DIN Standard 5566-3 "Driver Cabs, Part 3, Additional Requirements for Urban and Suburban Rolling Stock", and the French STRMTG Standard "Ergonomie des Postes de Conduite des Tramways", Version 2, December 2012.

1.2.5 Audible Warnings

Streetcars should be fitted with one or more adequate audible warning devices at each operating end in compliance with applicable local regulations. The warning emitted should be in keeping with the environment in which the streetcar runs. The warning should be loud enough to indicate the approach of a streetcar without causing undue alarm to those in the proximity.

The warning device(s) should have two levels of sound:

- **The lesser level,** for use on-street to alert people of the streetcar's presence, should produce a sound that is distinctive compared with that emitted by other road vehicles. Streetcars have traditionally employed a bell known as a "gong" (either electronic or electromechanical), which can be rung at different rates depending on how rapidly the operating pedal or button is depressed. A horn similar to those of buses or cars would not normally be considered suitable for this function.

- **The greater sound level,** for use in emergencies and in off-street operation, should be appropriate for the operating environment and speed. A horn is typically used for this function.

1.2.6 Stop Request

Where stops are made "on demand," a streetcar requires a passenger stop request system similar in function to a transit bus. Passenger "door open" pushbuttons fitted to the inside of the doors can usually double as stop request buttons. A stop request should be indicated both in the cab and in a prominent position in the passenger compartment(s). Because the streetcar operator will normally be located in an enclosed cab that is physically separated from the passenger compartment, suitable equipment should be provided to permit the passengers and the operator to communicate with one another, and for the operator to observe the interior of the passenger compartment using a camera surveillance system when required[5].

1.2.7 Train-to-Wayside Communication (TWC) / Intelligent Transportation Systems (ITS)

At minimum, a streetcar should be equipped with a system of communication that will permit it to be detected by roadway signal controllers so that the appropriate stage and phase can be called on the road traffic-light signals (which may include some form of traffic signal priority). The system, or a similar one, may also be able to request a specific route at junctions and to actuate powered turnouts as applicable. The system also should be equipped with some means to permit operators on vehicles entering service to confirm that the equipment is in working order.

In rail transit, such a system has traditionally been described as train-to-wayside communication (TWC). However, urban transit vehicles are now using advanced communication technologies to address a far greater range of needs. Intelligent transportation systems (ITS) is an umbrella term used to describe a variety of technologies, treatments and strategies that allow improvements to the operations of transit systems. Systems such as traffic signal priority, automatic passenger counting, passenger information, fare collection, surveillance systems, computer-aided dispatching and others are being integrated under the ITS sphere.

New streetcar systems should consider opportunities to adopt a local transit agency's existing ITS equipment and practices. A video recording capability, for example, may be an especially helpful accident / incident investigation tool, particularly for new systems where other road users are unfamiliar with sharing the roadway with streetcar operations. Equipment designed for bus application (where there is only one operator's position) may, however, require modification to adapt it for use on a double-ended streetcar. It is

[5] Because of the potential for operator distraction, agency policy varies with regard to this issue. On some systems, camera surveillance system images from the passenger compartment are available to the operator only when the vehicle is stopped. On other systems, images are always available, but only on a separate screen located outside the operator's normal field of forward vision. Additional industry study of this issue would be useful.

recommended that detailed information about the requirements for integrating any owner-supplied/specified equipment be incorporated into the vehicle procurement process from the beginning instead of being treated as a change order or after-purchase retrofit.

1.2.8 Street Operation Environmental Considerations

Streetcar vehicles should be designed with full consideration of water and snow issues associated with in-street operation. In climates where winter conditions can be expected, some aspects of vehicle design should be given stronger consideration. The system's operating and maintenance plan will also need to include planning for operations and related maintenance in adverse winter conditions.

Where salt is applied to road surfaces in winter, its corrosive effect on vehicle structural members should be taken into consideration. Underfloor construction that allows salt-laden dirt and slush to accumulate should be avoided or corrosion-resistant materials used. Truck designs should likewise take into account the effects of salt and water accumulation in and on structural members and at interfaces of equipment connected to or resting on truck members.

All underbody areas exposed to splash should be arranged so that salty water cannot wick up into interfaces such as found on side panels and door panels. Streetcar running gear is often equipped with wheel guards in order to minimize wheel splash onto underbody surfaces. Equipment ventilation should be arranged such that snow or other salt-bearing moisture is not ingested into any electrical equipment, including traction motors.

1.3 Capacity

The passenger capacity of a streetcar vehicle is a function of its physical size and interior layout. Streetcar capacity varies widely throughout the world, with a wide range of vehicle lengths available, along with three standard widths. Higher vehicle capacity can be used to lower operating costs, and more room inside the vehicle can also improve accessibility, dwell time and passenger comfort. Multiple unit operation is another option for increasing capacity while maintaining operational flexibility, although due to its added cost and less efficient utilization of station and street length (lost distance for cabs and couplers), the global tramway/streetcar marketplace has moved toward longer vehicles as the prevailing solution.

Overall system capacity is dependent not only on service frequency and vehicle capacity, but also on system operating speeds; a broader set of operating conditions all contribute to delay in getting from one end of the line to the other (stop spacing, fare collection and dwell time, priority/separation from other traffic, etc.). There are thus three basic approaches to adding capacity to a streetcar line; use of longer vehicles, increasing fleet size, and increasing operating speed. Failure to address capacity needs for the medium and long term can create service reliability problems. Crowding exponentially increases dwell time, which can lead to irregular service and reduction in schedule speed. These conditions create additional operating costs and can convey a poor image for the service.

For additional information on capacity concepts and other system operating fundamentals, reference "Urban Transit, Systems and Technology," by Vukan Vuchic (2007), and "Transit Capacity and Quality of Service Manual, Second Edition," TCRP Report 100.

1.3.1 Vehicle Length

Length is the primary determinant of vehicle capacity. Vehicle length varies widely, with market direction in Europe clearly toward vehicles longer than the 66 ft (20 m) length common on the first generation of U.S. modern streetcar systems. The 66 ft (20 m) length represents the short end of the spectrum of modular vehicle lengths (and thus capacity), being only slightly longer than a typical articulated bus, with similar capacity. Streetcar vehicle lengths in the range of 98 ft (30 m) (and in some cases even longer) are more common in other parts of the world, reflecting their use as high-capacity transit. See **Figure 1-2** for an illustration of the range of streetcar lengths now in service worldwide.

1.3.2 Factors to Consider in Selecting Vehicle Length

- **Capacity (both start-up and future):** System planning should address the issue of how capacity will be expanded in the future to accommodate growth in demand. Vehicle capacity can be increased either by adding additional vehicles or by procuring longer vehicles initially, (provided the infrastructure can support their use). A third option is to procure vehicles whose modular design allows additional sections to be added when needed. This approach is logistically complex and would require the procurement to identify this as a specific goal from the outset. Each approach has its advantages and limitations, requiring that the costs and benefits be carefully considered in light of local conditions.

  Increasing fleet size (adding vehicles) is generally the most expensive way to add capacity, given the high cost of vehicles and the fact that labor is the largest component of operating costs. Service frequency must also be considered, so it is recommended that the system planning process consider the capacities of different vehicle lengths, together with frequency and other operational factors, in order to determine how best to meet overall level-of-service goals.

- **Urban fit:** The length of the vehicle impacts its relationship to normal street traffic and the perception of urban form and aesthetics. In motion, the difference between a 66 and 98 ft (20 and 30 m) streetcar vehicle is likely to be negligible. When stopped in traffic, a longer vehicle may present some additional interference with traffic and parking, depending on street geometry (including block length) and other local factors. As vehicle length increases, space for stops must also increase proportionally. Where the streetcar alignment is immediately adjacent to a parking lane and uses bulb-out platforms, platform length can also impact on-street parking, sidewalk configuration, and adjacent land uses. A vehicle's size and configuration (including low-floor percentage) and its overall aesthetics will also play an important role in how the streetcar blends with the urban environment.

  Planners should weigh the potential capacity and operating cost benefits for different vehicle lengths against possible traffic and other impacts. The potential impacts of any local restrictions imposed on roadway vehicle length should also be reviewed, although legal limits on vehicle length typically either do not apply to rail vehicles or are quite liberal. This is due to the fact that the guidance and body articulation of rail vehicles result in a narrow, precise path of travel. Depending on what other forms of rail transport may already be in the area, public perceptions and concerns about vehicle length may also vary.

- **Other impacts:** Low-floor vehicles have little choice but to use roof space to accommodate the majority of vehicle equipment. In a short [66 ft (20 m)] vehicle, it may become challenging to find enough space to accommodate extra equipment, for example for energy storage and higher-capacity HVAC. In some cases, lack of space on the vehicle roof has forced components such as energy storage devices to be relocated into the passenger compartment, impacting interior layout.

  Even if 66 ft (20 m) vehicles are selected for initial startup, design of terminals as well as maintenance and storage facilities should consider the possibility of longer vehicles being needed in the future. Longer vehicles will require longer work areas and additional vehicle lifting apparatus in the maintenance facility, as well as longer turnback and storage tracks.

GUIDANCE: CAPACITY and VEHICLE LENGTH

A priority in the system planning process should be consideration of how system capacity will be expanded in the future to accommodate growth in demand. System capacity is dependent not only on service frequency and vehicle capacity, but also on system operating speeds; a broader set of operating conditions all contribute to delay in getting from one end of the line to the other (stop spacing, fare collection and dwell time, priority/separation from other traffic, etc.). There are thus three basic approaches to adding capacity to a streetcar line; use of longer vehicles, increasing fleet size, and increasing operating speed.

Vehicle capacity can be increased either by adding additional vehicles or by procuring longer vehicles initially, (provided the infrastructure can support their use). A third option is to procure vehicles whose modular design allows additional sections to be added when needed. This approach is logistically complex and would require the procurement to identify this as a specific goal from the outset. Each approach has its advantages and limitations, requiring that the costs and benefits of different vehicle lengths, starting with the baseline minimum vehicle length of 66 ft (20 m), be carefully considered in light of local conditions.

The ability to significantly lower per passenger operating costs by utilizing increased vehicle capacity is one of the key benefits of the rail mode. Depending on frequency and other operational factors, a 66 ft (20 m) long vehicle may be quite adequate for some systems. Longer vehicles make sense where demand is high or is expected to grow significantly, taking advantage of rail's high-capacity features and encouraging ridership growth.

It is important to remember that operating costs are eternal; if the design of a new system "locks in" to using only shorter vehicles, a primary cost justification for investment in rail, i.e. the ability for one vehicle (operator) to carry significantly higher numbers of passengers than other modes, disappears. Given that vehicle life is typically 30 years, this decision should be carefully considered during the system planning process. At a minimum, the future use of longer vehicles should not be precluded in the design of the initial line segment, requiring consideration of the future impacts of longer vehicles on stops, terminals and maintenance/storage facilities.

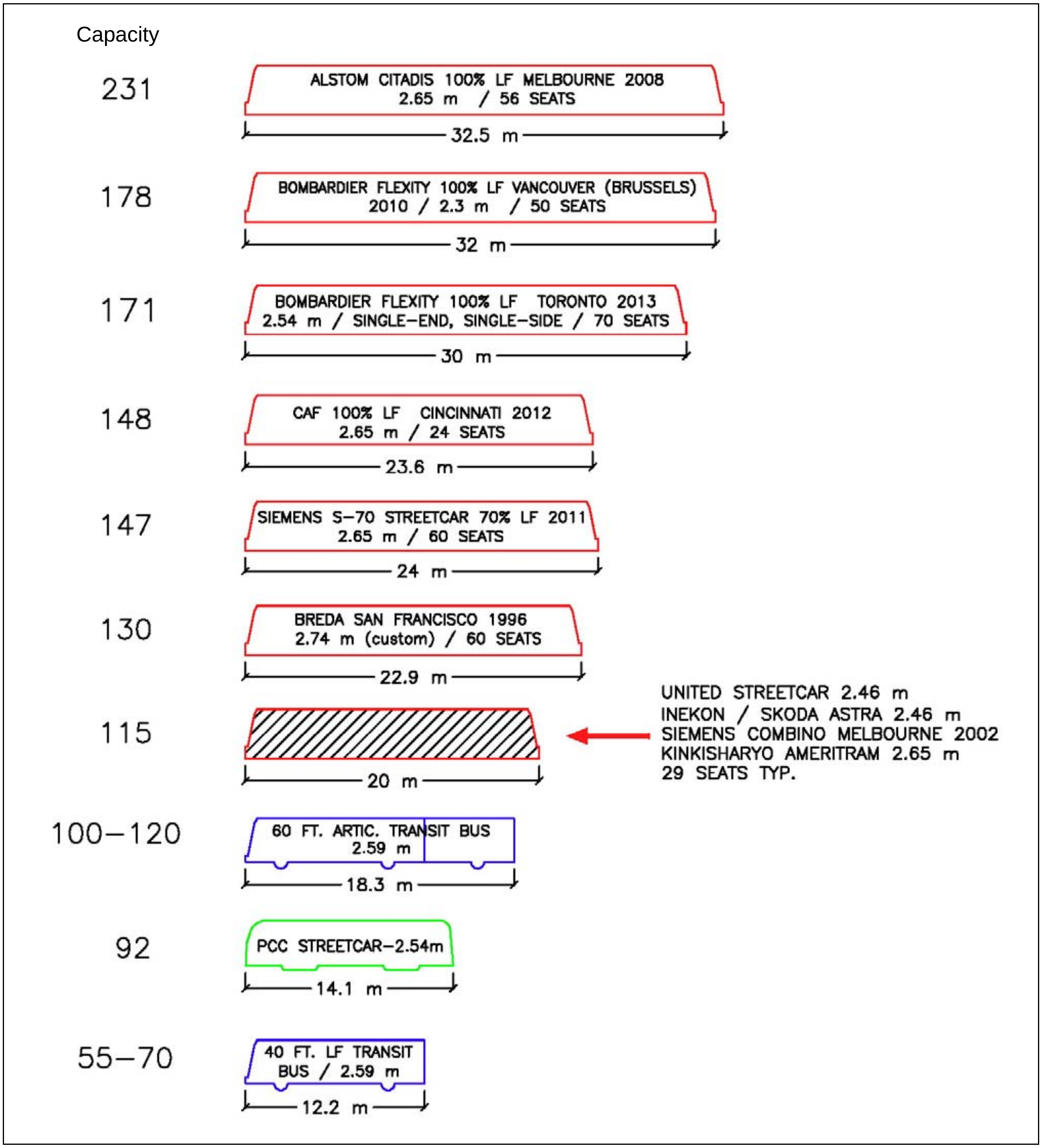
When comparing the capacities of different vehicles, it is also important that the same passenger loading standard is used in order to ensure that a true direct comparison is being made. Use of the standard AW2 loading level (seated load plus four passengers per square meter of suitable standee space[6]) is suggested for use in such comparisons.

[6] "Suitable standee space" includes the aisle and other usable floor space where passengers may normally stand inside the vehicle when all seats are already occupied. Floor space between transverse seats, legroom associated with aisle-facing seats and other areas where passengers do not normally stand should not be included in the standee space calculation. A true direct comparison between vehicles also requires a uniform approach to addressing wheelchair berths, tip-up seats and other space utilization issues. It is recommended that the capacity calculation be based on EN 15663 "Definition of Vehicle Reference Masses", Section 5 "Standing Area Calculation", which uses maximum standee load (standees occupy all wheelchair berths and any areas with tip-up seats).

FIGURE 1-2

Length / Width / Capacity Comparison for Representative Vehicles (even longer vehicles also exist)

Capacity comparison based on seated load plus standing at 4 passengers / m^2 (2.7 ft^2 per standee)



1.4 Vehicle Width and Interior Layout

Vehicle width is an especially important issue for new systems because of its inter-relationship with platform design and interior layout. The system's initial vehicle order/stop design will likely limit future procurements to the same carbody width, so the question should be examined carefully (see Chapter 2, "Vehicle/Platform Interface").

1.4.1 Standard Widths

As the result of many years of standardization work within the European vehicle market, the major carbuilders have developed three "standard" vehicle widths; 7 ft-6.5 in. (2.3 m), 7 ft-10.5 in. (2.4 m) and 8 ft-8.3 in. (2.65 m). (For simplicity's sake, hereafter only the metric figures will be used when referring to these three widths.) Other widths are generally considered to be "custom" orders. The 2.3 m (and sometimes even narrower) vehicle width is offered because it is required by the physical constraints of some legacy systems. Such narrow widths are not typically appropriate for new systems, where wider vehicles can normally be used.

An 8 ft-0.9 in. (2.46 m) vehicle width is also used in the United States, carried over from Czech vehicle designs, which were imported beginning in 2000. It is important to note that all of these widths are maximums over the carbody, not including door threshold extensions or mirrors[7]. Vehicle sides may also be tapered, so the critical dimension when interfacing with a platform is vehicle width at the door threshold extensions. Door threshold extensions will typically protrude several inches beyond the vehicle sides. For these reasons, the small 1.2 in. (30 mm) difference per side between a 2.4 m and a 2.46 m wide vehicle may make little or no practical difference where "near level" boarding is in use. Where fully level boarding is used, a door threshold extension could be employed on a 2.4 m vehicle to make it the same effective width at the doorways as a 2.46 m vehicle.

The majority of new streetcar systems can therefore be served with one of two basic vehicle widths, either a "narrow" (in either the 2.4 m or the 2.46 m variant) or a "wide" vehicle (2.65 m). Use of a non-standard width could impact the availability of competitive bids for future vehicle orders and is strongly discouraged. For systems where future expansion/upgrade/interoperability with light rail is envisaged, the use of 2.65 m wide vehicle may have important interoperability advantages, as this width is used by most U.S. light rail systems. For comparison purposes, a typical U.S. transit bus is 8 ft-6 in. wide (2.59 m), and the standard U.S. PCC streetcar width was 8 ft-4 in. (2.54 m), although the PCC was also offered in wider versions up to 9 ft-0 in. (2.74 m).

1.4.2 Lane Widths / Urban Fit

In choosing vehicle width, local roadway geometry should also be considered. Consult **Figure 1-3** for a visual comparison of cross sections for various lane widths and the most common transit vehicle widths. It is also important to remember that streetcars are not *required* to run in mixed traffic; they often do because there is no viable alternative, but they can also use segregated lanes or other rights-of-way where space may be available. Physical separation from other traffic, along with traffic priority measures, are common methods of improving overall service speed and thus service reliability and system capacity. A system-level perspective is also needed; if, for example, the use of a "narrow" vehicle permitted the alignment to incorporate lanes segregated from other traffic, it might easily justify the small reduction in individual vehicle capacity.

[7] Some streetcar vehicles have convex sides, permitting more room at seat level while restraining width at the door thresholds to fit existing infrastructure originally designed for narrower vehicles.

In all cases, adequate clearance must be provided to allow streetcars to pass each other on adjacent tracks, or between streetcars and other road users in adjacent lanes. The system design criteria document is used to define the vehicle dynamic envelope on both tangent and curved track (refer to Section 3.1.1 "Turning Radius and Urban Fit"). Additional clearances between streetcars and fixed structures should be provided to allow for the presence of pedestrians, cyclists and other road users.

Other horizontal clearance factors should be considered based on the individual alignment to determine the appropriate "buffer" on either side of the vehicle. For example, a parallel parking lane alongside the streetcar lane might require a wider buffer to allow for cars that are not fully parked behind the line, or delivery vehicles with mirrors that may extend over the line. This is particularly true in snowy climates where snow accumulation may shrink the effective width of the parking spaces.

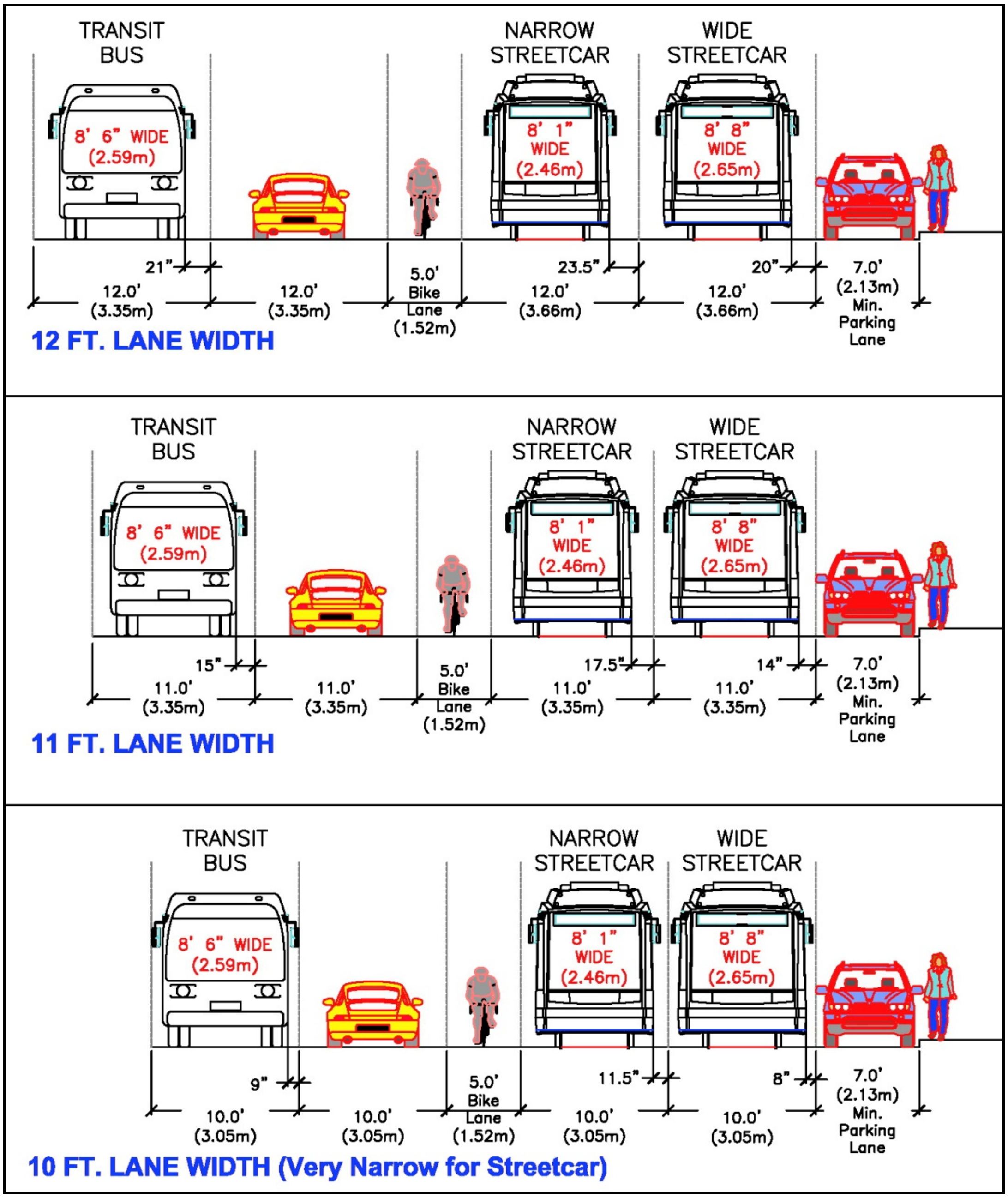
GUIDANCE: VEHICLE WIDTH

Vehicle width is an especially important issue for new systems because the initial vehicle order/stop design will likely limit future expansion to the same carbody width. In selecting vehicle width, capacity and passenger comfort must be balanced with urban fit. Vehicle sides are typically tapered, so the critical dimension when interfacing with a platform is vehicle width at the door thresholds.

The major carbuilders have standardized light rail/streetcar vehicle widths. The majority of new streetcar systems can therefore be served with one of two basic vehicle widths, either a "narrow" (in either 2.4 m or the 2.46 m variant) or a "wide" vehicle (2.65 m). The use of a standard vehicle width will increase the likelihood of competitive bids being available for future vehicle procurements, as well as facilitate future sales of secondhand vehicles.

Both the 2.4 m and 2.65 m standard vehicle widths are commonly used on new tramway, light rail and streetcar systems throughout the world. For systems where future expansion/upgrade/interoperability with light rail is envisaged, the use of 2.65 m wide vehicle may have important interoperability advantages, as this width is used by most U.S. light rail systems. Also in favor of selecting the wider 2.65 m vehicle, the cost differential for the additional vehicle width will typically be inconsequential in comparison with the overall vehicle cost.

FIGURE 1-3
Urban Fit: Streetcars and Lane Widths



Tracks shown centered in lane, but may be offset. Vehicle dimensions are maximum width over static carbody, not including mirrors. For reference, standard U.S. PCC streetcar width was 8 ft-4 in. (2.54 m).

1.4.3 Interior Layout

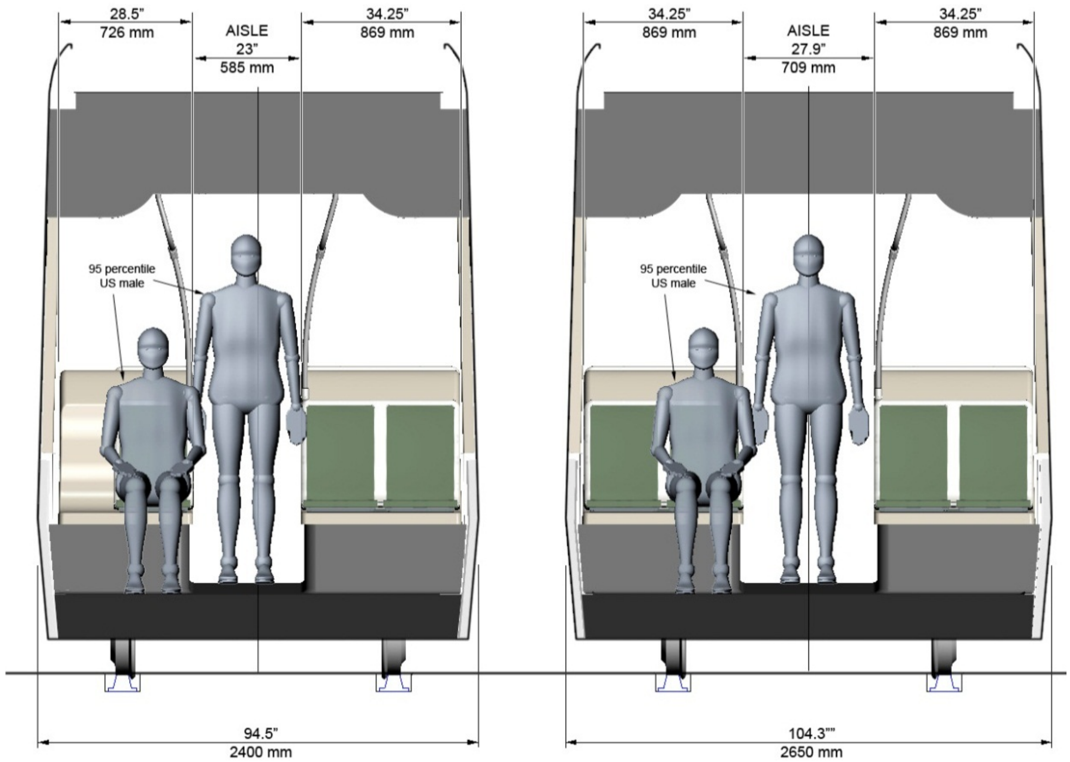
Overall interior layout will be influenced by a mixture of local conditions, accessibility considerations and various constraints associated with an individual vehicle design, as well as the vehicle's width.

1.4.3.1 Ratio of Seating to Standing Space

While seating configuration can generally be readily altered as part of initial vehicle purchase, implementation of 2+2 transverse seating is more practical in a 2.65 m wide vehicle. A 2.4 m wide vehicle can also accommodate 2+2 seating, but at the expense of seat pitch and aisle width. 2.4 m wide vehicles more commonly have 2+1 seating, or transverse seating on one side and longitudinal seating on the other side. See **Figures 1-4 and 1-7** for illustrations of how width impacts aisle width and seat pitch.

FIGURE 1-4

Vehicle Width and Passenger Comfort



Comparison of the 2.4 m (left) and 2.65 m (right) vehicle widths in the low-floor area over the trucks. Note the differences in aisle width and seating arrangement (these dimensions are specific to vehicle type and will vary). Graphics courtesy of Bombardier

A 2+2 seating arrangement throughout the vehicle might not, however, be optimal for streetcar service. Streetcars usually have more standee space than light rail vehicles because trips tend to be shorter, there may be more doorways, and standing is typically more acceptable to passengers. The inherently stable ride of a railed vehicle makes the ride more comfortable for standees, and so it is common to see extra standee room and related accommodations in streetcar applications.

Using floor space for standees can also significantly increase overall capacity over fitting additional seating. Whenever large amounts of open floor space may be incorporated, an adequate number of handholds, whether attached to seats or other parts of the car structure, such as the ceiling, need to be provided. Because four to six standees can occupy every square meter[8] of suitable floor space, this will also present a significantly

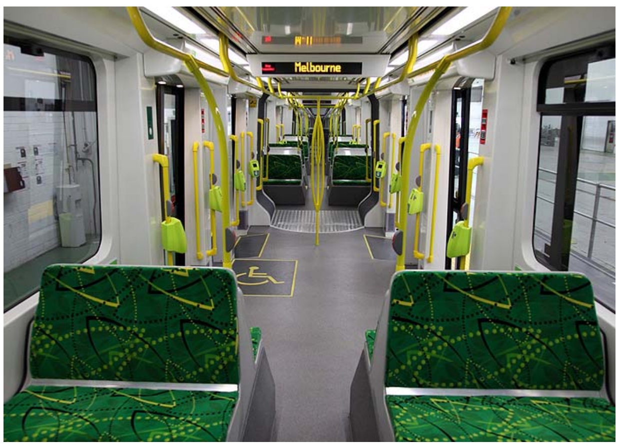
[8] Four passengers per square meter of suitable standee space (2.7 ft^2 per standee) is a commonly used loading level for comparing vehicle capacity. Some transit systems will, however, use more conservative numbers in capacity calculations, such as 3.5 passengers per square meter. Six passengers per square meter (slightly more than 1.5 ft^2 per standee) is sometimes used to calculate crush loading conditions. Even higher loadings are used in structural calculations but do not generally represent practical in-service loading levels.

higher maximum loading than seated space inside the vehicle. Maximum weight will impact axle loading and weight distribution and should therefore be closely coordinated with the carbuilder.

Generally speaking, having large areas of interior space devoted to standees has always been common in streetcars, especially near the doors, where it is important to prevent congestion. Larger areas of standee space also become flexible "multipurpose areas" (**Figure 1-5**), useable for multiple passenger needs. In addition to mobility aids, consideration should be given to other potential passenger carry-on items, such as bicycles, strollers and luggage (**Figure 1-6**). Folding ("tip-up") seats are another commonly used tool for providing flexibility for varying passenger loads. During interior layout design, consideration should also be given to minimizing the distances that unsecured mobility devices and other passenger carry-on items can travel during rapid deceleration events.

FIGURE 1-5

Multipurpose Area



Large interior areas are often configured without fixed seats. These "multipurpose areas" are useable for standees, mobility devices and other permitted passenger carry-on items.

FIGURE 1-6

Accommodating a Range of Passenger Items

Policies are typically created to control and organize how space is used for bikes, strollers, etc.

1.4.3.2 ADA Access

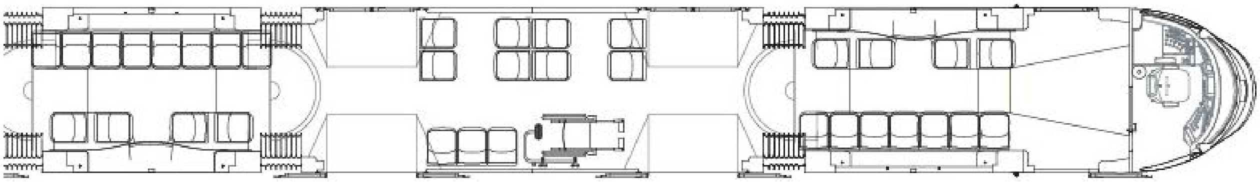
Low-floor streetcars offer improved accessibility for all users, especially those in wheelchairs or with other mobility impairments, elderly people, and passengers with strollers or luggage. The Americans with Disabilities Act (ADA) regulations set standards for minimum aisle widths, the size of the wheelchair berths, and other access issues that, combined with vehicle width, will influence interior layout/seating configuration.

Unless all stops on the system are on only one side of the track, a passenger using a wheelchair or other mobility aid must be able to board via an accessible doorway, maneuver to a wheelchair berth, and then have the option of leaving the vehicle at a stop located on the opposite side from where they boarded. This is easily achieved where the vehicle's accessible doorways are located directly across from each other. Where they are not, there must be an adequate passage through the vehicle to reach an accessible doorway on the opposite side. A commonly applied solution is to configure the accessible portion of the streetcar largely with standee/multipurpose floor space instead of seating, a configuration that also permits easy wheelchair maneuverability (**Figure 1-5**).

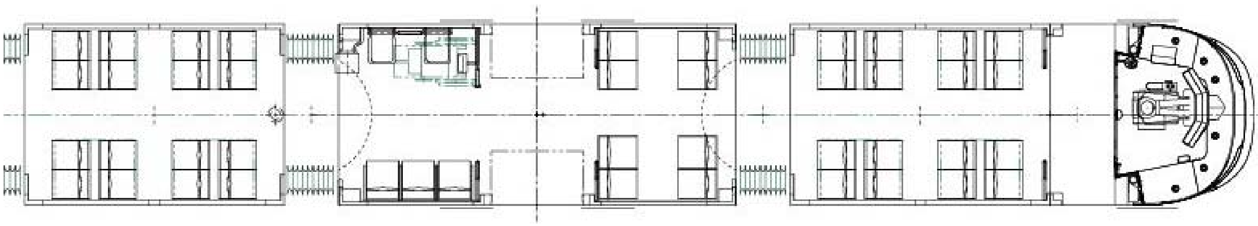
In low-floor vehicles, the "wheel wells" that protrude into the passenger compartment to accommodate the running gear (**Figure 1-9**) typically create the greatest constraint on aisle width. This is especially true in a narrow vehicle (2.3 or 2.4 m). Because the wheel wells cannot be eliminated, they become de facto seat locations, and in most cases the narrowness of the adjacent aisle prevents a wheelchair from passing. For this reason, the low-floor sections on most vehicles will have only specific areas arranged to accommodate wheelchairs.

FIGURE 1-7
Sample Floor Layouts for Different Widths

2.4 m wide vehicle



2.65 m wide vehicle



Graphics courtesy of Bombardier

Note variations in seating arrangements to suit vehicle width, including use of 2+2 seating in the 2.65 m vehicle.

1.4.3.3 Fare Collection

The method of fare collection used on the streetcar system may also impact vehicle interior layout. It should be understood that low-floor streetcars (as with light rail systems in general) are intended to be deployed together with a fare collection system that does not involve the vehicle operator, maximizing the benefits of multiple low-floor doorways, with an accompanying positive impact on dwell time. This commonly takes the form of a proof-of-payment system using off-vehicle fare collection with on-board validation. Some agencies provide ticket vending machines on board the vehicle, and a few European and Australian systems use a second employee on board the vehicle (a conductor) for fare collection. Other fare collection issues commonly encountered in streetcar projects include fare enforcement, regional coordination of fare structures, smart card use and bus-streetcar fare coordination.

As with any owner-supplied/specified equipment, where onboard ticket machines and/or validators are to be used, it is important to incorporate this information into the vehicle procurement process from the beginning instead of treating it as a change order or after-purchase retrofit. Passenger flow around any onboard ticket machine(s) must also be considered in interior layout in order to avoid congestion.

If an operator-collected (pay-on-entry) fare system were to be used, the interior layout would need to provide sufficient room for entering passengers to flow past the operator. Most modern streetcars utilize some form of full-width cabs, and so unlike a bus, doorways are not located immediately adjacent to the operator at the extreme ends of the vehicle (although in some streetcars there is a doorway immediately behind the cab wall). Operator-collected fares would be even more difficult to accommodate in a partial low-floor streetcar, where the cab and any end doorways are in the high-floor portion of the vehicle.

GUIDANCE: INTERIOR LAYOUT

"Urban Transit, Systems and Technology" (Vuchic 2007) advises: "The design of the vehicle interior is a compromise among the requirements for capacity, comfort (seating), and easy circulation (aisle and door areas). The relative importance of these requirements depends mostly on trip duration, peaking of passenger volume, and intensity of passenger exchange at individual stations."

Interior layout will also be influenced by accessibility considerations, various constraints associated with an individual vehicle design (including door layout and running gear locations), as well as the vehicle's width. Other than in any areas around running gear "wheel wells", seating configuration can generally be readily altered as part of initial vehicle purchase. Because streetcar trips tend to be short, standing is usually more acceptable to passengers, and so having large areas of interior space devoted to standees has always been common in streetcars, especially near the doors. These areas become flexible "multi-purpose areas", useable for multiple passenger needs.

When reviewing ADA access requirements, wheelchair berth locations must be considered together with the locations of the accessible doorways and the configuration of the wayside platforms. Because accommodating bicycles and other passenger "carry on" items will also impact interior layout, the system planning process should determine related policies prior to beginning the vehicle procurement process.

Low-floor streetcars are intended to be deployed together with a fare collection system that does not involve the vehicle operator, maximizing the benefits of multiple low-floor doorways, with an accompanying positive impact on dwell time. This commonly takes the form of a proof-of-payment system using off-vehicle fare collection, although some agencies also provide ticket vending machines on board the vehicle. This is another policy area which should be resolved prior to beginning the vehicle procurement process.

1.5 Partial vs. 100 Percent Low-Floor

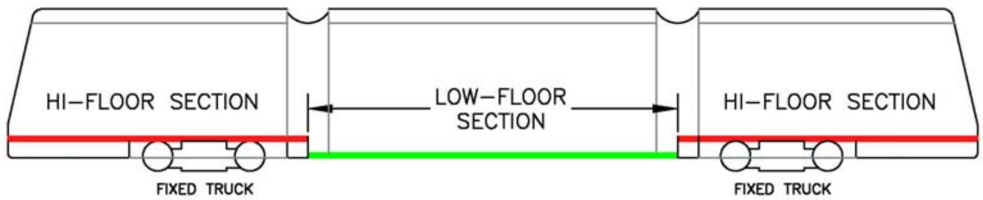
The term "partial low-floor" refers to a vehicle with a low floor in only a portion of the interior (typically 50 to 70 percent of the total length of the passenger compartment). "100 percent low-floor" refers to a vehicle with a low floor (no steps) throughout the passenger compartment, although there are often other compromises such as ramped aisle ways and elevated seats in the "wheel well" areas around the running gear. In all, more than 8,000 low-floor vehicles have been ordered in the 25 years since the advent of low-floor technology, about half being 100 percent low-floor. Recent European orders suggest that the market trend is decidedly in favor of 100 percent low-floor vehicles for tramways and streetcars, with the 70 percent configuration still popular for LRVs, including the emerging Tram-Train application[9]. In 2012, there were 1,040 partial and five 100 percent low-floor vehicles in service or on order in the U.S. (representing a modest 13 percent of world production of low-floor rail vehicles). In Canada, Toronto has a total of 386 100 percent low-floor vehicles on order to replace its existing streetcar fleet and to equip its new light rail network.

Although 100 percent low-floor vehicles are new to North America, they have been in service in Europe since 1990. The cost and performance differences compared to partial low-floor vehicles have narrowed considerably in this time, a trend which is expected to continue. While it continuously gained popularity in other parts of the world, adoption of the 100 percent low-floor configuration in the United States was hindered in part by differing regulatory approaches to crashworthiness and fire safety. The release of the ASME RT-1 crashworthiness standard in 2009, together with parallel standards work in the EU (including EN 15227), have helped open the door for the 100 percent low-floor configuration to be implemented in the U.S. **Figure 1-8** illustrates three common streetcar vehicle configurations; each of these concepts also has been extended beyond the minimum-length versions shown by adding additional modular body sections.

[9] "Long Term Orders Dominate the Market" and "Diligent Newcomers Drive Up the Competition," H. Hondius articles in Metro Report International, 2010 and 2011.

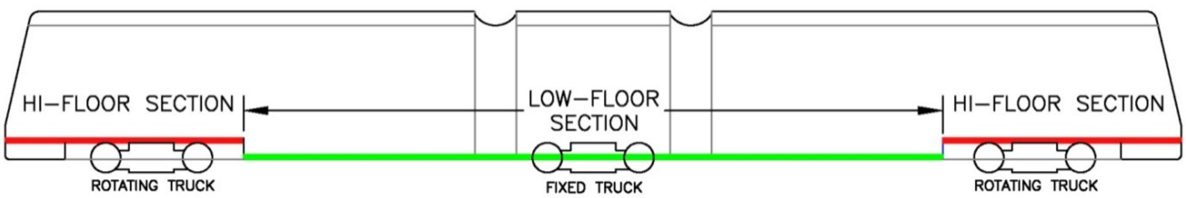
FIGURE 1-8
Common Vehicle Configurations

Three-Section 50 Percent Low-Floor Vehicle



Three-section 50 percent low-floor vehicles utilize only two trucks, with a suspended center section between the outer vehicle modules. The trucks are fixed, though they do use conventional axles. The vehicle typically has a lower top operating speed (less than 43 mph [70 kph]) intended for application on streetcar-type alignments where higher speeds are not required. The first generation of U.S. modern streetcar systems (Portland, Tacoma and Seattle) all used this vehicle configuration.

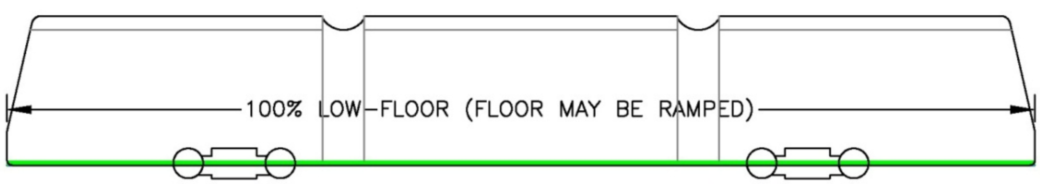
Three-Section 70 Percent Low-Floor Vehicle



Three-section 70 percent low-floor vehicles utilize conventional rotating running gear at their outer ends, with an unpowered fixed[1] axleless[2] truck under the center section. This vehicle configuration is most commonly used in longer-distance light rail applications but has also been adapted for streetcar application. Where specified for light rail application, it is typically capable of higher-speed (50 to 62 mph [80 to 100 kph]) running on open track. The extra underbody room provided by the high-floor sections permits the use of conventional rotating running gear at the outer ends, with the potential for some accompanying benefits (simpler construction and improved ride quality due to more room for suspension and drive elements).

1. Reference Chapter 3, Section 3.2.2, "Fixed vs. Rotating Trucks."
2. An "axleless truck" uses independently rotating wheels (IRWs) in lieu of conventional wheelsets with axles.

Multi-Section 100 Percent Low-Floor Vehicle



Multi-section 100 percent low-floor vehicles offer further improved access because they can provide low-floor doors along their entire length. They have no interior steps in the passenger area (**Figure 1-9**), although the floor is often ramped and seats over the running gear may be elevated. Having low-floor doors along the entire length of the vehicle can permit a considerable decrease in dwell time, especially where operations are optimized to take full advantage of the vehicle configuration with complementary system elements such as full-length platforms. Minimizing dwell time is especially important on high-ridership routes and/or alignments where roadway traffic may be halted whenever the streetcar is stopped.

The access improvements of the 100 percent low-floor configuration come at the price of more technically complex running gear due to the lack of room for conventional suspension and drive elements. Consequently, some 100 percent low-floor vehicles may require a less-demanding alignment (including curvature) in order to be successful. Top operating speed varies depending on vehicle type; some have a top speed of 43 mph (70 kph) and are thus used only on streetcar-type alignments where higher speeds are not required. Other 100 percent low-floor vehicles have top speeds of between 50 and 62 mph (80 and 100 kph).

FIGURE 1-9
100 Percent Low-Floor Interior

The “100 percent low-floor” vehicle has no steps in the passenger compartment, but “wheel wells” (which become de facto seat locations) intrude into the passenger space, just as they do in low-floor buses.

FIGURE 1-10
Partial Low-Floor Interior

View of the steps leading to the high-floor section of a “partial low-floor” streetcar in Seattle. The height difference between sections varies between different vehicle designs.

GUIDANCE: PARTIAL vs. 100 PERCENT LOW-FLOOR

Both the partial and 100 percent low-floor vehicle configurations are used successfully in cities throughout the world (the percent figure referring to the percentage of passenger compartment *length* at the low-floor level). As with other aspects of system design, there are benefits and trade-offs associated with each approach. All low-floor vehicle configurations require some form of compromise with regard to the floor. Because the lowered floor line is actually below portions of the running gear, there will always be some restriction on floor space; there will either be steps inside the passenger compartment (partial low floor) (**Figure 1-10**), or narrowed aisles around the running gear (100 percent low-floor) (**Figure 1-9**). In all configurations, only specific sections of the vehicle will normally be arranged to accommodate wheelchairs and other mobility aids.

Although 100 percent low-floor vehicles are new to North America, they have been in service in Europe since 1990. The cost and performance differences compared to partial low-floor vehicles have narrowed considerably in this time, a trend which is expected to continue. To inform the decision about which technology is better suited for a particular system, the various trade-offs should be evaluated in light of local conditions. **Table 1** in the on-line Carbuilder Survey (see Appendix 1) summarizes some of the key design trade-offs.

1.6 Single vs. Double-Ended

Streetcar vehicles are produced in both single-ended (a.k.a. unidirectional) and double-ended (a.k.a. bidirectional) configurations, meaning an operating cab at either one or both ends of the vehicle. It is normal for double-ended vehicles to also be double-*sided* (doors on both sides). Many single-ended vehicles have doors on only one side (single-*sided*), because they run exclusively on double-track alignments with all of the stops on only one side of the track. A typical transit bus or the PCC streetcar are both familiar examples of single-ended, single-sided transit vehicles. A number of large European systems still purchase single-ended, single-sided streetcars, although there are currently no single-*sided* modern streetcar or LRVs in operation in the United States.[10]

1.6.1 Tradeoffs between Single-Ended and Double-Ended Configurations

- **Operational Flexibility:** Double-ended, double-sided vehicles provide the highest degree of operational flexibility. Unlike single-ended vehicles, they do not require a turning loop or wye to reverse direction, and can therefore be "turned back" at any location along the line where a track cross-over is installed, for example in case of a service disruption. Double-sided vehicles also accommodate stops on either side of the track, permitting a mix of both side and center platforms.

- **Additional Passenger Space:** In a single-*ended* vehicle, the interior space normally occupied by the rear cab is replaced with additional passenger space. Similarly, the doorway areas along one side of the single-*sided* vehicle are replaced with additional passenger space.

- **Cost:** The purchase price of a single-ended vehicle will generally be less than for a double-ended vehicle, the differential varying depending on the carbuilder, other vehicle options and the order quantity. Ongoing inspection and maintenance costs are reduced for the single-ended, single-sided vehicle due to the smaller number of doors and single set of cab equipment. Because of their constant use, door systems are one of the most maintenance-intensive subsystems on any modern transit vehicle.

- **Infrastructure Impacts:** Implementation of single-ended vehicles has major infrastructure implications for both operating trackage and maintenance/storage facilities. Single-ended vehicles require turning loops or wyes in order to reverse direction, although they are equipped with backup controls for non-revenue moves. If single-ended vehicles are used, turning radii will determine space requirements for turning facilities. Use of single-*sided* vehicles also assumes a double track alignment with all stops located on the same side of the track (typically the curb side). On a bidirectional single-track alignment, platforms would be needed on both sides of the track in order to use a single-sided vehicle. On a double-track alignment, center platforms (which typically require the use of double-sided vehicles) have the advantage of providing the narrowest possible right-of-way at stops.

GUIDANCE: SINGLE-ENDED VS. DOUBLE-ENDED

Because of their operational flexibility, double-ended (operating cabs at both ends), double-sided (doors on both sides) vehicles are used almost universally on new streetcar systems, while single-ended vehicles continue to be supplied for legacy systems with established infrastructure to support their use. The operating advantages of double-ended vehicles are obtained at the cost of somewhat greater maintenance requirements, additional vehicle cost and a loss of seating. The operating agency should evaluate the pros and cons of the two approaches, factoring in any cost impacts of single-ended operation on guideway construction.

[10] The last new single-ended, single-sided streetcar vehicles built for a U.S. system were the 1981 fleet of 112 vehicles for SEPTA in Philadelphia. Toronto, Ontario, operates a fleet of single-ended, single-sided vehicles built between 1978 and 1984. In 2009 and 2012, Tri-Met in Portland, Oregon, purchased single-ended, double-sided light rail vehicles, although it operates them only in coupled back-to-back pairs. In Canada, Toronto's large new fleet of 100 percent low-floor streetcars will be single-ended, single-sided.

1.6.2 Cabs

A modern streetcar cab has more in common with an LRV than with a typical transit bus or a heritage trolley. Full-width cabs are normally used, physically isolated from the rest of the passenger compartment by a partition wall, although this wall is often transparent, at least in part (**Figure 1-11**). This isolation provides additional security for the operator and permits the operator to focus on the road ahead and the general safe operation of the vehicle. Distracting passenger noise levels are reduced, radio communications are not heard by passengers, and the arrangement facilitates the operator darkening the cab to improve night vision. As is the case with cabs in other types of light rail vehicles, some form of emergency passenger intercom system is normally fitted to permit passenger-operator two-way communication (see Section 1.2.7, "Train-to-Wayside Communication/Intelligent Transportation Systems"). The use of a full-width cab also means that low-floor streetcars are not well suited for adaptation to operator-collected fares. Refer to Section 1.4.3.3, "Fare Collection."

Access to the cab is most commonly via a lockable door into the passenger compartment. Generally the operator's seat should be in a central position in the cab. A "trainer's seat" may also be incorporated to permit a trainer or supervisor to also occupy the cab. Use of a 5th percentile female through a 95th percentile male is recommended as a reasonable approach to specifying anthropometric data relating to the cab. Beyond these numbers, disproportionate cost impacts are likely to occur.

GUIDANCE: CABS

The basic design concepts for a streetcar cab are similar to those for a conventional light rail vehicle. The important differences center on the dynamic nature of the in-street operating environment and the use of line-of-sight operating principles. These conditions result in an increased need for the operator to have unobstructed forward and side vision. See Section 1.2.3, "Forward and Side Visibility."

The use of a full-width cab also means that low-floor streetcars are not well suited for adaptation to operator-collected fares. Refer to Section 1.4.3.3, "Fare Collection."

FIGURE 1-11
Clear Cab Partition Wall

In many modern streetcars, passengers are able to see out through the vehicle ends, making it easier to recognize where they are along the route and generally improving interior aesthetics. Different techniques (in this case tinting the upper half of the partition) are used to ensure that the passenger compartment lighting does not cause reflections on the windshield.

CHAPTER 2: VEHICLE/PLATFORM INTERFACE

2.0 Introduction

Unlike a "station" on a light rail line, a streetcar "stop" is usually more akin to an urban bus stop. Streetcar stops are an integrated part of the street environment, and the basic design concepts are similar throughout the world, although local climatic conditions influence the types of shelters that may be provided. Worldwide, new streetcar systems incorporate platforms to maximize the benefits of low-floor vehicles and take advantage of their length. The use of platforms improves overall travel time by reducing one of its most significant components, dwell time at stops. Travel time in turn determines the number of vehicles needed to provide a given headway on a transit line.

2.1 The Evolution of the Streetcar Stop

Worldwide, by the early part of the 20th century, electric street railway construction typically took the form of a pair of tracks laid in a center strip within the street. Passengers simply walked from the curb across traffic lanes to the tracks to board the streetcar when it arrived (**Figure 2-1**). As automotive traffic began to crowd the streets, some cities instituted boarding islands within the roadway to improve passenger safety and to allow streetcar boarding and traffic movements to continue independently of each other. These narrow "safety zones" sometimes included a raised platform and were typically supplemented with signage and/or physical barriers to protect passengers from traffic. North American cities that retained extensive streetcar systems, such as San Francisco and Toronto, still have these boarding islands as well as traditional in-street loading in many locations.

FIGURE 2-1
Street Boarding

By necessity, legacy systems such as Toronto still use street boarding at some locations. New streetcar systems use some type of platforms at all stops to improve safety, speed boarding and provide ADA-compliant access.

The streetcars in most U.S. cities were replaced with buses, which could pull to the curb to pick up and discharge passengers. In contrast, many more European cities retained their streetcar systems, incrementally upgrading them over time. Vehicles evolved from the earlier high-floor types to partial low-floor, in many cases retrofitting older vehicles by adding a low-floor section. The 100 percent low-floor vehicle was the next step in this evolution, driven by a desire to make access easier for all passengers, and in doing so, further reduce dwell time at stops. Because streetcars stopped in traffic lanes impact overall traffic speeds, reducing dwell time helps to improve travel times for all roadway users.

Platforms have evolved along with the vehicles, although in many world cities, passengers are still required to make a small step up into the vehicle. This “one-step” or “near level” boarding is, however, a significant improvement over boarding via the stairs on a high-floor vehicle. In some European cities, platforms have also been upgraded to achieve fully level boarding or conditions closer to it, and many new systems use fully level boarding. Other systems have upgraded to low-floor vehicles but still retain some boarding directly from the street, with no platform of any kind.

When comparing vehicle/platform interface between the United States and Europe, it is helpful to remember that there is a key difference between the U.S. and European accessibility standards that influences the overall design approach. Specifically, the ADA requires a smaller vertical step, ±⅝ in. (16 mm), vs. -0 to +2 in. (50 mm) permitted in some European regulations (although both stress an overall goal of minimizing any vertical step). Maximum permissible horizontal gap is similar in both the ADA and European regulations: 2 to 3 in. (50 to 76 mm) for European regulations and 3 in. (76 mm) for ADA. Both also recognize that an excessive “negative step” into the vehicle can be hazardous and discourage the practice.

2.2 New vs. Legacy Systems

Vehicle/platform interface is an example of an issue where conversion of an existing system is a different process than planning a new one. A legacy system must maintain service using existing infrastructure at least in part, and so its choices with regard to vehicle/platform interface may be limited. Vehicle width may also be limited by established track centers and wayside clearances.

Typically, legacy systems are incrementally adapted for low-floor vehicles over a period of time, with the requirement that each incremental step along the way provide a fully functional system. In contrast, a new system will typically have a clean slate with which to work and, aside from physical constraints associated with an alignment, can (and should) adopt system design elements that provide much higher levels of customer service and accessibility, as well as operational efficiency.

2.3 Platform Configuration

Streetcar platforms come in many shapes, sizes and locations. Depending on the track alignment, streetcar platforms may be located on the side of the street, in the center of the street (a single platform with tracks on both sides) or configured as “islands” between traffic lanes, with a platform serving only one travel direction. Side platforms may simply use part of the existing sidewalk or may comprise an extension of the sidewalk area that “bulbs out” into the street. In all cases, the platform must be compatible with its surroundings, blending into the streetscape and/or sidewalk in a safe and integrated manner.

2.3.1 Platform Offset from Track

The distance between the track centerline and the platform edge is determined by the width of the vehicle plus a small clearance dimension. Vehicle width is therefore an especially important issue for new systems, because the initial vehicle order/stop design will likely limit future expansion to the same carbody width. Where ballasted or other non-embedded track forms are used at stops, consideration must also be given to accurately maintaining the track-to-platform spacing over the life of the system.

2.3.2 Platform Length and Capacity

Platforms may be "full length" or "partial length." Factors include vehicle configuration, available space, cost, capacity, interaction with other transit services, and community acceptance/urban blending (considering such issues as fit with local conditions, traffic, parking impacts, available space, city block length, etc.) At a minimum, all doors on the vehicle must open onto some part of the platform. Depending on the vehicle configuration, door locations may be grouped closer together or spread out along the length of the vehicle, impacting the minimum length of the platform. This "overall door dimension" is illustrated in **Figure 2-4**. Platform length should also be considered together with platform width and capacity needs, not just the minimum needed to accommodate the vehicle doors.

- **Partial-Length Platform:** Shorter than the full length of the vehicle, sometimes accommodating only the doors within a streetcar or a bus's low-floor area (**Figure 2-2**).
- **Full-Length Platform:** As long as, or longer than, the vehicle(s) (or combinations of different transit vehicles) that use it (**Figure 2-3**). A platform might, for example, be designed to simultaneously accommodate both a streetcar and a bus. Platform length should also include some buffer for inaccurate stopping.

FIGURE 2-2
Partial-Length Platform, Multi-Level

Partial length platform, Seattle, Washington. 10 in. raised area accommodates only the low-floor section of the vehicle. The lower portion of the platform can be used to access the step-entry front door.

FIGURE 2-3
Full-Length Platform, Single-Level

Full-length platform, Tacoma, Washington. 10 in. uniform height; length exceeds overall vehicle length.

2.3.3 Platform Height and Accessibility

A nominal 14 in. (355 mm) floor height at the doorways is most common for low-floor vehicles (some may be slightly lower), and the corresponding platforms typically range from 8 to 14 in. (204 to 355 mm). The platform may be of uniform height, or it may incorporate one or more raised (ramped) sections adjacent to the berthing point for the accessible doorway(s) on the vehicle(s). ADA-compliant boarding is implemented using both partial and 100 percent low-floor vehicles and is done in two different ways, either "fully level" or "near level," depending on local conditions. Where fully level boarding is to be applied to a system, it may be desirable to consider a slightly lower vehicle floor height (12.5 to 13 in.), as is done on some European systems, although consideration should also be given to whether or not the system may later be upgraded to, or interoperate with, light rail. In all cases, platform design must be considered together with the locations of the accessible doorway(s) and wheelchair berth(s) on all of the vehicles that will use the stop (see Section 1.4.3.2, “ADA Access”).

TABLE 2-1

Advantages and Disadvantages of “Fully Level” Boarding

<table>
<tr><td colspan="2">“Fully Level” Boarding: The vehicle floor and platform are at the same height [14 in. (355 mm)] nominal. Bridgeplates are unnecessary, but an active suspension (automatic load leveling) is required on the vehicle to maintain compliance with the ADA $\pm\frac{5}{8}$ in. (16 mm) vertical gap requirement over the full range of passenger loading.

A streetcar vehicle is typically equipped with either load leveling or bridgeplates but not both. While it is technically possible to equip a vehicle for use with both boarding approaches, mixing the two has the potential to create confusion for passengers, and a consistent approach is therefore preferable. Attempting to install both features might also preclude the use of door threshold extensions (a common feature of fully level boarding) at doorways fitted with bridgeplates.</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>• The vertical step from the platform into the vehicle is eliminated; best passenger boarding experience.

• Typically has better dwell time compared with bridgeplates, which becomes important in high-ridership applications. Although the impact on travel time may be negligible on a short initial line segment with only moderate ridership, future system needs should also be considered (especially where streetcars may be in the roadway’s only travel lane).

• Eliminates the need for bridgeplates, thus removing a high-maintenance item from an already complicated vehicle subsystem (doors).


</td><td>• More demanding on infrastructure, and therefore less flexible for application to an urban in-street environment. Precisely maintaining the $\pm\frac{5}{8}$ in. (16 mm) vertical step and 3 in. (76 mm) horizontal gap requires a systems approach (it’s not just a vehicle function). Platform height tolerance is a function of both vehicle characteristics (wheel wear and compensating shimming, suspension characteristics, operational range of the leveling system) and infrastructure (rail wear, type of construction, construction and maintenance tolerances).

• A 14 in. (355 mm) platform (or section of the platform) is generally not compatible with buses, especially outward-folding doors.

• 14 in. (355 mm) platforms, especially full-length platforms, may be more challenging to blend with sidewalks and streets. Typical “blending” issues include minimizing impacts on narrow sidewalks, maintaining the slopes required for ADA access, and compatibility with curb design criteria and drainage flows.

• Locating a fully level platform on a curve is difficult at best, but is possible with the “near level” platform combined with bridgeplates.

• Depending on the carbuilder, some vehicles may not have load leveling capability as a standard feature or option.

• In a mixed fleet situation (both step-entry high-floor vehicles and low-floor vehicles), a 14 in. (355 mm) platform may not be compatible with older step-entry vehicles (which may have a first step that is lower than the platform).

• In a situation where trackage may be shared with other rail services (typically applies only to light rail), clearance regulations may limit the height of the platform to 8 in.</td></tr>
</table>

TABLE 2-2

Advantages and Disadvantages of “Near-Level” Boarding

<table>
<tr><td colspan="2">“Near Level” Boarding: Vehicle floor and platform are “near level”; 13 to 14 in. (330-355 mm) vehicle floor (may be slightly lower at doorways), 8 to 10 in. (203 to 254 mm) platform height. Requires bridgeplates for ADA compliance (see <u>Section 2.5, “Bridgeplates [if used]”</u>).</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>
• Much less demanding on infrastructure tolerances (the horizontal and vertical gap can vary somewhat) and thus more flexible with regard to where the platform can be located. Flexibility is important because in contrast to a light rail alignment on a dedicated right-of-way, streetcar alignments are influenced by a variety of factors associated with the street environment.

• Facilitates integration of streetcar and bus routes. Lower platform heights are typically necessary for permitting buses to share streetcar stops.

• The lower platform height will typically be easier to blend into sidewalks and the street, especially where side platforms are used. Typical “blending” issues include minimizing impact on narrow sidewalks, maintaining the slopes required for ADA access, and compatibility with curb design criteria and drainage flows.

• With the use of bridgeplates, the near-level platform can be located on a curve. The permissible degree of curve is dependent on several factors relating to the geometry of the vehicle.

</td><td>
• Small step (3 to 6 in.) required to board vehicle from platform.

• Bridgeplates add further complexity to already-complicated door systems. Bridgeplates are also subject to damage (passengers jumping on bridgeplates, stepping on them before they are fully deployed, overloading them) and other maintenance issues. However, load leveling (required for fully level boarding) is not without its own maintenance issues.

• Snow and ice conditions may cause problems with bridgeplate operation, particularly if snow is allowed to accumulate.

• Use of bridgeplates may increase dwell time, which may be a significant factor in high-ridership applications or where the streetcar blocks traffic when stopped. Dwell time is also dependent on a number of other issues, including the number and location of accessible doorways, platform configuration, passenger loading levels, etc.

• Tactile warning strip area on platform edge may require modification, providing a flat “landing area” for the edge of the bridgeplate.


</td></tr>
</table>

GUIDANCE: PLATFORMS

New streetcar systems use some type of platform throughout the system because of the need for ADA compliance and the significant dwell time and customer experience/safety benefits. Legacy systems are likely to still have some boarding directly from street level.

As with other aspects of streetcar system design, vehicle, platform and operating conditions must be considered together as a system. By eliminating any step from the platform into the vehicle, “fully level” boarding provides the best passenger boarding experience, and is considered the optimal solution from an accessibility standpoint. However, there are trade-offs associated with both the “fully level” and “near level” boarding approaches. To inform the decision about which approach is better suited to achieving ADA compliance for a particular system, the trade-offs in **Table 2-1** and **Table 2-2** should be evaluated in light of local conditions, including integration with the region’s other transit modes. While it is technically possible to equip a vehicle for use with both boarding approaches, mixing the two has the potential to create confusion for passengers, and a consistent approach is therefore preferable.

A system’s design criteria document is typically used to establish uniform system-wide standards for key platform dimensions such as height, offset from track, and minimum width / length. In all cases, platform design must be considered together with the locations of the accessible doorway(s) and wheelchair berth(s) on all of the vehicles that will use the stop. Consideration should also be given to whether the system may later be upgraded to, or interoperate with, light rail.

2.4 Vehicle Doors

Streetcars typically make frequent stops, carry large numbers of passengers for short distances, and often compete for space in shared traffic lanes. Optimizing passenger flow on and off the vehicle is important in order to minimize dwell time at stops. For this reason, modern streetcars generally have a large number of doors spread over the length of the vehicle sides, based on the objective of minimizing the distance from the doors to any point within the vehicle. Doorway widths vary depending on the particular vehicle, but the general approach is to use double doors wherever possible.

Various vehicle characteristics impact where the doors can (or can’t) be located in a low-floor vehicle, with the need to keep the low-floor doorways clear of the running gear and articulation locations being the primary factor. **Figure 2-4** illustrates variations in door locations and “overall door dimension” on various vehicles now in use. The number of doorways also impacts seating capacity; in general the more doors a vehicle has the faster its boarding / alighting process at stops, but the smaller its seating capacity. Where the application of special equipment to the vehicle requires space inside the passenger compartment, (such as batteries for off-wire capabilities), this may limit the number of doors and their locations.

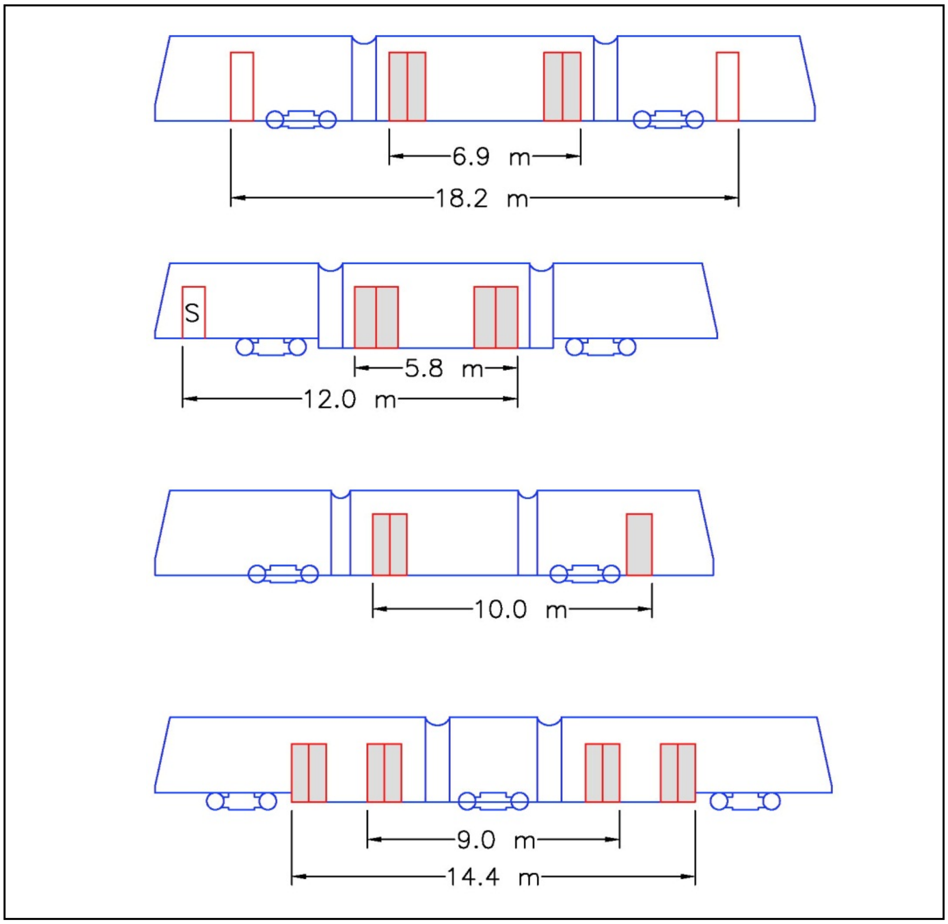
Most modern streetcar vehicles utilize sliding “plug”-type doors, so-called because they “plug” into the vehicle sides upon closing, providing a flush fit. This door type also has the advantage of not taking up any extra room inside the vehicle, (as compared with a pocketed door) and reducing the likelihood of interfering with passengers (as compared to folding doors). Plug doors also provide good door sealing, which reduces wind and water leakage, as well as noise transmission. Because they sweep out over the platform when opening, system design must consider clearances for plug door operation at all conditions of vehicle load and grade, particularly where fully-level boarding is in use.

Most streetcars use passenger-actuated doors that open only on demand—that is, when the operator has enabled door operation after stopping *and* a passenger presses the door-open button for that particular doorway from either inside or outside the vehicle. This reduces wear and tear on door mechanisms (which are already a very maintenance-intensive subsystem), and also helps reduce HVAC demand by minimizing the amount of time doors are open. The operator can also open all doors on one side of the vehicle simultaneously if desired (such as at terminals or other busy stops). Depending on local operating philosophy and available equipment options, the doors will either close automatically based on individual timers, or remain open until the operator presses an "all close" button. Where doors close automatically, some type of "enhanced stop request" feature is typically employed to assist passengers who may need extra time to board or exit. One type of enhanced stop request activates the same door open function but also locally cancels the automatic closure and notifies the operator. The operator is then required to initiate the door close function from the cab after observing that boarding has been completed.

Vehicles which will be used in cold / snowy climates may also incorporate wind screens adjacent to the doors and floor heating in the doorway area. Heating strips can also be applied to door surface contact areas to eliminate ice buildup that could interfere with complete closure of the door.

FIGURE 2-4

Variation in Overall Door Dimension



Overall door spacing varies between different vehicle types, impacting platform configuration. Accessible doorways shown as shaded. Step-entry to high floor area marked as "S"

GUIDANCE: VEHICLE DOORS

Streetcars typically make frequent stops, carry large numbers of passengers for short distances, and often compete for space in shared traffic lanes. Optimizing passenger flow on and off the vehicle is important in order to minimize dwell time at stops. For this reason, modern streetcars generally have a large number of doors spread over the length of the vehicle sides. The 100 percent low-floor vehicle has the advantage of being able to provide low-floor doors along its entire length. In a partial low-floor vehicle, low-floor doorways are limited to the low-floor section, with traditional step-entry doorways sometimes included in the high-floor portions of the vehicle.

2.5 Bridgeplates (if used)

In the context of this document, the term "bridgeplate" refers to a manual or automatic retractable ramp on a low-floor streetcar, which is used as a boarding assistance device in conjunction with a "near level" platform. Bridgeplates are generally fitted to only some of the doorways on the streetcar, these being designated as the vehicle's accessible doorways.

Streetcar bridgeplates are intended to work with a platform, not for providing a ramp between the vehicle doorway and street level (there are other devices that can be used for this application[11]), In U.S. applications to date, bridgeplates on low-floor streetcar and light rail vehicles are powered devices, deploying and retracting automatically without the need for the vehicle operator to leave the cab. In Europe and other parts of the world, manual bridgeplates are also used, requiring the vehicle operator or conductor to manually deploy and retract the bridgeplate.

Bridgeplates are available in different widths and lengths and are typically capable of spanning a vertical step difference of up to 6 in. (152 mm). Assuming a nominal 14 in. (355 mm) vehicle floor height, bridgeplates therefore require a minimum platform height of approximately 8 in. (203 mm) in order to keep the ramp angle within ADA slope requirements. The most common nominal platform height (maximum) for new U.S. streetcar systems is 9.8 in. (250 mm). 49 CFR 38.83(c)5, "Slope," requires that with the height of the vehicle floor under 50 percent passenger load[12] the ramp slope cannot be steeper than 1:6 for spanning vertical steps between 3 and 6 in., and 1:4 for steps not exceeding 3 in.

Because the powered bridgeplate moves in an arc as it deploys, there is also a *minimum* height difference required between the platform and the vehicle floor for bridgeplates to function reliably. Typically, a differential of about 2 in. (50 mm) is needed to reliably avoid having the bridgeplate strike the platform while deploying.

2.5.1 Bridgeplate Operating Protocol

The following bridgeplate operating protocols should be reviewed during system planning and the intended operating plan communicated in the vehicle procurement process. Bridgeplate operating protocol should also be considered in light of door operating philosophy for any other rail operations in the area.

[11] On some European legacy systems, low-floor streetcars are fitted with powered "wheelchair lifts" for accessible boarding directly from street level. More commonly, systems use manually deployed "wheelchair ramps" that can deploy either onto a platform or all the way down to street level. The new low-floor streetcar fleet to be introduced in Toronto beginning in 2012 will have an automatic wheelchair ramp capable of deploying either onto a platform or all the way down to street level.

[12] For streetcar vehicles that do not have automatic load leveling, the amount that the floor height will change between unloaded and fully loaded conditions will vary depending on vehicle suspension characteristics. Information supplied by Portland Streetcar indicates a variation of up to 2 in. (50 mm) for a fully loaded vehicle, or approximately 1 in. (25 mm) at 50 percent loading.

- **On-Demand Deployment:** Bridgeplates take time to deploy and are complex mechanisms that are subject to wear from use. In order to minimize dwell time and reduce wear on the bridgeplate mechanisms, they are typically deployed only on demand. ADA-compliant passenger-actuated bridgeplate-request buttons and/or tape switches are provided separately from any door-open buttons. The request switches should be located so as to comply with ADA but also to minimize accidental actuation, such as from a passenger leaning against them.

- **"Request" Protocol:** Because a deploying bridgeplate can be damaged if passengers step on it before it is fully extended, or could otherwise create confusion for passengers at an open doorway, the associated door is sometimes held closed while the bridgeplate below it deploys or retracts[13]. In this instance, when the bridgeplate is requested (whether by passenger or operator) prior to the door opening at a stop, it can deploy in the minimum added time prior to the normal opening sequence for the associated door.

  However, when the bridgeplate is requested *after* the normal door open sequence has already begun, or after the doors are already open, it is typically necessary to first cycle that door closed, deploy the bridgeplate, and then cycle the door open again. This extra door closing cycle is detrimental to dwell time, so it is beneficial to provide operating procedures that can, at a minimum, emphasize the operator initiating the bridgeplate sequence if he or she notices a wheelchair passenger waiting to board. Similarly, signage, announcements, and other public outreach to passengers can be used to emphasize the time savings associated with the passenger requesting the bridgeplate deployment prior to the vehicle stopping (as well as only when actually needed).

- **Manual Operation:** Like any mechanical device, it is possible that the bridgeplate may fail during operation. Bridgeplates should always be equipped with an effective means for manual retraction and cut-out in the event of a power failure or other mechanical problem.

2.5.2 Bridgeplate Configuration

- **Bridgeplate Width:** The width of the accessible doorway(s) in a vehicle's low-floor section are typically wider than the minimum 32 in. width required by the ADA. Bridgeplates are available in different widths and can thus range from the full useable width of the doorway down to the ADA minimum 32 in. When a bridgeplate is not as wide as the associated doorway, it is typically interlocked with the door system such that when it is deployed, the doors move to a partially open position, narrowing the doorway opening to the approximate width of the bridgeplate. As this practice reduces effective doorway width and adds further complexity to door operations, it is preferable to have a bridgeplate that is the same width as the maximum usable space of the open doorway.

  A full-width bridgeplate also tends to minimize delays by allowing freer passenger movement, in some cases permitting ambulatory and mobility device users to board or alight together. It is worth remembering that in addition to the wide variety of wheelchair styles, there are many other mobility aids used by passengers, including scooters, crutches and different types of walkers.

  As bridgeplate width increases, deflection may become an issue, and some vehicle designs may not be readily adaptable to the use of full-width bridgeplates. This is another example of a design trade-off that needs to be analyzed in the vehicle procurement process.

- **Bridgeplate Side Barriers:** When the ADA regulations were adopted in 1990, there were no low-floor light rail or streetcar vehicles in operation in the United States. At that time, the typical

[13] On the new fleet of LRVs that began entering service in Salt Lake City in 2011, doors are permitted to continue opening during bridgeplate deployment. Initial experience with this method of operation has not revealed any significant problems.

application of a "bridgeplate" was between a high-floor rail vehicle and a high-block platform. In that application, the bridgeplate was typically deployed over a stairwell and thus several feet in length and several feet in the air (**Figure 2-5**). In this application, side barriers are appropriate for safety, preventing the wheels of a mobility aid from slipping off the edge.

The use of a bridgeplate on a low-floor streetcar in conjunction with an 8 to 10 in. (203 to 254 mm) high platform (**Figure 2-6**) is a significantly different application that was not contemplated in the original regulations; here the bridgeplate is typically wider, significantly shorter in length, and is deployed only a few inches above a platform surface (the maximum height difference between it and the platform surface is 3 to 6 in.). In contrast to boarding from a narrow high-block platform, passengers using mobility aids on a streetcar platform also have some freedom to approach the bridgeplate from different angles.

FIGURE 2-5
Manual Bridgeplate with High-Block Platform

Manually deployed bridgeplate positioned between high-block platform and a high-floor streetcar.

FIGURE 2-6
Automatic Bridgeplate with Low Platform

Automatic bridgeplate deployed onto a 10 in. platform. Note also that a narrow strip of truncated domes have been removed from the tactile platform edge, permitting the edge of the bridgeplate to land perfectly flat.

Agencies around the world now have substantial experience with using bridgeplates on low-floor light rail and streetcar vehicles[14]. To date, low-floor rail vehicles using bridgeplates together with platforms have not utilized side barriers, although the language in 49 CFR 38.83(c)4 states that "each side of the ramp or bridge plate shall have barriers at least 2 inches high to prevent mobility aid wheels from slipping off." The agencies operating these vehicles have gone through the process of obtaining a "Finding of Equivalent Facilitation" in order to use bridgeplates without side barriers. The ADA regulations make provision for "equivalent facilitation" for use in instances "where the alternative designs and technologies used will provide substantially equivalent or greater access to and usability of the vehicle." The process exists to provide flexibility in addressing "unique and special circumstances and to facilitate the application of new technologies."[15] All such instances are addressed on a case-by-case basis in order to consider public input from the local disabled community. In making such requests, agencies have typically pointed out the mobility benefits (for all passengers) associated with removing the side barriers from the bridgeplate and have carefully documented the public involvement process with their local disabled community.

[14] TriMet in Portland, Oregon, was the first U.S. transit agency to put low-floor light rail vehicles into service, beginning in 1997.

[15] Access Board Transit Manual, Subpart A §1192.2, Equivalent Facilitation.

In order to further improve ease of wheelchair use, several rows of truncated domes are sometimes also removed from the tactile strip at the platform edge (**Figure 2-6**). This modification permits the edge of the bridgeplate to land perfectly flat on the platform, improving the ease with which mobility aids can move onto the bridgeplate. This modification must also be covered by a Finding of Equivalent Facilitation.

As with other vehicle subsystems, bridgeplate technology is also improving as suppliers and operators gain additional experience. Various prototype designs for streetcar bridgeplates with side barriers now exist, although the addition of the barriers can have the unwanted effect of reducing the overall width of the plate and increasing the minimum height differential needed between platform and vehicle floor. This is therefore a topic that would benefit from further industry study.

GUIDANCE: BRIDGEPLATES

If bridgeplates are used, wheelchair berths and paths through the vehicle (which influence seating options) must be planned together with the bridgeplate/accessible doorway locations and the wayside platforms. See Section 1.4.3.2, "ADA Access."

The bridgeplate operating protocols in the preceding section should be reviewed during system planning and the intended operating plan communicated in the vehicle procurement process. Where streetcar bridgeplates are in use with 8 to 10 in. (203 to 254 mm) high platforms, an agency must either provide side barriers on the bridgeplates or request a Finding of Equivalent Facilitation. When seeking the latter, this procedure should be started early in the system design process.

As with other vehicle subsystems, bridgeplate technology is also improving as suppliers and operators gain additional experience. Performance measures such as time to deploy and stow, options for dealing with obstacles, and mean time between failures (MTBF) should be reviewed when selecting a bridgeplate technology/supplier.

2.6 Streetcar and Bus Sharing a Platform

The nature of the streetcar mode is such that streetcar and bus routes may overlap. This can present opportunities for different types of vehicles to share stops (buses, different streetcar types, heritage trolleys) (**Figure 2-7**). Shared stops can improve passenger convenience and reduce costs by facilitating transfers and saving space in dense urban settings. Depending on the nature of the transit services using the stop, separate stopping places may also be desirable for capacity or other reasons; a longer stop area, split stops (**Figure 2-11**) or adjacent stops (**Figure 2-12**) may be used to provide separate but proximate stopping places.

FIGURE 2-7
Shared Bus/Streetcar Platform; Near-Level

Having multiple vehicle types sharing a platform impacts both platform height and length. This image shows a bus sharing a 10 in. near-level streetcar platform in Portland.

FIGURE 2-8
Shared Bus/LRT Platform; Fully Level

Buses and light rail sharing a 14 in. platform in Seattle, where special mitigations have been applied (pavement ramp adjacent to platform edge and larger tires on bus).

Implementing shared stops involves a number of variables centering around the height of the platform. Generally, as streetcar platform heights increase above 8 in. (203 mm), additional design coordination is required to ensure compatibility with buses. The ability of a transit bus to interface with a shared streetcar platform is dependent on several factors:

- **Platform Location:** Other than special-purpose applications, transit buses generally have doors only on the curb side. Therefore, streetcars and buses can share certain types of side and island platforms, but buses cannot use streetcar center platforms. Where center platforms are in use, the bus can use a separate curbside stop nearby, although any traffic impacts of having both a streetcar and a bus stopped simultaneously in this arrangement should be considered. Platform and trackway must also be compatible with any guidance system used by the bus.
- **Platform Height:** Sharing of stops is generally more compatible with the lower heights associated with the near-level platform concept. In some cases, a bus that can deploy its front door ramp without kneeling can interface successfully with a 10 in. (254 mm) platform. Above this height, additional mitigations are typically required. For example, low-floor buses and light rail vehicles share a common 14 in. platform in the downtown transit tunnel in Seattle, Washington (**Figure 2-8**), but special measures have been applied[16].
- **Bus Floor Height:** Floor heights vary for different models of low and high-floor buses. The floor height also varies based on passenger loading and kneeling features.
- **Bus Door And Ramp Configuration:** Configurations vary significantly between different types of buses:
    - Low-floor transit buses typically utilize an outward deploying ramp at the front door, designed to deploy onto a curb (nominal 6 in. [152 mm] height). In order to deploy the ramp onto a platform (8 in. [203 mm] and higher), the height of the bottom step on the bus cannot drop below the platform height (**Figure 2-9**).

[16] Buses using the Seattle Transit tunnel are fitted with slightly larger tires, the pavement has been "ramped" slightly between the inside rail and the platform edge, and because there is only one lane in each direction, the buses are maneuvering to and from the platform with only a very minimal angle.

   - Many transit buses use outward folding rear doors that can be blocked from opening or get stuck where platform height is above the bottom step height (**Figure 2-10**).
   - High-floor or express type buses typically use "over the road" vehicle designs with 3 to 4 steps for entry and a wheelchair lift that deploys from a special side door.

- **Bus Ramp Deployment / Kneeling Interlock:** On some buses, in order to deploy the front door ramp, the bus's kneeling feature must be activated (the two features are "interlocked"). If kneeling the bus lowers the bottom step height below the height of the platform, then the ramp will not be able to deploy onto the platform (**Figure 2-9**).

- **Bus Approach and Departure Angle:** Where a platform is in use, it is particularly important that both the front and rear doors of the bus end up close to the platform. Where the streetcar and bus are sharing the same travel lane on approach to the stop, a bus can normally come straight in and get both the front and rear doors close to the curb/platform. Where it is not possible for the bus to make a straight approach to a platform, it will need adequate clearance for suitable approach and departure angles. At stops where the platform is higher than 8 in. (203 mm) there is a risk that the bus (which has an overhang at the front and back of the vehicle) may contact the platform when it sweeps over the platform on approaching the stop or pulls away at an angle afterward. Use of a mountable curb, instead of a traditional barrier type, is another tool that can be employed in some situations to facilitate docking the bus as close to the curb as possible, while protecting tires and vehicle edges. Many European cities are using specially shaped curbs (e.g., Kassel Kerbs) for this purpose.

FIGURE 2-9

Ramp Incompatibility with 10 in. Platform

Front door ramp blocked while deploying onto simulated 10 in. platform (the bus's kneeling feature has lowered the door height below platform level)

FIGURE 2-10

Rear Door Incompatibility with 14 in. Platform

Incompatibility between outward-folding rear doors on bus and a 14 in. platform.

FIGURE 2-11
Split streetcar / bus stop

Stop design is impacted by the choice of lane for the streetcar alignment. Here, the track is in the curb lane, and streetcar and bus stops are separated into a near-side/far-side stop arrangement.

FIGURE 2-12
Adjacent streetcar / bus stop

With the track in the center lane, these streetcar and bus stops are separated but adjacent.

GUIDANCE: BUS AND STREETCAR SHARING PLATFORM

The nature of the streetcar mode is such that streetcar and bus routes may overlap. This may present opportunities for different types of vehicles to share stops (buses, different streetcar types, heritage trolleys). Shared stops can improve passenger convenience and reduce costs by facilitating transfers and saving space in dense urban settings. Depending on the nature of the transit services using the stop, separate stopping places may also be desirable. A *system* approach is required; there is little point in optimizing one part of the overall transit system (the streetcar) if doing so creates accessibility issues for other parts of the network.

Implementing shared stops involves a number of variables centering on the height of the platform. Generally, as streetcar platform heights increase above 8 in. (203 mm), additional design coordination is required to ensure compatibility with buses.

CHAPTER 3: VEHICLE/TRACK INTERFACE

3.0 Introduction

Streetcar alignments must typically follow existing roadways through constrained urban areas, frequently requiring sharper curves and steeper gradients than are normally found on a light rail system. This chapter is intended to provide an overview of these and other unique aspects of vehicle/track interface in the streetcar context. It emphasizes the use of a *system* approach to design that takes these unique features into account while avoiding overuse of design minimums and maximums. And by defining certain standard ranges of vehicle design characteristics, it should also be possible to identify areas where imposing requirements on the infrastructure is preferable to modifying the vehicle, and vice versa. The use of standard gauge track [4 ft-8-1/2 in. (1435 mm)] is assumed for all new systems, except potentially in cities where other track gauges are already in use.

Other than to emphasize the general message that design criteria for light rail/streetcar track are significantly different than for mainline and other “heavy rail” applications, this chapter is not intended to provide detailed information on track design and construction, which is well covered in other resources. **Table 1** provides a checklist of vehicle/track interface issues that should be addressed during system design. Sections 3.1 and 3.2, respectively, provide additional information on unique aspects of streetcar track and vehicles.

For more detailed information on light rail/streetcar track design and construction, see TCRP Report 155, “Track Design Handbook for Light Rail Transit” (2012), “Trackway Infrastructure Guidelines for Light Rail Circulator Systems TRB Light Rail Circulator Committee” (2007), and “Track Geometry for Light Rail Systems, Novales, Orro, Bugarin” (Transportation Research Circular E-C145, 2010).

FIGURE 3-1
Extremes of Curvature and Gradient on Legacy Streetcar Systems

Legacy streetcar systems throughout the world use sharper curves (Munich at left) and steeper gradients (San Francisco at right) than would otherwise be specified for a new system. Because of the inherent flexibility of the light rail/streetcar mode, it is *possible* to operate over extremely demanding alignments in terms of curvature and gradient. However, minimizing the use of such extremes brings numerous benefits in terms of passenger comfort, higher operating speeds, lower operating costs and the ability to purchase “standard” vehicles from multiple suppliers.

TABLE 3-1

Vehicle / Track Interface Basics Checklist

<table>
<tr><td colspan="2">It is essential that the type of system be kept in mind from the beginning:</td></tr>
<tr><td>Legacy system?</td><td>If yes, then the existing system track design criteria and interfaces will apply. Presuming performance is satisfactory, changing any of those parameters should only be undertaken with extreme caution after detailed investigation.</td></tr>
<tr><td>New system?</td><td>If yes, then the likelihood of the new streetcar line eventually being upgraded into a light rail line (in whole or in part) should be established. If this is likely, then light rail design criteria should be adopted from the beginning in order to avoid significant system rebuilding in the future. If not, then streetcar design criteria can be used. In a situation where multiple modes serve the same region, in some cases it may be desirable to accept that track geometry and wayside clearances may effectively segregate certain modes/lines.</td></tr>
<tr><td colspan="2">For all new systems, the following vehicle / track interface criteria need to be addressed during design:</td></tr>
<tr><td>Turning radius</td><td>Reference Section 3.1, “Turning Radius and Urban Fit.”</td></tr>
<tr><td>Vehicle dynamic envelope (VDE)</td><td>Reference Section 3.1, “Turning Radius and Urban Fit.”</td></tr>
<tr><td>Single or two-point curving</td><td>Decide whether to use single-point (no restraining rail function) or two-point (restraining rail function) contact for curving. Both approaches are used successfully on systems throughout the world. The important point is to pick one approach and apply it consistently. The selected approach must also be clearly communicated in the vehicle procurement process. Reference TCRP Report 155, Section 2.5.5.4 “Inboard versus Outboard Bearing Trucks”</td></tr>
<tr><td>Grades and vertical curves</td><td>Reference Section 3.1.2 “Grades”</td></tr>
<tr><td>Track gauge, wheel gauge and wheel contours</td><td>Reference TCRP Report 155, Section 2.6 “Track gauge, wheel gauge and wheel contours” from which these excerpts are taken:

Vehicle wheel gauge (the distance between defined points on the face of the wheel flange) is always less than track gauge by some freeplay dimension. This is a very important interface issue that must be addressed jointly by vehicle and track designers. Failure to coordinate this issue can lead to interface problems with very costly long-term consequences.

Wheel profile is one of the most critical vehicle parameters to consider in track design, since the wheel is the primary interface between the vehicle and the track structure. The wheel profile must be compatible with the rail section(s); the special trackwork components, including switch points and frog flangeways or moveable point sections; the guard rail positions to protect special trackwork components; and restraining rail if used on sharp radius curves.

Once accepted, any changes to the wheel profile (especially tread and flange width) must be evaluated by both vehicle and track designers. In more than one instance, the wheel profile has been altered at the last minute by the vehicle side of a project without informing the track designer, resulting in unsatisfactory performance of both the track and vehicle.

In a region where streetcars and light rail may share trackage, vehicle compatibility with both special trackwork and any girder/groove rail sections can be facilitated by adopting common wheel gauge standards (including both gauge freeplay and back-to-back dimensions), along with compatible wheel profile elements (including uniform flange height and width).</td></tr>
<tr><td>Axle Loading</td><td>Reference TCRP Report 155, Section 2.2 “Light Rail Vehicle Design Characteristics”</td></tr>
<tr><td>Compatible rail sections</td><td>Limit the number of rail sections used on a system and ensure that they are compatible with pavement design, as well as the selected back-to-back wheel spacing and profile.</td></tr>
</table>

TABLE 3-1
Vehicle / Track Interface Basics Checklist

Track twist	Explore thoroughly the implications of horizontal and vertical curves, especially combined, and the resulting track twist. Reference Section 3.2.3 "Track Twist and Wheel Unloading".
Specialwork	(1) Decide whether or not to use flange-bearing special work.(2) If more than one type of vehicle will use the same track, decide what the best "universal" flangeway openings and check rail gauges are. (3) Ensure special trackwork is compatible with being embedded in pavement from the standpoints of performance, maintenance and safety.
Wheel / rail interface study	A detailed specification for the wheel-rail interface should be produced at an early stage that includes compatibility of the selected wheel and rail profiles for main line, turnouts and other specialwork. The specification should state performance and expected life of both wheels and rails and consider future maintainability. A "safety against derailment" analysis is typically included.
Maintenance of the wheel / rail interface	A decision is required on how wheel truing will be performed, which will in turn influence maintenance facility design. Reference Section 3.2.4 "Running Gear Maintenance". Maintenance of the track side of the wheel/rail interface, principally through a comprehensive program of grinding and strategic lubrication, is equally important. Reference TCRP Report 155, Section 2.6.4 "Maintenance of the Wheel/Rail Interface".

3.1 Unique Aspects of Streetcar Track Design

Although the basic concepts are the same, light rail track designs are very different from mainline / heavy rail practice. To a large degree, these differences relate to the vehicle and how it is configured. There are subtle but critical differences in the designs of wheels and how they are mounted on many light rail and virtually all streetcar vehicles. And when compared with light rail, streetcar track geometry and vehicles will have further differences centering around the sharper curvature typically needed to integrate into the urban environment.

The "Trackway Infrastructure Guidelines for Light Rail Circulator Systems" document advises:

> "While seemingly simple, wheel-rail relationships can be highly complex and sophisticated. This is especially true for streetcar systems, where curves of very small radius, and site-constrained, compact special (track)work arrangements are typically employed. Wheel and rail must function as a *system*, and when that is not adequately addressed, problems can arise that result in increased rates of wear and even derailments."

3.1.1 Turning Radius and Urban Fit

By definition, a streetcar alignment must have the capability to thread its way through an urban area where the ability to acquire land is minimal and where street widths and traffic patterns inhibit the use of wide-radius curves. Therefore, it is usually important to have a vehicle capable of negotiating horizontal curve radii less than the 82 ft (25 m) minimum typically used for light rail alignments[17]. It is, however, important to understand the trade-offs involved; curve radius is a trade-off between space requirements, operating speed, noise, and wear on both the wheels and the rails.

Legacy streetcar systems throughout the world use sharper curves and steeper gradients than would otherwise be specified for a new system. An example is curve radius; 40 to 50 ft (12.2 to 15.2 m) centerline radius curves are found throughout the world on legacy systems, with the U.S. having the most extreme curvature in its remaining heritage cities; Philadelphia is the most extreme case at 35 ft (10.7 m). Similar examples in Canada and Europe include Toronto and Lisbon (old network), both at 36 ft (11 m). See **Figure 3-1**.

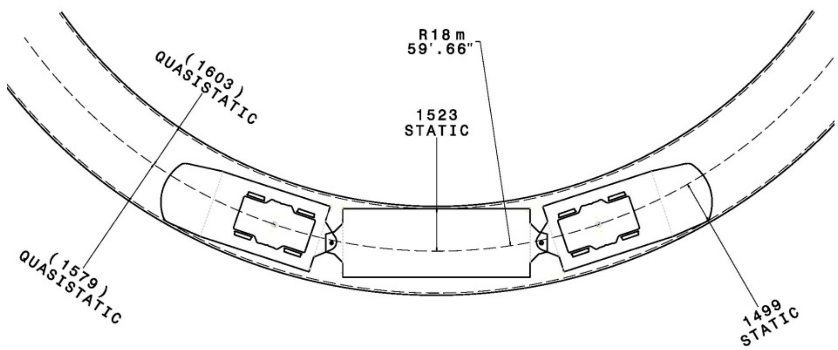
[17] The EU and U.S. track design guidelines on minimum radius for embedded track on new light rail systems are similar; UITP recommends 66 to 82 ft (20 to 25 m), and TRB 82 ft (25 m). These values may be overly conservative for urban streetcar systems.

The vehicle's dynamic envelope needs to be accommodated in the trackway design, not only on tangent track as discussed in Section 1.4.2, "Lane Widths/Urban Fit," but also in curves. In horizontal curves, the dynamic swept envelope expands as determined by the distance between turning centers or articulation points of the vehicle, distance from the front turning center to the end of the vehicle (end overhang), and the styling of the front end (squared or tapered). Although rail guidance and vehicle articulation result in a narrow, precise path in negotiating curves (in contrast to buses and other road vehicles), the swept envelope is still specific to each vehicle design.

Figure 3-2 shows a typical swept envelope for a 8 ft (2.46 m) wide Portland type streetcar vehicle with 24.6 ft (7.5 m) turning centers and a 20.72 ft (6.32 m) end overhang. Note how the taper at the ends of the vehicle reduces the clearance requirements at the outside of the curve. For additional information about determining vehicle clearances and vehicle dynamic envelope, consult TCRP Report 155 "Track Design Handbook for Light Rail Transit, Second Edition," Section 2.3 "Vehicle Clearances."

FIGURE 3-2

Dynamic Swept Envelope on Curve

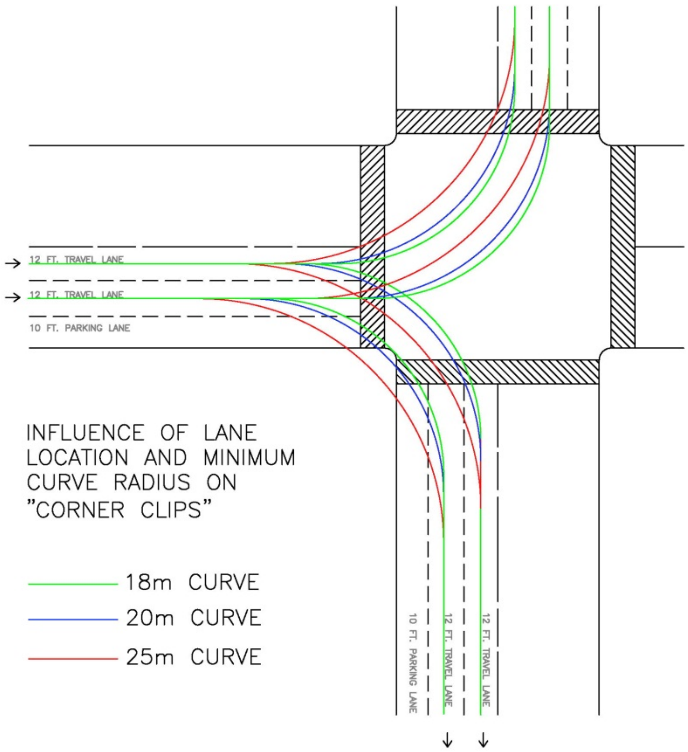


Graphic courtesy of United Streetcar

The vehicle's minimum horizontal curving radius ("turning radius") and associated dynamic swept envelope thus have an impact on lane use when making turns, which can also affect the streetscape along the trackway. **Figure 3-3** compares the impacts of different lane locations and turning radii on urban street corners. When turning from the right-hand lane of one street into the right-hand lane of the next street, the impact on the corner is noticeably greater for the 82 ft (25 m) curve radius than for the sharper curves. These impacts are referred to as "corner clips." The figure also illustrates how the selected running lane for the streetcar alignment influences the way in which a curve fits into a given intersection. Where the choice exists in multiple-lane streets, center lane alignments have a significant advantage over the curb lane because they further reduce corner clips.

Where the combination of street width/vehicle minimum turning radius/selected running lane would not prevent a corner clip, there are other alternatives to taking property at the corner. These include extending the track into an adjacent parking lane prior to initiating the turn or shifting the track into an adjacent lane after the turn (**Figure 3-4**). The resultant traffic conflicts associated with such movements across multiple lanes are typically mitigated with special traffic signal phasing.

FIGURE 3-3
Curve Radius and Lane Location Influences Corner Clips



Influence of vehicle curving radius and lane selection on "corner clips" (circular curves only, no spirals shown).

FIGURE 3-4
Avoiding Corner Clips

Shifting track alignment into adjacent lane to avoid a corner clip in Seattle, Washington.

3.1.1.1 Vehicle Turning Radius

Minimum horizontal curving radius ("turning radius") does vary among the different modern streetcar vehicle designs in the marketplace, but the standard "off the shelf" vehicles currently available from the major carbuilders tend to fall into the three basic ranges detailed in **Table 3-2**. To meet the requirements of legacy systems, vehicles are often customized to accommodate even sharper turns. However, custom vehicles will have a higher cost unless ordered in large quantities. In small order quantities, major customization of vehicles will likely be economically infeasible. For this reason as well as the other associated trade-offs, alignment design for new systems generally stays with these standard ranges of vehicle curving radii.

The minimum turning radius of a given vehicle is influenced by the following physical characteristics:

- Running gear characteristics (axle and truck spacing, fixed or rotating trucks, axles or independently rotating wheels)
- Articulation arrangement
- Number and lengths of carbody sections, truck locations (influencing swept path including end overhang, tolerance for vertical curves)

Table 3-2 summarizes the typical ranges of horizontal curvature that standard modern streetcar vehicles can accommodate.

TABLE 3-2
Horizontal Curvature and Standard Vehicle Designs[1]

Minimum radius		Description
(meters)	(feet)	
25	82	LRT standard - unlimited vehicle selection, but may not be practical for typical streetcar alignment
20	66	20 m is a commonly used minimum for streetcars, wide range of vehicle choices
18	59	18 m has a smaller range of vehicle choices, but is not uncommon. Below 18 m, a custom vehicle may be required

1. Mainline curvature; yard curvature (operated only with empty vehicles) may be less.

3.1.2 Grades

3.1.2.1 Maximum Grades

The abilities of electrically powered transit vehicles to climb and descend hills/grades are well known. In the United States, light rail vehicles and streetcars in San Francisco operate over grades as steep as 9% every day (**Figure 3-1**), and Boston has 8% grades. Importantly, in these examples the vehicles were specified for this capability and have propulsion and braking systems designed accordingly. Like other aspects of streetcar system design, steep gradients are also a trade-off with vehicle cost, operational speed and long-term maintenance costs.

Light rail alignments tend to make use of a fully or partially segregated right-of-way that is typically kept within the limits for grades shown in **Table 3-3**. In contrast, streetcar alignments are typically in existing streets designed for automobile traffic where grades and vertical curves are not as tightly controlled, and where project budgets allow only for retrofitting, rather than rebuilding, the streets. In short, the streetcar must take the city as it finds it, not attempt to rebuild the city to meet an arbitrary set of engineering parameters. In some cases, a short, steep gradient could potentially create a major project cost-savings or other significant operational benefit if it permitted the use of an otherwise advantageous alignment.

The maximum gradient that a rail transit vehicle can reliably negotiate is dependent on the adhesion of the steel wheel on the steel rail. The traction power capacity can always be increased, but the physics of friction limit the maximum grade on which a steel-wheeled vehicle can be operated. As a general guideline, the system's maximum vertical grade and its corresponding length will drive the vehicle motorization requirements (the number of powered wheels). A streetcar's ability to negotiate a vertical grade is determined chiefly by the number of powered wheels and the percentage of vehicle weight on those wheels, which in turn establishes the level of adhesion available for either traction or braking.

The potential for rail surface contamination (such as during the autumn leaf season), must also be considered, as well as rescue scenarios and degraded operation. Typically, in a rescue scenario, one dead vehicle is pulled or pushed by another fully functioning vehicle (see Section 1.2.2 "Breakdown Provisions / Failure Management"). "Degraded operation" refers to a mode where vehicle propulsion and/or braking systems are not fully functional (e.g. some number of motors or brakes are cut out).

Section 1.1 "Duty Cycle" emphasizes the importance of accurately communicating detailed information about alignment and operating conditions (for both initial and future alignments) during the early stages of the vehicle procurement process. This information can be used to "right-size" the vehicle propulsion and braking systems, optimizing safety, power requirements and cost.

TABLE 3-3
Light Rail Maximum Main Track Gradients[1]

Desired Maximum Unlimited Sustained Grade, (any length)	4.0%
Desired Maximum Limited Sustained Grade (up to 2500 feet [750 Meters] between PVIs of vertical curves)	6.0%
Desired Maximum Short Sustained Grade (no more than 500 feet [150 Meters] between PVIs of vertical curves)	7.0%
Absolute Maximum Grade unless restricted by the vehicle design (acceptable length to be confirmed with vehicle designers)	9.0%

1. Excerpt from TCRP Report 155, Table 3.3.1

Accompanying the numbers presented in **Table 3-3**, TCRP Report 155 provides the following advice (which is especially relevant for the streetcar mode):

> There are ample examples of grades in existing LRT lines that are both steeper and longer than the desired figures given in Table 3.3.1. For that reason alone, the gradients and lengths above are general guidelines and, within reason, should not be considered as inviolate.
>
> Very long hills that incorporate multiple segments with gradients at or near the maximums should also be carefully coordinated with the vehicle engineers. For example, inserting a short segment of 2.0 % grade between two segments of 6% grade, each of which individually meets the maximum length criteria, does not necessarily mean that the vehicle won't have issues; for example the thermal capacity of the friction braking system. Engineering judgment, guided by an interdisciplinary systems approach and considering project and site-specific information, should govern, not arbitrary guidelines, such as the figures cited in Table 3.3.1.

3.1.2.2 Vertical Curves

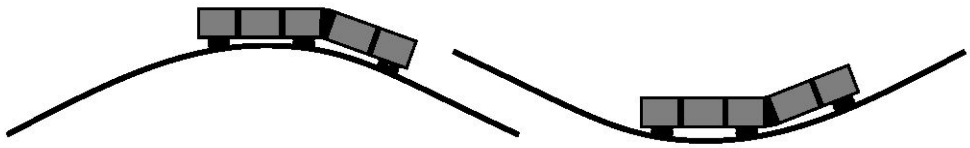
Changes in the grade of the trackway are connected by vertical curves. In a streetcar application, vertical curves are required to conform to the existing roadway pavement profiles, which may result in exceptionally sharp crest and sag conditions. A common vertical curve consideration for a streetcar alignment would be an overpass or underpass with sharp changes in the vertical profile of a roadway.

In setting minimum vertical curve values, consideration needs to be given to both passenger comfort and physical interference between vehicle and ground (including a worst-case condition of suspension system failure), as well as the maximum angle that the running gear can achieve relative to the carbody and the maximum angle that the articulation joint/gangway bellows can withstand.

Combinations of horizontal and vertical curvature are also likely in a streetcar alignment and should be reviewed with vehicle suppliers. Consideration must also be given to pantograph/OCS interface with regard to the maximum permissible rate of separation or convergence between the track grade and the contact wire gradient.

Table 3-4 presents the minimum vertical curve values given in several world sources. The Subcommittee's Carbuilder Survey (see Appendix 1) suggests that all of the standard vehicles included in the survey are capable of negotiating absolute minimum crests of between 820 to 1148 ft (250 to 350 m) and sags of between 820 to 1148 ft (250 to 350 m). Using an absolute minimum value of 1148 ft (350 m) for both crest and sag should therefore be sufficient to not preclude any of the current modern streetcar vehicle designs. The minimum undercar clearance of 2 in. commonly utilized in US practice should also be sufficient.

TABLE 3-4
Minimum Vertical Curve Radius[1]



Source	Vertical Curve Crest	Vertical Curve Sag
TCRP Report 155 (LRT)	820 ft (250 m)	1148 ft (350 m)
UITP (LRT)	2297 ft (700 m)	1148 ft (350 m)
BOStrab	2051 ft (625 m)	1148 ft (350 m)
LRTN Network Type A	410–820 ft (125–250 m)	820–984 ft (250–300 m)
Suggested guideline for new streetcar systems:	**1148 ft (350 m)**	**1148 ft (350 m)**

1. The cited U.S. light rail guideline (TCRP Report 155) provides considerably more tolerance for cresting than the UITP (European light rail) or BOStrab (German light rail) references. The Light Rail Thematic Network (LRTN) topic report “Derailment Prevention and Ride Quality” incorporates a distinction between streetcar/tramway mode (Network Type A) and light rail (Network Type B), and the Network Type A number is cited here.

GUIDANCE: UNIQUE ASPECTS OF STREETCAR TRACK DESIGN

Because of the inherent flexibility of the light rail/streetcar mode, it is *possible* to operate over extremely demanding alignments in terms of curvature and gradient. However, minimizing the use of such extremes brings numerous benefits in terms of passenger comfort, higher operating speeds, lower operating costs and the ability to purchase "standard" vehicles from multiple suppliers.

Worst-case design criteria should be applied only when general criteria will not produce a feasible design. Designers are advised to apply design minimums and maximums thoughtfully and in the context of a *system* approach that considers the vehicles to be used and balances operational benefits with the related trade-offs. For example, a short steep grade or sharp curve that allows an alignment to access a major source of ridership, or which might eliminate the need for an expensive infrastructure component such as a tunnel or flyover, could justify the associated trade-offs. At the other end of the spectrum, an alignment could become too flexible. If trying to please too many constituencies results in a circuitous route that offers poor connectivity to other transit services and is vulnerable to congestion, operating speeds and service reliability will suffer, potentially burdening the line with low ridership and high operating costs.

Designers should understand the inherent trade-offs and take a balanced approach to design; sharp horizontal curves are a trade-off with long-term costs for track and wheel maintenance as well as noise, operating speed and passenger comfort, and compatibility with standard vehicle designs. Overly broad curvature is a trade-off with space requirements / urban fit, potentially precluding certain alignment options or creating "corner clips" that could necessitate property acquisition. Steep gradients are a trade-off with vehicle cost, operating speed and maintenance costs. Overly-conservative gradient criteria may rule out certain otherwise beneficial alignment options.

"Urban Transit, Systems and Technology" (Vuchic 2007) provides another useful summation; "Easy fitting to the existing street networks and other convenient R-O-W facilities usually reduces investment costs but may not provide high system performance (speed, capacity, comfort). Independent alignment, on the other hand, requires higher investment but provides high performance and lower operating costs. Geometric standards of the alignment should be based on the trade-offs between these factors." Above all, whether an existing system introducing new vehicles, or a new start, a *system* approach is required; the parties responsible for vehicles and for infrastructure (especially track design) must be working in concert to produce optimum compatibility.

3.2 Unique Aspects of Streetcar Vehicles

Partial low-floor vehicles were introduced in Europe in 1984 and in the United States in 1997. Immediately prior to the advent of modern low-floor technology, the prevailing vehicle types were high-floor 4-, 6- or 8-axle configurations with rotating trucks. In contrast, today's modern streetcar vehicles are typically multi-articulated low-floor vehicles using short carbody sections. Low-floor sections of the vehicle use special running gear that is very different from the trucks found on a typical high-floor vehicle design. The characteristics of this running gear need to be taken into consideration during track design and maintenance.

3.2.1 The Continuing Evolution of Low-Floor Vehicle Designs

Section 1.5 "Partial vs. 100 Percent Low-Floor," provides an overview of basic low-floor vehicle configurations. For the introduction of the modern streetcar in the United States beginning in 2001, the prevailing approach was to utilize a short 66 ft (20 m), three-section, 50 percent low-floor design with two fixed motorized trucks. This concept of using a suspended carbody section between adjacent fixed-truck carbody sections has also been widely applied in other European designs, although typically in greater multiples within the same vehicle, meaning longer overall vehicle lengths with five or more sections.

100 percent low-floor vehicles are new to North America, although they have now been in service in Europe since 1990. Vehicle designs have evolved considerably since then and are continuing to do so. Running gear and articulation concepts in particular have progressed significantly based on carbuilder experience with earlier designs, although the fundamental challenge of trying to fit the running gear into very small spaces under the vehicle remains. Depending on the carbuilder, low-floor running gear will incorporate either independently rotating wheels (IRWs) mounted on cranked axles, or conventional wheels and axles.

The latest generation of European 100 percent low-floor vehicle designs are now incorporating adaptations of more conventional running gear arrangements, including fixed trucks that incorporate conventional axles in place of independently rotating wheels and, in a few cases, rotating trucks. Many of the running gear concepts prevalent in the first generation of low-floor vehicles (including very small-diameter wheels[18], body-mounted motors and self-steering wheelsets) are largely gone in the new designs. Noise and vibration generated by urban rail systems also continues to receive industry attention. Issues of particular relevance to low-floor streetcars include minimizing unsprung mass in running gear, optimization of resilient wheels, and the use of new on-board lubrication technologies.

3.2.2 Fixed vs. Rotating Trucks

The term "fixed truck" is used to distinguish from a conventional rotating truck; "fixed trucks" are, however, necessarily capable of some limited degree of rotational displacement relative to the carbody (typically less than 2 degrees in most designs, but up to 5 degrees in some cases)[19] through horizontal deformation of the secondary suspension. Most low-floor streetcars utilize fixed trucks for at least a portion of their running gear. Currently, many 100 percent low-floor designs use fixed trucks throughout the vehicle. 70 percent low-floor designs typically use rotating trucks at the outer ends of the vehicle and a fixed truck under the center section. 50 percent low-floor designs use two fixed trucks. The Subcommittee's Carbuilder survey (see Appendix 1) includes information about the running gear used on each of the vehicles.

With fixed trucks, the entire carbody section must move along with the truck when entering a curve, instead of being pulled over more gradually, as would be the case with a conventional rotating truck. For this reason, it is especially important that all mainline curves be appropriately spiraled in order to maintain ride quality and reduce lateral forces.

3.2.3 Track Twist and Wheel Unloading

Streetcar alignments must typically follow existing roadways through constrained urban areas. The crown and slope of existing roadway surfaces must be considered in order to ensure compatibility of the trackway with other traffic. Track twist (the rate of change of cross-level) can become a significant issue in streetcar trackway design. Under conditions where there are rapid variations in cross-level (as permitted by the governing track geometry standards) vehicle trucks and suspension need to provide sufficient wheel load equalization to permit the development of the steering forces required for curve negotiation. Excessive track twist can cause wheel unloading (and potentially clearance problems under the vehicle), a significant derailment risk factor. Modern multi-articulated vehicles, many of which have suspended carbody sections, may be relatively "inflexible" with regard to twisting movements, elevating the importance of the track twist issue.

[18] "Very small diameter" refers to wheel diameters less than 16.1 in. (410 mm), per TCRP Report 2, "Applicability of Low Floor Light Rail Vehicles in North America."

[19] In comparison, a conventional double-truck vehicle with 25 ft (7.62 m) truck centers (e.g., SEPTA single-ended Kawasaki streetcar) on a 35 ft (10.7 m) curve would have approximately 21 degrees of truck rotation.

GUIDANCE: UNIQUE ASPECTS OF STREETCAR VEHICLES

Track design for new streetcar systems should be undertaken specifically with the use of low-floor vehicle technology in mind. Track designers should understand that modern streetcar vehicles are significantly different from earlier vehicles, having evolved into designs with smaller body sections and a greater number of articulations, and incorporating special running gear to accommodate the low-floor section(s) of the vehicle. While modern low-floor vehicles have evolved considerably since their first introduction in 1987, these unique vehicle characteristics, when combined with the requirements to integrate the trackway with existing street geometry, impact several aspects of track design:

- Minimum horizontal and vertical curve radius
- Curve design, including the significance of spiral transitions, even where speeds are low and there is no superelevation present
- Newer vehicle designs may have a lesser degree of tolerance for track twist than conventional non-articulated designs

Because of their special running gear, modern low-floor designs may also present wheel/rail interface challenges when used on legacy systems, where track design criteria may be based around the use of a substantially different vehicle configuration. Trucks with IRWs may also be unable to reliably track through single-point turnouts, although these turnouts are now found only on a few legacy systems and are generally not used for new systems.

Track designers/maintainers should be aware of these issues and be governed accordingly.

3.2.4 Running Gear Maintenance

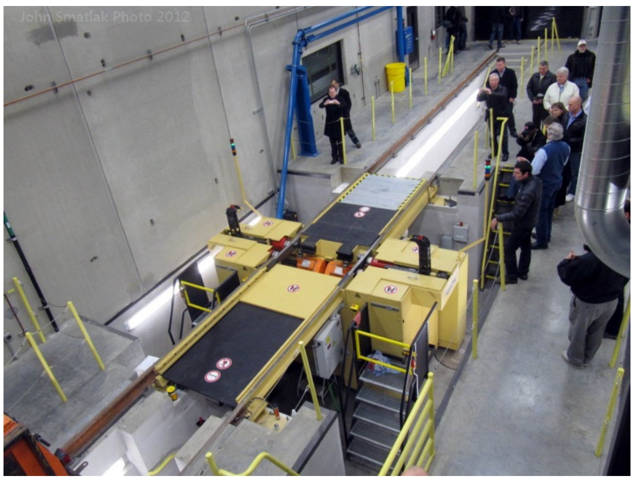
As with all rail transit vehicles, streetcar running gear components require frequent inspection, and wheels must be periodically machined to keep them within necessary dimensional tolerances for safe and quiet operation. Known as “wheel truing,” this process is done on a *mileage* basis that varies depending on local conditions, and also on a *corrective* basis when wheels are damaged by slid flats and other defects. The interval between wheel truings varies widely depending on local conditions but can be as frequent as several times annually under adverse conditions. Also of note, today’s low-floor vehicles utilize smaller wheel diameters than their high-floor predecessors; 23 - 26 in. (590-660 mm), compared to 28 in. (711 mm), which can contribute to a shorter wheel life.

Wheel truing can be performed on the vehicle using a wheel-truing machine installed in a pit under a track in the maintenance facility (**Figure 3-5**) (a.k.a. a “drive-over” or “underfloor” wheel-truing machine) or by use of a portable wheel-truing machine. Alternatively it may be performed off the vehicle by removing the trucks for truing in a facility equipped with an underfloor truing machine or by removing the wheels from the truck for truing in a wheel lathe.

The scale of wheel truing operations for a small system with only a few vehicles will understandably be different from that of a larger system. The first three U.S. modern streetcar systems that opened in the 2000s all began operations without a drive-over wheel truing machine. These relatively small startup systems relied instead on sending trucks to other local transit facilities and/or removing / replacing wheel tires from the trucks for truing (**Figure 3-6**). The type of running gear used and the small number of vehicles helped make this practical. The Portland Streetcar System added a drive-over wheel-truing machine as part of its system expansion in 2011.

The removal of trucks from a vehicle is a time-consuming process that will keep a vehicle out of service until it can once again be re-trucked and tested. Maintaining a float of refurbished spare trucks to allow a quick truck exchange will reduce the time the vehicle is out of service, but the process is still very labor intensive, and a complete set of spare trucks may themselves cost almost as much as a wheel-truing machine. When considering options for wheel truing on a new system, it is also important to consider the vehicle designer's intent. Many low-floor vehicles are designed to minimize the need to remove trucks from under a vehicle, with inspections and routine maintenance accomplished from an inspection pit with the trucks still in place under the vehicle. This design philosophy has, however, assumed the availability of a drive-over wheel truing capability.

FIGURE 3-5
Drive-Over Wheel-Truing Machine



A drive-over wheel-truing machine, Portland Streetcar.

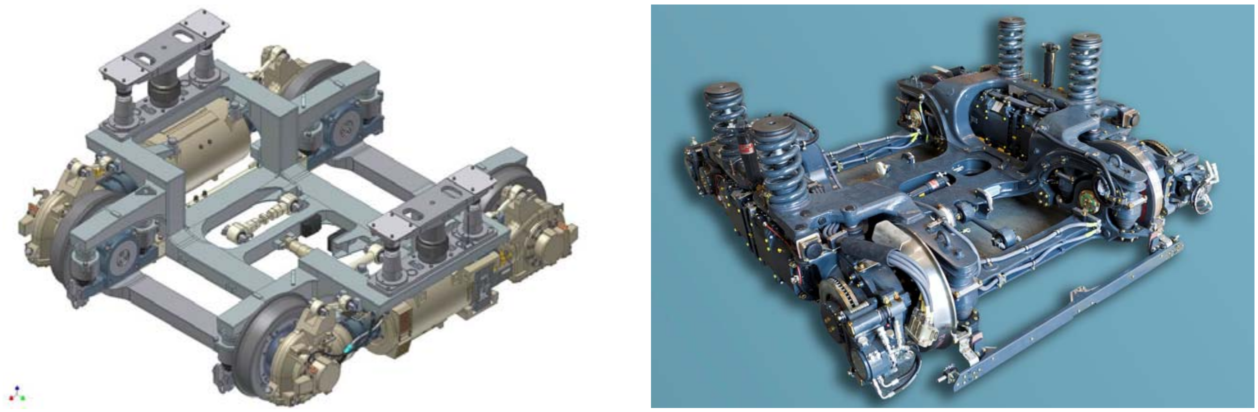
FIGURE 3-6
Inboard Bearing Truck with Wheel Tires Removed

On trucks with inboard frames and drive train components, removal of wheel tires is relatively straightforward, although some designs may have braking components outboard of the wheels that will also need to be removed.

Removal of individual wheel tires from trucks (**Figure 3-6**) may require the removal of other truck components in order to gain access to the tires. This process may be further complicated for running gear designs with drive components (traction motors and gearboxes) outboard of the wheels (**Figure 3-7**), as is common on 100 percent low-floor vehicles. In contrast, a drive-over wheel-truing machine simply requires that each of the wheel pairs needing truing be positioned over the cutting head for a few hours.

FIGURE 3-7

Running Gear for 100 Percent Low-Floor Vehicles



Graphics courtesy of Kinkisharyo and CAF

Running gear for 100 percent low-floor vehicles typically places the traction motors and drivetrain outside the wheels. This arrangement will complicate wheel removal and increase the importance of having a drive-over wheel-truing capability. Note also that in these designs the driven wheel pair may be on the same side of the truck, as opposed to opposite sides as in a truck using axles.

A drive-over wheel-truing machine has a significant capital cost, and due to its large size, foundation requirements and location under the rails, it will have a significant impact on facility design. Retrofitting one to an existing facility will likely be significantly more costly than incorporating one into the design of a new facility. Despite the initial capital cost, the payback on this investment can be significant on a life-cycle cost basis, because it allows wheels to be trued without removing the trucks from under the vehicle, saving both vehicle-out-of-service time and direct labor. It also facilitates the use of an overall wheel life management program wherein more frequent "maintenance" truings, with minimal depth cuts, are undertaken to extend the overall life of the wheels. Together with the strategic use of friction modifiers, such a program becomes part of an ongoing program of wheel and track maintenance that maintains the wheel/rail interface over the life of the system, extending the life of both, and helping minimize noise and vibration. As fleet size grows, the cost/benefit analysis for using the drive-over wheel-truing machine thus changes, effectively becoming the standard approach for large fleets.

In some circumstances, it may be possible to provide wheel truing on the vehicle using a portable wheel-truing machine. However, additional research is needed regarding the potential costs and benefits of using portable wheel-truing machines with low-floor streetcar vehicles. Many portable wheel-truing machines currently on the market are designed for heavy rail freight car/locomotive maintenance and would need to be carefully evaluated as to fitness for purpose.

GUIDANCE: STREETCAR RUNNING GEAR MAINTENANCE

Because wheel truing is a fundamental maintenance activity that will need to occur routinely throughout the life of the vehicle, it should be thoroughly considered during system design. The continuing evolution of low-floor vehicle and propulsion technology has also brought about changes in how streetcar running gear is inspected and maintained. Ease of access to running gear for inspection and wheel truing/change-out varies between different streetcar vehicle designs and should also be considered during facility design.

The following are the most common wheel-truing solutions.

On-vehicle:

- Using a drive-over wheel-truing machine
- Using a portable wheel-truing machine[20]

Off-vehicle:

- Removing entire truck assemblies from under a vehicle and either:
    - utilizing a portable wheel-truing machine to true wheels;
    - transporting the trucks to a location where there is a suitable wheel-truing machine; or
    - removing the wheel tires or the wheelsets from the truck, having them trued and then reinstalling them.

The off-vehicle alternatives require varying levels of truck disassembly. In general, use of a drive-over wheel-truing machine will be significantly more efficient than the other options. Although it has a significant capital cost, life-cycle cost savings over the other alternatives can be significant due to labor savings and the ability to maximize the useable life of the wheels. It is recommended that during the vehicle procurement process, carbuilder input be sought regarding wheel maintenance requirements and options.

[20] Whether or not it is possible to use a portable wheel-truing machine without removing trucks from under the vehicle depends on various factors, including truck configuration, pit configuration and the configuration of the portable wheel-truing equipment. Additional research is needed to further investigate the potential costs and benefits of using portable wheel-truing machines with low-floor vehicles.

CHAPTER 4: POWER SUPPLY

4.0 Introduction

This chapter is intended to provide an overview of basic traction electrification system concepts and their relation to new power supply technologies now being introduced for vehicle propulsion. It is not intended to provide detailed information on electrification system design and construction.

The term "power supply" is used to refer broadly to the various components comprising the Traction Electrification System (TES) and related apparatus on the vehicle. A conventional TES provides electrical power to the vehicles by means of the Traction Power System (TPS) (substations and related connections) and the Overhead Contact System (OCS) (overhead wires and related support structures).

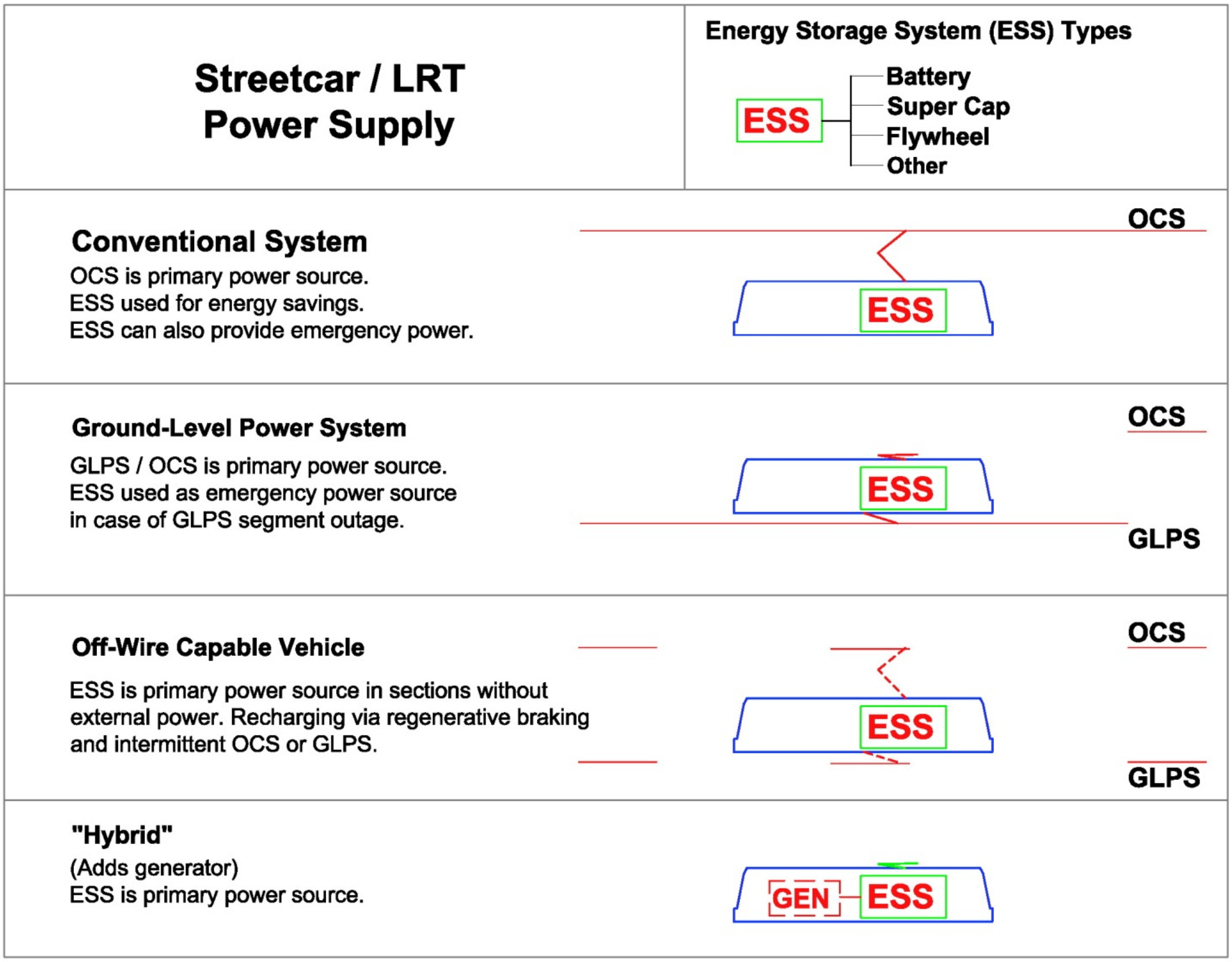
A TES is designed with consideration of a line's track plan and profile, operating plan (including the number of vehicles in operation at various times), climatic conditions and the specific vehicle(s) to be used. The number of traction power substations, their size and their locations are determined accordingly. The TES is designed to maintain line voltage within a specified range over the entire alignment under all operating conditions, without causing harmful heating of the wire or other adverse conditions that could shorten the life of system components. Computer simulations are typically used to model different operating scenarios (including operation with one or more substations out of service) and confirm design assumptions.

OCS has become accepted over the past 120 years as the preferred power distribution method for light rail and streetcar systems. However, several other options have recently entered the marketplace. New types of ground-level power supply systems are now in limited use, and onboard energy storage capabilities are becoming increasingly common to reduce energy costs. Also, some vehicles can now be equipped with enough energy storage capacity to permit short range (<1 mile [1.6 km]) off-wire operation[21]. Vehicles with longer off-wire range are also in development.

Figure 4-1 reviews the basic types of power supply now being applied to streetcar and light rail applications, highlighting how on-board energy storage is used in each case. The following sections of this chapter discuss these different systems in detail. More than any other section of this document, the power supply topic is the most fluid in terms of the speed with which the technology is evolving. Consequently, the content merely reflects the current state of the industry with regard to this topic, with the expectation that it may be distinctly different in the near future.

[21] As distinguished from "emergency" off-wire capability intended to permit a vehicle to clear an intersection in the event of a power failure or make other very short moves "off wire".

FIGURE 4-1
Streetcar / Light Rail On-Board Energy Storage



4.1 Operating Voltage and Current Collection

Beginning in the 1890s, streetcar systems adopted operating voltages of between 500 to 600 volts DC. Some rapid transit and interurban electric railways adopted higher voltages, but 600 volts was the most common and remains in use today on legacy systems throughout the world. The electric motors of the early 20th century streetcar fit into the trucks under the car floor, and voltage was limited by the practical diameter of the DC motor's commutator and the available insulating materials. With advancements in motor design and materials, it became practical to raise the voltage to 750 volts and higher. This higher voltage results in a lower current draw along the power distribution system while delivering equal power levels. Operating at lower current levels reduces the power loss due to electrical resistance in power supply lines. Therefore, for equal power availability, higher-voltage systems permit substations to be installed at greater distances apart.

Today, the most common traction power operating voltages for streetcar and light rail applications are 600 and 750 volts DC, with 750 volts being the most common in new systems[22]. 1,500 volt DC systems also starting to be applied in light rail projects. 750 volts is the most common for new systems. An important

[22] In response to the subcommittee's survey, carbuilders indicated that from a vehicle perspective, the choice of either 600 or 750 V power supply voltage was not a major issue.

consideration in selecting an operating voltage may be the presence of multimodal operation, i.e., jointly operating various types of vehicles such as light rail and trolley bus within a defined region. Adopting the same operating voltage as other systems in the region and establishing other compatible power supply design criteria could provide important benefits that should be fully explored during system planning.

Current collection for streetcar and light rail vehicles is typically by pantograph, although some North American legacy and heritage systems still use trolley poles. Trolley bus systems throughout the world also use trolley poles exclusively, due to the need to have separate positive and negative contact wires in close proximity and the ability for vehicles to deviate from the overhead alignment as they maneuver in traffic. Where the use of trolley pole current collection, particularly a trolley pole with a swivel head as used on trolley bus systems, might provide the ability to overcome operational limitations imposed by infrastructure clearances, their use should not be ruled out for a new streetcar system. As with other aspects of system design, a hazard analysis approach should be employed to evaluate their operational limitations in light of local conditions.

Nominal system wire height will vary somewhat based on local practice, but 19 ft (5.8 m) is a commonly used value. This value is higher than the 18 ft (5.5 m) minimum clearance required in the National Electrical Safety Code for use above streets, providing an allowance for wire sag between support points. Restricted vertical clearances are also common in urban areas, and streetcar alignments may need to pass under bridges and other low clearances. From a physical clearance standpoint, the minimum vertical clearance under which a streetcar vehicle can operate will be determined by the vehicle height plus the minimum *operating* height of the pantograph (as distinguished from *lockdown* height). This total height will be different for each vehicle type, but will generally be between 11 ft- 10 in. and 13 ft- 4 in. (3.6 and 4.1 m). Local roadway clearance regulations will also influence how low the overhead wire can be placed in such a situation. At the opposite end of the vertical clearance spectrum, where streetcar lines may cross a mainline railroad at grade, overhead wire height will typically need to be raised to between 22.5 and 23.5 ft (6.9 and 7.2 m) at the crossing. Wherever such extreme minimum and maximum clearances exist, this information should be included in the vehicle procurement documentation in order to inform consideration of pantograph operating range (see Section 1.1 “Duty Cycle”).

For purposes of charging on-board energy storage devices, there may be limitations on how much current can be drawn from a conventional overhead line while a vehicle is stationary vs. when it is in motion. Where the vehicle’s pantograph may be used for stationary charging of on-board energy storage devices, it may be necessary to modify the pantograph and/or overhead conductor designs to accommodate the high current levels required.

4.2 Energy Savings

Energy expense is a significant component of operating costs for electric transit. Modern streetcars with high-performance propulsion systems and air conditioning consume substantially more power than their predecessors from the first half of the 20th century. As a result, the rail transit industry has devoted substantial attention to weight-reduction and energy-saving technologies in recent decades.

Energy recovery through regenerative braking is the most mature of the energy-saving technologies applied to electric railways[23]. It permits electricity generated by traction motors acting as generators during the braking cycle to be redistributed back through the OCS and made available to other vehicles nearby that need more current during acceleration. Newer technology is now being applied to capture and reuse the generated braking energy even when there are no other vehicles in the vicinity. Both stationary (wayside) and mobile

[23] Electric (motor) braking is used on virtually all modern electric transit vehicles. It has multiple benefits, including a significant reduction in the need for friction braking, with attendant maintenance cost savings.

(on-board) energy storage technologies have advanced substantially in recent years and can provide numerous benefits in addition to reducing a system's overall energy consumption.

The start-and-stop nature of streetcar operations are particularly well suited for use with on-board energy storage systems, because the frequent braking presents ample opportunity for energy recovery. Mobile energy storage is also being used to improve performance in conventionally powered systems, for example by reducing current peaks during acceleration, reducing demand and potentially permitting smaller substations to be used. From these technologies, the off-wire capable vehicle has been developed (see Section 4.3, "Off-Wire Capability").

Where conventional regenerative braking is in use, OCS voltage may be raised considerably above the nominal voltage during the times that vehicles are braking. The degree to which the added power corresponding to this voltage increase is used depends on the range in voltage limits permitted by the vehicle propulsion design, as well as the supply line electrical receptivity. In all cases, other vehicles operating on the same line must be designed to withstand these higher voltages. For this reason, the "Duty Cycle Checklist" in Section 1.1 notes that data relating to regenerative braking operations should be included in the description of a line's operating characteristics.

4.3 Off-Wire Capability

4.3.1 OCS Aesthetics

The OCS system of power distribution is well proven and non-proprietary, with components available from multiple suppliers. The principal objections to it, where they exist, are aesthetic. Good OCS design practice recognizes the importance of context-sensitive aesthetics and treats in-street and other sensitive areas accordingly. Where this effort is not made, whether for cost or other reasons, the resulting installations can be seen by the public as inappropriate for their surroundings and generally unattractive (**Figure 4-2**).

OCS design is also an iterative process that must be closely coordinated with track design and other alignment elements. TCRP Report 7, "Reducing the Visual Impact of Overhead Contact Systems," advises that "the visual impact of OCS can only be reduced if such reduction is made a specific goal throughout the design process." Commonly used approaches for improving OCS aesthetics include minimizing pole counts by using alternative anchor points on buildings and other structures, and by combining lighting, traffic signal and OCS poles where possible. Synthetic span wires (whose insulating properties may permit a reduction in the number of fittings) have also been used as the basis for more aesthetically pleasing designs (**Figure 4-2**).

FIGURE 4-2
Two Ends of the Spectrum of OCS Aesthetics

At left, a heavily built catenary type overhead that overwhelms a street setting. At right, minimalist overhead optimized for urban application, in this case incorporating anchor points on adjacent buildings in order to minimize pole count.

For urban streetcar applications, a single contact wire over each track (instead of a multi-wire "catenary" arrangement) is acceptable operationally[24], though it requires a greater number of support points. When using a single contact wire, current draw considerations may also require the additional expense of an underground parallel feeder, but this item has a long, low maintenance life, and cross connections to the contact wire can be neatly handled. Alternately, some new streetcar systems use "feederless" systems that use a larger number of small, closely spaced substations in place of a parallel feeder[25].

4.3.2 Off-Wire Capability

Although OCS is the most common and reliable method of power distribution, developing technology is now offering some significant new options. Technology advances originally driven by the need for energy savings, combined with the desire to eliminate the visual impact of overhead wires in certain areas, have led to the development of "off-wire capable" vehicles. This term refers to a vehicle that can operate from traditional OCS (or ground-level power system) as well as over line segments that have no external power supply. The elimination of overhead wires may be desired for aesthetic concerns in a historically sensitive area or for route optimization (e.g. simplifying a complicated OCS junction or other wire arrangement, mitigating conflicts with traffic signal infrastructure, or to permit an alignment to pass under a severely restricted vertical clearance such as a low bridge).

Off-wire operation is accomplished through some form of mobile (on-board) energy storage. Systems based on batteries and/or super-capacitors are the most common at this time, although other technologies including flywheels are also in development (with prototype vehicles now in use). The vehicle's energy storage devices are recharged en route by capturing the energy generated during the vehicle braking cycle and when the vehicle is operating on powered alignment sections. Stationary "charging stations" can also be used, typically in conjunction with passenger stops or terminal locations where vehicles will normally be stopped anyway.

[24] The stability of multi-wire catenary-type OCS offers significant benefits for higher-speed operation, but this is not of major value in the speed range and single-unit operation encountered in the typical streetcar operation.

[25] "Feederless Traction Power Design Considerations for New Streetcar Lines," Collins, Ueno, Transportation Research Circular E-C058, 2003.

A vehicle's off-wire "range" will depend not only on the specific technology employed, but also on the characteristics of the particular route. Operating conditions, including acceleration requirements, grades and climatic conditions requiring air conditioning or heating will thus have a significant influence on vehicle range and the longevity of energy storage components. Vehicle energy storage and management systems are typically optimized according to the requirements of a particular application, with designers seeking to balance space, weight and performance requirements. Sizing of batteries, for example, is based on the need to limit discharge levels in order to maximize their operating life. Importantly, while operating off-wire, vehicles will typically operate in a reduced performance mode in order to reduce energy consumption and lengthen range. Acceleration rates may be reduced, and the vehicle will automatically begin "load shedding", for example by reducing or turning off HVAC equipment.

4.3.3 Extended Range Off-Wire Operation

Regular operation through short "wire free" segments of otherwise conventional tramway lines has already begun to occur in Europe. Nice, France[26], has operated two short wire-free segments (0.27 and 0.3 mi) since 2007. Seville, Spain, has had a 0.28 mi (450 m) off-wire segment in operation since 2010 and Zaragoza, Spain began operating with a 1.25 mi (2 km) off-wire section starting in 2012. Other systems with off-wire segments are now under construction, including the First-Hill Line in Seattle, Washington. Extended testing of off-wire capable vehicles in regular service has also been conducted in several other European cities and a prototype vehicle toured several U.S. systems in 2011.

Market interest has also been focused on extending off-wire range. The development of an off-wire capable vehicle with enough range to permit an entire line to be operated without overhead or ground level power supply, other than where minimally necessary for charging purposes, is also being pursued. A commonly discussed scenario in the United States is a short (<3 mi) circulator system operating with a small number of vehicles. As of this writing, numerous prototype vehicles have successfully operated off-wire for distances as long as 5 mi (8 km) in tests, but no such systems are yet in revenue service.

A "wire free" line would still need power and related distribution (either OCS or a Ground Level Power System) at certain locations for charging purposes. Anticipating that extended charging periods may be required at the end of a run, an operational analysis should be conducted (taking into account vehicle range and charging times) to determine whether or not extra vehicles might be required to maintain the desired headway and schedule.

Additionally, the potential for system expansion should also inform decision-making concerning potential cost-saving measures for infrastructure construction. For track construction, for example, because an off-wire capable vehicle does not return propulsion current through the rails when operating off-wire, stray current concerns would theoretically be eliminated for line segments operated in this manner. Thus it might be argued that track construction could forgo electrical isolation and bonding of rails and other measures relating to stray-current safeguards, reducing construction costs. However, what might start out as a single isolated line might later be incorporated into a larger system. Consideration should be given to the realities of using such track if future expansion someday justified conversion to wired operation. It would not be practical to change such fundamental aspects of embedded track by retrofit, so this issue would need to be decided during system planning.

Finally, another option for extending the range of off-wire operation is the "hybrid" vehicle, which augments the energy storage system with some type of on-board power generation (a fuel-electric generator or a fuel

[26] Opened in 2007, the 5.4 mi Nice tramway line passes through two historic city squares, where conventional OCS was considered to be unsuitable. It was also desired to permit unimpeded passage of parade floats through these squares. Use of a ground level power supply system, an approach used successfully in other French cities, was originally considered, yet the relatively short distances for off-wire operation (0.27 and 0.3 mi), led to the decision to use on-board nickel metal hydride battery power. The relatively long sections of conventional OCS on the line provide for ample charging time.

cell) in order to create an autonomous vehicle. In the United States, a few such vehicles have been developed experimentally in the form of heritage trolleys for use in tourist-orientated operations. These examples do not have air conditioning requirements and have a less-demanding duty cycle than would be encountered in full-scale transit operations. Other experimental hybrid rail vehicles have also been developed in Europe. As of this writing, the hybrid concept has not evolved beyond a small number of rail vehicles, although hybrid transit buses are increasingly common.

4.3.4 Comparing Systems

Cost issues are frequently cited when comparing conventional and off-wire capable vehicles. The related capital and maintenance costs will be saved for line segments without OCS or ground-level power supply (although charging infrastructure cannot be overlooked) and impacts on other infrastructure such as traffic signals may also be significantly reduced. However, while infrastructure may become less costly to build and maintain, the opposite will happen to the vehicle; it will become more technically complex and may also become heavier (how much heavier depends on the type of energy storage equipment used and any offsetting weight changes made), more costly to purchase and maintain, and operationally less flexible (because of the potential impacts on interior layout or rooftop equipment space due to added energy-storage equipment, the need for recharging, and any impacts on performance required to maximize range).

For these reasons, system size and future expansion impact the comparison of power supply options. The cost-benefit analysis for conventional overhead wire vs. off-wire capable vehicles changes as larger numbers of vehicles are needed. The costs for an OCS alternative remain relatively fixed regardless of the number of vehicles in use, whereas the costs for the off-wire vehicle alternative rise significantly with each vehicle needed. A 2 mile system with only a few vehicles and 20-minute headways would thus be a different equation than a 6 -mile system with 20 vehicles running on five-minute headways.

As with other aspects of system design, the different power supply options and energy storage technologies each have different advantages and disadvantages, and each should be examined in light of local operating conditions. It is also important to make all technology comparisons on the basis of life-cycle cost, incorporating consideration of any energy savings as well as maintenance costs over the life of the system. This is especially important with consumable energy-storage devices (e.g., batteries and super-capacitors), which will have a finite number of operating cycles and a substantial replacement/disposal cost. The impact of "real-world" operating scenarios on the life of system components must also be considered, understanding that in transit operations it may sometimes be necessary to push these components beyond "theoretical" normal levels of use.

Finally, it should be noted that energy storage technologies for transport application are evolving very rapidly, being driven largely by other industry sectors, such as the electric car. The costs and capabilities of different solutions are continuously changing, as are energy costs. Despite the high number of suppliers competing in this market, only a relatively limited number of systems have actually been put into revenue service. The reason is that even though the potential benefits have been clearly demonstrated, at this time most technologies are still at an early phase of development, with many still in the prototype stage. This makes investment decisions difficult for project proponents due to the lack of industry experience, and uncertainties about return on investment and long-term risks of potentially "orphan" technologies.

Costs are generally expected to decrease as the market expands and the technology continues to improve; component suppliers are expanding the power and range of storage devices while reducing their weight, size and cost. The streetcar of 10 years from now may therefore be very different from the vehicle of today in terms of its energy-storage capabilities. The ability to add energy-storage equipment to the vehicle in a manner that minimizes the risks associated with the use of proprietary technology is also an important consideration. Some carbuilders are in fact stating that their energy-storage products are suitable for retrofit to not only their own vehicles, but to vehicles from competitors as well. In general, a modular approach to adding technology, removable without affecting other aspects of vehicle performance, is highly desirable.

GUIDANCE: POWER SUPPLY

More than any other section of this document, the power supply topic is the most fluid in terms of the speed with which the technology is evolving. The streetcar of 10 years from now may therefore be very different from the vehicle of today in terms of its energy-storage capabilities. Important principles include the following:

- **OCS aesthetics matter.** OCS has become accepted over the past 120 years as the preferred power distribution method for light rail and streetcar systems. The principal objections to it, where they exist, are aesthetic. Good OCS design practice recognizes the importance of context-sensitive aesthetics and treats in-street and other sensitive areas accordingly.

- **Energy storage has multiple roles.** Some alternatives to using only OCS power distribution have now entered the marketplace. New types of ground-level power supply systems are now in limited use, and onboard energy storage capabilities are becoming increasingly common to reduce energy costs. Also, some vehicles can now be equipped with enough energy storage capacity to permit short range off-wire operation. Vehicles with longer off-wire range are also in development.

- **Examine life-cycle cost when comparing technologies.** When considering off-wire capable vehicles, recognize that while infrastructure may be made less costly to build and maintain, the opposite will happen to the vehicle; it will become more technically complex, and may also become heavier, more costly to purchase and maintain, and operationally less flexible. For these reasons, system size and future expansion impact the comparison of power supply options. The cost analysis for conventional overhead wire vs. off-wire capable vehicles changes as larger numbers of vehicles are needed. The costs for an OCS alternative remain relatively fixed regardless of the number of vehicles in use, whereas the costs for the off-wire vehicle alternative rise significantly with each vehicle needed.

  Operating scenarios for off-wire capable vehicles must also take charging time into account and recognize that vehicles typically need to operate in a reduced performance mode when "off wire" in order to reduce energy consumption and lengthen range. It is also important to make all technology comparisons on the basis of life-cycle cost, incorporating consideration of maintenance costs over the life of the system. This is especially important with consumable energy-storage devices (e.g., batteries and super-capacitors), which will have a finite number of operating cycles and a substantial replacement/disposal cost.

- **Apply new technology in a manner that minimizes impacts of proprietary designs.** Because energy storage systems are still largely in a developmental stage, they can be expected to continue changing rapidly as the technology evolves. The ability to add energy storage equipment to the vehicle in a manner that minimizes the risks associated with the use of proprietary technology is therefore an important consideration.

4.4 Ground-Level Power Systems

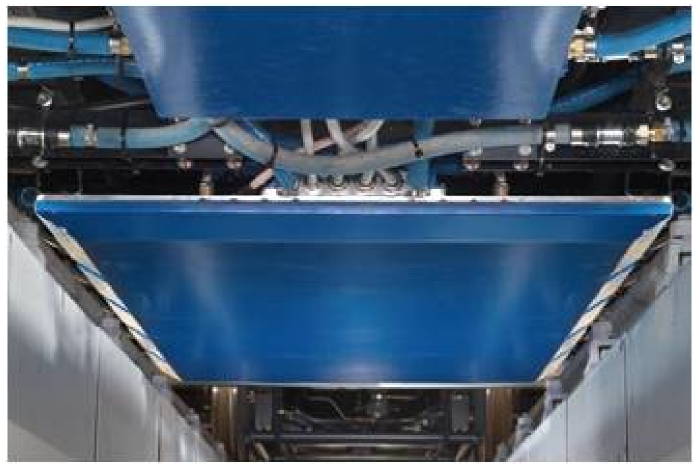
Ground-level power systems (GLPS) are external to the vehicle and require specialized infrastructure and vehicle equipment. Ground-level systems use a segmented power rail or induction coil system, located between the running rails and energized only when a vehicle is present.

The ground-level power system can be provided as either a "contact" or a "contactless" type of system. In a contact type system, a pickup shoe rides along the surface of a power rail. In a contactless system, the electrical connection between vehicle and guideway is provided using induction technology (**Figure 4-3** and **Figure 4-4**).

FIGURE 4-3
Sample Section of "Contactless" Guideway

"Contactless" ground-level power supply uses embedded induction coils installed on portions of the alignment. Here the front portion of the guideway sample is sectioned to show the coils.

FIGURE 4-4
Vehicle Pickup



Pickup for the "contactless" ground level power supply. Wayside inverters convert the 750 V DC from the substation to three-phase AC for transmission to the vehicle.

Ground-level systems effectively take the traditional overhead power source and locate it in the ground instead. Unlike an OCS system, however, power must be switched on only when a vehicle is present over one or more of the short segments, resulting in significant added complexity. The system still requires traction power substations and related electrical distribution found in a conventional TPS, and in a contact-type system, propulsion current is still returned via the running rails as with an overhead contact system. The ability to use regenerative braking to return energy to the power distribution system is lost with ground-level power supply, although as covered in the following paragraphs, this energy may be captured instead by on-board energy storage.

The first modern ground-level power system[27] had its commercial debut in Bordeaux, France, in 2003, and is a contact type system (**Figure 4-5**). The typical application of this technology to date has been to portions of a system otherwise equipped with traditional OCS, although it has been announced that the first system designed to use entirely ground-level power supply is to be built in Dubai. To date, all of the contact-type ground level power systems are installed in a "continuous" fashion, referring to the fact that the guideway power source is present over the entire "wire-free" portion of the alignment. The vehicles used with all of the

[27] Ground-level power supply was used for some U.S. and European streetcar systems beginning in the 1890s. Most were quickly replaced with overhead line, but some systems retained ground-level power until abandoned (Washington, D.C., and Bordeaux, France, being two examples). Unlike modern GLPS, these earlier systems used separate positive and negative conductor rails that were not switched on/off as vehicles passed, necessitating their placement in complex below-ground infrastructure.

contact-type systems are also equipped with batteries as a backup power supply should individual power segments fail to operate.

For the "contactless" type ground-level power system, vehicles are anticipated to be equipped with enough on-board energy storage capacity in the form of batteries to permit guideway power elements to be installed only over portions of the alignment (a non-continuous format). Based on an analysis of alignment characteristics, ground power will be located at station and other stop locations, as well as over segments where vehicles will be accelerating away from stops, climbing grades or other locations with high power demand. The on-board batteries will provide all power over the remaining unpowered portions of the alignment. By keeping the amount of guideway power infrastructure to a minimum (a target of only 25 percent of the alignment is sought, the remaining 75 percent using battery power), this technology seeks to reduce infrastructure costs for ground level power supply (as compared to the contact-type systems, which utilize a power rail continuously throughout all "wire free" sections of the alignment).

FIGURE 4-5
Ground Level Power System

Bordeaux, France, makes extensive use of a ground-level power system through several historic districts. Use of a ground level power system complicates trackwork. Special designs are required to permit the contact rail to cross over the running rails. The power rail stands 0.5 in. (12 mm) above the road surface, and installations to date have avoided placement in mixed traffic lanes.

GUIDANCE: GROUND LEVEL POWER SYSTEM

Ground-level power supply systems are external to the vehicle and require specialized infrastructure and vehicle equipment. Ground-level systems use a segmented power rail or induction coil system, located between the running rails and energized only when a vehicle is present. Ground-level systems effectively take the traditional overhead power source and locate it in the ground instead. Unlike an OCS system however, power must be switched on only when a vehicle is present over one or more of the short segments, resulting in significant added complexity.

Due to their technical complexity, ground-level power systems cost significantly more than conventional OCS at this time. They are also highly proprietary, potentially complicating system expansion. To date, all such systems have had vehicles and guideway power infrastructure sourced together as a system from a single supplier. Ground level power also makes the track engineer's and installer's jobs significantly more challenging, particularly if it must be installed where special trackwork is involved, due to the complexity in routing the guideway power source (**Figure 4-5**). Although there is now a system that has proven itself in Europe, it has not yet been approved for use in the United States, so at this time it should be anticipated that such a system will also require a more substantial safety certification effort than a traditional OCS system.

As with all new technology, it can also be expected that ground-level power systems will continue to evolve as additional experience is gained. The one technology that has already entered commercial operation has in fact developed a second generation of equipment, incorporating lessons learned from the initial installations. It is, however, notable that at this time, the four existing, and two planned or under-construction ground level supply systems[28] (all from the same supplier) are all located in climates without heavy snowfall. How well ground level systems will work in areas with heavy snow, ice, high rainfall or heavy leaf-fall is not yet known.

[28] Ground-level power supply systems in operation in 2012 (distance shown is route kilometers with GLPS): Bordeaux (13 km), Angers (1.5 km), Reims (2 km), Orleans (2 km). Planned/under construction: Tours (1.8 km), France, and Dubai, UAE (10 km). Total mileage: 29.3 km

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6.0 Abbreviations and acronyms

ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
AVL	automatic vehicle location
BRT	bus rapid transit
CCTV	closed-circuit television
CFR	Code of Federal Regulations
FTA	Federal Transit Administration
GLPS	ground-level power system
IRW	independently rotating wheel
LRTN	Light Rail Thematic Network
LRV	light rail vehicle
MTBF	mean time between failure
OCS	overhead contact system
PCC	Presidents' Conference Committee
TCRP	Transit Cooperative Research Program
TES	traction electrification system
TPS	traction power system
TWC	train-to-wayside communication
UITP	L'Union Internationale des Transports Publics (International Association of Public Transport)

7.0 Glossary

100 percent low-floor: See *low-floor, 100 percent.*

Americans with Disabilities Act of 1990 (ADA): Federal law that requires that facilities and services be made accessible to individuals with disabilities.

AW0: Weight of empty, ready-to-run vehicle.

AW1: AW0 plus full seated load, including crew.

AW2: AW1 plus standees at 4 passengers m^2

AW3: AW1 plus standees at 6 passengers m^2

AW4: AW1 plus standees at 8 passengers m^2

boarding, level: Boarding from a platform that is at the same level as (or slightly lower than) the low-floor portion of the vehicle. Used to improve accessibility and to speed boarding, especially for passengers using wheelchairs or other mobility aids, as well as passengers with strollers or carrying belongings.

boarding, fully level: Boarding from a platform that is at the same level as the vehicle's low-floor section (typically 14 in.).

boarding, near-level: Boarding from a platform that is slightly lower (typically 3–6 in.) than the vehicle's low-floor section. A bridgeplate is provided as a boarding aid at the vehicle's accessible doorways.

bridgeplate: A manual or automatic retractable ramp on a low-floor vehicle that is used as a boarding-assistance device in conjunction with a near-level platform.

car: Rail vehicles are often referred to as "cars".

carbuilder: General term for a supplier of complete rail transit vehicles.

closed circuit television (CCTV): A security camera system.

clearance envelope: The space occupied by the maximum vehicle dynamic envelope, plus effects due to curvature and superelevation, construction and maintenance tolerances of the track structure, construction tolerances of adjacent wayside structures, and running clearances.

crash energy management: A method of design and manufacture of vehicle structures that enhances crashworthiness by assigning certain sections of the carbody the task of absorbing a portion of the energy of collision by crushing in a controlled manner in order to preserve occupant volume and minimize the consequences of occupant impacts with the vehicle interior. The controlled crushing and energy absorption functions are typically assigned to special carbody structural members in the structural energy absorption zone that are designed to crush in a predictable and stable manner over a distance that depends on the design of the member and the desired amount of energy absorption. The use of supplementary energy-absorbing element(s) may be specified.

crashworthiness: The ability of a carbody to manage the energy of collision while maintaining structural integrity, so as to minimize casualties to occupants, other vehicles, and pedestrians.

diesel light rail vehicle: A light rail vehicle that uses a diesel-electric generator as its primary power source.

door threshold extension: A short fixed floor extension at the vehicle doorways that helps close the gap between the vehicle and the platform, while still allowing reasonable speeds to be achieved if not stopping. Typically made of a resilient material to limit damages in case of accidental interference with a foreign object or the platform.

double-ended: A vehicle with an operating cab at each end; also called bi-directional. Double-ended vehicles are normally also double-sided. See also *single-ended*.

double-sided: A vehicle with doors on both sides. See also *single-sided*.

duty cycle: The operating conditions to which a transit vehicle is subject. Includes factors such as daily service duration, stops per mile, grades, climatic conditions, etc.

dwell time: The time a transit vehicle spends at a station stop, measured as the interval between its stopping and starting times.

dynamic envelope: The maximum space that the vehicle will occupy as it moves over the track. Includes overhang on curves, lean due to the action of the vehicle suspension and track superelevation, track wear, wheel/track spacing, and abnormal conditions that may result from failure of suspension elements.

emergency off-wire capability: On-board energy storage intended only for making very short moves "off wire" (<656 ft [200 m]) such as permitting a vehicle to clear an intersection in the event of a power failure, to bypass a dead segment in a ground-level power supply system, or to make a short move inside a maintenance facility.

end change: The process of changing the vehicle's operating direction. The operator moves from one operating position (cab) to the other, switching required control, communication, lighting and other directional functions in the process.

fixed truck: See *truck, fixed.*

fully level boarding: See *boarding, fully level*

gong: An electronic or electromechanical bell installed on a streetcar or a light rail vehicle that can be rung at different rates depending on how rapidly the operating pedal or button is depressed. The bell sound produced is intentionally distinctive compared with audible warnings emitted by other road vehicles.

gradability: A vehicle's ability to climb and descend grades in a controlled manner

ground-level power system (GLPS): An external power system for electric vehicle propulsion located on the guideway directly beneath the vehicle's path of travel. The guideway power source is divided into segments that are shorter than the vehicle length, and for safety reasons these individual segments are energized only when a vehicle is over one of them. Can either be a contact or contactless type system; in the contact type, a pickup shoe rides along the surface of a power rail, and in a contactless type the electrical connection between vehicle and guideway is provided through inductive transmission technologies.

hybrid vehicle: An off-wire capable vehicle that is also equipped with an on-board energy generation capability arranged to automatically charge the vehicle's energy storage devices. Energy generation can be provided by a fuel-electric generator, hydrogen fuel cell or other suitable method. The hybrid vehicle can operate indefinitely without the use of an external power supply, provided that the generator or other on-board energy source is kept operating. The hybrid vehicle is distinguished from a diesel light rail vehicle by virtue of the fact that the generator is used only to charge the on-board energy storage device, as opposed to being the primary power source.

island platform: See *platform, island.*

legacy system: One of the relatively small number of streetcar systems that was not entirely replaced with buses, being kept in continuous service into the present day. In some cases, all or a portion of the system has been upgraded to light rail standards. Legacy systems in the United States and Canada include Boston, Cleveland, New Orleans, Philadelphia, Pittsburgh, San Francisco and Toronto.

level boarding: See *boarding, level.*

light rail: A form of urban rail public transportation that generally has a lower capacity and lower speed than heavy rail metro systems, but higher capacity and higher speed than streetcar systems. The term is typically used to refer to rail systems with rapid transit-style features that usually use electric rail cars operating mostly in private rights-of-way separated from other traffic but sometimes, if necessary, mixed with other traffic in city streets.

line-of-sight operation: A method of rail vehicle operation using manual control, with vehicles operated at a speed that will allow the operator to identify, react and stop short of any obstruction ahead. This is the typical method for operating streetcars, and for light rail when operating in street-running alignments.

low-floor vehicle: A light rail or streetcar vehicle with a low floor in either all or part of the passenger compartment for level boarding. Floor height in the low-floor section is typically 14 in. (355 mm) at doorways, designed to interface with a platform or raised curb of between 8 and 14 in. for boarding. Wheelchair access is provided directly or by a retractable bridgeplate.

low-floor, partial: A vehicle with a low floor in only a portion of the interior (typically 50 to 70 percent of the total length of the passenger compartment). Has internal steps to access the high-floor area(s) over trucks. In this way, conventional trucks and suspension elements can be used at the outer ends of the vehicle.

low-floor, 100 percent: A vehicle with a low floor throughout the interior. A 100 percent low-floor vehicle has no internal steps in the passenger compartment, but the floor may be ramped. There may be a step up into the cab area. This type of vehicle requires the use of special running gear, because the floor structure occupies the space that would normally be used by conventional running gear.

nearly level boarding: See *boarding, nearly level.*

off-wire capable vehicle: A light rail or streetcar vehicle that is capable of operating both from an external power supply (either overhead contact system or ground-level power supply), or from on-board energy storage. The on-board energy storage can be provided (either alone or in combination) by batteries, super capacitors, a flywheel or other means. Recharging the on-board energy storage is accomplished by capturing regenerative braking energy and by use of external power supply sources, including overhead contact system or ground-level power supply, while the vehicle is in motion and/or while stopped.

overhead contact system (OCS): That part of the traction electrification system comprising the overhead conductors (or single contact wire), aerial feeders, overhead contact system supports, foundations, balance weights and other equipment and assemblies, which delivers electrical power to non-self-powered electric vehicles.

PCC (Presidents' Conference Committee) car: A type of streetcar first produced in 1935. Its performance and efficiency were significantly improved over those of any streetcar previously built. The PCC car, characterized by lightweight, streamlined construction; smooth and rapid acceleration and deceleration; and a soft ride, became the standard for U.S. streetcars for many years. About 5,000 PCCs were manufactured in North America, and 15,000 in Europe.

platform, center: A passenger platform located between two tracks so that it can serve them both.

platform, island: A passenger platform located between traffic lanes in the street, serving one track, as distinguished from a center platform serving two tracks. Often protected with signage and/or physical barriers for the protection of passengers.

platform, side: A passenger platform located to the outside of the tracks, as distinguished from a center platform located between the tracks.

rotating truck: See *truck, rotating.*

running gear: The system of parts that provides safe motion of the vehicle along the track. Includes such components as wheels, axles (where used), suspension, brakes, traction drive, and the means to transmit traction and braking forces to the carbody.

schedule speed: The one-way distance between terminals divided by the scheduled travel time between the terminals, exclusive of layover or recovery time.

single-ended: A vehicle with an operating cab at one end; also called unidirectional. See also *double-ended*.

single-sided: Vehicle with doors on only one side. Such vehicles are typically also single-ended. See also *double-sided*.

slid flat: Wheel defect caused by skidding or sliding, resulting in a flat spot on the wheel tread.

streetcar: A form of urban rail public transportation operating entire routes predominantly on streets, often in mixed-traffic. Typically operates with single-car trains powered by an overhead contact system and with frequent stops.

switch splitting: A type of derailment in which the vehicle's trucks follow different paths at a switch. Often damages the vehicle by subjecting the trucks to excessive rotation and may also cause them to derail.

track twist: The rate of change of track cross-level.

traction power system (TPS): Comprising the Traction Power Substations (TPSS) and the Traction Power Feeder System (TPFS) (i.e. duct banks and traction power feeder and return cables).

train-to-wayside communication (TWC): General term used to describe a system of communication between the vehicle and wayside track and signal apparatus. In the streetcar mode, TWC is used primarily for traffic signal interface and may also be used for route selection. Can be implemented with various technologies, including optical and inductive systems.

traction electrification system (TES): The entire system used to transfer power from the local power utility to the vehicle, comprised of the Traction Power System (TPS) and the Overhead Contact Systems (OCS) and/or ground level power supply (GLPS).

truck: (bogie, *British usage*) Rail vehicle component that consists of a frame, wheels, axles (where used), brakes, suspension, and other parts, which supports the vehicle body. Powered trucks also contain traction motors and related drive elements. See also *truck, fixed* and *truck, rotating.*

truck, fixed: As distinguished from a rotating truck. A truck capable of only a limited degree of rotation relative to the carbody (typically less than 2 degrees in most designs, but up to 5 degrees in some cases). (In comparison, a conventional double-truck vehicle with 25 ft [7.62 m] truck centers (e.g. SEPTA single-ended Kawasaki streetcar) on a 35 ft [10.7 m] curve would have approximately 21 degrees of truck rotation).

truck, rotating: As distinguished from a fixed truck. Rotating trucks are designed to rotate under the vehicle on curves.

wheel unloading: A vehicle condition in which one or more wheels bears less than its normal, static vertical load (nominal wheel load or NWL) because of anomalies in the suspension and/or track geometric features such as excessive twist. Problems arise when the vertical load decreases but the lateral load does not, as in curving, as the L/V ratio can rise to unsafe levels and increase the danger of derailment. APTA Standard SS-M-014-06 describes wheel unloading (WUL) as: "Wheel load difference as a percentage of NWL; [WUL = {(NWL-WL)/NWL} x 100]", with WL being the actual vertical load on the wheel of interest.

8.0 Summary of changes

This is a new document, hence no changes.

9.0 Document history

Document Version	Working Group Vote	Public Comment/ Technical Oversight	CEO Approval	Policy & Planning Approval	Publish Date
First published	Nov 29, 2012	Dec 10, 2012	February 2013		

Appendix 1: Carbuilder survey

In conjunction with developing this Guideline, the APTA Streetcar Subcommittee has also conducted a Carbuilder Survey. The purpose of the survey is to gain an understanding of the range of low-floor streetcar vehicles currently being offered to the North American market. By applying a standard format to all information received, the survey facilitates direct comparisons between different vehicles. It also helps differentiate between "standard" features/options readily available to customers, and features that would require "custom" engineering to implement.

The survey is intended to be periodically updated, and as such has been placed on-line instead of being included here. You can access the document at: http://www.modernstreetcar.org/vehicles.htm